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Abstract

Indoor flow behaviour can strongly impact safety in the case of a fire event. Indeed, when air inlet and outlet are correctly placed, stratification allows a fresh air layer to be maintained in the room that can be favourable for the egress. However, in the case of a naturally ventilated building, the presence of the wind will interact with the indoor flow pattern. Hence, fire smoke extraction in naturally ventilated buildings can strongly be influenced by the wind. Indeed, when wind opposed buoyancy, a change in the ratio between buoyancy forces and wind forces can impact the internal flow pattern resulting in a mixed ventilation mode, which is unfavourable for egress, in the case of a fire event. Flow pattern inside a room and their transitions are then a safety purpose.

In this paper, natural ventilation of a singular room with two asymmetrical and opposed openings was studied experimentally when wind opposes buoyancy. The buoyant source was generated by an injection of an air/he mix. Varying wind and injection conditions, the ventilation regimes change as well as the indoor flow dynamic. Three ventilation regimes are experimentally observed depending on the balance between J and Fr :buoyancy-driven, bi-directional and wind-driven. From dimensional analysis, we shown that the ventilation regimes can be described via the Froude number, based on the injection flow rate Fr, and the momentum flux ratio J. in the literature, transitions between these regimes is still difficult to estimate as far as it depends on the assumption made on the initial indoor flow pattern (layered or fully mixed). Hence, an experimental investigation on the transition from each extreme regime (buoyancy-driven or wind-driven) to the bi-directional one, has been conducted. The transitions are found to follow a power low in the form $Fr \propto J^{3/4}$.

A discussion on the inner flow pattern for this bi-directional regime is also proposed and a focus on how the knowledge of the behaviour of the inflowing flow contributes to improve the modelling is made.

Keywords: Natural ventilation, Wind opposing buoyancy, Regime transitions, Flow behaviour

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1. Introduction

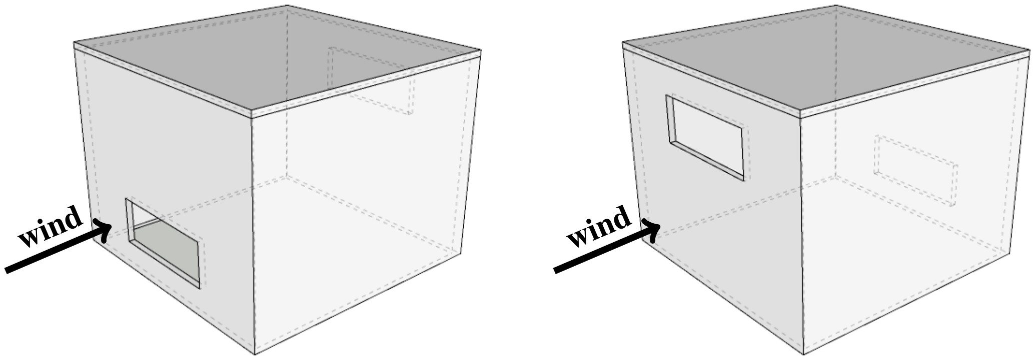
The two main forces that drives internal air movement in buildings, wind forces and buoyancy, can have a significant impact on air quality [9], thermal comfort [6] and even on safety in terms of smoke movement [18] in the case of a building fire. In both wind-driven or buoyancy-driven flow, openings position inside a space has a significant impact on the internal flow.

When buoyancy acts alone, displacement ventilation appears when a heat source is placed in an enclosure and develops a buoyant plume in the room. This latter impinges the ceiling and a hot layer grows following the mechanism of filling box described by Baines & Turner [1]. When this room is connected to the outdoor ambient through openings (doors, windows, horizontal vents...), fresh air inflows through the lower openings while buoyant fluid outflows through the upper openings. If a clear interface separates the fresh air in a lower layer and the buoyant fluid in an upper layer, this buoyancy driven flow is called displacement ventilation. This simultaneous filling and emptying mechanism has been studied and modeled by Linden *et al.* [2], especially at steady state for which the hot gas flux brought to the upper layer is balanced by the buoyant flux emptied by natural convection. In contrast, mixed ventilation appears if no interface exist and inflowing air is instantaneously mixed with the buoyant fluid (or heated), a well stirred reactor approach is considered and the situation leads to the so called mixed ventilation [14].

