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Smoke control in tunnel with a transverse ventilation system: an experimental study

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8 ABSTRACT

9 We carried out a series of experiments in a small-scale tunnel to study the confinement of smoke flow between two exhaust
10 vents located on either side of a buoyant source placed at ground level within a ventilated tunnel. The objective of our study
11 is to quantify the influence of the shape and the position (with respect to the tunnel axis) of the dampers, including the

12 specific case of full-width dampers, on the performance of the transverse ventilation system. To that purpose, we investigated

- specific case of full-width dampers, on the performance of the transverse ventilation system. To that purpose, we investigated the extent of the backflow length downstream of the dampers, the "confinement velocity" (suppressing the back-layering flow
- downwind of the vents) and the stability of the smoke stratification. The results show that the best performances are achieved
- 15 when the width of the dampers is the same as the tunnel width: this minimises the extent of the back-layering flow (for given
- 16 extraction flow rates) and ensures the stability of the smoke stratification. The worst conditions are observed with square-
- 17 shaped dampers located on the side of the ceiling, this configuration disturbs the stratification of the smoke layer before the
- 18 confinement conditions are reached. Subsequently, we evaluated the effect of solid barriers -placed on the tunnel ceiling
- 19 downstream of same three dampers typologies- on the propagation of the smoke. The results show that these barriers
- 20 improve significantly the efficiency of system with square-shaped dampers located on the side of the ceiling: they reduce the
- 21 confinement velocity and enhance the stability of the smoke stratification.

Keywords: Road tunnel safety, Smoke control, Transverse ventilation, Buoyant plume, Back-layering, Confinement velocity,
 Solid barriers.

24 Nomenclature 25 Η Height of the tunnel (m) 26 W Width of the tunnel (m) 27 h Height of the barrier (m) 28 D_i Diameter of the source (m) 29 L Smoke back-layering flow length (m) 30 B_i Buoyancy flux (m^4/s^3) 31 Gravity acceleration (m/s^2) g 32 Volume flow (m^3/s) q 33 Density (kg/m^3) ρ 34 Q_c Heat release rate of the fire (kW) 35 Т Temperature (K) 36 C_p Specific heat at constant pressure (kJ/kg K) 37 U_0 Induced longitudinal ventilation velocity (m/s) 38 U_e Extraction velocity (m/s) 39 W_i Injection velocity of the gas mixture at the source (m/s) 40 $U_{0,c}$ Confinement velocity (m/s) 41 Extraction confinement velocity (m/s) $U_{e,c}$ 42 Cross-sectional area of an extractor vent (m^2) A_d 43 V Sensor output voltage (volt) 44 R_c Confinement velocity ratio (-) 45 Longitudinal Froude number (-) Fr_0 46 Extraction Froude number (-) Fr_e

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- 47 $Fr_{0,c}$ Confinement Froude number (-)
- 48 $Fr_{e,c}$ Extraction confinement Froude number (-)
- 49 *Ri* Tunnel Richardson number (-)
- **50** Γ_i Plume Richardson number (-)
- 51 α Plume entrainment coefficient (-)
- 52 Ls Left side of the tunnel (-)
- **53** Rs Right side of the tunnel (-)
- 54 P_d Position of the dampers (-)
- 55 S_d Shape of the dampers (-)

56 Subscripts

- 57 ₀ Property of the ambient condition
- 58 i Property of the plume at the source
- 59 *he* Helium Properties
- 60 e Property of the flow at the exhaust vents
- 61 r Property of the flow in the rotameter

62 Acronyms/ Abbreviations

- 63 HRR Heat Release Rate
- 64 FDS Fire Dynamics Simulator
- 65 RSD Rectangular-Shaped Damper
- 66 SSD-PC Square-Shaped Damper Placed in the Centre of the tunnel ceiling 67 SSD-PS Servers Shaped Damper Placed in the Centre of the tunnel ceiling
- 67 SSD-PS Square-Shaped Damper Placed in the Side of the tunnel ceiling
- **68** ACH Air Changes per Hour

69 1 INTRODUCTION

- 70 The consequences of an event such as a fire or an accident in confined spaces such as a tunnel can be tragic. In these 71 structures, due to the components and materials of the vehicle (plastics, tires, etc.) as well as all hazardous substances
- transported (fuel, wood, textile, plastic, etc.), fires can produce a large amount of toxic smoke. This smoke causes a loss of
- visibility that can prevent the evacuation of users who end up inhaling harmful gases and toxic substances. The smoke is
- 74 indeed the major source of death in tunnel fires. Therefore, the installation of safety systems is imperative to ensure good
- rs safety conditions for tunnel users and emergency services in case of fire. Ventilation is one of the most important systems for
- 76 fighting fires and controlling the dispersion of toxic smokes in these spaces. Based on traffic mode (i.e. one-directional or bi-
- directional) and flow regime (i.e. congested or uncongested) in the tunnels, two types of mechanical ventilation can be
- 78 defined: longitudinal and transverse ventilation systems.
- 79 Longitudinal ventilation is required for road tunnels with unidirectional low traffic and is designed to produce a longitudinal 80 flow in the same direction as vehicle traffic (Fig. 1a). With this strategy smoke and combustion products are pushed 81 downstream of the fire source location to ensure the safe evacuation of people located upstream of the fire and to facilitate 82 the intervention of rescue forces. Transverse ventilation systems are instead suitable for long bidirectional tunnels or 83 congested unidirectional traffic tunnels (Fig. 1b). These are cases in which longitudinal ventilation is not suitable because, in 84 these cases, pushing the smoke in one direction can endanger the tunnel users. With transverse ventilation, the smoke is 85 extracted through dampers, which are generally located on the ceiling, whilst controlling the longitudinal air flow in the 86 tunnel. Two objectives are generally pursued: the preservation of the natural stratification and the confinement of the smoke
- 87 within a limited section of the tunnel, in which the extraction takes place.







Fig. 1. a) Fire-induced smoke longitudinal control [1]. b) Fire-induced smoke transverse control [1].

