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NUMERICAL STUDY OF THERMAL PLUME CHARACTERISTICS AND ENTRAINMENT IN AN ENCLOSURE WITH A POINT HEAT SOURCE

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ABSTRACT: The structure of a buoyant plume above a point heat source in a ventilated enclosure has been investigated using large-eddy simulation (LES). The aim of the work is to assess the performance and the accuracy of LES for modelling buoyancy-driven displacement ventilation of an enclosure and investigate the role of coherent structures in the plume entrainment mechanism which is important in these flow types because, for example, entrainment determines the ventilation flow rate. The Smagorinsky subgrid-scale model is used for the unresolved small-scale turbulence. The Rayleigh number \( Ra \) is chosen in the range where spatial transition from laminar to turbulent flow takes place \( (Ra=1.5\times10^9) \). The stratification height and temperature of the stratified layer deduced from the mean field of the LES data is in good agreement with the theory of Linden, Lane-Serff and Smeed (1990). The plume entrainment coefficient is in good agreement with experimental values determined by Morton, Taylor and Turner (1956), Rouse, Yih and Humphreys (1952), and Baines and Turner (1969). Instantaneously, the plume develops through expansion and contraction phases, where the expansion phase is associated with the existence of coherent large-scale structures leading to an outward stretching of the plume and the contraction occurs as a result of partial breakdown and/or loss of coherence of these structures. As a result, the instantaneous entrained mass (and thus the entrainment coefficient) at different heights below the mean interface height were found to fluctuate about a mean value. Visualization of the computed flow showed that the stretching mechanism of the large-scale structures, which governs the expansion-contraction behaviour of the plume, occurs in such a way that the coherent structure dominating the flow below the interface height takes a spiral shape.

Keywords: large-eddy simulation, natural ventilation, turbulence, buoyant plume, entrainment

1. INTRODUCTION

Natural ventilation is currently receiving much attention by the building industry as it can potentially provide an economical and energy efficient alternative to air conditioning. In addition to energy savings, natural ventilation reduces noise from mechanical devices, avoids maintenance of mechanical components and contributes to environmental conservation by reducing CO\(_2\) emissions.

Natural ventilation of an enclosure with upper and lower openings driven by a point source of buoyancy leads to a steady stratified two-layer flow (Linden, Lane-Serff and Smeed, 1990). The researchers combined analytical models with small-scale experiments to provide an insight into the fluid dynamics of natural ventilation flows in rooms. Cook (1998) and Cook and Lomas (1998) used computational fluid dynamic (CFD) to investigate steady natural ventilation flows driven by buoyancy forces alone in enclosures with ventilation openings located at the top and bottom of the space. The buoyancy force was produced by a localised heat source located at floor level which generated a rising turbulent plume. These numerical studies used a dynamically similar arrangement to that used by Linden, Lane-Serff and Smeed (1990). Cook and Lomas (1998) noted that treatment of plume entrainment, and hence turbulence modelling, was one of the most important factors influencing the prediction of plume growth and thus the overall properties of the flow. In their work the standard k-\( \varepsilon \) and the RNG k-\( \varepsilon \) models based on the Reynolds-Averaged Navier-Stokes (RANS) approach were used. The CFD predictions were in good agreement with the experimental and theoretical work of Linden, Lane-Serff and Smeed (1990). Much theoretical and experimental work has been done for pure thermal plumes (with no stratification). For example, Bill and Gebhart 1975 concentrated on the transition mechanism from laminar to turbulence which was described
by Bastiaans et al. (2000) as Hopf-pitchfork bifurcation for small values of heat input. In addition, there exist many articles addressing the characterisation of buoyant flows through studies dedicated to static thermal plumes. Of interest is the analytical study of Agrawal and Prasad (2004) which showed that (contrary to conventional belief) entrainment velocity was not proportional to the vertical velocity in an axisymmetric plume. This point contradicted many experimental studies (e.g. Dehmani, Doan and Ghaboue, 1996; Shabbir and George, 1994; Agator and Doan, 1982). Studying transitional plumes from a line source in an unventilated enclosure, Bastiaans et al. (2000) reported a meandering motion of the entire flow structure which they believe to be due to the strong intermittency of interacting vortices and could be the main reason complicating experimental measurements in plume flow. In a recent experimental study, Pham, Plourde and Kim (2005 & 2006) conducted experimental work to study the behaviour of a pure thermal unenclosed plume with and without the effect of swirl. Using a new technique by measuring the velocity outside of the plume, they found that the instantaneous entrainment coefficient fluctuated around a mean value.

The aim of the work in this paper was to investigate transitional plume behaviour within a naturally ventilated enclosure using LES and to obtain a qualitative picture of the ventilation flow. Focus is on the plume features displayed by the instantaneous flow parameters (temperature and pressure fields) and analysis of the complex entrainment processes that occur below and above the interface height. The role played by the large-scale structure on the flow development and on plume entrainment mechanisms are also discussed. The paper is laid out as follows. The work of Linden, Lane-Serff and Smeed (1990) is summarised in section 2. A description of the case and details of the CFD model are presented in section 3 and the results from the simulations are discussed in section 4. The conclusions of the work are presented in section 5.

2. ANALYTICAL AND EXPERIMENTAL WORK

Linden, Lane-Serff and Smeed (1990) studied natural ventilation driven solely by buoyancy forces. Three main assumptions were made. These are: (i) the rate of entrainment at the edge of the plume is proportional to the velocity on the plume axis at that height, (ii) the profiles of mean vertical velocity and mean buoyancy force in horizontal sections are similar at all heights, and (iii) the largest local variations of density in the field of motion are small in comparison to some reference density, chosen to be the density of the ambient fluid at the level of the source. The experimental work of Linden, Lane-Serff and Smeed (1990) showed that displacement ventilation driven by a continuous point source of buoyancy on the floor of the space produces steady stratification consisting of two homogeneous fluid layers separated by a horizontal interface at height \( h \) above the floor (Fig. 1). The steady level of the interface is defined as that height at which the volume and buoyancy fluxes through the upper openings equal that supplied to the upper layer by the plume. The lower layer is at ambient temperature and the upper layer has a temperature equal to the plume temperature at height \( h \) (Linden, Lane-Serff and Smeed, 1990).

![Fig. 1 Schematic illustrating notation and steady natural displacement ventilation flow in an enclosure of height \( H \) with a heat source in the centre of the floor (adapted from Linden, Lane-Serff and Smeed (1990)).](image-url)
Hunt and Linden (2001) showed that when openings of area $a_t$ and $a_b$ are made in the top and bottom of the space, respectively, these areas may be combined and expressed as an “effective” opening area $A^*$, where,

$$A^* = \frac{C_D a_t a_b}{\left(\frac{1}{2}\left(\frac{C_D^2}{C_e}a_t^2 + a_b^2\right)\right)^{\frac{1}{2}}}$$  \hspace{1cm} (1)

The quantities $C_e$ and $C_D$ are the coefficients of expansion and discharge, respectively.

Linden, Lane-Serff and Smeed (1990) showed that the normalised interface height $\xi = h/H$ is given by:

$$\frac{A^*}{H^2} = C^3 \left[\frac{\xi^{5\frac{3}{2}}}{1-\xi}\right]$$  \hspace{1cm} (2)

where

$$C = \frac{6\alpha_f \left[\frac{9\alpha_f}{10}\right]^{\frac{1}{5}}}{\frac{\pi^\frac{5}{2}}{5}}$$  \hspace{1cm} (3)

is a parameter dependent upon the entrainment coefficient $\alpha$ for the plume. A value of 0.1 has been assumed here in keeping with the assumptions of the analytical work in Linden, Lane-Serff and Smeed (1990).

