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Thermal characterization of downward ventilation flows through a smoke layer

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Abstract. Understanding the behaviour of downward flows of fresh air in temperature-stratified compartments is crucial for improving oxygenation of fire in confined compartment. This study investigates the axial temperature profiles of such flows and their sensitivity to injection rates. Experimental tests in a stratified compartment reveal a naturally bounded flow that transitions between a plume and a collapsing fountain, with the ability to transport heat and to affect the thermal stratification. However, different injection rates reveal potential distinct flow configurations. Low rates limit heat transfer potential to upper locations, while high rates lead to colder air reaching the lower part of the compartment. These findings highlight the significance of injection conditions in predicting the fire source environment. Improving such predictions is critical for ensuring accurate prediction of oxygen concentration in the near field of a fire.

1 Introduction

Fire safety assessment remains a major concern for nuclear and industrial installations. Among the configurations considered, that of a confined fire with maintained ventilation generally leads to a vertical thermal stratification, which can influence the combustion process. It creates a significant coupling between the fire source, the compartment, and the ventilation [1], [2]. This complex interaction presents a challenge for the simulation of such scenarios using CFD or zone-based simulations [3], [4]. Ventilation, by removing smoke from the room and supplying in fresh air, contributes to the vertical distribution of smoke [5] and influences the oxygen concentration in the near field of the fire [6]. The effect of the ventilation on the fire induced flow in the compartment depends on both fire scenario and ventilation design [7]-[10]. A complex configuration is the one involving a vertical inlet immersed in hot smoke. The turbulent flow of fresh air, heavier than the smoke layer, would form a downward plume entraining hot smoke. Depending on the thermal vertical stratification induced by the fire, the downward plume may be stopped before reaching the bottom of the compartment and therefore the near field of the fire. Oxygen supplied is then diluted in the smoke and eventually extracted by the ventilation system, without



being able to feed the fire. This flow is complex to model and can lead to significant errors in the prediction of oxygen concentration around the fire.

The flow of vertical plume in a stratified environment has been already discussed in the past. The analogue case of rising plumes in stratified ambient fluid has been studied theoretically by Caulfield and Woods [11], who established that the flow total length can be limited or not, depending on stratification decay speed. The case of two-layer stratified environment is addressed theoretically and numerically by Vaux et al. [12], who determine a trapped/escaped criterion for plume depending on injection and stratification parameters. Intermediate stratification configurations allow four different scenarios to be identified: (1) The downward plume is trapped in the smoke layer (2) the downward plume escapes the smoke layer but is naturally bounded inside the compartment and spread horizontally at a specific level as a fountain, (3) the downward plume escapes the smoke layer and is virtually bounded but reaches the floor, and the last one (4) the downward plume escapes the smoke layer and reaches the floor without being bounded. Each scenario has a distinct effect on fire oxygenation. Some of these theoretical configurations have been recently investigated experimentally by Tsuji et al. [13]. They have carried out reduced-scale experiments aimed at measuring the temperature and velocity fields of a descending plume and evaluating smoke entrainment in the lower part of the room. Their tests parameters allowed them to experience trapped plumes, spreading plumes and floor impacting plumes. To date, this experimental work is the only one to focus on this phenomenon in fire conditions, whose effects are not incorporated into zone-based simulation codes. The present study aims to investigate experimentally and at laboratory scale the effect of downward vertical flow of fresh air through a constant thermal gradient stratification which is typical of a fire in a ventilated compartment. The aim of this work is to provide a better understanding of these vertical flows to correctly characterize the way inlet ventilation line feeds oxygen to the fire and consequently to improve the performance of simulation tools for under-ventilated compartment fire. The first part describes the experimental setup, the vertical thermal stratification set and the test protocol. The second part focuses on the results, describing the temperature profiles and the effect of the injection rate on the characteristic positions of the temperature difference profiles.

2 Materials and methods

2.1 Experimental setup

The experiments are carried out in the IRSN STYX facility, a reduced scale compartment consisting of one room of 1.6 m³ (1.6 m x 1 m x 1 m) made of a metal frame, insulating panel and glass window (Figure 1). The compartment is mechanically ventilated by two intake and exhaust circuits that permit to stabilize a vertical thermal stratification. The admission vents are in the lower left part of the compartment, while the extraction vent is in the upper right part. In the present study, the intake circuit is kept closed while the exhaust circuit is left open to limit the pressure rise during the test. A distinct air injection system is set to generate the downward vertical flow of fresh air without affecting the thermal stratification. It is located at ceiling level, in the middle of the 1-m depth and at 2/3 of the length the compartment. The heat source that generates the thermal stratification is a 2-kW, 20 cm wide, flat spiral electrical resistor located near the top left edge of the box, centred in depth.