88 While the smoke control in longitudinal ventilation has been the subject of extensive research [2-5], the literature is much 89 scarcer regarding transverse ventilation. In this latter strategy, a main flow control parameter is referred to as 'the 90 confinement velocity', defined as the minimum adverse velocity required to prevent the smoke from propagating beyond the 91 extraction dampers, and the associated extraction flow rate at the ceiling vents. Vauquelin and Mégret [6] conducted fire 92 experiments in a small-scale tunnel equipped with two mechanical exhaust ducts located one on either side of a fire source to 93 study the influence of their location and their shape on the exhaust system efficiency for different fire heat release rates 94 (HRR). They concluded that a duct with the transverse rectangular shape located at the tunnel ceiling is more efficient than 95 the other ducts tested, whatever their shape and location. Vauquelin and Telle [7] performed another experimental study with 96 a single vent activated downstream of the source (and assuming that smoke flow would be symmetrical with respect to the 97 fire location). They evaluated the stratified smoke layer length downstream of the vent and the confinement velocity, for 98 several values of HRR. Vauquelin [1] then performed other experiments with the same experimental set-up, but with a two 99 vents system, to estimate the extraction flow rate required for a given HRR. Wang et al. [8] carried out a series of full-scale 100 burning experiments in tunnel with roof openings to study the effect of natural smoke exhaust on the behaviour of smoke 101 propagation, velocity and temperature fields under the ceiling, height of smoke layer and backflow distance. Due to the high 102 costs and the difficulties inherent when conducting such fire experiments in a real tunnel, they extended this study by 103 performing numerical simulations to include other fire scenarios with various vertical shaft arrangements on tunnel roof [9]. 104 Ingason and Li [10] conducted a series of small scale fire experiments to investigate the efficiency of a single extraction 105 system and a two-point extraction system. They concluded that the induced longitudinal velocity required to confine all 106 smoke is low in the case with two-point extraction system. Fan et al. [11] conducted experimental simulations of fires in a 107 tunnel equipped with a vertical shaft to quantify the effect of plug-holing on the smoke exhaust efficiency under natural 108 ventilation. Their results showed that a high mixing process between the hot smoke layer and the cold air layer occurs 109 because of the stack effect inside the shaft. Li et al. [12] used the Fire Dynamics Simulator (FDS) software to study the plug-110 holing phenomenon that occurs under the mechanical smoke exhaust in a tunnel when fresh air is drawn directly into the 111 smoke extraction system from the bottom layer. This phenomenon is undesirable and should be avoided as it greatly reduces 112 the efficiency of smoke extraction in tunnel fires [1, 13-17]. In recent years, further experimental [18-21] and numerical [22-113 24] studies investigated the performance and efficiency of extraction systems on smoke control in the case of a fire focusing 114 on the vent size and fire source location [22], the tunnel slope [20], the location and shape of the exhaust vents [6].

115 The ventilation of road tunnels can be also controlled by combining both ventilation systems, transverse and longitudinal, an 116 approach that has been recently considered in the tunnel ventilation literature. Lee et al. [25] conducted fire tests in a small-117 scale tunnel to evaluate the performance of the smoke extraction duct under natural and longitudinal ventilation flow 118 conditions. Their results showed that the efficiency of the smoke extraction through the dampers is better with natural 119 ventilation than with longitudinal ventilation, because of the preservation of the smoke stratification in the tunnel. Chen et al. 120 [26] carried out experiments in a reduced-scale tunnel to study the effect of the distance between ceiling extraction and heat 121 source on thermal buoyant smoke back-layering length in a tunnel with combination of longitudinal ventilation and ceiling 122 extraction opening at the downstream side only. They found that the smoke back-layering length increases with increasing 123 distance between the ceiling extraction opening and the heat source. Yao et al. [27] considered the case with a vertical shaft

upstream of the fire source to investigate the length of the smoke back-layering flow in longitudinal ventilated tunnel fires. Their experimental results showed that the vertical shaft can considerably reduce the smoke back-layering flow length (compared to the tunnel without a vertical shaft). In the same small-scale tunnel previously used by Chen et al. [26] and with the same ventilation system, Tang et al. [28] carried out a series of experiments to investigate the behaviour of the buoyant smoke flow stratification. They found that the combination of both ventilation systems had a strong influence on the smoke

129 stratification and the flow configuration could be classified into different regimes.

130 In this study, we present the results obtained in the experimental analysis of smoke control using transverse ventilation in a 131 scale model tunnel. The fire smoke in the tunnel is modelled by the continuous release of a light gas (mixture of air and 132 helium), a method which has been consolidated through the study of the critical velocity and back-layering phenomenon [29-133 30]. The smoke is extracted through two mechanical exhaust vents located on the ceiling of the tunnel, one on each side of 134 the source and equidistant from the buoyancy source. As already mentioned, the confinement velocity is defined as the 135 minimum induced longitudinal velocity required to prevent the smoke from flowing downstream of the vent. When the 136 induced longitudinal velocity is lower than the confinement velocity, a smoke backlayering flow appears downstream of the 137 exhaust vent. The back-layering length is measured between the downstream edge of the exhaust vents and the extremity of 138 the smoke backlayer. We test two different shapes of the extraction dampers, a square shape and a transverse rectangular 139 shape (Fig. 3). The two dampers have the same cross-sectional area and the rectangular damper extends across almost the 140 whole width of the tunnel (Fig. 3a). The square-shaped exhaust vent is placed on the ceiling in two different locations: firstly 141 in the centre of the ceiling (Fig. 3b) and the secondly on one of the ceiling edges (Fig. 3c), over a width about one-third the 142 tunnel width. Our work focuses on the measurement of smoke back-layering lengths, the determination of confinement 143 velocities and the potential provision of qualitative information on stratification according to the source conditions and the 144 extraction flow rates. The aim is to compare the results obtained with the different exhaust vents in order to evaluate the 145 influence of the previously defined parameters (i.e. shape and location of the extraction dampers) on the performance of the 146 smoke extraction system. Once this analysis has been carried out, we test the effect of the solid screens on the smoke 147 confinement by fixing barriers to the tunnel ceiling, one downstream of each damper. In full scale tunnel, these barriers are 148 designed to be mobile and would be deployed in the event of fires only. The influence of these barriers on the propagation of 149 buoyant smoke in the tunnel with a longitudinal ventilation has already been studied [31]. The results showed that the large 150 barriers prevent the smoke back-layer downstream of the source even at low ventilation velocities. The goal here is to 151 examine their effects on the confinement velocity as well as on the stratification of the buoyant smoke layer in order to 152 determine if they can improve the efficiency of the smoke extraction system.

153 2 EXPERIMENTAL SET-UP AND MEASUREMENT TECHNIQUES

154 2.1 The reduced scale model

155 Fire simulation experiments are carried out in a 1/25 reduced-scale model tunnel developed at the Laboratoire de Mécanique 156 des Fluides et Acoustique (LMFA) at the Ecole Centrale de Lyon (Fig. 2a). A schematic view of the experimental setup is 157 presented in Fig. 2b. The model tunnel is a channel with a rectangular cross-section. It is 8.4 m long, 0.36 m wide and 0.18 m 158 high. Fire-induced smoke is simulated by a release of a light gas, a mixture of air and helium, into ambient air. The air and 159 helium flow rates are controlled and measured using two flow meters. Both gases are well mixed in a long pipe and seeded 160 with nebulised oil before being injected in the plenum. The air flow used to seed the oil particles, controlled by a flowmeter, 161 is low so as not to influence the density of the mixture [35]. The mixture is then injected through a circular source of diameter 162 $D_i = 0.1$ m placed at the centre of the tunnel at ground level. The side wall of the tunnel is made of transparent toughened 163 glass, enabling visualisation of the buoyant fluid (seeded with particles) on a two-dimensional longitudinal plane illuminated 164 by a laser beam emitted from a lens located at the inlet box of the tunnel.



a)

Fig. 2. Experimental setup with transverse smoke control system. a) A real picture of the setup. b) A schematic of the setup.

