Flows produced by a forced plume in a ventilated enclosure

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Abstract. The purpose of this communication is to present new results concerning velocity fields within the enclosure and close to the openings of a ventilated room with a buoyant turbulent 2D plume originating at its bottom. The enclosure is ventilated through lower and upper openings located on the two opposed vertical walls and separated by a vertical distance H. Depending on the enclosure geometry and forced plume characteristics, this situation can drive different kinds of flow regimes (blocked, intermediate and displacement) through the lower and upper openings. Three flow regimes are successively studied by adjusting a new densitometric Froude number $\overline{Fr_H}*\text{ related to the source flow rate, the densities inside and outside the enclosure and the area of the upper opening. When } \overline{Fr_H} * < 2, \text{ buoyancy forces are larger than inertial forces and the displacement regime is then observed. In cases where inertial forces are larger than buoyancy forces then } \overline{Fr_H} * > 2 \text{ and the intermediate or blocked regimes are involved and forced convection dominates. Results of velocity fields measured by 2D PIV in the mid plane of the enclosure are presented for the three regimes. By using velocity and temperature measurements performed at the nozzle and at the lower and upper openings in seven x-y planes located at } z/l = 0, \pm 1/8, \pm 1/4, \pm 3/8, \text{ balance of mass flow rate is verified and heat loss by conduction through the walls is evaluated for the three studied regimes.}

1. Introduction

The mixed convection produced by a buoyant and inertial source within a semi confined region has received a great deal of attention due to its importance in a large number of engineering applications. For instance, this situation is of great interest in ventilation of buildings, cooling of electronic devices or dynamics of flows in fire situation. Initially this problem has been studied by considering a small source of buoyancy $B_0$ at low level in a space where two openings located at the floor and the ceiling of the room connect the interior and the exterior of the enclosure [1], [2], [3]. In this case a single regime of flow was observed, characterized by inflow through the lower opening and outflow through the upper opening. In a similar geometric configuration, when a non-zero mass flux $Q_0$ is associated to the effect of this source of buoyancy $B_0$, this leads to various regimes of ventilation. Woods et al. [4], Paranthoën and Gonzalez [5] have shown that two main regimes were 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. Woods et al. [4] observed that naturally ventilated two-layer stratification was established for small mass fluxes and a blocked regime occurred for large mass fluxes. By using a simple model and density measurements they
showed that the limit between the two regimes was obtained when \( Q_0 = 2 B_0 H C_A S \). Paranthoën and Gonzalez [5] using a similar model based on Boussinesq approximation mentioned that the transition between flow regimes occurred when the densitometric Froude number \( F_{Fr} = \frac{Q_0^2}{(\Delta \rho \mu_\eta / \rho_{ext}) g H (C_A A_s)^2} \) was about two. By means of visualizations and differential pressure measurements, they showed that due to the non-negligible size of the lower opening an intermediate regime also exists between these two main regimes. In this situation, inflow and outflow were both present at the lower opening. However, up to now detailed information only concerns the manner in which the flows regimes may be established but detailed velocity or density fields within the enclosure and at the openings is not yet available. In this paper, we develop a simple analytical model without using Boussinesq approximation and we carry out experimental analysis to understand and describe the velocity fields within a ventilated enclosure resulting from a buoyant forced plume located at the bottom. The analytical analysis is presented in section 2. The experimental set-up is described in section 3. Velocity measurements are presented and discussed in section 4.

2. The analytical model

As shown in Figure 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 \( D_s \) ) located on the floor of the room. This flow has an initial velocity \( V_0 \) and is at a temperature \( \Delta T_0 \) above the external temperature \( T_{ext} \). 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 conditions of Woods et al. [4] where the buoyancy forces act downwards.

![Figure 1. Schematic diagram of the ventilated enclosure (displacement regime)](image)

2.1 Displacement regime

In this analytical approach, the upper and the lower openings are assumed of small vertical extent \( H_S \) and \( H_E \), separated by a distance \( H \) (\( H \gg H_S \) and \( H_E \)). 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 \( A_s \). Unlike the analysis developed by Paranthoën and Gonzalez [5] with Boussinesq assumption the density variations are not assumed to be small. We use the aerostatic pressure distribution instead of the full vertical momentum
equation. This remains valid as long as the vertical velocity component in the room is negligible 
\( \frac{u \partial \nu}{\partial x} + v \partial \nu/\partial y < g \Delta \rho/\rho \), Jones and Marshall [6].

