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CLOTHING VENTILATION AND HUMAN THERMAL RESPONSE

by

Lisa M Bouskill

A Doctoral Thesis

Submitted in fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

1999
Abstract

Given the importance of heat balance being maintained between a person and their environment an appropriate clothing choice is essential. Since military personnel are required to work effectively when deployed in any of the world's climates it is important that the thermal protection afforded by their clothing is considered as well as its more obvious protective properties such as those relating to the chemical and abrasive environments.

Clothing descriptions restricted to details of heat and water vapour transfer characteristics alone, as is commonly the case, are recognised as being insufficient. Of particular note, where these data are obtained under 'artificial' conditions, ie intrinsic values, they are unlikely to represent the 'resultant' values as observed when worn by human subjects engaged in actual work tasks. Where intrinsic data are used in predictive standards calculations, to estimate safe work times etc, the workforce under consideration may not always be protected.

One source of change in the thermal properties of clothing, when in the workplace, occurs due to increased convective and evaporative heat transfer at the wearer's skin surface caused by air movement through the clothing. This may occur as a result of wearer body movements or increased environmental air speed. The Ventilation Index has previously been suggested as an accurate and repeatable method for quantifying clothing ventilation characteristics. Although several other measurement techniques have also been suggested, the Ventilation Index is simple (albeit laborious) to conduct, and does not require the use of expensive equipment. Work conducted towards this thesis has shown that the Ventilation Index may be suitable for use in either manikin testing or human studies assessments of clothing.

The aim of this thesis was to investigate the suitability of the Ventilation Index as a measurement technique for the assessment of clothing ventilation characteristics, particularly to consider the relationship between clothing ventilation and wearer physiological responses and to identify the factors which can affect this. The Ventilation Index measurement systems constructed as part of this research have improved on those used previously in similar research. New materials technology has provided an improved air-tight oversuit for use during measurement of the clothing micro-environment (a constant source of frustration, it appears, for previous authors), while extensive calibration of the whole system has proved its accuracy.

Using the Ventilation Index has shown that the ingress and egress of air into and from the clothing micro-environment may induce a physiological response from the wearer of the clothing (chapter 6) such increases in air movement being reflected by a drop in insulation afforded by the clothing (chapter 7). Of particular interest to persons involved in the thermal assessment of clothing, will be the suggestion that clothing may exhibit different ventilation characteristics when tested on a thermal manikin to when worn by human subjects. This difference appearing to be related to clothing fit (investigated in chapter 9). Of interest to wearer's of protective, is the observation that air-impermeable clothing does not necessarily withstand changes in environmental air movement (chapter 10).

The technique is not without criticism. The standard tracer gas technique, used to calculate clothing air exchange rate, considers only air movement occurring next to the wearer's skin. In multi-layer clothing ensembles, the movement of air in clothing layers more distant will change the clothing micro-environment and thus have consequences for the wearer. Preliminary investigation suggests that distribution of nitrogen to each clothing layer should enable assessment of air movement in each of these layers.
STATEMENT

The work presented in this thesis was carried out for the Defence Evaluation Research Agency Centre for Human Sciences (DERA CHS) under CHS contract number 5003 with Loughborough University. Results have been published by Loughborough University as a series of reports (Bouskill et al 1997, Bouskill et al 1998 a, Bouskill et al 1998 b and Jay et al 1998) and have not been used by the Author to obtain other qualifications; they appear in this thesis with the kind permission of the Ministry of Defence. The Author was responsible for the planning and execution of the work with the following exceptions.

The study described in Chapter 9 represents work conducted jointly by the Author and N Sheldon. The Author was responsible for supervision of N Sheldon during this, her BSc dissertation work and for the data analysis of the data as presented in this chapter.

The study described in Chapter 10 represents work conducted jointly by the Author and D R Livingston. The Author was responsible for supervision of D R Livingston during this, her BSc dissertation work and for the data analysis of the data as presented in this chapter.

The study described in Chapter 8 represents work conducted jointly by the Author and O E Jay. The Author was responsible for supervision of O E Jay during this, his BSc dissertation work and for the data analysis of the data as presented in this chapter.

The study described in Chapter 11 represents work conducted jointly by the Author and M Dennis. The Author was responsible for supervision of M Dennis during this, his BSc dissertation work and for the data analysis of the data as presented in this chapter.

The study described in Chapter 7 represents work conducted in conjunction with the National Institute for Working Life, Sweden. The Author was responsible for the VI measurements on both clothing ensembles, and for the clothing insulation measurements made on the GoreTex™ ensemble.
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This thesis was written in the fond memory of my mother, father and my great friend Lorna.
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</tr>
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<td>(Laboratory study 5)</td>
<td></td>
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### Notation

The choice of notation is based on that used by the American Society of Heating, Refrigerating and Air Conditioning Engineers in Chapter 8 of the Handbook Fundamentals (1989).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{cov}$</td>
<td>percentage of body surface area covered by a garment</td>
<td>%</td>
</tr>
<tr>
<td>$A_D$</td>
<td>DuBois body surface area</td>
<td>m²</td>
</tr>
<tr>
<td>$A_R$</td>
<td>effective radiating area of the body</td>
<td>m²</td>
</tr>
<tr>
<td>$C$</td>
<td>convective heat loss per unit body area</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$C_{ambient}$</td>
<td>concentration of ambient air</td>
<td>g m⁻³</td>
</tr>
<tr>
<td>$C_{env}$</td>
<td>tracer gas concentration outside clothing</td>
<td>%</td>
</tr>
<tr>
<td>$C_{in}$</td>
<td>concentration of in-going air</td>
<td>g m⁻³, %</td>
</tr>
<tr>
<td>$C_{mi}$</td>
<td>tracer gas concentration inside clothing</td>
<td>%</td>
</tr>
<tr>
<td>$C_{out}$</td>
<td>concentration of sample air</td>
<td>g m⁻³</td>
</tr>
<tr>
<td>$C_{res}$</td>
<td>dry respiration heat loss per unit body surface area</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>CL</td>
<td>clothed light pumping activity</td>
<td>ND</td>
</tr>
<tr>
<td>CM</td>
<td>clothed maximal pumping activity</td>
<td>ND</td>
</tr>
<tr>
<td>CS</td>
<td>clothed stationary</td>
<td>ND</td>
</tr>
<tr>
<td>DRY</td>
<td>dry heat loss from the skin</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>E</td>
<td>evaporative loss per unit body surface area</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$E_{dif}$</td>
<td>evaporative loss by diffusion through skin per unit area</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$E_{max}$</td>
<td>maximum evaporative potential per unit area</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$E_{res}$</td>
<td>evaporative loss through respiration</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$E_{sw}$</td>
<td>evaporation of sweat secreted due to thermoregulatory control</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$E_{sk}$</td>
<td>total evaporative heat loss from the skin</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$f_c$</td>
<td>clothing area factor</td>
<td>ND</td>
</tr>
<tr>
<td>$F_{cl}$</td>
<td>Burton thermal efficiency factor</td>
<td>ND</td>
</tr>
<tr>
<td>$F_{pcl}$</td>
<td>permeation efficiency factor</td>
<td>ND</td>
</tr>
<tr>
<td>$h$</td>
<td>combined heat transfer coefficient</td>
<td>W m⁻² K⁻¹</td>
</tr>
<tr>
<td>$h_c$</td>
<td>convective heat transfer coefficient</td>
<td>W m⁻² K⁻¹</td>
</tr>
<tr>
<td>$h_e$</td>
<td>evaporative heat transfer coefficient</td>
<td>W m⁻² kPa⁻¹</td>
</tr>
<tr>
<td>$h_r$</td>
<td>radiative heat transfer coefficient</td>
<td>W m⁻² K⁻¹</td>
</tr>
<tr>
<td>H</td>
<td>Height</td>
<td>m</td>
</tr>
<tr>
<td>i.d.</td>
<td>inside diameter</td>
<td>mm</td>
</tr>
<tr>
<td>$i_m$</td>
<td>moisture permeability index (clothing)</td>
<td>ND</td>
</tr>
<tr>
<td>$I_a$</td>
<td>thermal insulation of the boundary layer on a nude person</td>
<td>Clo, m² °C W⁻¹</td>
</tr>
<tr>
<td>$I_{cl}$</td>
<td>intrinsic clothing insulation</td>
<td>Clo, m² °C W⁻¹</td>
</tr>
<tr>
<td>$I_{cle}$</td>
<td>effective clothing insulation</td>
<td>Clo, m² °C W⁻¹</td>
</tr>
<tr>
<td>$I_{elo}$</td>
<td>effective clothing insulation in Clo units</td>
<td>Clo</td>
</tr>
<tr>
<td>$I_{cla,i}$</td>
<td>effective clothing insulation of garment i</td>
<td>Clo, m² °C W⁻¹</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>$I_{ea}$</td>
<td>Resistance of air layer to the transfer of water vapour</td>
<td>m² kPa W⁻¹</td>
</tr>
<tr>
<td>$I_{cl}$</td>
<td>Resistance of clothing to the transfer of water vapour</td>
<td>m² kPa W⁻¹</td>
</tr>
<tr>
<td>$I_t$</td>
<td>Total clothing insulation</td>
<td>Clo, m² o°C W⁻¹</td>
</tr>
<tr>
<td>$k_s$</td>
<td>Thermal conductivity for sensible heat</td>
<td>W m⁻² o°C</td>
</tr>
<tr>
<td>$K$</td>
<td>Heat transfer by conduction</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$K_e$</td>
<td>Thermal conductivity of water vapour</td>
<td>W m⁻² kPa⁻¹</td>
</tr>
<tr>
<td>$M$</td>
<td>Metabolic free energy production per unit body area</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$M$</td>
<td>Measured Nitrogen concentration in sample <em>(applies in calculations by Reischl et al, 1987)</em></td>
<td>%</td>
</tr>
<tr>
<td>o.d.</td>
<td>Outside diameter</td>
<td>mm</td>
</tr>
<tr>
<td>$P_a$</td>
<td>Partial pressure of water vapour in air</td>
<td>kPa</td>
</tr>
<tr>
<td>$P_{cl}$</td>
<td>Saturated water vapour pressure at clothing surface temperature</td>
<td>kPa</td>
</tr>
<tr>
<td>$P_o$</td>
<td>Asymptote of oxygen</td>
<td>ND</td>
</tr>
<tr>
<td>$P_{sa}$</td>
<td>Saturated water vapour pressure at air temperature</td>
<td>kPa</td>
</tr>
<tr>
<td>$P_{sk,s}$</td>
<td>Saturated water vapour pressure at skin temperature</td>
<td>kPa</td>
</tr>
<tr>
<td>$P_t$</td>
<td>Constant such that $P_o - P_t = \text{initial value at time } t = 0$ [36/37]</td>
<td>%</td>
</tr>
<tr>
<td>$Q_{sk}$</td>
<td>Total rate of heat loss from the skin</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$Q_{res}$</td>
<td>Total rate of heat loss through respiration</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>rh</td>
<td>Relative humidity</td>
<td>ND</td>
</tr>
<tr>
<td>$R$</td>
<td>Radiative heat loss per unit body area</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>$R$</td>
<td>Exponential decay parameter of oxygen return curve <em>(applies</em>(time⁻¹)* in equations 36/37)*</td>
<td></td>
</tr>
<tr>
<td>$R_{c,el}$</td>
<td>Intrinsic evaporative resistance of clothing</td>
<td>m² kPa W⁻¹</td>
</tr>
<tr>
<td>$R_{cl}$</td>
<td>Intrinsic thermal insulation of clothing</td>
<td>m² K W⁻¹</td>
</tr>
<tr>
<td>S</td>
<td>Rate of heat storage per unit body area</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>SF</td>
<td>Supply gas flow rate</td>
<td>l min⁻¹</td>
</tr>
<tr>
<td>SN</td>
<td>Semi-nude</td>
<td>ND</td>
</tr>
<tr>
<td>$t_a$</td>
<td>Air temperature</td>
<td>° C</td>
</tr>
<tr>
<td>$t_{aural}$</td>
<td>Aural temperature</td>
<td>° C</td>
</tr>
<tr>
<td>$t_b$</td>
<td>Mean body temperature</td>
<td>° C</td>
</tr>
<tr>
<td>$t_{cl}$</td>
<td>Surface temperature of clothed body</td>
<td>° C, K</td>
</tr>
<tr>
<td>$t_{core}$</td>
<td>Core temperature</td>
<td>° C</td>
</tr>
<tr>
<td>$t_o$</td>
<td>Operative temperature</td>
<td>° C</td>
</tr>
<tr>
<td>$t_r$</td>
<td>Mean radiant temperature</td>
<td>° C</td>
</tr>
<tr>
<td>$t_{sk}$</td>
<td>Mean skin temperature</td>
<td>° C</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Air temperature</td>
<td>K</td>
</tr>
<tr>
<td>TG</td>
<td>Tracer gas concentration</td>
<td>%</td>
</tr>
<tr>
<td>$T_u$</td>
<td>Local air turbulence</td>
<td>%</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>$v$</td>
<td>air velocity (speed)</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$V$</td>
<td>clothing ventilation rate</td>
<td>l min$^{-1}$</td>
</tr>
<tr>
<td>$V_{\text{circ}}$</td>
<td>circulation rate of pump</td>
<td>l min$^{-1}$</td>
</tr>
<tr>
<td>$V_{\text{in}}$</td>
<td>supply rate of gas</td>
<td>l min$^{-1}$</td>
</tr>
<tr>
<td>$V_{\text{vent}}$</td>
<td>ventilation rate</td>
<td>l min$^{-1}$</td>
</tr>
<tr>
<td>$w$</td>
<td>skin wettedness</td>
<td>ND</td>
</tr>
<tr>
<td>$W$</td>
<td>external mechanical work per unit body area</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$W$</td>
<td>weight <em>(applies in DuBois surface area calculation [4]</em>)</td>
<td>kg</td>
</tr>
<tr>
<td>$\varnothing$</td>
<td>Relative humidity</td>
<td>ND</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>emmissivity</td>
<td>ND</td>
</tr>
</tbody>
</table>
Chapter 1
Chapter 1

INTRODUCTION

1.1. Introduction

Humans need to achieve a balance between the amount of heat which they gain from their environment and the amount of heat which they lose to it. This dynamic balance is influenced by exposure to hot or cold thermal environments - the result being reflected in a rise or fall in deep body temperature as the quantity of heat storage within the body changes. Within a narrow range of thermal environments humans are able to initiate thermoregulatory responses such as sweating, shivering, piloerection and vasoconstriction (or dilation) to achieve this thermal balance. Beyond this range, and particularly with long exposure periods, thermal strain will occur, with consequences ranging from mild effects, such as discomfort and reduced productivity, to more severe effects such as hypo- or hyperthermia.

As well as thermoregulatory response mechanisms, humans also show behavioural responses such as seeking shelter or changing clothing choices in order to achieve thermal comfort. Today, in most societies, a thermally comfortable environment can be achieved by using air conditioning and/or heating systems. However, exposure to extreme thermal environments is an increasingly regular occurrence in modern lifestyles, either through outdoor pursuit based leisure activities or as part of the daily working routine. Thermal strain, from hot and cold environments, has been documented for industrial engineers performing maintenance and emergency repair work and for workers from many industries where protective clothing is worn. In some instances this thermal strain may have been, in some part, due to the properties of the (protective) clothing being worn. Military personnel can be called upon to work in extreme thermal environments and should be provided with suitable clothing and equipment, designed to provide adequate protection, in order to be effective when deployed.

Current methods of clothing description are insufficient, usually restricted to details of dry (sensible) heat transfer and evaporative resistance. These descriptions do not always meet clothing-provider (eg the military) and ultimately wearer needs. Values measured artificially, for instance using a standing manikin may provide ‘inappropriate’ data, inaccurate in that the values will invariably be different when worn by humans.
International Standards developed to aid the protection of workers from thermal stress are capable of predicting human thermal responses and thus also the length of time that a worker can safely stay in a given environment (e.g., ISO 7933, 1989). However, while these standards calculate the rates of heat exchange (by conduction, convection, radiation, and evaporation) between a person and their environment, clothing properties are described using 'artificial' values which may lead to a level of inaccuracy in the model outputs. Some calculations assume that the values of the sensible and evaporative resistances required in the calculations can be the 'intrinsic' values measured in laboratory conditions. However, several studies have shown that the values obtained in working conditions - the 'resultant' values can be much lower (Havenith et al. 1990a). Part of this difference may be explained by the increased convective heat transfer caused by air movement through the clothing as a result of wearer movement and wind speed. The use of empirical data to adjust intrinsic insulation values is a dangerous practice which may lead to under- and over-protection of the wearer. It is better to be able to measure the factors which differ between empirical observations and actual situations. As described in this thesis, one source of inaccuracy between 'laboratory values' and 'actual wear values' is the effect of air movement through the clothing.

While clothing properties such as the resistance to heat and water vapour transfer have been extensively investigated, leading to databases of such values being available, comparatively little has been done with respect to the ventilation characteristics of clothing. Air flow through clothing is easily quantified using the Ventilation Index, or similar measurement techniques. Provision of clothing ventilation data, during the design stages and then when manufactured, may reduce the incidence of inappropriate clothing choice. Considering the ventilation properties of clothing in the heat transfer calculations of standards such as ISO 7933, as is already the case for heat and water vapour transfer characteristics, could improve the overall performance of such standards.

Air exchange occurs naturally between a clothing ensemble and the surrounding environment by permeating across the clothing fabrics, the air permeability properties of these fabrics determining the rate of this air exchange. Body movements, even the apparently insignificant movements during breathing, will induce an increase in this air exchange. When the clothing fabrics are air-impermeable a bellows effect (or pumping of air) will be seen with activity; increasing the rate of air exchange above the baseline no-movement level. When the clothing
fabrics are air-permeable a low level of ‘pumping’ may be seen during activity, air exchange mostly occurring directly across the fabrics by permeation.

Cold air entering an ensemble will act as a heat sink, while hot air entering it will raise the temperature of the micro-environment air. The length of time which this air spends in the micro-environment will determine its temperature and water vapour content when it ultimately leaves the ensemble. Where these values are higher when leaving the ensemble, than during the air’s ingress, an amount of heat will be transported away from the wearer, with possible physiological consequences. Birnbaum (1975) suggests that in a cool thermal environment a 100 l min\(^{-1}\) through-flow of air could remove 27.39 W m\(^{-2}\) of heat because of the increased convective and evaporative heat transfer it causes.

Current clothing assessments can include biophysical tests, involving measurements of the heat and water vapour transfer resistance of the clothing fabrics using thermal manikins, and human studies, which may range from small scale climatic chamber tests to larger scale field trials. At present clothing ventilation characteristics are not considered as part of the overall assessment. Such properties could easily be measured during either biophysical tests with thermal manikins or during human studies and field trials. Ventilation rate data obtained from these tests could then be used together with those obtained regarding the clothing’s resistance to heat and water vapour transfer to give a better indication of the clothing’s overall performance.

Several methods for quantifying the ventilation characteristics of clothing are available. The advantage of the Ventilation Index being that it does not require the use of expensive equipment, and that the techniques are generally easy to conduct. Work presented by various authors prior to that given in this thesis, has shown the Ventilation Index to be an accurate method of quantifying clothing ventilation characteristics. Both elements of the Ventilation Index measurement method: the tracer gas dilution method of determining air exchange rate and the air evacuation technique of measuring micro-environment volume, have been demonstrated as being highly repeatable.
1.2 Aims of thesis

The work described in this thesis investigates the suitability of the Ventilation Index as a measurement technique for the assessment of clothing ventilation characteristics. Having established the accuracy and repeatability of the Ventilation Index measurement techniques, the primary aims of this thesis, using the Ventilation Index as a measurement tool, were:

1. Investigate the relationship between clothing ventilation and wearer physiological responses during activity.

2. Assess the effects of increased micro-environment ventilation on the thermal insulation properties of clothing.

3. Quantify clothing ventilation differences between ensembles when worn by human subjects and when tested using a thermal manikin.

4. Assess the effects of ‘external’ factors which influence clothing ventilation characteristics (fit of clothing, and environmental air speed)
Chapter 2
Chapter 2

SUBJECT REVIEW - HUMANS, CLOTHING AND THERMAL ENVIRONMENTS

2 Introduction

2.1 Aim of this overview

a) To give an overview of current knowledge of human thermal responses; the interactions between humans, their clothing and thermal environments.

2.2 General introduction

Heat exchange between humans and their environment occurs according to a dynamic relationship dependant on the characteristics of their thermal environment, the person's clothing and their work rate. When this heat transfer is not balanced it will be reflected by physiological responses. Further, if heat storage within their body is changed and their deep body temperature rises above or falls below a 'normal' range the person may experience thermal strain. The degree and period of exposure will dictate the level of this strain, with consequences to the person ranging from discomfort to potentially life threatening conditions (hyperthermia / hypothermia) emphasising the necessity of achieving thermal balance.

2.3 Defining thermal environments.

It is a fundamental principle that human response to thermal environments is determined by at least six basic parameters. These are the air temperature, mean radiant temperature, air velocity and humidity of the environment, and a person's metabolic heat production and the thermal properties of their clothing (ISO 11399, 1995):

- **air temperature** is the temperature of the air around the human body, expressed in Kelvins ($T_a$) or in degrees Celsius ($t_a$) (ISO 7726, 1985).

- **mean radiant temperature** is the 'uniform temperature of an imaginary enclosure in
which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure’ and is ‘expressed in Kelvins ($T_r$) or in degrees Celsius ($t_r$)’ (ISO 7726, 1985). Two different measures of radiant temperature are commonly taken: mean radiant temperature provides an overall average value while plane radiant temperature provides data relating to the direction of radiant exchange. The later is particularly important where large radiant sources are present at a specific orientation to the body, providing an asymmetric radiant load.

- the absolute *humidity* ($P_a$) of the air characterises any quantity related to the actual mass of water vapour contained in the air and is expressed as pressure (kPa). ‘With regard to exchanges by evaporation between a person and their environment, it is absolute humidity of the air which should be taken into account. This is often expressed in the form of partial pressure of water vapour.’ (ISO 7726, 1985). The term relative humidity ($\varnothing$) is also used, expressing the amount of water vapour in the air in relation to the maximum amount that it could contain at a given temperature. From this, relative humidity is defined as the ratio of the prevailing partial pressure of water vapour ($P_a$) to the saturated water vapour pressure ($P_{sa}$) at that temperature,

$$\varnothing = \frac{P_a}{P_{sa}} \quad \text{ND} \quad [1]$$

where saturated water vapour pressure refers to the point at which no more moisture may be held by the air. The saturated water vapour pressure ($P_{sa}$) at a temperature $t$ ($^\circ\text{C}$) is approximated by Antoine’s equation:

$$P_{sa} = \exp (18.956 - \frac{4030.18}{t + 235}) \quad \text{kPa} \quad [2]$$

- *air velocity* ($v$) is a measure of the magnitude and direction of air movement within an environment. It is expressed in meters per second.’ (ISO 7726, 1985) and for convenience, in thermal assessments, air velocity can be considered to be the ‘mean’ air velocity intensity over an exposure time of interest and integrated over all directions. However, air velocity in an environment will rarely be entirely uniform, for
indoor environments a separate measure, that of turbulence intensity \( (T_u) \), the ratio of standard deviation of the air velocity to the mean air velocity, is often given in addition to the measure of air velocity. The gusting nature of air movement in external environments is often the cause of much discomfort for personnel working outdoors and as such must be considered in its own right.

The various combinations of these measures give three ‘basic’ thermal environments: hot, moderate and cold, with hot and cold environments being further classified as either dry or wet, hence a series of five thermal environments (‘cold wet’, ‘cold dry’, ‘moderate’, ‘hot wet’, and ‘hot dry’).

To fully assess a person’s thermal environment their physiological responses must also be described. These responses are not only dependant on the characteristics of their thermal environment but also on their own physical characteristics (age, ‘size’, body composition, gender and fitness), the task with which they are engaged (metabolic heat production, activity level, period of duration and participation in work-rest schemes) and the clothing being worn (description commonly limited to resistance to heat transfer and water vapour transfer).

2.4 Humans and thermal environments

On the whole, humans exist in moderate thermal environments. Any seasonal variations due to climate are where possible counteracted with the use of artificial heating and / or air conditioning systems. This is the modern-day adaptation of our natural behavioural response of seeking shelter either to provide warmth during cold exposure or to provide shade during hot conditions. Similarly, improved clothing choices now facilitate thermal comfort. Simply adding or removing a layer of clothing can alleviate thermal strain. When this is not possible regulation of heat generated through activity may be implemented ie reducing activity levels when too warm and increasing them when too cold.

Exposure to extreme thermal environments is an increasingly regular occurrence as part of modern lifestyles. This may be as a result of outdoor pursuit based leisure activities or as part of the daily working routine. In the workplace it is often during the course of maintenance procedures or emergency operations, such as repair work, that exposure of personnel to thermal stress is unavoidable. Heat strain is documented due to high ambient and radiant
temperatures; with industrial engineers performing routine maintenance operations in
decommissioned nuclear reactors which have not fully cooled down (Featherstone, 1988), and
similarly with engine room personnel performing emergency repair work onboard ships
(Collins, 1971). When air and water vapour impermeable clothing is worn to protect personnel
from hazardous environments this will further increase thermal strain. Add to this, high levels
of (strenuous) activity, as in the case of some activities of firefighters, and the level of thermal
strain may become unbearable (Mawby and Street, 1985). Medical consequences of heat strain
vary from minor to life threatening, including: heat syncope (fainting), heat stroke, skin
disorders such as prickly heat and dermatitis, heat exhaustion, water depletion dehydration, salt
and electrolyte depletion, heat oedema and local heat injuries (Ministry of Defence Standard
00-35, 1987). At the very least, heat strain reduces the productivity of workers and increases

Cold stress environments are equally hazardous. In particular, exposures to cold environments
tend to be more prolonged than is the case with hot conditions, for example, food preparation
and cold storage workers handle cold materials repeatedly and / or work inside refrigeration
units for long periods (Williamson et al, 1984, Nielsen, 1986, O Leary and Parsons, 1994 and
Bird, 1996). Medical consequences of cold strain range from discomfort, loss of dexterity and
grip strength and local cold injuries to hypothermia (Ministry of Defence Standard 00-35,
1987). Again cold exposure quickly reduces the productivity of workers and also increases the
likelihood of accidents.

2.4.1 Military scenarios - thermal environments
A wide range of climates exist on earth, and military personnel can be called upon to work in
any of them. Individual personnel should be prepared for these environments and should be
provided with suitable clothing, and equipment, in order to be effective when deployed.
Ministry of Defence Standard 00-35 (1987) defines the world’s climates according to their air
temperatures, solar load and humidities. It categorises these climates into hot, warm, cold and
marine as given in Annex A.

In addition, it is recognised that environmental conditions (ambient air temperature, relative
humidity and solar radiation levels) will vary throughout each 24 hour period. An example of
this is given in Table 2.1 - the diurnal cycle for category ‘A’ environmental conditions (from Ministry of Defence Standard 00-35, 1987).

Table 2.1 Diurnal cycle for category ‘A’ environmental conditions (MOD Standard 0035).

<table>
<thead>
<tr>
<th>Local Time (hours)</th>
<th>A1 Ambient temp (°C)</th>
<th>A1 Relative humidity (%)</th>
<th>A1 Solar load (W/m²)</th>
<th>A2 Ambient temp (°C)</th>
<th>A2 Relative humidity (%)</th>
<th>A2 Solar load (W/m²)</th>
<th>A3 Ambient temp (°C)</th>
<th>A3 Relative humidity (%)</th>
<th>A3 Solar load (W/m²)</th>
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</tbody>
</table>
Heat strain / cold strain may arise for personnel, in these conditions, who are inadequately equipped for the hottest or coldest periods of each day (i.e., extreme solar load at midday or cold conditions at night). Knowledge of such environments, in terms of the thermal strain likely to be endured by personnel when deployed is vital if high casualty rates are to be avoided. An indication of thermal strain can be obtained by ‘auditing’ the environment using the human heat balance equation calculations (Parsons 1992).

2.5 The human heat balance equation

As already explained, the sum of the heat generated within the body and that which is gained from the environment must balance with the heat lost to the environment from the body to prevent deep body temperature rising (or falling) above (or below) the recognised ‘safe’ body temperature limits. A dynamic balance between the three mechanisms of heat transfer; ‘heat gain’, ‘heat loss’ and ‘heat generation’ exists and is described by the conceptual heat balance equation. This includes all three elements with heat losses and gains included as one value - either as a net positive or negative value depending on the overall direction of heat transfer:

\[ M - W = E + R + C + K + S \]  \( \text{Wm}^{-2} \) \[3\]

where,

- \( M \) = rate of metabolic heat production (\( \text{Wm}^{-2} \))
- \( W \) = work (output) (\( \text{Wm}^{-2} \))
- \( E \) = heat transfer by evaporation (\( \text{Wm}^{-2} \))
- \( R \) = heat transfer by radiation (\( \text{Wm}^{-2} \))
- \( C \) = heat transfer by convection (\( \text{Wm}^{-2} \))
- \( K \) = heat transfer by conduction (\( \text{Wm}^{-2} \))
- \( S \) = rate of heat storage (\( \text{Wm}^{-2} \))

Here, positive values of \( E, R, C \) and \( K \) represent net heat losses from the body. Conversely, negative values represent net heat gains from the environment. The rate of heat storage within the body must be zero for heat balance (i.e., for the body to remain at a constant temperature). A positive storage rate will result in a rise in deep body temperature while a negative storage rate will result in a drop in deep body temperature.
In order to standardise across people of different ‘builds’ units of Wm\(^{-2}\) are used, where total body surface area is calculated from:

\[
A_D = 0.202 \times W^{0.425} \times H^{0.725} \quad \text{(DuBois and DuBois, 1916)} \quad \text{m}^2 \quad [4]
\]

where,
- \(A_D\) = Dubois surface area (m\(^2\))
- \(W\) = weight of body (kg)
- \(H\) = height of body (m)

2.5.1 Heat generation

The metabolism of food by cells liberates energy as heat. Where activity is undertaken some external work, requiring energy, will be performed. Due to the inefficient operation of many activities the amount of work (energy) is often regarded as zero and any metabolic energy production regarded as being liberated as heat. However, with some activities (eg walking against a gradient) the work value becomes larger and should therefore be considered.

2.5.2 Heat transfer equations

The conceptual heat balance equation may be further refined to provide separate values for heat transfer at the skin and through respiration:

\[
M - W = Q_{sk} + Q_{res} = (C + R + E_{sk}) + (C_{res} + E_{res}) \quad \text{Wm}^{-2} \quad [5]
\]

where,
- \(M\) = rate of metabolic heat production (Wm\(^{-2}\))
- \(W\) = rate of mechanical work (Wm\(^{-2}\))
- \(Q_{res}\) = total rate of heat loss through respiration (Wm\(^{-2}\))
- \(Q_{sk}\) = total rate of heat loss from the skin (Wm\(^{-2}\))
- \(C_{res}\) = rate of convective heat loss from respiration (Wm\(^{-2}\))
- \(E_{res}\) = rate of evaporative heat loss from respiration (Wm\(^{-2}\))
- \(C\) = rate of convective heat loss from the skin (Wm\(^{-2}\))
- \(R\) = rate of radiative heat loss from the skin (Wm\(^{-2}\))
- \(E_{sk}\) = rate of total evaporative heat loss from the skin (Wm\(^{-2}\))
For further analysis, the rate of evaporative heat loss from the skin should be considered in terms of both moisture diffusion as well as sweat transfer:

\[ E_{sk} = E_{sw} + E_{dif} \quad \text{Wm}^{-2} \quad [6] \]

where,

\( E_{sk} = \) rate of total evaporative heat loss from the skin (Wm\(^{-2}\))
\( E_{sw} = \) rate of evaporative heat loss from the skin through sweating (Wm\(^{-2}\))
\( E_{dif} = \) rate of evaporative heat loss from the skin through moisture diffusion (Wm\(^{-2}\))

### 2.5.3 Heat transfer - by respiration

Although not considered in this thesis, heat loss due to respiration occurs by convection and evaporative heat transfer. Here air is inhaled, assumes a similar temperature to that of deep body temperature, and is moistened to saturation before being exhaled.

### 2.5.4 Heat transfer and clothing - Sensible heat loss

Adding a layer of clothing will naturally change the heat transfer mechanisms at the skin’s surface. The mechanisms of sensible heat transfer at the skin (C + R), when clothing is worn, may be represented separately (C) and (R) as follows (ASHRAE, 1989):

- convection heat transfer (C) is dependant on the temperature gradient between clothing and environment (air temperature) and the surface area available for heat exchange to occur:

\[ C = f_{cl}.h_{c} (t_{cl} - t_{a}) \quad \text{Wm}^{-2} \quad [7] \]

where,

\( C = \) rate of convective heat loss from the skin (Wm\(^{-2}\))
\( f_{cl} = \) clothing area factor (ND)
\( h_{c} = \) convection heat transfer coefficient (W m\(^{-2}\) K\(^{-1}\))
\( t_{cl} = \) surface temperature of clothed body (°C)
\( t_{a} = \) air temperature (°C)
- radiative heat transfer (R) is again dependent on the temperature gradient between clothing and environment (radiant temperature) and the area of body covered by the clothing:

\[ R = f_{cl} \cdot h_r (t_{cl} - t_r) \quad \text{Wm}^{-2} \quad [8] \]

where,

- \( R \) = rate of radiative heat loss from the skin (Wm\(^2\))
- \( f_{cl} \) = clothing area factor (ND)
- \( h_r \) = radiative heat transfer coefficient (W m\(^2\) K\(^{-1}\))
- \( t_{cl} \) = surface temperature of clothed body (°C)
- \( t_r \) = radiative temperature (°C)

Combining these elements gives (C + R):

\[ (C + R) = f_{cl} \cdot h (t_{cl} - t_o) \quad \text{Wm}^{-2} \quad [9] \]

given that

\[ t_o = \left( h_r \cdot t_r + h_c \cdot t_a \right) / (h_r + h_c) \quad \text{°C} \quad [10] \]

where,

- \( C \) = rate of convective heat loss from the skin (Wm\(^2\))
- \( R \) = rate of radiative heat loss from the skin (Wm\(^2\))
- \( f_{cl} \) = clothing area factor (ND)
- \( h \) = combined heat transfer coefficient (h = hc + hr) (W m\(^2\) K\(^{-1}\))
- \( h_c \) = convective heat transfer coefficient (W m\(^2\) K\(^{-1}\))
- \( h_r \) = radiative heat transfer coefficient (W m\(^2\) K\(^{-1}\))
- \( t_{cl} \) = surface temperature of clothed body (°C)
- \( t_o \) = operative temperature (°C)
- \( t_r \) = mean radiant temperature (°C)
- \( t_a \) = air temperature (°C)
It is suggested that, for simplicity, the total transfer of heat through clothing (by conduction, convection and radiation) can be combined into a single thermal resistance value ($R_{cl}$):

\[
(C + R) = \frac{(t_{sk} - t_{cl})}{R_{cl}}
\]

where,

- $C$ = rate of convective heat loss from the skin (Wm$^{-2}$)
- $R$ = rate of radiative heat loss from the skin (Wm$^{-2}$)
- $t_{sk}$ = skin temperature ($^\circ$C)
- $t_{cl}$ = surface temperature of clothed body ($^\circ$C)
- $R_{cl}$ = intrinsic thermal insulation of clothing (m$^{-2}$ K W$^{-1}$)

Removing $t_{cl}$ (again for further simplicity) gives:

\[
(C + R) = \frac{(t_{sk} - t_{o})}{R_{cl} + 1/[f_{cl} \cdot h]}
\]

where,

- $C$ = rate of convective heat loss from the skin (Wm$^{-2}$)
- $R$ = rate of radiative heat loss from the skin (Wm$^{-2}$)
- $t_{sk}$ = mean skin temperature ($^\circ$C)
- $t_{o}$ = operative temperature ($^\circ$C)
- $R_{cl}$ = intrinsic thermal insulation of clothing (m$^{-2}$ K W$^{-1}$)
- $f_{cl}$ = clothing area factor (ND)
- $h$ = combined heat transfer coefficient ($h = h_c + h_r$) (W m$^{-2}$ K$^{-1}$)

An estimate, for a standing person, of $h_c$ may be calculated for these equations according to:

- in natural convection:
  \[
h_c = 2.38 (t_{sk} - t_o)^{0.25}
  \]
  (ISO 7933, 1989) Wm$^{-2}$ K$^{-1}$[13]

- in forced convection:
  \[
h_c = 3.5 + 5.2 \sqrt{V_{ar}} \quad \text{for } V_{ar} < 1 \text{ ms}^{-1}
  \]
  (ISO 7933, 1989) Wm$^{-2}$ K$^{-1}$[14]
  \[
h_c = 8.7 \sqrt{V_{ar}}^{0.6} \quad \text{for } V_{ar} > 1 \text{ ms}^{-1}
  \]
  (ISO 7933, 1989) Wm$^{-2}$ K$^{-1}$[15]
where,

\[ V_{ar} = \text{relative air velocity in ms}^{-1} \text{ (i.e. resultant air velocity of components from body movements)} \]

- calculated from:

\[ V_{ar} = V_a + 0.0052 (M - 58) \]  
**(ISO 7933, 1989)**  
ms\(^{-1}\)  \[16\]

where,

\[ V_a = \text{air velocity with respect to a stationary object (ms}^{-1}) \]

\[ M = \text{metabolic rate (Wm}^{-2}) \]

In a similar manner, the radiative heat transfer coefficient \((h_r)\) can be given by:

\[ h_r = \sigma \varepsilon_{sk} A_r \left[ \frac{(t_{sk} + 273)^4 + (t_r + 273)^4}{(t_{sk} + t_r)} \right] \]  
**(ISO 7933, 1989)**  
Wm\(^{-2}\) K\(^{-1}\)  \[17\]

where,

\[ h_r = \text{radiative heat transfer coefficient (Wm}^{-2}) \]

\[ \varepsilon_{sk} = \text{emissivity at the skin surface - assumed to be between 0.95 and 1 (ND)} \]

\[ \sigma = \text{Stefan-Boltzman constant (5.67 x 10}^{-8}) \]

\[ A_r = \text{effective radiating area of the body (m}^2) \]

\[ A_D = \text{Dubois surface area (m}^2) \]

\[ t_{sk} = \text{surface temperature of clothed body (°C)} \]

\[ t_r = \text{mean radiant temperature (°C)} \]

### 2.5.5 Heat transfer and clothing - Insensible heat loss

ASHRAE (1989) provides the following equations to describe evaporative heat loss from the skin \((E_{sk}):\)

\[ E_{sk} = w (P_{sk} - P_a) \]  
\[ (R_{e,cl} + [1 / f_{cl} h_c]) \]  
Wm\(^{-2}\)  \[18\]

where,

\[ E_{sk} = \text{rate of total evaporative heat loss from the skin (Wm}^{-2}) \]

\[ w = \text{skin wettedness (the fraction of wetted skin area) (ND)} \]

- a maximal \(E_{sk}\) value \((E_{max})\) is obtained by substituting \(w\) with 1, i.e. fully wetted skin.
\[ P_{a,s} = \text{water vapour pressure at the skin (normally assumed to be that of saturated}
\text{water vapour at skin temperature)} \text{ (kPa)} \]
\[ P_a = \text{water vapour pressure in the ambient air. (kPa)} \]
\[ R_{e,cl} = \text{evaporative heat transfer coefficient at the clothing surface (m}^2\text{kPaW}^{-1}) \]
\[ f_{cl} = \text{clothing area factor (ND)} \]
\[ h_e = \text{evaporative heat transfer coefficient at the clothing surface (Wm}^{-2}\text{kPa}^{-1}) \]
\[ -(h_e = LR h_e) \text{ where } LR = \text{Lewis Relation} \]

Where the overall heat balance between a person and their environment becomes unbalanced, either because of thermal strain imposed by the environmental conditions, their clothing or the metabolic heat produced in undertaking their assigned task this will be reflected in ‘self defence mechanisms’ ie their physiological and behavioural responses.

2.6 Human thermoregulatory responses

As homeotherms, humans must regulate their deep body temperature within a narrow range around 37 °C. Beyond this range (> 44 °C), proteins within the body become inefficient in performing their specific functions. Deviations of just a few degrees Celsius from the acceptable range result in the changes observed with hypothermia and hyperthermia.