Moreover, with no wind, Fitzgerald & Woods [10] highlighted that openings position (the difference in height in particular) not only affects the ventilation flow, but also the ventilation regime for initially displacement regime generated by a localised buoyancy source. In an extreme case, when the supplied buoyant flux cannot be balanced by the natural exhaust in upper part, buoyant fluid fill the box until it reaches the lower opening and then exhaust through it too. This situation treated by Woods *et al.* [11], Vauquelin *et al.* [12] is considered as a blocked regime.

Wind forces also implies air movement, inside a room by changing the pressure field around the building, while openings position induces different internal flow pattern when wind acting alone. Hence, Karava *et al.* [7] demonstrated, *via* Particle Image Velocimetry (PIV) measurements in a single-zone building, the complexity of the airflow pattern in the room as a function of openings position, which strongly impacts ventilation performance. In this context, inner streams could affect efficiency of the classical orifice equation. With similar apparatus, Tominaga & Blocken [8, 9] investigate both air change and decontamination performance. Injecting a passive non buoyant contaminant, they shown, by describing the inner path of the inflowing wind with openings on opposite sides, that openings location is crucial for both ventilation rate and decontamination. They also shown that if any geometry can satisfy both objectives with different performances, they can lead to the reverse result, in terms of decontamination or ventilation efficiency, when the wind acts in the opposite direction for the same geometric configuration with opposed top and bottom openings.

Nevertheless, in the most common situation of buildings natural ventilation, wind and buoyancy act simultaneously. A cross flow induced by the wind will hence affect the interior buoyancy driven flow [3, 23, 4]. Not only the



(a) (b)

Figure 1: Single-zone building with (a) bottom opening on the windward and top opening on the leeward, and (b) top opening on the windward and bottom opening on the leeward.

ratio between the thermal and wind forces but also the openings position choice are key parameters in order to chose satisfying ventilation strategy. Therefore, depending on the chosen ventilation strategy, the knowledge of indoor airflow patterns as well as the ability of such a flow pattern to be maintained faced with a change in wind or buoyancy conditions Craske & Hughes [13] are essential. For instance, for fire safety purpose, the existence of a stratified layer is required while for thermal comfort the flow pattern should be chosen in order to create a significant air velocity on the occupant. Hence, for safety purpose, the transitions between the mixed or stratified ambiance, and the physical parameters that involve the change between wind dominated or buoyancy dominated regimes, can be considered as crucial.

Consequently, depending on the wind and buoyancy intensities, duality between the building design and the building environment can leads to many natural ventilation regimes. The wind-driven mixed one (for which buoyancy is negligible compared with wind), buoyancy-driven stratified (for which wind is negligible compared with buoyancy) but also the buoyancy-driven mixed one.

A single room with opposed asymmetrical lower and upper openings seems to be the most adequate geometry in order to illustrate this duality, where wind can assists buoyancy, and the situation where wind opposes buoyancy. These two configurations are represented on figure 1 for a single-zone building with both opening on opposite windward and leeward facades. Wind assists buoyancy when an opening is located near the floor on the windward and one near the ceiling on the leeward (figure 1(a)), and wind opposes buoyancy when an opening is located near the ceiling on the windward and an other near the floor on the leeward (figure 1(b)).

When wind assisted buoyancy, Hunt & Linden [14, 15] shown that the net flow rate increases with the increasing wind (for a given initial buoyancy). Furthermore, for a wide range of wind velocity the displacement ventilation is maintained. This configuration can be considered favourable for hot smoke extraction for instance.

However, when wind opposes buoyancy, literature shows that indoor airflow behaviour can be whether homogeneous (mixed ventilation) or stratified (displacement ventilation) depending on wind and buoyancy intensities. Then, for a geometric configuration similar to figure 1(b), studies focused on these transition conditions by different ways.

Analytical theories for a well mixed single zone building are proposed by Li & Delsante [16], Lishman & Woods [17] or Chen *et al.* [18] with similar conclusions. They found buoyancy-driven and wind-driven as stable regimes, and a wind-driven unstable regime for which a small change in wind intensity quickly leads to on or the other stable regime.