165 The tunnel is equipped with two dampers placed on the ceiling, one on each side and set the same distance from the source 166 (i.e. 5*H*, *H* is the height of the tunnel). Each of them is connected to a mechanical exhaust fan. Both fans are remotely 167 controlled and their rotation speed is easily adjusted by means of a potentiometer wired to each of them. Each fan produces 168 an extraction airflow in the range 5 - 150 m³/h. Assuming a tunnel of infinite length with dampers located at a distance of 169 10H, by taking as reference the volume of the area between each two exhaust vents (i.e. $10H \times H \times 2H \approx 0.117 \text{ m}^3$), the 170 extraction rate produced by each fan in terms of "air changes per hour (ACH) " ranges from about 43 to 1286 ACH.

171 Two different forms of dampers were used to carry out these experiments, a square shape "SSD" (Fig. 3b and Fig. 3c) and a

transverse rectangular shape "RSD" (Fig. 3a) with an identical surface area of about 0.011 m². Their dimensions are 0.104 m

173 x 0.104 m and 0.32 m x 0.034 m, respectively. Two different positions of the square-shaped dampers were tested, the first

- position in the centre, referred to as "SSD-PC" (Fig. 3b), and the second on one of the sides of the tunnel ceiling, referred to
- 175 as "SSD-PS" (Fig. 3c).

176The dampers are designed to be easily installed in the tunnel ceiling with fixed connections (8 screws). On each side, a177rotameter (see § 2.3) with a range $6.4 - 64 \text{ m}^3/\text{h}$ (and from 16 to 160 m $^3/\text{h}$ for high flow rates) is used to measure the178extraction flow rates through the exhaust duct. The nozzle placed between the damper and the rotameter particularly helps to

179 ensure a uniform flow velocity at the rotameter entrance in order to avoid fluctuations of the rotating float inside the

180 rotameter. The position of the float on a linear scale indicates the flow rate passing through the rotameter. However, the

181 density of the smoke flows is lower than that of the air and a correction of the flow rates measured according to their

182 densities is therefore required. For this purpose, a calibrated oxygen sensor is placed above each rotameter to measure the

183 concentration of air within the exhaust smoke flow. A honeycomb cylinder is placed before the oxygen sensor to protect it

184 from oil particles that could degrade its measurements.



Fig. 3. Schematic top view of the different exhaust vents with their location on the tunnel ceiling. **a**) Exhaust vent with transverse rectangular shape (RSD). **b**) Exhaust vent with square shape placed in the centre of the tunnel ceiling (SSD-PC). **c**) Exhaust vent with square shape placed on the sides of the tunnel ceiling (SSD-PS).

185 To study the effect of barriers on the propagation of the smoke, two large barriers used in our recent work [31] were 186 considered. Their heights are h = H / 4 and h = H / 3 and their widths are equal to the width of the tunnel. The barriers are 187 solid to withstand the smoke flow forces and the induced longitudinal airflow forces. For each case of dampers, two barriers 188 are fixed to the ceiling of the tunnel, one on each side of the source. The barriers (which are transparent to allow the smoke to 189 be visualised) are located just downstream of the dampers, as is shown in Fig. 4. The idea is to evaluate the additional 190 benefits they can offer to improve the efficiency of transverse ventilation systems, by comparing the results obtained with 191 and without barriers. Note that in real tunnels, these barriers are designed to be mobile and will only be deployed in the 192 instance of a fire.



Fig. 4. Diagram of the experimental setup with large barriers (h = H / 3) fixed to the tunnel ceiling just upstream of the dampers (in this case, the exhaust vents are represented by square-shaped dampers placed in the centre of the tunnel ceiling, the same is applied for other types of dampers and for the barrier of height h = H / 4).

193 2.2 Flow control parameter and similarity

- As customary in small scale experiments, the fire source within the tunnel is modelled by means of the injection of light gas,
- a mixture of helium and air [32, 33]. As shown by Jiang et al. [32] in experiments with longitudinally ventilated tunnel, thesedensimetric plumes can be considered to reliably reproduce the smoke behaviour produced by a fire, provided that the size of
- 197 the flames does not exceed the tunnel half-height. Of course, adopting this approach, we will fully neglect any dynamic and
- thermal effect induced by heat transfers from conduction at the tunnel walls or by radiation [1].
- 199 We consider a flow in an infinitely long tunnel equipped with a transverse ventilation system while fixing the geometrical
- 200 parameters of the tunnel (the height H and the width W). We can assert that the extension L of the smoke back-layer could
- 201 depend on the source parameters (i.e. the diameter of the source D_i , the velocity W_i and the density ρ_i of the buoyant gas
- release) and on the induced longitudinal velocity U_0 [30, 34], as well as on the geometrical parameters of the exhaust vents
- 203 (i.e. the cross-sectional area A_d , the shape S_d and the position P_d). Adopting basic dimensional arguments [32, 33], assuming
- 204 negligible diffusive effects, the dimensionless length of the back-layer can then expressed as:

$$\frac{L}{H} = f\left(\Gamma_i, \frac{\rho_i}{\rho_0}, \frac{D_i}{H}, \frac{U_0}{W_i}, \frac{A_d}{H^2}, S_d, P_d\right), \qquad 1$$

205 where ρ_0 is the ambient air density and $\Gamma_i = \frac{5}{4\alpha\pi} \frac{B_i}{D_i W_i^3}$ is the "plume Richardson number", with $\alpha = 0.12$ (a reference value

for the 'top-hat' entrainment coefficient [36] and where

$$B_i = g q_i \frac{\rho_0 - \rho_i}{\rho_0} , \qquad 2$$

is the buoyancy flux, with g the gravitational acceleration and q_i the total volume flow of the mixture at the source. Note that the buoyancy flux B_i can be directly linked to an equivalent heat release rate (Q_c) by the relation:

$$Q_c = B_i \left(C_p \rho_0 T_0 \right) / g \quad , \tag{3}$$

- where T_0 is the ambient air temperature and C_p is the specific heat capacity (assumed constant).
- 210 Since the confining velocity $U_{0,c}$ is defined as that inducing a null back-layering length, from (Eq. 1) we can write

$$\frac{U_{0,c}}{W_i} = f\left(\Gamma_i, \frac{\rho_i}{\rho_0}, \frac{D_i}{H}, \frac{A_d}{H^2}, S_d, P_d\right)$$

$$4$$

211 Previous studies [30, 35] have shown that, considering highly buoyant releases, i.e. for $\Gamma_i > 1$, the relations (Eq. 1) and (Eq. 4) 212 can be highly simplified. In these conditions the back layering length and the confinement velocity do not show any clear 213 dependence on single source parameter, such as the diameter of the source D_i and the density ρ_i and exit velocity W_i of the 214 buoyant gas release. These parameters affects the flow instead only as far as they induce variations in the source buoyancy 215 flux B_i (Eq. 4). In these conditions (Eq. 1) therefore reduces to:

$$\frac{L}{H} = f\left(Fr_0, \frac{A_d}{H^2}, S_d, P_d\right)$$
5

with $Fr_0 = U_0/(B_i/H)^{1/3}$ a Froude number, which expresses the ratio between the inertia forces induced by the ventilation flow and the buoyancy forces induced by the injection of the buoyant plume at the source. The relation (Eq. 5) is sometimes