On a cellular level each cell must maintain homeothermy, each cell producing metabolic heat which is transferred to surrounding cells either by conduction, due to temperature gradients, or through convection where the transport is provided by blood or extra-cellular fluid (Chato, 1985). Heat generated within cells will eventually be transferred to the environmental surroundings, the rate of this transfer being governed by the characteristics of the specific body tissues. These characteristics change continually due to age, diet and fitness. Furthermore, the rate of blood flow and the degree of blood perfusion in tissues influences their biophysical properties and as such also the rate of heat transfer. Thus constriction (dilation) of blood vessels, as observed during exposure to cold (or hot) environments will naturally affect the heat transfer within the body between tissues as well as the heat transfer between the surface body tissues and the surrounding environment.

ASHRAE (1989) provides a simple 2-node model of blood flow and heat transfer for the human body based on the work of Gagge et al (1971). This model is limited given that it does
not truly represent the complexity of the range of human thermal responses and added to this the changes due to exercise or physiological responses such as shivering and the over simplicity of the average values from the 2-node model becomes apparent.

In terms of responding to the thermal environment, the human thermoregulatory system consists of ‘sensors’, which provide information regarding the body’s thermal state, and ‘effectors’, which act to reduce any (impending) thermal strain.

2.6.1 Thermosensors in the human thermoregulatory system

The epidermis of the skin is known to contain temperature sensitive free nerve endings (Weddel and Miller, 1962) which, together with other thermosensors (identified) in the hypothalamus and (suggested as being present) in the midbrain, medulla oblongata, spinal cord, blood vessels, the abdominal cavity and a number of other sites (Hensel, 1981) are the ‘sensors’ of the body’s thermal state.

Although not fully understood in terms of structure, central and skin thermoreceptors are said to be either ‘warm’ or ‘cold’ types according to their response to the environment. They respond to both static and dynamic stimuli by changing the firing rate with which they stimulate their associated nerve (Kenshalo 1970, McIntyre 1980 and Hensel, 1981).

Thermosensors connect with the hypothalamus via several nervous pathways; with the anterior hypothalamus being largely responsible for the control of vasodilation and heat loss by sweating while the posterior hypothalamus works to control shivering and vasoconstriction mechanisms. Edholm and Weiner (1981) suggest possible thermoregulatory effector pathways. Additionally, direct heating and cooling of tissues will also create a response from local blood vessels and following prolonged exposure to heat or cold the human endocrine system also becomes able to initiate thermoregulatory changes (Bligh, 1985).

2.6.2 Human thermoregulatory responses to heat exposure

As body temperature rises, sweat is secreted over the skin through eccrine glands located (almost) all over the body’s surface. It is the evaporation of sweat which usually provides the main avenue for heat loss in hot environments, complete evaporation of 1g of sweat removing approximately 2.5 KJ of heat. Where sweat is not successfully removed from the skin’s
surface Edholm and Weiner (1981) suggest that “continually wetted skin reabsorbs water, leading to epidermal swelling and poral closure” which in turn causes a reduction in sweat production. Even in standard working environments when the skin becomes fully wetted, or struggles to evaporate sweat for other reasons, such hidromeiosis may occur.

Vasodilation will also occur during heat exposure, increasing the amount of blood flow near the skin’s surface, up to 25 fold. In doing so skin temperature is raised by the transferral of heat from deep body tissues, which alters the gradient between skin and air temperatures which, providing the environmental temperature is lower than the resulting skin temperature, will increase the convective heat loss from the skin’s surface. Skin temperature, in limited locations, can be further increased by the opening of arterio-venous anastomoses.

Considering the core-shell model suggested by Burton and Edholm (1955), the volume occupied by the core and shell elements vary with the degree of vasodilation. A representation of the core-shell model during vasodilation is given in Figure 2.1

2.6.3 Human thermoregulatory responses to cold exposure
During cold exposure blood vessels (vaso-) constrict to reduce skin temperature thus also lowering the temperature gradient between skin and environment temperatures and so reducing heat loss to the environment. A representation of the core-shell model during vasoconstriction is given in Figure 2.1 Even during maximal vasoconstriction, a small amount of blood still
passes through the vasoconstricted vessels to provide oxygen to cells beyond the area of constriction. These cells will however be at a lower temperature than the ‘body’ temperature and as such are at increased risk of cold injury. The venous return from hands and feet, these cells will commonly be at a lower temperature than that of the ‘body’, passes close to their arterial supply. At the point of this close passage the cold (or at least cooler) venous return is warmed by the arterial supply. This counter-current heat exchange pre-warms cold blood returning to the body’s ‘core’ and thereby limits any drop of deep body temperature.

Exposure to cold environments may also initiate piloerection, the stimulation of body hair follicles to ‘stand on end’; trapping a layer of air, next to the skin, which acts to insulate the body. Even though humans have little body hair it is recognised that piloerection should be considered as an “interactive parameter in determining thermal insulation of clothing” (Parsons, 1993) particularly in ‘still-air’ conditions.

A more noticeable response to cold exposure is that of shivering. Either voluntarily controlled or involuntary when initiated by a drop in deep body and / or skin temperatures, shivering may vary from ‘mild’ to ‘violent’ and can increase metabolic heat production by up to 5 times the basal level, if only for short periods (BOHS, 1996). It is known for shivering to “arrest a fall in body core temperature” but suggested that, in air, the induced body movements may slightly “increase heat loss to the environment” (Parsons, 1993).

2.6.4 Human behavioural responses to heat and cold exposures

In addition to thermoregulatory responses humans also exhibit behavioural responses:

- adding or removing clothing layers
- moving away from a source of discomfort
- changing orientation to a source of discomfort
- changing posture
- increasing metabolic heat production by increasing level of activity
- changing working practices / workplace environments

Hensel (1981) also describes technical regulation, whereby we build shelters and design the ‘micro-climates’ within them. May be in this category we should also include the extensive
clothing development work currently being undertaken with a view to improving ‘working micro-climates’.

2.6.5 Thermal comfort
Humans will naturally strive to achieve the ‘feeling’ of thermal comfort, either by behavioural, technical or thermoregulatory responses to maintain a careful balance between the heat gain and heat loss mechanisms described in section 2.5.

Thermal comfort is described as “that condition of mind which expresses satisfaction with the thermal environment” (ASHRAE, 1966), and as such it is a subjective rather than objective measure. While it is relatively easy to describe different levels of discomfort the description of ‘comfort’ is more difficult. From this, McIntyre and Griffiths (1975) suggest that “thermal comfort occurs when there is a lack of thermal discomfort”. Further to this Fanger (1970) describes four whole body comfort requirements:

a. Sweat rate is within comfort limits
b. Mean skin temperature is within comfort limits
c. Body is in heat balance
d. Absence of local thermal discomfort

The PMV (predicted mean vote) index (Fanger 1970) is used to determine a predicted mean vote of thermal sensation for persons exposed to a given environment. Generated from environmental parameters ($t_a$, $t_s$, $rh$ and $v$) together with estimated values for a person’s metabolic heat production in that environment and their clothing insulation the PMV calculates values based on a 7-point scale (cold, cool, slightly cool, neutral, slightly warm, warm and hot) originally produced from extensive human subject responses during thermal comfort tests.

Allied to the PMV index is the PPD (predicted percentage dissatisfied) index which establishes a quantitative prediction of the number of thermally dissatisfied people among a large group of people placed in these conditions. Dissatisfaction may be caused by warm or cool discomfort of the body as a whole as expressed by the PMV and PPD indices or because of local thermal discomfort. A model of draught rating is also available which provides an estimate of the number of persons thermally dissatisfied due to draft as based on $t_a$, $v$ and $Tu$. 
Discomfort may also occur when engaged in activities with a too high metabolic rate or when heavy clothing is worn. In both these instances the discomfort is likely to have arisen from a build up of sweat within the clothing. This would increase the relative humidity of air trapped between clothing layers and most importantly increase that value for air trapped next to the wearer’s skin. High humidity in this air layer may lead to inefficient evaporation of sweat from the skin’s surface and thus increased skin wettedness. Several studies have concluded that thermal comfort is a function of skin wettedness (Fanger, 1970, Fort and Hollies, 1970 and Gonzalez and Gagge, 1973).

The correlation between mean skin temperature and the reported sensation of thermal comfort has also been extensively documented (Bedford, 1936; Hardy, 1967; Fanger, 1970 and Gagge, Stolwijk and and McIntyre 1980), the relationship between them appearing to be linear for mean skin temperatures in the range 25 °C to 33 °C. Beyond the upper end of this range, mean skin temperature will be affected by local cooling due to sweat evaporation and thus the feeling of thermal discomfort is seen to increase more dramatically as mean skin temperature rises.

International standards recognise the need to assess thermal comfort in terms of PMV and PPD. ISO 7730 (1984), and British Standard BS EN ISO 7730 (1995) include calculation of the PMV and PPD indices as part of thermal environment assessments.

2.7 Computer models of human thermoregulation
Combining the heat balance equation together with environmental and personal variables provides the mathematical base from which the thermal responses of a person, presented with such conditions, can be estimated. Empirically derived models, such as that of Givoni and Goldman (1972, 1973), may be used to predicted heart rates and rectal temperatures.

The main ‘arguments’ against using thermal modelling are: those of incomplete knowledge regarding the interactions between complex physiological and physical responses and of the wide variability both within and between humans. As such models are not fully representative of the situations which they pertain to simulate. This imperfect representation of reality is not necessarily a problem if the imperfections do not significantly affect model outcomes (Parsons, 1993). However, in ‘real situation’ use, model predictions are regarded as poor for cold...
temperatures, and some models poorly predict ‘core’ temperatures and heart rate rises during exercise conditions.

A specific instance where the performance of modelling is ‘dangerously’ poor is that of the International Standard ISO 7933 (1989). ISO 7933 is based on the heat balance equation and was designed to be used to predict levels of thermal strain before persons are actually exposed to the conditions. However, ISO 7933 does not always protect its subjects! As suggested by Ramsey and Chai (1983), models such as ISO 7933 which are used in decision making processes are suitable for offering general guidelines but should also be followed up with other measures, such as workplace assessments, to ensure that workers are indeed protected.

Work to improve current models is ongoing, aiming to reduce any points of inaccuracy by considering human, manikin and other test data. Recent improvements have included work to consider specific anthropometric differences between subjects and to also ‘clothe’ the models so as to allow modelling to take into account the various characteristics of clothing which a subject may be wearing. The current clothing description provided to thermal models is less than ‘complete’ (Neale, 1998). The clothing representation would be improved by providing clothing fit data, air exchange rate (between clothing and environment) data, including multi-layer ensemble characteristics and to provide all data for each individual body / clothing area.

2.8 Summary

The aim of this overview was to provide a discussion of current knowledge of human thermal responses. The importance of quantifying the dynamic transfer of heat which occurs between a person and their environment is evident, with high levels of heat gain from the environment or heat loss to it resulting in thermal strain for that person. Reflecting this, modern lifestyles are mainly lived in thermally neutral conditions by the provision of heating and air conditioning systems and the wearing of suitable clothing.

The rate of heat transfer, between a human and their environment, is ‘directed’ by the thermal characteristics of their clothing, the resistance of the clothing materials to the transfer of heat and passage of water vapour influencing the rate of heat transfer, by conduction, convection, radiation and evaporation, at the skin’s surface and thus determines the characteristics of the clothing micro-environment. It is within this micro-environment that the nude body exists and thus to which any physiological responses are initiated. In extreme conditions, *ie* as is the case
with some protective clothing ensembles where the body is encapsulated in an air and water vapour impermeable and high heat resistant material, the sensible and evaporative heat produced by the body will not be lost to the environment but will instead be trapped inside the protective clothing layer causing thermal discomfort and inducing thermal strain for the wearer.

The movement of air through this micro-environment, either due to permeation directly through clothing materials or by the pumping action generated by body movements, also influences the characteristics of the clothing micro-environment. Evaporative and convective heat transfer will usually be increased as more air is exchanged between the clothing micro-environment and the surrounding air. This increased transfer being beneficial in instances where heat strain occurs because of a build up of heat in the micro-environment, but possibly being detrimental during cold exposures.

The methods for assessment of the thermal properties of clothing are further discussed in Chapter 3 and those for assessment of the ventilation characteristics of clothing is Chapter 4.
Chapter 3
Chapter 3

SUBJECT REVIEW - THERMAL PROPERTIES OF CLOTHING

3 Introduction

3.1 Aims of this overview

a) To give an overview of current knowledge of the thermal properties of clothing; resistance to heat and water vapour transfer and air exchange characteristics.

b) To provide an overview of current clothing test methodologies and their respective contributions during the garment design process.

c) To detail the importance of including the assessment of clothing ventilation characteristics in clothing tests.

3.2 General introduction

As explained in Chapter 2, the heat balance achieved between a person and their environment is dependant on several factors, including their personal characteristics, their clothing, the task being performed and the thermal environment to which they are exposed. All these elements interact and meet in the clothing system, with the thermoregulatory responses of the body and the thermal properties of the clothing determining the clothing microclimate. The nude body exists within and responds to this microclimate.

Clothing provides resistance, to both heat and water vapour transfer, between the wearer and their environment. The interactions between clothing, the wearer and their environment are complex. These dynamic relationships are not yet fully understood and as such are described in relatively ‘incomplete’ terms, with clothing descriptions often restricted to just insulation (sometimes including water vapour permeability) properties. The importance of knowing the (various) characteristics of clothing has long been identified. Indeed, much research has been conducted in this area but with little improvement in how the clothing is ultimately described to
end users. Factors with a recognised effect on the ‘thermal’ properties, and thus the behaviour of clothing include:

a) dry thermal insulation
b) moisture and water vapour transfer through the clothing
c) heat exchange with (and within) clothing (by conduction, convection, radiation, evaporation and condensation)
d) air penetration (eg through fabrics, vents and openings) and pumping effects (eg air exchange caused by body movements)
e) compression (eg caused by high wind or by pressure exerted by ‘outer layer’ clothing / items)
f) subject posture

(Parsons 1993)

3.3 The science of clothing

The effects of the thermal properties of clothing on heat exchange between the wearer and their environment has been extensively investigated in terms of the wearer’s physiological responses and their sensation of comfort. Models and mathematical descriptions of heat and water vapour transfer through clothing are presented here.

3.3.1 The science of clothing - thermal properties

The resistance to heat transfer between the skin and the external surface of the clothing is termed the intrinsic (or basic) insulation of the clothing. First measured in terms of the resistance to heat transfer through the clothing (m²°C W⁻¹) based on the wearer’s body surface area (m²), the temperature gradient between the clothing surface and the wearer’s skin (°C) and the thermal conductance of the clothing (Wm⁻² °C), this has since been supplemented by the term ‘clo unit’ (Gagge et al, 1941). One clo is often described as ‘the thermal insulation required to keep a sedentary person comfortable at 21 °C’, has ‘an average value of 0.155 m² °C W⁻¹’ and ‘is representative of the insulation of a typical business suit.’ The clo value is an estimate of the clothing’s insulation if it were uniformly distributed over the entire body, a factor which may cause difficulty when considering the thermal properties of a clothing ensemble where the insulation is not necessarily distributed in this manner.
The thermal insulation of material can be defined separately in terms of ‘tog units’ (Pierce and Rees, 1946). Here the measurement is made with the material held flat, as opposed to the methodology for clo in which measurements are made with the clothing worn as complete garments and thus hanging ‘off’ the wearer. One tog equates to 0.1 m² °C W⁻¹ where m² refers to the surface area of the material tested, rather than the body surface area of the wearer.

3.3.2 The science of clothing - measuring clothing insulation
Standardised heated flat plates and cylinders or more sophisticated heated manikins are used to measure clothing insulation. By heating the test equipment to a temperature representative of human skin temperature and measuring the heat flow / temperature gradient across a sample of material, placed on top, the thermal resistance of that material can be calculated (Kerslake, 1972; Olesen et al, 1982; McCullough and Jones, 1984; and Wyon et al, 1985). Further descriptions of the methods used to measure, calculate or estimate clothing insulation values are given in Chapter 9.

3.3.3 The science of clothing - clothing insulation, dry heat exchange
Various ‘simple’ models (as per Figure 3.1) have been suggested to describe heated bodies surrounded by a layer of insulation. The obvious clothing thermal insulation provision is from the material fibres which make up the clothing garment(s), this is termed intrinsic insulation (Iᵦ). Studies suggest that insulation gain with increased fabric thickness is between 0.1 and 0.16 clo/mm, depending on the fabric structure and the amount of air trapped within it.

In addition to this, the boundary layer of air which surrounds the clothing, given that it also impedes heat transfer from the wearer to the surrounding environment, must also provide thermal insulation (Iᵦ). The characteristics of this air layer depend largely on the environmental conditions, in particular those parameters which influence heat exchange by convection and radiation:

Considering a nude body;

\[ I_a = \frac{1}{h} \quad \text{(where } h = h_r + h_c) \quad \text{clo} \quad [20] \]

Page 29
where,

- $I_s$: thermal insulation of the boundary layer on a nude person (clo)
- $h$: combined heat transfer coefficient (W m$^{-2}$ K$^{-1}$)
- $h_r$: radiative heat transfer coefficient (W m$^{-2}$ K$^{-1}$)
- $h_c$: convective heat transfer coefficient (W m$^{-2}$ K$^{-1}$)

**Definitions**

- $t_{sk}$: skin temperature
- $t_{cl}$: clothing temperature
- $I_{cl}$: intrinsic clothing insulation
- $I_a$: thermal resistance of air layer.
- $I_T$: total clothing insulation

Figure 3.1 A simple thermal model of a heated body surrounded by an insulation layer.

Adding a layer of clothing increases the surface area from which heat can be lost, i.e., the total surface area of a clothed person is greater than that of a nude person. To reflect this the $I_a$ calculation is adjusted:

$$I_s = \frac{1}{f_{cl} \cdot h}$$

[21]
where,

$I_a =$ thermal insulation of the boundary layer on a nude person (clo)
$h =$ combined heat transfer coefficient (Wm$^{-2}$K$^{-1}$)
$f_d =$ clothing area factor (ND)

However, $f_d$ is difficult to determine; suggested $f_d$ measurement techniques include sophisticated photography and computer aided anthropometric scanning. Alternatively, estimations based on the intrinsic insulation of ensembles can be made (McCullough and Jones, 1984):

\[ f_d = 1.0 + 0.34I_d \] (McCullough and Jones, 1984) \hspace{1cm} \text{ND} \ [22]

\[ f_d = 1.0 + 0.15I_d \] (Fanger, 1970) \hspace{1cm} \text{ND} \ [23]

The total insulation ($I_T$) provided by a clothing ensemble and its boundary air layer is of interest to the clothing designer and is calculated according to:

\[ I_T = I_d + I_a \] \hspace{1cm} \text{clo} \ [24]

Taking into account the increased surface area from which heat may be lost when clothed:

\[ I_T = I_d + I_a \hspace{1cm} \text{therefore} \hspace{1cm} I_T = \frac{I_d + I_a}{f_d} \] \hspace{1cm} \text{clo} \ [25,26]
where,

\[ I_T = \text{total clothing insulation (clo)} \]

\[ I_d = \text{intrinsic clothing insulation (clo)} \]

\[ I_a = \text{thermal insulation of the boundary layer on a nude person (clo)} \]

\[ f_d = \text{clothing area factor (ND)} \]

\[ h = \text{combined heat transfer coefficient (Wm}^{-2}\text{K}^{-1}) \]

The need to incorporate the effects of increased surface area for heat exchange due to the addition of a layer of clothing makes the measurement of clothing insulation complex since \( f_d \) is difficult to measure. Thus the term effective insulation (I_{\text{cle}}) was conceived:

\[ I_{\text{cle}} = I_T - I_a \]

\[ \text{clo} \quad [27] \]

where,

\[ I_{\text{cle}} = \text{effective clothing insulation (clo)} \]

\[ I_T = \text{total clothing insulation (clo)} \]

\[ I_a = \text{thermal insulation of the boundary layer on a nude person (clo)} \]

To simplify all these equations representing dry heat loss from the skin Oohori et al (1984) suggest using the Burton thermal efficiency factor (F_{cl}):

\[ \text{Dry} = F_{cl} \cdot f_d \cdot h \cdot (t_{sk} - t_a) \]

\[ \text{Wm}^2 \quad [28] \]

where,

\[ \text{Dry} = \text{dry heat loss from the skin (Wm}^2\text{)} \]

\[ F_{cl} = \text{Burton thermal efficiency factor (ND)} \]

\[ f_d = \text{clothing area factor (ND)} \]

\[ h = \text{combined heat transfer coefficient (Wm}^{-2}\text{K}^{-1}) \]

\[ t_{sk} = \text{skin temperature (°C)} \]

\[ t_a = \text{air temperature (°C)} \]

In view of the complexity of some of the measurement methods and calculations given, the most widely accepted method for describing dry heat transfer properties of clothing is to use
values of $I_{cl}$. Various databases of $I_{cl}$ values are available world-wide (McCullough and Jones, 1984; Parker and Parsons, 1990 and ISO 9920, 1992). Tables 3.1 and 3.2 show ISO 9920 database entries (measured insulation values) for clothing ensembles and individual garments.

Table 3.1 Example of ensemble database - 'work clothing' description from ISO 9920

<table>
<thead>
<tr>
<th>No</th>
<th>Clothing ensemble</th>
<th>Weight (g)</th>
<th>$f_{cl}$ (ND)</th>
<th>$I_{cl}$ (clo)</th>
<th>$I_{cl}$ ($m^2\cdot{}°C/W$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>122</td>
<td>Briefs 3, T shirt 30, work jacket 153, work pants 90, belt, calf length socks 254, shoes 250</td>
<td>2050</td>
<td>1.39</td>
<td>0.99</td>
<td>0.153</td>
</tr>
<tr>
<td>123</td>
<td>Briefs 3, T shirt 30, Shirt 76, fitted trousers 102, belt, Work jacket 153, work pants 90, calf length socks 254, shoes 260</td>
<td>2628</td>
<td>1.40</td>
<td>1.27</td>
<td>0.197</td>
</tr>
<tr>
<td>125</td>
<td>Briefs 3, Shirt 75, fitted trousers 102, Coveralls 114, Calf length socks 265, shoes 260</td>
<td>1607</td>
<td>1.25</td>
<td>0.96</td>
<td>0.149</td>
</tr>
<tr>
<td>420</td>
<td>Underpants 23, undershirt 31, Shirt 70, trousers 91, Coverall 112, Socks 254, shoes 255</td>
<td>2573</td>
<td>1.31</td>
<td>1.18</td>
<td>0.183</td>
</tr>
<tr>
<td>483</td>
<td>Underpants 47, undershirt 31, shirt 73, Coverall 120, Socks 254, shoes 255</td>
<td>1430</td>
<td>1.30</td>
<td>0.94</td>
<td>0.146</td>
</tr>
</tbody>
</table>

Where a particular (type of) clothing ensemble is not available from ISO 9920 or other databases, Olesen and Dukes-Dobos (1988) suggest that a close estimate of $I_{cl}$ for the ensemble can be obtained by summing the $I_{cl}$ values of the individual garments. However, it must be noted that, this simple method does not take into account the increase in the surface area from which heat can be lost. ISO 9920 provides the following equations to estimate the intrinsic clothing insulation for the clothing ensemble taking into account $f_{cl}$ values:
\[ I_{cl} = I_T - I_s \]
\[ f_{cl} \]
\[ I_{cl} = 0.82 \sum I_{cl} \]

where,

- \( I_{cl} \) = intrinsic clothing insulation for the clothing ensemble (clo)
- \( I_{cl_i} \) = basic insulation for garment i (clo)
- \( I_T \) = total clothing insulation (clo)
- \( I_s \) = thermal insulation of the boundary layer on a clothed person (clo)
- \( f_{cl} \) = clothing area factor (ND)

Table 3.2 Example of garment database - ‘sweater’ description from ISO 9920

<table>
<thead>
<tr>
<th>No</th>
<th>Garment description</th>
<th>Type No</th>
<th>Fabric No</th>
<th>Garment weight (g)</th>
<th>( I_{cl} ) (clo)</th>
<th>( I_{cl} ) (m²°C/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>135</td>
<td>Long-sleeve, V-neck</td>
<td>1</td>
<td>6</td>
<td>215</td>
<td>0.25</td>
<td>0.039</td>
</tr>
<tr>
<td>136</td>
<td>Long-sleeve, V-neck cardigan</td>
<td>2</td>
<td>6</td>
<td>215</td>
<td>0.23</td>
<td>0.036</td>
</tr>
<tr>
<td>137</td>
<td>Short-sleeve, V-neck</td>
<td>3</td>
<td>6</td>
<td>188</td>
<td>0.20</td>
<td>0.031</td>
</tr>
<tr>
<td>138</td>
<td>Long-sleeve, turtle-neck</td>
<td>11</td>
<td></td>
<td>815</td>
<td>0.54</td>
<td>0.084</td>
</tr>
<tr>
<td>139</td>
<td>Short-sleeve, V-neck cardigan</td>
<td>4</td>
<td>6</td>
<td>188</td>
<td>0.17</td>
<td>0.025</td>
</tr>
<tr>
<td>140</td>
<td>Long-sleeve, round-neck cardigan</td>
<td>7</td>
<td></td>
<td>460</td>
<td>0.29</td>
<td>0.045</td>
</tr>
<tr>
<td>141</td>
<td>Sleeveless, V-neck</td>
<td>5</td>
<td>6</td>
<td>130</td>
<td>0.13</td>
<td>0.020</td>
</tr>
<tr>
<td>142</td>
<td>Long-sleeve, round-neck</td>
<td>6</td>
<td>7</td>
<td>424</td>
<td>0.36</td>
<td>0.056</td>
</tr>
<tr>
<td>143</td>
<td>Long-sleeve, round-neck cardigan</td>
<td>7</td>
<td>7</td>
<td>424</td>
<td>0.31</td>
<td>0.048</td>
</tr>
<tr>
<td>144</td>
<td>Short-sleeve, round-neck</td>
<td>8</td>
<td>7</td>
<td>355</td>
<td>0.28</td>
<td>0.043</td>
</tr>
<tr>
<td>145</td>
<td>Short-sleeve, round-neck cardigan</td>
<td>9</td>
<td>7</td>
<td>355</td>
<td>0.22</td>
<td>0.034</td>
</tr>
<tr>
<td>146</td>
<td>Sleeveless, round-neck</td>
<td>10</td>
<td>7</td>
<td>301</td>
<td>0.22</td>
<td>0.034</td>
</tr>
<tr>
<td>147</td>
<td>Long-sleeve, turtle-neck (thin)</td>
<td>11</td>
<td>8</td>
<td>231</td>
<td>0.25</td>
<td>0.040</td>
</tr>
<tr>
<td>148</td>
<td>Long-sleeve, turtle-neck (thick)</td>
<td>11</td>
<td>7</td>
<td>459</td>
<td>0.37</td>
<td>0.057</td>
</tr>
</tbody>
</table>

3.3.4 The science of clothing - clothing insulation, water vapour transfer

The movement of moisture through clothing to the environment becomes an important avenue of heat loss in hot conditions when the wearer undertakes strenuous activities and sweats. A
build up of sweat within the clothing micro-environment is not only uncomfortable for the wearer in terms of 'dampness' but may also increase thermal strain since moisture trapped within the clothing is less readily evaporated than is moisture located on the wearer’s skin surface. Fourt and Hollies (1970) further show that the build up of moisture in clothing correlates well with physical discomfort. Thus the description of water vapour transfer characteristics is of considerable importance when defining clothing properties.

Again a simple model to describe the behaviour of clothing has been suggested (Figure 3.2). It is apparent that this model resembles that for dry heat transfer, the main difference being that as well as considering the temperature gradient between the wearer’s skin, the surface of the clothing and the environment this model also considers the water vapour pressure gradient between these points. In this model, sweat is produced at the skin’s surface, evaporates to form moisture which passes through the clothing ensemble, eventually reaching the surface of the clothing, passing through the boundary air layer and transferring to the environment (in extreme thermal conditions wet clothing may behave differently than described here, and may in some conditions even be protective to the wearer).

Figure 3.2 A simple thermal model showing the resistance to moisture transfer by a layer of insulation surrounding a heated body.

**Definitions**
- $t_{sk}$ - skin temperature
- $t_{cl}$ - clothing temperature
- $I_{ecl}$ - resistance of clothing to the transfer of water vapour
- $I_{ea}$ - resistance of air layer to the transfer of water vapour
- $P_{sk}$ - saturated water vapour pressure at skin temperature
- $P_{cl}$ - saturated water vapour pressure at clothing temperature
In the simplest condition, i.e., a nude body, moisture travels through the boundary air layer only. This represents the maximal evaporation possible between the skin’s surface and the environment:

\[ E_{\text{max}} = h_e(P_{sk,s} - P_a) \text{ Wm}^{-2} \]  \[ 31 \]

where,

\( E_{\text{max}} \) = maximum evaporative potential per unit area (Wm\(^{-2}\))

\( h_e \) = evaporative heat transfer coefficient (Wm\(^{-2}\) kPa\(^{-1}\))

\( P_a \) = partial pressure of water vapour in air (kPa)

\( P_{sk,s} \) = saturated water vapour pressure at skin temperature (calculated from [2]) (kPa)

Taking into account the resistance of the air layer gives:

\[ h_e = \frac{1}{I_{ea}} \text{ Wm}^{2}\text{kPa}^{-1} \]  \[ 32 \]

thus

\[ I_{ea} = \frac{1}{h_e} = \frac{1}{16.5 h_e} \text{ m}^{2}\text{kPa}^{-1} \text{ W}^{-1} \]  \[ 33 \]

where,

\( h_e \) = evaporative heat transfer coefficient (Wm\(^{-2}\) kPa\(^{-1}\))

\( I_{ea} \) = resistance of air layer to the transfer of water vapour (m\(^2\) kPa W\(^{-1}\))

\( h_c \) = convective heat transfer coefficient (W m\(^{-2}\) k\(^{-1}\))

(given that \( h_e = LR h_c \), with \( LR = \) Lewis number)

Add to this the resistance of the clothing layer(s) the maximum heat loss from the skin through the clothing is given as:

\[ E_{\text{max}} = \frac{1}{I_{ea} + I_{cl}} (P_{sk,s} - P_a) \text{ Wm}^{-2} \]  \[ 34 \]
where,

\[ E_{\text{max}} = \text{maximum evaporative potential per unit area (W m}^{-2}) \]

\[ I_{\text{ea}} = \text{resistance of air layer to the transfer of water vapour (m}^2\text{ kPa W}^{-1}) \]

\[ I_{\text{cl}} = \text{resistance of clothing to the transfer of water vapour (m}^2\text{ kPa W}^{-1}) \]

\[ P_{\text{sk,s}} = \text{saturated water vapour pressure at skin temperature (kPa)} \]

\[ P_{a} = \text{partial pressure of water vapour in air (kPa)} \]

\[ f_{\text{cl}} = \text{clothing area factor (ND)} \]

Equations 31 to 34 assume a completely wet body. This is not usually the case, indeed sweating is typically more localised so to account for this partial wetting, skin wettedness is described as \( w \):

\[
    w = \frac{E}{E_{\text{max}}} \quad \text{ND} \quad [35]
\]

where,

\( w = \text{skin wettedness (ND)} \)

\( E = \text{evaporative loss per unit body surface area (W m}^{-2}) \)

\( E_{\text{max}} = \text{maximum evaporative potential per unit area (W m}^{-2}) \)

Thus:

\[
    E = \frac{w}{I_{\text{ea}} + I_{\text{cl}}} (P_{\text{sk,s}} - P_{a}) \quad \text{W m}^{-2} \quad [36]
\]

where,

\( E = \text{evaporative loss per unit body surface area (Wm}^{-2}) \)

\( w = \text{skin wettedness (ND)} \)

\( P_{\text{sk,s}} = \text{saturated water vapour pressure at skin temperature (kPa)} \)

\( P_{a} = \text{partial pressure of water vapour in air (kPa)} \)

\( I_{\text{ea}} = \text{resistance of air layer to the transfer of water vapour (m}^2\text{ kPa W}^{-1}) \)

\( I_{\text{cl}} = \text{resistance of clothing to the transfer of water vapour (m}^2\text{ kPa W}^{-1}) \)
As with the indices aimed at simplifying the dry thermal characteristics of clothing, there are several water vapour permeability indices. It is again debatable whether these indices simplify the situation, indeed it is possible that they actually serve to disorientate the user. Woodcock (1962) proposed (further assessed by Goldman (1988) and Lotens (1988)) the permeability index, \( i_m \), where the sensible and evaporative heat transfer qualities of clothing are compared with those of air. In addition, analogous with the Burton thermal efficiency factor \( F_{cl} \) for dry heat transfer Nishi and Gagge (1970) proposed a permeation efficiency factor \( F_{pc} \) for evaporative transfer. This has since been refined (Lotens and Linde, 1983 and Oohori et al, 1984) to produce the current permeation efficiency equation:

\[
F_{pc} = \frac{1}{1 + 0.344 h_c I_{clo}}
\]

where,

\( F_{pc} \) = permeation efficiency factor (ND)

\( h_c \) = convective heat transfer coefficient (W m\(^{-2}\) K\(^{-1}\))

\( I_{clo} \) = effective clothing insulation (clo)

The models represented in Figures 3.1 and 3.2 over-simplify the true behaviour of clothing. Few clothing ensembles are single-layer in design, so a better representation is to include (at least) two layers of clothing and to represent the movement of moisture through the different layers. Sweat secreted onto the skin rarely evaporates before some is absorbed into the clothing ‘base’ layer. Kerslake (1972) suggests a model which includes evaporation of moisture from within the clothing, based on sweat being held in clothing layers close to the wearer’s skin in a liquid form but as vapour in layers which are closer to the environment.

3.3.5 The science of clothing - clothing insulation, ventilation characteristics

Further description of a clothing system is seen in Figure 3.3 where the layers of air trapped between clothing layers and between the skin and first clothing layer are also included. These air layers contribute significantly to the overall insulation afforded by a clothing ensemble. Movement of air into and out of these air layers will have a large effect on the clothing’s insulation and water vapour transfer characteristics.
Cold air moving into these air layers will act as a heat sink and be warmed by mixing with the warmer air already present. The loss of this air to the environment will result in both sensible and insensible heat losses. Conversely, hot air moving into these air layers (as in the case of fire fighters’ clothing) will cause an increase in the temperature of air trapped within the clothing and most importantly the air trapped next to the skin. The associated fall or rise in skin temperature, in these scenarios, will not only be uncomfortable for the wearer, but prolonged exposure to these conditions is likely to result in thermal strain due to the imbalance of heat transfer to and from the body.

Of the three main avenues of heat transfer from (to) the clothed body two methods depend in particular on there being a sufficient flow of air through the micro-environment (points 2 and 3 described below):

1. Sensible heat can be directly transferred across the clothing ensemble, the quantity depending on the thickness of the clothing layers and the inter-layer gaps.

2. Sensible heat is transferred to the air of the micro-environment which then leaves the clothing, so transporting it away.

3. Insensible heat is transferred to the air of the micro-environment which then leaves the clothing, so transporting it away.

Birnbaum and Crockford, 1978

The development of new fabrics, designed to be both windproof and waterproof allow the movement of water vapour (i.e. evaporated sweat), but because of their windproof qualities micro-environment air is not able to move out of the clothing without permitting the ingress of external air. Thermal strain may occur when wearing such clothing in high activity and / or high (or low) environmental temperature conditions. Adding protective clothing to this type of ensemble will accentuate such heat strain problems, because of the associated reduction of avenues available for heat transfer, which will in turn unbalance the heat transfer occurring between environment and wearer.
Figure 3.3 Schematic model of air exchange between the clothing micro-environment and the external environment.

Crockford, 1988 suggests that the rate of air exchange between the clothing micro-environment (that is all the air trapped within the clothing, including that which is trapped next to the skin’s surface) and the environment is determined by:

a) Air permeability of the fabrics * (chapter 7)
b) Design of garments - * (chapters 6 and 7)
   - number and location of vents / ability to pump air in bellows manner
c) Wearer’s body movements * (chapters 6, 7, 8, 9 and 10)
d) Environmental wind speed * (chapters 7 and 10)
e) Clothing fit - amount of air trapped within the clothing micro-environment * (chapters 8 and 9)
f) Presence of restrictions - such as a belt or harness - which impede air movement through the air layers

Key:  * = discussed in the laboratory experiment chapters of this thesis.
3.4 Protective clothing

One particular clothing type which may benefit from air exchange investigation is protective clothing, since the protective nature of its constituent fabrics can cause heat strain for wearers. Assessment of this clothing in terms of its thermal insulation and water vapour resistance alone provides an incomplete description. Measurement of the rate of air exchange between its micro-environment and the external environment will provide an indication of the amount of sensible and insensible heat which may be transferred by this air movement. These data could then be used in predictive modelling to allow the assessment of safe working times for wearers of the protective clothing.

Many environmental hazards can be overcome by wearing personal protective equipment (PPE). The Health and Safety at Work Act 1974 (HSWA) requires employers to provide measures to ensure the health and safety of their workers “so far as reasonably practicable”. It is usual that health and safety hazards in the work environment are managed primarily by their elimination, use avoidance or hazard control, and where this is not possible, through the provision of personal protective equipment (PPE). The many occupations requiring different levels of protection have lead to a wide variety of protective clothing and personal equipment, with new products being constantly introduced. Worker safety guidelines, recommendations and rules have, for many hazardous situations, been issued by governing agencies such as the Ministry of Defence (MOD), Occupational Safety and Health Administration (OSHA) and Environmental Protection Agency (EPA). PPE standards have also been developed by industry and independent organisations.

All clothing provides some degree of protection from the environment. It often has to meet numerous - probably incompatible - requirements, between which an optimal balance should be held. Reluctance to wearing PPE is often found because of associated wearer discomfort, common ‘problems’ associated with PPE including:

- restrictions to the wearer’s visual field
- hearing impedance
- increased workload - not least due to carrying extra weight from the PPE
- restrictions to the wearer’s mobility
• blocking of some body movements
• increased dressing and undressing times
• effects on body temperature during standing / working times
• effects on body temperature during decontamination time


A well known contradistinction is comfort versus protection, (for example, clothing which protects its wearer from heat and abrasion while also being required to maintain thermal comfort, as in the case of fire-fighters). In such instances, 'which element should take priority - comfort which is appreciated all the time or the protection that is only required during emergencies'. It is acknowledged that military clothing, in particular, has to meet a multitude of such conflicting requirements.

Increasingly hostile working environments, such as those encountered during chemical warfare, fires and other hazardous tasks, require new higher-performance PPE, often fully encapsulating in design. However, the same properties of PPE that protect against a hostile environment also impair the loss of any heat generated by the wearer. Garments having a protective function, which dominates their design and determines the materials used for their construction, are very often thermally uncomfortable, particularly when the wearer is doing physical work (Birnbaum and Crockford, 1978). The clothing design and / or type of fabric used can mean that the body is unable to lose sufficient heat. While it is possible that a proportion of the metabolic heat load can be lost via the head and hands most must be lost from the trunk and in doing so must pass through clothing. The resulting heat (and water vapour) amassed in the PPE, and particularly the undergarment micro-environments, will rapidly increase wearer thermal strain and thus limit the duration for which work can be safely performed. Where PPE systems include protective gloves, head-wear and face-protectors or respirators the loss of any metabolic heat via hands and face becomes impossible.

Possible solutions to overcome this inability to exchange sufficient heat include the provision of conditioned clothing, either air or liquid cooled, (Konz, 1984; Haisman, 1988; Richardson et al, 1988 and Constable et al, 1994;) or the use of other active cooling methods. However, the bulky nature of conditioned clothing usually limits it to use during sedentary tasks (eg driving)
where the provider of the cooling ‘power’ can be mounted separately from the worker. Instances where the worker already wears several layers of clothing, perhaps for protection from a hazardous environment, may also preclude this as a suitable method due to the impairment of limb movements when ‘over-dressed’. Furthermore, the cost and complexity of these systems often renders them unsuitable for many applications.

A more suitable way of alleviating heat strain caused by heat build up in the micro-environment may be to increase the rate of air exchange between the clothing and the environment. Obviously, where the environmental hazard, requiring the use of PPE, is air borne the protective requirements must still be met. Where the hazard is such that the PPE can be constructed of air permeable materials or designed to include suitable air vents, eg if protection is required from a splash hazard only, then safe work times will be extended and wearer comfort, and thus performance and productivity, improved; because of the increased convective and evaporative heat loss to the environment.