In a different way, Hunt & Linden [19] proposed a theory supported by experimental investigations, where they differentiate a two layers stratified indoor ambiance (buoyancy-driven displacement ventilation) and a mixed one (wind-driven ventilation). They used an upside-down scaled model where buoyancy effects are reproduced by density difference between brine and clear water (nevertheless, for clarity, we will still discuss as if the manipulation was not reversed and the buoyant fluid on the ceiling). Opposite windward and leeward openings are horizontal series of small circular orifices. They tested the effects of the opposing wind velocity, of the openings surfaces and of the buoyancy flux on the mixed or stratified natural ventilation. Increasing the wind for a constant buoyancy flux, they observed that between the two classical regimes (displacement ventilation and wind driven ventilation), the windward inflowing wind dilutes the stratified layer. Therefore the buoyant fluid (which can no longer escape through the top windward opening) accumulates in the volume, increasing the buoyancy forces, which then compensates for the wind and allows again the buoyant fluid to outflows through the windward opening. This unstable wind-driven regime is similar to the remarks of [16, 17, 18], but they observed that its existence conditions differ according to the initial stratified or mixed indoor ambiance, highlighting hysteresis phenomena.

However, for both approaches, authors assume an uni-directional flow through openings. Which implies a negligible vertical density gradient through the openings validated experimentally in [19] by means of low height openings.

For larger openings, the vertical density gradient cannot be neglected, and the presence of a neutral axis, defined by the equilibrium between the indoor and outdoor pressure marks the boundary between an inflowing and outflowing streamlines. If the neutral axis is out of opening boundaries, the flow is uni-directionnal through the opening, while if the neutral axis is within these limits, the flow is bi-directionnal through the opening. Consequently, the so called unstable regime aforementioned may no longer exists.

This is the reason why, for fire preoccupations, Gao *et al.* [20], took into account the neutral axis. They focused on critical conditions in terms of wind velocity leading to the spread of flames through the leeward opening for for identical and symmetrical openings in a well mixed (post-flash over) indoor ambiance single zone building. They obtained an analytical solution and expressed the quantities from an imbalance of the reference situation without wind for which the neutral axis, as a function of the height of the opening, is obtained by a mass balance in the control volume. In the same context, Li *et al.* [21] extended this work for asymmetrical openings. In both experiments, the leeward facade is isolated from blowing, the injected mass from the fire is negligible, and the ambiance is considered as well mixed.

Then, it seems interesting to complete these works and to study the transition from a stratified to a mixed indoor ambiance accompanied by change in the uni- and bi-directional flows through the openings. In this study, we propose to extend the experimental investigations aforementioned ([7, 9, 19]) and analyse the internal flow pattern when wind opposes the natural buoyant emptying-filling process in a single-zone building with two asymmetrical large openings on windward and leeward facades. In particular, we focus on the transition between the displacement ventilation (buoyancy dominated) and the mixed ventilation (wind dominated), and especially the flow behaviour in the zone bounded by these two known ventilation regimes. We propose to explore large range of density difference highlighting differences between fire (or light fluid leakage) and thermal comfort. To do so we carried out a set of experiences in a wind tunnel on a single-zone building identical to that of [7, 9], varying wind velocity and source buoyancy flux.

This paper is organised as follows: we describe the experimental set-up and the protocol to observe the different flow behaviours in § 2. Experimental results are presented in § 3. Finally, conclusions are proposed in § 4.

2. Material and methods

A single-spaced enclosure of internal cross section 0.2 m × 0.2 m and height 0.16 m made in transparent 0.008 m width PMMA was positioned in the middle of a 0.5 m × 0.25 m flow section and 10 m length wind tunnel. The windward and leeward sides of the box included a rectangular hole 0.092 m × 0.036 m located near the ceiling and the floor respectively (see Figure 2). As mentioned by [14], even if the occupancy ratio of the tunnel section is important (29 % in the present study against 40 % in [14, 15, 19]), the pressure drop between the windward and leeward openings (induce by the velocity in the flow channel) governs the in-box flow and in this case, the flow around the box is not so important.

