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Mixed convection in a ventilated enclosure

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ABSTRACT

This paper presents analysis, visualizations and differential pressure measurements of the flow within a confined ventilated space resulting from a buoyant turbulent 2D plume originating at the bottom of the enclosure with initial source volume flux, Q_0 and buoyancy flux, B_0. The enclosure is ventilated through lower and upper openings of heights H_E and H_S separated by a vertical distance H. Simple analysis shows that flow regimes between the interior and the exterior of the enclosure depends on a densitometric Froude number $\overline{\mathrm{Fr}}_\mathrm{H} = Q_0^2/(\overline{\Delta\rho}_\mathrm{H}/\rho)gH(C_SA_S)^2$ related to the source flow rate, the density inside the enclosure and the area of the upper opening. For $\overline{\mathrm{Fr}}_\mathrm{H} < 2$, a displacement regime is observed with inflow at the lower opening and outflow at the higher opening. For $\overline{\mathrm{Fr}}_\mathrm{H} > 2$, the regime is blocked with two outflows. When the enclosure is well mixed the value $\overline{\mathrm{Fr}}_\mathrm{H} = 2$ corresponds to the criteria given by Woods et al. (2003). Experiments show that the natural regime is observed for $\overline{\mathrm{Fr}}_\mathrm{H} < 2$ while the blocked regime appears when $\overline{\mathrm{Fr}}_\mathrm{H} > 2.6$. There is an intermediate regime for $2 > \overline{\mathrm{Fr}}_\mathrm{H} > 2.6$. This last regime where inflow and outflow are both present through the lower opening is due to the non negligible size of this opening not taken into account in the analysis.

1. Introduction

The free, mixed or forced convection produced by a buoyant or inertial source within a confined or semi confined region has received a great deal of attention due to considerable practical interest in a large number of engineering applications. For instance, this situation occurs in the natural or forced ventilation of buildings, the cooling of electronic devices or the dynamics of flows in fire situation. This problem has been at first developed by considering the effect of a small source of buoyancy B_0 on environment in a closed space (Baines and Turner, 1969; Cesini et al., 1999). Then, this study of natural ventilation has been extended to the case where one or two openings located at the floor or/and the ceiling of the room connect the interior and the exterior of the enclosure (Linden et al., 1990; Gladstone and Woods, 2001; Bouzinaoui et al., 2005). In this case, the presence of a heated fluid within the room lowers further the interior hydrostatic pressure gradient in comparison with the exterior one. This drives inflow through the lower opening and outflow through the upper opening. In a similar geometric configuration, the effect of a source of buoyancy B_0 and mass Q_0 leads to various flow regimes (Woods et al., 2003; Allano et al., 2008).

Two main regimes of ventilation have been observed. The displacement regime has inflow through the opening nearer the source and outflow through the other opening while the blocked regime has outflows through both openings. These two regimes were obtained in the experiment with a dense source by changing the flow rate of the source (Woods et al., 2003), and in the experiment with a buoyant source by changing the dimensions of the upper opening (Allano et al., 2008).

In this paper, an analytical and experimental analysis is performed to understand the flow regimes within a ventilated enclosure resulting from a buoyant forced plume located at the bottom. As shown in Fig. 1, the enclosure is ventilated through lower and upper openings. The analytical analysis is presented in Section 2. Flow visualisations and differential pressure measurements are presented in Section 3 and discussed in Section 4.

2. The analytical model

As shown in Fig. 1, the room of rectangular cross section (length L, span l and height H) is ventilated through upper and lower openings of areas $A_S = l \times H_S$ and $A_E = l \times H_E$. There is a source of constant buoyancy B_0 and volume flux Q_0 of light fluid (heated air) flowing up through a rectangular slot (length l, width D_0) located on the floor of the room. This flow has an initial velocity U_0 and is at a temperature ΔT_0 above the external temperature T_∞. The suffix 0 refers to the initial conditions of the forced plume. Buoyancy driven flow is generated using heated air which is lighter than exterior air, therefore the buoyancy forces act upwards in contrast to the experimental condi-

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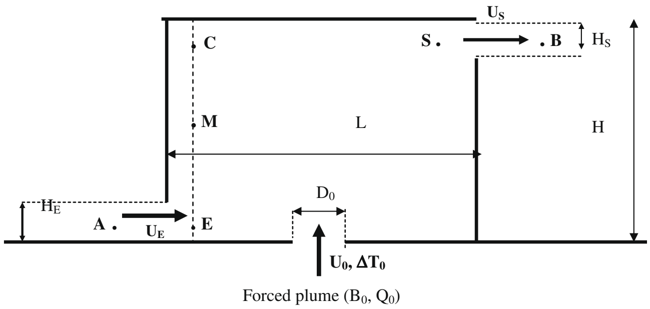

Fig. 1. Schematic diagram of the ventilated enclosure (natural regime).

tions of Woods et al. (2003), where the buoyancy forces act downwards.