Assumption (ii) of Linden, Lane-Serff and Smeed (1990) allows the “top-hat” profiles to be used to represent their Gaussian counterparts. The shape of the Gaussian plume profile is usually determined by characteristic width of the plume $b_G$ defined as the radial distance from the plume axis to the point at which the velocity has fallen to $1/e$ of its axial value. The rate of increase of $b_G$ with height provides a measure of the rate of entrainment, $a_G$, into the plume. $a_G$ is the proportionality constant relating the inflow of fluid at the edge of the plume (at $r=b_G$) to the vertical velocity on the plume axis, $V_G$ (assumption (i)). The relationships between the top-hat quantities and their Gaussian counterparts can be written as (Cook, 1998):

$$\alpha_f = 2^{\frac{1}{3}} \alpha_G$$  \hspace{1cm} (4)

$$V_T = \frac{V_G}{2}$$  \hspace{1cm} (5)

$$He_T = \frac{He_G}{2}$$  \hspace{1cm} (6)

$$b_T = 2^{\frac{1}{2}} b_G$$  \hspace{1cm} (7)

3. THE NUMERICAL PROCEDURE

3.1 Computational domain, boundary conditions and mesh

Two LES simulations were carried out to determine the flow in an enclosure with the computational domains shown in Figs. 2a and b. The dimensions of the enclosure in Fig. 2a are the same as those used by Cook and Lomas (1998). The simulation of this, the larger domain (Fig. 2a), is used to assess the influence of the computational domain and mesh resolution on the flow field. Most of the results presented in this paper are from the simulation of the computational domain shown in Fig. 2b. In this...
case, the smaller domain enables a refined mesh to be used while still being large enough to allow for the free development of the plume flow in a way similar to the case in Fig. 2a. An important parameter characterizing convective heat transfer and a strong indicator of whether or not the buoyancy-driven flow is turbulent, is the Rayleigh number (Turner, 1973) defined as:

\[ Ra = \frac{\beta g \rho l^3 \Delta T C_p}{\mu \lambda} \]  

(8)

where \( l \) is a typical length scale (taken here to be \( H \)) and \( \Delta T \) is a temperature difference (taken as that between the upper layer and the ambient air). For the geometry in Fig. 2b and a point heat source of strength 20 W (total heat input), \( \Delta T \) is expected to be of the order of 2 K which leads to a value of Rayleigh number of the order of \( 10^9 \) (\( 10^{10} \) for the simulation of Fig. 2a). The onset of turbulence is in the range \( 10^6 \leq Ra \leq 10^9 \) (Jones and Whittle, 1992). Bastiaans et al. (2000) observed a transitional plume at \( Ra \sim 10^{10} \). It is therefore reasonable to assume that the flows investigated here are transitional.

The enclosure (Fig. 2b) was ventilated by two square-shaped openings symmetrically positioned (about the floor centre) at the bottom, each with area \( a_{b}/2 = 1 \times 10^{-2} \) m\(^2\). (0.1 m\(^2\) for Fig. 2a) through which ambient air could enter the domain to replace the warmer air displaced through the top openings each with area \( a_{t}/2 = 4.4 \times 10^{-2} \) m\(^2\). (0.044 m\(^2\) for Fig. 2a). An opening boundary condition was assigned to each of the top and bottom openings which permits the fluid to cross the boundary in either direction according to the pressure loss defined by Ansys CFX (2005):

\[ \Delta P_{loss} = \frac{1}{2} f_{loss} \rho U_n^2 \]  

(9)

where \( U_n \) is normal component of velocity (m/s). The loss coefficient, \( f_{loss} \), is related to the discharge coefficient, \( C_d \) as: \( f_{loss} = 1/C_d^2 \). The value of \( C_d \) used in this computation is unity justified by the fact that the flow through the opening boundaries is laminar in nature and the velocity of both the cold air entering and the warm air leaving the opening boundaries is quite low.

The heat source is represented by a square-shaped surface having an area of \( A = 1 \times 10^{-2} \) m\(^2\) in the center of the floor and was given a heat flux boundary condition of 20000 W/m\(^2\) (20 W total heat input) for the two cases. The reference temperature for the two simulations is 18 °C or 291.15 K.

The mesh for a vertical slice passing through the centre of the two computational domains is shown in Figs. 2a and b. However, many test runs were performed employing both structured and unstructured meshes in order to ensure that the mesh was sufficiently refined to resolve the high temperature gradients expected around the heat source. Coarse meshes generated inaccurate temperature fields close to the heat source (an example is the mesh shown in Fig. 2a) and will be discussed in section 4.1.1. This is the main reason behind using the smaller enclosure in Fig. 2b thus saving computational time. For the results presented in this paper, a total of 1.5 million hexahedrals (structured) cells were used and found to be adequate in resolving the flow features for the domain shown in Fig. 2b. The mesh density was 148×106×94 along the x, y and z-axes respectively and unevenly distributed with more cells concentrated around the heat source and the plume axis.

### 3.2 The computer code and LES method

The CFD code used in this work is Ansys CFX (2005). The code calculates the 3D flow field and heat transfer using the continuity, momentum and energy equations. The finite volume method (Versteeg and Malalasekera, 1995) is implemented for the spatial discretisation of the computational domain.

The code uses a co-located (non-staggered) grid layout such that the control volumes are identical for all transport equations. For discretisation of the continuity equation (pressure-velocity coupling) a second order central difference approximation is used. A second order backward Euler scheme is used to approximate the transient term. A scalable and fully implicit coupled solver is used for the solution of the equations, which is one of the key advantages of this code. The implicit coupled solver requires the equations to be converged within each time step to guarantee conservation. The number of loops required to achieve this is a function of the time step size which in turn depends on the mesh size. The time step size should be sufficiently small to achieve convergence in a relatively small number (about 3–5) of iterations. Time step sizes which require more iterations than this tend to degrade solution accuracy.

The standard Smagorinsky LES model (Lilly, 1967) is used for representing turbulence. Most of the sub-grid models used in LES documented in
the literature are concerned with shear flows (Voke and Collins, 1983; Ferziger, 1983). However, in many cases, the standard Smagorinsky model (with Smagorinsky constant $C_s=0.1$), has been used successfully for predicting buoyant flows (Bastiaans et al., 2000; Zhou, Luo and Williams, 2001). The assumption of Linden, Lane-Serff and Smeed (1990) that the largest local variations of density in the field of motion are small in comparison with some chosen reference density enables the use of the Boussinesq approximation. In this approximation, the density variations in the inertia terms of the governing equations of motion are neglected, but those in the buoyancy force term are retained, where they are of primary importance. Here, the density is set to be a constant, $\rho_0$, except in the momentum equation where the following equation of state is used:

$$\rho = \rho_{Bref}(1 - \beta(T - T_{Bref}))$$

(10)

where $\rho_{Bref}$ is the reference density; $T_{Bref}$ is the buoyancy reference temperature and $\beta$ is the thermal expansion coefficient given by $\frac{1}{\rho} \frac{\partial \rho}{\partial T}$.

Either $T_{Bref}$ or $\rho_{Bref}$ must be specified by the user. For the simulation described herein the reference temperature was specified and the reference density was calculated using Eq. (10).