218 [30] presented as a function of "tunnel Richardson number" $Ri_0 = \frac{B_i}{U_0^{3}H} = Fr_0^{-1/3}$. If we further assume that cross-sectional

219 area A_d is unaltered we finally obtain that:

$$\frac{L}{H} = f(Fr_0, P_d, S_d) \tag{6}$$

220 Which implies that the critical Froude number

$$Fr_{0,c} \propto U_{0,c}/(B_i/H)^{1/3} = \text{constant}$$
 7

is a function of the shapes and positions of the extractor vents, i.e. that

$$Fr_{0,c} = f(P_d, S_d)$$

- 222 The determination of the dependences expressed by (Eq. 6) and (Eq. 8) constitutes the object of our study.
- 223 Note that from (Eq. 7) we have that the confinement velocity can be related to the buoyancy flux as $U_{0,c} \propto B_i^{1/3}$ (which
- 224 means that the fire plume is only characterised by its buoyancy flux) and therefore to the heat release rate as $U_{0,c} \propto Q_c^{1/3}$.

225 2.3 Calibration of rotameters and oxygen sensors

The rotameter is a device used to measure the volumetric flow rate of fluid, it consists of a tapered tube with a rotating float inside that is pushed up by the drag force of the flow and pulled down by gravity. Since the drag force depends on the fluid density, for our purposes, the flowmeter scale requires a calibration to take into account the variation of the density of the gas, providing the relationship between the flow rate (indicated by the rotameter) for a reference air density and the actual flow rate, for any gas mixture. For this purpose, tests were carried out in another experimental set-up (Fig. 5), made up of: two flow meters to independently control air and helium flows; a long pipe to ensure a good mix of air and helium, a rotameter for flow measurements, two oxygen sensors to measure the concentration of oxygen in the gas mixture.

- 233 The tests were carried out for varying density ratios $\rho_i/\rho_0 = 0.5, 0.6, 0.7, 0.8, 0.9$ and 1. For each of these values of the
- 234 density ratio, the calibration of the rotameter is performed with mixing rates (q_i) ranging from 130 L/min to 700 L/min (i.e. 8
- m^{3}/h to 42 m³/h). The density of the gas mixture is estimated by measuring the oxygen concentration by means of
- electrochemical sensors placed downstream of the rotameter. This concentration is associated to a voltage value, it is
- 237 acquired by an Arduino board (ARDUINO UNO DIP REV3) and displayed on a digital screen (Grove LCD RGB Backlight).
- **238** Two rotameters with different measuring ranges of 6.4-64 m³/h and 16-160 m³/h were calibrated. Only the latter has actually
- been used in our experiments.



Fig. 5. Experimental set-up for calibration of rotameters and oxygen sensors.

Fig. 6 shows the relationship between the flow rate provided by the rotameter (q_r) and the actual flow rate (q_i) . Fig. 6a and Fig. 6b show the results of the rotameter with measuring ranges of 6.4 m³/h to 64 m³/h and 16 m³/h to 160 m³/h, respectively. A linear fit of the data is performed for each density ratio and a correlation is obtained in the form: $q_r = \beta * q_i$ where β is a constant, whose value depends only on the density of the gas mixture (it decreases with decreasing gas density). From these

data we can plot the curve corresponding to any density ratio between 0.5 and 1 by a simple linear interpolation.

8



Fig. 6. The dependence between the measured flow rate q_r and the prescribed flow rate q_i for $0.5 \le \rho_i / \rho_0 \le 1$. ' β ' is the linear correlation factor between q_r and q_i . **a**) Rotameter with a range: 6.4-64 m³/h. **b**) Rotameter with a range: 16-160 m³/h.

Fig. 7 shows the results on the oxygen concentration measured by both sensors depending to the density of the mixture. With the type of sensor used in these experiments, we know the percentage of oxygen in the gas mixture (or in the ambient air) through the given output voltage of each sensor. Fig. 7a shows that the output voltage V_i increases with the density ρ_i and changes from one sensor to another. Fig. 7b shows the dimensionless voltage V_i/V_0 (V_0 is the output voltage of each sensor measured in the ambient air) versus the dimensionless density ρ_i/ρ_0 . The two curves are similar, we can then conclude that both sensors have the same voltage response.



Fig. 7. Variation of the oxygen concentration measured by the two sensors (expressed in Volt) against the density of the mixture. a) The voltage V_i versus the density ρ_i . b) The dimensionless voltage V_i/V_0 versus the dimensionless density ρ_i/ρ_0 .

From the two output voltage curves plotted in Fig. 7a, the density of the gas mixture in the two exhaust ducts can therefore be
obtained. Knowing the density of the extraction smoke, the actual flow corresponding to that measured by each rotameter is
obtained using the curves (or interpolation curves) plotted in Fig. 6.

254 2.4 Experimental protocol

position) as (see Fig. 8):

264

Experiments were performed for a fixed density ratio $\rho_i/\rho_0 = 0.7$, a fixed source diameter $D_i/H = 0.56$, and a plume Richardson number in the range $1 \le \Gamma_i \le 40$. With these conditions, the average injection velocity (W_i) at the source varies from 0.13 m/s to 0.73 m/s, the buoyancy flux (B_i) is between $3*10^{-3}$ m⁴/s³ and $2*10^{-2}$ m⁴/s³ (and the corresponding heat

258 release rate (Q_c) is between 0.11 kW and 0.71 kW in this reduced scale model).

259 The average extraction velocities through the dampers (U_e) were calculated by dividing the extraction flow rate (once they

are determined and corrected to the fluid density) by the cross-sectional area of the damper. As shown in Fig. 2b, the tunnel is equipped with a pitot tube at one end to estimate the ventilation flow rate. However, for most of the experiments, the

ventilation flow rate was too low to be measured by this system. Therefore the longitudinal induced velocity U_0 and the relative air flow q_0 are estimated by a mass balance (assuming that the flow is perfectly symmetric with respect to the source

$$q_0 = \frac{\rho_e}{\rho_0} q_e - \frac{\rho_i}{\rho_0} \frac{q_i}{2}$$

where $q_0 = q_{01} = q_{02}$, $q_e = q_{e1} = q_{e2}$ and ρ_e is the density of the extraction smoke flow. Note that the symmetry of the flow has been verified, for a given range of airflow, by directly measuring the longitudinal velocities with a Pitot tube and comparing them to those calculated with Eq. 9.