3.5.1 ‘Testing’ of clothing - overview

Textile materials are the basic building blocks with which clothing systems are built. It is acknowledged that ideal fibres and manufactured materials for the provision of military protection do not exist, and that nor are they likely to be developed in the foreseeable future.

The objective of current materials research and development is therefore to meet as many of the critical requirements as possible (without creating new problems in the process). A solution to one problem may well create another problem and as such little or no gain would result. For example, where the mass of clothing is increased to improve its durability, problems associated with extra weight, extra bulkiness and reduced moisture vapour transmission away from the body may be encountered.

The assessment of clothing during the development process, should identify any problems with that clothing, either intrinsic to the basic ensemble or caused by modifications to ‘improve’ that basic design. A series of tests are conducted on the fabrics, garments and ultimately the whole clothing ensemble. By iterative process improvements to the clothing will be made, with the not-so-suitable and more importantly the problematic and even ‘dangerous’ clothing designs and ensembles rejected. Umbach (1988) describes this process of assessment in terms of a
triangle (Figure 3.4) The wide base of the triangle signifies the large number of tests conducted and the narrowing to the point at the top of the triangle signifies that increasingly fewer tests are conducted at these advanced stages. The more-advanced tests are inherently more expensive and time consuming to conduct, but provide actual human data from field situations. Thus materials and garments tested at the lower stages must be shown to be effective in their performance before progressing to the higher level tests. As such, many materials and garment designs may be tested at these lower levels before the best ones are put forward for higher level testing.

Figure 3.4. A five-level system for the analysis of the physiological properties of textiles and garments (Umbach, 1988).

3.5.2 ‘Testing’ of clothing - Level 1, Biophysical analysis of clothing

Biophysical tests are available to assess material characteristics such as: thermal resistance, water vapour permeability, wicking and condensation effects, and drying times. As explained, the resistance to heat transfer of the material determines it’s thermal insulation, which as one of the basic properties of the clothing, is of prime interest and is therefore measured at the onset of clothing assessment and development. Measurements of the resistance to heat transfer are made using a flat metal plate heated electrically to be representative of the temperature of the human skin (taken to be 30 °C for cold environments and 34°C for hot conditions). With ambient temperature and air movement held constant, the amount of electrical energy required to maintain this (skin) temperature when the plate is covered with the fabric provides an indication of the thermal resistance of the fabric and thus the insulation it provides. Adding a
reservoir of water to this equipment provides the measurement tool for assessing the fabric's water vapour resistance characteristics and further adaptations of this test set up facilitate the assessment of the fabric with respect to its ability to wick moisture away from the skin's surface, the amount of condensation build up within the clothing and drying times following moisture ingress.

Umbach suggests that the data obtained from biophysical tests has very good agreement with human subject comfort sensation responses during the higher level testing. Higher level tests would not be necessary if Umbach’s confidence in these tests were corroborated by more experimenters! However, this agreement with human subject sensation responses occurs only within a limited range of conditions. So while higher level tests are still necessary, these biophysical tests provide a useful means of identifying textiles which warrant further investigations with such tests.

3.5.3 ‘Testing’ of clothing - Level 2, Manikin tests
Having ‘passed’ the biophysical test assessments the fabrics may be made into garments and tested using thermally instrumented manikins. These simulate ‘real life situations’ more closely than hot plates and flat plates in that they represent the human shape and allow garments and ensembles rather than fabrics to be studied. Again, as with the heated flat plate, the manikin is heated to approximately the temperature of the human skin and with ambient temperature and air movement held constant, the amount of electrical energy required to maintain this (skin) temperature with the manikin wearing a garment (or garments) is measured to provide an indication of the thermal resistance of the fabric and thus the insulation the garment(s) provide(s). Insulation values obtained from this technique include effects due to garment design, clothing drape and fit (looseness). However, as investigated in Chapter 10, the measurements made with manikins do not necessarily replicate those made using human subjects. Complex manikins, capable of sweating, allow the effects of moisture trapped within the clothing to be included in the clothing insulation measurements, but again with limited realism. Sophisticated manikins capable of performing ‘human-like’ body movements will measure clothing insulation with the pumping effect of air within the clothing taken into account. A manikin capable of the full range of movements exhibited by humans and/or able to sweat will be expensive to operate (needing constant maintenance during continual operation) a factor which may preclude manikin testing of garments in some instances.
Measurement of clothing insulation values, using a thermal manikin, can require two separate exposures; one with the manikin clothed to measure the total insulation for that ensemble and the other with the manikin nude to measure the insulation provided by the boundary air layer.

3.5.4 ‘Testing’ of clothing - Levels 3, 4 and 5, Human studies

Three types of human studies (controlled wear test, limited field tests and full scale field tests) may be undertaken in the assessment of clothing characteristics. Following a thermal audit (Parsons, 1992) of a specified thermal environment the conditions found in that environment can be replicated in climatic chamber facilities, such as those at the Defence Evaluation Research Agency Centre for Human Sciences (DERA CHS) and in the Human Thermal Environments Laboratory (HTEL) at Loughborough University. Controlled wear tests, conducted in climatic chambers such as these provide a high level of control, both of subjects and of the thermal environment, but with limited realism.

Once assessed on a small scale the clothing progresses to larger scale field studies, either limited or full scale field tests. These will usually be conducted with persons already familiar with the environment and tasks (ie persons already employed in the relevant ‘field’ - thus the proposed end users of the clothing) wearing the clothing day to day under normal operating conditions. The principle of such tests is to investigate clothing while in actual use and hence to provide practical information.

Considering military clothing, the best evaluation ought to emerge from a field trials during actual military deployment. However, because of the practical difficulties involved, artificial tests are used. These may vary from abstract tests to large scale ‘mock manoeuvres’. As such the major question from such studies is the validity of the test methods for prediction of military performance. Large scale field tests are expensive to conduct and time consuming both for investigators and subjects, thus following controlled wear tests in climatic chambers small scale field trials will be conducted and then if necessary larger scale user trials may follow.

Subjective data recorded in clothing investigations using humans subjects will, in some instances, be just as useful as objective data to the clothing designer. Where a preference between two different ensembles is expressed this will be of particular importance to the clothing designer. Commonly subjective measurements taken during investigations will involve
subjects being asked for their rating of perceived exertion (Borg, 1982), their thermal sensation rating (ASHRAE, 1966) and their rating of thermal discomfort (ASHRAE, 1966). These ratings will normally be requested from the subjects at 10 - 15 minute intervals throughout exposures. The ASHRAE 4 point discomfort scale is shown in Figure 3.5. The ASHRAE 7 point sensation scale is shown in Figure 3.6. The rating of perceived exertion (RPE - Borg scale) is shown in Figure 3.7.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very uncomfortable</td>
<td>4</td>
</tr>
<tr>
<td>Uncomfortable</td>
<td>3</td>
</tr>
<tr>
<td>Slightly uncomfortable</td>
<td>2</td>
</tr>
<tr>
<td>Not uncomfortable</td>
<td>1</td>
</tr>
</tbody>
</table>

![Figure 3.5 ASHRAE 4 point discomfort scale.](image)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>7</td>
</tr>
<tr>
<td>Warm</td>
<td>6</td>
</tr>
<tr>
<td>Slightly warm</td>
<td>5</td>
</tr>
<tr>
<td>Neutral</td>
<td>4</td>
</tr>
<tr>
<td>Slightly cool</td>
<td>3</td>
</tr>
<tr>
<td>Cool</td>
<td>2</td>
</tr>
<tr>
<td>Cold</td>
<td>1</td>
</tr>
</tbody>
</table>

![Figure 3.6 ASHRAE 7 point sensation scale.](image)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
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<td>very very hard</td>
<td>19</td>
</tr>
<tr>
<td>very hard</td>
<td>18</td>
</tr>
<tr>
<td>hard</td>
<td>17</td>
</tr>
<tr>
<td>somewhat hard</td>
<td>16</td>
</tr>
<tr>
<td>fairly hard</td>
<td>15</td>
</tr>
<tr>
<td>very light</td>
<td>14</td>
</tr>
<tr>
<td>very very light</td>
<td>13</td>
</tr>
</tbody>
</table>

![Figure 3.7 Rating of perceived exertion scale (Borg scale)](image)

Discussion exists between investigators who prefer to use human subjects over the data obtained from manikin tests and further with those who prefer to use human subjects in controlled wear tests over field studies. It is suggested that, since manikin techniques need to be further developed to improve replication of human behaviour, using human subjects to evaluate clothing is the only way of providing a realistic and comprehensive evaluation. However, it becomes apparent when considering field trials for the thermal properties of clothing that any evaluation will be context dependant. Isolating only thermal properties will be difficult as they interact with many other factors, such as, ventilation properties, clothing
bulk and fit (ease of movement). When considering the thermal properties of clothing in user trials, therefore, it will be necessary to consider the wider context.

Related to this, is the usefulness of assessing clothing for other, non-thermal, characteristics. Although a majority of biomedical problems with clothing are related to heat and cold strain, the non-thermal characteristics are equally worth considering. As such, the measurement techniques “used depend upon the clothing application, for example, an evaluation of boots may include a measure of the frequency and severity of blisters as well as questions concerning sweating or cold feet” (Parsons 1993).

3.5.5 ‘Testing’ of clothing - Clothing development

Three phases have been identified in the development of clothing and equipment:

1. The determination of the requirements.
2. The technical development, including prototypes.
3. The qualification by the user resulting in a final selection.

Faults in design are unlikely to pass technical evaluation tests with the inclusion of highly experienced subjects preventing imperfections. By employing a wide variety of data collection methods, such as questionnaires, interviews, diaries as well as direct observation of subjects for objective physiological and subjective data the whole ‘picture’ should be obtained.

3.5.6 Translating data between measurement techniques - is it possible?

The ‘use’ of some artificial laboratory measured clothing values as being representative of the clothing when worn by persons undertaking actual work tasks can be dangerous, eg consider the scenario where a clothing ensemble is measured on a stationary manikin the effects of dampening of the fabrics from sweat and of increased pumping of air within the ensemble and between it and the environment due to body movements will not be included in the measured clothing insulation value. Thus, the ability to translate clothing insulation data measured using a thermal manikin (probably standing stationary during the measurements) into data which reflects more accurately the values obtained when the clothing is worn by an ‘active’ human has obvious advantages for the clothing designer. Quantifying the amount of sensible and
insensible heat lost (or gained), by the wearer of a clothing ensemble, due to air movement between it and the environment could provide a method to facilitating this type of translation.

3.6 Summary

The primary aim of this review was to provide details of current knowledge of the thermal properties of clothing and the relevant test methodologies. Models and mathematical descriptions of heat and water vapour transfer and air exchange between the clothing and the environment are available to demonstrate the thermal properties of clothing. Umbach’s five-level system for the analysis of the physiological properties of textiles and garments (1988) describes a recommended system for clothing assessment, beginning with low level biophysical tests of the clothing materials and culminating in more sophisticated human subject measurements. Although not currently included as routine, assessment of clothing ventilation properties is of particular importance considering the potential effects of increased air flow through clothing on the heat transfer balance between wearer and the external environment. Assessment of these properties could be included at any level between 2 and 5, but would provide the most useful data if included as part of the manikin testing and/or human study assessments. The measurement techniques available to quantify the ventilation characteristics of clothing are described in Chapter 4.
Chapter 4
Chapter 4

SUBJECT REVIEW - DEVELOPMENT OF THE VENTILATION INDEX

4 Introduction

4.1 Aims of this overview

a) To give an overview of current clothing ventilation measurement techniques and specifically of the development of the Ventilation Index measurement techniques.
b) To provide a description of the current method of Ventilation Index measurement techniques.

4.2 General introduction

If garments of limited air and water vapour permeability are worn, in hot environmental conditions, then the design of the clothing in so far as it impedes the micro-environment air flow becomes critical in determining heat exchange between wearer and environment. Equally critical is the design of clothing used in cold environmental conditions, where excessive air movement can induce cold thermal strain for the wearer. The ideal situation is one in which the wearer's thermoregulatory system is able to determine their respective heat losses by conduction, convection, radiation and sweat evaporation. Furthermore, sufficient air must flow through the micro-environment to ensure complete (and thus rapid) evaporation of the sweat produced. Hence it is clear that, in certain environments, large quantities of air must flow through the clothing micro-environment if a worker is to remain comfortable within their clothing. Therefore, it is an advantage to the designer to be able to measure the through flow of air in clothing during the development of garments / ensembles and to then determine the effect of different design approaches on that air flow.

4.3 Current methods for assessing clothing ventilation characteristics

Three approaches to measuring the ventilation characteristics of clothing exist. A basic method to quantify air exchange (per minute) between clothing and the surrounding environment is possible through simple gas dilution techniques (described in section 4.4.1). These data alone
provide only a comparison between ensembles. By evacuating the air trapped within an ensemble the volume of air which is available to exchange with the surrounding environment can be measured. Combining these data with those for air exchange rate, quantifies clothing ventilation in terms of a Ventilation Index (VI) (Birnbaum and Crockford, 1978). This method has been investigated, and modified, by several authors (these modifications and the current measurement techniques are detailed in section 4.4) The VI measurement technique is now very accurate and highly repeatable, but is usually conducted to look at whole ensembles, rather than to quantify localised ventilation rates.

Following Crockford’s early work, and in response to industry requests Reischl et al (1987) sought to design a tool which would evaluate design alternatives and reinforce design decisions quickly, cheaply and effectively. As part of this, it was highlighted as necessary to be able to consider regional changes in garment design as separate entities from the overall total ventilation, thus allowing local modifications in the clothing to be assessed. To this end Reischl et al (1987) developed a sensor in which nitrogen gas is pumped diluting the content of the air inside the sensor proportionally with the ventilation in the area of the sensor. The clothing ventilation rates are then calculated using a simple mass-based equation (see section 4.4.4).

Work by Lotens and Havenith (1988) replicated Crockford’s ‘decay curve’ method and found that the decay curves were not of a simple exponential shape, rather that they were a series of curves. In response to this, Lotens and Havenith describe a technique whereby a tracer gas (N₂O) is distributed over the whole body and an average concentration value is recorded for the complete clothed body surface area (see section 4.4.4).

The main advantage of using the Ventilation Index measurement techniques is that it does not require the use of expensive equipment and that they can be undertaken by a relatively unskilled workforce. Havenith (1999) provides a comparison of the clothing ventilation measurement techniques (Table 4.1):
Table 4.1. Comparison of ventilation measurement techniques (Havenith G in Lumley et al., 1991).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>air exchange rate</td>
<td>local ventilation - air exchange rate &amp; air speed</td>
<td>average total ventilation</td>
</tr>
<tr>
<td></td>
<td>micro-environment volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation units</td>
<td>1 min⁻¹</td>
<td>1 min⁻¹ &amp; / or m s⁻¹</td>
<td>1 min⁻¹ m²</td>
</tr>
<tr>
<td>Allows vapour resistance calculation</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Complexity</td>
<td>more complex</td>
<td>simple</td>
<td>more complex</td>
</tr>
<tr>
<td>Amount of work involved in technique</td>
<td>laborious</td>
<td>fast</td>
<td>fast</td>
</tr>
</tbody>
</table>

4.4 Ventilation Index - overview of measurement techniques

Measurement of the ventilation characteristics of clothing, using the Ventilation Index (VI), involves two separate techniques. A tracer gas dilution technique is used to calculate the rate constant (per minute) for air exchange between the clothing micro-environment and the external environment. In addition the volume (litres) of air trapped within the micro-environment, and thus available for this exchange, is measured by evacuating the air from within the clothing.

In simple terms the tracer gas dilution technique, currently used, is based on the calculation of a rate constant, for the time taken for oxygen concentration, in an ensemble, to return to (almost) environmental levels after being reduced to much lower levels by the input of Nitrogen gas. A fuller description of this methodology is given in Chapter 5, section 5.2. The micro-environment volume measurement technique involves an air-tight oversuit being worn on top of the test ensemble, and the air trapped within them being evacuated, firstly until the oversuit lay on top of the test ensemble and then further until the oversuit and test ensemble
are ‘drawn’ tight to the subject’s skin. A fuller description of this methodology is given in Chapter 5, section 5.4

The current techniques differ slightly from those originally developed to measure VI. Several authors have each suggested refinements to these techniques, resulting in the changes seen with the current VI methodology. There is still much scope for improvement to the VI methodology, as discussed in Chapter 12.

4.4.1 Ventilation Index development - tracer gas technique

Air exchange rates have, for many years, been determined in connection with the ventilation of rooms and buildings. In 1896 Hertz proposed a simple method using water vapour concentrations to monitor air movement. Dufton and Marley (1934) and Marley (1935) extended this idea of a ‘tracer substance’ to carbon dioxide (CO₂) and hydrogen (H₂). Later, Collins and Smith (1955) investigated the use of radio-active materials as tracers. In all these studies the method involves releasing a quantity of harmless, monitoreable tracer substance (usually a gas) into a room. Complete mixing with the air takes place and the concentration of the tracer substance is monitored over a period of time as the air within the room (or building) is exchanged with that in the external environment or neighbouring structures (ie. other rooms) either by convection or by mechanical ventilation.

The transfer of this principle to the assessment of clothing was instigated at industrial request (Crockford et al, 1972). A high mortality rate, due to drowning, had been identified amongst fisherman and was largely attributed to their clothing design. Their weather proof outer garments were heavy, and it was suggested that they limited the survival time for the wearer once in the water. The original research outline was to “improve [this] protective clothing so that it not only protected the wearers but it was also able to dissipate heat during periods of high activity by the wearer and yet could keep the wearer afloat during sea immersion”. To fulfil the requirement for facilitating sufficient heat loss during activity, Crockford et al (1972) suggested that convective heat loss, and thus rate of air flow through the clothing, was critical. They developed a tracer gas technique to measure the rate of mixing of micro-environment air with that from the external environment. Initially carbon dioxide was used as the tracer gas, but as an improvement to the methodology this was later replaced by the use of oxygen (gas). The
diffusion of air through fabrics can be quantitatively measured using a simple technique. Placing a layer of test fabric over a container and sealing it securely is the basic equipment required. The container is filled with a tracer gas until the concentration of oxygen within that container is reduced. The tracer gas supply is turned off and the oxygen concentration monitored. The rate of rise in oxygen concentration is related to the air permeability of the fabric. Air exchange rate values, where the exchange occurs only through the fabric (and not through openings at wrists etc, have been obtained in the range of 0.0138 min⁻¹ for air permeable fabrics such as open weave cotton and in the range of 0.00038 min⁻¹ for air impermeable fabrics such as GoreTex (Sullivan et al. 1987a).

Monitoring the micro-environment air mixture of a clothing ensemble provides the basis for the calculation of the air exchange rate for that ensemble as a whole. The oxygen percent versus time curve depicts the turn over rate of the micro-environment air (Figure 4.1) “The tracer gas technique is based upon a number of assumptions:

1. That oxygen and water vapour molecules behave in the same way, in their movement through a clothing system.
2. That the dilution of the sampling system is very fast compared with that of the micro-environment
3. That the air exchange next to the skin is the important exchange rate and not the one(s) between the clothing layers
4. That the volume of sample extracted does not influence the exchange rate or suck down air from higher levels in the clothing
5. That the nitrogen is distributed evenly and starts off at the same value at all sampling points”

Crockford, 1988
The rate of air exchange is calculated from the equation representative of the oxygen time return curve (Crockford et al, 1972). Birnbaum (1975) describes this in detail:

'Let the total volume of gas inside the clothing assembly be $V_T$ litres; this is assumed to be the constant in time. Also let the proportion of oxygen in the micro-environment at time $t$ seconds from the start of the run be $P(t)$, the other $V_T(1-P(t))$ litres being chiefly nitrogen.

The mixing of oxygen and nitrogen inside the micro-environment is exchanged during a run with air from outside which contains a proportion $P_o$ (approximately 21%) of oxygen. We assume that the rate of this exchange is constant in time and that the gas mixture inside the clothing is homogeneous at all times. Gas is also drawn off for sampling at a constant rate. The sum of these two rates will be denoted by $R$ and called the 'exchange rate’, so that $R V_T$ litres of gas per minute are exchanged between the micro-environment and the ambient air.'
It may be shown that $P(t)$, the micro-environment oxygen concentration at time $t$, is satisfied by the differential equation:

$$\frac{dp}{dt} = R(P_\infty - (P_i))$$ \hfill [38]

which integrates to:

$$P(t) = P_\infty - P_1 \exp\left(-Rt\right)$$ \hfill (%) [39]

where,

- $P(t)$ = oxygen concentration at time $t$ (%)  
- $P_\infty$ = asymptote of oxygen (eventual value of $P(t)$)  
- $P_1$ = difference between $P_\infty$ and starting value of $P$  
- $R$ = exponential decay parameter of the curve *ie.* rate at which the curve approaches the asymptote or stability (and as such can be regarded as a measure of the speed of air exchange in the clothing). (time$^{-1}$)

Birnbaum (1975) further suggests that ‘the parameter $R$ may be regarded as a single measure of speed of air exchange in the garment.’ However, Crockford *et al* (1972) suggests that from experiment data ‘the model may actually involve more than one exponential, due to several component air exchange rates attributable to pockets of nitrogen remote from the sampling area, exchanging gas with the rest of the micro-environment relatively slowly’ (Birnbaum, 1975). Having said this, the acceptable conclusion is that this equation ‘nevertheless gives a fairly accurate and easily computed interpretation, and thus justifies its use’ (Birnbaum, 1975)

This technique would prove to be a useful tool in assessing and then quantitatively rating different clothing designs, for example, Crockford, *et al*(1972) were able to assess ‘their’ fisherman’s clothing with respect to the effects of design changes such as adding cuffs that inhibit air flow, or adding a thin lining to trap air as a float rather than including buoyancy pads which would inhibit the transfer of heat during activity periods.
Crockford, 1988, suggests that the advantages of the tracer gas technique are:

1. The results obtained are not influenced by the subject’s physiological state (including fitness or state of heat acclimatisation)
2. The exchange rate is quantified
3. It can look at parts of a garment
4. It is fast
5. It is inexpensive
6. It does not require expensive facilities
7. It does not require (particularly) highly skilled staff
8. It enables the clothing designer to get a feel for those aspects of garment design which determine air exchange

Air exchange rate values are shown in Table 4.2 from Crockford et al (1972). The single-piece ensemble (foamed neoprene boiler suit) had the lowest air exchange rate in the trunk region, complete micro-environment air exchange occurring approximately once per minute, attributable to its air-tight zipper front fastening. The ankles of this ensemble were only partly restricted and thus allowed some air exchange, this being reflected by two complete air exchanges within the trousers every minute. The lowest air exchange rate within trousers occurred with the bibbed trouser and jacket ensemble, because the trousers were elasticated at the ankles, the trousers of the foamed back bibbed trousers and jacket ensemble were not elasticated. The air exchange rate of the jacket in this ensemble was lower than for the bibbed jacket and trousers ensemble because of the added foam restricted air exchange. The duck suit had the highest air exchange rates (~3 per minute) in both regions because of its loose design.

Table 4.2 Air exchange rate values (mean of 2 subjects) from Crockford et al (1972).

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Trunk air exchange rate (min⁻¹)</th>
<th>Trousers air exchange rate (min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foamed neoprene boiler suit</td>
<td>1.05</td>
<td>2.02</td>
</tr>
<tr>
<td>Foamed (3mm / 5mm) back bibbed trousers + jacket</td>
<td>1.31</td>
<td>2.74</td>
</tr>
<tr>
<td>Bibbed trouser and jacket</td>
<td>1.45</td>
<td>1.27</td>
</tr>
<tr>
<td>Duck suit (loose)</td>
<td>3.62</td>
<td>3.55</td>
</tr>
</tbody>
</table>

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However, the air exchange rates calculated by this technique could not be used to make qualitative comparisons between different designs when the clothing micro-environments differed in volume.

4.4.2 Ventilation Index development - micro-environment volume measurement

After considering the possible ways of measuring micro-environment volume an additional measurement, that of micro-environment volume of clothing ensembles, was included in the clothing ventilation work of Crockford and Rosenblum (1974).

For a given clothing ensemble, the actual volume of the clothing micro-environment will change with changes in body position and during activity. When kneeling, sitting or lying in the prone position, the clothing material will be both bunched up and crushed against the wearer’s body. The micro-environment volume is likely to be at its greatest value when the wearer is standing, thus when the clothing material falls off the wearers shoulders, chest and waist. It would be technically difficult to follow postural changes when they occur, so the simpler approach is to standardise on a given body position. Thus micro-environment volume measurements are usually made with subjects adopting the standing position.

Wearing clothing in a ‘windy’ environment may also change its micro-environment volume. Lighter materials can easily be crushed onto the body of the wearer by wind. It is suggested that a 30mph wind exerts a pressure equivalent to 12.7 mm H₂O (Fourt and Hollies, 1970). As with the suggestion of testing in a standardised position, it is also suggested that the clothing micro-environment volumes should be measured under still air conditions.

There are at least two ways of measuring micro-environment volume, indirectly as for example by the dilution of a trace gas; or directly, by measuring the volume of air contained within it. Both methods involve sealing the micro-environment in some way, probably the most straightforward method being to enclose the clothing and wearer (to neck level) in an air tight, lightweight, plastic oversuit. Clothing which extends above the wearer’s neck level are, at the very least, cumbersome to measure because of the air-tight oversuit sealing at that level. The positioning and drape of garments which are worn around, or reach as far as, the neck may need to be adjusted to allow for ‘successful’ sealing of the air-tight oversuit around the neck. Such adjustments may in turn have a small affect on the micro-environment volume of the
ensemble. The micro-environment volume of head-wear, such as hats, helmets etc cannot be measured with the air-tight oversuit because they are worn above the neck level. Other items, such as balaclava helmets, smoke hoods etc should be removed from the ensemble prior to micro-environment volume measurement, as the oversuit will not seal with such items around the neck. Thus these items should also be removed from the ensemble during air exchange rate determinations. Removing such items may affect the air exchange rate for the ensemble; especially if they were designed so as to reduce, or prevent, air movement through neck openings. These changes should be described, and accounted for, when describing the ventilation characteristics of the ensemble following the VI measurement.

Original work by Crockford and Rosenblum (1974) used a lightweight, air-tight plastic oversuit for this. Constructed from 0.17 mm thick PVC sheeting, the oversuit was designed to be light and loose fitting, which together with its lightweight nature meant that the test clothing was subjected to minimal crushing during the early stages of evacuation. The extremities were permanently sealed as part of the oversuit design, entry to the suit being through a front opening which during testing was sealed with surgical adhesive tape. An air-tight seal at the neck was achieved using double-layered 0.25 mm thick latex rubber strips stretched over a ring frame which was then attached to the oversuit by means of a large diameter hose clip. A 100 mm diameter hole cut into the latex allowed for passing of the head of a subject, whilst also maintaining an adequate seal. A tube, welded to the suit at waist height and connected to a water manometer, continuously monitored the pressure inside the suit. A second tube, also welded to the suit at waist height, provided the point of suction from, or inflation of the oversuit. The methodology, suggested by Crockford and Rosenblum in 1974, begins with the extraction of air from the oversuit until the pressure within it was reduced to a negative pressure of 650 mm H₂O, well below atmospheric levels, causing the test clothing ensemble to be crushed onto the body. The suction line was then sealed and the system checked for leaks, by monitoring an influx of external environment air, this would be reflected in changes in the pressure as measured within the oversuit. Small changes in pressure were tolerated as the actual volume of air which could enter before the suit was re-inflated by the metered air supply would only induce small errors. The micro-environment volume was then determined by sucking the over suit down to 650 mm of water gauge, the accuracy of the measurement being ensured by the use of both a water monometer and an inclined monometer (the inclined monometer being used to ensure that the start point of each measurement was correct). After
sealing the suction line, air was fed into the oversuit at a set rate of 3 litres per minute. This re-inflated the micro-environment, the air initially filling the ‘stiff’ clothing layers and then beginning to inflate the lightweight oversuit. The start of the re-pressure in the micro-climate was monitored at 15-second intervals until it approached zero. The subject was then asked to move in such a way as to ‘settle’ the clothing in its normal position and measurements of pressure continued. The oversuit was seen to ‘drop away’ from the test clothing and a plateau observed with respect to micro-environment pressure readings measured within the test clothing. It was considered that the micro-environment was fully re-inflated when the subject’s ‘settling’ movements produced only a transient pressure change while the body was moving after the pressure had returned to zero. The volume of the micro-environment was calculated by multiplying the air flow (inflation) rate by the time taken to reach zero. The equipment set up required for this technique is shown in Figure 4.2.

![Figure 4.2 Equipment set up for micro-environment volume measurement technique (Crockford and Rosenblum, 1974)](image)

Using this technique Crockford and Rosenblum (1974) identified significant differences between different garments (P < 0.01) and between the same garments worn by differently sized subjects (P < 0.01). Birnbaum (1975) suggested that this technique was capable of assessing the effects of the presence of drawstrings, ankle and wrist seals and belts on the
micro-environment volume of clothing, but that these types of restrictions could lead to pockets of air being trapped within this micro-environment volume.

The end micro-environment volume value depends (to a small degree) on how precisely the garment(s) return to their original thickness and drape. The subject shuffling their limbs is intended to aid the restoration of the original state of the clothing, although, in part, the clothing returns to original points because of its compressional resistance. The weight of the clothing material affects the drape and fall of the fabric on the wearer. Obviously, the plastic oversuit will exert some pressure on the clothing when evacuated. Errors in micro-environment volume measurements may occur with very soft garments that lack ‘compressional resistance and resilience’ and as such are therefore sensitive to the presence of the plastic suit. Conversely, high resistance to compression items, such as shoes or boots, will never totally collapse during the micro-environment evacuation. In such instances the micro-environment volume will be under-estimated. It is possible that more accurate and reproducible results may be obtained by using a thinner gauge material for the oversuit and a more sensitive manometer.

The micro-environment volume measurement technique was reviewed and improved by Sullivan et al (1987b). While the original method proposed by Crockford & Rosenblum (1974) specified evacuation of air from the micro-environment, to an internal pressure of 600 mm H₂O, preliminary studies by Sullivan et al (1987b) indicated that an internal pressure of 300 mm H₂O would be sufficient to ensure adequate evacuation of micro-environment air.

With Sullivan et al’s conclusion that the Crockford and Rosenblum approach lead to an over-estimation of the micro-environment volume, the methodology was significantly changed. Unlike the original method, which attempted to monitor the amount of air needed to re-inflate the suit, micro-environment volume was determined only during the evacuation phase. The flow rate, of evacuation, was integrated to obtain the volume of air exhausted. The beginning and end points chosen for volume determinations were -9 and -300 mm H₂O of internal micro-environment pressure, respectively. The beginning point was chosen as -9 mm H₂O since at this point the outer-suit was just in full contact with the clothing assembly. Thus the volume derived from this point to the end of evacuation would represent the amount of air trapped within the clothing micro-environment. However, the value obtained in this procedure would include a given volume due to the compliance of the over-suit. To overcome this problem, the
volume of air recorded due to the compliance of the oversuit was measured by running the system with no test clothing underneath. Where the test clothing was single layer in design, and subjects were allowed to wear their own underwear, this additional measurement meant that the volume of air trapped by this underwear could be measured.

With improvements in materials technology, Angel (1995) was able to improve the micro-environment volume measurement technique further by using a more compliant oversuit. Made of Tyvek C material (Remploy, Merseyside UK), this oversuit exerted less pressure on the test ensemble beneath it, so ensuring that test clothing was not unduly 'squashed' prior to starting the measurement and thus a more accurate volume could be measured.

Micro-environment volume values are given in Tables 4.3 to 4.5 for Crockford and Rosenblum (1974), Birnbaum and Crockford (1978) and Angel (1995) respectively. The results from Crockford and Rosenblum (1974) suggest that the both the tightness of fit of a clothing ensemble and the compressional resistance of its constituent fabrics are related to the micro-environment volume of that ensemble. Loose clothing, such as the fabric lined duck suit, as expected, had a higher micro-environment volume than did the tighter fitting ensembles such as the foamed neoprene coverall ensembles and the shirt, sweater and trousers ensemble. Additionally, the presence of non-compliant materials, such as foam, are also seen to affect the ensemble micro-environment volumes, with the foam lined duck suit having a much lower micro-environment volume than an identical suit which is fabric lined. Results from Birnbaum and Crockford (1978) show the effect of additional clothing layers increasing the ensemble's micro-environment volume since each additional clothing layer traps a layer of micro-environment air. Results of Angel (1995) show the micro-environment volume of a standard protective outer layer ensemble.

Table 4.3 Micro-environment volume values from Crockford and Rosenblum (1974).

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Micro-environment volume (litres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shirt, sweater + trousers</td>
<td>26.2</td>
</tr>
<tr>
<td>Duck suit (foam lined)</td>
<td>23.1</td>
</tr>
<tr>
<td>Foamed neoprene (3mm) coverall</td>
<td>16.3</td>
</tr>
<tr>
<td>Foamed neoprene (5mm) coverall</td>
<td>27.9</td>
</tr>
<tr>
<td>Duck suit + fabric lined</td>
<td>43.9</td>
</tr>
</tbody>
</table>
Table 4.4 Micro-environment volume values from Birnbaum and Crockford (1978).

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Micro-environment volume (litres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracksuit</td>
<td>~ 23</td>
</tr>
<tr>
<td>Foul weather suit</td>
<td>~ 32</td>
</tr>
<tr>
<td>Duck suit</td>
<td>~ 42</td>
</tr>
</tbody>
</table>

Table 4.5 Micro-environment volume values from Angel (1995).

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Micro-environment volume (litres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goretx single layer suit</td>
<td>19.4</td>
</tr>
</tbody>
</table>

4.4.3 Ventilation Index development - calculating VI

Algebraic combination of air exchange rate and micro-environment volume values by Birnbaum and Crockford (1978) lead to the air exchange characteristics of clothing being described in terms of the Ventilation Index. A term which misrepresents what it actually describes, since it does not provide values as an index:

\[
\text{Ventilation Index} = \text{Micro-environment volume} \times \text{Air exchange rate} \quad \text{[38]}
\]

\[
\text{(litres per minute)} \quad \text{(litres)} \quad \text{(per minute)}
\]

Birnbaum and Crockford (1978)

In their review of clothing ventilation, Lumley et al (1991) describe the Ventilation Index, including the improvements to the micro-environment volume measurement technique suggested by Sullivan et al (1987b), as 'a quantitative, relatively inexpensive, fast, reliable and repeatable technique. Furthermore, [suggesting] it could be used in context, in the working environment to predict the effectiveness, performance and suitability of garments and clothing ensembles'.

Using the Crockford VI methodology, Thomas (1983) extended the range of test items to include continental quilts (sewn up to make sleeping bags), given that the importance of thermal comfort during sleep had been identified and thus the thermal properties of sleeping materials (eg quilts) were to be analysed. In this study, the micro-environment volume and ventilation characteristics of the items were assessed and correlated with the insulation
provided to the user. Subjective responses from the subjects were also assessed in comparison with the quilt’s ventilation characteristics, and as expected, showed an appreciable relationship.

4.4.4 Other clothing ventilation measurement techniques

An alternative method of assessing clothing ventilation characteristics is provided by Reischl et al (1987) with their development of a sensor in which nitrogen gas is pumped into the micro-environment at the same flow rate as a sample in close proximity is simultaneously extracted. Thus there is no pressure differential generated within the clothing. The nitrogen gas dilutes the content of the air inside the sensor proportionally with the ventilation in the area of the sensor. (So where ventilation in the clothing is zero the nitrogen concentration will be 100%.) Each ventilation measurement takes 45 seconds, so to ensure accuracy of the technique several replicated measurements are made, the technique still remaining quick to carry out. The clothing ventilation rates are calculated using a simple mass-based equation:

\[
VR = \frac{TG \times SF - SF}{M} \quad 1 \text{ min}^{-1} \quad [41]
\]

where,

VR = Clothing ventilation rate (l min\(^{-1}\))

TG = Tracer gas concentration (%)

SF = Supply gas flow rate (l min\(^{-1}\))

M = Measured nitrogen concentration in sample (%)

Although this technique allows regional ventilation characteristics of clothing to be assessed, it is also limited in that these data should be used with extreme care. The regional ventilation values represent the situation within that localised area only, ventilation rates in areas very close to these may be substantially different to those recorded, eg ventilation rates near clothing openings and where fabric characteristics allow more air exchange by diffusion will be higher. Combining these values to produce a total ventilation rate for the whole clothing ensemble may therefore give misleading information. Again because of this regional approach the technique will not be suitable for use to calculate the vapour resistance properties of the clothing, a calculation possible when a whole ensemble ventilation rate is obtained.
As already explained, work by Lotens and Havenith (1988) replicated Crockford’s decay curve method and found that the decay curves were not of a simple exponential shape, rather that they were a series of curves. This was explained by the fact that clothing is not a first-order system, ie it consists of several coupled compartments (be these layers, limb segments etc) each with different ventilation characteristics. In response to this, Lotens and Havenith (1988) describe a technique whereby a tracer gas (N₂O) is distributed over the whole body and an average concentration value is recorded for the complete clothed body surface area according to the following equation:

\[
Vent = \frac{(inflow + circ) \left(C_{in}/C_{out} - 1\right)}{1 - C_e/C_{out}} \text{ } 1 \text{ min}^{-1} \tag{42}
\]

where,

\(Vent\) = Ventilation rate (1 min\(^{-1}\))

\(inflow\) = flow of pure trace gas (1 min\(^{-1}\))

\(circ\) = circulating flow (1 min\(^{-1}\))

\(C_{in}\) = concentration of in-going air, in distribution harness (g l\(^{-1}\))

\(C_{out}\) = concentration of sample air, in sampling harness (g l\(^{-1}\))

\(C_e\) = concentration in immediate environment (background concentration, g l\(^{-1}\))

This technique is fast but can be expensive to set up since it is easiest to conduct using a mass spectrometer. The flow rates used may be quite large, and even given that the extracted air is re-circulated, this may change the natural ventilation characteristics of the air trapped with the layers of air trapped between clothing layers as well as those of the layer of micro-environment air trapped next to the wearer’s skin.

More recently, Anttonen et al (1997) presented work using Lotens and Havenith’s method (1988) with CO\(_2\) as the tracer gas, to quantify the effects on ventilation and clothing insulation of adding vents in the outer layer of a cold weather ensemble. As with the Lotens and Havenith (1988) method, the method adopted by Anttonen et al (1997) does not require clothing micro-environment volume measurements, instead of this the clothing ventilation characteristics are calculated from tracer gas flow rates and concentrations (within the clothing and outside), ventilation is calculated using an equation derived from that of Lotens and Havenith (1988):
\[ V_{\text{vent}} = \frac{(V_{\text{in}} + V_{\text{circ}}) (C_{\text{in}} - C_{\text{mi}})}{(C_{\text{mi}} - C_{\text{env}})} \text{ } \text{1 min}^{-1} \text{ [43]} \]

where,

\( V_{\text{vent}} \) = ventilation rate (\text{1 min}^{-1})
\( V_{\text{in}} \) = supply rate of tracer gas (\text{1 min}^{-1})
\( V_{\text{circ}} \) = circulation rate of pump (\text{1 min}^{-1})
\( C_{\text{in}} \) = input tracer gas concentration (%)
\( C_{\text{mi}} \) = tracer gas concentration inside clothing (%)
\( C_{\text{env}} \) = tracer gas concentration outside clothing (%)


VI data from Birnbaum and Crockford (1978) show that an air-permeable clothing ensemble (foul weather suit) had a much higher ventilation rate than did an air-impermeable ensemble (duck suit). In both ensembles, increased environmental air velocity gave higher VI values as measured within the clothing next to the wearer's skin. Similarly, VI was increased with activity. The lowest values recorded for both ensembles were measured in still air conditions during a slow pacing activity. VI would be expected to be lower than these if the measurements had been made with the wearer standing stationary.

