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Experimental study of the indoor flow behaviour transitions in a naturally ventilated single-zone building opposing wind and buoyancy

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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 law 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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29 1. Introduction

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

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

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

49
50 Wind forces also implies air movement, inside a room by changing the pressure field around the building, while
51 openings position induces different internal flow pattern when wind acting alone. Hence, Karava *et al.* [7] demon-
52 strated, *via* Particle Image Velocimetry (PIV) measurements in a single-zone building, the complexity of the airflow
53 pattern in the room as a function of openings position, which strongly impacts ventilation performance. In this context,
54 inner streams could affect efficiency of the classical orifice equation. With similar apparatus, Tominaga & Blocken
55 [8, 9] investigate both air change and decontamination performance. Injecting a passive non buoyant contaminant,
56 they shown, by describing the inner path of the inflowing wind with openings on opposite sides, that openings loca-
57 tion is crucial for both ventilation rate and decontamination. They also shown that if any geometry can satisfy both
58 objectives with different performances, they can lead to the reverse result, in terms of decontamination or ventilation
59 efficiency, when the wind acts in the opposite direction for the same geometric configuration with opposed top and
60 bottom openings.

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

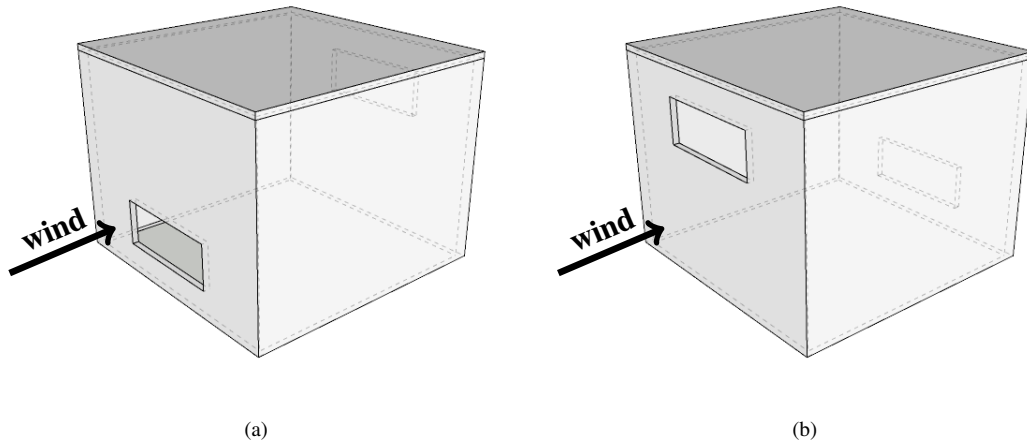


Figure 1: Single-zone building with (a) bottom opening on the windward and top opening on the leeward, and (b) top opening on the windward and bottom opening on the leeward.

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

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

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

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

84 However, when wind opposes buoyancy, literature shows that indoor airflow behaviour can be whether homoge-

85 neous (mixed ventilation) or stratified (displacement ventilation) depending on wind and buoyancy intensities. Then,
86 for a geometric configuration similar to figure 1(b), studies focused on these transition conditions by different ways.

87 Analytical theories for a well mixed single zone building are proposed by Li & Delsante [16], Lishman & Woods
88 [17] or Chen *et al.* [18] with similar conclusions. They found buoyancy-driven and wind-driven as stable regimes,
89 and a wind-driven unstable regime for which a small change in wind intensity quickly leads to on or the other stable
90 regime.

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

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

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

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

119 Then, it seems interesting to complete these works and to study the transition from a stratified to a mixed indoor

120 ambiance accompanied by change in the uni- and bi-directional flows through the openings. In this study, we propose
 121 to extend the experimental investigations aforementioned ([7, 9, 19]) and analyse the internal flow pattern when wind
 122 opposes the natural buoyant emptying-filling process in a single-zone building with two asymmetrical large openings
 123 on windward and leeward facades. In particular, we focus on the transition between the displacement ventilation
 124 (buoyancy dominated) and the mixed ventilation (wind dominated), and especially the flow behaviour in the zone
 125 bounded by these two known ventilation regimes. We propose to explore large range of density difference highlight-
 126 ing differences between fire (or light fluid leakage) and thermal comfort. To do so we carried out a set of experiences
 127 in a wind tunnel on a single-zone building identical to that of [7, 9], varying wind velocity and source buoyancy flux.
 128