Fig. 8. Schematic view of all input and output flows in a tunnel with two extraction points.

268 To ensure a symmetrical dispersion of the smoke flow in the tunnel with respect to the location of the source, the two exhaust 269 fans must be controlled simultaneously and their power adjusted to impose the same flow on both sides. In this way, using 270 flow visualisation and camera recordings, we can then measure the smoke back-layering lengths, determine the confinement 271 velocities according to the source conditions, and report qualitative information about the stratification of the smoke layers in 272 the tunnel with and without barriers. By regulating the power of the exhaust fans, we could set the front of the back-layering 273 flow at the position of the extraction dampers, at the confinement conditions, characterised by a "confinement velocity" $U_{0,c}$ 274 within the tunnel, and to an associated extraction confinement velocity $U_{e,c}$. Fig. 9 shows an example of smoke visualisation 275 in the tunnel with rectangular exhaust vents for two different ventilation velocities. In case of a ventilation flow lower than 276 the confinement condition (with $U_{e1}=0.52$ m/s and $U_{e2}=0.50$ m/s and $U_{01}=0.069$ m/s and $U_{02}=0.063$ m/s), a stratified 277 smoke layer develops downstream of the exhaust vents (Fig. 9a). The smoke layer is stable and symmetrical with respect to 278 the position of the source, its length is equal to twice the tunnel height (i.e. L/H = 2). 279 By increasing the extraction flow rate of the two fans (Fig. 9b), the longitudinal velocity of the induced fresh air increases

and the back-layering length downstream of the exhaust vents decreases progressively on both sides, until reaching

281 confinement ventilation conditions (i.e. L/H = 0), here obtained for $U_{e1,c} = U_{e2,c} = 0.58$ m/s and $U_{01,c} = U_{02,c} = 0.08$ m/s.



Fig. 9. Smoke visualisation in the tunnel with a two-point transverse extraction system (rectangular dampers, Γ_i =8). a) Nonconfinement ventilation conditions: smoke back-layer appears downstream of the dampers. b) Confinement ventilation conditions: smoke backflow is completely suppressed.

282 3 RESULTS AND DISCUSSIONS

283 3.1 Smoke backflow length

284 Measurements of the smoke back-layer lengths downstream of the dampers were performed for given source conditions 285 $(D_i/H = 0.56, \rho_i/\rho_0 = 0.7 \text{ and } \Gamma_i = 8)$. The flow rate of the two exhaust fans was first set to the minimum, then increased 286 gradually. For each ventilation flow condition, the backlayer length downstream each of the two extraction vents and the 287 corresponding extraction flow rates were recorded. Note that the uncertainty on the estimate of the flow rates with the 288 rotameters is approximately $\pm 1 \text{ m}^3/\text{h}$, while the uncertainty on the smoke length measurement is approximately $\pm H/2$. The 289 results obtained for different shapes and locations of the exhaust vents are presented in Fig. 10. For all cases, the 290 dimensionless backflow lengths L/H measured on both the left and right sides of the tunnel are plotted against the extraction 291 Froude number $Fr_e = U_e/(B_i/H)^{1/3}$ in Fig. 10a and against the longitudinal Froude number $Fr_0 = U_0/(B_i/H)^{1/3}$ in Fig. 292 10b. As expected (Eq. 9), the relationship between U_0 and U_e is linear (as well as between F_{r_e} and F_{r_0}), and each curve 293 shown in Fig. 10a has the same trend as its corresponding curve in Fig. 10b. The results show that the backflow length 294 decreases with the increase of the Froude number. For each type of exhaust vent and for a fixed value of Froude number, the 295 back-layering length on the right side (Rs) of the tunnel is greater than that measured on the left side (Ls). This is because the 296 inlet flow at the two tunnel entrances are asymmetric, resulting in uneven distribution of head losses. However, for a reduced 297 backlayering length (i.e. $L/H \le 1$), the effect of these uneven head losses becomes negligible and the backflow becomes 298 perfectly symmetrical (relative to the source location).

299 Two features can be distinguished from the comparison of the results obtained with dampers of square (SSD) and rectangular 300 shapes (RSD): firstly, the length of the back-layer flow and secondly, on its correlation against the Froude number. With 301 regard to the first point, for the same back-layering length, the Froude number is lower with the rectangular-shaped dampers 302 than with the square-shaped dampers. This means that even though the cross-sectional area of the two shapes of dampers is 303 the same, their efficiency in smoke extraction is different. Concerning the second point, the evolution of the backflow length 304 against the extraction velocity is different for the two different shapes. For rectangular-shaped dampers, the back-layering 305 length decreases very rapidly with increasing smoke extraction rate. As shown in Fig. 10, the dimensionless length (L/H) is 306 reduced from 14 to 0 for an extraction Froude number (Fr_e) increasing from 1.10 to 1.72 (i.e. from 0.13 to 0.22 for Fr_0). In 307 this particular case of full-width dampers, the smoke propagation downstream of the exhaust vents can be controlled with 308 relatively low extraction rates, while preserving the stratification of the smoke layers (as illustrated in the example of Fig. 309 9b). For square-shaped dampers (SSD), the development of smoke back-layer exhibits different regimes, depending on the 310 value of the Froude number. The first regime is characterised by a significant decrease in the back-layering length, as well as 311 by the asymmetry of the smoke backflow with respect to the source location (i.e. Ls and Rs curves are not identical). This 312 behaviour can be clearly observed in Fig. 10 for L/H > 1. The second regime is characterised by the case when L/H < 1: the 313 backflow becomes perfectly symmetrical relative to the source location and its length is only slightly affected by changes in 314 the extraction flow rate. In this regime, as observed during flow visualisation experiments, the smoke backlaver is suppressed

- for the extraction rate values that perturbs the stratification of the smoke layer, i.e. inducing a significant mixing between the
- ambient air layer and the smoke layer. Furthermore, for these high flow rates we observe the occurrence of a phenomenon
- 317 called 'plug-holing', i.e. the extraction of a large amount of fresh air flowing through the smoke layer. This phenomenon is
- 318 clearly undesirable since it reduces the effectiveness of transverse ventilation systems. Fig. 10 also shows that the position of 319 the square-shaped dampers plays a major role in the smoke back-layering lengths. Indeed, with the same ventilation
- --- and square shaped dampers plugs a major role in the smoke back-rayering lenguis. Indeed, with the same ventuation
- 320 conditions, the length of the backflow measured in each side of the tunnel is larger with the vents located on the sides of the
- 321 tunnel ceiling (SSD-PS) than with the vents in the centre (SSD-PC).a)

b)



Fig. 10. a) Dimensionless back-layering length L/H against the extraction Froude number Fr_e . b) Dimensionless back-layering length L/H against the longitudinal Froude number Fr_0 , for different shapes and locations of the exhaust vents.