2.1. Displacement regime

In this first analytical approach, for simplicity the upper and the lower openings are assumed of small vertical extent H_S and H_E and separated by a distance H with $H \gg H_S$ and $H \gg H_E$. The flow is unidirectional through each opening. In the displacement regime, there is inflow of velocity U_E through the lower opening E of area A_E and outflow of velocity U_S through the upper opening S of area A_S. It has been also assumed that density variations are small. Using the aerostatic pressure distribution instead of the full vertical momentum equation remains valid as long as the vertical velocity component in the room is negligible ($u\ \partial v/\partial x + v\ \partial v/\partial y << g\Delta\rho/\rho$) (Jones and Marshall, 1993).

Then two equations can be derived by relating the air velocities U_E and U_S to the pressure differences between inside and outside openings (points A and E and points B and S) by using Bernoulli equation.

$$P(H) - P_{\text{ext}}(H) = \frac{1}{2}\rho U_S^2 \quad P_{\text{ext}}(0) - P(0) = \frac{1}{2}\rho U_E^2 \tag{1}$$

The pressure differences between two points distant of H in the vertical direction and located either inside the room (points E and C) or outside the room (points A and B) are related by the aerostatic pressure distribution:

$$P(H) - P(0) = -\int_0^H \rho(y) g\, dy \quad P_{\text{ext}}(0) - P_{\text{ext}}(H) = \rho_{\text{ext}} gH \tag{2}$$

As the value of ρ is not constant within the room, we define its spatial mean $\bar{\rho}_H$ as:

$$\bar{\rho}_H = (1/H)\int_0^H \rho(y) dy \tag{3}$$

Furthermore, calculating the pressure difference $(P(H) - P_{\text{ext}}(H))$ between inside and outside of the upper opening and using previous relations lead to:

$$U_S^2 + U_E^2 = 2(\rho_{\text{ext}} - \overline{\rho_H})gH/\rho = -2\overline{\Delta\rho}_H gH/\rho \tag{4}$$

Eq. (4) allows to link the volume fluxes through, respectively, the lower opening Q_E and the upper opening Q_S by using $Q_E = C_E A_E U_E$ and $Q_S = C_S A_S U_S$, where C_E et C_S are the discharge coefficients for the openings E and S.

$$(Q_S/Q_0)^2 + (C_S A_S/C_E A_E)^2 (Q_E/Q_0)^2 = (2\overline{\Delta\rho}_H/\rho)gH(C_S A_S)^2/Q_0^2 \tag{5}$$

It is therefore possible to define two parameters α and $\overline{\text{Fr}}_\text{H}$:

$$\alpha = C_S A_S/C_E A_E \quad \text{and} \quad \overline{\text{Fr}}_H = Q_0^2/(\overline{\Delta\rho}_H/\rho)gH(C_S A_S)^2 \tag{6}$$

By defining $q_E^* = Q_E/Q_0$ and $q_S^* = Q_S/Q_0$, Eq. (5) and conservation lead to:

$$\begin{aligned} &q_S^{*2} + \alpha^2 q_E^{*2} = 2/\overline{\text{Fr}}_\text{H} \\ &q_S^* = 1 + q_E^* \quad \text{where } q_E^* \quad \text{and} \quad q_S^* \geqslant 0 \end{aligned} \tag{7}$$

Resulting in an equation for the normalized volume flux through the lower opening:

$$(1+\alpha^2)q_E^{*2} + 2q_E^* + (1 - 2/\overline{\text{Fr}}_\text{H}) = 0 \tag{8}$$

By solving Eq. (8), it appears that the displacement regime only exists for $\overline{\text{Fr}}_\text{H} < 2$ due to the existence of a positive root which is the greatest root of Eq. (8). In this case, solutions are:

$$\begin{aligned} q_E^* &= \frac{-1 + \sqrt{2/\overline{\text{Fr}}_\text{H}}(1 + \alpha^2(1 - \overline{\text{Fr}}_\text{H}/2))^{1/2}}{1+\alpha^2}, \\ q_S^* &= \frac{\alpha^2 + \sqrt{2/\overline{\text{Fr}}_\text{H}}(1 + \alpha^2(1 - \overline{\text{Fr}}_\text{H}/2))^{1/2}}{1+\alpha^2} \end{aligned} \tag{9}$$

This simple analysis shows that the displacement regime is possible when $\overline{\text{Fr}}_\text{H} < 2$. This densitometric Froude number is function both of characteristics of the upper opening and Q_0 $(\overline{\Delta\rho}_H/\rho)$ and H_S. The characteristics of the lower opening are not present explicitly in $\overline{\text{Fr}}_\text{H}$ but appear through α in the expressions of volume flows q_E^* and q_S^*. In this displacement regime some effect of α on $\overline{\text{Fr}}_\text{H}$ may exist by the influence of q_E^* on $(\overline{\Delta\rho}_H/\rho)$.

2.2. Blocked regime

The same analysis is undertaken for the blocked regime and leads to an equation for the normalized volume flux though the lower opening

$$(1-\alpha^2)q_E^{*2} - 2q_E^* + (1 - 2/\overline{\text{Fr}}) = 0 \tag{10}$$

By solving Eq. (5), it appears that the blocked regime is only present for $\overline{\text{Fr}}_\text{H} > 2$ due to the fact that for these values Eq. (10) has a positive root lower than 1.