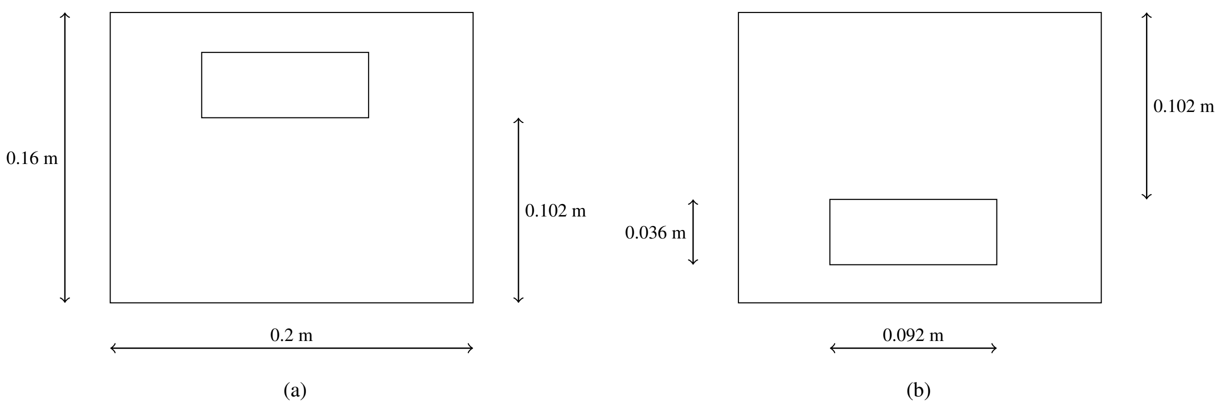


Figure 2: Interior dimensions of the (a) windward and (b) leeward sides of the experimental set-up.

The characteristic velocity of the flow in the channel was measured via a 0-5 m s^{-1} hot wire anemometer located in the middle of the flow section upstream from the box. Buoyancy source was generated by supplying in the box an air/helium mix through a circular 0.014 m diameter nozzle located in the middle of the box cross-section. The air and helium flow rates were controlled thanks two mass flowmeters 0-200 l min^{-1} (accuracy 2 % of full scale). The buoyant plume was seeded with passive ammonium salt particles obtained by a reaction between hydrochloric acid (HCl) and ammonia (NH_3). To observe the flow behaviours, a 2 W, 532 nm laser lighted the box through a cylindrical lens in order to generate a thin light sheet of high intensity. The in box flows were recorded at 30 fps during 2 min via a 12 Mpx CCD camera positioned in front of the box, and the RGB image matrix (in 8 bits) were analysed. This experimental configuration is presented on Figure 3.

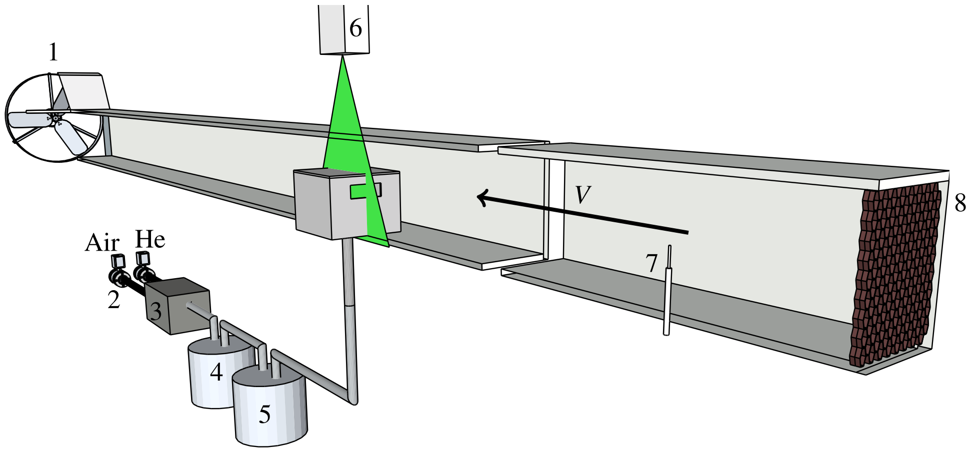


Figure 3: Sketch of the experimental set-up. 1 controlled fan, 2 flowmeters, 3 mixing chamber, 4 HCl, 5 NH_3, 6 laser source, 7 hot wire anemometer, 8 flow straightener.

The experimental varying parameters are the cross flow velocity V, flow rate q_i and the gas density ρ_i at the injection. These last two parameters are regulated by means of the air and helium flow rates (respectively q_{air} and q_{he}), and expressed as follows:

$$q_i = q_{air} + q_{he}, \tag{1}$$

$$\rho_i = \rho_{air} - \chi(\rho_{air} - \rho_{he}), \tag{2}$$

where $\chi = q_{he}/q_i$ is the volume fraction of helium in the gas mix, $\rho_{air} = 1.2\,\mathrm{kg\,m^{-3}}$ and $\rho_{he} = 0.18\,\mathrm{kg\,m^{-3}}$ are the densities of air and helium respectively.