- 322 The difference between the results obtained with the different dampers can be explained as follows: when the buoyant plume 323 impinges the ceiling, the smoke layer extends in both longitudinal directions of the tunnel, it moves near the tunnel ceiling 324 over its entire width. Once the smoke reaches the location of the vents, it is trapped by the full-width dampers, even at 325 relatively low extraction rates. However, if the width of the dampers is much smaller than the width of the tunnel, only the 326 smoke passing through the location of the exhaust vents is directly trapped, while the remaining smoke can flow downstream 327 of the dampers through the remaining width of the tunnel (i.e. width not occupied by the dampers). To prevent this smoke 328 from moving away from the vents, it is necessary to increase the induced longitudinal air flows on both sides of the tunnel. 329 However, the extraction rates required with the vents located in the centre are significantly smaller than those needed with the 330 vents placed on the sides.
- 331 Note that the non-dimensional density of the smoke measured by the sensors at the exhaust vents increases with the 332 extraction flow rate for each of the three vent shapes investigated. The variation of ρ_e/ρ_0 was between 0.92 and 0.94 for the 333 rectangular vents and between 0.95 and 0.98 for the square centre vents and square side vents (where ρ_e is the density of the 334 smoke measured at the exhaust vents). This implies that, under the same source conditions, the higher the extraction rate the 335 greater the proportion of ambient air extracted. In other words, the higher the value of ACH the lower the concentration of 336 smoke in the extracted air. This also explains why the density ratios measured with the square vents are higher than those 337 measured with rectangular vents. This is because the airflow needed to reduce or prevent the smoke back-layering with 338 square vents is greater to that required for rectangular vents.

339 3.2 Confinement velocity

- 340 In principle, the confinement condition is reached when the smoke backflow downstream the damper is suppressed, i.e. for
- L/H = 0. However, as can be observed in Fig. 10, this condition is difficult to reach for the cases with square shaped dampers
- 342 (SSD). In these cases the confinement conditions are therefore defined differently, i.e. as those inducing an extent of the
- backflow which is equal to the tunnel height, i.e. for L/H = 1, which will then be assumed as the reference length corresponding to the confinement velocity (a similar criterion was adopted by Vauquelin and Telle [7]). We therefore
- 345 consider that the confinement condition will be attained when L/H = 0 (i.e. total confinement) for the rectangular shaped
- dampers (RSD) and when L/H = 1 for the square shaped dampers (SSD).
- 347 The study was performed with the different vents, the velocity measurements are taken from both sides of the tunnel (Ls 348 refers to left side and Rs to the right side). The results on the confinement velocity are represented in Fig. 11a as a function of 349 buoyancy flux, with the corresponding best-fit curves. The associated extraction confinement velocities and heat release rates 350 are shown on the right y-axis and at the top x-axis of the graph. Fig. 11a shows that for each shape (or position) of dampers, 351 the results for the two sides (curves Ls and Rs) are very similar to each other. Moreover, as expected, $U_{0,c}$ (as well as $U_{e,c}$) 352 increases with increasing buoyancy flux Bi and therefore with increasing HRR. In all cases considered, the general 353 dependence between these quantities can be expressed in the form $U_{0,c} = a B_i^{1/3} = b Q_c^{1/3}$ (similar with $U_{e,c}$), where 'a' 354 and 'b' are proportionality constants whose values depend on the shape and the location of the dampers (they are low with 355 RSD) as well as on other parameters not considered in this study, such as the shape and the aspect ratio of the tunnel cross 356 section [4, 5], the size of the source [32, 34] and the distance between the source and the extraction points.
- 357 The confinement Froude number $Fr_{0,c}$ (as well as $Fr_{e,c}$) is estimated and plotted in Fig. 11b against the plume Richardson 358 number Γ_i . As shown in the figure, this number does not depend on the source conditions (Γ_i), it is only related to the shape 359 and position of the damper, which is in accordance with what is expected (Eq. 8). Its value is low with RSD ($Fr_{0,c}$ is around 360 0.22) and high with SSD-PS ($Fr_{0,c}$ is around 1.10). Note that this latter value exceeds that for a longitudinally ventilated 361 tunnel [35] (which is of the order of unity). This proves that the square-shaped dampers placed on one side of the ceiling are 362 not an effective means with which to control smoke propagation. Moving the dampers from the edge to the centre of the 363 tunnel ceiling reduces the value of the confinement Froude number by approximately one-half and thus improves the 364 efficiency of the ventilation systems.



b)



Fig. 11. a) The confinement velocity $U_{0,c}$ and the associated extraction confinement velocity $U_{0,e}$ against the buoyancy flux B_i and the associated heat release rate Q_c . b) The confinement Froude number $Fr_{0,c}$ and the associated extraction

confinement Froude number $Fr_{0,e}$ against the plume Richardson number Γ_i , for different shapes and locations of the exhaust vents.

- 365 It is worth noting that the results presented in Fig. 11 demonstrated that: i) the width of the damper is the relevant length scale
- 366 for the smoke spread control in the tunnel with mechanical extraction systems, ii) the location of the damper relative to the
- 367 centre of the tunnel plays a significant role in the confinement and extraction of smoke and iii) the confinement Froude
- 368 number does not depend on the source conditions but only on the geometry of the exhaust vents.
- 369 It should be noted that, in confinement conditions, the density ratio (between the smoke and ambient air density) measured at
- the exhaust vents for each configuration increases with the plume Richardson number (i.e. with buoyancy flux and thus with
- 371 the heat release rate). For $1 \le \Gamma_i \le 40$ (i.e. $3*10^{-3} \le B_i(m^4 s^{-3}) \le 2*10^{-2}$), ρ_e/ρ_0 ranged from 0.91 to 0.97 with rectangular
- vents and from 0.96 to 0.99 with square vents. This can be explained by the fact that the higher the buoyancy flux (or the
- 373 firepower), the higher the extraction rate, which causes a strong suction of the ambient air through the dampers. This means
- that the smoke concentrations in the extracted air decrease with increasing confinement values of ACH.

375 3.3 Effect of extraction rate on smoke stratification

376 Furthermore, we also focus on the stability of the smoke stratification within the tunnel. To that purpose, for each type of 377 damper, the tests are performed with releases characterised by two values of Richardson number ($\Gamma_i = 8$ and $\Gamma_i = 40$) and a 378 fixed density ratio 0.7. The procedure to investigate this effect is to increase (simultaneously) the flow rate of the two exhaust 379 fans and at the same time observing the significant changes in the behaviour of the buoyant smoke flow. Images of these 380 smoke behaviours are then recorded using a video camera and the flow regimes are expressed according to the Froude 381 number Fr₀. The camera used is the "Canon LEGRIA HF G40". This includes an HD CMOS PRO sensor that provides a 382 high-quality image of 2.07 mega pixels (i.e. an array of 1920 x 1080 pixels) along with precise 20 x optical zoom. The camera can be used to record outstanding high bitrate AVCHD 1080p video with variable frame rates. 383

384 3.3.1 Rectangular-shaped dampers (RSD)