Thermocouple masts (type K 1.5 mm) are positioned along the axis of the air injection outlet to assess thermal stratification as the temperature rises and to measure the temperature profile of the flow during fresh air injection sequences. One thermocouple is located every 0.05 m between 0.25 m and 0.95 m. The injected air flow is controlled by a flow meter. Finally, a differential pressure transducer is used to ensure equilibrium between the inside of the compartment and the laboratory atmosphere.

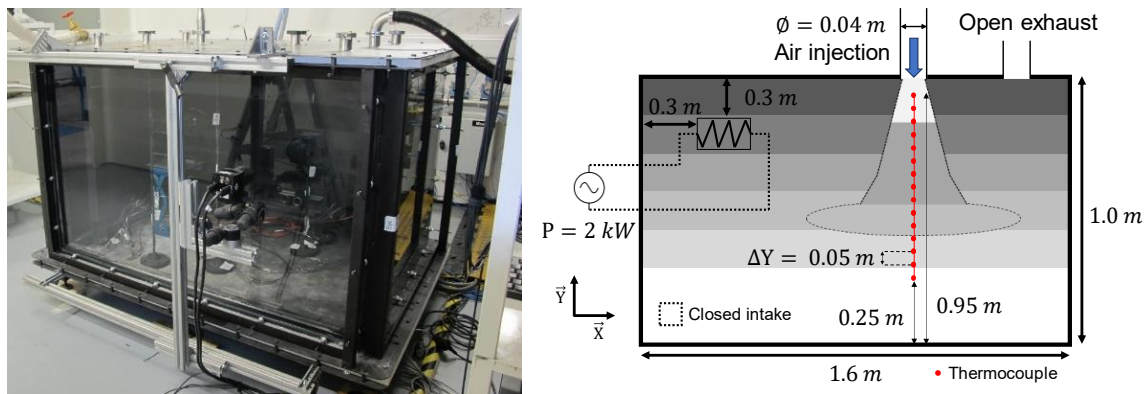


Figure 1: Picture and schematic of the experimental set-up (IRSN STYX facility).

2.2 Flow configuration

The study focuses on the scenario of a vertical downward flow of air at ambient temperature in a stratified gas layer. The outputs of interest are the temperature profiles in the axis of a vent during downward vertical injection sequences of fresh air into the stratified gas layer.

The vertical stratification is generated by the electrical resistor which operates throughout the test. The vertical downward flow is activated when the temperatures rises are less than $0.2\text{ }^{\circ}\text{C}/\text{min}$ and when the temperature of the highest thermocouple is $95\text{ }^{\circ}\text{C}$, i.e. after about 5000 s (Figure 2 - left). These conditions establish a common starting reference for all injection sequences. After about 500 s the vertical temperature profile within the air jet is stabilized and maintained to acquire the maximum data over the period. The air jet is then stopped, and the vertical stratification is recovered (Figure 2 - left). The injection of air can be repeated several times with various injection flow rates under the same stratification conditions. The stratification just before air injection is linear over the height of the chamber with a constant gradient of temperature, except near the ceiling where the temperature increases more rapidly with height (Figure 2 - right). This vertical stratification is typical of a fire scenario in a mechanically ventilated compartment [5] [6].

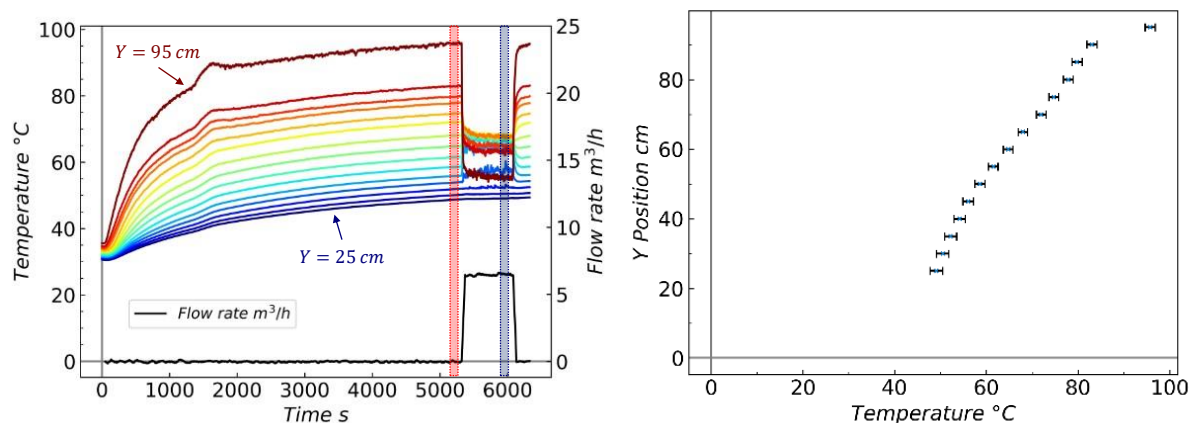


Figure 2: Left – Temperatures along the jet axis (vertical positions from 0.25 m to 0.95 m with increment of 0.05 m) and injection's air flow versus time during temperature rise phase follow by and injection. Representative recording period for flow temperature (blue dots) and stratification reference (red dots) profiles. Right – Mean temperature and standard deviation of stratification reference profiles acquired prior to the injection sequences.