Then two equations can be derived by relating the air velocities \( U_E \) and \( U_S \) to the pressure differences between inside and outside at the upper and lower openings by using Bernoulli equation.

\[
P_{in}(H) - P_{ext}(H) = \frac{1}{2} \rho_{in}(H) U_S^2 \quad \text{and} \quad P_{ext}(0) - P_{in}(0) = \frac{1}{2} \rho_{ext} U_E^2
\]  

(1)

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

\[
P_{in}(H) - P_{in}(0) = -\int_0^H g \rho_{in}(y) dy = -\overline{\rho_{in} g H} \quad \text{and} \quad P_{ext}(0) - P_{ext}(H) = \rho_{ext} g H
\]  

(2)

As the value of \( \rho_{in}(y) \) is not constant within the room, we define its spatial mean \( \overline{\rho_{in} g H} \) as:

\[
\overline{\rho_{in} g H} = (1/H) \int_0^H \rho_{in}(y) dy
\]  

(3)

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

\[
\left( \frac{\rho_{in}(H)}{\rho_{ext}} \right) U_S^2 + U_E^2 = 2 \left( \frac{\rho_{ext}}{\overline{\rho_{in} g H}} \right) g H / \rho_{ext}
\]  

(4)

Equation (4) allows to link the mass fluxes through, respectively, the lower opening \( Q_{mE} \) and the upper opening \( Q_{mS} \) by using \( Q_{mE} = \rho_{ext} C_E A_E U_E \) and \( Q_{mS} = \rho_{in}(H) C_S A_S U_S \) where \( C_E \) and \( C_S \) are the discharge coefficients for the openings E and S.

\[
(Q_{mS}/Q_{mE})^2 + (C_S A_S/C_E A_E)^2 (Q_{mE}/Q_{m0})^2 = (2\overline{\rho_{in} g H} / \rho_{ext}) g H (C_S A_S)^2 / Q_{m0}^2
\]  

(5)

For this displacement regime mass conservation leads to:

\[
Q_{mS} = Q_{m0} + Q_{mE}
\]

By defining \( q_{mE}^* = Q_{mE}/Q_{m0} \), equation (5) results in an equation for the normalized volume flux through the lower opening:

\[
(1 + \alpha^2 \beta / \gamma) q_{mE}^* + 2 q_{mE} + (1 - 2 \beta \gamma / \overline{F_{rH}}) = 0
\]  

(6)

where

\[\alpha = C_S A_S/C_E A_E \quad \beta = \rho_{in}(H)/\rho_0 \quad \gamma = \rho_{ext}/\rho_0 \quad \overline{F_{rH}} = Q_0^2 \left( \frac{\Delta \rho_{in}/\rho_{ext}}{\rho_{ext}} \right) g H (C_S A_S)^2 \]

By solving equation (6), it appears that the displacement regime only exists when this new densitometric Froude number:

\[
\overline{F_{rH}} = q_0^2 \left( \frac{\Delta \rho_{in}/\rho_{ext}}{\rho_{ext}} \right) g H (C_S A_S)^2 \left( \frac{\rho_0}{\rho_{ext}} \right) (\rho_0 / \rho_{out}(H)) \leq 2.
\]  

(7)
Unlike the densitometric Froude number $Fr_H^*$ defined by Paranthoën and Gonzalez [5] $Fr_H^*$ depends on the density of source gases.

In this case, solutions are:

$$q_{mE}^* = \frac{-1 + \sqrt{1 - (1 + \alpha^2 \beta / \gamma)(1 - 2/Fr_{H}^*)}}{1 + \alpha^2 \beta / \gamma}$$
and

$$q_{mS}^* = \frac{\alpha^2 \beta / \gamma + \sqrt{1 + (1 + \alpha^2 \beta / \gamma)(1 - 2/Fr_{H}^*)}}{1 - \alpha^2 \beta / \gamma}$$

(8)

2.2 Blocked regime

The same analysis is undertaken for the blocked regime and leads to the following equation for the normalized mass flux through the lower opening

$$(1 - \alpha^2 \beta / \delta)q_{mE}^* - 2q_{mE}^* + (1 - 2\beta \gamma / Fr_H^*) = 0$$