The time step and the number of inner iterations within each loop are explicitly specified. For the simulation with the finer mesh (Fig. 2b) a physical time step of $7.5 \times 10^{-4}$ s was used. For the simulation with the coarser mesh (Fig. 2a) a time step of $4 \times 10^{-3}$ s was used. The fully implicit coupled solver used for the solution of the equations is unconditionally stable with respect to time step size, however, for accuracy, it is recommended that the magnitude of the time step should be selected such that the resulting Courant (or CFL) number should be of order 0.5–1.0. Larger values can give stable results, but the turbulence may be damped (under predicted). For the selected values of time steps above, the CFL number was kept to a value of $0.6 \pm 5\%$ in the two simulations. The convergence criteria for each time step was set such that the root mean square (rms) residuals of the momentum, mass and the energy equations were less than $1 \times 10^{-4}$. This criterion was achieved after two inner loop iterations with the residuals for the velocity components and energy falling to the order of $5 \times 10^{-6}$ and the pressure to $1 \times 10^{-5}$.

4. CFD RESULTS

The simulation with the finer mesh in Fig. 2b ran for 39000 time steps to allow turbulent mixing within the computational domain to become established, i.e. the flow to reach a statistically stationary state. This was monitored and checked by observing the main feature of this flow, which is the formation of a two-layer steady stratification. After 35000 time steps there was no noticeable change in the height of the interface separating the two layers or the temperature of the warm, upper layer. After time step 39000 (29.25 s), statistical sampling of the flow began and continued for an additional 72900 time steps, equivalent to 54.675 s. The simulation with the coarser mesh (Fig. 2a) ran for 15000 time steps (60 s) for the flow to develop and the statistical samples are collected over a further 11000 steps (44 s). All the results presented below are from the simulation with the finer mesh unless indicated otherwise.

4.1 Mean flow field

The mean temperature at the surface of the heat source was approximately 575 °C. In the experiment of Pham, Plourde and Kim (2006), the heat source surface was kept to a temperature of order 400 °C (which is comparable to the case here) and their experimental technique was to ensure that no stratification occurs, which is contrary to the current study in which stratification is a characteristic of the flow. The mean vertical velocity profiles in the plume are shown in Fig. 3a. Almost all the profiles display a Gaussian distribution at levels below and close to the mean interface height ($y = 0.46$ m, $y/d = 14.55$). Far above this point and into the warmer upper layer, the mean velocity profiles (not shown here) start to deviate from this distribution as expected. The maximum mean velocity close to the heat source is comparable to the measurements of Pham, Plourde and Kim (2006) who measured the mean velocity for a pure thermal plume originating from a point heat source. For example, Pham, Plourde and Kim (2006) reported a maximum peak velocity of order 0.55 m/s at the axial locations 0.15 and 0.2 m above the heat source compared to 0.5 m/s and 0.45 m/s from the current simulation at the two positions, respectively. At higher points the LES results show lower peak values compared to the experimental work which is most likely due to the stratified nature of the current flow field. The following sections compare the LES results with
the analytical solution of Linden, Lane-Serff and Smeed (1990).

### 4.1.1 Interface height

The mean position of the interface height is an important parameter characterizing this flow. For the current geometry, where $A'/H^2 = 6.934 \times 10^{-3}$, Linden, Lane-Serff and Smeed (1990) predicted a value of $h/H = 0.46$ for a point source plume with identical buoyancy flux. The position of the interface in the CFD results was estimated using a vertical mean temperature profile away from the plume centre (Fig. 4). Figure 4 shows a sudden increase in temperature in the range $0.4 \leq h/H \leq 0.6$, suggesting an interface in this region. This layer of warm stratified air drives a ventilation flow rate of $0.0027 \text{ m}^3/\text{s}$ which compares well with the analytical prediction of $0.0026 \text{ m}^3/\text{s}$ by Linden, Lane-Serff and Smeed.
It is worth mentioning here that whilst stratification is different, the close agreement between the predicted volume flow rate and the theoretical value is due to the independence of this parameter on stratification as can be read from Eq. (11) Linden, Lane-Serff and Smeed (1990).

\[
Q = A^* \left( \int_{z=0}^{H} g' dz \right)^{\frac{1}{2}}
\]

(11)

Fig. 4 Mean vertical temperature profile away from the plume centre at \(x = 0.475\) m, \(z = 0.245\) m.

Fig. 5 Mean temperature contours over a vertical plane through the centre of the source \((z = 0.25\) m).

The mean temperature field from the simulation with the finer mesh is shown in Fig. 5. The temperature contours indicate that the position of the interface is at approximately \(y = 0.46\) m (or \(y/d = 14.55\)). The same height was predicted by the mean temperature contours from the simulation with the coarse mesh (Fig. 2a)—not shown here. This indicates that the primary features of the flow were captured by both the coarse and fine meshes. However, inaccuracies in the form of unphysical streak-like structures were present in the results using the coarse mesh in the region close to the heat source which indicates the sensitivity of the mesh issue when resolving the high temperature gradient in this specific region.

4.1.2 Plume properties

Before evaluating characteristic parameters of the plume, it is informative to check the development of the evolving buoyant plume (below the mean interface region). This can be done by checking the self-similarity of the plume. It is expected that transitional/turbulent plumes attain self-similarity some distance downstream from their buoyancy source.

Figure 3a shows the mean vertical velocity profiles for 9 locations above the heat source and just below the mean interface height \((y/d = 14.55)\) while Fig. 3b show the profiles normalised using the maximum value at each height. The x-axis in Fig. 3b is normalised using the characteristic plume width deduced from the velocity profile at each height. The normalised values are used to check for self-similarity of the thermal plume below and close to the interface height. Locations close to the heat source in the range \(1.6 \leq y/d \leq 8\) indicate that the plume is still in the development region which is expected. However, for all the locations at and above \(y/d \geq 8\) shown in Fig. 3b, the normalised velocity profiles strongly indicate that the plume has attained self-similar behaviour (as identified by overlapping plume profiles) and is in the fully developed region.

It is worth to mention that Morton, Taylor and Turner (1956) noted that for the lower region of the plume in a stably stratified ambient fluid the assumptions concerning entrainment and similarity are expected to be satisfied. This seems to disagree with Fig. 3b results which indicates that in a range close to the heat source \((1.6 \leq y/d \leq 8)\) self-similarity is not achieved. However, the Morton, Taylor and Turner (1956) statement is associated with turbulent plumes, and in this regard, the LES results has shown that self similarity was achieved only when the plume is passing the transitional region to the fully turbulent status which is in agreement with the Morton, Taylor and Turner (1956) statement.

The top-hat value of entrainment, \(\alpha_T\), can be calculated as follows. From the graphs of the
mean vertical velocity profiles (Fig. 3a), it was possible to measure the characteristic plume width $b_G$. The corresponding top-hat values were then calculated (Table 1) and the variation of the top-hat width $b_T$ with height above the source plotted (Fig. 3c). The gradient of the linear fit is related to the entrainment constant $\alpha_T$ thus:

$$\text{gradient} = \frac{6}{5} \alpha_T$$

resulting in $\alpha_T \approx 0.14$ which is slightly higher than that used by Linden, Lane-Serff and Smeed (1990) which is 0.10. The values of $\alpha_T$ from the experimental work of Morton, Taylor and Turner (1956) and Baines (1983) are respectively 0.093 and 0.074 while Turner (1986) suggested that $\alpha_T = 0.08$ is a suitable empirical value. Employing the RANS turbulence modelling in a similar case, Cook and Lomas (1998) predicted a value of $\alpha_T = 0.14$ using the standard $k$-$\varepsilon$ model and $\alpha_T = 0.11$ with the RNG $k$-$\varepsilon$ model. Dehmani, Doan and Ghaboue (1996) reported a value of $\alpha_T = 0.15$.