In a first time, we investigated the influence of these quantities on the different indoor flow behaviours, and the sensibility of each flow pattern to be maintained varying these three parameters.

We then generated three different injection flow rates (q_i = 5, 13 and 30 l min^{-1}) for four gas densities (χ = 25, 50, 75 and 100 %, then ρ_i = [0.945, 0.69, 0.435, and 0.18] kg m^{-3}). Depending on the injection flow rate and gas density couples, we generated between five and ten wind velocities varying, increasing or decreasing, in the range $0.1 \leq V \leq 2.5\,\mathrm{m\,s^{-1}}$.

After identified the different in-box flow patterns depending on q_i, ρ_i and V, we explored more accurately the conditions needed to pass from the buoyancy-driven flow pattern to the wind-driven one, highlighting the transition range between these two stable regimes. We then generated eight injection flow rates (6, 8, 10, 12, 14, 16, 18 and 20 l min^{-1}) for the same four injected gas densities used in the first campaign. The transition conditions were found by progressively increasing the volume flow rate in the channel (with a waiting period about 3 min between each wind speed increase) until changing the characteristic permanent flow pattern.

3. Results

We first discuss on the in-box flow behaviour. As illustrating example, lets consider the different flow behaviours obtained for a given buoyancy source flux (given for q_i = 5 l min^{-1} and ρ_i = 0.69 kg m^{-3}) and an increasing wind shown on Figure 4.

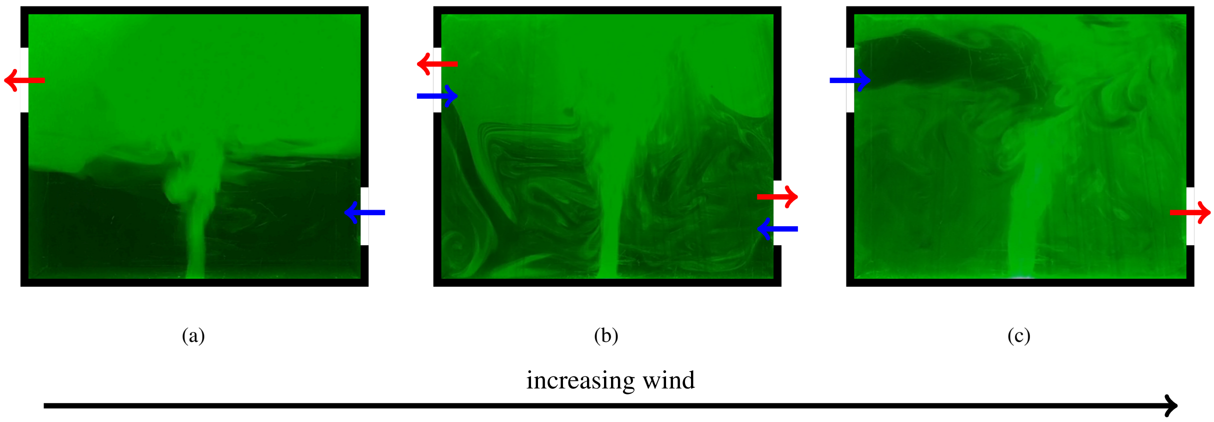


Figure 4: Example of indoor flow behaviour of a naturally ventilated single-zone building when wind opposes buoyancy for a given buoyancy source flux (q_i = 5 l min^{-1} and ρ_i = 0.69 kg m^{-3}) and an increasing wind. (a) V = 0.1 m s^{-1}: buoyancy-driven regime, (b) V = 0.28 m s^{-1}: bi-directional regime, (c) V = 0.37 m s^{-1}: wind-driven regime. The red and blue arrows represent the outflowing buoyant gas and the inflowing fresh air respectively.

As expected we found three ventilation regimes described as follows:

1. a stratified buoyancy-driven regime (corresponding to the displacement ventilation regime describe by [19]) where buoyancy drives the light fluid to leave the box from the upper windward opening, generating a pressure drop in the box balanced by an inflow of fresh air through the leeward orifice (see Figure 4(a)). In this case, depending on the involved forces, the induced incoming flow rate can disturb the plume growth and then generates a flapping plume mode, or a inclined plume mode for a high incoming flow rate.