(9)

By solving (8), it appears that the blocked regime is only present for $Fr_{H}^*/Fr_H^* > 2$. In this case, solutions are:

For $\alpha \neq \sqrt{\delta / \beta}$

$$q_{mE}^* = \frac{1 - \sqrt{1 - (1 - \alpha^2 \beta / \delta)(1 - 2/Fr_{H}^*)}}{1 - \alpha^2 \beta / \delta}$$
and

$$q_{mS}^* = \frac{-\alpha^2 \beta / \delta + \sqrt{1 - (1 - \alpha^2 \beta / \delta)(1 - 2/Fr_{H}^*)}}{1 - \alpha^2 \beta / \delta}$$

(10)

For $\alpha = \sqrt{\delta / \beta}$

$$q_{mE}^* = \frac{1}{2} \left( 1 - 2/Fr_{H}^* \right)$$
and

$$q_{mS}^* = \frac{1}{2} + 1/Fr_{H}^*$$

(11)

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 $Fr_{H}^*$, the more valid this analysis.

3. Experimental set up

The experiments are carried out in a box with inner length $L$, width $l$ and height $H$ dimensions such $L \times l \times H = 500 \times 225 \times 180$ mm$^3$. This box is ventilated through lower opening E of height $h_E = 30$ mm and width $l_E = 225$ mm and upper opening S of same width $l_S = l_E$ and height $H_S = 27.5$ 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 visualisation. The thermal forced plume is injected in the enclosure through a rectangular nozzle ($D_0 = 30$ mm and $l_0 = 225$ 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 source flow rate $Q_0$ is controlled by a flow meter Alicat. The power of the heater is controlled by type T thermocouples linked to a data acquisition GL1.

Three cases were studied corresponding to the various regimes:

- Displacement regime: $Q_{m0} = 100$ Nl/min, $\Delta T_0 = 68$ K, $H_S = 27.5$ mm ($Fr_{H}^* = 1.5$)
- Intermediate regime: $Q_{m0} = 135$ Nl/min, $\Delta T_0 = 51$ K, $H_S = 27.5$ mm ($Fr_{H}^* = 2.3$)
- Blocked regime: \( Q_{m0} = 250 \text{Nl/min}, \ \Delta T_0 = 31 \text{K}, \ H_S = 27.5 \text{mm} \) (\( FrH^* = 6.5 \))

Values of \( FrH^* \) were calculated from values of \( Q_0, H_S, (\Delta \rho / \rho_{ext}), (\rho_0 / \rho_{ext}), (\rho_0 / \rho_m(H)) \) with \( C_S = 0.7 \). Initial Reynolds numbers of the forced plume were between 1050 and 2000.

Visualisations and PIV measurements have been performed by seeding the forced thermal plume with oil droplets. Artificial smoke created by a fog machine was also used for the ambient in PIV measurements. The flow field was illuminated by double pulsed Nd: Yag laser system producing a vertical thin light sheet. Two cameras configurations were successively used. In the first configuration devoted to the measurement of the U, V velocity field within the enclosure, three CCD digital cameras (1280x1024 pixels) were mounted on a traversing system with an angle of 0° and ±16° to the normal position of the light sheet. In the second configuration devoted to the measurement of the U, V velocity field at the nozzle and at the lower and upper openings, the same three CCD digital cameras (1280x1024 pixels) were mounted on a traversing system with an angle of 0° to the normal position of the light sheet. In the two configurations, images of a 2D calibration target were recorded in order to reconstruct the U, V velocity components. For each experimental case, 200 PIV image sets were acquired. The images were processed by using refinements steps from an initial resolution of 64x64 pixels to a final resolution of 32x32 pixels per interrogation area and an overlap of 50% was used between interrogation areas. Figure 1 shows the space and velocity coordinates to be used in the presentation of experimental results.

4. Experimental results
4.1 Large scale structure

The global structure of the flow is visualized in Figures 2, 3 and 4 for the blocked, intermediate and displacement regimes. These results show the time averaged normalized module of velocity \( \sqrt{(U/U_0)^2 + (V/V_0)^2} \) and velocity streamlines at the vertical X-Y mid-plane.