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

131 2. Material and methods

132 A single-spaced enclosure of internal cross section $0.2 \text{ m} \times 0.2 \text{ m}$ and height 0.16 m made in transparent 0.008 m
 133 width PMMA was positioned in the middle of a $0.5 \text{ m} \times 0.25 \text{ m}$ flow section and 10 m length wind tunnel. The
 134 windward and leeward sides of the box included a rectangular hole $0.092 \text{ m} \times 0.036 \text{ m}$ located near the ceiling and the
 135 floor respectively (see Figure 2). As mentioned by [14], even if the occupancy ratio of the tunnel section is important
 136 (29 % in the present study against 40 % in [14, 15, 19]), the pressure drop between the windward and leeward openings
 137 (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.

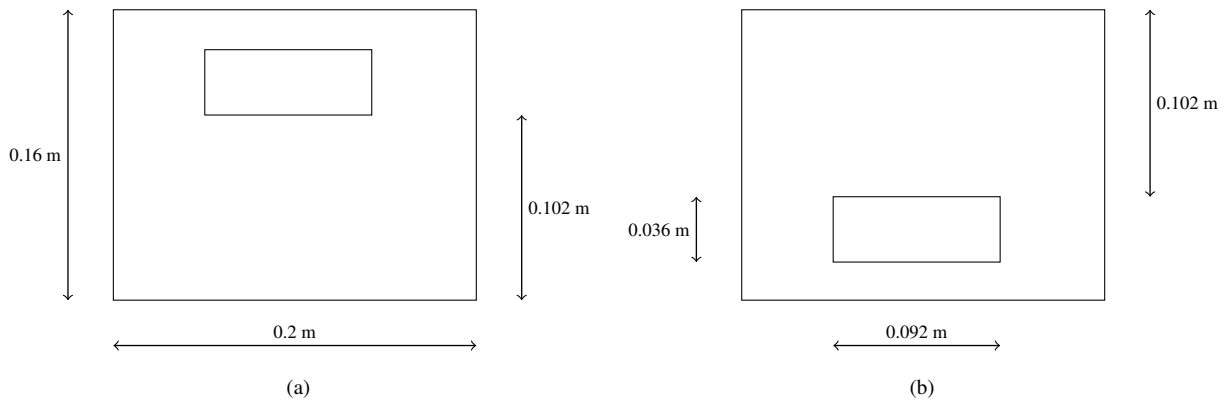


Figure 2: Interior dimensions of the (a) windward and (b) leeward sides of the experimental set-up.

138 The characteristic velocity of the flow in the channel was measured via a $0\text{-}5 \text{ m s}^{-1}$ hot wire anemometer located
 139 in the middle of the flow section upstream from the box. Buoyancy source was generated by supplying in the box
 140 an air/helium mix through a circular 0.014 m diameter nozzle located in the middle of the box cross-section. The air
 141 and helium flow rates were controlled thanks two mass flowmeters $0\text{-}200 \text{ l min}^{-1}$ (accuracy 2 % of full scale). The
 142

143 buoyant plume was seeded with passive ammonium salt particles obtained by a reaction between hydrochloric acid
 144 (HCl) and ammonia (NH₃). To observe the flow behaviours, a 2 W, 532 nm laser lighted the box through a cylindrical
 145 lens in order to generate a thin light sheet of high intensity. The in box flows were recorded at 30 fps during 2 min
 146 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.