385 Fig. 12 shows the behaviour of the buoyant smoke flow for different stratification regimes with rectangular-shaped dampers 386 (only the right side of the tunnel is shown). Fig. 12a shows the smoke in confinement conditions (for $Fr_{0,c} = 0.22$). In this 387 flow configuration, we can see the existence of two distinct layers, an ambient air layer at the bottom and a smoke layer at the 388 top, without any exchange of particles between the two layers. Thus, we consider that stratification is well preserved and 389 refer this to as a 'stable stratification' regime. The stratification remains relatively well-preserved until $Fr_0 = 0.60$, when a 390 thin smoke appendix is formed below the exhaust vent (Fig. 12b). By further increasing the extraction rates, more ambient air 391 is extracted through the exhaust vents and a larger amount of smoke is directed to the lower air layer (i.e. the plug-holing 392 phenomenon). In this case, several vortices appear at the interface between the two layers, as well as in the lower air layer 393 (Fig. 12c). Nevertheless, the visibility remains clear at the bottom of the tunnel. This configuration (i.e. when $0.6 \le Fr_0 \le 1.1$ 394 approximately) marks the transition between a stable and unstable stratification regime. As the extraction rate increases further, the suction force increases, resulting in an increase in the induced longitudinal flow rate. The shear of generated 395 396 instabilities induces the mixing between the upper and the lower fluid layers (see Fig. 12d). In this case, the whole area 397 between the both vents is completely filled with smoke giving rise to a flow regime that we refer to as 'unstable'.



Fig. 12. Visualisation of the different stratification regimes of the buoyant smoke flow in the tunnel equipped with rectangular shaped dampers (RSD).

398 3.3.2 Square-shaped dampers positioned in the centre (SSD-PC)

399 Fig. 13 shows the flow visualisations for square-shaped dampers placed in the centre (SSD-PC). As previously mentioned (§ 400 3.2), the confinements conditions with the square-shaped vents are attained when the backflow downstream of the dampers 401 becomes insensitive to the induced longitudinal air flow (i.e. for $L/H \approx 1$). The confinement Froude number is equal 402 approximately to 0.60 (Fig. 13a). In this configuration, the stratification of the smoke layer is preserved. We can however 403 notice the appearance of a small appendix (identical to that observed in Fig. 12b) at the bottom of the vents. This highlights 404 the beginning of a transition between a stable stratification and an unstable stratification, which occurs for a Froude number 405 identical to that estimated with rectangular-shaped dampers (i.e. $Fr_0 = 0.60$). By increasing the extraction flow rate, large 406 smoke vortices are produced in the lower air layer (Fig. 13b), which we consider as representative of the unstable 407 stratification regime. This happens for $Fr_0 = 0.80$, which is lower than that observed for the case of rectangular-shaped 408 dampers (i.e. $Fr_0 = 1.10$). Fig. 13c and Fig. 13d show the configurations with a partial and complete de-stratification of the 409 buoyant smoke layer. In these cases, the bottom of the tunnel is completely filled with smoke, therefore severely restricting 410 the visibility.



Fig. 13. Visualisation of the different stratification regimes of the buoyant smoke flow in the tunnel equipped with square-shaped dampers located in the centre (SSD-PC).

411 3.3.3 Square-shaped dampers positioned in the side (SSD-PS)

412 Fig. 14 shows the flow visualisations for square shaped dampers placed on one side of the tunnel ceiling (SSD-PS). We413 observe that: i) the vortices at the interfacial regions (see Fig. 14a) are well developed and clearly visible, due to the strong

414 shear; ii) the smoke layer is slightly thicker than that observed in the previous case where the position of the vents is aligned

- 415 on the same axis as the source location; iii) the stratification of the buoyant smoke layer is completely suppressed even before
- 416 reaching the confinement conditions (see Fig. 14c), i.e. $Fr_{0,c} = 1.10$. In summary, the smoke stratification pattern can be
- 417 classified into three regimes identical to those observed with square shaped dampers located in the centre: stable stratification
- 418 for a $Fr_0 < 0.6$, stable-unstable transition for a $0.6 \le Fr_0 \le 0.8$ and unstable for a $Fr_0 > 0.8$.



Fig. 14. Visualisation of the different stratification regimes of the buoyant smoke flow in the tunnel equipped with square-shaped dampers located on the side of the tunnel ceiling (SSD-PS).

419 Finally, it should be noted from Fig. 12, Fig. 13 and Fig. 14 that the smoke stratification behaviour for a constant Froude

- 420 number is independent of the plume Richardson number (a similar smoke behaviour is observed with $\Gamma_i = 8$ and $\Gamma_i = 40$),
- 421 however, it seems that this changes with the shape (or position) of the exhaust vents. This confirms that the Froude number is
- 422 the only flow control parameter.

423 3.4 Effect of solid barriers on the propagation and behaviour of smoke

424 Our results show that the confinement conditions can be reached for flow rates that already induce a de-stratification of the 425 smoke layer within the tunnel. It is therefore interesting to seek solutions to improve the efficiency of smoke extraction 426 systems, i.e. the preservation of the stratification and the confinement of the smoke within a limited section of the tunnel, in 427 which the extraction takes place. For this purpose, we consider here the effect of solid barriers downstream of the dampers on

428 the reduction of the confinement velocity and on the stratification conditions.

429 The study was carried out in the same conditions as those established in the § 3.2. The results, shown in Fig. 15, are 430 presented in terms of a dimensionless number R_c ; defined as the ratio between the confinement velocity in the tunnel with 431 barriers and the confinement velocity in the tunnel with no barriers (for the same conditions). This ratio is written in the form

- 432 $R_c = \frac{U_{0,c \text{ with barriers}}}{U_{0,c \text{ without barriers}}}$ and the quantity $(1 R_c)$ characterises the reduction rate of the confinement velocity due to the
- 433 presence of the barrier. It was verifies that the confinement velocity reduction was the same for both sides of the tunnel. As
- 434 shown in Fig. 15, the reduction of the confinement velocity is independent of the source conditions (i.e. in all cases the ratio
- 435 R_c is independent of Γ_i). But it is very different according to the shape of the dampers.
- 436 With the rectangular-shaped dampers in place, the effect of the barriers on the reduction of the confinement velocities is very
- 437 low (the reduction is less than 10% and is almost the same for both barriers H/4 and H/3). We have to conclude that the

- 438 rectangular dampers are so effective in the smoke extraction, that the presence of the barriers has a very little effect on the 439 smoke confinement. In tunnels equipped with such dampers, the use of barriers is therefore not necessary.
- 440 With the square-shaped dampers in place, the results show instead that the barriers can significantly reduce the confinement
- 441 velocities. This reduction increases with the height of the barriers and depends only slightly on the position of the dampers: it
- 442 is slightly better with dampers placed in the centre of the tunnel ceiling where the reduction rates $(1 R_c)$ are 38% and 58%
- 443 (with the barriers H/4 and H/3) against 32% and 55% with dampers placed on the side. This means that, in this case, the
- 444 barriers can effectively control the spread of smoke downstream of the dampers even for relatively low extraction flow rates.
- 445 They block the smoke that accumulates close to the dampers and is then easily extracted by the exhaust ducts. The smoke
- remains completely confined in the area between the two positions of the dampers, unlike the case with no barriers where a
- 447 small layer of smoke appears downstream of the dampers, particularly with the dampers placed at the edge of the tunnel,
- 448 even if the extraction rate is very high (as shown in Fig. 14).