From the “top-hat” plume properties given in Table 1, the CFD predictions of the volume flux in the plume, $M_T$, and buoyancy in the plume, $G'_T$, were calculated using equations from Cook (1998):

$$M_T = \pi b_G^2 V_T$$

and

$$G'_T = \beta \left[ \frac{H_T - H_{ref}}{C_p} \right]$$

The values of the enthalpy shown in Table 1 were used to calculate $G'_T$ while the theoretical values were calculated using the relationship (Linden, Lane-Serff and Smeed, 1990):

$$M = C \left[ By^5 \right]^{\frac{1}{3}}$$

with the buoyancy strength $B$ evaluated using the formula:

$$B = \frac{g \beta q}{\rho C_p}$$

and

$$G'_T = \left[ B y^{-5} \right]^{\frac{1}{3}}$$

(Linden, Lane-Serff and Smeed, 1990).

<table>
<thead>
<tr>
<th>Height above source (m)</th>
<th>$V_T$ (m/s)</th>
<th>$b_T$ (m)</th>
<th>$H_T$ (J/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.325</td>
<td>0.0127</td>
<td>$6.179 \times 10^4$</td>
</tr>
<tr>
<td>0.1</td>
<td>0.312</td>
<td>0.0194</td>
<td>$3.127 \times 10^4$</td>
</tr>
<tr>
<td>0.15</td>
<td>0.28125</td>
<td>0.0252</td>
<td>$1.674 \times 10^4$</td>
</tr>
<tr>
<td>0.2</td>
<td>0.25</td>
<td>0.03382</td>
<td>$1.03 \times 10^4$</td>
</tr>
<tr>
<td>0.25</td>
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</tr>
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<td>0.3</td>
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<td>0.0523</td>
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</tr>
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<td>0.0616</td>
<td>$2.063 \times 10^3$</td>
</tr>
<tr>
<td>0.4</td>
<td>0.19125</td>
<td>0.0736</td>
<td>$9.472 \times 10^2$</td>
</tr>
</tbody>
</table>

Table 1 Top-hat plume data predicted by LES model.

Figure 3d shows the variation of $M$ with height above the source compared with the theoretical prediction using $\alpha_T = 0.1$ (used by Linden, Lane-Serff and Smeed (1990)) and $\alpha_T = 0.14$ predicted by the LES. It can be seen that the agreement between the LES data and the theoretical solution of Linden, Lane-Serff and Smeed (1990) and Morton, Taylor and Turner (1956) is good for $y \leq 0.25$ m. The slight shift of the CFD results from the theoretical prediction is thought to be due to the assumption of a point source in the theoretical analysis. In the CFD simulation the source has a finite area. It is also noticeable that at heights close to the heat source $0.04 \text{ m} \leq y$ the LES results predict very small volume flux ($0.00007 \text{ m}^3/\text{s}$ at $y = 0.04 \text{ m}$). Although the difference between the LES and the theoretical solution increases with height both the LES and the theory show the same trend. As discussed in the previous paragraph in this section, Morton, Taylor and Turner (1956) noted that for the lower region of the plume in a stably stratified ambient fluid the assumptions concerning entrainment and similarity are expected to be satisfied. However, in the upper region, where the flow is driven by momentum and exhibits a fully turbulent nature, neither of the assumptions are expected to represent the mean motion in the plume accurately. The fact that the difference in volume flux between the theory and the LES increases rapidly above $y = 0.25 \text{ m}$ suggests that above this height the flow is either fully turbulent or in the late stages of transition.

The values of the enthalpy shown in Table 1 were used to plot the variation of plume buoyancy ($G'_T$) with height as shown in Fig. 3e. The graph clearly shows that the LES data predict the same qualitative variation as the theory. The difference in plume buoyancy between the LES and the analytical solution is most likely due to the higher
rate of entrainment predicted by the LES results. It is also noticeable that the trends of agreement between the computed volume flux and plume buoyancy with the theoretical solutions do not match. Better agreement with the theoretical solution is obtained at lower value of \( y \) \( (y \leq 0.2 \text{ m}) \) for the volume flux but at higher values of \( y \) \( (y \geq 0.2 \text{ m}) \) for the plume buoyancy. This discrepancy is most likely associated with the high enthalpy values predicted by the LES results close to the heat source and used in estimating the plume buoyancy.

4.2 Instantaneous flow development and plume entrainment mechanism

4.2.1 Instantaneous temperature field

Figures 6 and 7 are temperature fields for x-y and y-z vertical slices passing through the centre of the domain at \( t = 72.534 \text{ s} \). Figures 8a to h show the corresponding horizontal slices at heights: \( y = 0.05 \text{ m}, 0.1 \text{ m}, 0.15 \text{ m}, 0.2 \text{ m}, 0.25 \text{ m}, 0.3 \text{ m}, 0.35 \text{ m} \) and \( 0.45 \text{ m} \) respectively. Both of the vertical slices indicate that below the position of the interface height, the instantaneous topology (shape) for the temperature contours is non-uniform. Evidence of hot eddies (fluid parcels) breaking away from the plume body and cold fluid moving into the plume are two characteristics shown by the vertical slices of the instantaneous temperature contours in Figs. 6 and 7. A necking phenomena (shrinking and enlargement) of the plume topology below the interface is very clear in Fig. 7.

![Fig. 6 Temperature contours for an x-y slice passing through the centre of the computational domain at \( t = 72.534 \text{ s} \).](image)

![Fig. 7 Temperature contours for a y-z slice passing through the centre of the computational domain at \( t = 72.534 \text{ s} \).](image)

The horizontal slices shown in Figs. 8a to h demonstrate that one of the mechanisms through which the plume enlarges or entrains is by releasing hot parcels of air from its periphery into the surrounding air (Figs. 8c and d). It is also noticed that the hot energetic parcels or eddies of hot air that detach from the plume dissipate very fast into the ambient air but significantly raise the surrounding temperature (Figs. 8e and g). It is also evident that pockets of cold fluid penetrate the plume body and become trapped within the hot environment of the plume body. This could be a direct result of detachment of hot eddies leaving the main body of the plume and subsequently enveloping pockets of the surrounding (cooler) air. Hence the interaction of such hot eddies with the cold ambient environment surrounding the plume appear to be the main mechanism through which the plume entrains surrounding air and increases in width with height.

Although the current case is one of a purely buoyant plume, the process of eddy detachment from the main body of the plume is due to a combined mechanism of inertial (momentum) and buoyancy forces. It is thought that the buoyancy effects provide the dominant driving force causing hot eddies to separate from the plume. After detachment, both the dynamics of the separated eddy and buoyancy forces play a similar role in the interaction of the hot eddy while it is dissipating and raising the temperature of the surrounding air. However, at this stage of
the entrainment process, the ratio of buoyant forces to inertia forces imposed by dissipating eddies is not clear. This is a key feature in determining the dominant force contributing to the entrainment mechanism of the plume. Having observed the above-mentioned features of the plume development below the interface height (especially the necking of the main body of the plume) from the instantaneous temperature field, it is also of interest to investigate the impact of this on the entrainment mass flow rate.