2. A transition regime (Figure 4(b)), where a bi-directional flow appears in the two openings. The plume develops normally but the two layers stratification begins to be broken down. A continuous inflowing heavy fluid flow, drops along the wall from the windward opening to the floor. An increase in wind speed contribute to progressively straighten the inflowing jet and to increase its windward opening occupancy ratio until it occupies all the

opening. In the same time, a similar behaviour is observed through the leeward opening with the outflowing fluid. Thereafter this regime will be called bi-directional regime.

3. A 'wind-driven' for which a mixed homogeneous gas escapes through the leeward opening and fresh air inflows through the windward opening (Figure 4(c)). We then differentiate two cases:
   (a) the plume still develop but is constrained and disturbed by the inflowing jet from the windward opening. This regime is quite close to the one describe by [19] as the mixing ventilation regime.

   (b) An highly stirred regime for which the buoyant source effects are negligible and no plume develops. The fresh air inflowing through the windward orifice raises to the ceiling until it reaches the corner made by the ceiling and the leeward side. There, this flow falls against the wall. Along this streamline, the initially dense fluid is lighted by a mix with the injected gas. The injected buoyant gas is directly sucked by a large eddy which develops in the box (this flow behaviour was described by [9] (Figure 5) as the case where a passive non buoyant pollutant is extracted by wind).

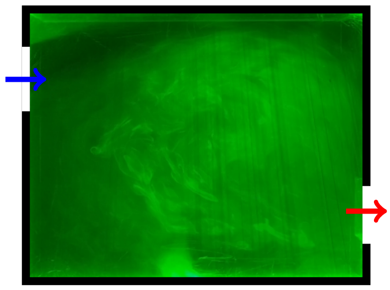


Figure 5: Indoor flow behaviour of a naturally ventilated single-zone building when the buoyancy effects are negligible against the opposed wind ($q_i = 5\,\mathrm{l\,min^{-1}}$, $\rho_i = 0.69\,\mathrm{kg\,m^{-3}}$, and $V = 2.3\,\mathrm{m\,s^{-1}}$).

These experiments shown that for high injection flow rate, the change in ventilation flow regime occurs in a reduce range of high wind velocities whatever the injected gas density, while for weaker injection flow rates and the heavier injected gas, a small variation in a reduce range of small wind velocity induces a quick change in the ventilation flow regime. One can notice that the particular blocked regime studied by [11, 12], for which the injected buoyancy source is so strong that the box is saturated, still exist when wind opposes buoyancy, but it has not been reached experimentally or taken into account in this study.

In order to get further and examine quantitatively the relationship between the buoyancy and the opposed wind in these ventilation flow regimes, we can find a number of relationships based on our study parameters. A dimensional analysis (not presented here) allows us to express the situation from only two parameters: the plume reduce Froude number which characterize the balance between buoyancy and inertia forces, and the the jet (plume) to cross-flow (wind) momentum flux ratio which express the ability of the plume to develop freely in the presence of a cross-flow. So lets introduce the reduce Froude number

$$Fr = \frac{q_i}{\sqrt{\eta_i g D^5}}, \quad (3)$$

where $\eta_i = (\rho_{air} - \rho_i)/\rho_i$ is the density deficit at the injection, g is the acceleration due to gravity and D is the injection nozzle diameter (we draw attention to the fact that $Fr \propto \sqrt{1/\Gamma_i}$, where Γ_i is the plume function, initially introduced by Morton [22]). The plume-to-wind momentum flux ratio is expressed in our case as follows:

$$J = \frac{\rho_i w_i^2}{\rho_{air} V^2}, \quad (4)$$

where $w_i = q_i/(\pi D^2/4)$ is the injected gas velocity....

Based on these two parameters, we plot all the experimented conditions on Figure 6 expressing the indoor flow regime as a function of J and Fr.

On this representation, each observed indoor flow pattern is associated with a different symbol. We observe in particular that the displacement and the mixed ventilation regimes can be expressed according to the intensity of J and Fr as follows:

- $J >> 1$ and $Fr << 1$, opposing wind effects are negligible and at the injection, buoyancy forces dominate inertia forces. This behaviour describes the buoyancy-driven regime studied by [19].
- $J << 1$ and $Fr >> 1$, the wind dominates the in-box movement. Buoyancy is negligible. That corresponds to wind-driven regime described by [9].