Table 4.6 Ventilation Index values from Birnbaum and Crockford (1978)

<table>
<thead>
<tr>
<th>Clothing ensemble</th>
<th>Air velocity</th>
<th>Activity</th>
<th>VI (1 min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foul weather suit</td>
<td>still air (&lt;0.2 ms(^2))</td>
<td>slow pacing</td>
<td>45.4</td>
</tr>
<tr>
<td></td>
<td>still air</td>
<td>jog-trotting</td>
<td>99.2</td>
</tr>
<tr>
<td></td>
<td>wind @ 10 knots</td>
<td>slow pacing</td>
<td>108.7</td>
</tr>
<tr>
<td></td>
<td>wind @ 10 knots</td>
<td>jog-trotting</td>
<td>113.8</td>
</tr>
<tr>
<td>Duck suit</td>
<td>still air (&lt;0.2 ms(^2))</td>
<td>slow pacing</td>
<td>18.6</td>
</tr>
<tr>
<td></td>
<td>still air</td>
<td>jog-trotting</td>
<td>44.7</td>
</tr>
<tr>
<td></td>
<td>wind @ 10 knots</td>
<td>slow pacing</td>
<td>48.7</td>
</tr>
<tr>
<td></td>
<td>wind @ 10 knots</td>
<td>jog-trotting</td>
<td>63.0</td>
</tr>
</tbody>
</table>
These data are corroborated by the findings of Reischl et al (1987), who shows VI is lowest (in all regions of measurement) when standing but increases (again in all regions) during activity. An important difference between human and manikin measurements is also highlighted given that clothing ventilation properties are shown to be different when worn by human subjects and by a thermal manikin.

Table 4.7 Ventilation values (1 min⁻¹) from Reischl et al (1987)

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Manikin / human activity</th>
<th>Leg ventilation</th>
<th>Arm ventilation</th>
<th>Chest ventilation</th>
<th>Back ventilation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-shirt</td>
<td>manikin</td>
<td>13.5</td>
<td>17.0</td>
<td>5.6</td>
<td>5.6</td>
<td>41.7</td>
</tr>
<tr>
<td></td>
<td>stood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>human</td>
<td>10.6</td>
<td>16.7</td>
<td>0.7</td>
<td>2.6</td>
<td>30.6</td>
</tr>
<tr>
<td></td>
<td>stood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>human</td>
<td>57.1</td>
<td>56.3</td>
<td>2.5</td>
<td>3.3</td>
<td>119.2</td>
</tr>
<tr>
<td></td>
<td>walk (1.5 mph)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>human</td>
<td>117.0</td>
<td>56.3</td>
<td>2.7</td>
<td>4.2</td>
<td>180.2</td>
</tr>
<tr>
<td></td>
<td>walk (2.5 mph)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-shirt + workshirt</td>
<td>manikin</td>
<td>12.9</td>
<td>6.8</td>
<td>2.9</td>
<td>3.5</td>
<td>26.1</td>
</tr>
<tr>
<td></td>
<td>stood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>human</td>
<td>11.7</td>
<td>5.0</td>
<td>0.2</td>
<td>1.7</td>
<td>18.6</td>
</tr>
<tr>
<td></td>
<td>stood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>human</td>
<td>57.1</td>
<td>6.3</td>
<td>2.0</td>
<td>3.2</td>
<td>68.8</td>
</tr>
<tr>
<td></td>
<td>walk (1.5 mph)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>human</td>
<td>117.0</td>
<td>4.7</td>
<td>2.1</td>
<td>3.5</td>
<td>127.3</td>
</tr>
<tr>
<td></td>
<td>walk (2.5 mph)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.7 (continued) Ventilation values (l min⁻¹) from Reischl et al (1987)

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Manikin / human activity</th>
<th>Leg ventilation</th>
<th>Arm ventilation</th>
<th>Chest ventilation</th>
<th>Back ventilation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-shirt + workshirt + workpant</td>
<td>manikin stood</td>
<td>8.5</td>
<td>5.5</td>
<td>1.9</td>
<td>2.6</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>human stood</td>
<td>6.4</td>
<td>5.2</td>
<td>0.2</td>
<td>0.2</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>human walk (1.5 mph)</td>
<td>27.1</td>
<td>7.1</td>
<td>2.3</td>
<td>3.8</td>
<td>40.3</td>
</tr>
<tr>
<td></td>
<td>human walk (2.5 mph)</td>
<td>37.1</td>
<td>6.7</td>
<td>2.5</td>
<td>4.4</td>
<td>50.7</td>
</tr>
<tr>
<td>T-shirt + workshirt + workpant + coverall</td>
<td>manikin stood</td>
<td>6.4</td>
<td>5.7</td>
<td>0.3</td>
<td>1.3</td>
<td>13.7</td>
</tr>
<tr>
<td></td>
<td>human stood</td>
<td>4.5</td>
<td>4.8</td>
<td>0.2</td>
<td>0.7</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>human walk (1.5 mph)</td>
<td>27.1</td>
<td>7.1</td>
<td>0.7</td>
<td>2.6</td>
<td>37.5</td>
</tr>
<tr>
<td></td>
<td>human walk (2.5 mph)</td>
<td>37.1</td>
<td>7.5</td>
<td>1.4</td>
<td>2.5</td>
<td>48.5</td>
</tr>
<tr>
<td>T-shirt + workshirt + workpant + coverall + apron</td>
<td>manikin stood</td>
<td>6.4</td>
<td>5.2</td>
<td>0.2</td>
<td>0.6</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td>human stood</td>
<td>3.8</td>
<td>4.2</td>
<td>0.1</td>
<td>0.7</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>human walk (1.5 mph)</td>
<td>27.1</td>
<td>6.7</td>
<td>1.3</td>
<td>2.0</td>
<td>37.1</td>
</tr>
<tr>
<td></td>
<td>human walk (2.5 mph)</td>
<td>27.1</td>
<td>8.3</td>
<td>2.3</td>
<td>2.5</td>
<td>40.2</td>
</tr>
</tbody>
</table>
Lotens and Havenith (1988) continue the measurement of regional ventilation properties of clothing and further demonstrate the effect of adding a gap between clothing and wearer. The increased ventilation when this gap is present demonstrates a limitation of the Reischl et al approach, this being that if their sensors are located within a loose area of clothing the ventilation rate calculated will be higher than if it were measured in a tighter fitting area, i.e. if sensors are located in the middle of the back of a garment then the ventilation rate would be higher than if the measurement were made closer to the shoulders where the garment fabrics will ‘fall onto’ the wearer more.

Table 4.8 Ventilation values from Lotens and Havenith. (1988)

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Activity</th>
<th>Ventilation (l min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacket (closed)</td>
<td>5kmh⁻¹ walk &amp; 2ms⁻¹ wind</td>
<td>56.0</td>
</tr>
<tr>
<td>Trousers (closed)</td>
<td></td>
<td>149.0</td>
</tr>
<tr>
<td>Jacket (closed) with spacer</td>
<td></td>
<td>125.0</td>
</tr>
</tbody>
</table>

Havenith et al (1990), using their tracer gas method with Argon gas, continued the investigation of the effects of activity and environmental air velocity showing that both factors can greatly increase clothing ventilation. For each ensemble, subjects in the sitting position had the lowest ventilation rates. The data measured in this study show that the outermost clothing layer is the limiting factor for the ensemble’s ventilation characteristics, given that adding an air-impermeable outer layer (rain coverall) lowers the ensemble’s ventilation rate considerably.

Table 4.9 Ventilation values from Havenith et al (1990)

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Activity</th>
<th>Air velocity (ms⁻²)</th>
<th>Ventilation (l min⁻¹) ± 1 SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpants, polo shirt + sweater</td>
<td>Sitting</td>
<td>0</td>
<td>69.6 ± 25.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>97.1 ± 44.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1</td>
<td>258.3 ± 273.4</td>
</tr>
<tr>
<td></td>
<td>Stood</td>
<td>0</td>
<td>77.2 ± 20.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>105.1 ± 36.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1</td>
<td>270.2 ± 259.7</td>
</tr>
<tr>
<td></td>
<td>walking (0.3 ms⁻¹)</td>
<td>0</td>
<td>101.3 ± 12.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>125.9 ± 26.1</td>
</tr>
</tbody>
</table>
Table 4.9 (continued) Ventilation values from Havenith *et al* (1990)

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Activity</th>
<th>Air velocity (ms(^{-2}))</th>
<th>Ventilation (I min(^{-1})) ± 1 SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpants, polo shirt + sweater</td>
<td>walking (0.3 ms(^{-1}))</td>
<td>4.1</td>
<td>269.8 ± 287.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>walking (0.9 ms(^{-1}))</td>
<td>0</td>
<td>123.8 ± 15.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>140.7 ± 22.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1</td>
<td>276.2 ± 217.6</td>
</tr>
<tr>
<td>Workpants, polo shirt, sweater + coverall</td>
<td>Sitting</td>
<td>0</td>
<td>43.0 ± 17.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>89.1 ± 48.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1</td>
<td>236.1 ± 273.8</td>
</tr>
<tr>
<td></td>
<td>Stood</td>
<td>0</td>
<td>56.1 ± 13.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>85.7 ± 37.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1</td>
<td>237.0 ± 101.4</td>
</tr>
<tr>
<td></td>
<td>walking (0.3 ms(^{-1}))</td>
<td>0</td>
<td>86.3 ± 18.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>113.7 ± 58.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1</td>
<td>221.0 ± 38.2</td>
</tr>
<tr>
<td></td>
<td>walking (0.9 ms(^{-1}))</td>
<td>0</td>
<td>128.6 ± 28.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>149.6 ± 35.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1</td>
<td>252.2 ± 126.9</td>
</tr>
<tr>
<td>Workpants, polo shirt, sweater + rain coverall</td>
<td>Sitting</td>
<td>0</td>
<td>7.2 ± 3.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>11.0 ± 1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1</td>
<td>63.0 ± 7.6</td>
</tr>
<tr>
<td></td>
<td>Stood</td>
<td>0</td>
<td>11.3 ± 3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>23.3 ± 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1</td>
<td>120.6 ± 15.6</td>
</tr>
<tr>
<td></td>
<td>walking (0.3 ms(^{-1}))</td>
<td>0</td>
<td>20.0 ± 2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>27.0 ± 2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1</td>
<td>124.0 ± 13.9</td>
</tr>
</tbody>
</table>
Table 4.9 (continued) Ventilation values from Havenith et al (1990)

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Activity</th>
<th>Air velocity (ms(^{-2}))</th>
<th>Ventilation (l min(^{-1})) ± 1 SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpants, polo shirt, sweater + rain coverall</td>
<td>walking (0.9 ms(^{-1}))</td>
<td>0</td>
<td>49.4 ± 4.5</td>
</tr>
<tr>
<td>''</td>
<td>''</td>
<td>0.7</td>
<td>55.3 ± 3.5</td>
</tr>
<tr>
<td>''</td>
<td>''</td>
<td>4.1</td>
<td>156.2 ± 18.3</td>
</tr>
</tbody>
</table>

Assessments of standard work wear types of clothing has shown air-permeable ensembles can have ventilation rates as high as \(\approx 276\) l min\(^{-1}\) (Havenith et al) while air-impermeable ensembles can have ventilation rates as low as 7.2 l min\(^{-1}\) when the wearer is sedentary (Havenith et al, 1990). Ensembles with air-tight protective functions would be expected to have lower ventilation rates than these. Sullivan et al (1987) investigated the ventilation properties of four types of helicopter crew immersion suits. In accordance with the nature of these suits, i.e. to protect the wearer during water immersion, they each had very low ventilation rates. As expected, the suits which were slightly air impermeable (but which upon immersion in water would become air tight) had the greatest ventilation rates.

Table 4.10 Ventilation values from Sullivan et al (1987).

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Ventilation (l min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goretex helicopter crew suit</td>
<td>(\approx 0.028)</td>
</tr>
<tr>
<td>Cotton ventile helicopter crew suit</td>
<td>(\approx 0.914)</td>
</tr>
<tr>
<td>Nomex / Insulite helicopter crew suit</td>
<td>(\approx 0.068)</td>
</tr>
<tr>
<td>Nomex coverall helicopter crew suit</td>
<td>(\approx 1.534)</td>
</tr>
</tbody>
</table>

The data reported by Angel (1995) clearly demonstrates the effect of increased activity on the ventilation rates within a single-layer, air-impermeable, protective outer ensemble.

Table 4.11 Ventilation values from, Angel (1995).

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Activity</th>
<th>Ventilation (l min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goretex single layer suit</td>
<td>Standing</td>
<td>(\approx 6.18)</td>
</tr>
<tr>
<td>''</td>
<td>Stepping</td>
<td>(\approx 15.0)</td>
</tr>
<tr>
<td>''</td>
<td>Rotate limbs</td>
<td>(\approx 14.44)</td>
</tr>
</tbody>
</table>
Anttonen et al (1997) also investigate the effects of activity, as well as those of increasing environmental air velocity, on clothing ventilation properties, their study considering these effects using an air-permeable 3-layer ensemble. The effects of adding vents within the ensemble are also considered, showing that adding vents increases clothing ventilation rates in moving air conditions but did unexpectedly reduce it in low air movement conditions.

Table 4.12 Ventilation values from Anttonen et al (1997).

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Air velocity (ms⁻¹)</th>
<th>Activity</th>
<th>Ventilation (L/min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-layer winter ensemble</td>
<td>1</td>
<td>Standing</td>
<td>without vents = 86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>with vents = 77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stepping</td>
<td>without vents = 145</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>with vents = 139</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Standing</td>
<td>without vents = 452</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>with vents = 539</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stepping</td>
<td>without vents = 488</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>with vents = 584</td>
</tr>
</tbody>
</table>

4.5 Heat exchange by clothing ventilation

"From a physiological aspect, the rate of through-flow of air in the micro-environment has a pronounced effect on the removal of excess heat from the body" (Birnbaum, 1975). As well as acting as a heat sink cold air whilst inside the clothing micro-environment will be heated by the surrounding micro-environment air and, depending upon it’s starting water vapour pressure, may absorb any water vapour present due to sweating (depending on the temperature of the micro-environment). (Conversely warm environmental air entering clothing will act to raise the temperature of the micro-environment air and again may change the water vapour pressure of the micro-environment air.) Birnbaum (1975) calculated that 100 L/min⁻¹ of air exchange between a clothing ensemble and the environment (tₐ = 15 °C, rh = 60 %, still air) could remove 49.3 W (27.39 Wm⁻² for a person with a Dubois surface area of 1.8m²) by evaporative cooling. The effects of this through-flow of air on convective heat exchange would be expected to increase the figure for heat removal.
4.6 Summary

The primary aim of this overview was to demonstrate the variety of approaches available for the assessment of clothing ventilation characteristics, with particular attention to the Ventilation Index methods. In summary, the comparison of these methods showed that while the techniques described by Reischl et al (1987) and by Lotens and Havenith (1988) were usually less laborious and may be simpler to conduct they required the use of expensive equipment. Work previously conducted in the Human Thermal Environments Laboratory (HTEL) (Angel, 1995) had shown the Ventilation Index measurement techniques to be highly repeatable. This work provided the HTEL with sets of equipment for measurement of the air exchange rate and micro-environment volume of clothing. In view of this fact, and because the method described by Reischl et al required the development of a measurement sensor while the method described by Lotens and Havenith is best conducted using a mass spectrometer (not available, at HTEL, at this time), the Ventilation Index measurement techniques were chosen as the basis for the work described in this thesis. The original (Angel, 1995) measurement systems, together with the adjustments, adaptations and other changes made to them, during the course of the work described in this thesis is described in Chapter 5.
Chapter 5
Chapter 5
CONSTRUCTION AND CALIBRATION OF TEST EQUIPMENT.

5 Introduction

5.1 Aim of this chapter

a) To describe the equipment used in the air exchange rate and micro-environment volume measurement techniques of the Ventilation Index.

5.2 General introduction

A Ventilation Index measurement system had previously been developed jointly between the Human Thermal Environments Laboratory (HTEL), Loughborough University and the Defence Evaluation Research Agency Centre for Human Sciences (DERA CHS), Farnborough (Angel, 1995). Although largely acceptable, this system was shown to have some practical deficiencies during the experimental work of this current research. Adjustments, adaptations and other changes to the system are detailed here.

5.3 Tracer gas technique

The tracer gas technique, as described by Birnbaum and Crockford (1978) makes several assumptions about the equipment used:

- The sampling of the tracer gas is uniform.
- The distribution of nitrogen is uniform throughout the clothing ensemble, such that when tracer gas sampling begins all sampling points have the same start value.
- The volume of sample extracted does not influence the exchange rate or suck down air from higher levels in the clothing (ie, outer layers in multi-layer clothing).

5.3.1 Nitrogen distribution system - tubing network

The ‘basic’ nitrogen distribution tubing system consisted of a set of six 5mm internal diameter flexible silicon tubes (order code 330 834, RS Components Ltd, Corby, UK). These were sealed at their distal ends and were perforated every 100 mm by orthogonal pairs of 1mm i.d. holes. Extensive development work by Angel (1995) ensured that a tubing system constructed in the manner described here, provided a uniform distribution of nitrogen around the clothing micro-environment. The nitrogen distribution tube system specifications are given in Table 5.1,
note, the tubes supplying the arms were not perforated for the first 300 mm to avoid excessive nitrogen being supplied across the chest area. The nitrogen distribution tubing system is shown in Figure 5.1

Table 5.1 Nitrogen distribution tube system specifications.

<table>
<thead>
<tr>
<th>Body segment</th>
<th>Number of tubes</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arms</td>
<td>2</td>
<td>1300</td>
</tr>
<tr>
<td>Chest</td>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>Back</td>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>Legs</td>
<td>2</td>
<td>1000</td>
</tr>
</tbody>
</table>

Figure 5.1 Nitrogen distribution tubing system.

5.3.2 Nitrogen distribution system - manifold

The existing 'Angel' nitrogen distribution systems consisted of various manifolds, each of different design and size specifications. For this research a standard moulded distribution manifold was developed. This could either be mounted to the standard sampling manifold (Figure 5.7) or located separately to avoid unnecessary disruption of the clothing micro-environment. The moulded distribution manifold is shown in Figure 5.2 The combined, moulded distribution and sampling manifold is shown in Figure 5.3.
5.3.3 Nitrogen distribution system - nitrogen supply

A single 9mm i.d. non-kink flexible silicon tube emerged from the manifold in the Angel studies. Although described as 'non-kink', this tube was prone to kinking when required to twist through layers of a clothing ensemble, often invalidating data during experimental runs. In addition when higher flow rates of nitrogen were required, for instance when the clothing had a high baseline ventilation rate (e.g., air permeable clothing), the silicon tubing was found to expand (balloon out) and was liable to split with very high flow rates. To overcome these problems, the new moulded manifolds also included an elbow joint onto which a reinforced flexible 6mm i.d. (11mm o.d.) PVC Nalgene tube (Nalge Company, Rochester, New York, USA) was connected. This reduction in internal diameter of the outlet tubing would reduce the dead space (air trapped within the tubing system) and thus improve response time for the system. However, the length of this tubing was increased to allow more distance between subject and experimental measuring equipment, thus the problem of time-lag due to dead space was not overcome.

Nitrogen was provided from a bottled nitrogen (100%) supply. A flowstat between subject and nitrogen bottle regulated nitrogen flow rate. The baseline flow rate was set to 15 l/min⁻¹ (nitrogen cylinder gauge = 34.4 KPa), although this was increased as necessary where the baseline ventilation characteristics of the clothing being assessed were higher than this value. Details of such adjustments are given separately for individual experiments. Calibration was always conducted using the Flowstat and a calibrated Gapmeter (type - lab kit, Croydon, UK).
A T-junction located in-line between nitrogen bottle and subject provided an entry point for the oxygen analyser exhaust gasses. Thus giving a complete circuit system during the tracer gas measurements and negating any effects due the removal of the micro-environment air samples.

An overview of the nitrogen distribution and tracer gas sampling systems during nitrogen distribution stage is given in Figure 5.4

Figure 5.4 Nitrogen distribution and tracer gas sampling systems during nitrogen distribution stage.

5.3.4 Nitrogen distribution system - Location of tubes (subjects and manikins)
The location of tubes during subject (or manikin) instrumentation is given in Figure 5.5 Tubes were affixed to subject skin or manikin surface using Micropore tape (3M Health Care, UK). Care was needed to ensure that the Micropore tape did not obstruct any holes along the length of the tubes and that the holes did not point directly towards the subject’s skin.
5.3.5 Tracer gas sampling system - tubing network

The ‘basic’ tracer gas tubing system consisted of a set of ten 1.5mm i.d. flexible PVC tubes of equal length (1050 cm) and open at their distal ends. Work previously conducted in the Human Thermal Environments Laboratory at Loughborough University showed, by water displacement, that each tube provided a similar flow of air (Angel, 1995). An assumption made with the tracer gas technique is that the oxygen sampling system samples equally at all sampling points. The inherent flexibility of the PVC tubing allowed for ‘easy’ fixation of the sampling tubes to the subject’s skin / manikin surface, however these tubes were prone to kinking, either following prolonged coiled storage or from pressure of overlaying clothing during experimentation. In such instances the uniform sampling of air was prevented. Trials to test various types of tubing showed that teflon tubing i.d. 1.5 mm, o.d 3.2 mm (Order number 003011, Omnifit, Cambridge, England) provided a compromise between the flexibility required, when attaching the tubes to subjects for experimentation, and the rigidity required to prevent kinking. A comparison of tracer gas air exchange rate values obtained using both tubing systems (described in chapter 4) showed little difference between them (air exchange rate = 1.41 min⁻¹ with existing PVC system, air exchange rate = 1.38 min⁻¹ with ‘new’ teflon system). Furthermore, in terms of practical significance this represents a difference less than
that which is measurable using the air exchange rate measurement technique. The teflon tubing system is shown in Figure 5.6

5.3.6 Tracer gas sampling system - manifold

The existing ‘Angel’ tracer gas sampling systems consisted of various manifolds, each of different design and size specifications. For this research a standard moulded sampling manifold was developed. This could either be mounted to the standard distribution manifold (Figure 5.2) or located separately to avoid unnecessary disruption of the clothing micro-environment. The moulded tracer gas sampling manifold is shown in Figure 5.7

A single 5mm i.d. flexible silicon outlet tube connected to the ‘Angel’ manifolds emerged from the clothing system at waist level. However this was prone to kinking when required to twist through layers of a clothing ensemble, often invalidating data during experimental runs. To overcome this problem, a non-kink flexible 3mm i.d. (6mm o.d.) PVC Nalgene tube (order code ST02-005G, Nalge Company, Rochester, New York, USA) was used and connected to
the outlet from the manifold. This reduction in internal diameter of the outlet tubing would reduce the dead space (air trapped within the tubing system) and thus improve response time for the system. However, the length of this tubing was increased to allow more distance between subject and experimental measuring equipment, thus any slight response time-lags due to dead space were not overcome.

5.3.7 Tracer gas sampling system - vacuum pump and oxygen analyser.

The manifold outlet tube was connected to the air inlet line of a Charles Austin Dynamax 30 pump (29/94, Charles Austin pumps Ltd, Weybridge, UK). As with Angel’s study, the flow rate from this pump was calibrated to be 0.3 l min⁻¹ using a calibrated G.A. Platon Gapmeter (type - lab kit, Croydon, UK) and periodically by water displacement. Such a small sampling rate was acceptable during experimentation as it would not influence the air exchange rate.

A 3mm i.d. non-kink, flexible, PVC tube connected the air outlet line of the pump to a Sybron/Taylor - Servomex oxygen analyser (type OA580, Taylor Instrument Analytics Ltd, Servomex (UK) Ltd, Crowbrough, UK). This was calibrated, to 1% accuracy, prior to each experimental session using both 100% Nitrogen supply and a known 20% oxygen supply. The oxygen analyser output was connected to a Grant 1200 Series squirrel data-logger (order code 1201, Grant Instruments Ltd, Cambridge, UK).

The exhaust flows from the analyser’s sample cell and by-pass were joined together via a ‘y’ connector and led by a single 5mm i.d. non-kink flexible silicon tube to a three-way valve. This controlled the analyser exhaust flow into the nitrogen feed line and the atmosphere. During tracer gas measurements this valve was closed to the atmosphere to ensure that air removed during sampling was also returned to the clothing micro-environment. This ensured that the micro-environment remained constant through experimentation and as such that the tracer gas sampling had minimal effect on the air exchange rate exhibited by the clothing. Beyond the three-way valve 5mm i.d. tubing connected with a stop-tap attached to the nitrogen distribution system. During the distribution of nitrogen, throughout the clothing ensemble, this stop-tap was switched to the off position to prevent back pressure pushing through to (and damaging) the oxygen analyser. With the stop-tap in the off position the three-way valve was turned to exhaust to the environment in order to prevent a build up of pressure in the oxygen analyser sample cell and by-pass system.
An overview of the nitrogen distribution and tracer gas sampling system during the tracer gas sampling stage is given in Figure 5.8

Figure 5.8 Nitrogen distribution and tracer gas sampling system during the oxygen sampling stage.

5.3.8 Tracer gas sampling system - Location of tubes (subjects and manikins)

The location of tubes during subject / manikin instrumentation is given in Figure 5.9 Tubes were affixed to subject skin / manikin surface using Micropore tape (3M Health Care, UK). Care was needed to ensure that the Micropore tape did not obstruct the ends of the tubes and that the ends of the tubes were not located too close to any neighbouring nitrogen distribution system tubes.

5.3.9 Calculation of air exchange rate

Prior to flushing the clothing through with nitrogen the oxygen analysers and Dymax vacuum pumps were switched on. The 3-way valve(s) was switched to ensure that any back pressure from the nitrogen supply did not damage the oxygen analysers. The clothing was then flushed through with nitrogen and the oxygen concentration within the base layer monitored. When this reached 10% the nitrogen supply was turned off and the 3-way valve turned such that the exhaust flow(s) from the oxygen analyser(s) was directed back into the clothing ensemble via the nitrogen distribution system. The time taken for the oxygen concentration to return to (almost) environmental levels was recorded. For simplicity this was taken to be 18 % (as
opposed to 21% as would normally be quoted as the environmental level). In experimental terms this saved time without influencing the air exchange rate results obtained. Figure 5.10 shows a subject undergoing the tracer gas technique.

The method used to calculate the rate of air exchange is given in Chapter 4.

Figure 5.9 Tracer gas sampling system sites.

Figure 5.10 Tracer gas technique in operation.
Between successive runs subjects opened jacket zips etc and 'ruffled' their clothing to ensure no pockets of nitrogen were trapped in the clothing and thus to ensure that the next run was not affected by such pooling.

5.4 Micro-environment volume measurement technique

The micro-environment volume measurement technique has been considered difficult and 'cumbersome' by numerous authors. The technique described here represents the latest (best) method. This is an air evacuation technique, as opposed to the re-inflation technique of the early Crockford work, using a new material technology air-tight oversuit.

5.4.1 Air-tight oversuit

The existing ‘Angel’ air impermeable oversuit was constructed from Tyvek C material (Remploy, Merseyside UK) and had a limited ‘use-life’ given that the suit seams were prone to parting after just a few experiment runs. For the work detailed in this thesis several air impermeable oversuits were constructed, this time from Tyvek F material (Remploy, Merseyside UK), using seam sealing technology which increased the suit’s user-life. The limbs of these suits were extended and sealed at their distal ends. Entry into the suit was via a reinforced diving zip, to guarantee an air-tight seal once closed, located diagonally across the rear of the suit. A diving neck seal ensured an air tight seal at the subject’s neck, and was further reinforced using sleek tape where the neck seal was not held to the wearer’s skin tightly or where the wearer had slight facial hair (shaving stubble) and thus a totally air tight seal was not obtained using the neck seal alone. This oversuit was made sufficiently large so as to eliminate the possibility of the oversuit being in contact with any test ensemble worn underneath it, prior to evacuation of the micro-environment air during testing. Thus the micro-environment volume recorded during testing would not be affected by crushing of the test ensemble by the oversuit.

5.4.2 Oversuit manifolds

Two manifolds were secured through the suit at waist level, these were designed such that the manifold dimensions inside the suit were : 6mm i.d. and 9mm o.d. and outside the suit were 6mm, i.d. and 12 mm o.d. Inside the suit the right-hand side manifold connected through an elbow joint adapter to a flexible non-kink PVC tube (approximately 800 mm in length with i.d. 8mm and o.d. 12mm). This tube then connected through another elbow joint adapter to the
manifold of the air removal tubing system worn next to the subject’s skin. For convenience this system is the same as that used for nitrogen distribution during the tracer gas technique (see section 5.2.1)

5.4.3 Connection to vacuum pump and dry gas meter

Outside the suit the manifold was connected to a non-kink PVC tube (1450 mm in length, with i.d. 12 mm and o.d. 15 mm.). A shut-off tap was located in this tube to allow for testing of the system’s ability to withstand the required vacuum pressure (see section 5.4.5). The distal end of this tube was connected, through a chamber of silica gel drying agent, to a vacuum pump (type MZ2C, Vacuubrand GMBH.CO, W. Germany) and then to a dry gas meter (Harvard diaphragm type - order code 6162, Cranlea Medical Electronics, Birmingham, UK.).

5.4.4 Micro-environment pressure monitoring equipment

A non-kink flexible tube (length 1000 mm and i.d. 5mm, perforated at 100mm intervals with orthogonal pairs of 1mm i.d. holes) was located down the inside of the left trouser leg of the ensemble during instrumentation. Where several layers of clothing were worn this tube was located between the subject’s skin and the first layer of the ensemble. This was connected to the inside of the left-hand side oversuit manifold. The outside of this was connected to a vertical U-tube monometer via a non-kink flexible tube of length 2250 mm and i.d. 8 mm (o.d. 12 mm).

5.4.5 Calculation of micro-environment volume

The volume of air contained within the ensemble was determined by evacuating the total air trapped. Subjects donned the air-tight oversuit on top of the test ensemble. Air was evacuated from this suit until pressure, as recorded from the perforated tube fed down the ensemble left trouser leg and attached to a U-tube manometer, began to change. This was taken to be the point at which the oversuit had been evacuated and lay on top of the ensemble. Further evacuation until no more air could be removed from the suit took place (pressure = -300 mm H₂O), the amount of air being evacuated in the process being taken to represent the micro-environment volume. Figure 5.11 shows a subject undergoing the technique to measure micro-environment volume.
5.5 Calibration of equipment

Prior to and again following each test session each item of test equipment used was calibrated. The calibration techniques for each item of test equipment are detailed in sections 5.5.1 to 5.5.6.

5.5.1 Nitrogen supply flow rate calibration

The flow rate of the nitrogen gas into the clothing, measured using a flow-stat, was calibrated using a G.A. Platon Gapmeter (type - lab kit, Croydon, UK) and by water displacement.

5.5.2 Oxygen analyser calibration

The oxygen analyser (resolution of 1%) was calibrated first by passing through oxygen free nitrogen (100 % N₂) to obtain a zero measure and then passing through a known oxygen concentration gas (20 %) to obtain a known O₂ concentration measure.
5.5.3 Dynamax vacuum pump calibration

The Dynamax vacuum pump was calibrated using a G.A. Platon Gapmeter (type - lab kit, Croydon, UK) and water displacement, to ensure that the rate of sampling of micro-environment air during the tracer gas technique was constant throughout testing and at a low level (0.3 l min⁻¹) as the volume of air extraction would be included in the VI obtained during testing.

5.5.4 Squirrel data logger calibration

Prior to testing each Squirrel data logger (resolution 1 mV, ie 1% O₂ concentration) was preset with the correct time and date and checked for adequate battery life. The value displayed on the data logger screen was also checked against that displayed on the oxygen analyser.

5.5.5 Dry gas meter calibration

The dry gas meter was calibrated using a known volume syringe (3 l). The syringe was connected to the dry gas meter and its contents expelled into the dry gas meter. The reading on the dry gas meter display was then checked for accuracy. This procedure was repeated several times, each time expelling the syringe one more time, until the range of volumes expected to be measured during the micro-environment volume technique had been ‘included’.

5.5.6 Full system calibration

Passing nitrogen gas through a clothing ensemble at a known flow rate to simulate ventilation and measuring the Ventilation Index of that ensemble during this period provided a means of calibrating the whole measurement technique. These calibration VI measurements were made using the test Goretex ensemble (described in chapter 6), being worn by a ‘standard’ shop mannequin. Calibration calculations of VI involved several repetitions of the ‘standard’ measurement of the clothing micro-environment volume (typical micro-environment volume values, when worn by this manikin are shown in Table 5.2), but an adapted air exchange rate was calculated using the tracer gas technique equipment.
Table 5.2 Sample micro-environment volume data, measured with a 'standard' shop mannequin wearing a Goretx™ leisure suit.

<table>
<thead>
<tr>
<th>Run No</th>
<th>Micro-environment volume (litres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.4</td>
</tr>
<tr>
<td>2</td>
<td>32.6</td>
</tr>
<tr>
<td>3</td>
<td>33.3</td>
</tr>
<tr>
<td>4</td>
<td>32.4</td>
</tr>
<tr>
<td>5</td>
<td>32.8</td>
</tr>
<tr>
<td>Mean</td>
<td>32.7</td>
</tr>
<tr>
<td>1 SD</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The rate of air exchange, during whole system calibration, was calculated from the time taken for oxygen concentration within the clothing to drop from 18% to 10% when nitrogen gas was flushed through the clothing ensemble at a known flow rate (Figure 5.12). Using equation 39 (Chapter 4) the rate of air exchange was calculated according to:

\[
\text{air exchange rate} = \frac{-\ln (P_a - P_t)}{P_t} \cdot \left(\frac{60}{t}\right) \text{ (min}^{-1}\right) [44]
\]

where,
- \(P_t\) = difference between \(P_a\) and the initial value at time \(t = 0\)
- \(P_a\) = asymptote of oxygen (eventual value of \(P(t)\))
- \(P(t)\) = oxygen concentration at time \(t\) (%)
- \(t\) = duration of measurement (s)

Since the clothing ensemble used in these calibrations is not entirely air tight (ie it is a 2-piece ensemble with openings at the wrists and neck of the jacket and at the ankles of the trousers) there will be some air exchange which occurs between the ensemble and the environment during the input of nitrogen gas. The calibrations have shown that this air exchange means that it is unlikely that the oxygen concentration within the ensemble will be reduced below \(\sim 3\)%.

Thus in equation 44, \(P_0\) (the eventual value of oxygen concentration) was taken to be 3%.
Air exchange rate calculations were repeated 3 times for each nitrogen gas input flow rate and an average air exchange rate calculated (Table 5.3). The Ventilation Index for the ensemble, during each calibration run, was calculated by combining the ensemble’s mean micro-environment volume with its mean air exchange rate for that flow rate of nitrogen input.

Calibration Ventilation Index measurements were made for a range of nitrogen gas flow rates, this range representing the expected clothing ventilation properties of air-permeable and air-impermeable ensembles in typical working conditions (ie, not high air velocity conditions). The range was based on previous author data from typical work-wear ensembles similar to those used in this thesis, eg air-permeable foul weather suit = 45 l min\(^{-1}\) when wearer is slow pacing (Table 4.6) and air-impermeable duck suit = 18.4 l min\(^{-1}\) when wearer is slow pacing.

The whole system based calibration, using the Goretex single layer ensemble, showed both the air exchange rate and micro-environment volume measurements to be highly repeatable and the Ventilation Index measurement to be accurate (Figure 5.13). This accuracy is demonstrated since linear regression of whole system calibration Ventilation Index data and nitrogen gas input data shows \(r^2 = 0.9997\), while Pearson correlation analysis shows \(P < 0.05\).

<table>
<thead>
<tr>
<th>Run (^{\text{th}})</th>
<th>Air exchange rate (per minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.06</td>
</tr>
<tr>
<td>2</td>
<td>1.06</td>
</tr>
<tr>
<td>3</td>
<td>1.02</td>
</tr>
<tr>
<td>Mean</td>
<td>1.05</td>
</tr>
<tr>
<td>1 SD</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 5.3 Sample air exchange rate data, measured with a ‘standard’ shop mannequin wearing a Goretex \(\text{TM}\) leisure suit.

This calibration method, however, is not without criticism and can be questioned for a number of reasons:

- Is it appropriate to assume that the end value of oxygen concentration within the ensemble is 3%? This figure represents a best estimate, higher ventilation rates (nitrogen inputted) into the clothing ensemble may slightly reduce this figure.
Is it appropriate to begin measuring at 18 % oxygen concentration? At this point the nitrogen within the ensemble will not be uniformly mixed throughout it. The result being a reduced air exchange rate value, and an under estimate of VI as seen in this calibration.

Is it appropriate to assume the same micro-environment volume for the clothing ensemble for all nitrogen input flow rates? The air-impermeable nature of the calibration ensemble results in it having naturally low ventilation properties. With high input flow rates of nitrogen the ensemble would be expected to balloon a little thereby increasing its micro-environment volume and as such increasing the VI values obtained, again this may explain the difference between the higher nitrogen input flow rates and their respective VI values.

Should the baseline VI data for the ensemble be taken into account? With low nitrogen input flow rates the baseline ventilation properties of the clothing may have an effect, the lowest ventilation rate used in the current calibration is approximately equal to the baseline properties of the ensemble and would thus not be greatly affected.

Figure 5.12 Air exchange rate measurement period during calibration of whole system.
5.6 Summary

The aim of this chapter was to describe the air exchange rate and micro-environment volume measurement equipment used in the current Ventilation Index technique. The equipment presented here represents the latest in a series of systems and has overcome problems such as tubes, in the nitrogen distribution and tracer gas sampling tubing systems, kinking during activity or when being worn under tight clothing. The repeatability of both the air exchange rate and micro-environment volume measurement techniques is shown by the small deviation between replications (Tables 5.2 and 5.3) The air-impermeable clothing assessed during calibration of the whole systems shows ventilation characteristics similar to those observed for the same clothing by Angel (1995). Furthermore, these data are also in agreement with those measured by other authors (Birnbaum and Crockford, 1978 and Havenith et al, 1990a) using similar air-impermeable ensembles. Calibration of the whole system, although not perfect, confirms the accuracy of the measurement as had been suggested by previous authors (Angel, 1995 and Birnbaum 1975). Chapters 5 to 11, of this thesis, further demonstrate the usefulness of the Ventilation Index in assessing a worker’s thermal environment (ie in measurements of clothing insulation and wearer physiological responses in a cold environment) and provides evidence of it’s sensitivity to external factors (clothing fit and environmental air speed) as well as it’s use with multi-layer ensembles.

Figure 5.13. Whole system calibration data.
Chapter 6
6.1 Introduction

The exchange of air between a clothing ensemble micro-environment and the surrounding environment will have physiological effects on the wearer of that ensemble. Ingress of air colder than that trapped within the clothing will act as a heat sink and will lower the temperature of the micro-environment air. This lower micro-environment air temperature will lower the wearer’s skin temperature and again they may feel discomfort. In addition, while this external air is trapped within the clothing it will become warmer, given a long enough time period trapped within the clothing it will continue to be warmer until it reaches the same temperature as the micro-environment. Conversely, movement of air warmer than that trapped within clothing will raise the temperature of the micro-environment air. In turn, this may increase the wearer’s skin temperature leading to thermal discomfort.

Where the micro-environment air has a higher partial water vapour pressure than the ‘ingressed’ air, the ‘new’ air will become saturated until reaching the same level as the micro-environment air. When this air is subsequently lost, back to the external environment, it will take with it this extra heat and water vapour and in doing so remove both sensible and insensible heat.

Thus it can be seen that air exchange between a clothing ensemble and the surrounding environment can have a large effect on the thermal properties of the clothing’s micro-environment air, which in turn affects both the wearer’s skin temperature and their feelings of thermal sensation. Where an exposure is prolonged, or where air exchange is rapid, more acute thermal strain may be experienced as deep-body temperature responds to the changes in skin temperature.
As described in Chapter 4, exchange of air between a clothing ensemble and the surrounding environment will occur in all layers of the ensemble (Figure 6.1). When the air permeability of the fabrics, from which the different clothing layers are made, vary then the rates of air exchange between these layers will also change.

The insulation provided by a clothing ensemble depends not only on the thermal properties of the fabrics, from which it is made, but also on the 'thickness' and number of air layers trapped within and between these layers. Air moving into these layers will reduce the ensemble insulation. Further, the disruption of the external boundary air layer by wearer activity and external air movement also reduces this insulation. From these observations, 'the measurement and control of the pumping effect [and air exchange by permeation] seems to be the key for further advances in the field of thermal insulation of clothing ensembles' (Vogt et al 1983).