Fig. 15. The velocity ratio R_c -given by the confinement velocity in the tunnel with barriers to the confinement velocity in the empty tunnel- against the plume Richardson number Γ_i , for different shapes and locations of the exhaust vents and with both barriers of height H/4 and H/3.

449 Fig. 16 shows a typical example of the visualisation of smoke behaviour in the tunnel with and without barriers equipped 450 with square-shaped dampers placed on the side (i.e. case in which the confinement flow rates are higher and the level of 451 stratification is worse). The three flow visualisations are obtained for same source conditions ($\Gamma_i = 40, \rho_i / \rho_0 = 0.7$ and D_i / H 452 = 0.56) but for different ventilation flow. Fig. 16a shows the configuration with no barriers, which is the same as that 453 presented previously in Fig. 14c, where we have seen that the stratification of the gases is completely disturbed even before 454 reaching the confinement conditions. The visualisation of the flow in the tunnel with a barrier of height h = H/4 is presented 455 in Fig. 16b. In this case, the total confinement is reached for a $Fr_{0,c} = 0.75$ and the stratification condition of the smoke is 456 better preserved compared to the case of a tunnel without barriers. Small vortices appear and disappear at the interface 457 between the smoke layer and the underlying air flow, but the mixing between the two is small. The behaviour of the 458 confinement smoke can therefore be considered to be in a transition between the stable and unstable stratification regime, 459 which is however significantly different from the unstable regime observed in the case without barriers (Fig. 16a). The 460 visualisation of the smoke flow in the tunnel with the largest barrier (H/3) is presented in Fig. 16c. In this case, the 461 confinement Froude number is reduced by 55% of its reference value, i.e. in the tunnel without barriers. The stratification of 462 the smoke layer is well preserved so that its behaviour can be identified as a 'stable' regime. This means that the barrier H/3463 allows a complete confinement of the smoke with a transition from an unstable stratification regime in the empty tunnel (Fig. 464 16a) to a fully stable regime in the tunnel with largest barriers (Fig. 16c). The presence of these barriers therefore results in

465 an increased efficiency of the mechanical extraction systems and thus in an improvement of the safety conditions for the

tunnel users.



Fig. 16. Visualisation of the smoke flow in the tunnel equipped with square shaped dampers placed on one of the sides of the tunnel ceiling (confinement conditions with $\Gamma_i = 40$). a) Tunnel without barriers ($Fr_{0,c} = 1.10$). b) Tunnel with a large barrier H/4 ($Fr_{0,c} = 0.75$). c) Tunnel with a largest barrier of height H/3 ($Fr_{0,c} = 0.50$).

467 4 CONCLUSIONS

In this study, we performed a series of experiments in a small-scale tunnel to study the propagation of buoyant smoke injected into a tunnel where the plume is confined between two exhaust vents located on each side of the source. Our analysis focuses on two main geometrical parameters: the shape of the dampers (square and rectangular with same surface area) and the position of the square-shaped dampers (in the centre and on the side of the tunnel ceiling). Our aim was to evaluate the influence of these parameters on i) the backflow length downstream of the dampers, ii) the confinement velocity and iii) the preservation of the stratification of the smoke flow. The main findings are:

- 474 The back-layering length decreases more rapidly with rectangular shaped dampers. Its evolution, in the case of 475 square-shaped dampers, begins with a rapid decline followed by a slight decrease when $L/H \approx 1$.
- 476 The Froude number defined as $Fr_{0,c} = U_{0,c}/(B_i/H)^{1/3}$ (or as $Fr_{0,c} = U_{0,c}/(Q_c/H)^{1/3}$ for a fire plume) is the 477 only flow control parameter. The confinement conditions are reached with a constant Froude number, this gives the 478 relationship between $U_{0,c}$ and B_i/H (or Q_c/H) as follows: $U_{0,c} = Fr_{0,c} (B_i/H)^{1/3}$ (or $U_{0,c} = Fr_{0,c} (Q_c/H)^{1/3}$). 479 The proportionality factor ($Fr_{0,c}$) depends on both the shape and the position of the dampers, its values are lowest 480 with the rectangular dampers and are highest with the square dampers placed on the side of the tunnel ceiling.
- 481 The stratification of the smoke layer is affected by the extraction rate. The higher the flow rate, the more unstable
 482 the smoke stratification. Depending on the Froude number, the flow configurations can be classified into three
 483 regimes: stable, transient and unstable.
- 484 The confinement conditions are achieved in the stable regime with rectangular dampers, in the transition regime
 485 with square dampers placed in the centre and in unstable regime with square dampers placed on the side.

In conclusion, the shape and location of the dampers play an important role on the control of smoke in transverse ventilation tunnels. The results highlight two main features: first, the width of the damper is the relevant length scale; the larger it is, the better the smoke control and the second, the location of the vents on the tunnel ceiling is critical; the closer they are to the centre, the more effective they are.

- 490 Subsequently, we evaluated the effectiveness of solid barriers, placed at the tunnel ceiling downstream of the dampers, on
- 491 improving the efficiency of the ventilation system. The results showed that they only have an influence when the width of the 492 dampers are smaller than the width of the tunnel. In such a case, the confinement velocity is significantly reduced and the
- 493 stratification level of the smoke layer is greatly enhanced, especially when the height of the barrier is large.
- 494 These results provide interesting indications for the optimisation of transverse ventilation systems. The reduction of the
- 495 extraction flow rates is first and foremost an economical solution, since it allows for a reduction of the energy consumption.
- 496 In addition, the definition of the optimal flow rate is also essential to ensure the safety of the tunnel users, by identifying the
- 497 ventilation conditions preserving the stratification of the smoke layer confined between the two dampers. Installing mobile
- 498 barriers can help with this, these barriers improve the performance of the smoke extraction system and therefore ensure a
- 499 highest level of safety for users in the instance of a fire.
- 500 In this study, we focused on geometrical configurations of the dampers in which their distance from the buoyant source was
- 501 fixed, and equal to 5H. Further work will be then needed to study the effect of asymmetric dampers location (relative to the
- 502 source position), of the variation of the distance between the source and the dampers, of the variation of the cross-sectional
- 503 area of the extractor vents as well of the presence of traffic flows on the smoke propagation [31] will be studied. Other
- 504 research work will also have to investigate the role of heat losses induced by radiation and thermal conduction at tunnel walls
- 505 (see Salizzoni et al. [30] for a similar study in the case of longitudinal ventilation).

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