Although not obvious on figure 6, data seem to be gathered depending on the ventilation regime on this representation as a function of Fr and J. Furthermore, as mentioned previously, for given injection conditions (i.e. Fr = cste) all the four ventilation regimes are reached successively in the same order, by varying wind velocity (increasing or decreasing J). and it can be observed on Figure 6 that the transitions between all regimes appear to be nonlinear functions.

In order to complete this analysis, and quantify these transition functions, especially the boundaries of the bi-directional regime, experiments were carried out to define the transition between the buoyancy-driven and the bi-directional regimes (and *vice-versa*), and between the wind-driven and the bi-directional (and *vice-versa*). The transition between the wind-driven mixing ventilation regime (Figure 4(c)) and wind-driven highly stirred regime (Figure 5) appears to us to be too subjective (no indisputable criterion clearly mark the transition) to be investigated strictly.

Figure 7 presents the representation of these two transitions as a function of J and Fr. It can be observed that both transitions can be express by a function in the form of $Fr = kJ^n$, where k and n are constants. Furthermore, the data show that these functions have the same order (same n), which means that on the studied range of J and Fr, all the four ventilation regimes exist.

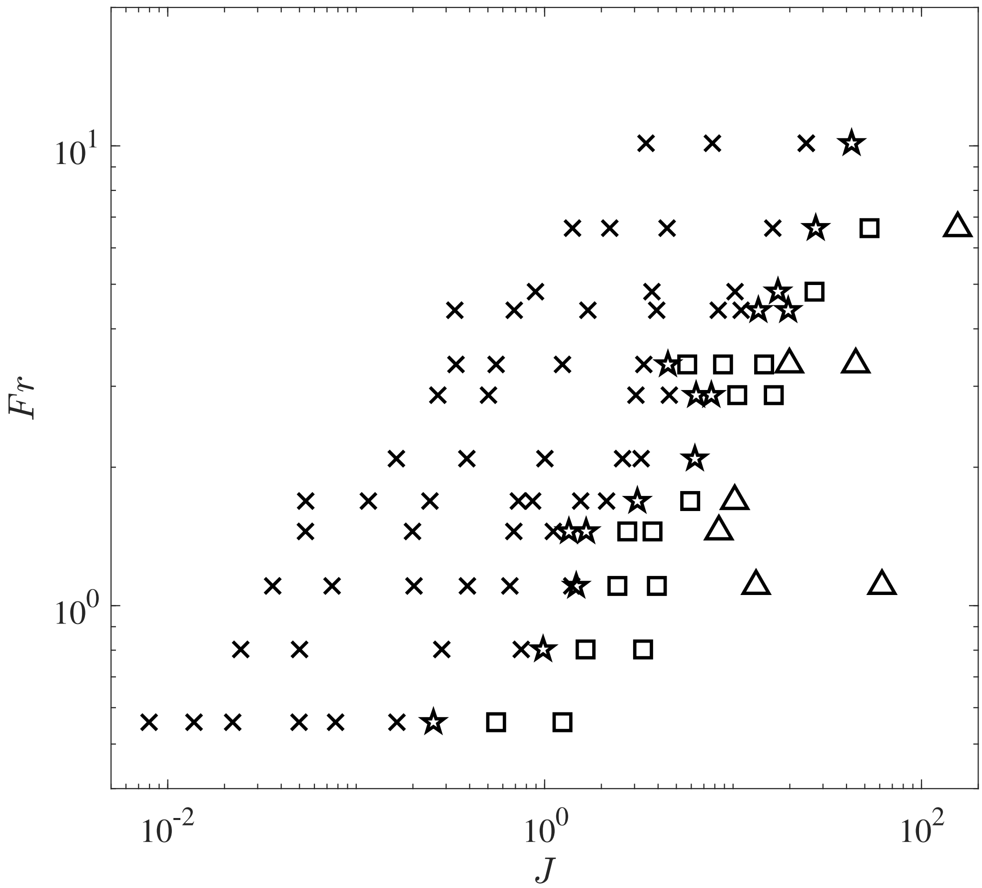


Figure 6: Mapping of the different flow regimes as function of J and Fr. The triangles are for the buoyancy-driven regime, the squares are for the bi-directional regime, stars are for the wind-driven regime 3a and the cross symbols are for the wind-driven regime 3b.