Where a material is permeable to air then most of the air exchange between the clothing micro-environment and the surrounding environment will take place directly across the fabric either
by diffusion or aided by wind pressure from the surrounding environmental air movement. Where a material is impermeable to air then the air exchange between the clothing micro-environment and the surrounding environment will be low in baseline conditions (ie no body movements and still environmental air conditions) but will be increased by the pumping effect during body movements. Perhaps better described as the bellows effect, this occurs because the air impermeable nature of the fabric does not allow the direct permeation of air across it. With activity, thus body movements, the micro-environment air becomes ‘pumped’ along the air layer(s) until it is able to leave the clothing via a vent or other opening (eg wrist cuff, jacket waist or neck opening). At the same time, air from the surrounding environment is drawn into the clothing through such openings. The fit of the clothing will dictate the amount of air trapped within the micro-environment and thus the amount of air which may be pumped during this bellows effect. The presence of restrictions, such as a belt, harness or rucksack straps will impede (or totally prevent) the movement of air through spaces in the clothing and thus change the ventilation characteristics of the ensemble worn beneath them.

Of primary interest when quantifying the ventilation characteristics of an ensemble is the quantity of air exchange which occurs at the wearer’s skin’s surface, since air movement and exchange at this level will be reflected in the wearer’s physiological responses. Parsons (1988, 1993) describes a user performance method for quantifying the effects of ‘pumping’ on thermal strain. The method is based upon the differences in mean skin temperature, $t_{sk}$, at the end of a 1-hour exposure in 5 °C air temperature between those measured on stationary subjects and those performing a physical activity of interest.

The aim of this laboratory study was to examine the relationship between Ventilation Index and the physiological effects of the ventilation. The null hypothesis ($H_0$) was that physiological response would not be related to VI. The alternative hypothesis ($H_1$) was that increased ventilation would result in reductions in mean body temperature. If such a relationship can be reliably demonstrated then it should be sensible to relate Ventilation Index directly to resultant insulation of the ensemble.
6.2 Materials and Methods

6.2.1 Subjects

Eight, healthy, physically active males, age range 19 to 30 years, volunteered to participate in this study. They were recruited from the undergraduate and postgraduate populations at Loughborough University, volunteering following ‘poster’ advertisements located in communal areas around the university campus. They were fully informed of the objectives, procedures and possible hazards of the experiment, completed a health screen questionnaire and signed a Form of Consent prior to testing. The completed health screen questionnaire and declaration of consent were then kept on file.

Subjects were asked to refrain from alcohol, tobacco and excessive caffeine intake for the 12 hours preceding testing. They were also requested to have a full night’s sleep and to eat what they considered a ‘normal’ meal (either breakfast or lunch according to test schedule) prior to testing. Individual subjects were always tested at the same time of day to avoid biorhythm and circadian rhythm effects on their physiological responses. Exposures were separated by several days to prevent subjects becoming acclimatized to the environmental conditions.

Anthropometric measurements prior to testing consisted of measurements of standing height and body weight, these were then used to calculate Dubois surface area according to:

\[ A_D = 0.202 \times W^{0.425} \times H^{0.725} \]

where,

- \( A_D \) = Dubois surface area
- \( W \) = weight
- \( H \) = height

Standing height was measured using an a stadiometer. Subjects were asked to focus on a point directly in-front of them so that their neck posture was not strained. Accuracy of measurement was within 0.25cm. Subject weight was measured using a calibrated Mettler ID1 multi-range weighing platform (order code ID1s, Albstadt, Germany). Subjects stood in the middle of the platform with feet shoulder width apart and were again asked to focus on a point directly in-front of them. A dynamic measurement of their weight was taken (average value from those
measured at 1-second intervals, total measurement time 9 seconds). Accuracy of measurement: was within 0.005 Kg. (Subject physical characteristics are given in Table 6.1)

Table 6.1 Subject physical characteristics.

<table>
<thead>
<tr>
<th>Subject identifier</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>Dubois surface area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.70</td>
<td>71.05</td>
<td>1.82</td>
</tr>
<tr>
<td>2</td>
<td>1.78</td>
<td>84.89</td>
<td>2.02</td>
</tr>
<tr>
<td>3</td>
<td>1.84</td>
<td>77.77</td>
<td>2.00</td>
</tr>
<tr>
<td>4</td>
<td>1.73</td>
<td>73.25</td>
<td>1.86</td>
</tr>
<tr>
<td>5</td>
<td>1.80</td>
<td>69.36</td>
<td>1.87</td>
</tr>
<tr>
<td>6</td>
<td>1.83</td>
<td>78.45</td>
<td>2.00</td>
</tr>
<tr>
<td>7</td>
<td>1.88</td>
<td>92.22</td>
<td>2.18</td>
</tr>
<tr>
<td>8</td>
<td>1.80</td>
<td>64.16</td>
<td>1.81</td>
</tr>
<tr>
<td>Mean</td>
<td>1.80</td>
<td>76.39</td>
<td>1.95</td>
</tr>
<tr>
<td>1 SD</td>
<td>0.06</td>
<td>8.99</td>
<td>0.13</td>
</tr>
</tbody>
</table>

In compliance with laboratory ethics procedures, subject heart rate was recorded at 1-minute intervals using a polar sports tester heart rate monitor (order code PE4000, Cranlea Medical Electronics, Birmingham, UK). The sensor and transmitter unit was worn around the chest, and the data stored in a wrist monitor. Manually recorded back-ups of these data were made at 10-minute intervals throughout each exposure. To avoid interference from other equipment subjects were not allowed to wear their own watches, and testing was conducted away from any computerised equipment and at least one meter distant to other subjects.

Similarly, in compliance with laboratory ethics procedures, subject aural temperature was measured using an aural thermistor (Grant, order code TH, Grant Instruments Ltd., Cambridge, UK) inserted to a depth of 1cm in the left ear. Accuracy of measurement was within 0.1 °C. For comfort and ease of insertion the thermistor was retained by an acrylic plastic hearing aid ear-piece. Since it is known that such acrylic ear-pieces conduct heat well, and can cause aural thermistors to register false readings, cotton wool pads were placed over the ear and held in place by fully adjustable ear defenders to reduce any such effects. These
data and those obtained from the right ear were used to represent deep-body temperature and to calculate mean body temperature (described in section 6.3.1). The aural thermistors were calibrated, across the expected range of use (35 °C to 39 °C), against a mercury-in-glass thermometer in a water bath prior to and following use. All aural temperature data were stored using a Grant 8-bit or 12-bit squirrel data logger (order codes SQ32-160 and 1201 respectively). Manually recorded back-ups of these data were made at 10-minute intervals throughout each exposure.

To obtain an assessment of subject well-being during testing they were asked to rate their thermal discomfort, sensation and rating of perceived exhaustion using the ASHRAE 4-point discomfort scale (Figure 3.5), the ASHRAE 7 point sensation scale (Figure 3.6) and the Borg rating of perceived exertion scales respectively (Figure 3.7). All data were recorded manually.

6.2.2 Test Clothing
During this study subjects wore a GoreTex™ single-layer leisure suit. The GoreTex suits had been used for experimental purposes within the Human Thermal Environments Laboratory for several years prior to this study. As a result the clothing had been washed repeatedly, in a non-standard way. The fabric showed some minimal signs of wear and tear. Studies conducted previously (Henry, 1996) using this test clothing showed the GoreTex ensemble characteristics to be as expected (ie waterproof and highly permeable to water-vapour). During this set of studies the washing and drying of clothing was standardised: an automatic washing machine was used with Ariel liquid detergent on a 40 °C wash setting and then the clothing allowed to dry naturally without forced heating.

The GoreTex™ ensemble was single-layer in design and consisted of a jacket and trousers. The trousers were elasticated at the waist and of a straight cut. The ankles could be tightened with the use of popper fasteners (2 stage fastening - tight & tighter). The trousers also featured an external pocket (rear) and 2 access slits (length 17cm each) at hip level, one each on the left and right sides (if the leisure suit were worn on top of another pair of trousers these would allow the wearer access to the pockets of the inner most clothing). The jacket was elasticated at the waist and had a full length front zip protected by a popper fastened wind baffle. The zip extended up to and including the high neck of the collar. The wrists cuffs were located
approximately 5cm inside the sleeves of the jacket and were cotton and elasticated. The jacket had two pockets located around the mid-abdomen area. Subjects wore the same suit for each of their test exposures.

When investigating the GoreTex ensemble subjects wore their own undergarments. They were requested to wear normal length shorts for this purpose. They also wore their own soft training shoes and short socks.

6.2.3 User Performance Test
The test protocol for determination of physiological effects due to ventilation consisted of four separate exposures to an environment of: $t_a = 5.4 \ (1 \text{SD} = 0.8) ^\circ \text{C}$, $t_r = 6.5 \ (1 \text{SD} = 1.2) ^\circ \text{C}$, $v = 0.17 \ (1 \text{SD} = 0.03) \text{ms}^{-1}$ and $rh = 65.8 \ (1 \text{SD} = 4) \%$. Subjects were allocated a pre-defined activity for 1-hour, on each attendance at the laboratory. These activities were:

a. Semi-nude.
   Standing stationary, wearing shorts only.
   Standing as still as possible, with head facing straight forward. Body movements in this exposure would be limited to chest expansions and contractions through breathing movements and occasional ‘natural shuffling’ movements - few subjects could stand perfectly still!

b. Stand
   Standing stationary, clothed (Goretex™ leisure suit).
   As per semi-nude condition.

c. Stepping
   Stepping routine, clothed (Goretex™ leisure suit). (Figure 6.2)
   Step-ups were performed on a vertical rise of 150 mm, onto a Reebok™ aerobic step. Each full step (one foot up onto step, other foot up onto step, first foot down onto floor, other foot down onto floor) took 4.8 seconds to complete, each foot movement being cued by a metronome beep. Subjects were advised to change their choice of lead foot from time to time during
exposure to avoid uneven muscle strain. This exposure was chosen, based on previous research (Langendoen, 1990) which suggested it would induce moderate ventilation into the clothing.

d. Rotate limbs

Maximal pumping routine, clothed (Goretex™ leisure suit). (Figures 6.3 & 6.4)

Subjects performed slow arm and leg circles as follows, each complete series of clockwise rotations being followed by a counter-clockwise series:

1. Subject moves extended right arm at a 45° angle to the horizon in a clockwise arc completing a circle 4.8 seconds
2. Subject moves extended left arm at a 45° angle to the horizon in a clockwise arc completing a circle 4.8 seconds
3. Subject moves extended right leg at a 30° angle to their body in a clockwise arc completing a circle 4.8 seconds
4. Subject moves extended left leg at a 30° angle to their body in a clockwise arc completing a circle 4.8 seconds

The order of performing these activities was balanced over all subjects to reduce possible training effects.

During the study, left and right aural temperatures and 8-point, weighted mean skin temperature (thermistors located according to ISO 9886: forehead, chest, scapular, high upper arm, low upper arm, hand, thigh and calf) were recorded at 1-minute intervals, all thermistors previously having been calibrated in a water bath against a mercury-in-glass thermometer. Samples of expired air were collected using Douglas bags after 45 minutes of exposure and analysed for oxygen content (Sybron Taylor, oxygen analyser - order code OA 570, Taylor Instrument Analytics Ltd / Servomex (UK) Ltd, Crowborough, UK), carbon dioxide content (ADC carbon dioxide analyser - order code SS2 MK1-4905, The Analytic Development Co Ltd, Hoddesdon, UK), temperature (grant squirrel thermistor, order code EU, Grants, Cambridge UK) and volume (dry gas meter - order code 6162, Cranlea Medical Electronics, Birmingham UK).
6.2.4 Determination of the Ventilation Index

VI was calculated as the product of the clothing air exchange rate and micro-environment volume. These were determined with each subject for the stand, stepping and rotate limbs activities, the air exchange rate and micro-environment volume measurements being made, in separate test sessions as described in sections 5.3 and 5.4. Tracer gas measurements were made (and air exchange rates determined) 3 times for each activity, from which an average value was calculated. The 3 tracer gas measurements for an activity were made consecutively, with the order of presentation of the different activities being balanced across subjects. For each individual subject the average air exchange rate value for each activity was combined with that individual's average micro-environment volume (average from triplicate measurements) to give the VI value for that activity.
6.3 Results

6.3.1 User performance test

The mean body temperature for each individual subject was calculated for all conditions from values measured at the end of the 1-hour exposure using the following equation:

\[ t_b = 0.67 \, t_{aural} + 0.33 \, t_{sk} \quad ^\circ C \quad [42] \]

where,

- \( t_b \) = mean body temperature \(^\circ C\)
  
  (note, equation represents a vasoconstriction situation since the environment is cold)

- \( t_{sk} \) = 8-point mean skin temperature (calculated according to ISO 9886) \(^\circ C\)

- \( t_{aural} \) = deep-body temperature (calculated as mean of left and right aural temperatures) \(^\circ C\)
  
  (left and right aural temperatures were always within 0.2 \(^\circ C\) of each other)

Table 6.2 represents the mean body temperature for each subject and condition. Following unsuccessful attempts to model the effects of clothing ventilation using the 2-node model (Gagge et al, 1971) a heat balance calculation approach was taken. To allow comparison of the thermal strain imposed by the pumping (ie to take account the metabolic heat produced by the physical activity) a correction was made to the mean body temperature values. This involved a reduction of mean body temperatures by an amount equivalent to the increase in metabolic rate above the clothed stationary value. This was achieved using a value of 60Wh./m\(^2\) as equivalent to a 1\(^\circ C\) change in mean body temperature (ISO 7933, 1989). The corrected values are also shown in Table 6.2.
Table 6.2. Mean body temperature following 1 hour of exposure (5°C) and corrected mean body temperature according to the increase due to activity.

<table>
<thead>
<tr>
<th>Subject</th>
<th>At 1 hour</th>
<th>Corrected</th>
<th>At 1 hour</th>
<th>Corrected</th>
<th>At 1 hour</th>
<th>Corrected</th>
</tr>
</thead>
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<td>33.2</td>
<td>32.7</td>
<td>32.2</td>
</tr>
<tr>
<td>4</td>
<td>33.0</td>
<td>33.0</td>
<td>33.7</td>
<td>32.8</td>
<td>33.0</td>
<td>32.5</td>
</tr>
<tr>
<td>5</td>
<td>33.4</td>
<td>33.4</td>
<td>34.0</td>
<td>32.3</td>
<td>34.0</td>
<td>32.9</td>
</tr>
<tr>
<td>6</td>
<td>32.8</td>
<td>32.8</td>
<td>33.6</td>
<td>32.7</td>
<td>32.6</td>
<td>32.4</td>
</tr>
<tr>
<td>7</td>
<td>33.8</td>
<td>33.8</td>
<td>34.2</td>
<td>32.6</td>
<td>33.3</td>
<td>32.9</td>
</tr>
<tr>
<td>8</td>
<td>33.5</td>
<td>33.5</td>
<td>33.3</td>
<td>32.0</td>
<td>32.8</td>
<td>33.0</td>
</tr>
<tr>
<td>Mean</td>
<td>33.3</td>
<td>33.3</td>
<td>33.8</td>
<td>32.6</td>
<td>33.2</td>
<td>32.7</td>
</tr>
<tr>
<td>1 SD</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

6.3.2 Ventilation Index

Micro-environment volumes (mean of triplicate measurements) with the subjects in the standing position are given in Table 6.3. The rate of air exchange for each subject in each condition was calculated using equation 37, the mean value from triplicate measurements for each subject and condition are given in Table 6.4. VI values for each subject and condition are given in Table 6.5.

Table 6.3 Micro-environment volumes, measured in the standing position.

<table>
<thead>
<tr>
<th>Subject</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-environment volume (litres)</td>
<td>43.0</td>
<td>45.0</td>
<td>43.0</td>
<td>50.0</td>
<td>26.25</td>
<td>20.5</td>
<td>27.0</td>
<td>26.3</td>
</tr>
</tbody>
</table>
Table 6.4 Air exchange rates for each subject and condition.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Stand</th>
<th>Stepping</th>
<th>Rotate limbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.17</td>
<td>0.27</td>
<td>0.26</td>
</tr>
<tr>
<td>2</td>
<td>0.18</td>
<td>0.23</td>
<td>0.42</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
<td>0.22</td>
<td>0.48</td>
</tr>
<tr>
<td>4</td>
<td>0.11</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>5</td>
<td>0.07</td>
<td>0.23</td>
<td>0.34</td>
</tr>
<tr>
<td>6</td>
<td>0.11</td>
<td>0.20</td>
<td>0.23</td>
</tr>
<tr>
<td>7</td>
<td>0.16</td>
<td>0.25</td>
<td>0.34</td>
</tr>
<tr>
<td>8</td>
<td>0.11</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>Mean</td>
<td>0.13</td>
<td>0.23</td>
<td>0.31</td>
</tr>
<tr>
<td>1 SD</td>
<td>0.04</td>
<td>0.02</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 6.5 Ventilation Index values.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Stand</th>
<th>Stepping</th>
<th>Rotate limbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.70</td>
<td>11.62</td>
<td>11.00</td>
</tr>
<tr>
<td>2</td>
<td>7.88</td>
<td>10.32</td>
<td>18.98</td>
</tr>
<tr>
<td>3</td>
<td>6.61</td>
<td>9.57</td>
<td>20.54</td>
</tr>
<tr>
<td>4</td>
<td>5.26</td>
<td>11.13</td>
<td>10.77</td>
</tr>
<tr>
<td>5</td>
<td>1.84</td>
<td>5.95</td>
<td>8.84</td>
</tr>
<tr>
<td>6</td>
<td>2.24</td>
<td>4.04</td>
<td>4.63</td>
</tr>
<tr>
<td>7</td>
<td>4.31</td>
<td>6.80</td>
<td>9.20</td>
</tr>
<tr>
<td>8</td>
<td>2.80</td>
<td>5.98</td>
<td>5.69</td>
</tr>
<tr>
<td>Mean</td>
<td>4.83</td>
<td>8.18</td>
<td>11.21</td>
</tr>
<tr>
<td>1 SD</td>
<td>2.42</td>
<td>2.83</td>
<td>5.75</td>
</tr>
</tbody>
</table>
Differences in the rate of air exchange were observed both between subjects and between activities. When subjects stood stationary (stand) the rate of air exchange between their clothing micro-environment and the surrounding environment varied from a low of 0.07 min\(^{-1}\) to a high of 0.179 min\(^{-1}\) with a mean rate (1 SD) of 0.131 (0.038 min\(^{-1}\)) ie one complete change of micro-environment air approximately every 7.5 minutes. When subjects performed the stepping activity the rate of air exchange between their clothing micro-environment and the surrounding environment varied from a low of 0.197 min\(^{-1}\) to a high of 0.270 min\(^{-1}\) with a mean rate (1 SD) of 0.231 (0.022 min\(^{-1}\)) ie one complete change of micro-environment air approximately every 4.3 minutes, these data representing a 76 % rise on those obtained when standing stationary. When subjects performed the rotate limbs activity the rate of air exchange between their clothing micro-environment and the surrounding environment varied from a low of 0.215 min\(^{-1}\) to a high of 0.478 min\(^{-1}\) with a mean rate (1 SD) of 0.311 (0.100 min\(^{-1}\)) ie one complete change of micro-environment air approximately every 3 minutes, these data representing a 137 % rise on those obtained when standing stationary and a 35 % rise on those obtained when performing the stepping activity.

These differences, together with the different micro-environment volumes observed with each subject, gave variation in VI values during this study:

- **Stand**
  - Range = 1.84 to 7.88 l min\(^{-1}\), mean VI = 4.83 l ± 2.42 min\(^{-1}\)

- **Stepping**
  - Range = 4.04 to 11.62 l min\(^{-1}\), mean VI = 8.18 l ± 2.83 min\(^{-1}\)

- **Rotate limbs**
  - Range = 4.63 to 20.54 l min\(^{-1}\), mean VI = 11.21 l ± 5.75 min\(^{-1}\)

These data suggest a 69 % increase in ventilation between the stand and stepping activities and a 132 % increase in ventilation between the stand and rotate limbs activities (37 % difference between stepping and rotate limbs activities). Analysis of variance of these data (blocked, balanced design with subjects as a random factor, showed the effect of activity to be significant (P < 0.05). Differences between the separate levels of activity (stand, stepping and rotate limbs) were tested by Tukey’s pairwise comparisons and showed significance between the stand and rotate limbs activities only (P < 0.05).
As expected, with increased ventilation mean body temperature was seen to decrease (linear least squares analysis: $r^2 = 0.1057$), as shown in Figure 6.5. This low correlation shows no significant relationship between clothing ventilation and corrected mean body temperature of the wearer.

![Figure 6.5 The relationship between Ventilation Index and mean body temperature corrected for increases in metabolic rate, individual subject data.](image)

6.4 Discussion

The primary aim of this study was to examine the relationship between Ventilation Index and the physiological effects it induces. Initial attempts, using reverse modelling techniques, ie inputting environmental parameters and subject data (metabolic rate and deep body and mean skin temperatures from 1 hour of exposure to the cold environment) into the 2-node model (Gagge et al, 1971) in order to assess the effects of clothing ventilation on clothing insulation and thus also on wearer physiological responses, were unsuccessful since more than one clothing condition could initiate the same thermal response from the wearers and also because each wearer had their own response which was often not matched by the thermoregulatory responses (particularly shivering response) of the 2-node model. In response to this a heat balance calculation approach was used. Since the environment was cold it was assumed that
Mean body temperature data measured in this study show that increased activity, used to generate ventilation within the clothing ensemble, had a direct effect on subject thermal response. While the stepping activity increased ventilation within the clothing, the effects of this ventilation on heat transfer from the wearer’s skin were negated by the rise in mean body temperature caused by the actual activity. This rise in mean body temperature occurring since mean subject metabolic rate during stepping activity was 152.6 Wm$^{-2}$ but during the stand activity this was much lower at 75.1 Wm$^{-2}$. Using Birnbaum’s (1975) suggestion that 100 l min$^{-1}$ of air flow through the clothing can remove approximately 27 Wm$^{-2}$ of heat, the ventilation rates observed during this activity would remove only a small amount of that required to overcome the increased heat production during activity. The actual amount of heat removed estimated to be in the region of 1.1 to 3.2 Wm$^{-2}$ using Birnbaum’s suggestion.

The rotate limbs activity also increased the subject mean body temperatures. This activity resulted in only a slight increase in metabolic heat production (average metabolic rate of subjects during rotate limbs activity was ~ 102.3 Wm$^{-2}$). Again, if the suggested rate of heat transfer used by Birnbaum (1975) is considered the ventilation rate within the clothing induced by this activity would not be sufficient to overcome the increase in mean body temperature cause by the activity. However, the data obtained in this study suggest that the rotate limbs activity did increase the clothing ventilation rate sufficiently so as to negate the effects of the increased activity on mean body temperature.

Figure 6.5 shows the trend that increased clothing ventilation lowered wearer mean body temperature, when corrected for the effects of increased metabolic rate during that activity, after 1 hour of exposure to a cold environment. In practical terms, during the stepping activity the increased ventilation within the clothing limited the rise in the wearer’s mean body temperature as a result of the increased metabolic heat production which occurred due to the nature of that activity. This information would be useful in situations where workers undertake high workload tasks. If their clothing could be designed to allow more ventilation then any thermal strain effects of the high workload may be alleviated. In contrast, where activities
conducted in a cold environment do not induce such a high work load, measurement of the clothing’s ventilation characteristics will be equally as important given that too much ventilation at the wearer’s skin surface will be detrimental to the wearer.

As expected, each individual has their own unique relationship between ventilation rate and drop in mean body temperature. Variation between subject responses to the maximal pumping routine may be explained by the extension and sweep of the arm and leg movements differing, both between subjects and throughout a subject’s activity routine which would alter the level of pumping.

The stationary activity generally showed relatively low values for Ventilation Index and lower heat strain, convective air exchange by the ‘chimney’ effect (Renbourn, 1972) accounting for the low ventilation and heat loss values. Activity, and hence pumping, generally increased the Ventilation Index and subject mean body temperature. The increase in mean body temperature was limited in proportion to the ventilation rate of the clothing for that activity. It can be suggested therefore that the Ventilation Index can provide a valid index of the pumping properties of clothing and its consequences for thermal strain in terms of heat loss from the body.

The ventilation rates measured in this study are close of those measured by Angel (1995) using the same clothing ensembles in similar environmental conditions and activities:

- stand = \( \sim 6.2 \text{ l min}^{-1} \) / stepping = \( \sim 15.0 \text{ l min}^{-1} \) / rotate limbs = \( \sim 14.4 \text{ l min}^{-1} \)

They are also of the same order of magnitude as values obtained by other authors using air-impermeable clothing ensembles:

- duck-suit = \( \sim 18.6 \text{ l min}^{-1} \) for slow pacing activity (Birnbaum and Crockford, 1978)
- work ensemble + rain coverall = \( \sim 7.2 \text{ l min}^{-1} \) for sitting (still air)
  - " = \( \sim 11.3 \text{ l min}^{-1} \) for standing (still air)
  - " = \( \sim 20.0 \text{ l min}^{-1} \) for walking at 0.3 ms\(^{-1}\) (still air)

(Havenith et al, 1990a)

The low number and location of temperature measuring sensors, to provide the mean skin temperature, in this study means that an incomplete representation of thermal strain induced by pumping may have been observed. Extra measurements made in locations of air ingress and
thus of possibly high levels of pumping (e.g., near clothing openings or in areas where clothing is particularly loose as suggested by Lotens and Havenith (1988)) would also provide an indication of the effects of cold air ingress into the clothing. From this suggestion, the assessment of clothing insulation and ventilation characteristics using a thermally instrumented manikin is recommended. Data from such an assessment is given in Chapter 7.

The large variation in micro-environment volumes measured in this study suggest that the test clothing worn by these subjects would have fitted each one differently. These fit effects will have caused some of the variation observed for the VI values in this study. Data from an assessment of the effects of clothing fit on ventilation characteristics is given in Chapter 9.

6.4 Conclusions

1. The physiological strain of subjects caused by pumping may be related to the Ventilation Index when worn by subjects carrying out physical activity in the thermal environment represented here.

2. Air movement through clothing can significantly affect the heat exchange between human subjects and the environment.

3. Increased activity raises mean body temperature, an effect still seen after 1 hour of exposure to a cold environment.

4. In a cold environment increased clothing ventilation, as a result of activity, can limit the increase in mean body temperature during high work loads and may cause thermal strain where the activity induces high ventilation but does not increase the wearer’s metabolic rate (and mean body temperature) greatly.

5. Further work, using a thermally instrumented manikin, is needed to investigate the full extent of the relationship between clothing ventilation and insulation characteristics.

6. Further work may be beneficial to investigate the relationship between clothing fit and its ventilation characteristics.
Chapter 7
Chapter 7

LABORATORY STUDY 2
THE RELATIONSHIP BETWEEN VENTILATION INDEX
AND THERMAL INSULATION

7.1 Introduction

As demonstrated in Chapter 6, activity can increase air exchange even in clothing constructed from relatively air impermeable fabric. This exchange can decrease clothing thermal insulation and water vapour resistance which in turn, will influence the heat balance of the wearer with physiological consequences.

These effects are seldom taken into account when defining the clothing needed for safe work in hot or cold conditions. This occurs even though measurements using articulated, thermal manikins have shown that movement and wind can cause reductions of 50% in thermal insulation (Holmer And Nilsson, 1995) and of 88% in evaporative resistance (Havenith et al 1990b)). Consequently, the choice of clothing based on measurements of intrinsic insulation and intrinsic evaporative resistance alone may lead to under-protection in the cold, and over-protection in the heat.

To overcome this limitation, ISO TR 11079 (1993) calculates a resultant insulation and ISO 9920 (1992) gives an empirical correction to account for the effects of body movement. However, this approach is limited because there are no data relating the change of thermal insulation to the amount of air exchanged between the clothing and the external environment.

The aim of this study was to quantify, using an articulated thermal manikin the relationship between VI and thermal insulation in two clothing ensembles. Continuing from Chapter 6, the null hypothesis (H₀) for this study was that physiological response, and thus insulation provided by clothing, would not be related to VI. The alternative hypothesis (H₁) was that increased ventilation would result in a drop in insulation provided by the clothing. If such a relationship can be reliably demonstrated then it should now be sensible to relate Ventilation Index directly to resultant insulation of the ensemble.
7.2 Materials and methods

7.2.1 Test clothing:
A GoreTex™ (GT), 1-layer ensemble and a woven, 3-layer ensemble (IREQ) were investigated:

The GoreTex™ ensemble is described fully in chapter 6. The IREQ (name previously assigned during laboratory work) ensemble was a standard ensemble used for manikin test work at the National Institute for Working Life, Stockholm, Sweden. As a result the clothing had been washed repeatedly, in a non-standard way. The fabric showed some minimal signs of wear and tear. During this study the washing of clothing was standardised: an automatic washing machine was used with Ariel liquid detergent on a 40 °C wash setting and the clothing allowed to dry naturally without forced heating.

The IREQ ensemble consisted of 3 layers of garments:

base layer: - long socks (cotton), Helly Hansen thermal long john trousers (100% polypropylene) and Helly Hansen thermal shirt (100% polypropylene) (Figure 11.1)

middle layer: - Thermal trousers (Polyamide / nylon) and thermal jacket (Polyamide / nylon) (Figure (11.2)

outer layer: - Dungarees (52% cotton, 48% nylon), jacket (52% cotton, 48% nylon), woollen scarf, gloves (67% Polyester, 33% nylon) and balaclava (wool). (Figure 11.3)

The IREQ ensemble also consisted of a pair of protective boots.

The IREQ ensemble had been adapted for use with the articulated (TORE) manikin at NIWL. These adaptations included holes in the fabric at ankle and wrist locations where the hydraulic rods used to make the manikin walk were attached. In addition other parts of the ensemble had been modified to ensure an even fit on the manikin. The adaptations are given in Table 7.1
7.2.2 Measurement of thermal insulation:
The ‘TORE’ heated, articulated manikin (Figures 7.1 and 7.2) was used to measure clothing
total insulation ($I_T$). $I_T$ was calculated from the measured heat loss, using the method given in
CEN ENV342 (1997), with environmental conditions of: $t_s = t_e = 10^\circ C$ ($1 \ SD = 0.1^\circ C$) and
$wvp = 0.73 \ kPa$.

Measurements were made at 2 wind speeds: ‘still air’ ($v < 0.2 \ ms^{-1}$) and with moving air ($v
=1\ ms^{-1}$), created by 3 Indola fans (type VWB 50) drawing through a honeycomb screen and
then over the manikin, and with the manikin walking at 3 speeds: standing stationary, walking
at 0.37 $ms^{-1}$ and walking at 0.8 $ms^{-1}$. The walking movement was realistic, controlled by
pneumatic 500 mm cylinders to give a heel to heel step length of 645 mm at a rate of 23 steps
per minute for the 0.37 $ms^{-1}$ walking speed and 48 steps per minute for the 0.8 $ms^{-1}$ walking
speed.

Prior to measurements being made, TORE was positioned in the climatic chamber until steady
state was reached. Thermal resistance of the boundary air layer ($I_a$) was measured using the
nude manikin and total insulation of the test ensemble was measured using the manikin clothed
in that ensemble. Effective insulation ($I_{ele}$) was calculated as the difference between $I_T$ and $I_a$
[27]. Repeatability between runs was high, with the difference between double determinations
of both $I_T$ and $I_a$ less than 5%.

Insulation measurements were always made without the manikin instrumented with any
Ventilation Index measurement tubing systems.
Table 7.1 Modifications to IREQ ensemble for use with articulated manikin trials.

<table>
<thead>
<tr>
<th>Item of ensemble</th>
<th>Modification and reason</th>
</tr>
</thead>
</table>
| Balaclava        | Material cut for full length to rear of balaclava.  
|                  | Reason - during walking operation manikin is suspended from a hook  
|                  | fixed into its head.  |
| Socks            | Holes at ankle level.  
|                  | Reason - attachment point of hydraulic rod for walking.  |
| Long john trousers  | Holes at ankle level.  
| (base layer)  | Reason - attachment point of hydraulic rod for walking.  |
| Thermal trousers  | Holes at ankle level.  
| (middle layer)  | Reason - attachment point of hydraulic rod for walking.  |
| Dungarees (outer layer) | Holes at ankle level.  
|                  | Reason - attachment point of hydraulic rod for walking.  
|                  | Shoulder straps cut - now secured with safety pins  
|                  | Reason - ease of dressing manikin.  |
| Thermal shirt (base layer) | Holes at wrists  
|                  | Reason - attachment point of hydraulic rod for walking.  
|                  | Hole located middle of shoulders  
|                  | Reason - exit point of manikin control cables.  |
| Thermal jacket (middle layer) | Holes at wrists  
|                  | Reason - attachment point of hydraulic rod for walking.  
|                  | Hole located middle of shoulders  
|                  | Reason - exit point of manikin control cables.  |
| Jacket (outer layer) | Holes at wrists  
|                  | Reason - attachment point of hydraulic rod for walking.  
|                  | Hole located middle of shoulders  
|                  | Reason - exit point of manikin control cables.  |
7.2.3 Determination of Ventilation Index:

The TORE manikin has a hollow centre, which without special precautions would have affected both the tracer gas and micro-environment volume measurements. In the tracer gas technique this dead space would have been included in the tracer gas dilution, and as such would have delayed the time taken for the oxygen concentration within the clothing to return to environmental levels during the air exchange rate calculation technique. The dead space would also have been included in the micro-environment volume measurement technique. In addition to this, it is possible that environmental air would have been drawn into the dead space through joints outside the manikin’s body covered by the air-tight oversuit (e.g. joint between manikin head and torso). Ingress of air in this way would give a false (higher) micro-environment volume measurement, which would in turn affect the calculated VI values.

To avoid the hollow centre of TORE being included in these measurements, as a dead space, points of possible leakage were sealed prior to both parts of the VI measurement. Initial attempts to seal these areas (e.g. shoulder joints where the arms join the torso and hip joints where the legs join the torso) using 'cling-film' material (Figure 7.3) were unsuccessful.
because the walking action of the manikin acted to tear these ‘seals’. This problem was overcome, using stronger material (Tyvek c) held in place with duct tape (Figures 7.4 and 7.5). The Tyvek c material and duct tape were removed during insulation measurements, to ensure that the insulation value measured was that of the actual ensemble only. All Tyvec c seals were made as tight as possible, without adding the problem of them tearing when walking, in order to minimise any effect they had on the ventilation characteristics of the clothing in these areas.

Figure 7.3
Cling film sealing

Figure 7.4
Tyvek sealing (legs)

Figure 7.5 Tyvek sealing (upper body)
Immediately after each measurement of $I_T$, VI of the clothing layer next to the skin was determined from separate measurements of micro-environment volume and air exchange rate (described in sections 5.3 and 5.4). Thus a total of 6 VI conditions were measured, for each condition, air exchange rate was measured in triplicate and mean value calculated. Micro-environment volume was measured in triplicate in the standing stationary condition, and the mean value combined with the appropriate mean air exchange rate to calculate VI values for all conditions.

7.3 Results

7.3.1 Clothing micro-environment volumes and air exchange rates
In terms of micro-environment volume the two ensembles differed substantially, the results of the triplicate measurements made on each ensemble are given in Table 7.2. Differences were also observed between ensembles in terms of air exchange rates, $P < 0.05$ (Table 7.3). The 1-layer Goretx ensemble had one complete air exchange, at the skin’s surface, every five minutes as compared one per minute as with the 3-layer IREQ ensemble. Statistical analysis (2-way ANOVA) showed neither activity nor environmental air velocity had a significant effect on rate of air exchange for the IREQ ensemble. With this analysis, effects were seen for both activity ($P < 0.05$) and environmental air velocity ($P < 0.05$) with the Goretx ensemble. Contrast analysis showed differences between stand and walk @ 0.37 ms$^{-1}$ activity ($P < 0.05$) and between stand and walk @ 0.8 ms$^{-1}$ activity ($P < 0.05$).

7.3.2 Clothing insulation values
$I_T$ and $I_a$ values are given in Tables 7.4 and 7.5 respectively, and effective clothing insulation ($I_{eq}$) values calculated, for each of the conditions for both ensembles, from these data are given in Table 7.6. Compared with the 1-layer Goretx ensemble the 3-layer IREQ ensemble provided between 2.5 and 4 times more insulation. The reduction in insulation with increased ventilation was, however, much greater with the 1-layer Goretx ensemble.
Table 7.2. Micro-environment volumes (Goretex and IREQ clothing ensembles).

<table>
<thead>
<tr>
<th>Micro-environment volume (litres)</th>
<th>Goretex</th>
<th>IREQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>40</td>
<td>59</td>
</tr>
<tr>
<td>Run 2</td>
<td>41</td>
<td>61.3</td>
</tr>
<tr>
<td>Run 3</td>
<td>39</td>
<td>62.6</td>
</tr>
<tr>
<td>Average</td>
<td>40</td>
<td>60.97</td>
</tr>
<tr>
<td>1 SD</td>
<td>1</td>
<td>1.82</td>
</tr>
<tr>
<td>1SD as %</td>
<td>2.5</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 7.3. Air exchange rates (Goretex and IREQ clothing ensembles).

<table>
<thead>
<tr>
<th>Air exchange rate (1 SD) (per minute)</th>
<th>Goretex</th>
<th>IREQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>still air</td>
<td>0.14 (0.01)</td>
<td>0.92 (0.00)</td>
</tr>
<tr>
<td>$V_a = 1 \text{ m s}^{-1}$</td>
<td>0.17 (0.01)</td>
<td>0.96 (0.02)</td>
</tr>
<tr>
<td>walking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>still air</td>
<td>0.17 (0.00)</td>
<td>0.95 (0.00)</td>
</tr>
<tr>
<td>$(0.37 \text{ m s}^{-1})$ $V_a = 1 \text{ m s}^{-1}$</td>
<td>0.22 (0.01)</td>
<td>1.08 (0.02)</td>
</tr>
<tr>
<td>walking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>still air</td>
<td>0.21 (0.01)</td>
<td>1.03 (0.02)</td>
</tr>
<tr>
<td>$(0.8 \text{ m s}^{-1})$ $V_a = 1 \text{ m s}^{-1}$</td>
<td>0.24 (0.00)</td>
<td>1.11 (0.05)</td>
</tr>
</tbody>
</table>

Table 7.4. Values of total insulation ($I_T$), for Goretex and IREQ clothing ensembles.

<table>
<thead>
<tr>
<th>Total Insulation (clo)</th>
<th>GT</th>
<th>IREQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>still air</td>
<td>1.46</td>
<td>2.54</td>
</tr>
<tr>
<td>$V_a = 1 \text{ m s}^{-1}$</td>
<td>1.08</td>
<td>2.01</td>
</tr>
<tr>
<td>walking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>still air</td>
<td>1.13</td>
<td>2.20</td>
</tr>
<tr>
<td>$(0.37 \text{ m s}^{-1})$ $V_a = 1 \text{ m s}^{-1}$</td>
<td>0.86</td>
<td>1.91</td>
</tr>
<tr>
<td>walking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>still air</td>
<td>0.96</td>
<td>2.16</td>
</tr>
<tr>
<td>$(0.8 \text{ m s}^{-1})$ $V_a = 1 \text{ m s}^{-1}$</td>
<td>0.76</td>
<td>1.85</td>
</tr>
</tbody>
</table>
Table 7.5. Values of air layer insulation ($I_a$) measured on TORE nude.

<table>
<thead>
<tr>
<th>Air layer insulation(clo)</th>
<th>Standing</th>
<th>$V_a = 1 \text{ m s}^{-1}$</th>
<th>walking</th>
<th>$V_a = 1 \text{ m s}^{-1}$</th>
<th>(0.37 m s$^{-1}$)</th>
<th>$V_a = 1 \text{ m s}^{-1}$</th>
<th>(0.8 m s$^{-1}$)</th>
<th>$V_a = 1 \text{ m s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>standing still air</td>
<td>0.71</td>
<td>0.41</td>
<td>walking still air</td>
<td>0.59</td>
<td>0.37</td>
<td>(0.37 m s$^{-1}$)</td>
<td>0.55</td>
<td>0.35</td>
</tr>
<tr>
<td>$V_a = 1 \text{ m s}^{-1}$</td>
<td>0.41</td>
<td>0.37</td>
<td>$V_a = 1 \text{ m s}^{-1}$</td>
<td>0.37</td>
<td>0.35</td>
<td>$V_a = 1 \text{ m s}^{-1}$</td>
<td>0.35</td>
<td>0.35</td>
</tr>
</tbody>
</table>

7.3.3 Ventilation Index

VI values (and $I_{ce}$) for the two clothing ensembles are given in Table 7.6 and shown in Figure 7.6. Compared with the 3-layer (IREQ) ensemble, the 1-layer (Goretex) ensemble had an 8 to 10-fold lower VI and half the $I_{ce}$. For both ensembles, $I_{ce}$ was correlated with VI ($P<0.01$): linear regression, $r^2$ was 0.65 for the 3-layer ensemble and 0.81 for the 1-layer ensemble.