Several volumetric air flow rates, q_v , are considered between 1.5 m³/h and 10 m³/h through an orifice diameter D of 0.04 m. This corresponds to an injection Froude number range between 0.53 and 3.53 with $Fr = u / (gD)^{1/2} = 4 / \pi \cdot q_v / (g^{1/2} D^{5/2})$ and a Reynolds number range between 860 and 5700 ($Re = uD / \nu$) and a maximum air renewal rate $Tr = q_v / V$ of 6.25 h⁻¹.

3 Results

3.1 Thermal characterization of the downward air flow

A total of 35 injection sequences with various flow rates were performed over seven tests showing similar and reproducible results. Figure 3 - left shows a representative example of the mean axial temperature profiles of the flow over minutes-long period during an injection phase (in blue), as well as the stratification reference temperature profile obtained before injection and representative of the overall stratification of the compartment (in red). The profile of the difference between the downward flow and stratification temperatures is also presented in black.

Close to the injection inlet, the temperature in the flow is lower than that in the compartment because the 17°C air is injected into the upper part of the compartment. As a result, the temperature of the downward flow increases under the effect of entrainment, which stirs in the surrounding hot air, until the flow temperature reaches a position of local equilibrium with its surroundings. This part of the flow, where the temperature along the flow axis is lower than compartment stratification so that buoyancy forces align with the initial velocity of the flow, is akin to a plume structure.

Below the transition point Y_{Tr} , the flow entrains the ambient colder air. Therefore, the temperature gradually decreases as the distance from the injection vent increase until a new equilibrium point is reached. This point Y_{Low} is the lowest position reached by the flow, as the temperature difference between the axis of the flow and the reference remains zero below it. This second phase, in which the buoyancy forces oppose the inertia of the flow, corresponds to the structure of a fountain collapsing before reaching the bottom of the compartment, as observed in Figure 3 - right, which also shows a typical radial spreading of the flow. As a result, the temperature difference profile that is negative above the transition point, presents a bounded positive region between Y_{Tr} and Y_{Low} , with a maximum at $Y = Y_p$. Its existence indicates heat is transported by the flow from the upper part of the compartment to a lower level. In such conditions, the air injection fails to provide fresh air to its lowest part of the compartment and participates in the thermal destratification.

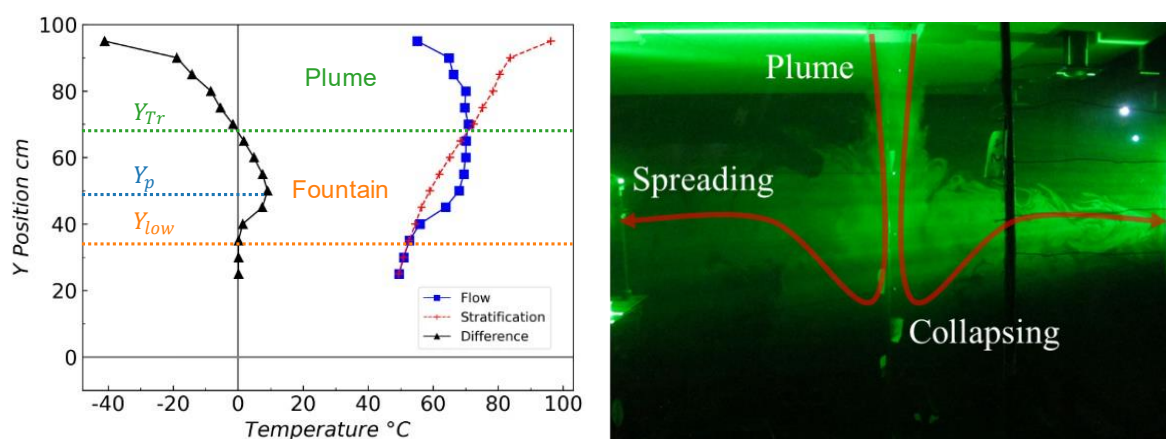


Figure 3: Left – Flow temperature (blue squares), stratification reference (red crosses) and flow-stratification difference (black triangles) profiles for 5 m³/h injection flow rate. Right – Visualization through laser and seeding of downward plume followed by a collapsing and spreading structure.