### 4.2.2 Instantaneous entrained mass flux

Before discussing more features of the plume development using flow visualization, it is helpful to evaluate the variation of the entrainment flow rate with time which will reveal the instantaneous entrainment behaviour of the plume at different heights above the heat source. Early work in directly measuring the entrainment flux (of turbulent jets) was carried out by Ricou and Spalding (1961). In their method, the jet is

Fig. 8 Temperature contours for horizontal x-z slices at t=72.534 s.
surrounded with a porous-walled cylinder equipped for measuring the mass flow rate passing through the porous wall and that feeding the core flow of the jet. Ricou and Spalding (1961) related the pressure loss through the porous medium to a precise amount of mass entrained by the vertical flow motion. A major draw back of this method is the influence of the cylinder on the pressure field leading to inaccuracy in the measurement.

Inspired by the ideas of Ricou and Spalding (1961), Pham, Plourde and Kim (2006) used analytical technique to measure the entrainment flow rate by integrating the normal velocity \( u_n \) along a boundary surrounding the plume between two different heights. As the surface which encloses the ascending flow field is difficult to define, Pham, Plourde and Kim (2006) suggested a conical surface with its lower and upper diameters determined by the mean characteristic width of the plume. Pham, Plourde and Kim (2006) then estimated the (non-dimensional) entrainment flow rate by the relation:

\[
\dot{m}_e = \rho_\infty \int_{z_1}^{z_2} u_n^2 \pi r \cos \tau \, dz
\]

(18)

where \( \tau \) is the angle of inclination of the surface with the vertical axis.

In order to evaluate the entrained mass between \( z_1 \) and \( z_2 \), it is straight forward to construct the conical shape surrounding the plume based on the characteristic plume widths calculated using the method in section 4.1.2 at the two heights. However, it is difficult to estimate the normal velocity to the conical surface and hence to follow the method of Pham, Plourde and Kim (2006) in estimating the entrainment flow rate using Eq. (18). Moreover, the entrainment of the plume is a function of the three velocity components rather than one. Also, since the plume expands while evolving between the heat source and the interface height, it is essential to realise that between any two heights there is flow going into the plume as well as flow going out of the plume as shown by the temperature contours in Figs. 6, 7 and 8. Since the plume is expanding upwards from the heat source, the net flow through any surface surrounding the plume should represent the entrained mass as long as \( z_1 \) and \( z_2 \) are below the mean interface height. This is exactly the methodology of Ricou and Spalding (1961) who measured the entrained mass flow directly. Based on this methodology, a conical surface between the plume origin and four heights at \( y = 0.1 \) m, 0.2 m, 0.3 m and 0.35 m was constructed. An example showing the conical surface surrounding the velocity vectors for a longitudinal slice passing through the domain centre is shown in Fig. 9. The lower diameter fits within the heat source area while the upper diameter corresponds to the mean characteristic plume width at that height (Table 1). The entrainment rate was evaluated at the four heights mentioned above. The variation of the instantaneous entrainment flow rate with time for each height is shown in Fig. 10. The range of values revealed by these graphs is close to that measured by Pham, Plourde and Kim in 2006.

The graphs show that the mass flow rate in the plume fluctuates around a mean value at each height and that as the mean interface height is approached, the fluctuation of the entrainment becomes less significant (i.e. the entrained mass approaches a single (presumably a mean) value).

It is also noticeable that at distances close to the mean interface height (Figs. 10c and d), the mass flow rate increases with time up to approximately half of the time span (10–45 seconds) but settles down and fluctuates about a mean value in the second half of the time span (after 45 seconds and onward). This indicates that flow stationarity of the plume flow is achieved only after 45 seconds of simulation time. This behaviour was not reflected in Figs. 10a and b and c at the lower region of the plume which support the fact that the plume is most likely in laminar phase in those regions as mentioned previously.
The entrainment fluctuation suggests that, instantaneously, the entrainment coefficient also fluctuates around a mean value.

The graphs illustrate how the entrainment increases at some instances and decreases at others. For example, at $t = 65.5$ s, the entrained mass flow rate shows a sharp decrease for $y = 0.1$ m, moderate decrease for $y = 0.2$ m but an increase for $y = 0.3$ m and $y = 0.35$ m. This indicates that the plume is passing through different phases at these heights at the same instant in time. It is worth mentioning that although the current plume under investigation is considered as a transitional one in the sense that the regions slightly above the heat source are yet to exhibit the behaviour of a fully turbulent plume, a similar behaviour to that of Morton, Taylor and Turner (1956). To obtain more detailed information regarding this phenomenon, it is useful to consider the dynamics of the flow by analysing the instantaneous behaviour of the large-scale coherent structures within the flow.

4.3 Large-scale structures and their role in the entrainment mechanism

It is well known that large-scale organised motions, usually called coherent structures (CS), exist in many transitional and turbulent flows. An analysis of the dynamics of these structures is useful for understanding turbulence phenomena such as entrainment and mixing and the resulting heat and mass transfer. The topology and range of scales of these large-scale structures vary between flow types. They include counter-rotating vortices in wake flows (Hill and Saffman, 2002), streaks and hairpin vortices in turbulent boundary layers (Gongxin et al., 1989). However, it is not well established what kind of large-scale structures exist in buoyancy-driven transitional plumes, especially those within ventilated enclosures such as those studied here. The impact of the dynamics of such coherent structures on the flow topology and entrainment has not been explored. Despite the fact that many methods are evolving for identifying CS in flows (such as the proper orthogonal decomposition (POD) method of Aubry et al., 1988), computational flow visualization remains the traditional method for showing that there are indeed large coherent fluid motions present. A common parameter used for identifying coherent vortices in free shear flows is the vorticity modulus. Dubief and Delcayre (2000) adopted local minimum pressure as a means to identify coherent structures in a flow field. A criterion which shares some properties with both the vorticity and the pressure criterion is the $Q$-criterion. The $Q$-criterion was named after the second invariant of velocity gradient tensor $\Delta u$ by Hunt, Wray and Moin (1988). The second invariant $Q$ is defined as:

$$Q = \frac{1}{2}(\Omega_y \Omega_{ij} - S_{ij} S_{ij})$$

where $\Omega_y = (u_{ij} - u_{ij})/2$ and $S_{ij} = (u_{ij} + u_{ij})/2$ are the antisymmetric and the symmetric components of $\Delta u$ respectively. In other words, $Q$ is the balance between the rotation rate $\Omega = \Omega_y \Omega_y$ and the strain rate $S^2 = S_{ij} S_{ij}$. The implication of the latter observation is fairly straightforward: positive $Q$-isosurfaces indicate areas where the strength of rotation overcomes the strain, thus making those surfaces eligible as vortex envelopes. Plotting $Q$-isosurfaces throughout the...
computational domain helps to generate a qualitative picture of the nature and shape of the flow structure.

In the current study, the vorticity field, the $Q$-criterion of Hunt, Wray and Moin (1988) and the low-pressure isosurfaces flow visualization methods, in addition to the temperature field, have been used to identify the flow structure and its role in the plume development. It was found that the vorticity modulus and the $Q$-criterion led to the identification of almost identical features.