Table 7.6: Values of Ventilation Index (VI) and effective insulation ($I_{ce}$) measured on Goretex and IREQ clothing ensembles

<table>
<thead>
<tr>
<th></th>
<th>GoreTex</th>
<th>IREQ</th>
<th></th>
<th>GoreTex</th>
<th>IREQ</th>
<th></th>
<th>GoreTex</th>
<th>IREQ</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>standing</td>
<td>still air</td>
<td>5.50</td>
<td>0.75</td>
<td>standing</td>
<td>56.30</td>
<td>1.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_a = 1 \text{ m s}^{-1}$</td>
<td>6.93</td>
<td>0.67</td>
<td>walking</td>
<td>still air</td>
<td>6.77</td>
<td>0.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0.37 m s$^{-1}$)</td>
<td>$V_a = 1 \text{ m s}^{-1}$</td>
<td>8.84</td>
<td>0.49</td>
<td>walking</td>
<td>still air</td>
<td>8.54</td>
<td>0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0.8 m s$^{-1}$)</td>
<td>$V_a = 1 \text{ m s}^{-1}$</td>
<td>9.55</td>
<td>0.41</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An increased walking speed was reflected by an increase in VI and decrease in $I_{ce}$ as shown in Figures 7.7 and 7.8. Increasing the walking speed from 0 m s$^{-1}$ (standing stationary) to 0.37 m s$^{-1}$ resulted in an increase of 23% in VI for the Goretex ensemble and 3% for the IREQ ensemble.
A further increase of 26% was observed for the Goretx ensemble when the walking speed was increased to 0.8\(\text{ms}^{-1}\). In comparison a further increase of 8% was observed with the IREQ ensemble under similar conditions. Statistical analysis of these data, by ANOVA show no differences due to activity or environmental air velocity for the IREQ ensemble but a significant effect for the Goretx ensemble with respect to both factors (\(P < 0.05\)). Contrast analysis to find any differences between the activities showed significance only between the stand and walk at 0.8 \(\text{ms}^{-1}\) conditions (\(P < 0.05\)).

As expected, increasing walking speed reduced the \(I_{\text{cl}}\) of both ensembles. Reductions in \(I_{\text{cl}}\) of 28\% and 12\% respectively for the Goretx and IREQ ensembles were observed when the walking speed was increased from 0\(\text{ms}^{-1}\) (standing stationary) to 0.37\(\text{ms}^{-1}\). Increasing the walking speed to 0.8\(\text{ms}^{-1}\) had no further effect on \(I_{\text{cl}}\) for the IREQ ensemble, but reduced the Goretx value by another 24\%. Increasing the external air speed again increased VI and decreased \(I_{\text{cl}}\) values of both ensembles. The average VI increases (across all walking speeds) due to an increase in external air speed, from \(< 0.2\text{ms}^{-1}\) to \(1\text{ms}^{-1}\), were 23\% (1SD = 10\%) for the Goretx ensemble and 12\% (1SD = 4\%) for the IREQ ensemble. In comparison, \(I_{\text{cl}}\) dropped by 7\% (1SD = 6\%) for the Goretx ensemble and by 8\% (1SD = 4\%) for the IREQ ensemble in similar conditions. The effect of the highest walking speed and air speed was to increase VI by 20\% in the IREQ ensemble, and by 74\% in the Goretx ensemble, resulting in decreases in \(I_{\text{cl}}\) of 18\% and 45\% respectively.

Pearsons correlation analysis of absolute Ventilation Index and effective insulation values (Figure 7.6) and of relative increases in both data show a significant relationship, \(r = -0.907\) and \(P < 0.05\) for Goretx ensemble, \(r = -0.803\) and \(P < 0.05\) for IREQ ensemble.
Figure 7.6: Relationship between ventilation at the skin and effective insulation of a 1-layer (Goretex) and a 3-layer (IREQ) clothing ensemble.

Figure 7.7: The influence of increasing ventilation at the skin on effective insulation of a 1-layer (Goretex) and a 3-layer (IREQ) clothing ensemble.
Figure 7.8. The relationship between increasing ventilation at the skin and drop in effective insulation of a 1-layer (Goretex) and a 3-layer (IREQ) clothing ensemble.

7.4 Discussion

The use of empirical data to adjust intrinsic insulation to resultant values is a dangerous practice which may lead to under- (or over-) protection of the wearer. Thus it is better in practice to be able to measure the factors which differ between empirical observations and actual situations. The aim of this experiment was to determine the relationship between the ventilation in two clothing ensembles and their thermal insulation in order to overcome reliance on empirical data that adjust intrinsic to resultant insulation. The high correlation between VI and I_{cle} in both ensembles shows that this approach is valid.

The ensembles were chosen because they were made from fabrics with different air permeabilities and had different designs and intrinsic insulations. The Goretex ensemble, being single layer in design trapped only one layer of air between its fabric and the manikin’s surface. This is reflected in its ‘small’ micro-environment volume. In contrast the IREQ ensemble trapped 3 air layers between the clothing surface and the manikin’s surface. Although the base layer and middle layer of the IREQ ensemble were tight fitting, for the manikin, each
consecutive layer of clothing would with it trap with another air layer. This was reflected by the IREQ ensemble having a greater micro-environment volume than the Goretx ensemble.

As expected, the air exchange rates were greater with the air-permeable IREQ ensemble than with the air-impermeable Goretx ensemble. However, the increase in air exchange rate with activity and 'wind' was more pronounced with the air-impermeable ensemble. The IREQ ensemble had a high baseline air exchange rate, due to its air permeable nature, but increases in activity and 'wind' had little effect (P > 0.05) suggesting that a ceiling effect was observed whereby the maximal air exchange rate obtainable in such conditions had been achieved. In contrast, the Goretx ensemble had a low baseline air exchange rate, but this rose considerably with increases in activity (P < 0.05) and 'wind' (P < 0.05). Since the Goretx ensemble fabric was (almost) air impermeable it must be considered that the increased air exchange took place through the ensemble openings (wrists, ankles, jacket hem and neckline). Where the increase in air exchange was related to an increase in activity it is reasonable to suggest that this was facilitated by 'pumping' of micro-environment air, as generated by body movements.

The ventilation rate data obtained in this study are of the same magnitude as those obtained by previous authors. The ventilation data for the Goretx ensemble in this study are similar to those presented in Chapter 6, and thus as described in Chapter 6 they are comparable to data reported by Angel (1995), Birnbaum and Crockford (1978) and Havenith et al (1990b) for similar air-impermeable ensembles. The ventilation data for the IREQ ensemble in this study are also similar to data from comparable ensembles as investigated in similar conditions and activities by other authors:

foul weather suit = \sim 45 \text{ l min}^{-1} \text{ for slow pacing activity} \\
\text{(Birnbaum and Crockford, 1978)}

work ensemble = \sim 43 \text{ l min}^{-1} \text{ for sitting} \\
(workpants, shirt, sweater & coverall) = \sim 56 \text{ l min}^{-1} \text{ for standing} \\
= \sim 86 \text{ l min}^{-1} \text{ for walking @ 0.3 ms}^{-1} \\
= \sim 129 \text{ l min}^{-1} \text{ for walking @ 0.9 ms}^{-1} \\
\text{(Havenith et al, 1990b)}

The work ensemble described by Havenith et al (1990b) is not entirely 3-layers in design, ie wearer's legs are covered by only 2 layers, which may explain why the ventilation rate for this
ensemble is much higher in the walking activities than has been demonstrated in this study with a ‘fully’ 3-layer ensemble. It is also expected that the air-permeability of the fabrics of this 3-layer ensemble is different to those of the ensemble investigated by Havenith et al (1990b), which again would change the clothing’s ventilation characteristics.

The insulation data reported here is also comparable with data previously reported for similar ensembles. Olesen (1985) presents a rain-protective trousers of 0.17 clo and a rain-protective jacket of 0.31 clo in standing, still air conditions. No activity and increased environmental air velocity data are available. The tight fitting wrist cuffs and ankle popper fastenings of the 1-layer Gore-tex ensemble, investigated in the current study, may explain its higher insulation value. Havenith et al (1990a) describe a work ensemble which includes a rain-coverall as the outermost layer. This consistently has a slightly higher clothing insulation value during assessment in still and moving environmental air conditions and during walking activities (Table 7.7) than does the Gore-tex ensemble in the current study, this being attributable to the ensemble investigated by Havenith et al (1990b) being worn with workpants, a poloshirt and a sweater underneath it - all these items contributing to the insulation afforded by the ensemble. The IREQ insulation data obtained in this study shows similar baseline characteristics to other cold protective clothing ensembles as provided by Olesen (1985).

Table 7.7 Comparison of 1-layer, air impermeable, clothing insulation data presented here with a similar ensemble (work pants, polo-shirt, sweater & raincoverall) previously presented by Havenith et al (1990b)

<table>
<thead>
<tr>
<th>Icl data present in this chapter (clo)</th>
<th>Icl data presented by Havenith et al (1990b) lean subjects (clo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing (v = 0.2 ms⁻¹): 0.75</td>
<td>Standing (v = 0 ms⁻¹): 1.14</td>
</tr>
<tr>
<td>Standing (v = 1 ms⁻¹): 0.67</td>
<td>Standing (v = 0.7 ms⁻¹): 1.07</td>
</tr>
<tr>
<td>Walk @ 0.37 ms⁻¹ (v = 0.2 ms⁻¹): 0.54</td>
<td>Walk @ 0.3 ms⁻¹ (v = 0 ms⁻¹): 0.92</td>
</tr>
<tr>
<td>Walk @ 0.37 ms⁻¹ (v = 1 ms⁻¹): 0.49</td>
<td>Walk @ 0.3 ms⁻¹ (v = 0.7 ms⁻¹): 0.92</td>
</tr>
<tr>
<td>Walk @ 0.8 ms⁻¹ (v = 0.2 ms⁻¹): 0.41</td>
<td>Walk @ 0.9 ms⁻¹ (v = 0 ms⁻¹): 0.77</td>
</tr>
<tr>
<td>Walk @ 0.8 ms⁻¹ (v = 1 ms⁻¹): 0.41</td>
<td>Walk @ 0.9 ms⁻¹ (v = 0.7 ms⁻¹): 0.73</td>
</tr>
</tbody>
</table>
In both ensembles an increase in VI resulted in a drop in $I_{ele}$. The higher baseline VI for IREQ is a consequence of the high air-permeability of its fabrics, and the larger openings at the cuffs and ankles. As suggested, the relatively small increases in VI with movement and air speed indicates a plateau effect due to the ensemble’s air-permeable nature. This small increase in VI resulted in only a small change in thermal insulation. In contrast, the 1-layer GoreTex ensemble had a lower thermal insulation. However, its air-impermeable nature resulted in greater pumping of the micro-environment air, and a relatively greater decrease in $I_{ele}$.

7.5 Conclusions

For the ensembles investigated:

1. Micro-environment volume increased with the number of clothing layers in an ensemble (even where these layers were tight fitting).

2. Air exchange rate at the skin’s surface relates to the air permeability characteristics of the ensembles constituent fabrics.

3. The IREQ ensemble had a high baseline VI which increased only slightly with activity and ‘wind’ suggesting a plateau effect where the maximal (reasonable) ventilation rate had been reached.

4. The Goretex ensemble had a low baseline VI which increased significantly with activity and ‘wind’ suggesting that pumping of micro-environment air, due to body movements, increases the amount of transfer occurring at ensemble openings.

5. The IREQ ensemble had a high baseline $I_{ele}$ which dropped only slightly with activity and ‘wind’, again suggesting a plateau effect related to that observed with relation to VI.

6. The Goretex ensemble had a low baseline $I_{ele}$ which dropped significantly with activity and ‘wind’ again suggesting that pumping of micro-environment air, due to body movements, increases the amount of transfer occurring at ensemble openings. Furthermore, that the movement of this air through openings into the clothing ensemble as well as out of it is detrimental to the wearer in cold conditions since removes warmed and acts as a heat sink.
Chapter 8
Chapter 8

LABORATORY STUDY 3
A COMPARISON OF VENTILATION INDEX FOR GARMENTS AS WORN BY A THERMAL MANIKIN AND HUMAN SUBJECTS

8.1 Introduction

A discussion exists regarding the ‘usefulness’ of using thermal manikins in the assessment of clothing. While many authors consider manikin tests to be beneficial, not least because they are ‘easier’ to conduct than human studies (by the very fact that they do not require human subject participation !), there remain questions regarding the data obtained in this way. Scepticism about these data because of differences between manikin research and that using human subjects has arisen for numerous reasons:

a. manikin anthropometric characteristics, at best, represent a standard person, most probably based on data from a limited population (eg air-crew personnel). People from the world population will vary from this value depending on their gender, nationality, fitness and age. Thus the surface area over which heat is lost to the environment from the clothed manikin will be different to that for human subjects. This will in turn be reflected in the clothing insulation value when measured using both human subjects and a thermal manikin.

b. manikin skin temperature, while being programmable to represent comfort or survival conditions, in most instances is set to be uniform over the manikin’s entire surface. This pre-set temperature will not necessarily represent the human skin temperature during physiological responses. Since clothing insulation values are calculated from the measured heat loss from a manikin’s skin surface the temperature at the measurement points should be representative of those found with humans subjects.
c. Manikin body movements, are at best, limited to walking and cycling actions. Pneumatic control of limb movements often results in a ‘jerky’ action and can lead to the manikin adopting a swinging action while walking. Database values of clothing insulation have often been measured with a manikin standing stationary. Measurements made using human subjects standing stationary will be different to these because of the micro-environment air exchange induced by the wearer’s breathing movements. Furthermore, the insulation measurements made with a standing manikin will not be representative of the value during activity, again because of the induced micro-environment air exchange with the surrounding environment.

d. Manikins able to sweat are not widely available for use, and are expensive to run. Most manikin data have been obtained using ‘dry’ manikins and as such the effects of wicking of moisture through the clothing and of direct wetting of the clothing are not taken into account. It is difficult to locate sweat glands, on a manikin, in exactly the same positions as on a human thus using sweating manikins may not provide the ideal solution.

Each of these differences, between manikins and human subjects could have an effect on the ventilation characteristics of clothing when worn (by them) during testing. The anthropometric characteristics of both manikin and human will affect the micro-environment volume of their clothing and thus will affect the clothing’s ventilation characteristics. The temperature of the manikin’s skin surface may, in extreme cold conditions, affect convective air exchange and the jerky action of body movements will result in a different pumping action within the clothing and such will change the clothing’s ventilation characteristics. When clothing is inappropriately wetted through sweat (or more likely through lack of sweat) this will again affect these characteristics given that wetted fabrics will ‘cling’ to the wearer’s skin or to the next clothing layer and in doing so impede the pumping of air.
The aim of this study was to examine the relationship between Ventilation Index obtained using a thermal manikin with those obtained using human subjects undertaking identical walking activities. The null hypothesis (H₀) was that VI would be the same when measured with humans as when measured with the thermal manikin. The alternative hypothesis (H₁) was that VI would differ between the human subjects and the manikin. If a relationship can be quantified then it will be possible to relate clothing insulation values as measured on thermal manikins to the thermal properties of the clothing when worn by human subjects, thus making evaluations of thermal risk in the workplace more accurate.

8.2 Materials and methods

8.2.1 Subjects

Eight, healthy, physically active males, age range 18 to 24 years, volunteered to participate in this study. They were recruited and screened for suitability to take part in this investigation in the same manner as that described in section 6.2.1. The data obtained from these subjects would then be compared with that measured using the TORE manikin (Chapter 7).

Subjects were asked to adhere to a pre-designated routine with respect to eating, drinking alcohol etc for the 12 hours prior to testing (see section 6.2.1 for full details). Once at the laboratory for the clothing assessment they were weighed and their height measured (section 6.2.1 gives full details). Subject physical characteristics are given in Table 8.1.

Laboratory ethics procedures were adhered to, during the clothing assessment, including the measurement of deep body temperature and heart rate and the asking of subjects for responses regarding thermal comfort, thermal sensation and perceived exertion, throughout exposure to the cold environment (procedures detailed in section 6.2.1). Subject skin temperatures were not measured during this investigation.
8.2.2 Test Clothing

During this study subjects wore an air impermeable GoreTex™ leisure suit (described in section 6.2.2) and an air permeable IREQ ensemble (described in section 7.2.2).

8.2.3 Determination of the Ventilation Index

Air exchange rates were determined for both ensembles in all activity conditions, and micro-environment volume measured with subjects standing stationary. These different measurements being made in separate test sessions as described in Chapter 5.

The measurements were conducted in a controlled-environment chamber, with exposure to the following thermal conditions: $t_a = 10.4 \ (1 \ SD = 0.3) ^\circ C$, $t_r = 10.2 \ (1 \ SD = 0.2) ^\circ C$, $V_a = 0.20 \ (1 \ SD = 0.02) \ m^{-1}$ and $rh = 55 \ (1 \ SD = 5.8) \%$. During each air exchange rate measurement exposure subjects performed 3 activities:

a. Standing stationary. (Figures 8.1 and 8.2)

Previously described in section 7.2.3

---

Table 8.1 Subject physical characteristics.

<table>
<thead>
<tr>
<th>Subject identifier</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>DuBois surface area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.89</td>
<td>93.6</td>
<td>2.21</td>
</tr>
<tr>
<td>2</td>
<td>1.82</td>
<td>65.4</td>
<td>1.84</td>
</tr>
<tr>
<td>3</td>
<td>1.85</td>
<td>76.6</td>
<td>1.99</td>
</tr>
<tr>
<td>4</td>
<td>1.80</td>
<td>84.5</td>
<td>2.04</td>
</tr>
<tr>
<td>5</td>
<td>1.82</td>
<td>79.7</td>
<td>2.00</td>
</tr>
<tr>
<td>6</td>
<td>1.87</td>
<td>90.6</td>
<td>2.16</td>
</tr>
<tr>
<td>7</td>
<td>1.77</td>
<td>58.6</td>
<td>1.72</td>
</tr>
<tr>
<td>8</td>
<td>1.77</td>
<td>72.5</td>
<td>1.89</td>
</tr>
<tr>
<td>Mean</td>
<td>1.82</td>
<td>76.7</td>
<td>1.98</td>
</tr>
<tr>
<td>1 SD</td>
<td>4.0</td>
<td>11.3</td>
<td>0.15</td>
</tr>
</tbody>
</table>

* note, TORE DuBois surface area = 1.77 m²
b. Performing a ‘slow walk’ routine (Figures 8.3 and 8.4).
This was performed on a motor driven treadmill set to a walking speed of 0.37 ms⁻¹. Subjects were encouraged to step between two pieces of tape located 645 mm apart, on the treadmill base, to ensure the same step length as used with the TORE manikin. This walking speed and step rate is estimated to have resulted in 23 walking paces per minute, as with the manikin. During this routine subjects were encouraged to walk with arms swinging so as to further mimic the movements of the manikin.

C. Performing a ‘fast walk’ activity.
Again, this was performed on a motor driven treadmill, this time set to a walking speed of 0.8 ms⁻¹. Subjects were encouraged to step between two pieces of tape located 645 mm apart, on the treadmill base, to ensure the same step length as used with the TORE manikin. This walking speed and step rate is estimated to have resulted in 48 walking paces per minute, as with the manikin. During this routine subjects were encouraged to walk with arms swinging so as to further mimic the movements of the manikin.
Tracer gas measurements were made (and air exchange rates determined) 3 times for each activity, from which a mean value was calculated. Between each measurement subjects were asked to undo the jacket zip(s) and shuffle both the jacket and trousers in order to remove any pools of nitrogen gas trapped within them. The 3 tracer gas measurements were made consecutively, with the order of presentation of the different activities being balanced between subjects.

For each individual subject the mean air exchange rate value for each activity was combined with that individual’s mean micro-environment volume measurement for the suit to give the VI value for that activity.

8.3 Results

8.3.1 Relationship between DuBois surface area and Micro-environment volume

The values obtained for subject DuBois surface area and clothing micro-environment volumes are given in Tables 8.1 and 8.2 respectively. The relationships between subject DuBois surface area and clothing micro-environment volume where: $r^2 = 0.57$ for IREQ ensemble and $r^2 =$
0.3481 for GoreTex™ suit) is given in Figure 8.5. Pearson's correlation on these data show a significant relationship for wearer DuBois surface area ($r = -0.754$, $P < 0.05$) and micro-environment volume for the IREQ ensemble only, Goretex ensemble ($r = -0.590$, $P > 0.05$).

Table 8.2 Micro-environment volumes measured for IREQ ensemble and GoreTex™ ensemble.

<table>
<thead>
<tr>
<th>Subject identifier</th>
<th>Gore Tex™ ensemble</th>
<th>IREQ ensemble</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.9</td>
<td>29.9</td>
</tr>
<tr>
<td>2</td>
<td>25.2</td>
<td>34.5</td>
</tr>
<tr>
<td>3</td>
<td>22.9</td>
<td>38.2</td>
</tr>
<tr>
<td>4</td>
<td>17.7</td>
<td>33.6</td>
</tr>
<tr>
<td>5</td>
<td>21.3</td>
<td>34.5</td>
</tr>
<tr>
<td>6</td>
<td>21.8</td>
<td>29.9</td>
</tr>
<tr>
<td>7</td>
<td>25.1</td>
<td>42.9</td>
</tr>
<tr>
<td>8</td>
<td>22.1</td>
<td>31.3</td>
</tr>
<tr>
<td>Mean</td>
<td>22.3</td>
<td>34.6</td>
</tr>
<tr>
<td>1 SD</td>
<td>2.4</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Figure 8.5 Relationship between subject DuBois surface area and clothing micro-environment volume for a 1-layer Goretex ensemble and a 3-layer IREQ ensemble.
8.3.2 Air exchange rates

Air exchange rates for both suits were calculated from the time taken for oxygen concentration levels within the clothing to return to environmental values following the turning off of the nitrogen supply having reduced these levels to 10%. Air exchange rates between the clothing and the environment are given in Table 8.3. Ventilation Index values were calculated by combining these values with those for micro-environment volume and are given in Table 8.4.

As shown in Figure 10.6, when wearing the GoreTex™ suit air exchange rate values were increased by an mean of 0.04 per minute during the slow walk activity and by an mean of 0.09 per minute during the fast walk activity. In addition, when wearing the IREQ ensemble air exchange rate values were increase by an mean of 0.16 per minutes during the slow walk activity and by an mean of 0.24 per minute during the fast walk activity.

Table 8.3 Air exchange rates for GoreTex™ ensemble and IREQ ensemble during standing, slow walk and fast walk activities.

<table>
<thead>
<tr>
<th>Subject</th>
<th>GoreTex™ ensemble</th>
<th>IREQ ensemble</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air exchange rate (per minute)</td>
<td>Air exchange rate (per minute)</td>
</tr>
<tr>
<td></td>
<td>Stand</td>
<td>Slow walk</td>
</tr>
<tr>
<td>1</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>2</td>
<td>0.16</td>
<td>0.26</td>
</tr>
<tr>
<td>3</td>
<td>0.23</td>
<td>0.33</td>
</tr>
<tr>
<td>4</td>
<td>0.29</td>
<td>0.30</td>
</tr>
<tr>
<td>5</td>
<td>0.36</td>
<td>0.41</td>
</tr>
<tr>
<td>6</td>
<td>0.21</td>
<td>0.19</td>
</tr>
<tr>
<td>7</td>
<td>0.28</td>
<td>0.29</td>
</tr>
<tr>
<td>8</td>
<td>0.20</td>
<td>0.24</td>
</tr>
</tbody>
</table>
| Mean (1 SD) | 0.25 | 0.29 | 0.34 | 1.09 | 1.25 | 1.33 | (0.06) | (0.06) | (0.07) | (0.18) | (0.22) | (0.25)
Figure 8.6 Effect of activity (standing stationary, slow walk and fast walk) on air exchange rate for IREQ ensemble and GoreTex™ ensemble.

Table 8.4 Ventilation Index values for IREQ ensemble and GoreTex™ ensemble during standing, slow walk and fast walk activities.

<table>
<thead>
<tr>
<th>Subject</th>
<th>GoreTex™ ensemble</th>
<th>IREQ ensemble</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ventilation Index (Litres per minute)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stand</td>
<td>Slow walk</td>
</tr>
<tr>
<td>1</td>
<td>5.91</td>
<td>6.13</td>
</tr>
<tr>
<td>2</td>
<td>4.03</td>
<td>6.55</td>
</tr>
<tr>
<td>3</td>
<td>5.27</td>
<td>7.56</td>
</tr>
<tr>
<td>4</td>
<td>5.13</td>
<td>5.31</td>
</tr>
<tr>
<td>5</td>
<td>7.67</td>
<td>8.73</td>
</tr>
<tr>
<td>6</td>
<td>4.58</td>
<td>4.14</td>
</tr>
<tr>
<td>7</td>
<td>7.03</td>
<td>7.28</td>
</tr>
<tr>
<td>8</td>
<td>4.42</td>
<td>5.30</td>
</tr>
<tr>
<td>Mean</td>
<td>5.50</td>
<td>6.38</td>
</tr>
<tr>
<td>(1 SD)</td>
<td>(1.29)</td>
<td>(1.47)</td>
</tr>
</tbody>
</table>
8.3.3 Ventilation Index

As shown in Figure 8.7, when wearing the GoreTex™ ensemble Ventilation Index values were increased by 16% during the slow walk activity (mean increase of 1.87 litres per minute, 1 SD = 1.05 litres per minute) and by 37% during the fast walk activity (mean decrease of 2.01 litres per minute, 1 SD = 1.50 litres per minute). In addition, when wearing the IREQ ensemble Ventilation Index values were increased by 15% during the slow walk activity (mean increase of 5.50 litres per minute, 1 SD = 5.05 litres per minute) and by 21% during the fast walk activity (mean decrease of 7.93 litres per minute, 1 SD = 6.23 litres per minute).

![Figure 8.7 Effect of activity (standing stationary, slow walk and fast walk) on Ventilation Index for IREQ ensemble and GoreTex™ suit.](image)

8.3.4 Comparing human and manikin data

Clothing micro-environment volumes were smaller when worn by human subjects than when it was worn by TORE (22.3 (1SD = 2.4) l with human subjects and 40 (1SD = 1) l with TORE, difference of 79 %, for the Goretex ensemble and 34.6 (1SD = 4.3) l with human subjects and 60.97 (1 SD = 1.82) l, difference of 76 %, for the IREQ ensemble, Figure 8.8).
Air exchange rates were highest, for both ensembles, when worn by the human subjects than when worn by TORE (Figure 8.9). Statistical analysis (ANOVA) show a significant difference between human subject and manikin data (P < 0.05). When human subjects wore the Goretex ensemble air exchange rates were 79 % higher when standing stationary (still air), 71 % higher when walking at 0.37 ms\(^{-1}\) (still air) and 62 % higher when walking at 0.8 ms\(^{-1}\) (still air) than when the ensemble was worn by TORE (P < 0.05, from Contrast analysis). Similarly, when human subjects wore the IREQ ensemble these were 18 % higher when standing stationary (still air), 32 % higher when walking at 0.37 ms\(^{-1}\) (still air) and 29 % higher when walking at 0.8 ms\(^{-1}\) (still air) than when the ensemble was worn by TORE.

The differences in micro-environment volumes and air exchange rates, as measured with human subjects and the TORE manikin, are reflected in the Ventilation Index as measured for both ensembles in these test conditions (Figure 8.10). For the Goretex ensemble no difference between manikin and human values is observed when both are standing stationary, but when walking at 0.37 ms\(^{-1}\) the ventilation rate on the manikin 6 % higher than for the human subjects and when walking at 0.8 ms\(^{-1}\) this figure rises to give a 14 % difference. Considering the IREQ ensemble, the clothing when worn by the manikin standing stationary has a 52 % higher
ventilation rate than when worn by human subjects standing stationary. When both manikin and human subjects walk at 0.37 m/s\(^{-1}\) this value is reduced to a 37% difference, again highest when worn by the manikin, becoming a 40% difference when the walking speed is increased to 0.8 m/s\(^{-1}\). Statistical analysis of all IREQ data, comparing manikin data with that human subjects shows a significant difference (P < 0.05, by ANOVA).

Figure 8.9 Comparison of air exchange rate values measured for a Goretx single layer ensemble and IREQ multi-layer ensemble with human subjects and TORE manikin.
Figure 8.10 Comparison of Ventilation Index values measured for a Gore-tex single layer ensemble and IREQ multi-layer ensemble with human subjects and TORE manikin.

8.4 Discussion

The aim of this study was to compare Ventilation Index data obtained using human subjects and the thermal manikin TORE, data obtained from both measurements show a similar behaviour, with clothing worn by manikins having the greater ventilation characteristics.

The subjects in this study had a slightly larger body surface area than TORE, 1.98 (1 SD = 0.15) m² as compared with 1.7742 m² respectively which explains why the clothing has a smaller micro-environment volume when worn by the human subjects. Subjects were not selected to match the manikin’s body size, thereby ensuring that the study genuinely investigated differences between manikin measurements and those made on human subjects from the general population. Repetition of this study using subjects which had been selected to match the anthropometric characteristics of the manikin would enable assessment of any differences in clothing ventilation observed because of different walking styles alone.
The results presented in this chapter, suggest that air exchange rates are significantly different, for the two ensembles investigated, when worn by human subjects and when worn by the TORE manikin (P < 0.05). Additionally, when VI data is analysed a significant difference is observed for the IREQ ensemble when worn by human subjects and by the TORE manikin (P < 0.05). These data are in agreement with those found by Reischl et al (1987). Although measurements were only made on a standing manikin (ie without body movements) the data from Reischl’s study clearly show that under those conditions the ventilation rate of clothing is consistently higher when worn by a thermal manikin. Such differences observed for ensembles, questions the use of manikin clothing test data in designing clothing for humans.

The increased exchange of air between the clothing micro-environment and the surrounding environment when worn by the TORE manikin will result in greater sensible and evaporative heat exchange if the measurement is made in some (cold) environments. This will in turn be translated to give a lower clothing insulation value than would be measured directly on a human subject. Where protective clothing is worn, but a high workload is performed this could lead to heat stress problems for workers if higher insulation clothing is provided based on these low manikin insulation data.

Differences between manikin and human subject activity movements, during this study, are inevitable. The pneumatic control of TORE’s walking action ensured an identical step movement and arm swing every time. Conversely, with the human subjects although care was taken to ensure an even step and arm swing movement for each walking step this was not always achievable by the subjects. Particular difficulty was noticed in the fastest walking speed (0.8 ms⁻¹) where several subjects had trouble maintaining balance while walking so quickly at the required step rate and step length. Thus in some instances the arm and leg movements were curtailed! The long(er) sweeping walking and arm swing movements of the manikin will have induced more pumping in the Goretex ensemble (and may also have induced more air movement into the IREQ ensemble) than would have been the case with the human subjects.

Repetition of this study with the same activities conducted in moving air (1ms⁻¹), as per the study detailed in Chapter 7, would provide a fuller comparison between human subject and manikin data. In such a repetition the measurement of human subject temperatures (skin and deep body) should be included, which may provide evidence of convective heat losses being
different for humans as compared with those from the uniform skin temperature of the manikin. Similarly, work to look at the effects of 'clinging' from sweat laden clothing on clothing ventilation characteristics may also be possible in such work.

8.5 Conclusions

1. Clothing micro-environment volumes were highest, for both ensembles when worn by TORE, this being due to 'him' having different anthropometric characteristics to the human subjects. (This could be overcome by using subjects matched to the manikin for their anthropometric characteristics.)

2. Clothing air exchange rate values were highest, for both ensembles when worn by the human subjects, this being due to the reduced volume of air which could be exchanged, ie the clothing have smaller micro-environment volumes when worn by them.

3. Ventilation Index were highest when worn by TORE, this being explained by 2 factors: the amount of air available for exchange (micro-environment volume) was greatest when worn by TORE, and in the Goretex ensemble his walking action would better facilitate pumping of the micro-environment air than would the human subject walking action.

4. The manikin’s walking action was not representative of the human subject walking action, especially given that the human subjects struggled to replicate its movements.

5. Replication of this work, considering the effects of environmental air speed, wearer skin temperature, the presence of sweat in clothing layers, as well as matching subjects for anthropometric characteristics to those of the manikin may provided a fuller comparison between the manikin and human subject measurement methods.
Chapter 9
Chapter 9

LABORATORY STUDY 4
THE EFFECT OF CLOTHING FIT ON THE VENTILATION INDEX

9.1 Introduction

One suggested explanation for the difference in clothing ventilation when worn by human subjects and when worn by the TORE manikin is that of the effect of clothing fit on its ventilation properties. In terms of clothing design and thermal physiology, the fit of clothing influences both the micro-environment volume within the ensemble and the ability to generate ‘pumping’ within it. In turn, as shown in Chapter 8, these properties influence the ventilation characteristics of an ensemble and thus the effect the ensemble has on the exchange of sensible and evaporative heat between the wearer’s skin and the environment.

Further to this, it is not always the case that correctly fitting clothing is available for an individual when required. An inappropriate fit can be detrimental to the wearer’s performance due to a number of factors. Clothing which is too tight may restrict movement and may rub against areas of the body causing chafing. Similarly, clothing which is too loose may present a snag or trip hazard and may be generally uncomfortable to wear. The incorrect fit of clothing may also generate problems associated with incompatibility between garments in an ensemble or between garments and equipment used in association with the clothing.

The aim of this study was to examine the effect of fit of clothing on VI. The null hypothesis ($H_0$) was that VI would not be related to clothing fit. The alternative hypothesis ($H_1$) was that loose-fitting clothing would have a higher VI than tight fitting clothing. If a relationship can be quantified then it will be possible to relate clothing fit, through VI, to its effects on clothing insulation and on the heat exchange between the wearer and the environment, thus making evaluations of thermal risk in the workplace more accurate.
9.2 Materials and methods

9.2.1 Subjects

Nine, healthy, physically active males, age range 19 to 30 years, volunteered to participate in this study. They were recruited and screened for suitability to take part in this investigation in the same manner as that described in section 6.2.1.

Subjects were asked to adhere to a pre-designated routine with respect to eating, drinking alcohol etc for the 12 hours prior to testing (see section 6.2.1 for full details). Once at the laboratory for the clothing assessment they were weighed and their height measured (section 6.2.1 gives full details). Subject physical characteristics are given in Table 9.1.

Laboratory ethics procedures were adhered to, during the clothing assessment, including the measurement of deep body temperature and heart rate and the asking of subjects for responses regarding thermal comfort, thermal sensation and perceived exertion, throughout exposure to the cold environment (procedures detailed in section 6.2.1). Subject skin temperatures were not measured during this investigation.

Table 9.1 Subject physical characteristics.

<table>
<thead>
<tr>
<th>Subject identifier</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>DuBois surface area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.80</td>
<td>70.70</td>
<td>1.89</td>
</tr>
<tr>
<td>2</td>
<td>1.88</td>
<td>88.90</td>
<td>2.15</td>
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<tr>
<td>3</td>
<td>1.77</td>
<td>67.15</td>
<td>1.83</td>
</tr>
<tr>
<td>4</td>
<td>1.80</td>
<td>72.30</td>
<td>1.91</td>
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<tr>
<td>5</td>
<td>1.69</td>
<td>72.65</td>
<td>1.83</td>
</tr>
<tr>
<td>6</td>
<td>1.78</td>
<td>91.10</td>
<td>2.10</td>
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<td>7</td>
<td>1.88</td>
<td>88.96</td>
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<td>8</td>
<td>1.84</td>
<td>73.70</td>
<td>1.96</td>
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<tr>
<td>9</td>
<td>1.86</td>
<td>80.72</td>
<td>2.05</td>
</tr>
<tr>
<td>Mean</td>
<td>1.81</td>
<td>78.46</td>
<td>1.99</td>
</tr>
<tr>
<td>1 SD</td>
<td>0.06</td>
<td>9.13</td>
<td>0.13</td>
</tr>
</tbody>
</table>
9.2.2 Test Clothing

During this study subjects wore an air impermeable GoreTex™ leisure suit (described in section 6.2.2) Two sizes of GoreTex™ leisure suit were tested, for the purposes of this study they are called ‘small’ and ‘large’. The order of wearing the small and large suits was balanced over subjects.

When investigating the GoreTex ensemble subjects wore their own undergarments. They were requested to wear normal length shorts for this purpose. They also wore their own soft training shoes and short socks.

9.2.3 Clothing fit

For this study it was necessary to make an estimate of the way in which the suit fitted for each subject. Various ways to quantify this fit were considered. For reasons of speed practicability and simplicity the following technique was adopted. Seven anatomical landmarks were used as measuring sites:

- forearm midpoint of styloid process and olecranon process of ulna
- upper arm midpoint of greater tubercle of humerus and olecranon process of ulna
- chest level of xiphoid process
- abdomen level of navel
- hip level of iliac crest
- thigh midpoint of iliac crest and superior border of patella
- lower leg midpoint of head and lateral malleous of fibula

At each site the ‘excess’ fabric of the suit was ‘pinched’ away from the body, and the extent of this ‘excess’ measured. (The clothing fit measurement technique is shown in Figure 9.1 An example measurement from subject 7 is shown in Table 9.2.) The mean of these values were calculated and used as an indication of the fit of the suit. The average clothing fit measurements for all subjects in both small and large suits are shown in Table 9.3.
Table 9.2 Subject 7 clothing fit values from all measured sites
(all values given in mm).

<table>
<thead>
<tr>
<th></th>
<th>Forearm</th>
<th>upper arm</th>
<th>chest</th>
<th>abdomen</th>
<th>hip</th>
<th>thigh</th>
<th>lower leg</th>
<th>Mean</th>
<th>1 SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 7</td>
<td>60</td>
<td>100</td>
<td>110</td>
<td>155</td>
<td>45</td>
<td>42</td>
<td>54</td>
<td>81</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 9.3 Average clothing fit measurements for all subjects with both the small and large suits.

<table>
<thead>
<tr>
<th>Subject Identifier</th>
<th>Clothing fit (1 SD) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>small suit</td>
</tr>
<tr>
<td>Subject 1</td>
<td>66 (41)</td>
</tr>
<tr>
<td>Subject 2</td>
<td>43 (28)</td>
</tr>
<tr>
<td>Subject 3</td>
<td>61 (41)</td>
</tr>
<tr>
<td>Subject 4</td>
<td>97 (50)</td>
</tr>
<tr>
<td>Subject 5</td>
<td>118 (60)</td>
</tr>
<tr>
<td>Subject 6</td>
<td>76 (39)</td>
</tr>
<tr>
<td>Subject 7</td>
<td>81 (42)</td>
</tr>
<tr>
<td>Subject 8</td>
<td>98 (40)</td>
</tr>
<tr>
<td>Subject 9</td>
<td>102 (50)</td>
</tr>
<tr>
<td>Mean</td>
<td>82 (23)</td>
</tr>
</tbody>
</table>

9.2.4 Determination of the Ventilation Index

VI was calculated as the product of the clothing air exchange rate and micro-environment volume. These were determined for both sizes of suit, the air exchange rate and micro-environment volume measurements being made in separate test sessions as described in sections 5.3 and 5.4.