In this case, solutions are:

For $\alpha \neq 1$

$$\begin{aligned} q_E^* &= \frac{1 - \sqrt{2/\overline{\text{Fr}}_\text{H}}(1 - \alpha^2(1 - \overline{\text{Fr}}_\text{H}/2))^{1/2}}{1-\alpha^2} \quad \text{and} \\ q_S^* &= \frac{-\alpha^2 + \sqrt{2/\overline{\text{Fr}}_\text{H}}(1 - \alpha^2(1 - \overline{\text{Fr}}_\text{H}/2))^{1/2}}{1-\alpha^2} \end{aligned} \tag{11}$$

For $\alpha = 1$

$$q_E^* = \frac{1}{2}(1 - 2/\overline{\text{Fr}}_\text{H}) \quad \text{and} \quad q_S^* = \frac{1}{2} + 1/\overline{\text{Fr}}_\text{H} \tag{12}$$

It is worth to note that in the particular case where $\overline{\Delta\rho}_H/\Delta\rho_0 = 1$ the room is full of the incoming air. For this case, by introducing $B_0 = Q_0 g\Delta\rho_0/\rho$ in the expression of $\overline{\text{Fr}}_\text{H}$, the condition $\left(Q_0^3/B_0 H(C_S A_S)^2\right) = 2$ given by Woods et al. (2003), for the transition between displacement and blocked regimes is retrieved.

This analysis is only valid as long as the vertical velocity component in the room is negligible allowing to use the aerostatic pressure distribution instead of the full vertical momentum equation. This means the lower the value of $\overline{\text{Fr}}_\text{H}$, the more valid the Eqs. (9), (11), and (12).

3. Experimental set up

The experiments are carried out in a box with inner length L, width l and height H dimensions such $L \times l \times H = 500 \times 250 \times 200\ \text{mm}^3$. This box is ventilated through lower opening E of height $H_E = 36$ mm and width $l_E = 225$ mm and upper opening S of same width $l_S = l_E$ and height H_S which may take the following values: 0, 7, 17, 27, 37 and 46 mm. These openings connect the interior of the enclosure to a stationary ambient environment, at atmospheric pressure P_{ext} and temperature T_{ext}. The horizontal top and bottom walls are made of two 12 mm thick Plexiglas plates. The lateral (front and rear) walls and side walls are made of 6 mm thick glass plates in order to allow visualization. The side walls can move vertically in order to adjust the heights of the openings E and S.

The thermal forced plume is injected in the enclosure through a rectangular nozzle (D_0 = 30 mm and l_0 = 250 mm) located at the bottom of the room. This flow is supplied from the laboratory air supply and heated electrically before entering a convergent pipe which contracts to the rectangular nozzle. The power of the heater is controlled and delivers a maximum output power of 300 W. The source flow rate Q_0 and the temperature excess over the ambient ΔT_0 are controlled by a flow meter Alicat and two type T thermocouples linked to a data acquisition GL1.

Q_0 ranged from 80 l/mn to 250 l/mn and ΔT_0 from 0 to 80 K. Initial Reynolds numbers $\mathrm{Re}_0 = \frac{U_0 D_0}{\nu_g(T_0)}$ were between 350 and 1700. The ratio between the jet length $Lj = \frac{M_0\ /l_0}{(B_0\ /l_0)^{2/3}}$ and the height H characterizes the stratifying properties of the plane forced plume (Morton, 1959; Hunt et al., 2001). Here 0.3 < $Lj/H < \infty$. A pure jet has infinite Lj/H while as $Lj/H \to 0$ a stratified filling box occurs.

From (6) we need the values of Q_0, H, C_S, A_S and $\overline{\Delta\rho_H}/\rho$ to determine $\overline{\mathrm{Fr}}_{\mathrm{H}}$. Now, the density distribution is unknown until the experiment has been performed and this precludes to know in advance the true value of $\overline{\mathrm{Fr}}_{\mathrm{H}}$ and to use it to predict the flow. To overcome this difficulty $\overline{\Delta\rho}_{\mathrm{H}}/\rho$ was estimated as $\Delta T_{1/2}/T$ for the sake of simplification. Here $\Delta T_{1/2}$ is the temperature excess at M (located at $H/2$ on a vertical within the enclosure close to the lower opening E). $\Delta T_{1/2}/T$ seems an approximate value of $\overline{\Delta T_H}/T$ both for linear and constant temperature distribution but a crude simplification in the case of a two-layer stratification.

Assuming that $|\overline{\Delta\rho_H}|/\rho = \Delta T_{1/2}/T_{\mathrm{ext}}$. $\overline{\mathrm{Fr}}_{\mathrm{H}}$ can be calculated as

$$\overline{\mathrm{Fr}}_{\mathrm{H}} = Q_0^2/(\Delta T_{1/2}/T_{\mathrm{ext}})gH(C_S A_S)^2 \tag{13}$$

Here the measured value of the discharge coefficient for the opening S is Cs = 0.7.

