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Moisture Accumulation in Sleeping Bags at -7 and -20 °C in Relation to Cover Material and Method of Use

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ABSTRACT

Moisture accumulation in sleeping bags during extended periods of use is detrimental to thermal comfort of the sleeper, and in extreme cases may lead to sleep loss and hypothermia. As sub-zero temperatures were expected to affect vapour resistance of microporous membranes, the effect of using semipermeable and impermeable rain covers for sleeping bags on the accumulation of moisture in the bags during six days of use at -7 and five days at -20 °C were investigated. In addition, the routine of shaking off hoarfrost from the inside of the cover after the sleep period as a preventive measure for moisture accumulation was studied. Moisture accumulation (ranging from 92 to 800 grams) was found to be related to the vapour resistance of the materials used. The best semipermeable material gave the same moisture build-up as no cover at -7 °C, though build-up increased substantially at -20 °C. Shaking off the hoarfrost from the inside of the cover after each use was beneficial in preventing a high moisture build-up. It was concluded that semipermeable cover materials reduce moisture accumulation in sleeping bags at moderate sub-zero temperatures, but in more extreme cold (-20 °C) the benefits are reduced in comparison to routinely shaking frost from impermeable covers. Compared to fixed impermeable covers, the benefits of all semi-permeable covers are large. For long-term use without drying facilities, the differences observed do favour the semi-permeable covers above impermeable ones, even when regularly removing the hoar frost from the inside in the latter.

1. INTRODUCTION

In the use of sleeping bags in low temperatures, the accumulation of moisture in the bags over prolonged periods of use has been a major problem. This accumulated moisture causes a reduction in insulation due to the higher conductance of moisture compared to air and due to a constant evaporation/condensation cycle (Lotens & Havenith 1995, Lotens et al. 1995) which takes place from the warmer (inner) to the cooler (outer) parts of the bag.

The source of the moisture are the users of the bag themselves, who may expire warm moist air into the bag, and who lose moisture through their skin, as well as any moist clothing or equipment they take into the bag. The water may then enter the bag by wicking from the clothing or by evaporation and condensation. At or close to the user's skin, the temperature will be high, which means moisture

evaporates easily. As the environment is typically cool, with low moisture content, a water vapour gradient is present from the skin to the environment, and thus moisture will move in that direction. As the temperature decreases following this path from skin to environment, also the dewpoint for water vapour and thus the maximal water vapour concentration in the air decreases along this path. In the cold, the gradient in dewpoint may be steep enough for water vapour concentration to reach its saturation level, and condensation of water vapour can take place within the sleeping bag.

This moisture accumulation takes place in all types of sleeping bags, but the extent of the phenomenon is, apart from the environmental temperature, highly dependent on the vapour permeability of the sleeping bag materials. Especially when sleeping bags are used with water impermeable, rain protective covers, the problem will increase dramatically, as the vapour resistance of such covers is usually much higher than of normal fabrics. In military applications or in expeditions, where airing of the sleeping bags on a regular basis is not possible, the problem with moisture accumulation (loss of insulation) can be life threatening.

To minimize the problem, many manufacturers developed rain covers from waterproof, but vapour permeable materials (e.g. porous PU coatings or PTFE membranes with or without hydrophilic layers), to allow for optimal evaporation. The behaviour of these materials has been studied under various circumstances, as e.g. in different ambient humidities (Farnworth et al. 1990), with condensation at its surface (Osczevski 1993), at various atmospheric pressures (Fukazawa et al. 1999), and in various ambient temperatures (Finn et al. 2000). Studies on the behaviour of such materials at low temperature, however, have shown that the vapour resistance of some of these materials increases dramatically when temperatures fall below zero degrees Celsius (Osczevski 1993, 1996). The functionality of these materials in such conditions can therefore be questioned.

Initial studies on prolonged sleeping bag use (Havenith 2002) in mild cold (-7°C) did not observe any problems with these materials, but the question was raised whether the problems would occur at lower environmental temperatures. Further as the cost of such semi-permeable covers is relatively high, some researchers suggest (Vanggaard personal communication) that in the cold a cheap impermeable cover should be used. This will collect frost on the inner surface during the sleep period. This cover should then be removed after the sleep period, the frost shaken out and in that way the moisture removed.

In order to study these problems for their relevance for sleeping bags, an experiment was devised to answer the following questions: Is the use of semi-permeable versus impermeable rain covers for sleeping bags effective in removing excess moisture in moderate (-7°C) to severe cold (-20°C)? Will a daily 'shake' of an impermeable cover prevent moisture accumulation in these temperatures?