Recently, Zinoubi, Maad and Belghith (2004) carried out flow visualization and demonstrated three different regions in the plume, one of which is mainly driven by plume contraction above which, small (presumably 3D), structures appear, leading to uniform flow field behaviour. Zhou, Luo and Williams (2001) studied the vorticity field of a thermal plume using LES while Pham, Plourde and Kim (2006) studied the vorticity field through flow visualization in their experimental work. The Pham, Plourde and Kim (2006) visualization showed that there are two regions, the first close to the heat source ($y/D \leq 3.0$ where $D$ is the heat source diameter) in which the vorticity does not change significantly. The second is slightly above the heat source ($y/D \geq 3.0$) and is characterised by a rapid development of structures. They also noticed that the plume develops in conjunction with contraction and expansion phases, which are linked to the instantaneous width of the plume and that the plume enlarges due to a high spatial concentration of vortex structure. They mentioned that expansion phases are highly localised and enhanced by stronger vorticity fields—although this phenomena is not well understood at present.

### 4.3.1 $Q$-criterion and pressure contours

In section 4.2.2, it was shown that the plume entrainment appears to be decreasing in the range $0.1 \leq y \leq 0.2$ and increasing for $y=0.3$ m and $0.35$ m at $t=65.52075$ s (note that this instantaneous behaviour can happen at any other instance and not specifically unique to this time step). To obtain more details of the picture of the plume development and phases at this instant of time, it is informative to investigate both the $Q$-criterion and the pressure field. The $Q$-criterion contours and the pressure field are shown in Figs. 11a and b, respectively, for a plane passing through the plume’s vertical axis. Close to the heat source, the $Q$-contours clearly show that the plume develops through contraction and expansion zones. This feature is also displayed by the temperature contours shown in Fig. 7. Close to the heat source, the pressure field indicates that there are regions of positive pressures followed immediately by negative values and then positive again and so on. In the regions where the pressure is positive, fluid is able to move out from the plume centre and where the pressure is negative, fluid is drawn into the plume body. This could be a straightforward explanation to the contraction and expulsion of the flow while it is developing from the heat source upwards.

![Fig. 11](image)

**Fig. 11** (a) Q-criterion contour, (b) pressure contours; both at x-y slice passing through the centre of the computational domain at $t=65.52075$ s.

### 4.3.2 Vortex coherency and the expansion-contraction of the plume behaviour

To gain a better understanding of the processes occurring at the instant of time discussed above, the velocity vectors ($u,w$) on horizontal planes at $y=0.1$ m, $0.2$ m and $0.3$ m are shown in Figs. 12a, b and c, respectively. Superimposed on the
vectors are the contours of the Q-criterion (isosurfaces $Q = 100$). For $y = 0.1$ m, it is noticeable that the large-scale structures shown by the Q-contours are quite intact, dense, coherent and concentrated around the plume axis. As a result, the velocity vectors clearly indicate that the plume is expanding. At $y = 0.2$ m, the Q-contours are less concentrated and the velocity vectors in most of the regions at the plume edge indicate that the plume is in an expansion phase (although not at the same rate to that corresponding to $y = 0.1$ m). For $y = 0.2$ m, it is noticed that in

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**Fig. 12** Velocity vectors $(u, w)$ and Q-criterion isosurfaces ($Q = 100$) for horizontal slices below the interface height at $t = 65.52075$ s.
some regions of the plume surroundings, the velocity vectors are seen entering the plume body rather than leaving (i.e. the plume is not in 100% expansion phase). A close investigation of the Q-contours in regions where velocity vectors penetrate the plume body indicates that either there is no vortical structure or the structure has lost its coherence and is partially breaking down. This indicates that the plume is in transition from an expansion to a contraction phase. In other words the transition from contraction to expansion and vice versa is quite smooth and highly dependent on the intensity and coherence of the large-scale structures in the particular region. Figs. 12a and b are in fact a very clear explanation as to why the entrainment mass flow rate shown in Fig. 10 is decreasing. On the other hand, Fig. 12c clearly illustrates why the plume at \( y = 0.3 \text{ m} \) is almost entirely in a contraction phase. The Q-contours reveal that the vorticity structure at this height is less intense and broken into smaller scale structures compared to that in Figs. 12a and b. The velocity vectors bear out this point as they show that, from almost all directions, flow is entering the plume rather than leaving—indicating a clear contraction phase and hence a higher entrained mass.

Pham, Plourde and Kim (2005) mentioned that expansion phases are highly localised and enhanced by stronger vorticity fields—a point which is poorly understood. To address this point, and from previous work (Abdalla, 2004), it is well established in free shear flows that, as large-scale structures convect (mostly along the direction of motion) they are subjected to many processes of stretching in different directions depending on the flow topology. In this context, the large-scale structure is stretched and becomes larger at the expense of loosing its coherence. Eventually, different 2D and 3D modes of instability set in, causing the large-scale structure to lose its coherency and break into smaller scale structure generating a fully turbulent flow. Of course, the more intense and coherent the structure is, the longer it will retain its coherency while convecting upwards and the larger it becomes, thus entraining more mass. This illustrates one of the advantages of the LES technique over experimental methods where LES can be used to elucidate the transient evolution of the flow field.

In the current case (and in transitional plumes in general), the nature of the large-scale structure at smaller \( y \)-values measured from the lower surface (close to the heat source) is most likely two-dimensional in nature (though some plumes pass through abrupt changes into turbulence faster than others—depending on the excited flow from the heat source which in turn depends on the heat source strength). Both Fig. 12a and the low pressure isosurfaces shown in Fig. 15 support the two-dimensionality of the flow in the regions close to the heat source and below the mean interface height; or at least one could assume that the three-dimensional instabilities are not fully established in those regions. Hence, there is an opportunity for the size of such coherent structures to increase while convecting upward along the plume. Hence, the dynamical behaviour of coherent structures associated with plumes explains why the expansion phases are associated with the existence of an intense concentration of the (localised) vorticity field—a point which is poorly understood. Figs. 12a, b and c clearly indicate that the more coherent the large structures the more space they occupy. The reason is, no matter how incremental their time scale is, they keep their coherency while stretching and hence entrain more of their surroundings. The figures also show that whenever a large-scale structure is less intense or in the process of breaking down (as seen in Fig. 12b), the velocity vectors penetrate into the body of the plume indicating a region of contraction. The gradual and partial breakdown of coherent structures explains the helical shape visualised by the coherent structures in Fig. 15 and also illustrates that the change of phase from expansion to contraction is not as abrupt in nature as visualised by the Q- and pressure-contours of Fig. 11. Contrary to Pham, Plourde and Kim (2006), the results show that the development of the plume through such expansion and contraction phases begins close to the heat source. There are two reasons to explain this difference in results. The first is based on the fact that the plume in the current case was shown to be in the development phase in the region \( 1.6 \leq y/d \leq 8 \) as discussed in section 4.1.2 and shown in Fig. 3b. The local Rayleigh number values based on the local temperature difference at the specific height in the range \( 1.6 \leq y/d \leq 8 \) is shown in Table 2. It is clear that the range of Rayleigh number is below the range \( 10^9 \leq Ra \leq 10^{10} \) at which the plume is expected to be fully developed and turbulent. This fact also strongly supports the idea that the plume within the height range \( 1.6 \leq y/d \leq 8 \) is still in the development region and thus the difference observed when compared with Pham, Plourde and Kim (2006) is expected.
This difference in results mentioned above could also be attributed to the nature of the stratified flow under consideration compared to the pure buoyant plume of Pham, Plourde and Kim (2006) and most likely is due to a resistance-type of dynamics imposed by the interface on the flow below it. To shed more light on this point, it is worth investigating the Q-criterion isosurfaces and velocity vectors at and above the interface region. For \( y = 0.45 \) m (within the interface region), \( y = 0.6 \) m and \( 0.8 \) m (both above the interface), the flow characteristics change significantly.