The measurements were conducted in a controlled-environment chamber, with exposure to the following thermal conditions: \( t_a = 5.0 \) (1SD = 0.3) °C, \( t_r = 5.0 \) (1SD = 0.3) °C, \( V_a = 0.12 \) (1SD = 0.02 ms\(^{-1}\)) and rh = 62 (1SD = 1) % (water vapour pressure = 0.54 (1SD = 0.01) kPa).
During each air exchange rate measurement exposure subjects performed 3 activities:

a. Standing stationary.
Standing as still as possible, with head facing straight forward. Body movements in this exposure would be limited to chest expansions and contractions through breathing movements and occasional ‘natural shuffling’ movements - few subjects could stand perfectly still!

b. Performing a step-up routine (Figure 6.2).
Step-ups were performed on a 150 mm rise onto a Reebok™ aerobic step. Each full step (one foot up onto step, other foot up onto step, first foot down onto floor, other foot down onto floor) took 4.8 seconds to complete, each foot movement being cued by a metronome beep. Subjects were advised to change their choice of lead foot from time to time during exposure to avoid uneven muscle strain. This exposure was chosen,
based on previous research (Langendoen, 1990) which suggested it would induced moderate ventilation into the clothing.

c. Performing a rotate limbs activity (Figures 6.3 and 6.4).
Each limb was rotated individually in a large arc, with each arc taking 4.8 seconds to complete as cued by a metronome. Subjects performed slow arm and leg circles as follows, each complete series of clockwise rotations being followed by a counterclockwise series:

1. Subject moves extended right arm at a 45° angle to the horizon in a clockwise arc completing a circle 4.8 seconds
2. Subject moves extended left arm at a 45° angle to the horizon in a clockwise arc completing a circle 4.8 seconds
3. Subject moves extended right leg at a 30° angle to their body in a clockwise arc completing a circle 4.8 seconds
4. Subject moves extended left leg at a 30° angle to their body in a clockwise arc completing a circle 4.8 seconds

Tracer gas measurements were made (and air exchange rates determined) 3 times for each activity, from which an average value was calculated. Between each measurement subjects were asked to undo the jacket zip and shuffle both the jacket and trousers in order to remove any pools of nitrogen gas trapped within them. The 3 tracer gas measurements were made consecutively, with the order of presentation of the different activities being balanced between subjects.

For each individual subject the average air exchange rate value for each activity was combined with the individual's average micro-environment volume measurement for the suit to give the VI value for that activity.
9.3 Results

9.3.1 DuBois surface area, clothing fit and clothing micro-environment volumes

As expected, The GoreTex™ suit (both sizes) was tighter for subjects with a larger DuBois surface area. The relationships between subject DuBois surface area and fit of the small and large suits are shown in Figure 9.2, linear regression analysis gives $r^2 = 0.3544$ for the large suit and $r^2 = 0.1156$ for the small suit. Pearson correlation analysis shows a significant relationship between wearer DuBois surface area and clothing fit for the large suit only ($r = -0.595$, $P < 0.05$ for large suit, and $r = -0.340$, $P > 0.05$ for small suit). Also related to this, the micro-environment volume of the clothing is seen to be smaller for subjects with larger DuBois surface areas, micro-environment volumes are given in Table 9.4 and relationship shown in Figure 9.3, linear regression analysis gives $r^2 = 0.3353$ for the large suit and $r^2 = 0.6167$ for the small suit. Pearson correlation analysis shows a significant relationship between wearer DuBois surface area and suit micro-environment volume for the small suit only ($r = -0.785$, $P < 0.05$ for small ensemble and $r = -0.579$, $P > 0.05$ for large suit).

![Graph showing relationship between DuBois surface area and clothing fit](image)

**Figure 9.2** Relationship between subject DuBois surface area and clothing fit of both small and large suits.
Table 9.4 Subject micro-environment volumes in small and large GoreTex™ suit.

<table>
<thead>
<tr>
<th>Subject identifier</th>
<th>Small suit</th>
<th>Large suit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>32</td>
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<td>4</td>
<td>38</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>33</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>34</td>
<td>37</td>
</tr>
<tr>
<td>8</td>
<td>32</td>
<td>38</td>
</tr>
<tr>
<td>9</td>
<td>32</td>
<td>44</td>
</tr>
<tr>
<td>Mean (1 SD)</td>
<td>34.1 (3.7)</td>
<td>39.8 (3.7)</td>
</tr>
</tbody>
</table>

$\text{Mean (1 SD)} = 34.1 (3.7) \quad 39.8 (3.7)$

$\text{DuBois surface area (m2)}$

$r^2 = 0.3353$

$r^2 = 0.6167$

Figure 9.3 Relationship between subject DuBois surface area and micro-environment volume of both small and large suits.
Considering both suits together, the relationship between clothing fit and clothing micro-environment volume can be shown (Figure 9.4). Pearson correlation analysis of these data show a good relationship between clothing fit and clothing micro-environment volume ($r = 0.664$, $P < 0.05$).

![Figure 9.4 Relationship between clothing fit and clothing micro-environment volume.](image)

9.3.2 Air exchange rates

Air exchange rates for both suits were calculated from the time taken for oxygen concentration levels within the clothing to return to environmental values following the turning off of the nitrogen supply having reduced these levels to 10%. Air exchange rates between the clothing and the environment, ie the air exchange rates for this oxygen return, are given in Table 9.5. The low standard deviations (mean standard deviation for activities in the small suit are 0.03 min$^{-1}$, 0.03 min$^{-1}$ and 0.06 min$^{-1}$ respectively for the standing, stepping and rotate limbs activities, and in the large suit are 0.05 min$^{-1}$, 0.04 min$^{-1}$ and 0.05 min$^{-1}$ respectively for these activities) of these data indicates the high replicability of the technique. Ventilation Index values were calculated by combining the mean air exchange rate values with those for micro-environment volume. VI values are given in Table 9.6.
Table 9.5 Air exchange rates for small and large suits during standing, stepping and rotate limbs activities.

| Subject | Small suit | | | Large suit | | |
|---------|------------|------------|------------|------------|------------|
|         | Air exchange rate (min⁻¹) (1 SD) | | | Air exchange rate (min⁻¹) (1 SD) | | |
|         | Stand | Stepping | Rotate | Stand | Stepping | Rotate |
| 1       | 0.11 (0.02) | 0.17 (0.05) | 0.18 (0.02) | 0.14 (0.04) | 0.28 (0.03) | 0.23 (0.03) |
| 2       | 0.14 (0.02) | 0.27 (0.03) | 0.35 (0.04) | 0.17 (0.02) | 0.30 (0.05) | 0.38 (0.03) |
| 3       | 0.13 (0.04) | 0.15 (0.05) | 0.29 (0.05) | 0.14 (0.09) | 0.30 (0.02) | 0.26 (0.09) |
| 4       | 0.14 (0.01) | 0.32 (0.02) | 0.27 (0.02) | 0.17 (0.03) | 0.29 (0.07) | 0.32 (0.08) |
| 5       | 0.22 (0.01) | 0.43 (0.01) | 0.32 (0.01) | 0.24 (0.07) | 0.36 (0.08) | 0.33 (0.04) |
| 6       | 0.23 (0.02) | 0.32 (0.02) | 0.31 (0.05) | 0.21 (0.01) | 0.40 (0.05) | 0.28 (0.01) |
| 7       | 0.23 (0.07) | 0.35 (0.06) | 0.41 (0.12) | 0.27 (0.12) | 0.35 (0.03) | 0.45 (0.06) |
| 8       | 0.25 (0.02) | 0.45 (0.01) | 0.48 (0.02) | 0.35 (0.03) | 0.28 (0.01) | 0.40 (0.02) |
| 9       | 0.37 (0.05) | 0.51 (0.00) | 0.59 (0.12) | 0.29 (0.01) | 0.33 (0.03) | 0.32 (0.06) |
| Mean    | 0.20 (0.08) | 0.33 (0.12) | 0.36 (0.12) | 0.22 (0.07) | 0.32 (0.04) | 0.33 (0.07) |

As shown in Figure 9.5 and by statistical analysis by ANOVA and contrast comparisons, wearing the larger size suit had no significant effect on air exchange rate. Differences between activities were however, significant. Figure 9.5 also shows the increased rate of air exchange due to activity: stepping increased the rate of air exchange by 65% when wearing the small suit and by 45% when wearing the large suit, and rotate limbs increased the air exchange rate by a further 9% when wearing the small suit and by 3% when wearing the large suit. Overall the air exchange rate during the stepping activity was significantly higher than the stand activity (P < 0.05), as was the rotate limbs activity (P < 0.05).
Figure 9.5 Air exchange rates, for both small and large suits, during standing, stepping and rotate limbs activities (mean values from all subjects).

Table 9.6 Ventilation Index values for small and large suits during standing, stepping and rotate limbs activities.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Stand</th>
<th>Stepping</th>
<th>Rotate</th>
<th>Mean</th>
<th>Stand</th>
<th>Stepping</th>
<th>Rotate</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.8</td>
<td>5.8</td>
<td>6.3</td>
<td>5.3</td>
<td>5.9</td>
<td>11.8</td>
<td>9.8</td>
<td>9.2</td>
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<td>(3.3)</td>
<td>(2.9)</td>
<td>(2.0)</td>
<td>(2.2)</td>
<td>(1.8)</td>
</tr>
</tbody>
</table>
9.3.3 Ventilation Index

As shown in Figure 9.6 and by statistical analysis by ANOVA and contrast comparisons, wearing the larger size suit increased the Ventilation Index for all the activities (P < 0.05) (standing activity; mean increase of 28 %, 1.9 litres per minute, 1 SD = 1.3 litres per minute, stepping activity; mean increase of 15 %, 1.7 litres per minute, 1 SD = 3.9 litres per minute, and rotate limbs activities; mean increase of 8 %, 1.0 litres per minute, 1 SD = 2.6 litres per minute). Figure 9.6 also shows the increase in VI due to activity: stepping increased VI by 63 % when wearing the small suit and by 47 % when wearing the large suit, rotate limbs increase VI by 76 % when wearing the small suit and by 49 % when wearing the large suit. Overall VI during the stepping activity was significantly higher than the stand activity (P < 0.05), as was the rotate limbs activity (P < 0.05).

![Figure 9.6 Ventilation Index values, for both small and large suits, during standing, stepping and rotate limbs activities.](image)

However, the large variation in clothing fit seen for subjects with the same British surface area suggests (Figure 9.2) that the current method of selecting clothing fit is inadequate. Alternatively, these data may suggest that it is inappropriate to use British surface area measurements. Indeed, measurements of body volume may prove to be more informative, since...
9.4 Discussion

The aim of this study was to examine the effect of the fit of clothing on the clothing Ventilation Index. As expected, each individual had their own unique value of 'fit' of the GoreTex™ suit, and different values of Ventilation Index (Figure 9.7). In assessing this relationship it was noted that both clothing fit and the amount of air trapped within the clothing, ie micro-environment volume were related to the wearer's DuBois surface area. Thus a relationship between clothing fit and clothing micro-environment volume was found. Further work may provide data which strengthens the reliability of this relationship. If this is the case then for clothing with known air exchange qualities the overall ventilation qualities may be estimated by simply measuring the clothing fit for individual wearers.

However, the large variation in clothing fit seen for subjects with the same DuBois surface area suggests (Figure 9.2) that the current method of assessing clothing fit is inadequate. Alternatively, these data may suggest that it is inappropriate to use DuBois surface area measurements. Indeed, measurements of body volume may prove to be more informative, since
it is the volume of the person within the clothing that will affect the clothing’s microenvironment volume. Measuring excess fabric from alternative anatomical landmarks would (probably) give different values for clothing fit depending on the wearer’s individual body ‘make-up’ and composition. Realistically, the measurement of clothing fit from a limited number of sites will always provide some degree of error. Using photographic techniques such as the Loughborough Anthropometric Shadow Scanner (LASS), to provide an image of the wearer in the test clothing as well as nude (or just wearing underwear) may provide the answer, but are usually time consuming and expensive to conduct. Thus it is suggested that for the purposes of simple investigations, such as this, the technique used here to indicate clothing fit is adequate.

The small difference between triplicate measurements of air exchange rates measured in this study demonstrate the high repeatability of the tracer gas technique used as part of the VI measurement method. The deviation is greatest with the rotate limbs activity. This may be explained in that for the subjects, rotating their arms and legs in large arcs was not a natural movement, and as such the sweeping limb movements were not necessarily always completed in exactly the same way and in turn this would affect the movement of air into and out of their clothing.

Previous studies have demonstrated that clothing fit does indeed affect clothing ventilation rates but suggest that no significant relationship exists between clothing fit and air exchange rates (Birnbaum, 1975 and Havenith et al, 1990b). Birnbaum and Crockford (1978) by dressing a ‘small’ and ‘large’ subject in the same clothing ensembles found that the air exchange rate within those ensembles when worn by the smaller subject were higher than when worn by the larger subject. This corroborates the findings of Lotens and Havenith (1988), given that they found that adding a spacer between clothing garments and the wearer increased the ventilation in that region of the body. Havenith et al (1990b) were unable to show any effect of subject (and therefore any effect of clothing fit) during assessment of clothing ventilation using both ‘lean’ and ‘obese’ subjects to influence clothing fit.

The data presented in this chapter further suggests that air exchange rates are not significantly increased when wearing a larger suit, indeed that wearing a larger suit may reduce air exchange rates (Figure 9.5). This may be explained where a larger suit shows more creasing of its fabric.
which will affect its air permeation characteristics, or where the excess fabric overlaps at
openings, such as at the waist level between jacket and trousers and thus impedes loss of air at
these points. The effect seen by Birnbaum and Crockford (1978) where the test ensemble
would have been considerably too big for the smaller subject may have been due to the
stiffness of the clothing’s fabrics. If these were sufficiently stiff to prevent ‘crumpling’ where
the clothing was too big for the wearer then a reduction in air exchange rate as seen during the
present study would not be observed.

When Ventilation Index values were compared in this study, significant differences between the
small and large suits were observed (P < 0.05). Thus since suit size does not significantly affect
air exchange rate the differences observed with Ventilation Index values must be due to the
differences in micro-environment volumes of the two suits. The overall trend of the data is that
loose-fitting clothing allowed greater ‘pumping’ ie ventilation, than did the tight-fitting
clothing. This effect was largest for the standing stationary condition (28% difference between
small and large suits) presumably related to the large suit allowing air to exchange through
neck, wrist cuffs and trouser leg bottoms by means of natural convection. As expected,
Ventilation Index values were highest for the large suit during both the stepping and rotate
limbs conditions (differences of 15 % and 8 % respectively), although perhaps not as high as
expected if the looseness of the clothing resulted in the fabric ‘falling’ onto the wearer’s skin
due to its excess weight. The fact that clothing ventilation was increased with activity and with
wearing a looser fitting suit emphasises the importance of this avenue of sensible and
evaporative heat exchange with the environment for maintaining heat balance in the workplace.

GoreTex™ is relatively impermeable to air, so in this study, in which the ambient air speed was
low (0.12 ms⁻¹), most of the air exchange probably took place through the openings alone.
Clothing with a higher air permeability would be expected to allow air exchange by diffusion /
permeation through the fabric of the garments. In these circumstances the relative contribution
of the natural convection component (chimney effect) would be smaller. The practical
consequences of this must be taken into account when selecting clothing for work in
environments in which air speed could significantly lower resultant insulation, or in selecting a
limiting work environment when the clothing ensemble for that particular workplace is
invariable.
During this study it was also observed that when the clothing was very tight, the ability of the subjects to perform some tasks was impaired. Subjects with 'tight' fit values for the small (and in some cases also for the large) suit were restricted in both the stepping and rotate limbs activities, especially were the suits were particularly tight around their waist and thighs. This may have affected some subject Ventilation Index values.

This study has shown that it is in the interest of individuals and their employers to ensure that clothing is of a suitable fit, pumping may have detrimental physiological effects if the air temperature of the environment is cold. However, in warm and hot air temperatures pumping may assist heat loss by convection and evaporation, and thus be of benefit to the wearer. Conversely, ingress of hot air, from a hot environment, during high levels of activity may be detrimental to the subjects health in that it will increase subject skin temperature causing local or even whole body discomfort, reduction in personal performance and may even lead to heat stress physiological conditions. The subjects who in this study were unable to perform the assigned activity routines fully because of movement restrictions due to ill-fitting tight clothing, would agree that provision of clothing of a suitable fit is desirable.

9.5 Conclusions

1. Relationships have been shown between clothing fit, clothing micro-environment volume and wearer DuBois surface area, confirming that the effects of clothing fit may be implicated in the difference between values observed when clothing is worn by human subjects and by the TORE manikin.

2. The current method of measuring clothing fit is at best adequate. Using photographic techniques, such as the Loughborough Antropometric Shadow Scanner, may provide a better measure of clothing fit.

3. The small deviation between triplicate tracer gas measurements show the high repeatability of this method. Where this deviation is largest, with the rotate limbs activity, this may be explained because of the unnatural nature of the activity giving subjects some difficulty in completing the set movements.
4. Data from this study corroborate those of Birnbaum (1975) and Havenith et al (1990b) showing that air exchange rate is not necessarily higher when wearing a larger suit, indeed wearing a larger suit may reduce air exchange rates possibly because of fabric creasing or overlaps at openings.

5. The larger micro-environment of the large suit facilitates a greater amount of air available for exchange and thus larger VI values are observed with the large suit than with the small suit. The overall trend of the data us that loose-fitting clothing allowed greater pumping than did the tight fitting clothing.

6. VI values obtained with air permeable clothing would be expected to be higher than those for this test ensemble. In an air permeable ensemble air exchange would still occur through the clothing openings, although not being pumped to those points, but a higher amount would also occur directly through the clothing fabrics by permeation.

7. Where clothing is too tight for the wearer their ability to perform some tasks may be impaired. In turn, this will result in less air exchange between the clothing and the surrounding environment.
Chapter 10
Chapter 10

LABORATORY STUDY 5
THE EFFECT OF EXTERNAL AIR SPEED ON THE VENTILATION INDEX

10.1 Introduction
As shown in Chapter 9, even in still air conditions, the movement of environmental air across the surface of air-impermeable clothing and adjacent to any clothing openings increases the ventilation within that clothing. An increase in the movement of air through a clothing ensemble reduces both its thermal insulation and its apparent evaporative resistance, generally resulting in a higher heat loss from the skin than expected. This may be advantageous when working in circumstances which require heat loss to maintain a safe deep body temperature (eg in a hot work-place, or when wearing encapsulating clothing): however, it may be disadvantageous when circumstances require heat conservation.

Several mechanisms may operate when environmental air is blown across an ensemble. Air may enter garments through the fabrics, depending upon their air permeability, on the condition of the seams and on garment age and general condition. Air may also move through openings (sleeve cuffs, gaps around the collar) and pre-designed vents. The presence of restrictions such as a belt or harness, and a tighter fit of the clothing may reduce the magnitude of these effects.

It is therefore clear that for a complete evaluation of the worker and their thermal environment it is essential to quantify the relationship between the skin and the external environment. The aim of this study was to examine the effect of wind on the amount of air moving through a clothing ensemble, as measured by the clothing Ventilation Index (VI). The null hypothesis ($H_0$) was that, in the particular clothing ensemble chosen for the study, increased air speed would have no effect on the VI. The alternative hypothesis ($H_1$) was that increased air speed would increase VI.
10.2 Materials and methods

10.2.1 Subjects

Nine, healthy, physically active males, age range 19 to 30 years, volunteered to participate in this study. They were recruited and screened for suitability to take part in this investigation in the same manner as that described in section 6.2.1.

Subjects were asked to adhere to a pre-designated routine with respect to eating, drinking alcohol etc for the 12 hours prior to testing (see section 6.2.1 for full details). Once at the laboratory for the clothing assessment they were weighed and their height measured (section 6.2.1 gives full details). Subject physical characteristics are given in Table 10.1.

Laboratory ethics procedures were adhered to, during the clothing assessment, including the measurement of deep body temperature and heart rate and the asking of subjects for responses regarding thermal comfort, thermal sensation and perceived exertion, throughout exposure to the cold environment (procedures detailed in section 6.2.1). Subject skin temperatures were not measured during this investigation.

Table 10.1 Subject physical characteristics.

<table>
<thead>
<tr>
<th>Subject identifier</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>DuBois surface area (m²)</th>
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</thead>
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<td>1 SD</td>
<td>0.06</td>
<td>9.13</td>
<td>0.13</td>
</tr>
</tbody>
</table>
10.2.2 Test Clothing

During this study subjects wore an air impermeable GoreTex™ leisure suit (described in section 6.2.2) The suit tested had previously been designated as size-small (Chapter 9).

When investigating the GoreTex ensemble subjects wore their own undergarments. They were requested to wear normal length shorts for this purpose. They also wore their own soft training shoes and short socks.

10.2.3 Determination of the Ventilation Index

VI was calculated as the product of the clothing air exchange rate and micro-environment volume. The air exchange rates were determined in both air speeds and micro-environment volume measurements being made in a separate test session in still air conditions. The air exchange rate and micro-environment volume measurement techniques are described fully in sections 5.3 and 5.4.

The measurements were conducted in a controlled-environment chamber, with exposure to the following thermal conditions: \(t_a = 5.0\) (1 SD = 0.3) °C, \(t_r = 5.0\) (1 SD = 0.3) °C and \(r_h = 62\) (1 SD = 1) % (water vapour pressure = 0.54 (1 SD = 0.01) kPa).

All measurements were made in the climatic chamber within the Human Thermal Environments Laboratory, Loughborough University. This chamber was not adapted for wind tunnel type investigations. Subjects stood 750 mm in front of a Micromark 406.4 mm diameter, pedestal fan. Two separate air velocities were investigated: \(v = 0.12\) (1 SD = 0.02 m s\(^{-1}\)) and \(v = 3.06\) (1 SD = 0.04) m s\(^{-1}\). \(v\) was measured at chest height, by hot-wire anemometer. The order in which subjects were exposed to the low and high air speeds was balanced across subjects.

During each air exchange rate measurement exposure subjects performed 3 activities:

a. Standing stationary.

Standing as still as possible, with head facing straight forward. Body movements in this exposure would be limited to chest expansions and contractions through breathing movements and occasional ‘natural shuffling’ movements - few subjects could stand perfectly still!
b. Performing a step-up routine (Figure 6.2).

Step-ups were performed on a 150mm rise onto a Reebok™ aerobic step. Each full step (one foot up onto step, other foot up onto step, first foot down onto floor, other foot down onto floor) took 4.8 seconds to complete, each foot movement being cued by a metronome beep set at a 1.2 second interval. Subjects were advised to change their choice of lead foot from time to time during exposure to avoid uneven muscle strain. This exposure was chosen, based on previous research (Langendeon, 1990) which suggested it would induced moderate ventilation into the clothing.

C. Performing a rotate limbs activity (Figures 6.3 and 6.4).

Each limb was rotated individually in a large arc, with each arc taking 4.8 seconds to complete as cued by a metronome. Subjects performed slow arm and leg circles as follows, each complete series of clockwise rotations being followed by a counterclockwise series:

1. Subject moves extended right arm at a 45° angle to the horizon in a clockwise arc completing a circle 4.8 seconds
2. Subject moves extended left arm at a 45° angle to the horizon in a clockwise arc completing a circle 4.8 seconds
3. Subject moves extended right leg at a 30° angle to their body in a clockwise arc completing a circle 4.8 seconds
4. Subject moves extended left leg at a 30° angle to their body in a clockwise arc completing a circle 4.8 seconds

Tracer gas measurements were made (and air exchange rates determined) 3 times for each activity, from which an average value was calculated. Between each measurement subjects were asked to undo the jacket zip and shuffle both the jacket and trousers in order to remove any pools of nitrogen gas trapped within them. The 3 tracer gas measurements were made consecutively, with the order of presentation of the different activities being balanced over all subjects.
For each individual subject the average air exchange rate value for each activity was combined with the individuals average micro-environment volume measurement for the suit to give the VI value for that activity.

10.3 Results

10.3.1 Clothing micro-environment volumes

The subjects who undertook testing in this study had previously taken part in an investigation to examine the relationship between clothing fit and ventilation index (presented in chapter 9). The relationship between subject DuBois surface area and micro-environment volume of the GoreTex™ suit when worn by each subject are given in Figure 9.3 (small suit-size data). The micro-environment volume for the suit when worn by each subject is given in Table 9.3.

10.3.2 Air exchange rates

Air exchange rates for the suit was calculated, in both wind speeds, from the time taken for oxygen concentration levels within the clothing to return to environmental values following the turning off of the nitrogen supply having reduced these levels to 10%. Air exchange rates between the clothing and the environment are given in Table 10.2. The low standard deviations (mean standard deviation for activities in the still air condition are 0.02 min⁻¹, 0.04 min⁻¹ and 0.03 min⁻¹ respectively for the standing, stepping and rotate limbs activities, and in the moving air conditions are 0.05 min⁻¹, 0.08 min⁻¹ and 0.08 min⁻¹ respectively for these activities) of these data again indicate the high replicability of the technique. As shown in Figure 10.1 and by ANOVA and contrast statistical analysis, wearing the suit in a higher wind speed increased the rate of air exchange for all activities (P < 0.05): with the standing activity, mean increase of 0.07 per minute, 1 SD = 0.06 per minute, with the stepping activity, mean increase of 0.17 per minute, 1 SD = 0.18 per minute), and with the rotate limbs activity, mean increase of 0.18 per minute, 1 SD = 0.13 per minute). Figure 10.1 also shows the increased rate of air exchange due to activity: stepping increased the rate of air exchange by 50 % (P < 0.05) when wearing the suit in still air and by 77 % (P < 0.05) when wearing the suit in the moving air condition, and rotating limbs increased the air exchange rate by a further 20 % (P < 0.05) when wearing the suit in still air and by 17 % (P < 0.05) when wearing the suit in the moving air condition.
Table 10.2 Air exchange rates for both wind speeds during standing, stepping and rotate limbs activities.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Stand (V=0.12 ms⁻¹)</th>
<th>Stepping (V=0.12 ms⁻¹)</th>
<th>Rotate (V=0.12 ms⁻¹)</th>
<th>Stand (V=3.06 ms⁻¹)</th>
<th>Stepping (V=3.06 ms⁻¹)</th>
<th>Rotate (V=3.06 ms⁻¹)</th>
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<td>0.17 (0.01)</td>
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<td>0.26 (0.01)</td>
<td>0.30 (0.03)</td>
<td>0.34 (0.05)</td>
</tr>
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<td>0.34 (0.02)</td>
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<td>0.34 (0.05)</td>
<td>0.51 (0.08)</td>
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<td>0.29 (0.05)</td>
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<td>Mean (1SD)</td>
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<td>0.26 (0.04)</td>
<td>0.46 (0.15)</td>
<td>0.54 (0.12)</td>
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</table>

Figure 10.1 Air exchange rates, in both air speed conditions, during standing, stepping and rotate limbs activities.
### 10.3.3 Ventilation Index values

Ventilation Index values were calculated by combining air exchange rate values with those for micro-environment volume. VI values are given in Table 10.3. As shown in Figures 10.2 and 10.3 and by ANOVA statistical analysis, increasing the air speed increased the Ventilation Index for all the activities, $P < 0.05$ (standing activity; average increase of 37 %, 2.6 litres per minute, $1 \text{ SD} = 2.2$ litres per minute, stepping activity; average increase of 52 %, 5.5 litres per minute, $1 \text{ SD} = 5.7$ litres per minute, and rotate limbs activities; average increase of 50 %, 6.2 litres per minute, $1 \text{ SD} = 4.8$ litres per minute).

Figures 10.2 and 10.3 and contrast statistical analysis also show the increase (from stand values) in VI due to activity ($P < 0.05$): stepping increased VI by 54 % in still air and by 71 % in moving air, rotate limbs increased VI by 81 % in still air and by 98 % in moving air.

Analysis of the average Ventilation Index for each subject across all activities shows the significant differences between the different air speeds (Figure 10.4).

Table 10.3 Ventilation Index values in both still air and moving air conditions, during standing, stepping and rotate limbs activities.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Stand</th>
<th>Stepping</th>
<th>Rotate</th>
<th>Mean</th>
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<td>10.7</td>
<td>10.1</td>
<td>12.9</td>
<td>15.2</td>
<td>17.0</td>
<td>15.0</td>
</tr>
<tr>
<td>5</td>
<td>7.6</td>
<td>10.4</td>
<td>13.0</td>
<td>10.3</td>
<td>10.8</td>
<td>13.8</td>
<td>17.7</td>
<td>14.1</td>
</tr>
<tr>
<td>6</td>
<td>3.8</td>
<td>5.3</td>
<td>10.1</td>
<td>6.4</td>
<td>9.7</td>
<td>12.4</td>
<td>19.9</td>
<td>14.0</td>
</tr>
<tr>
<td>7</td>
<td>10.5</td>
<td>17.7</td>
<td>14.0</td>
<td>14.1</td>
<td>10.4</td>
<td>18.6</td>
<td>17.3</td>
<td>15.4</td>
</tr>
<tr>
<td>8</td>
<td>4.8</td>
<td>5.7</td>
<td>15.3</td>
<td>8.6</td>
<td>8.1</td>
<td>25.3</td>
<td>23.9</td>
<td>19.1</td>
</tr>
<tr>
<td>9</td>
<td>7.1</td>
<td>10.8</td>
<td>19.5</td>
<td>12.5</td>
<td>7.5</td>
<td>16.5</td>
<td>16.9</td>
<td>13.6</td>
</tr>
<tr>
<td>Mean (ISD)</td>
<td>6.7 (2.2)</td>
<td>10.3 (4.1)</td>
<td>12.1 (4.0)</td>
<td>9.7 (2.7)</td>
<td>9.2 (2.0)</td>
<td>15.7 (5.1)</td>
<td>18.2 (4.5)</td>
<td>14.4 (3.1)</td>
</tr>
</tbody>
</table>
Figure 10.2 Effect of activity and air speed on VI, individual subject data.

Figure 10.3 Ventilation Index values, for both air speed conditions, during standing, stepping and rotate limbs activities.
Figure 10.4 Individual subject mean VI values from all activities.

10.4 Discussion

This study has examined the effect of increasing external air velocity on the clothing Ventilation Index. It is suggested that the data obtained here could be used for a variety of practical purposes, for example, to set safe exposure times for hot or cold conditions, or to calculate effective work/rest schedules to maintain worker productivity and efficiency.

Some calculations, for example, BS EN ISO 12515, assume that the values of the sensible and evaporative resistances required in the calculations can be the ‘intrinsic’ values measured in laboratory conditions often using thermal manikins. However, several studies have shown that the values obtained in working conditions - the ‘resultant’ values - can be lower (Havenith et al 1990a). Part of this difference can be explained by the increased convective heat loss caused by air movement through the clothing as a result of wearer movement and ‘wind’ speed. The VI is a measure of air flowing through the micro-environment; it therefore has the potential to quantify the convective heat loss this will induce.
Comparisons of air exchange rates, for the suit in both air speeds, has shown that even though the suit is made from largely air impermeable fabric there was a significantly increased rate of air exchange when worn in a higher external air speed. If the suit were made from air-permeable material it would be expected that the air exchange rate would be considerably faster. The differences for the suit tested were pronounced with all the allotted activities. Again, as with the previous study, the small deviation between triplicate measurements of air exchange rates measured in this study demonstrates the high repeatability of the tracer gas technique used as part of the VI measurement method. The differences were again greatest with the rotate limbs activity. Again subjects appearing to have some difficulty with the unnatural rotate limbs movements. The air exchange rates recorded during moving air exposure tended to show a larger deviation than those recorded in still air conditions. This may be explained because of the turbulence intensity of the air flow past the subject varying during exposure and thus the pressure of air being forced against the clothing also changing.

When the air exchange rate values are combined with micro-environment volume values the extent of the effects of activity and the increased external air movement is highlighted. When standing stationary Ventilation Index is increased by 37 % in the higher air speed, when performing the stepping activity Ventilation Index is increased by 52 % in the higher air speed, and when performing the rotate limbs activity Ventilation Index is increased by 50 % in the higher air speed. The overall trend from these data suggest that air movement within clothing, even for clothing made from air-impermeable fabric, is increased if external air speed increases.

The Ventilation Index values measured in the different physical activities still air in this study are typical of those obtained in a previous study (Bouskill et al 1997), and are reproducible - the difference between the triplicate measures in the present study being less than 10 %. Previous authors had demonstrated the effect of increasing environmental air velocity on clothing ventilation. The data obtained in this study are much lower than those obtained for an ensemble with an air-impermeable outer layer by Havenith et al (1990b). The difference between measurements may have arisen since the increased air flow in the study presented in this thesis was directed mainly across the subject’s chest area. The use of a wind tunnel set up, as per the Havenith et al (1990b) study would have allowed an more uniform increase of environmental air across all of the clothing ensemble. The popper wind fastener on the jacket
...in the study presented here, would have withstood much of the increased environmental air movement resulting in the lower than expected Ventilation Index measurement.

The consistent effect of the increased air speed increasing the amount of air moving through the fabric even though it has a very low air permeability, shows that most of the wind-induced increase must have taken place through the openings in the suit, even though these were in the 'closed' position. The mechanism for this may be direct displacement of the micro-environment air, or convective exchange arising from the wind creating a duct effect at garment openings. From these data it can be concluded that wind (and activity level) has a significant effect on clothing ventilation, and therefore on sensible and evaporative heat transfer between the clothed worker and the external environment, even in wind-resistant clothing. This affects thermal strain, and should be considered in assessments of the worker's thermal environment.

10.5 Conclusions

1. A relationship has been shown between environmental air speed and the rate of air exchange between clothing and the surrounding environment.

2. Air exchange rate between the clothing micro-environment and the surrounding environment is higher in moving air conditions, even when wearing a suit made largely from impermeable fabric.

3. The small deviation between triplicate tracer gas measurements again show the high repeatability of this method. Where this deviation is largest, with the rotate limbs activity, this may be explained because of the unnatural nature of the activity giving subjects some difficulty in completing the set movements.

4. Since the clothing tested was made of fabric with a low air permeability most of the wind induced increase in ventilation must have taken place through the openings in the suit, even though these were in the closed position.

5. From these data it can be concluded that wind (and activity level) has a significant effect of clothing ventilation, and therefore on sensible and evaporative heat transfer between the clothed worker and the external environment, even in wind-resistant clothing.
Chapter 11
Chapter 11

LABORATORY STUDY 6
VENTILATION CHARACTERISTICS OF A
MULTI-LAYER CLOTHING ENSEMBLE

11.1 Introduction

Although the current tracer gas technique is able to measure the rate of air exchange which occurs at the skin surface, it does not take into account any air exchange which may occur within and between outer air layers of multi-layer clothing ensembles and the surrounding environment. While the ventilation rate at the skin surface is the most important in terms of quantifying heat transfer from the wearer, it may also be of interest to clothing designers to assess the ventilation characteristics of the air layers trapped more distant to the wearer in multi-layer ensembles.

With micro-environment air exchange, the removal of air from the skin’s surface to the external environment takes with it sensible and evaporative heat, while the ‘new air’ which replaces it changes the micro-environment characteristics. This will have physiological effects for the wearer of that clothing. The magnitude of this physiological response will depend on the nature and magnitude of micro-environment air exchange, these being the temperature and water vapour content of air removed and of the air ingress when it reaches the skin’s surface.

When clothing is single-layer in design such changes will occur quickly, depending on the air permeability characteristics of the clothing fabrics and on the size and positioning of any ensemble openings, so any physiological response will also be rapid. When clothing is multi-layer in design such changes will occur first in the outer-most air layer and then in each subsequent air layer until reaching that which is trapped next to the wearer’s skin, again depending on the air permeability characteristics of the constituent clothing fabrics and on the presence and location of any openings in each of these layers. Its ‘journey’ through the clothing layers will alter the temperature and water vapour content of this ‘new air’ making it
closer to those of the micro-environment air held next to the wearer’s skin. Thus this ‘new air’
will not induce the same degree of physiological response as if it entered directly next to the
wearer’s skin.

The Ventilation Index has been shown to be a sensitive and repeatable method for quantifying
the ventilation characteristics of single layer clothing. Improving this method, with respect to
accuracy when measuring multi-layer ensembles, would entail performing tracer gas
measurements in all air layers trapped within multi-layer ensembles. This would facilitate the
assessment of the air exchange within and between these layers, and thus to quantify rates of
ventilation throughout all layers, which in turn may ultimately be used to provide data
regarding the ‘journey’ of air through a clothing multi-layer ensemble. Measuring the micro-
environment volume of each successive air layer would also enable a Ventilation Index value to
be calculated for each of the clothing layers.

11.2 Materials and methods

11.2.1 Subjects
Eight, healthy, physically active males, age range 18 to 27 years, volunteered to participate in
this study. They were recruited and screened for suitability to take part in this investigation in
the same manner as that described in section 6.2.1.

Subjects were asked to adhere to a pre-designated routine with respect to eating, drinking
alcohol etc for the 12 hours prior to testing (see section 6.2.1 for full details). Once at the
laboratory for the clothing assessment they were weighed and their height measured (section
6.2.1 gives full details). Subject physical characteristics are given in Table 11.1.

Laboratory ethics procedures were adhered to, during the clothing assessment, including the
measurement of deep body temperature and heart rate and the asking of subjects for responses
regarding thermal comfort, thermal sensation and perceived exertion, throughout exposure to
the cold environment (procedures detailed in section 6.2.1). Subject skin temperatures were
not measured during this investigation.
Table 11.1 Subject physical characteristics.

<table>
<thead>
<tr>
<th>Subject identifier</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>Dubois surface area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.76</td>
<td>72.6</td>
<td>1.88</td>
</tr>
<tr>
<td>2</td>
<td>1.75</td>
<td>69.8</td>
<td>1.84</td>
</tr>
<tr>
<td>3</td>
<td>1.73</td>
<td>63.4</td>
<td>1.75</td>
</tr>
<tr>
<td>4</td>
<td>1.71</td>
<td>60.5</td>
<td>1.70</td>
</tr>
<tr>
<td>5</td>
<td>1.73</td>
<td>70.2</td>
<td>1.83</td>
</tr>
<tr>
<td>6</td>
<td>1.75</td>
<td>72.7</td>
<td>1.87</td>
</tr>
<tr>
<td>7</td>
<td>1.74</td>
<td>67.7</td>
<td>1.81</td>
</tr>
<tr>
<td>8</td>
<td>1.75</td>
<td>70.9</td>
<td>1.85</td>
</tr>
<tr>
<td>Mean</td>
<td>1.74</td>
<td>4.4</td>
<td>1.82</td>
</tr>
<tr>
<td>1 SD</td>
<td>0.02</td>
<td>11.3</td>
<td>0.06</td>
</tr>
</tbody>
</table>

11.2.2 Test Clothing

During this study subjects wore an air-permeable IREQ ensemble (described in section 7.2.2).

11.2.3 Determination of the Ventilation Index

Air exchange rates were determined for each clothing air layer. Subjects were first instrumented with both nitrogen distribution and tracer gas sampling systems, the tubes being located in accordance with Figures 5.5 and 5.9 respectively. After dressing in the base layer garments another tracer gas sampling system was added, again the tubes being located in accordance with Figure 5.9 (Figure 11.1). When dressed in the base and middle layer garments the final tracer gas sampling system was added (Figure 11.2). The subjects then donned the outer layer of garments. (Figure 11.3) Each tracer gas sampling system was connected to a Dynamax vacuum pump (details given in chapter 5) and Servomex Oxygen analyser (details given in chapter 5) from which the data were recorded using a squirrel data logger (details given in chapter 5). Nitrogen gas was supplied only to the base (air) layer of the ensemble. The air exchange rates for each of these air layers were calculated from the oxygen time return curve [39] (section 4.4.1).
Micro-environment volumes of the base layer garments, of the base and middle layer garments together of the whole ensemble were measured in a separate test session as described in section 5.4.

The measurements were conducted in a controlled-environment chamber, with exposure to the following thermal conditions: 

- $t_a = 10.2 \ (\text{1SD} = 0.1) \ ^\circ C$
- $t_e = 10.9 \ (\text{1SD} = 0.1) \ ^\circ C$
- $V_a = 0.12 \ (\text{1SD} = 0.03) \ \text{ms}^{-1}$
- $\text{rh} = 52 \ (\text{1SD} = 3.3) \ %$

During each air exchange rate measurement exposure subjects performed 3 activities:

a. Standing stationary. (Figure 8.2)

Standing as still as possible, with head facing straight forward. Body movements in this exposure would be limited to chest expansions and contractions through breathing movements and occasional ‘natural shuffling’ movements - few subjects could stand perfectly still!
b. Performing a ‘slow walk’ routine (Figure 8.4).
This was performed on a treadmill set to a walking speed of 0.37 ms\(^{-1}\). Subjects were encouraged to step between two pieces of tape located 645 mm apart, on the treadmill base, to ensure the same step length as used with the Tore manikin. This walking speed and step rate is estimated to have resulted in 23 walking paces per minute, as with the manikin (Chapter 7).