Building on an earlier study comparing cover materials at -7°C (Havenith 2002), data on the effect of the method of use on moisture accumulation at both -7 and -20°C were collected, together with data on the effect of different outer covers at both temperatures.

2. METHODS

Two separate experiments were performed. In the first, participants slept for six days at -7°C in sleeping bags with different covers and using different methods of usage. In the second, participants were replaced by 'manikins' producing an equivalent amount of heat and moisture as the participants. The latter experiment was performed at -20°C with different covers and methods of use.

2.1 Experiment 1

2.1.1 Participants: The physical characteristics of the participants are presented in Table 1.

2.1.2 Procedures: The bags were used in a climatic chamber, set at a temperature of -7 °C, wind of 0.2 m·s⁻¹, relative humidity 40-50%. They were used on top of a 15 mm thick polyurethane mattress. The climatic chamber floor was of aluminium, with hollow space underneath that was controlled at the room temperature as well. The bags were used for six consecutive days, with six hours 'sleep' per day. The bags were packed in impermeable plastic bags between use periods, to simulate field conditions, where no airing of the bags between uses is possible. Six participants used the bags, with a daily rotation over bags to avoid participant effects. Before entering the bag, the participants put on underwear and combat clothing. The latter was treated daily (dried and subsequently moistened), to contain a moisture amount of 150 grams when entering the bag. This was used to simulate moisture accumulation in the clothing due to daily activities (light sweating). Before and after each trial period, weights of the bags, clothing and participants were obtained in order to determine the moisture balance.

Participants' core (rectal) and skin temperatures (head, hand, arm, chest, back, leg, and foot) were logged at one-minute intervals. Twice during each session, metabolic rate was determined by measurement of oxygen uptake (Havenith et al. 1990).

Statistical analyses were performed using repeated measures ANOVA, with a significance level of 0.05 as criterion.

2.2 Experiment 2

Experiment 1 was replicated to study vapour transfer and condensation at a lower temperature of -20°C . Instead of humans, in this experiment a simple manikin was used consisting of a box sized 160 by 40 by 15 cm (Surface area 1.88m^2), with two 40-watt heating elements simulating a heat production of 80 W by a sleeping person. The manikin was equipped with a cotton cover in which 150 grams moisture was absorbed by the same procedure as in exp. 1. This manikin was placed in the sleeping bags for six hours at -20°C , with the bags lying on a wooden board for five consecutive days. When not in use the bags were packed in impermeable bags and stored. Weight change of the cotton cover, the bags and the system of wooden support, bags and manikin were determined before and after the session and for the whole system also after three hours.

As a control, the same protocol was repeated for one bag (semipermeable cover) at room temperature ($+20 \pm 1^{\circ}\text{C}$) over four days, with a heat load of 48W (reduced to avoid excessive manikin temperatures, but sufficient to support evaporation) and 250 grams of water (increased to avoid drying completely) in the cotton skins per day.

2.3 Sleeping bags

For the experiments, sleeping bags with identical insulation (including mattress: $0.93 \text{ m}^2\text{KW}^{-1}$, measured on the same human participants using heat balance technique (Havenith et al. 1990) were used, differing only in the type of outer cover or manner of use. In experiment one six conditions of outer cover were used (vapour resistances of covers (R_{cover}) measured according to Vanbeest & Wittgen (1986)(data given in brackets) and three in experiment 2:

Experiment 1:

- A. No cover (reference condition: $R_{\text{cover}}=0$ mm of equivalent standard still air, ESSA),
- B. Full semipermeable (PTFE membrane with hydrophilic component) cover ($R_{\text{cover}} = 3$ mm ESSA),
- C. Impermeable cover. Cover taken off after each use and frost shaken off interior, ($R_{\text{cover}} > 300$ mm ESSA),
- D. Full semipermeable (PU coating) cover ($R_{\text{cover}} = 6$ mm ESSA),
- E. Cover with semi-permeable top (PTFE membrane with hydrophilic component), impermeable bottom (60/40%). Cover taken off after each use and frost shaken off interior, ($R_{\text{cover, top}} = 3$ mm ESSA),
- F. Impermeable cover (worst case; $R_{\text{cover}} > 300$ mm ESSA),

Experiment 2:

- A. No cover (reference condition $R_{\text{cover}}=0$ mm of equivalent standard still air, ESSA),
- B. Full semipermeable (PTFE membrane with hydrophilic component) cover ($R_{\text{cover}} = 3$ mm ESSA),
- C. Impermeable cover, Cover taken off after each use and frost shaken off interior, ($R_{\text{cover}} > 300$ mm ESSA),

3. Results and Discussion

Visual inspection of the sleeping bag covers after each use showed that indeed moisture had condensed on the inside of the cover and that this moisture was present as hoar frost. This confirms that vapour transport at the cover took place at sub-zero temperatures. Based on the heat and vapour resistances of the bag, cover and air layer surrounding the bag, the cover temperature can be estimated to have been between -2 and -4 °C for the -7°C condition and below -10°C for the -20°C condition. In experiment 2, values at the surface around -11°C were measured.