Visualisations have been performed by seeding the jet flow or the ambient with incense smoke or oil droplets. The flow field was illuminated by laser system producing a vertical thin light sheet. The images were recorded by a CCD digital camera (1280 × 1024 pixels) and data acquisition system R&D Vision. Static pressure information $P(x, y)$ within the enclosure was obtained from pressure measurements on the wall by means of small openings taps normal to the surface of the enclosure. Static pressure $P_{\mathrm{ext}}(x_{\mathrm{ref}}, y_{\mathrm{ref}})$ was also determined at a reference location $(x_{\mathrm{ref}}, y_{\mathrm{ref}})$ outside the enclosure in quiet environment by means of the static pressure tap of a Pitot tube. Differential pressure measurement $(P(x, y) - P_{\mathrm{ext}}(x_{\mathrm{ref}}, y_{\mathrm{ref}}))$ was measured by means of a micro manometer Furness Control FC 014 down to 0.001 Pa. Due to the presence of vinyl lines between measurements points and inputs of the micro manometer, it turns out that the actual measured differential pressure corresponds to $(P(x, y) - P_{\mathrm{ext}}(x_{\mathrm{ref}}, y))$, the difference of pressure between a point of the enclosure and a point located outside the enclosure at the same altitude y.

4. Experimental results

4.1. Visualizations

Visualizations of the flow at the lower opening E are shown when a steady state is reached in the enclosure. There is always outflow from the higher opening S. We are looking for the effects of changes of H_S, Q_0 and $\Delta T_{1/2}$ on the structure of the flow at the lower opening when H_E = 36 mm as these H_S, Q_0 and $\Delta T_{1/2}$. Fig. 2 shows the location of the vertical visualization plane.

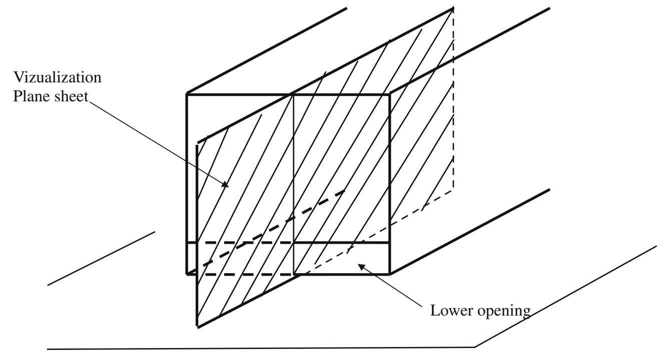

Fig. 2. Location of the vertical visualization plane.

4.1.1. Influence of H_S on the flow at the lower opening E

In this situation, source flow rate, Q_0, and temperature excess, $\Delta T_{1/2}$, are maintained at 147 l/mn and 24 K respectively and H_S takes the values: 7, 17, 27, 37 and 46 mm. Visualizations are presented in Fig. 3. For the higher values of H_S (37 and 46 mm), it appears that hot gases from the source do not leave the enclosure through opening E (Fig. 3a). Simultaneously, ambient fluid enters through E. For the smaller values of H_S (7 and17 mm), ambient air does not enter through the lower opening, (Fig. 3c). For intermediate values of H_S (27 mm), the flow is more unstable with inflow close to the wall and outflow through the upper part of the opening E (Fig. 3b).

4.1.2. Influence of Q_0 on the flow at the lower opening E

For this case, H_S = 27 mm and $\Delta T_{1/2}$ = 24 K are kept constant and Q_0 is in the range 100–250 l/mn. Visualizations are shown in Fig. 4. For the highest values of Q_0, hot gases from the inside leave the enclosure through E (Fig. 4c). For the smaller values of Q_0, the flow reverses and ambient fluid enters through the opening, (Fig. 4a). For intermediate values of Q_0, both inflow and outflows are also found (Fig. 4b).

4.1.3. Influence of ΔT_0 on the flow at the lower opening E

For this case, Q_0 = 147 l/mn, H_S = 27 mm and the temperature excess $\Delta T_{1/2}$ = 11.4 K and 27.6 K. Visualizations are shown in Fig. 5. For the higher value of the temperature excess $\Delta T_{1/2}$, there are both warm air leaving the enclosure near the top of the opening E and ambient air entering near the floor (Fig. 5a). When the temperature excess decreases, there is only outflow through E, (Fig. 5b).

The previous results show clearly that three flow regimes can exist in the present situation. The displacement and blocked regimes have been already mentioned in previous studies. In the intermediate regime observed here, there is inflow through the lower part of the E opening and outflow through the higher part of the E opening. In the second section of the paper, we have defined a densitometric Froude number $\overline{\mathrm{Fr}}_{\mathrm{H}} = Q_0^2/(\overline{\Delta\rho_H}/\rho)gH(C_S A_S)^2$ in order to look for the limit between the displacement and blocked regimes. We have shown that the blocked regime is present for $\overline{\mathrm{Fr}}_{\mathrm{H}} > 2$ and the displacement regime occurs when $\overline{\mathrm{Fr}}_{\mathrm{H}} < 2$.