![Figure 2. Mean velocity field in the enclosure (blocked regime)](image)

The velocity field corresponding to the blocked regime is presented in Figure 2. This field has a quasi-two-dimensional structure characterized by a vertical impinging forced plume, two horizontal ceiling jets and two vertical wall jets. Two large recirculation zones are also observed between the forced plume and the vertical walls. Small recirculation zones are noted at the corner and at the basis of the forced plume.
For the displacement regime, the same kind of airflow is observed in the upper part of the enclosure while some changes occur everywhere else as shown in Figure 4. The incoming air interacts with the impinging forced plume which is now more inclined. In the right part of the enclosure, the recirculation zone is reduced and now located closer the ceiling. In the left part of the enclosure the left one is suppressed and 3D effects appear. For the intermediate regime, as shown in Figure 5, the mean velocity field is very similar to that observed in the displacement regime.

4.2 Flows at the nozzle, upper and lower openings
Information concerning the flows at the nozzle and at upper and lower vents is presented for the three regimes in Figures 5, 6 and 7.
In the blocked regime, Figure 5, inner fluid moves out to outside through both upper and lower openings. For the intermediate regime, Figure 6, both inner air moves out to outside and air from outside enters the enclosure through the lower opening.

In the displacement regime, Figure 7, inner fluid moves out to outside through the upper opening while outer fluid moves in through the lower opening. In this case, the normalized values of the horizontal velocity component \( \frac{U}{V} \) at the upper vent show higher values in relation with mass conservation. Effect of buoyancy is also more apparent in this regime where the outside plume shows a more important vertical deflection.

### 4.3 Comparison with the analytical model

Information on both mass fluxes \( Q_{m0}, Q_{mS}, Q_{mE} \) and convective heat fluxes \( P_0, P_E, P_S \) at the nozzle and the upper and lower openings, were determined from velocity and temperature measurements. This allows checking the accuracy of the measurements and testing the validity of the analytical model. In order to take into account 3D effects, measurements were carried out in seven vertical X-Y planes located at \( z/l = 0, \pm 1/8, \pm 1/4 \) and \( \pm 3/8 \).

Values of \( q_{mE}^* = \frac{Q_{mE}}{Q_{m0}} \) for the displacement (\( Fr_H^* = 1.5 \)) and the blocked (\( Fr_H^* = 6.5 \)) regimes were 0.14 and 0.33 in comparison with values of 0.16 and 0.36 given by the model while experimental values of \( q_{mS}^* = \frac{Q_{mS}}{Q_{m0}} \) were respectively 1.19 and 0.65 instead of 1.16 and 0.64 given by the model. Values given by the model are also in agreement with measurements for the blocked regime where hypothesis of the model are less valid.

Furthermore balance of convective heat fluxes between inflow and outflow shows that about 30% heat is lost by conduction through the walls of the enclosure for the three studied regimes.
5. Conclusion
In this work, we have analysed and measured the flow produced by a source of hot gases within an enclosure ventilated through lower and upper openings. A simple analysis shows that flow regimes between the interior and the exterior of the enclosure are governed by a densitometric Froude number \( \tilde{Fr}_H^* = \frac{Q_0^2}{(\Delta \rho_H / \rho_{ca}) g (C_S A_S)^2 (\rho_0 / \rho_{ca})(\rho_0 / \rho_{wall} H)} \) mainly related to the source flow rate, the densities inside and outside the enclosure and the area of the upper opening. Depending on the value of \( \tilde{Fr}_H^* \) this situation can drive three different kinds of flows: blocked, intermediate (\( \tilde{Fr}_H^* > 2 \)) and displacement (\( \tilde{Fr}_H^* < 2 \)), through the lower and upper openings. New results concerning velocity fields within the enclosure and close to the openings have been presented. For the blocked regime, measurements show that the airflow in the enclosure is nearly 2D characterized by an impacting forced plume, wall jets and two large vortices. For the displacement regime, the same kind of airflow is observed in the upper part of the enclosure while some changes occur everywhere else due to the incoming of exterior flow and 3D effects.

By using velocity and temperature measurements performed at the nozzle and at the lower and upper openings, balance of mass flow rate has been verified and heat loss by conduction with the walls was about 30% of the injected power for the three studied regimes.

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