![Velocity vectors and Q-criterion isosurfaces](image)

**Fig. 13** Velocity vectors \((u, w)\) and Q-criterion isosurfaces for horizontal slices at and above the interface height at \( t = 65.52075 \) s. Isosurfaces lines for \( y = 0.8 \) m identify Q-isosurfaces less than 100 shown by the blue-coloured isosurfaces.

<table>
<thead>
<tr>
<th>Height above source</th>
<th>( \frac{y}{d} = 1.6 )</th>
<th>( \frac{y}{d} = 3.2 )</th>
<th>( \frac{y}{d} = 4.8 )</th>
<th>( \frac{y}{d} = 6.4 )</th>
<th>( \frac{y}{d} = 8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Rayleigh number</td>
<td>( 1.3 \times 10^6 )</td>
<td>( 5.6 \times 10^6 )</td>
<td>( 1.1 \times 10^7 )</td>
<td>( 1.8 \times 10^7 )</td>
<td>( 2.4 \times 10^7 )</td>
</tr>
</tbody>
</table>
interface region) and at the same instance of time discussed above (t = 65.52075 s), the Q-criterion isosurfaces and velocity vectors are shown at Figs. 13a, b and c respectively (isosurface Q = 100). There is an interesting feature shown by both the behaviour of the velocity vectors and Q-isosurfaces at y = 0.45 m at the vicinity of the mean interface height. It is quite noticeable that there is a high concentration of vortical structures at the region of the mean interface height and upon gradually moving upward such structures lose their coherence and break up into smaller structures as displayed by Figs. 13b and c.

The concentration of the large-scale structures in the mean interface region is thought to be a common feature of this stratified flow and not coincidental. Q-contours at the instant t = 60.996 s for the same y-locations are shown in Figs. 14a, b and c and almost display the same phenomena of vorticity concentration in the vicinity of the mean interface height (y = 0.45 m). The fact that the coherent structures break into smaller 3D structures above the mean interface height is understandable, being attributed to the turbulent nature of the warm layer above. However, the fact that the flow is characterised by high vorticity concentration is thought to be a common feature of this stratified flow and not coincidental.

![Figure 14](image)

Fig. 14 Velocity vectors (u, w) and Q-criterion isosurfaces (Q=100) for horizontal slices at and above the interface height at t = 60.996 s.
concentration within the mean interface region draws into question the influence of the interface height on the plume development both below and above it. At present, the flow visualization shows that the region between the ambient lower layer and the warmer upper layer acts as a buffer that resists and hinders any growth of coherent structures above it and hence limits the maximum entrainment rate and plume width. However, whether it has any impact on the growth or decay of the large-scale structures below it, and through which mechanism, remains uncertain. The best way to assess this point is to study a similar case with no stratification and compare the plume width at similar locations below the interface height. This will be the subject of further work.

Note that at positions above the interface region \((y = 0.6 \text{ m, } 0.8 \text{ m})\), the velocity vectors show some recirculation regions (away from the plume centre) which indicates the existence of a vortex—but this has not been identified by the \(Q = 100\) isosurfaces. However, by plotting lower \(Q\) isosurfaces, most of these recirculation regions indicate that there are vortical structures but with lower values compared to the \(Q = 100\) level. This is apparent in Fig. 13c where the \(Q\)-isosurfaces with values lower than 100 are shown as lines. Thus, the level \(Q = 100\) is used for comparison of the vorticity intensity for the three heights. However, it also supports the fact that the rate of rotation or the vorticity intensity decreases upon moving away from the plume axis.

### 4.3.3 Low-pressure isosurfaces

To visualise the plume structure in a three-dimensional format, the instantaneous low-pressure isosurfaces (coloured by temperature) at four points in time are shown in Figs. 15a, b, c, and d. The value of pressure used in the isosurface is \(-0.0125\) Pascal. All the figures show a ring-shaped structure (commonly associated with laminar rectangular free jets (Grinstein, 2001)) appears close to the source. A spiral structure \((\text{helix})\) forms around the buoyant plume in the region below the mean interface height. The helical nature exhibited by the evolving coherent structures here explains the phenomenon observed in the velocity vectors in Fig. 12b in

![Fig. 15 Low pressure isosurfaces (coloured with temperature) at (a) \(t = 54.15225\) s, (b) \(t = 60.096\) s, (c) \(t = 65.52075\) s and (d) \(t = 72.534\) s.](image-url)
which some regions show velocity vectors entering the plume, indicating a contraction phase. It is noticeable that the spirals enlarge with distance from the heat source and become increasingly deformed upon approaching the interface height. Eventually these coherent structures break down into smaller scale structures in the warm buoyant turbulent layer despite the fact that some of them survive and could collide with the top surface of the enclosure leading to a turbulent unsteady upper layer.

As mentioned previously, it appears that the interface region poses some sort of resistance to the evolving coherent structures. This is illustrated by Figs. 6, 7 and 11 which show that above the region of the interface height, both the pressure and temperature ranges are higher than below it. So, for a coherent structure to survive this region and convect through the positive pressure region above the interface height, depends very much on the energy content of the structure (its buoyancy flux). In other words, a larger buoyancy force relative to that of the warm upper layer (Figs. 6 and 7) is required for any eddy to travel through the warm upper layer.

It would be worthwhile studying the current case under a no stratification condition and investigate the speed of convection of such coherent structures (below the interface height) in order to assess whether the existence of an interface leads a slower movement of the structures and hence their rate of entrainment from their surroundings. It is worth mentioning that comparison of the pressure isosurfaces taken from the two simulations shows no significant difference and indicates that the extent of two computational domains are sufficient to allow free development of the flow with no interference.

![Fig. 16 Low pressure isosurfaces at t=54.15225 s.](image)

The three-dimensional nature of coherent structures discussed in this section questions the argument of a localised vorticity field leading to a higher instantaneous entrainment rate or expansion of the plume adopted by some researchers (such as Pham, Plourde and Kim, 2006). The helical shape of the coherent structures shown here (which is also shown in the study by Zhou, Luo and Williams, 2001) indicates that the development of the plume takes place quite dynamically through both vertical and lateral stretching of the concentrated vorticity field. However it is not localised in the sense that the plume is connected by the spiral between the expansion and contraction phase.

Figure 16 shows the pressure isosurfaces of Fig. 15a along a plume section. The figure also shows the position of 6 horizontal slices passing through regions of interest in the coherent structures revealed by the pressure isosurfaces discussed above. The first slice (at $y = 0.048$ m) was chosen to pass through what appears to be a coherent disc (ring) structure and the next two positions (at $y = 0.11$ m and $0.15$ m) passes through what appears to be a helical structure while the fourth position passes through what can be described as an enlarged deformed spiral. The last two positions are within the region where such coherent structures are on the verge of breaking down into smaller 3D structures close to the mean interface height. The main purpose is to use these horizontal slices and the Q-criterion to check whether the nature of the coherent structures revealed by the low pressure isosurfaces are indeed consistent with what the Q-criterion shows. The Q-criterion for these slices is shown in Figs. 17a–f. Figure 17a corresponds to the slice passing through the coherent ring vortex and as the Q-isosurfaces indicates, this region is occupied by stable and coherent structures indicated by a dense concentration of Q-isosurfaces. Both Figs. 17b and c shows a similar feature of a region occupied by a coherent structure but which does not extend the full 360 degree region (as seen in Fig. 17a); an indication that the coherent structure is partially broken which is consistent with spiral nature of the coherent structure associated with this flow region.