3.2 Effects of injection flow rate

Examples of flow-stratification difference profiles for various injection Froude numbers are shown in Figure 4 - left and the evolution of the plume transition Y_{tr} , peak temperature difference Y_p , lowest Y_{low} relative positions to compartment height H versus injection Froude in Figure 4 - right. Overall, all three locations (plume transition, peak temperature difference and lowest positions) decrease with Froude and without any reaching the floor which seemingly could not happen for the Froude maximal order of magnitude tested. However, the distance between the transition position and lowest position compared to the distance between the injection position and transition position shows that, over the Froude range tested, the length of the fountain part of the flow is of the same order of magnitude as the plume part. Which locates all tests in the configuration of a downward plume spreading at a specific level as described in introduction. Nevertheless, for injection Froude numbers less than 1, the fountain/plume length ratio is dropping thus indicating a reduced destratification capacity since the heat carried by the flow has a limited range. This configuration comes close to the trapped plume scenario, where injected fresh air is diluted in the smoke layer and no additional oxygen is supplied to the fire source [14] [15]. Different behaviours are observed regarding the effect of injection Froude on temperature difference amplitudes, depending on the region. In the upper region, where the flow is colder than the compartment, a higher injection Froude increases the negative temperature differences. However, in the fountain part of the flow, the maximum temperature difference decreases steadily for Froude greater than 3. Therefore, flows with a higher injection rate reach a lower part of the compartment with temperature differences closer to zero. This results in limited potential for destratification compared to mid-range injection flow rates and approaches the conditions of an unbounded flow, where the temperature remains lower than the stratification, supplying oxygen to the fire environment.

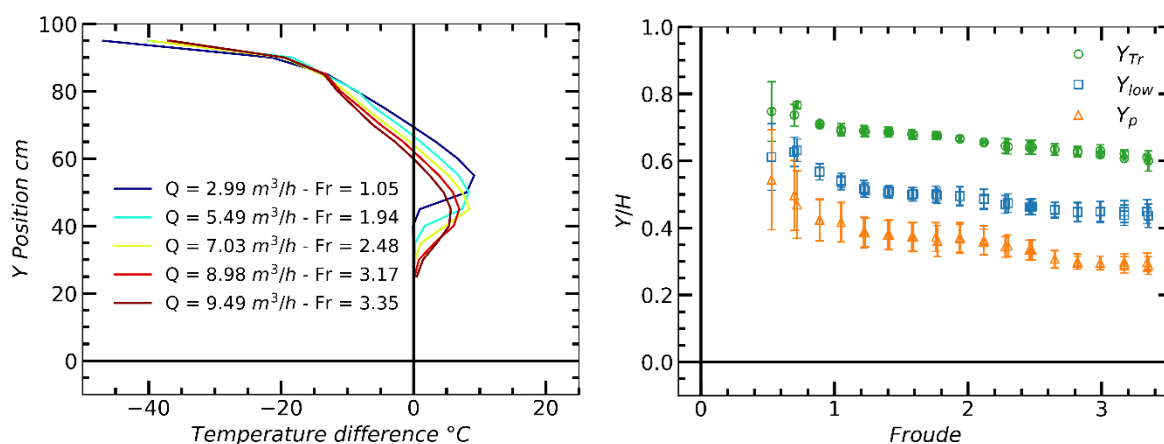


Figure 4: Left – Flow-stratification difference profiles ($\pm 1.1^\circ\text{C}$) for various injection Froude. Right – Plume transition Y_{tr} , peak temperature difference Y_p , lowest reached Y_{Low} relative position to compartment height $H=1\text{m}$ versus injection Froude.

4 Conclusion

The visualisation and measurement of the axial temperature profile of a downward flow of fresh air in a temperature-stratified compartment indicate the presence of a naturally bounded flow that collapses and spreads before reaching the bottom of the compartment. The flow is defined as a sequence of a plume and a collapsing fountain, separated by a transition point. Below this point, the temperature difference between the flow and the stratification is positive until it reaches zero. In this configuration, the prominence of the positive area of the temperature difference profile indicates the flow's ability to transport heat from the upper layers to the lower layers, thereby destratifying the compartment instead of supplying fresh air to the lower part of the compartment. The study also shows the effects of the injection rate on the flow profiles. Low injection Froude results in shorter flow lengths, particularly in

the fountain part. The heat transfer is then confined to the upper part of the compartment where the fresh air is diluted. On the other hand, higher injection Froude results in a longer and colder flow, which reduces the potential for destratification compared to mid-range injection Froude. The results demonstrate the impact of injection conditions on the flow pattern and the resulting oxygen supply to the fire's immediate vicinity, which is a crucial information for understanding under-ventilated fires.

5 Acknowledgment

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