The calculated values of $\overline{\mathrm{Fr}}_{\mathrm{H}}$ have been mentioned in the legend of Figs. 3–5. It appears that the transition between the displacement and blocked regimes occurs approximately at $\overline{\mathrm{Fr}}_{\mathrm{H}} = 2 - 3$. In fact, as mentioned above an intermediate regime exists between these two regimes where the flow through the lower opening is bidirectional. This last regime is similar to the exchange flow

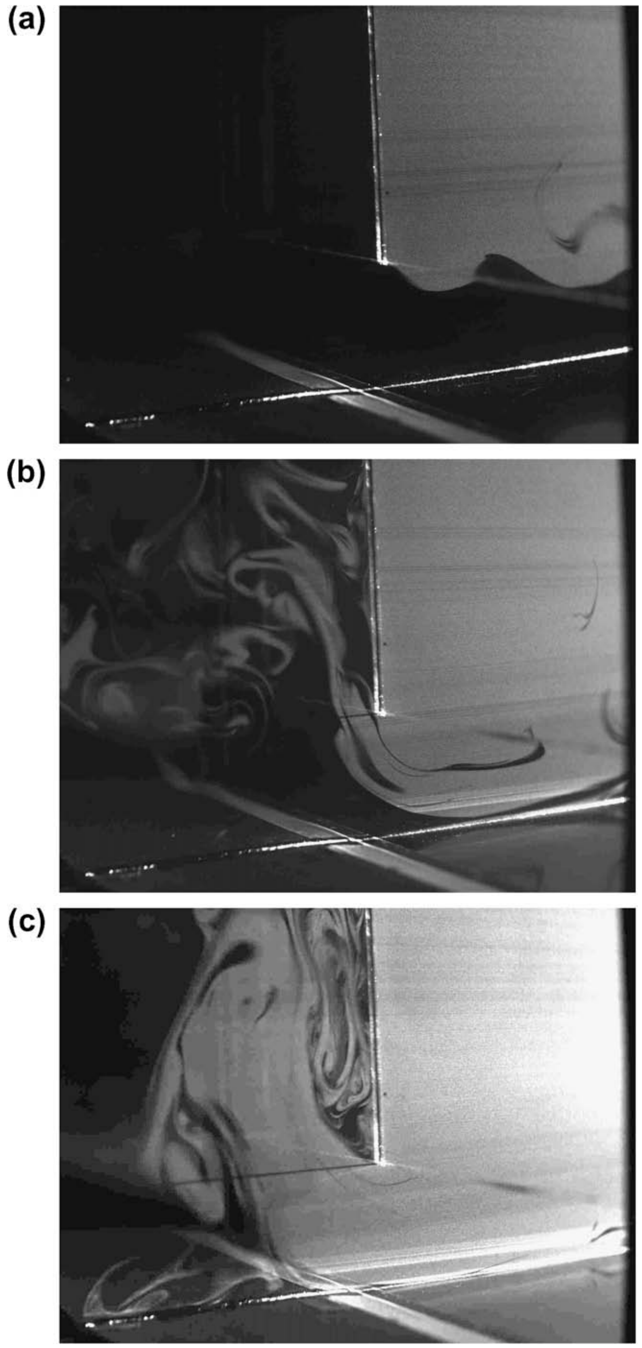

Fig. 3. Influence of Hs on the flow regime at the lower opening (Q_0 = 147 l/mn, $\Delta T_{1/2}$ = 24 K). (a) $\mathrm{Hs} = 37$ mm ($\overline{\mathrm{Fr}}_\mathrm{H} = 1.29$). (b) $\mathrm{Hs} = 27$ mm ($\overline{\mathrm{Fr}}_\mathrm{H} = 2.16$). (c) $\mathrm{Hs} = 17$ mm ($\overline{\mathrm{Fr}}_\mathrm{H} = 4.71$).