In experiment 1, body temperatures and skin temperatures differed significantly between participants, but did not show significant differences between bags. This should not be interpreted as that no effect of moisture accumulation is present. It is caused by the rotation of participants over bags and the high variability between individuals. In order to analyze the effect of moisture accumulation on participant's

responses, the experiment would have needed a different design: all participants using all bags for six days (Havenith and Heus, 2004). This would increase the size of the experiment six fold, which was unrealistic. For the current analyses, the moisture balance data will be used, which do not suffer from the participant specific data variability that much.

The results of the moisture balance for all experiments are presented in Figure 1. In this figure, the weight loss from the moistened clothing, which was measured daily, is presented cumulatively. For experiment 1 this represents the minimal amount of moisture introduced into the sleeping bag. In reality more will be added due to insensible perspiration through the participant's skin. This is estimated at around 100 to 130 g per session, but is the same in all bags. Being a constant factor, this was left out of the graphs. For Exp. 2, this represents the total amount of moisture introduced.

Also in figure 1, the weight increase of the sleeping bag is presented. This reflects the amount of moisture that does not leave the sleeping bag through openings, through the covers, or through the 'shake' procedure.

From this figure, following the time course of the moisture accumulation and evaporation over the six (five for -20°C) days, it is clear that the amount of moisture evaporating from the clothing is roughly identical for all cases within each experiment (differences are not significant). The amount staying within the sleeping bag is very different though. While in the no cover condition -A- the accumulation is minimal in both temperatures, it is almost equal to the amount evaporated from the clothing in the impermeable cover condition -F-, consistent with the expectation for the type of material.

Figure 1 about here

Shaking the frost out of the impermeable cover after each use -C- did not have an effect on the moisture accumulation in the bag for the first couple of days at -7°C. After four days, however, the total accumulated moisture amount seems to stabilize, and further accumulation takes place at a slower pace. At -20°C, the accumulation with the shaking procedure seemed slightly slower and more continuous, and did not show signs of levelling off after five days. Of the two semi-permeable covers, the one made from PTFE material -B- shows only minimal moisture accumulation at -7°C, which does not seem different from

that without a cover. At -20°C the accumulation clearly increases more than the no cover condition however. The other semi-permeable cover -D-, with a polyurethane based coating, reduces moisture accumulation compared to the impermeable cover, but does not perform as well as the PTFE based cover. Based on the higher vapour resistance for this specific PU cover, a difference was expected. However, as the total vapour resistance of bags + cover is relatively close due to the high vapour resistance of the thick bag itself, the observed difference is higher than expected based on room temperature vapour resistances alone. Whether this is due to a different effect of the hoarfrost on the vapour resistance for this material is unknown.

The semi-permeable cover, with the bottom half of the cover impermeable, and with a daily removal of frost from the inner surface -E-, performs quite well too, and comes close to the full semi-permeable cover in performance.

These results are brought together in Figure 2, which presents the total amounts of moisture accumulated in the bags on the last day (six days for -7, and five days for -20°C) as percentage of the total amount of moisture introduced into the bags. The baseline value for the no cover conditions is the same at both temperatures.

Based on the data on increases in vapour resistances of the hydrophilic component in PTFE membranes (Osczevski 1993, 1996), the resistance of the PTFE materials used was expected to increase by a factor of three at the temperature of around -3 °C of the membranes in the current experiment and by at least a factor of five to six at -10°C. Given the moisture load used, this apparently did not cause noticeable moisture build-up in the bags compared to no cover for these materials at -7°C environmental temperature but moisture build-up starts to be more substantial at -20°C where the relative absorption was about two-and-a-half times higher than in the no cover condition. That the absorption is affected by the climate can be seen when comparing the +20°C condition to the -7 and -20 °C condition. With decreasing temperature, absorption increases from 6 to 17 to 42%. For most sleeping bag applications in cold environments, the -7°C condition used can be regarded as representative, especially when tents are used.