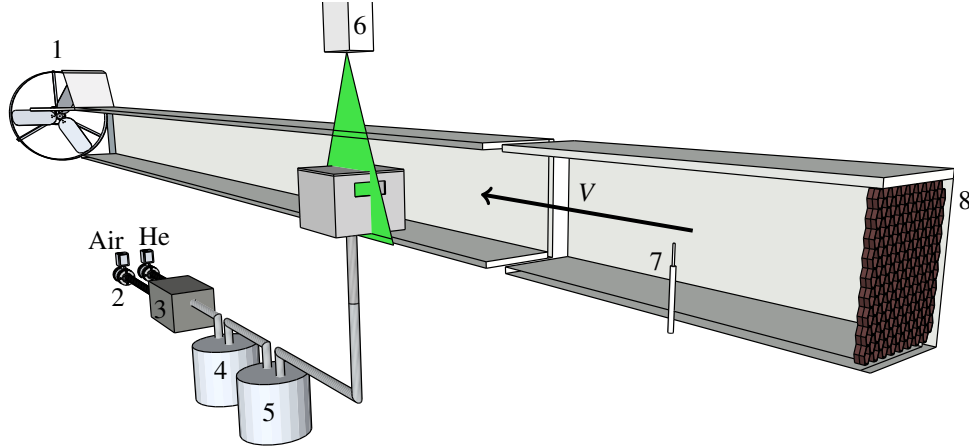


Figure 3: Sketch of the experimental set-up. 1 controlled fan, 2 flowmeters, 3 mixing chamber, 4 HCl, 5 NH₃, 6 laser source, 7 hot wire anemometer, 8 flow straightener.

147
 148 The experimental varying parameters are the cross flow velocity V , flow rate q_i and the gas density ρ_i at the
 149 injection. These last two parameters are regulated by means of the air and helium flow rates (respectively q_{air} and
 150 q_{he}), and expressed as follows:

$$q_i = q_{air} + q_{he}, \quad (1)$$

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

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

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

155 We then generated three different injection flow rates ($q_i = 5, 13$ and 301 min^{-1}) for four gas densities ($\chi = 25,$
 156 $50, 75$ and 100% , then $\rho_i = [0.945, 0.69, 0.435, \text{ and } 0.18] \text{ kg m}^{-3}$). Depending on the injection flow rate and gas
 157 density couples, we generated between five and ten wind velocities varying, increasing or decreasing, in the range
 158 $0.1 \leq V \leq 2.5 \text{ m s}^{-1}$.

159 After identified the different in-box flow patterns depending on q_i , ρ_i and V , we explored more accurately the
 160 conditions needed to pass from the buoyancy-driven flow pattern to the wind-driven one, highlighting the transition

161 range between these two stable regimes. We then generated eight injection flow rates (6, 8, 10, 12, 14, 16, 18 and
 162 20 l min^{-1}) for the same four injected gas densities used in the first campaign. The transition conditions were found
 163 by progressively increasing the volume flow rate in the channel (with a waiting period about 3 min between each wind
 164 speed increase) until changing the characteristic permanent flow pattern.

165 3. Results

166 We first discuss on the in-box flow behaviour. As illustrating example, let's consider the different flow behaviours
 167 obtained for a given buoyancy source flux (given for $q_i = 51 \text{ l min}^{-1}$ and $\rho_i = 0.69 \text{ kg m}^{-3}$) and an increasing wind
 shown on Figure 4.

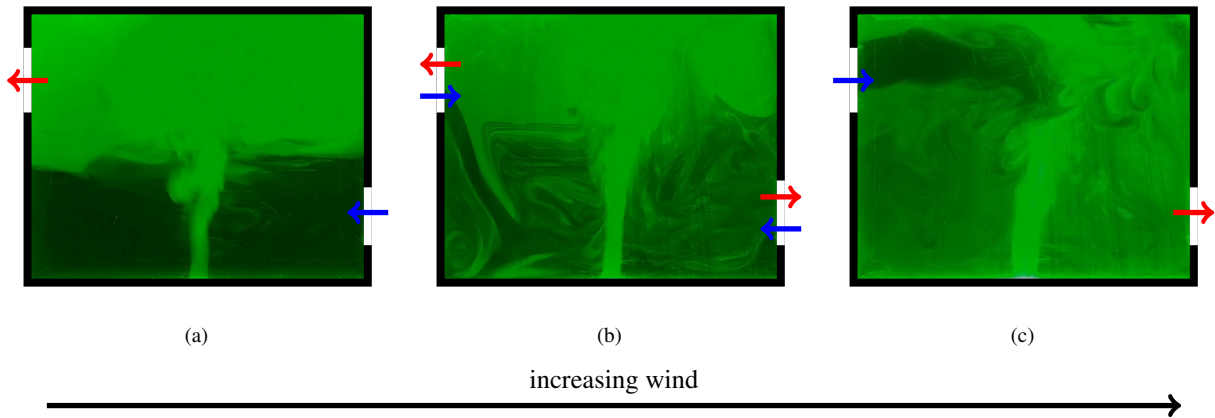


Figure 4: Example of indoor flow behaviour of a naturally ventilated single-zone building when wind opposes buoyancy for a given buoyancy source flux ($q_i = 51 \text{ l min}^{-1}$ and $\rho_i = 0.69 \text{ kg m}^{-3}$) and an increasing wind. (a) $V = 0.1 \text{ m s}^{-1}$: buoyancy-driven regime, (b) $V = 0.28 \text{ m s}^{-1}$: bi-directional regime, (c) $V = 0.37 \text{ m s}^{-1}$: wind-driven regime. The red and blue arrows represent the outflowing buoyant gas and the inflowing fresh air respectively.