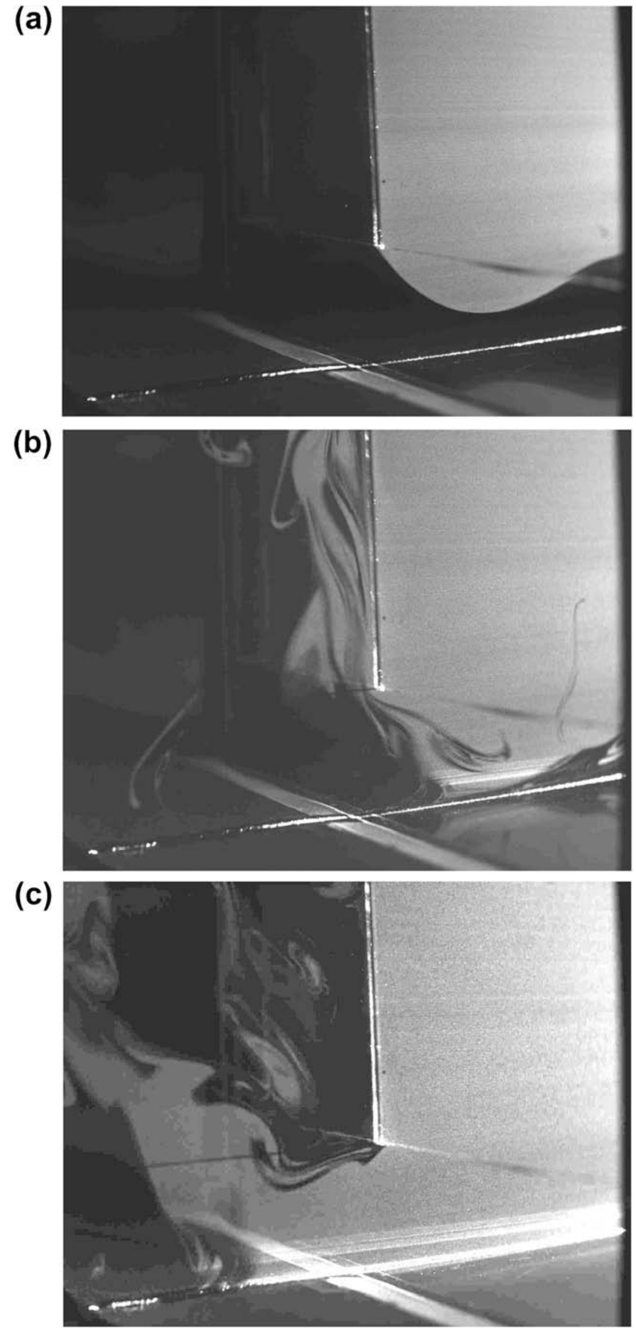

Fig. 4. Influence of Q_0 on the flow regime at the lower opening (Hs = 27 mm, $\Delta T_{1/2}$ = 24 K). (a) $Q_0 = 107$ l/mn ($\overline{\mathrm{Fr}}_\mathrm{H} = 1.06$). (b) $Q_0 = 147$ l/mn ($\overline{\mathrm{Fr}}_\mathrm{H} = 2.01$). (c) $Q_0 = 226$ l/mn ($\overline{\mathrm{Fr}}_\mathrm{H} = 4.6$).

through doorways where the opening serves as both an air inlet and outlet (Cockroft and Robertson, 1976).

4.2. Differential pressure measurements

In order to complete the information obtained by visualization, we have also measured the differential pressure at the wall at different y locations along a vertical located at $x/H = -1.1$. The reference pressure was taken outside the enclosure. As already mentioned in Section 3, this differential pressure measurement allows to determine $\Delta P_E(y) = P(y) - P_{\mathrm{ext}}(y)$.

Fig. 6 shows the profiles of the mean value of $\Delta P_E(y)$ obtained for several values of $\overline{\mathrm{Fr}}_\mathrm{H}$. Results show that for low values of $\overline{\mathrm{Fr}}_\mathrm{H}$ near to 2, $\Delta P_E(y)$ is always negative close to the wall. As y/H increases, $\Delta P_E(y)$ also increases as a result of the difference in the hydrostatic pressure gradient due to the heating between the inside and the outside of the enclosure. The negative values of $\Delta P_E(y)$ at the floor explain the displacement regime with inflow through the lower opening E. When the value of $\overline{\mathrm{Fr}}_\mathrm{H}$ increases, $\Delta P_E(y)$ becomes positive close to the wall which results in an outflow through the lower opening corresponding to the blocked regime. An intermediate regime occurs between the two previous regimes when the neutral line corresponding to $\Delta P_E(y) = 0$ occurs for $0 < y < H_E$.

In order to check more accurately the transition between these flow regimes, values of differential pressure coefficient $C_p(y)$ have

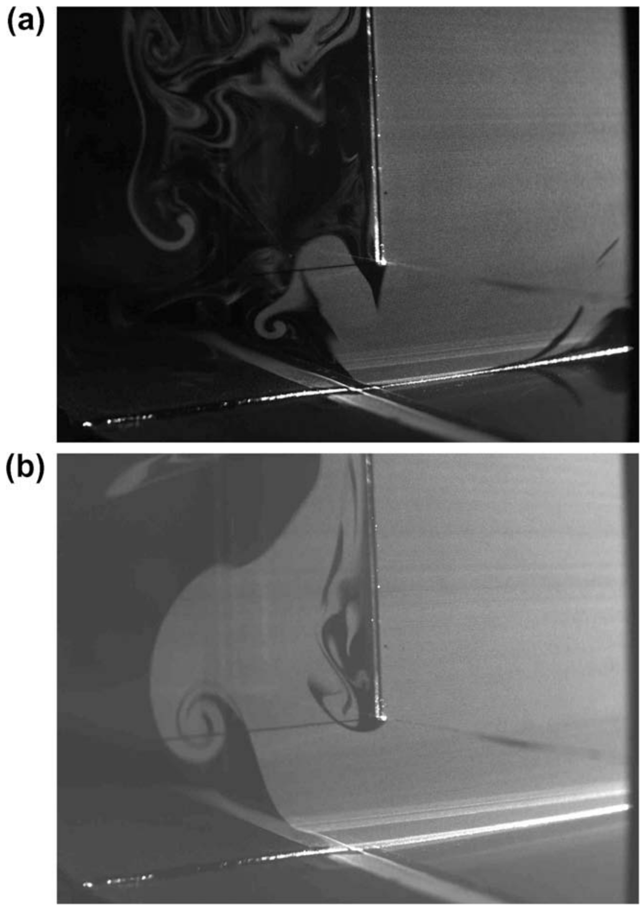

Fig. 5. Influence of $\Delta T_{1/2}$ on the flow regime at the lower opening (Hs = 27 mm, Q_0 = 147 l/mn). (a) $\Delta T_{1/2} = 27.6$ K ($\overline{\mathrm{Fr}}_{\mathrm{H}} = 1.95$). (b) $\Delta T_{1/2} = 11.4$ K ($\overline{\mathrm{Fr}}_{\mathrm{H}} = 4.7$).

been measured for $0 < y/H_E < 1.6$. Results are presented in Fig. 7 as a function of $\overline{\mathrm{Fr}}_{\mathrm{H}}$.