Figure 2, about here

4. Conclusions

The results show that using an impermeable, non-detachable, cover around a sleeping bag at sub-zero temperatures will lead to excessive moisture accumulation over a period of days. Having a detachable cover, from which accumulated condensation and frost can be removed after each use, can reduce this problem. It was observed however, that using a semi-permeable membrane is much more beneficial in the tested climatic conditions (-7 and -20°C), though the benefit decreases with reducing temperatures. The best semi-permeable cover, reduced moisture accumulation compared to the impermeable shake condition by 73% at -7°C, but at -20°C the reduction was less than 29%.

As the semi-permeable materials were selected based on availability, and not as 'best representatives of their kind', based on the evidence presented here it should not be concluded that the difference between them is related to their material type. Though the differences observed were higher than expected based on the materials vapour resistances at room temperature, drawing such conclusions would require further research.

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Table 1, Physical characteristics of the participants

Participant	Stature (m)	Mass (kg)	Body surface area (m ²)	Fat content (%)
1	1.84	75	1.97	15.2
2	1.80	73	1.92	14.7
3	1.95	72	2.02	10.0
4	1.77	68	1.84	9.2
5	1.82	74	1.95	13.7
6	1.92	69	1.96	8.7

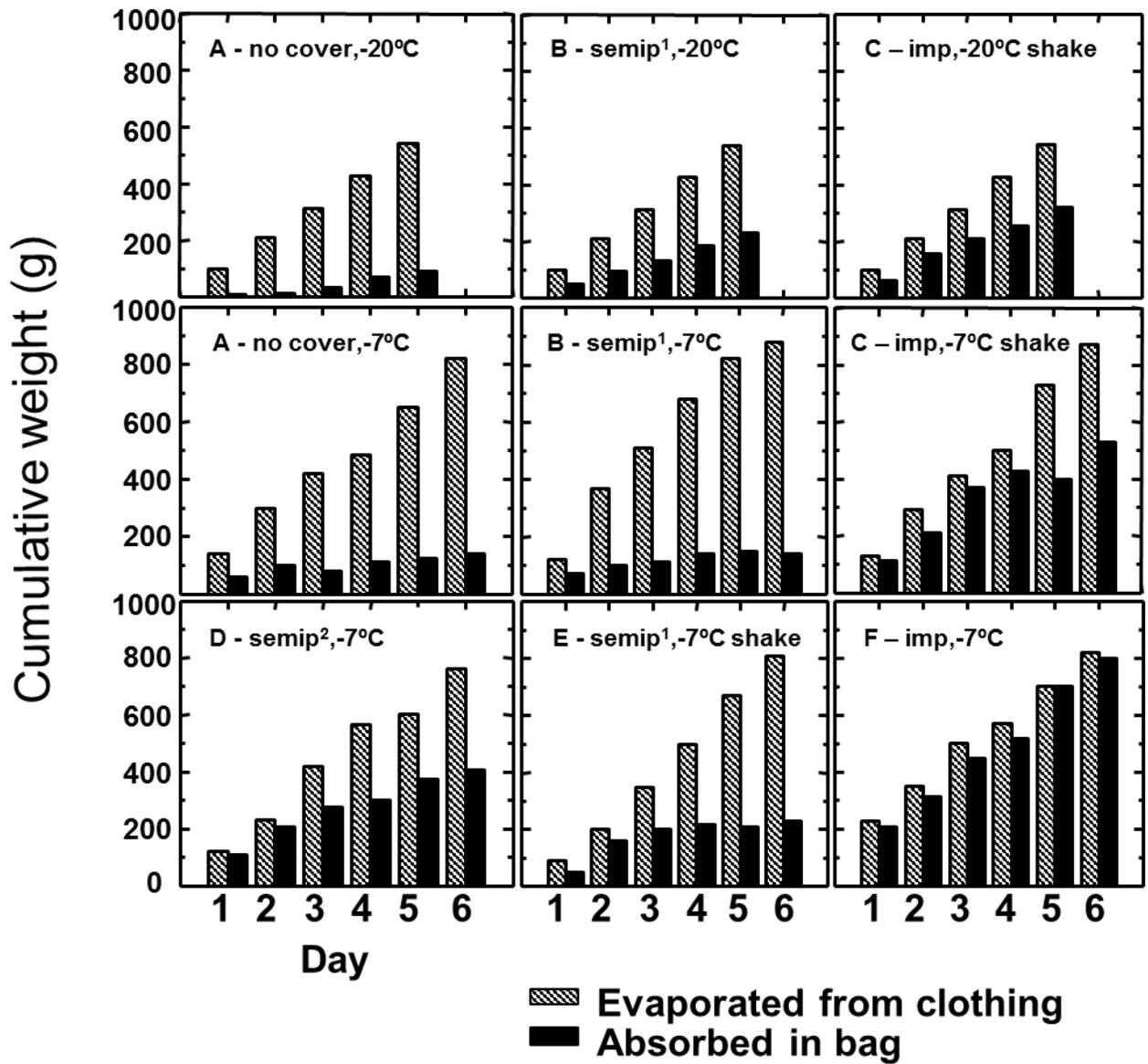


Figure 1, Cumulative weight change over six days of use of sleeping bags and cumulative weight change of clothing worn, for different sleeping bag covers. ¹=PTFE membrane cover with hydrophilic layer; ²=polyurethane coating.