C. Performing a ‘fast walk’ activity.
Again, this was performed on a treadmill, this time set to a walking speed of 0.8 ms\(^{-1}\). Subjects were encouraged to step between two pieces of tape located 645 mm apart, on the treadmill base, to ensure the same step length as used with the Tore manikin. This walking speed and step rate is estimated to have resulted in 48 walking paces per minute, as with the manikin (Chapter 7).

11.3 Results

11.3.1 Air exchange rates:
The return of oxygen into the each of the clothing air layers was noticeably different (Figures 11.4 to 11.6). The air exchange rates were highest in all layers when walking at the fastest speed. The data suggest that during all activities air exchange was highest is the base layer (Table 11.2).

<table>
<thead>
<tr>
<th>Activity</th>
<th>Base Layer (min(^{-1}))</th>
<th>Middle Layer (min(^{-1}))</th>
<th>Outer layer (min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand</td>
<td>1.09</td>
<td>1.03</td>
<td>0.52</td>
</tr>
<tr>
<td>Walk 0.37 ms(^{-1})</td>
<td>1.25</td>
<td>0.93</td>
<td>0.61</td>
</tr>
<tr>
<td>Walk 0.8 ms(^{-2})</td>
<td>1.33</td>
<td>0.99</td>
<td>0.64</td>
</tr>
</tbody>
</table>
Figure 11.4 Oxygen return to base, middle and outer air layers during standing stationary activity.

Figure 11.5 Oxygen return to base, middle and outer air layers during 0.37 ms\(^{-1}\) walk activity.

11.3.2 Micro-environment volumes

The micro-environment volumes of each environment layer of the system are defined, as shown in Table 11.3. The volumes for each air layer are given in Table 11.4.

Table 11.4: Individual air layer volumes (cubic meter)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Volume (m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base layer</td>
<td>25.1 (0.44)</td>
</tr>
<tr>
<td>Base &amp; Middle</td>
<td>33.5 (0.30)</td>
</tr>
<tr>
<td>All layers</td>
<td>60.6 (0.55)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Oxygen concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>
11.3.2 Micro-environment volumes:

Clothing micro-environment volumes, as each subsequent layer of garments is added, are shown in Table 11.3. The volumes for each air layer are given in Table 11.4.

Table 11.3. Whole ensemble and air layer micro-environment volumes as subsequent clothing layers are added. Mean from all subjects.

| Micro-environment volume (1 SD) (l) |
|---------------------------------|---------------------------------|-----------------|
| Base layer                      | Base & Middle layers            | All layers     |
| 25.1 (0.44)                     | 33.5 (0.51)                     | 44.1 (0.32)    |

Table 11.4. Individual air layer volumes (calculated from Table 11.3)

<table>
<thead>
<tr>
<th></th>
<th>Base layer</th>
<th>Middle layer</th>
<th>Outer layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>(l)</td>
<td>25.1</td>
<td>8.4</td>
<td>10.6</td>
</tr>
</tbody>
</table>
3.3 Ventilation Index values:

VI for the ensemble, for each activity, was calculated from the whole ensemble micro-environment volume and the mean (from all subjects) base layer air exchange rate (Table 11.5). VI, for each activity, for each individual air layer was calculated from that layer’s individual volume and its air exchange rates for the activities (Table 11.6). These data suggest that measurement of an ensemble’s ventilation characteristics using the individual air layer exchange rates under-estimates the ensembles VI by 14% when standing stationary and by 17% when either walking at 0.37 ms⁻¹ or 0.8 ms⁻¹.

Table 11.5. Ventilation Index values, whole ensemble, during activity.

<table>
<thead>
<tr>
<th>Standing stationary (1 min⁻¹)</th>
<th>Walking @ 0.37 ms⁻¹ (1 min⁻¹)</th>
<th>Walking @ 0.8 ms⁻¹ (1 min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48.1</td>
<td>55.1</td>
<td>58.7</td>
</tr>
</tbody>
</table>

Table 11.6. Ventilation Index values, individual air layers, during activity.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Standing stationary (1 min⁻¹)</th>
<th>Walking @ 0.37 ms⁻¹ (1 min⁻¹)</th>
<th>Walking @ 0.8 ms⁻¹ (1 min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>27.4</td>
<td>31.4</td>
<td>33.4</td>
</tr>
<tr>
<td>Middle</td>
<td>8.7</td>
<td>7.8</td>
<td>8.3</td>
</tr>
<tr>
<td>Outer</td>
<td>5.5</td>
<td>6.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Total</td>
<td>41.6</td>
<td>45.7</td>
<td>48.5</td>
</tr>
</tbody>
</table>

11.4 Discussion

The aim of this project was to assess the feasibility of conducting tracer gas measurements in each air layer of a 3-layer cotton ensemble and to examine the effect of activity on the air exchange rates and Ventilation Index values in each of these layers.

Tracer gas measurements made in each of the base, middle and outer air layers of the 3-layer cotton ensemble show similar air exchange behaviour. Since, in these measurements, nitrogen gas is distributed to the base layer only (as would be the case conducting a ‘standard’ tracer gas measurement, section 5.2) the oxygen concentration recorded in this layer had the lowest start value and remained lower than values recorded in the middle and outer layers throughout each test. Oxygen concentration values recorded in the middle layer were always slightly
higher than those observed in the base layer, but always slightly lower than those observed in the outer layer.

Air exchange rate data calculated from these air layer oxygen concentration data suggest that the base layer has the highest rate of air exchange and that the outer layer has the lowest. If the base layer of clothing were made of air impermeable fabrics and had large openings which would facilitate pumping of air this would explain the largest air exchange rate occurring at the base layer. Similarly, for the outer air layer to have such a low value this would require the outer clothing layer to be made of air impermeable fabrics and to have small openings which would impede air exchange. However, with each layer of the actual test ensemble being made of air permeable fabrics these air exchange rate data are not as expected. The calculation of air exchange rates requires there to be a 'significant' change between the start and end oxygen concentration values. Where the difference between these values is small this calculation becomes inaccurate. Lotens and Havenith (1988) suggest that this 'tail-end' part of the oxygen return curve is better represented by several elements.

Alternatively, if the initial values of oxygen concentration in the middle and outer layers could be reduced, thus being closer to those recorded in the base layer, this may improve their air exchange rate calculation accuracy. The oxygen return curve, measured in each of the base middle and outer layers of the 3-layer ensemble when worn by a standing dress-makers manikin, when nitrogen gas is distributed to the middle air layer only is shown in Figure 11.7, when nitrogen gas is distributed to the outer air layer only is shown in Figure 11.8 and when nitrogen gas is distributed to all layers is shown in Figure 11.9.
Figure 11.7 Oxygen return to base middle and outer air layers following nitrogen distribution to middle air layer only. (Measurement made on standing 'dressmakers' manikin.)

Figure 11.8 Oxygen return to base middle and outer air layers following nitrogen distribution to outer air layer only. (Measurement made on standing 'dressmakers' manikin.)
Figure 11.9 Oxygen return to base middle and outer air layers following nitrogen distribution to all air layers. (Measurement made on standing ‘dressmakers’ manikin.)

Distributing nitrogen gas into the outer layer was successful at reducing the initial oxygen concentration in the outer layer but was unsuccessful in reducing the initial oxygen concentration in the middle and base layers. Distribution to the middle layer was more successful and reduced the initial oxygen concentration in all three air layers. Air exchange rates for the base, middle and layers, after nitrogen distribution to the middle layer, were: 2.39 min⁻¹, 0.59 min⁻¹ and 0.24 min⁻¹ respectively. Given that the initial value for the base layer was reduced by nitrogen input into the middle layer suggests that the base clothing layer was highly air permeable. It was expected that inputting nitrogen into the middle layer would change the oxygen concentration values within the outer air layer (since the nitrogen would ultimately have pass through this outer air layer to reach the environment) but not that it would have such a great effect on the base layer.

Distribution to all layers simultaneously, also produced lower initial oxygen concentration values than the standard base layer distribution technique. Air exchange rates for the base, middle and layers, after nitrogen distribution to all layers, were: 2.15 min⁻¹, 0.43 min⁻¹ and 0.29 min⁻¹ respectively. The ideal method of nitrogen gas distribution would be were each of the initial oxygen concentration values were at 10%. Obtaining such initial values would require
precision control of the nitrogen supply for each air layer and on the air permeability and pumping characteristics of the fabric in each clothing layer.

Lotens and Wammes (1993) suggest a model of vapour transfer in two layer clothing, where each clothing layer has a vapour resistance. A similar approach may be possible for clothing ventilation characteristics. The construction of a model to show movement of air between air layers within a multi-layer clothing ensemble may be possible, in the future, given more investigation into air exchange rate data for these trapped air layers. The ideal model would contain interaction between layers as well as between the ensemble and the external environment (Figure 11.10 provides a possible basis for such a model).

Figure 11.10 Possible model basis for investigating air exchange between air layers trapped within a multi-layer clothing ensemble.

The change in base air layer data obtained when nitrogen is inputted into the middle air layer suggests that while an ensemble may have three clothing layers it may not be appropriate to consider the air layers trapped between them individually. The fact that oxygen concentration within the base air layer is greatly reduced when nitrogen is inputted into the middle layer suggests that rather than considering each clothing layer as a ‘wall’ that it should be considered to be more air-permeable and thus that there can be more free interaction between adjacent air layers. This suggestion raises questions regarding the uniform distribution of nitrogen around all air layers, where a multi-layer ensemble is tested. Further investigation, to assess whether the distribution of nitrogen in such ensembles is actually uniform is required.
As expected, the air exchange rate data obtained from the standard base distribution technique suggest that activity increases the rate at which micro-environment air, trapped in all layers, is exchanged with the surrounding environment.

The ensemble micro-environment volume measured in this study is similar to those measured, with this test ensemble, previously (Table 10.2). The breakdown of this micro-environment volume in terms of each of the air layers provides some information which may be useful in determining the ventilation rates for these layers. However, when a layer of clothing garments are added, to ones already being worn, this will usually change the micro-environment volume of those underneath. Only where the over garments are loose will there be no reduction in the micro-environment volume of those garments worn underneath. This test ensemble was tight fitting for most subjects, particularly when all 3 layers of garments were worn. Thus it is unlikely, that in the test conditions, i.e. when all garments were worn, the micro-environment volume of the base, middle and outer layers would actually be 25.1 l, 8.4 l and 10.6 l respectively as measured. The inclusion of nitrogen distribution and tracer gas sampling tubing systems in all layers of the clothing ensemble will have changed the micro-environment volume of each air layer trapped between the clothing layers. The use of tubing systems with smaller diameter tubes should overcome this problem.

The lower than expected air exchange rates obtained, using the standard base layer distribution technique, for the middle and outer layers resulted in lower than expected VI values being calculated. Since the fabrics in each layer of this clothing were air permeable it is reasonable to suggest that the middle and outer layers should have had higher Ventilation Index values than those calculated here. If the ventilation rate at the base layer is high, and the clothing is air permeable so does not encourage ‘pumping’ at openings, then it reasonable to assume that the ventilation rates in the middle and outer layers will also be high. This was not observed in this study.

As already suggested, more work is needed to consider air exchange rate measurements in the middle and outer air layers to ensure their accuracy.
11.5 Conclusions

1. Rate of air exchange in this study was highest in the base layer and lowest in the outer layer when standing stationary, walking at 0.37 ms\(^{-1}\) and walking at 0.8 ms\(^{-1}\).

2. Increasing activity increased the rate of air exchange in all air layers.

3. Distributing nitrogen to the base air layer, of this multi-layer ensemble, did not reduce the oxygen concentration of the middle and outer air layers by a large amount. This was reflected in the accuracy of the air exchange rate calculation for these air layers.

4. Distributing nitrogen to the middle air layer, of this multi-layer ensemble, reduced the oxygen concentration of all air layers. This was reflected in the accuracy of the air exchange rate calculation for these air layers.

5. Distributing nitrogen to the outer air layer, of this multi-layer ensemble, did not reduce the oxygen concentration of the middle and base air layers by a large amount. This was reflected in the accuracy of the air exchange rate calculation for these air layers.

6. Measurement of the micro-environment volume of each air layer was attempted, but the values obtained did not take into any effects due wearing garments over those worn during the measurement.

7. The lower than expected Ventilation Index values obtained for the middle and outer air layers occurred because of difficulties measuring the air exchange rates in these layers.

8. Further work is needed to consider improvements to the current tracer gas technique with respect to multi-layer ensembles.
Chapter 12

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

12.1 Discussion

Given the importance of heat balance being maintained between a person and their environment an appropriate clothing choice is essential. While thermal balance and comfort is often achieved by the use of external means such as air conditioning or heating systems an increasing level of versatility is offered by clothing choices. For military personnel, who can be deployed in any of the world’s climates, it is vital that the protection against the thermal environment afforded by their clothing is considered alongside other properties such as protection from the chemical and abrasive environments.

Clothing test methods, currently employed, to indicate the thermal performance of clothing are usually limited to assessments of its resistance to heat and water vapour transfer. Clothing descriptions based solely on these properties, particularly where measurements are made in artificial laboratory conditions (for instance with a standing manikin), are insufficient and can lead to under (or over) protection of the wearer; particularly when the ‘artificial’ data obtained in these tests are used in calculations as part of predictive standards (eg ISO 7933, BS EN ISO 12515). Several studies have shown that the values obtained in working conditions (resultant values) can be different to those obtained in the laboratory (intrinsic values) and that part of this difference can be explained by the increased convective and evaporative heat transfer caused by air movement through the clothing as a result of wearer body movements or environmental wind speed.

As detailed in this thesis; air will exchange naturally between a clothing ensemble and the surrounding environment by diffusing across the clothing fabrics. Body movements, even the apparently insignificant breathing movements, will induce an increase in this air exchange and, where the clothing fabrics are air impermeable, a bellows effect (or pumping of air) will be seen again further increasing the rate of air exchange. The induced ingress and egress of micro-environment air will affect the thermal insulation properties of the clothing, as demonstrated in Chapter 7 and as such will also have physiological consequences for the wearer (investigated in Chapter 6).
A battery of tests will commonly be used to assess clothing performance. These tests may include biophysical analysis using thermal manikins as well as human subjects in climatic chamber studies or field trials. At either stage of testing it would be easy to conduct assessments of the clothing’s ventilation characteristics. These data together with those for heat and water vapour transfer would provide a better indication of the clothing’s overall performance and suitability.

Clothing ventilation data presented in this thesis were obtained using the Ventilation Index measurement techniques. Although several other ventilation measurement techniques were available to the author the air exchange rate measurement and micro-environment volume measurement methods required to calculate Ventilation Index values do not necessitate the use of complex and expensive equipment. Previous authors had noted that both the tracer gas dilution and micro-environment volume measurement techniques were highly repeatable (small error between measurements) and that the Ventilation Index was accurate.

12.1.1 Suitability of the Ventilation Index as a measurement technique for the assessment of clothing ventilation characteristics.

The primary aim of this thesis was to investigate the suitability of the Ventilation Index as a measurement technique for the assessment of clothing ventilation characteristics, particularly to consider the relationship between clothing ventilation and wearer physiological responses. The studies conducted for this thesis all confirm previous findings to suggest that the tracer gas technique, conducted to obtain the air exchange rate between the clothing micro-environment and the surrounding environment, is highly repeatable (differences between triplicate measures, in each investigation, were minimal). The accuracy of the micro-environment volume measurement technique used in these investigations has been improved with the use of new materials technology to provide an air tight oversuit which can be securely sealed around a subject’s neck and which has a secure air tight entry point. The compliant nature of this material has also (largely) removed the element of crushing of clothing before the measurement has ‘started’. Garments which are particularly flimsy may still be crushed, but in terms of the assessment of military ensembles there should be a minimal effect. The use of a very large oversuit also removed the risk of this oversuit being held tight to subjects before the start of measurements. However, measurement of the micro-environment volume of more solid items, such as boots or body armour pieces will still not be possible. Similarly, because the air tight
oversuit encapsulates subjects only as far their necks the technique is not currently suitable for use with ensembles which include items such as smoke hoods etc. For the ensembles tested during the investigations of this thesis the Ventilation Index measurement data were of the order expected (see comparisons with previous author data as discussed in each laboratory study chapter), with whole system calibration confirming the measurement accuracy.

12.1.2.1 Relationship between clothing ventilation and wearer physiological responses during activity.

Having established the Ventilation Index as an accurate and highly repeatable measurement tool, investigation of the relationship between wearer physiological response and clothing ventilation was possible. This investigation, conducted in a cold environment, found that air movement through clothing significantly affected the heat exchange between human subjects and their environment which may in turn lead to physiological strain. As expected, each individual had their own unique relationship between clothing ventilation rate and their mean body temperature. When subjects stood stationary a low rate of air exchange was observed. In the absence of activity induced air exchange, and since the test clothing was made from air impermeable fabric and its openings were in the closed position, the exchange observed was ascribed to convective air movement - the ‘chimney effect’. As activity increased so the rate of air movement through the clothing increased. The heat exchange induced by this ventilation acted to limit any physiological strain caused by the activity, where the activity work rate was high. Where the activity work rate was not so high the increased ventilation rate lowered wearer mean body temperature.

A large variation in ventilation rates was observed between subjects in the activity routines, this being explained because of inter-subject differences with respect to their limb movements during these activities. Some subjects found unnatural movements of the rotate limbs (maximal pumping) activity particularly difficult to complete. Repetition of this study using treadmill exercises, to provide the means of increasing clothing ventilation rates, may overcome this problem (and thus produce a better relationship between clothing ventilation and its insulation properties) since other work conducted during this thesis has showed that subjects are better able to perform treadmill walking activities than they are stepping and rotate limbs activities. The physiological responses demonstrated by subjects in response to increased clothing ventilation suggested that cold air moving into and out of their clothing reduced its insulation.
This was investigated (Chapter 7), with an air-impermeable and an air-permeable ensemble, using a thermal manikin. With both ensembles, increased activity and environmental air speed gave increased ventilation in the layer of air trapped next to the manikin’s surface and reduced the clothing’s insulation.

12.1.2.2 Theoretical maximal heat transfer due to clothing ventilation.

Birnbaum and Crockford (1978) discuss the three main mechanisms by which heat is transferred from (to) a clothed body. As well as the transfer of sensible heat directly across the fabrics of a clothing ensemble the exchange of air trapped within the clothing micro-environment with that in the external environment surrounding the person can have a significant effect since it transports sensible and insensible heat away from the wearer’s skin.

Air entering a clothing ensemble will assume similar temperature and water vapour content characteristics as the air already trapped within the ensemble micro-environment. The changes in these characteristics for the ingressed air will be dependant upon the length of time that it remains within the ensemble. Where the rate of air exchange is slow the ingressed air will assume the same characteristics as those of the micro-environment air, while if it is much more rapid the changes will not be so large. In a cold environment, where ingressed air has been warmed, when it is lost back to the external environment it transports with it sensible and insensible heat given that it will now be warmed and have a higher water vapour content. Conversely, where air is ingressed into the micro-environment from a warmer external environment this will act to raise the temperature of the clothing micro-environment air and in doing so will transport sensible heat to the wearer. Similarly, where air is ingressed with a higher water vapour content than that already within the clothing micro-environment this will transport insensible heat to the wearer. Calculations of the amount of heat transfer likely to occur in such scenarios are possible using psychrometric charts as follows.

Example calculation of heat transfer by ventilation in a cold environment \(t_a = 8.5 \, ^\circ\text{C}, \, \text{rh} = 30\%\):

Find heat content of air entering clothing ensemble by following steps 1 to 4 given below.

Step 1 - with a psychrometric chart find specific volume for air at the specified \(t_a\) and rh values.
From CIBSE psychrometric chart (based on a barometric pressure of 101.325 kPa) these values give air a specific volume of 0.8 m³/kg (at \( t_a = 8.5 \, ^\circ C, \, rh = 30 \% \)).

Step 2 - Assuming 1 m³ of ventilation per minute find its mass according to:

\[
\text{mass} = \frac{\text{ventilation volume}}{\text{specific volume}}
\]

- For 1 m³ of air: \( \text{mass} = \frac{1}{0.8} = 1.25 \, \text{kg} \)

Step 3 - Using psychrometric chart find enthalpy of this air.

- For this example, enthalpy = 14 kJ/kg

Step 4 - Find heat content of air entering ensemble according to:

\[
\text{heat content} = \text{mass} \times \text{enthalpy}
\]

- For this example, heat content = \( 1.25 \times 14 = 17.5 \, \text{kJ} \)

Find heat content of air leaving clothing ensemble by following steps 1 to 4 given above. Assume temperature of air leaving ensemble is 30 °C (similar to that of the wearer’s skin in a cold environment) and has been fully moistened by sweat trapped within the clothing micro-environment (rh = 100 %).

Values obtained from steps 1 - 4 for \( t_a = 30 \, ^\circ C \) and \( rh = 100 \% \), 1 m³ of air:

Step 1. Specific volume = 0.897 m³/kg

Step 2. Mass = 1.115 kg

Step 3. Enthalpy = 100 kJ/kg

Step 4. Heat content = 111.5 kJ

Heat loss with air leaving the clothing micro-environment = heat content of air leaving ensemble - heat content when entering:

Thus for the example of 1 m³ of air per minute ventilation, the heat lost was

\[
= 111.5 - 17.5 = 94 \, \text{kJ/min}
\]

For conversion to W/m² first convert kJ/minute to kJ/second (divide by 60), thus:

\[
94 \, \text{kJ/min} = 1.567 \, \text{kJ/second}
\]
Since 1 kJ/ second = 1 kW, 1.567 kJ / second = 1.567 kW = 1567 W

Note, calculations so far made based on 1m³ of ventilation
- calculate value for 1 litre ventilation based on 1m³ = 1000 l
  1 litre = \(\frac{1567}{1000} \approx 1.567\) W

For a standard person (DuBois surface area = 1.8 m²) 1 litre of ventilation per minute through a clothing ensemble will remove approximately 0.87 W/m² of heat from the clothing’s micro-environment. In terms of the clothing ensembles assessed in cold environments in this thesis, this rate of heat exchange would account for approximately 7 W/m² heat loss per minute in standing conditions (ventilation rate ~ 8 l min⁻¹) and approximately 13 W/m² heat loss per minute in higher activity (ventilation rate ~ 15 l min⁻¹) conditions when wearing the air-impermeable Goretex ensemble. When wearing the IREQ ensemble while standing (ventilation rate ~ 55 l min⁻¹) a heat transfer of approximately 50 W/m² would be expected and when performing a walking activity (ventilation rate ~ 65 l min⁻¹) this would be expected to increase to approximately 56 W/m².

Repeating this procedure considering a hot environment (\(t_a = 40\) °C, rh = 60 %) shows a heat transfer to the clothing micro-environment from the external environment. Values obtained for air entering the ensemble, calculated from steps 1 - 4 (see above) for \(t_a = 40\) °C and rh = 60 %, for 1 m³ of air:
Step 1. Specific volume = 0.93 m³ / kg
Step 2. Mass = 1.075 kg
Step 3. Enthalpy = 116 kJ / kg
Step 4. Heat content = 124.7 kJ

Values obtained for air leaving the ensemble, calculated from steps 1 - 4 (see above) for \(t_a = 30\) °C and rh = 100 %, for 1 m³ of air:
Step 1. Specific volume = 0.897 m³ / kg
Step 2. Mass = 1.115 kg
Step 3. Enthalpy = 100 kJ / kg
Step 4. Heat content = 111.5 kJ
Since heat loss with air leaving the clothing micro-environment = heat content of air leaving ensemble - heat content when entering.

Thus for the example of 1 m³ of air per minute ventilation, the heat lost was:
\[ = 124.7 - 111.5 = 13.2 \text{ kJ} / \text{min} \]

For conversion to Wm⁻² first convert kJ / minute to kJ / second (divide by 60), thus:
\[ 13.2 \text{ kJ} / \text{min} = 0.22 \text{ kJ} / \text{second} \]

Since 1 kJ/ second = 1 kW, 0.22 kJ / second = 0.22 kW = 220W

Note, calculations so far made based on 1m³ of ventilation
- calculate value for 1 litre ventilation based on 1m³ = 1000 l
  \[ 1 \text{ litre} \approx \frac{220}{1000} \approx 0.22 \text{ W} \]

For a standard person (DuBois surface area = 1.8 m²) 1 litre of ventilation per minute through a clothing ensemble will transfer approximately 0.12 Wm⁻² of heat to the clothing’s micro-environment. In terms of the clothing ensembles assessed in cold environments in this thesis, this rate of heat exchange would account for approximately 0.96 Wm⁻² heat loss per minute in standing conditions (ventilation rate ~ 8 l min⁻¹) and approximately 1.8 Wm⁻² heat loss per minute in higher activity (ventilation rate ~ 15 l min⁻¹) conditions when wearing the air-impermeable Goretex ensemble. When wearing the IREQ ensemble while standing (ventilation rate ~ 55 l min⁻¹) a heat transfer of approximately 6.6 Wm⁻² would be expected and when performing a walking activity (ventilation rate ~ 65 l min⁻¹) this would be expected to increase to approximately 7.8 Wm⁻². In clothing with a high rate of air exchange this may cause thermal strain to the wearer. Table 12.1 demonstrates the amount of heat transfer expected between a clothing ensemble’s micro-environment and the external environment in hot and cold conditions with various ventilation rates. Air leaving the clothing micro-environment is assumed to be at \( t_s = 30 \text{ °C} \) and \( \text{rh} = 100 \% \).
Table 12.1 Heat transfer expected between ensemble micro-environment and external environment in hot and cold conditions, with various ventilation rates.

<table>
<thead>
<tr>
<th>Ventilation Rate (1 min⁻¹)</th>
<th>Heat transfer (Wm⁻²)</th>
<th>Heat transfer (Wm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cold Environment</td>
<td>Hot Environment</td>
</tr>
<tr>
<td></td>
<td>( t_a = 8.5 , ^\circ\text{C}, , \text{rh} = 30 , % )</td>
<td>( t_a = 40 , ^\circ\text{C}, , \text{rh} = 60 , % )</td>
</tr>
<tr>
<td>1</td>
<td>0.87</td>
<td>-0.12</td>
</tr>
<tr>
<td>10</td>
<td>8.70</td>
<td>-1.20</td>
</tr>
<tr>
<td>50</td>
<td>43.50</td>
<td>-6.00</td>
</tr>
<tr>
<td>100</td>
<td>87.00</td>
<td>-12.00</td>
</tr>
<tr>
<td>250</td>
<td>217.50</td>
<td>-30.00</td>
</tr>
</tbody>
</table>

Note, positive values = heat loss from wearer and negative values = heat gain by wearer.

Havenith et al (1990b) show that a standard work ensemble (work pants, polo shirt and sweater) has a ventilation rate of \( \sim 270 \text{ l min}^{-1} \) when worn by a standing person in an environment with air movement of \( 4.1 \text{ m s}^{-1} \). In a cold environment that ventilation rate would translate to \( \sim 235 \text{ Wm}^{-2} \) heat loss to the environment from that ensemble's micro-environment (and thus from the wearer). Conversely in a hot environment it would translate to a heat gain by the wearer of \( \sim 32 \text{ Wm}^{-2} \).

12.1.3 Effects of increased micro-environment ventilation on the thermal insulation properties of clothing.

Data presented in Chapter 7 demonstrate the relationship between clothing ventilation and thermal insulation. As expected, increasing micro-environment ventilation resulted in a decrease in insulation provided by both the 1-layer air-impermeable ensemble and a 3-layer air-permeable ensemble that were tested. These data confirm findings that increased clothing ventilation has a direct effect on wearer physiological responses.

The ventilation data obtained using the Ventilation Index methodology quantify the whole ventilation rate for the ensemble tested. The relative effects of increasing either diffusion or pumping could be investigated by testing ensembles in which either of these properties have been eliminated (eg sealing wrist and ankle cuffs etc would eliminate air exchange occurring by
pumping). Reductions of insulation in an ensemble such as this would be ascribable to increased ventilation due to diffusion only.

### 12.1.4 Manikin data compared with human subject data

Repetition of the manikin insulation investigation study using human subjects elicited different, lower Ventilation Index within both clothing ensembles. In terms of clothing assessments using manikins similar to TORE, if measurements were made in cold environments this could translate to greater sensible and evaporative heat losses from the manikin surface (than when worn by human subjects) which would in turn be reflected in the clothing insulation calculation. In practical terms, humans wearing that ensemble would be provided with more thermal insulation than that calculated using the manikin a factor which may lead to thermal strain in some high workload conditions.

Differences between manikin and human subject body movements were observed during this investigation; these would be reflected in the level of pumping generated within the clothing when worn by the manikin and human subjects and would thus be expected to further change the clothing insulation when worn by them. Add to this the difference due to the clinging effect of wet clothing when worn by humans (the manikin used here was dry) and it is easy to see just how different the ventilation characteristics of clothing can be when worn by human subjects and manikins (although this effect would not have been obvious in a cold environment such as the one investigated here, but in hot conditions, where clothing would become wet with sweat, from a human wearer, the ventilation characteristics would be quite different).

### 12.1.5 Effects of external factors which influence clothing ventilation characteristics

Laboratory study four (Chapter 9) investigated the magnitude of the effect of clothing fit on clothing ventilation. Data obtained in laboratory study three (Chapter 8) indicated that subject DuBois surface area was related to the micro-environment volume of their clothing and would therefore have an effect on their clothing’s ventilation characteristics. This was investigated in laboratory study four with the quantification of the effect of clothing fit on its ventilation characteristics. Data obtained in this study showed that the looseness of the clothing was reflected in the rate of air exchange between the clothing micro-environment and the surrounding environment. This rate of air exchange was reduced when wearing loose clothing, this being explained due to loose fabric folding over itself and also due to larger overlaps of
fabric at garment openings impeding air ingress and egress. Although the rate of air exchange was lower when wearing loose clothing the amount of air available for exchange was higher and thus combining the micro-environment volume data with air exchange rate data showed clothing ventilation to be highest when wearing loose clothing.

This increased ventilation would increase heat exchange between the wearer and their environment and thus the importance of assessing clothing using a suitably sized manikin and of wearing (and providing !) clothing (to the workforce), of a suitable fit for maintaining heat balance in the workplace should be emphasised. It does not however follow that in cold environments workers should wear tight clothing to minimise air exchange, while in warmer environments they should wear loose clothing to encourage this exchange. Where clothing is loose it presents other hazards to the wearer, such a snagging, tripping and incompatibility with other work items (eg protective gloves etc). As one subject in laboratory study two experienced, wearing clothing which is too tight will also be detrimental because limb movements will be restricted. It is acknowledged that the clothing fit measurement adopted in laboratory study two is not without fault, providing simply an indication of amount of excess fabric at the designated anatomical points. Using techniques such as image photography or the shadow scanning would provide a better indication of clothing fit.

Data obtained in laboratory studies one to four (Chapters 6 - 9) show that even with minimal environmental air movement baseline clothing ventilation values are not to be discounted. Furthermore, it is well documented that environmental air speed affects the thermal properties of clothing. Laboratory study five investigated the relationship between environmental air speed (wind) and clothing ventilation rates. This work described the presence of a duct effect at garment openings, this being concluded because of the air impermeable nature of the test clothing and the fact that testing was conducted with garment openings in the closed position. Direct micro-environment air displacement was also suggested as a possible mechanism for the observed air exchange. A larger deviation between triplicate tracer gas measurements was observed during the moving air test condition, this being suggested as an artefact of local air turbulence from the air movement inducing fan.
12.1.6 Assessing multi-layer clothing ensembles.

The standard Ventilation Index methodology, as used in laboratory studies one to five, considers only the ventilation characteristics of the air layer trapped next to the wearer’s skin. In multi-layer clothing the air exchange which occurs in air layers trapped between middle and outer clothing layers will also affect the thermal properties of the clothing’s micro-environment. Laboratory study six assessed the air exchange characteristics of these other trapped air layers and showed that air did indeed move differently between them. Measurement of the air exchange rates between these layers would provide a better indication of the ventilation characteristics of clothing and thus of the sensible and evaporative heat exchanges expected. When nitrogen is distributed only to the base air layer of a 3-layer ensemble, as per the standard tracer gas dilution technique, the oxygen concentration within the middle and outer air layers is only slightly reduced. The oxygen return curve must be steeper, than that provided in this way, in order to calculate an accurate air exchange rate for these layers. Laboratory study six demonstrated that distribution of nitrogen to each of the trapped air layers further reduced the oxygen concentration in each of these layers to enable better air exchange rate calculations.

However, the approach has not yet been acceptably ‘mastered’ to provide reasonable data and further more by adding such a large quantity of tubing systems into each of the clothing layers this will invariably have an effect on the clothing micro-environment, not least on the micro-environment volume. Further work, particularly to develop a less intrusive system of distribution and sampling systems, is required in order to overcome the measurement inaccuracies with multi-layer clothing.

In connection with this, with work presented from laboratory study six shows an attempt to measure the micro-environment volume of each clothing air layer. Again this technique is not yet satisfactory with further investigation suggested using loose clothing which will not squash air from clothing worn in the layers beneath it.

12.2 Conclusions and recommendations for further work

As an overall conclusion, data obtained during the course of these investigations suggests that the Ventilation Index measurement techniques are reliable and have a high repeatability. The use of these techniques as a clothing assessment tool is highly recommended for use with
single-layer clothing ensembles. However, the data presented here suggest that using the ‘standard’ VI measurement technique with multi-layer ensembles should be done with appreciation of the limitations of test values (i.e., high oxygen concentrations in trapped air layers at start of air exchange rate calculation and difficulty in quantifying air movement between layers).

Clothing ventilation data obtained in the course of this study are of the same magnitude as those obtained by previous authors of similar work (see chapter 4 and individual laboratory study chapters for full details, Table 12.2 provides a brief indication of clothing ventilation rates for different clothing types) and suggest that environmental air speed, wearer activity and clothing fit each have a significant effect on clothing ventilation and therefore also on sensible and evaporative heat transfer between the clothed worker and their surrounding environment, even in wind resistant clothing. As shown in these investigations clothing ventilation affects clothing insulation and thus also the physiological responses of the wearer, possibly leading to thermal strain and should therefore be considered in clothing assessments, included in the general clothing description and ultimately considered in assessments of the workers thermal environment.

Table 12.2 Sample ventilation data for a range of clothing ensembles - various authors.

<table>
<thead>
<tr>
<th>Baseline ventilation rate (l min⁻¹)</th>
<th>Clothing ensemble</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.028 - 1.534 (Very Low)</td>
<td>Helicopter crew suit (air-impermeable)</td>
<td>Sullivan et al (1987)</td>
</tr>
<tr>
<td>5.50 - 9.55 (Low)</td>
<td>Goretex ensemble - various activities (air-impermeable)</td>
<td>Present work - various chapters</td>
</tr>
<tr>
<td>56.30 - 67.51 (Medium)</td>
<td>IREQ ensemble - various activities (air-permeable)</td>
<td>Present work - chapters 7 &amp; 8</td>
</tr>
<tr>
<td>45.4 - 113.8 (High)</td>
<td>Foul weather suit - various activities (air-permeable)</td>
<td>Birnbaum &amp; Crockford (1978)</td>
</tr>
<tr>
<td>69.6 - 276.2 (Very High)</td>
<td>Workpants, polo shirt &amp; sweater - various activities and air velocities (air-permeable)</td>
<td>Havenith et al (1990b)</td>
</tr>
</tbody>
</table>

As suggested by previous authors, the value of this methodology is that determining the Ventilation Index of clothing ensembles with different fabrics and designs is highly repeatable, even with simple equipment. Furthermore, it can be done using human subjects, carrying out activities for which the clothing has been designed. The micro-environment volume and air
exchange rate measurement techniques are not without scope for improvement. The micro-environment volume measurement technique is currently conducted with subjects adopting a standing position rather than in positions more representative of those adopted when engaged in the activity of interest. Further investigation into the effect of posture on the fall and drape clothing (and thus also on micro-environment volume) would be useful. At present some clothing ensembles (for instance those with smoke hoods or high collars) would be measured inaccurately in terms of their micro-environment volumes because of the current air tight oversuit design. Further investigation, possibly using photographic imagery or scanning techniques may be capable of measurement of such ensembles.

Both the air exchange rate and micro-environment volume measurement techniques will be affected by the invasiveness of the nitrogen distribution and tracer gas sampling tube systems, particularly where several systems are used in the assessment of multi-layer clothing ensembles. This problem should be overcome, with the use of other sensors, or ‘smaller’ tubing systems. The debate regarding the use of manikins or human subjects in clothing assessments will continue .... The investigations presented here have provided information regarding the importance of the assessment of clothing ventilation characteristics and of the effects of the magnitude of air exchange between the clothing micro-environment and the surrounding environment. With further investigation, these data should be useful in the translation of data obtained using thermal manikins (standing stationary) to data which reflects more accurately how the clothing will ‘behave’ in response to a human wearer.

Since few clothing ensembles are truly single layer it is essential that the Ventilation Index methodology is improved to ensure accurate measurements of multi-layer ensembles. The solution may lie in individual air layer exchange rates combined to give an average (or total) exchange rate for the whole ensemble and then combined with the micro-environment volume of the whole ensemble. Conversely, with improved micro-environment volume measurements it may be possible to calculate ventilation index values for each constituent air layer, trapped within a multi-layer ensemble, which can then be combined to provide a whole ensemble value. With suitable improvements the Ventilation Index should become a useful measurement tool capable of assessing all types of clothing ensemble.
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Annex A
Annex A. World climates - as categorised in Defence Standard 00-35

Table A.1 Category A climates from Defence Standard 00-35

<table>
<thead>
<tr>
<th>Category</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| A 1 - Extreme hot dry | Very high temperatures and high levels of solar radiation.  
                       | *eg* hot, dry deserts of North Africa, parts of the Middle East, Northern India and South Western USA |
| A 2 - Hot dry   | Very high temperatures and high levels of solar radiation, but moderately low humidity. *eg* most southerly parts of Europe, most of the Australian continent, South Central Asia, Northern and Eastern Africa, coastal regions of North Africa, southern parts of USA and most of Mexico |
| A 3 - Intermediate | Moderately high temperatures and moderately low humidities. *eg* most of Europe, Canada, Northern USA and Southern parts of the Australian continent |

Table A.2 Category B climates from Defence Standard 00-35

<table>
<thead>
<tr>
<th>Category</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>B 1 - Wet warm</td>
<td>Moderately high temperatures and high humidities. Solar radiation is not a significant factor. <em>eg</em> Zaire and Amazon basins, South East Asia, North East coast of Madagascar and the Caribbean Islands</td>
</tr>
<tr>
<td>B 2 - Wet hot</td>
<td>Moderately high temperatures, high humidities and high solar radiation. <em>eg</em> wet tropical regions such as the Gulf of Mexico</td>
</tr>
<tr>
<td>B 3 - Humid hot, coastal desert</td>
<td>Moderately high temperatures, high humidities near the ground and high solar radiation. <em>eg</em> areas near large expanses of water such as the Persian Gulf and the Red Sea</td>
</tr>
</tbody>
</table>
Table A.3 Category C climates from Defence Standard 00-35

<table>
<thead>
<tr>
<th>Category</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| C 0 - Mild cold | Mildly low temperatures  
|             | *eg* Coastal areas of Western Europe, South East Australia and the lowlands of New Zealand |
| C 1 - Intermediate cold | Moderately low temperatures  
|             | *eg* Central Europe, Japan and Central USA |
| C 2 - Cold | Colder areas  
|            | *eg* Northern Norway, the prairie provinces of Canada, Tibet and much of the USSR |
| C 3 - Severe cold | The coldest areas of the North American continent |
| C 4 - Extreme cold | The coldest areas of Greenland and Siberia |

Table A.4 Category M climates from Defence Standard 00-35

<table>
<thead>
<tr>
<th>Category</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| M 1 - Marine hot | High ambient air temperatures  
|               | *eg* tropical bulk sea areas |
| M 2 - Marine intermediate | Moderately high temperatures and high humidity  
|                           | *eg* warmer, mid-latitude regions of the seas |
| M 3 - Marine cold | Low ambient air temperatures  
|                   | *eg* colder regions of the seas, particularly the Arctic zone |