They show that for $0 < y < H_E$, $C_p(y)$ is always negative when $\overline{\mathrm{Fr}}_{\mathrm{H}}$ is lower than 2 and is always positive when $\overline{\mathrm{Fr}}_{\mathrm{H}}$ is larger than 2.6. Over the range $\overline{\mathrm{Fr}}_H = 2 - 2.6$, the neutral level is located between 0 and H_E leading to $C_p(y) < 0$ when $0 < y < y_{\mathrm{neutral}}$ and $C_p(y) > 0$ when $y_{\mathrm{neutral}} < y < H_E$.

5. Discussion

Comparisons between the analytical model developed in Section 2 and the measurements presented in Section 4 show some agreement in spite of some restrictive assumptions made in calculations. In particular, in the simple analysis developed in Section 2, the height of openings H_E and H_S is assumed to be much lower than the height H of the enclosure. This assumption leads us to consider that the flow at the lower opening is constant and unidirectional. This is mainly why two flow regimes are found for the analysis, while three flow regimes are revealed by the experiment.

In addition, in the analysis of Section 2 the influence of the vertical velocity component in the enclosure is neglected in order to use the aerostatic pressure distribution instead of the full vertical momentum equation. This hypothesis leads us to neglect the inertia terms ($u\,\partial v/\partial x + v\,\partial v/\partial y$) in comparison with $g\Delta\rho/\rho$ and to assume that a densitometric Froude number $\mathrm{Fr} = k^2U_0^2/(\overline{\Delta\rho_H}/\rho)gH$ proportional to$\overline{\mathrm{Fr}}_{\mathrm{H}}$ is always lower than one. Here k is a constant lower than 1. It means that the solutions given by the analysis are all the more valid if $\overline{\mathrm{Fr}}_{\mathrm{H}}$ is low. This behaviour clearly appears in the experimental results when $\overline{\mathrm{Fr}}_{\mathrm{H}}$ increases. For $\overline{\mathrm{Fr}}_{\mathrm{H}} > 5$, the curves of Fig. 6 show that $\Delta P_E(y)$ decreases as y/H increases and the previous assumption is no more valid.

In the analysis of Section 2, the static pressure is assumed to be constant on horizontal levels outside the forced plume. Differential pressure profiles measured along the verticals EM, OM′ and M″S for the case $\overline{\mathrm{Fr}}_{\mathrm{H}} = 0.31$ are plotted in Fig. 8. Similar behaviour is found for the $\Delta P(y)$ profiles along EM and M″S in agreement with the previous assumption. The stronger increase of $\Delta P(y)$ along OM′ as the ceiling is reached is related to the impinging of the forced thermal plume on the upper wall.

It is worth to note that for $\overline{\mathrm{Fr}}_{\mathrm{H}}$ lower than 2, the studied situation looks like the classic displacement flow in a ventilated enclosure with an internal steady source of buoyancy, and a layer of warm air at the ceiling (Linden et al., 1990). Warm fluid leaves the enclosure through the upper opening and ambient air is drawn in through the lower opening. The buoyant plume entrains the surrounding air, at ambient temperature on the lower opening side and at higher temperature on the upper opening side. This entrainment controls the vertical density profile and the value of $\overline{\Delta\rho_H}$.

In this first approach, the values of $\overline{\mathrm{Fr}}_H$ have been estimated with $|\overline{\Delta\rho_H}|/\rho = \Delta T_{1/2}/T_{\mathrm{ext}}$ as mentioned in Section 3. This crude assumption ought to be withdrawn in a future approach.

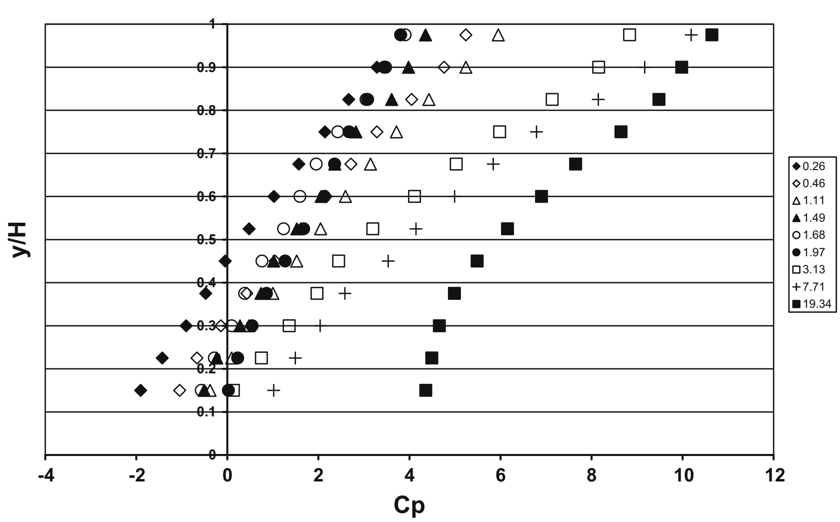

Fig. 6. Differential pressure coefficient (measured close to the opening E) versus the distance from the wall at various Fr_{H} values.