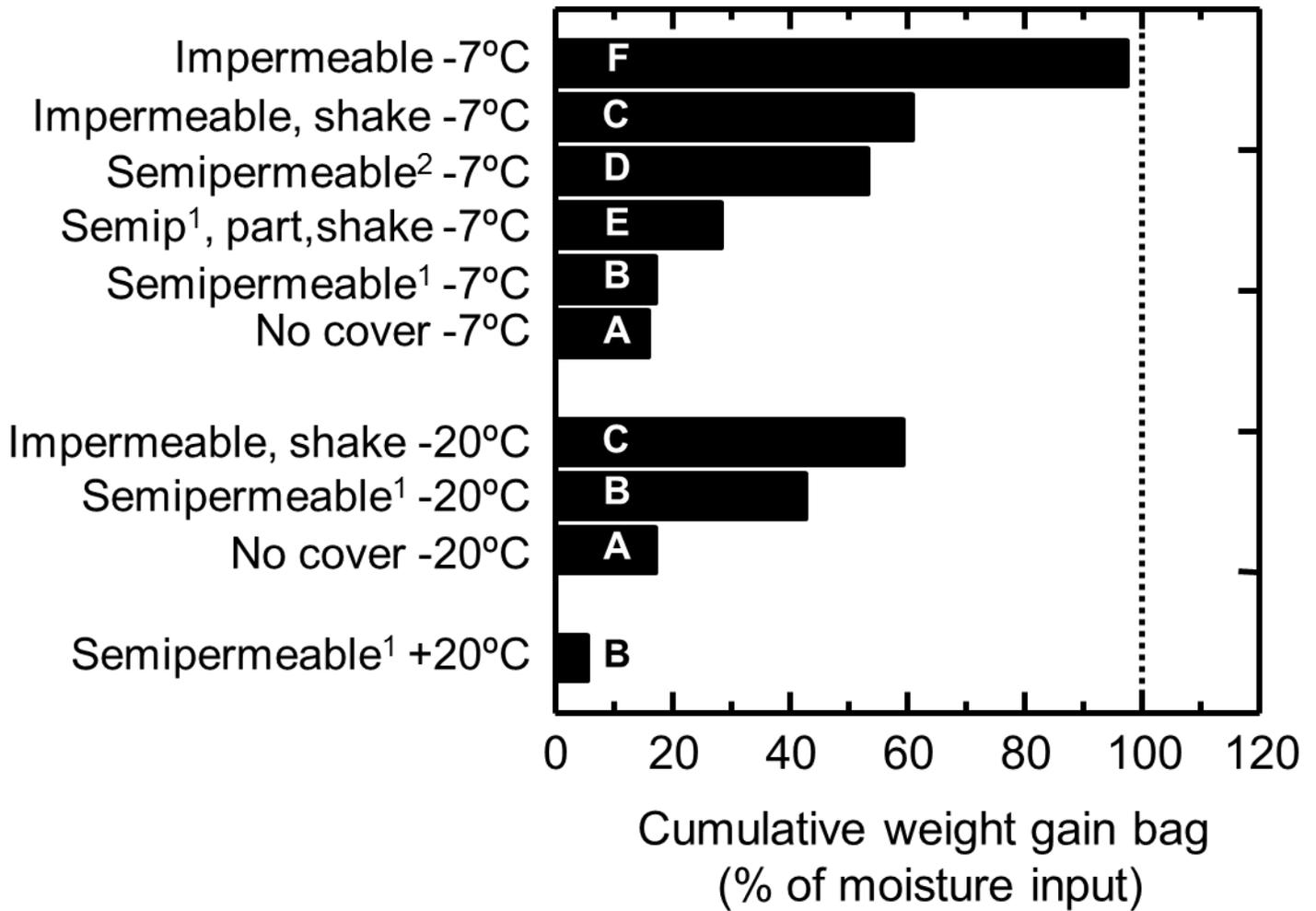


Figure 2, Total amount of moisture accumulated in the bags at the end of the experiment expressed as percentage of the moisture introduced in the bags. ¹=PTFE membrane cover with hydrophilic layer; ²=polyurethane coating