168

169 As expected we found three ventilation regimes described as follows:

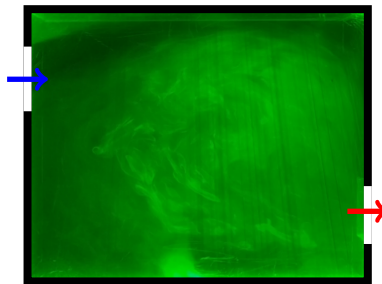
- 170 1. a stratified buoyancy-driven regime (corresponding to the displacement ventilation regime describe by [19])
 171 where buoyancy drives the light fluid to leave the box from the upper windward opening, generating a pressure
 172 drop in the box balanced by an inflow of fresh air through the leeward orifice (see Figure 4(a)). In this case,
 173 depending on the involved forces, the induced incoming flow rate can disturb the plume growth and then gener-
 174 ates a flapping plume mode, or a inclined plume mode for a high incoming flow rate.
- 175
- 176 2. A transition regime (Figure 4(b)), where a bi-directional flow appears in the two openings. The plume develops
 177 normally but the two layers stratification begins to be broken down. A continuous inflowing heavy fluid flow,
 178 drops along the wall from the windward opening to the floor. An increase in wind speed contribute to progres-
 179 sively straighten the inflowing jet and to increase its windward opening occupancy ratio until it occupies all the

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

182
183 3. A 'wind-driven' for which a mixed homogeneous gas escapes through the leeward opening and fresh air inflows
184 through the windward opening (Figure 4(c)). We then differentiate two cases:

185 (a) the plume still develop but is constrained and disturbed by the inflowing jet from the windward opening.
186 This regime is quite close to the one describe by [19] as the mixing ventilation regime.

187
188 (b) An highly stirred regime for which the buoyant source effects are negligible and no plume develops. The
189 fresh air inflowing through the windward orifice raises to the ceiling until it reaches the corner made by
190 the ceiling and the leeward side. There, this flow falls against the wall. Along this streamline, the initially
191 dense fluid is lighted by a mix with the injected gas. The injected buoyant gas is directly sucked by a large
192 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).



193
194 Figure 5: Indoor flow behaviour of a naturally ventilated single-zone building when the buoyancy effects are negligible against the opposed wind
($q_i = 5 \text{ l min}^{-1}$, $\rho_i = 0.69 \text{ kg m}^{-3}$, and $V = 2.3 \text{ m s}^{-1}$).

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

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

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:

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

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

202

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

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

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

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

217

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

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

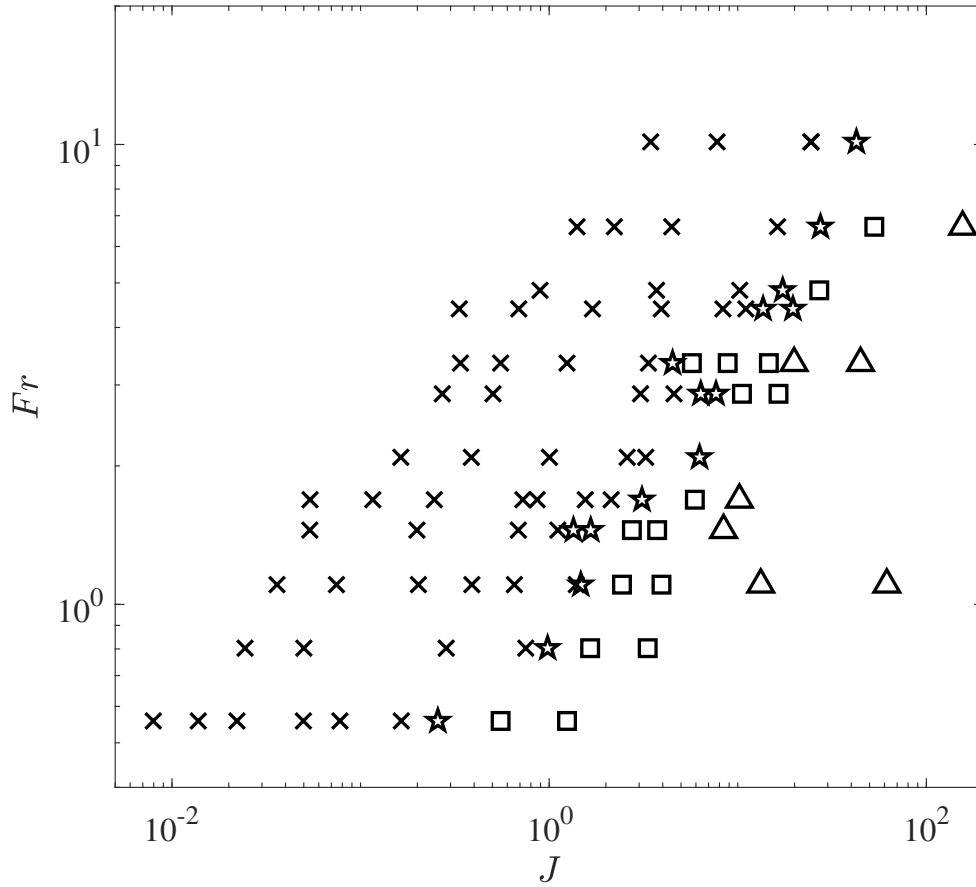


Figure 6: Mapping of the different flow regimes as function of J and Fr . The triangles are for the buoyancy-driven regime, the squares are for the bi-directional regime, stars are for the wind-driven regime 3a and the cross symbols are for the wind-driven regime 3b.

227

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

$$Fr = kJ^{3/4}, \quad (5)$$

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

228

4. Conclusion

229

In this paper, an experimental study was proposed to investigate transition flow regimes in the case of wind versus

230

buoyancy. Using a dimensional analysis, two dimensionless parameters were defined to characterize the internal

231

regimes. For a single room with upper windward window and lower leeward window, a small-scale experiment

232

was used to highlight a bidirectional regime of steady-state transitions. This internal flow regime is in addition to

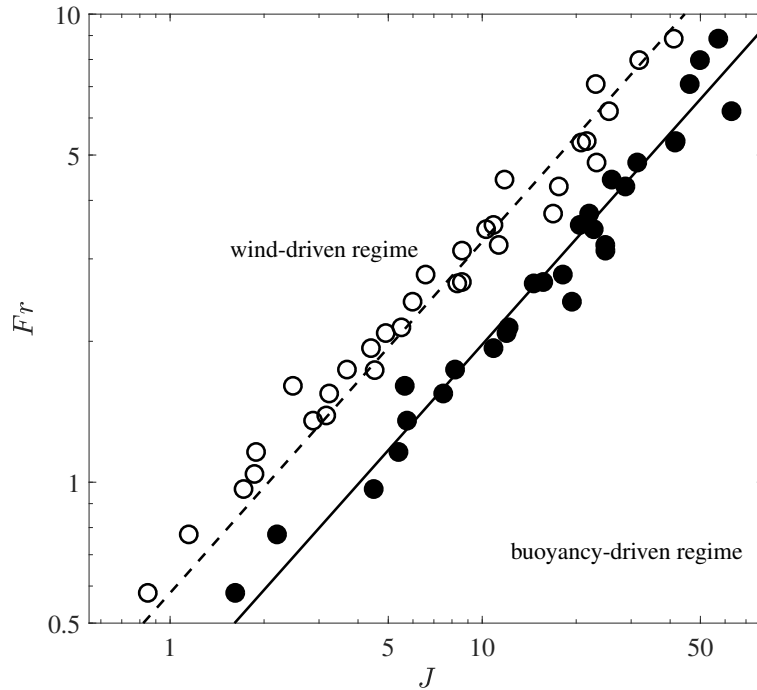


Figure 7: Representation of the transitions regimes as functions of Fr and J . The solid and hollow circles represent the transition from the buoyancy-driven regime and the transition to the wind-driven regime respectively. The dashed line is for the transition between the regimes 1 and 2, the solid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

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

248 angle and transitional flow pattern with respect to the opening emplacement.

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