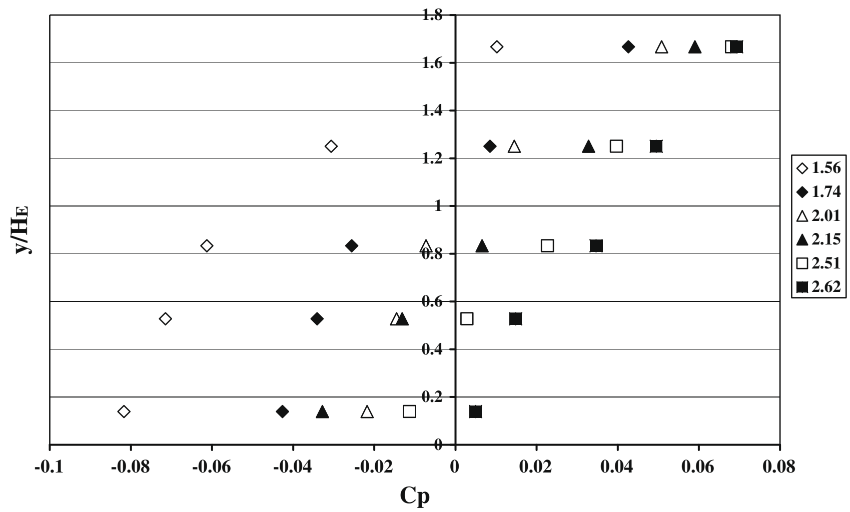

Fig. 7. Differential pressure coefficient (measured close to the opening E) versus the distance from the wall at various $\mathrm{Fr_H}$ values.

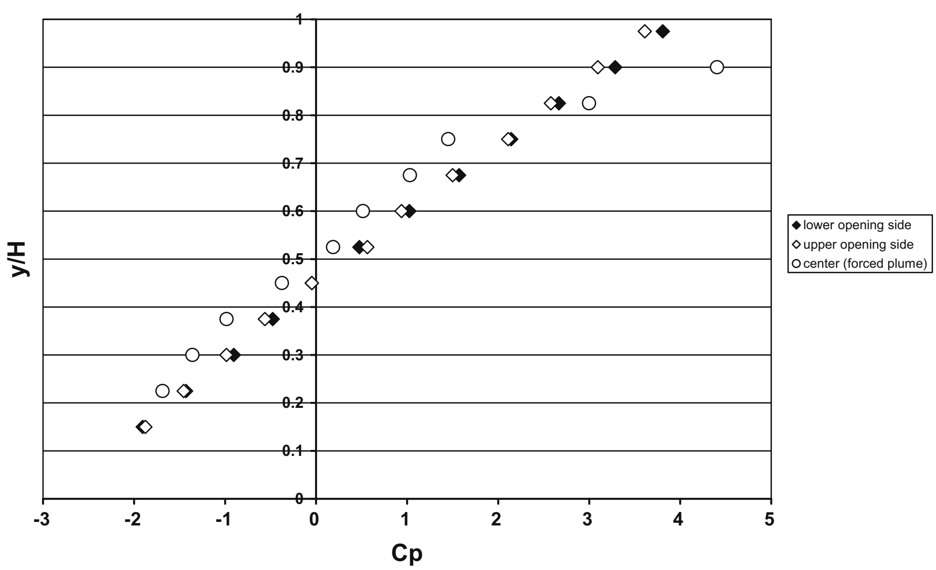

Fig. 8. Differential pressure on three verticals located close to openings E and S and in the forced plume as a function of the distance from the wall at $\mathrm{Fr_H} = 0.31$.

6. Conclusion

In this work, the flow produced by a source of hot gases within a semi confined enclosure has been analysed and measured.

From the analysis, it appears that two flow regimes are possible depending on a Froude number: $\overline{\mathrm{Fr}}_\mathrm{H} = Q_0^2/(\overline{\Delta\rho_H}/\rho)gH(C_SA_S)^2$. $\overline{\mathrm{Fr}}_\mathrm{H}$ is related to the source flow rate, the density inside the enclosure and the area of the upper opening. For $\overline{\mathrm{Fr}}_\mathrm{H} < 2$, the regime is natural with inflow at the lower opening and outflow at the higher opening. For $\overline{\mathrm{Fr}}_\mathrm{H} > 2$, the regime is blocked with two outflows. The value $\overline{\mathrm{Fr}}_\mathrm{H} = 2$ at the transition between the two regimes corresponds to the criteria given by Woods et al. (2003), when the enclosure is well mixed.

Experiments based on visualization and differential pressure measurements have been carried out. By expressing $\overline{\mathrm{Fr}}_\mathrm{H}$ as $\overline{\mathrm{Fr}}_\mathrm{H} = Q_0^2/(\Delta T_{1/2}/T_\mathrm{ext})gH(C_SA_S)^2$ the experiments show that the natural regime is observed for $\overline{\mathrm{Fr}}_\mathrm{H} < 2$ while the blocked regime appears when $\overline{\mathrm{Fr}}_\mathrm{H} > 2.6$. It also exists an intermediate regime for $2 > \overline{\mathrm{Fr}}_\mathrm{H} > 2.6$. The latter regime where inflow and outflow are both present through the lower opening is due to the non negligible size of this opening not taken into account in the analysis.

Work in progress is carried out to determine temperature within the enclosure in order to study the stratification or the mixing of the space when $\overline{\mathrm{Fr}}_\mathrm{H}$ evolves.

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