In the present experimental study, the following equation for the transitions is found:

$$Fr = kJ^{3/4}, \tag{5}$$

$$\text{with} \quad \begin{cases} k = 0.35, & \text{for transition between the buoyancy-driven and the bi-directional regimes.} \\ k = 0.58, & \text{for transition between the bi-directional and the wind-driven regimes.} \end{cases}$$

4. Conclusion

In this paper, an experimental study was proposed to investigate transition flow regimes in the case of wind versus buoyancy. Using a dimensional analysis, two dimensionless parameters were defined to characterize the internal regimes. For a single room with upper windward window and lower leeward window, a small-scale experiment was used to highlight a bidirectional regime of steady-state transitions. This internal flow regime is in addition to

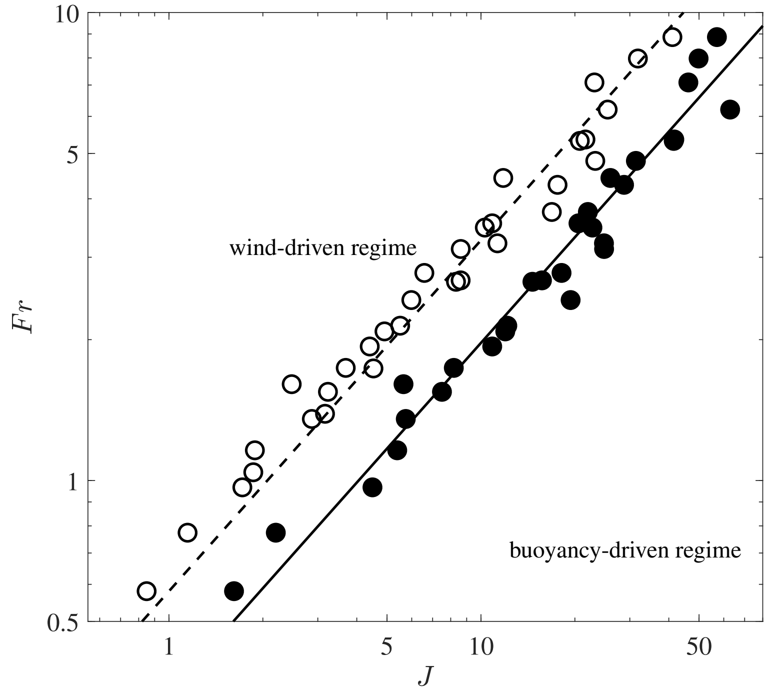


Figure 7: Representation of the transitions regimes as functions of Fr and J. The solid and hollow circles represent the transition from the buoyancy-driven regime and the transition to the wind-driven regime respectively. The dashed line is for the transition between the regimes 1 and 2, the solid line the transition between the regimes 2 and 3.

the experimental observations of Hunt and Linden and Andersen (Andersen et al., 2000; Hunt and Linden, 2005), which show either a mixed or a stratified regime. Using image processing, a second series of experiments allowed the characterization of zones separating flow regimes, on a diagram involving dimensionless parameters Fr and J. Transitions between regimes according to a power law were then characterized. This transition law can be decisive for real application cases. Indeed, for fire safety purpose, knowing the moment when flow pattern changes between stratified and mixed can be crucial in terms of casualties when wind interacts with buoyancy. If an opening is used for natural smoke control, one should know if the interaction with the wind will not make the smoke outlet to become an air inlet. This study also shows that further work should be done in order to explore the different observations that were revealed concerning the specific behaviour of the incoming air jet at the top. For a given injection rate and concentration, the incoming air jet gradually changes its inclination as the reference wind speed increases. We observed an incoming jet that is first constrained by buoyancy where fresh air is directly entrained into the lower layer, entraining light fluid at the same time. Then, as the velocity in the channel increases, for a same concentration of air helium jet, the incoming heavy jet rises, and impacts the plume of light fluid, deflecting it and causing mixing of the atmosphere. Finally, when the wind forces reach a certain value, the same behavior as a wind-driven internal flow is observed with a ceiling-placed jet. This observation makes us think of a possible correlation between inflowing jet angle and transitional flow pattern with respect to the opening emplacement.

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