As discussed above, the coherent structures enlarge and become more distorted as they convect upwards. This is clearly indicated by the Q-isosurfaces shown in Fig. 17d which shows coherent eddies detaching from the main body of the plume as a first sign of breakdown on a once a coherent structure. Figure 17e displays a coherent structure which is in the process to break down into a smaller 3D structure which is the case revealed in Fig. 17f. These figures show that the coherent structures revealed using the
low-pressure isosurfaces are consistent with what the Q-isosurfaces.

4.3.4 Temperature field

The instantaneous temperature isosurfaces (coloured with the vertical velocity) at \( t = 72.534 \) s shown in Fig. 18 display both the temperature field above and below the interface (at \( y = 0.46 \) m, \( y/d = 14.55 \)) separating the two layers. The temperature isosurfaces reveal the unsteady nature of the warm upper layer which is characterised by the interaction of different scales of buoyant motions (eddies) and reveal the non-horizontal nature of the instantaneous interface. Below the interface and in the plume, the isosurfaces indicate that the plume develops through lumps of hot energetic flow seeking a route to escape from the main body of the plume, and entraining the surrounding air as a consequence—the main mechanism of plume entrainment and expansion.

5. CONCLUSIONS

A transitional buoyant plume in a naturally ventilated enclosure has been investigated using the large-eddy simulation technique. The predicted mean interface height separating the ambient lower layer and the warmer upper layer was found to be in good agreement with the analytical solution of Linden, Lane-Serff and Smeed (1990). Comparison of the other parameters characterising the plume behaviour including the volume flux \( (M) \) and buoyancy \( (G') \) in the plume were also found to agree well with
theoretical findings of Linden, Lane-Serff and Smeed (1990). The plume entrainment coefficient evaluated using the mean (averaged) values of the flow is slightly higher than that used in the analytical model but within the range of values found by experimental work. It was also observed that the LES results suggested a linear growth of the plume entrainment coefficient with height rather than a constant value and that, instantaneously, both the entrainment flow rate and coefficient fluctuate in time. This behaviour is attributed to the transitional nature of the plume. Flow visualization has revealed that the plume flow below the interface height evolves through expansion and contraction phases characterised by helical shaped coherent structures spanning the region below the interface height. The expansion phases are associated with the existence of intense vortical structures which grow in size while convecting upward along the plume axis causing more entrainment from the plume surroundings. Such structures were observed to grow in size while convecting from the heat source towards the interface height which behaved as a resisting buffer to the convecting large-scale structures. The contraction phases usually represent a transition to an expansion stage and are mainly associated with lower concentration of vorticity or large structures undergoing some form of deformation.

The flow is also characterised by an unsteady instantaneous interface. The non-horizontal nature of this interface is thought to be due to the unsteady behaviour of the warmer layer in which interaction of vortices of different scales takes place. The LES technique has been successful in elucidating the evolution of the flow field in the ventilated enclosure driven by a transitional plume as well as producing mean values in good agreement with the analytical and solutions and experiment provided for the same flow.

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NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>$A^*$</td>
<td>effective opening area ($m^2$)</td>
</tr>
<tr>
<td>$a_b$</td>
<td>area of the lower opening ($m^2$)</td>
</tr>
<tr>
<td>$a_t$</td>
<td>area of the upper opening ($m^2$)</td>
</tr>
<tr>
<td>$B$</td>
<td>buoyancy flux ($m^3/s^3$)</td>
</tr>
<tr>
<td>$b_G$</td>
<td>Gaussian plume width (m)</td>
</tr>
<tr>
<td>$b_T$</td>
<td>top-hat plume width (m)</td>
</tr>
<tr>
<td>$C_D$</td>
<td>coefficient of discharge (-)</td>
</tr>
<tr>
<td>$C_e$</td>
<td>coefficient of expansion (-)</td>
</tr>
<tr>
<td>$C_p$</td>
<td>specific heat capacity (J/kgK)</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Smagorinsky constant (-)</td>
</tr>
<tr>
<td>CFL</td>
<td>Courant number (-)</td>
</tr>
<tr>
<td>$d$</td>
<td>width of the heat source (m)</td>
</tr>
<tr>
<td>$G'$</td>
<td>buoyancy in plume ($m/s^2$)</td>
</tr>
<tr>
<td>$g$</td>
<td>acceleration due to gravity ($m/s^2$)</td>
</tr>
<tr>
<td>$g_r$</td>
<td>reduced gravity ($m/s^2$)</td>
</tr>
<tr>
<td>$H$</td>
<td>total height of the computational domain (m)</td>
</tr>
<tr>
<td>$H_{eG}$</td>
<td>Gaussian value for enthalpy (J/kg)</td>
</tr>
<tr>
<td>$H_{eT}$</td>
<td>top-hat value for enthalpy (J/kg)</td>
</tr>
<tr>
<td>$h$</td>
<td>mean interface height (m)</td>
</tr>
<tr>
<td>$l$</td>
<td>length scale used in Rayleigh number formulation (m)</td>
</tr>
<tr>
<td>$M$</td>
<td>volume flux in plume ($m^3/s$)</td>
</tr>
<tr>
<td>$m_e$</td>
<td>entrained mass flow rate (kg/s)</td>
</tr>
<tr>
<td>$M_{out}$</td>
<td>volume flux out of ventilated enclosure ($m^3/s$)</td>
</tr>
<tr>
<td>$q$</td>
<td>heat source strength (Watts)</td>
</tr>
<tr>
<td>$r$</td>
<td>radial distance from plume axis (m)</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature (K)</td>
</tr>
<tr>
<td>$T_{Bref}$</td>
<td>reference temperature (K)</td>
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<tr>
<td>$V_m$</td>
<td>mean vertical velocity along plume axis (m/s)</td>
</tr>
<tr>
<td>$V_G$</td>
<td>Gaussian velocity (m/s)</td>
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<tr>
<td>$V_T$</td>
<td>top-hat velocity (m/s)</td>
</tr>
<tr>
<td>$(x,y,z)$</td>
<td>Cartesian coordinate system (m)</td>
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<tr>
<td>$\alpha_G$</td>
<td>Gaussian plume entrainment coefficient (-)</td>
</tr>
<tr>
<td>$\alpha_T$</td>
<td>top-hat plume entrainment coefficient (-)</td>
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<tr>
<td>$\beta$</td>
<td>coefficient of thermal expansion (-)</td>
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<tr>
<td>$\Delta t$</td>
<td>time step (s)</td>
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<tr>
<td>$\lambda$</td>
<td>thermal conductivity (W/mK)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>molecular viscosity (kg/ms)</td>
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<tr>
<td>$\rho_{Bref}$</td>
<td>reference density (kg/m$^3$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>air density (kg/m$^3$)</td>
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<tr>
<td>$\Delta T$</td>
<td>temperature difference (K)</td>
</tr>
<tr>
<td>$\xi$</td>
<td>normalised interface height ($h/H$) (-)</td>
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</tbody>
</table>

REFERENCES


