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Aerodynamics of buoyant releases within a longitudinally ventilated tunnel

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ABSTRACT

The dynamics of a positively buoyant release in a cross-flow within a rectangular channel are investigated. In particularly, we focus on the effects that determine the so-called 'critical ventilation velocity' that prevents the development of any back-layer flow upstream the buoyant source. To that purpose, we firstly identify the non-dimensional parameters that govern the flow dynamics within the tunnel. We then perform a parametric study by means of laboratory experiments, in order to draw the dependence of the non-dimensional critical velocity on these governing parameters. The results show that, in the range of values of the parameters investigated, the flow is mainly sensitive to only one parameter, the plume Richardson number, that expresses the balance between momentum and buoyancy at the source. In particular, it is remarkable that the non-dimensional critical velocity does not exhibit any significant dependence on the ratio of the ambient and the buoyant fluid densities, a parameter whose variations are usually related to the rising of non-Boussinesq effects. This has important implications in the simulation of these flows both by simple analytical models and by more complex CFD codes. The dynamical behaviour identified in the experiments provides also a reliable interpretation for the dependence of the critical velocity on the heat release rate of large fires observed by previous authors, both in laboratory and in situ experiments.

1. Introduction

When a buoyant fluid is continuously released in a longitudinally ventilated tunnel, it can be fully blown downstream the source location if the longitudinal velocity is high enough (Fig. 1a). Nevertheless, due to its buoyancy and its momentum, in some cases the buoyant release can flow upstream (against ventilation) in the form of a stratified layer (Fig. 1b), usually referred to as 'backlayering'.

Such a flow can be encountered in various environmental problems, as the dense pollutant discharge in coastal regions [3] or the dynamics of atmospheric cool pools [11], and it has been widely studied during the last 50 years for tunnel fire safety issues. From pioneer theoretical approaches by Thomas [12] and Danziger and Kennedy [2] to the recent laboratory experiments by Wu and Bakar [16] and Vauquelin [13], the longitudinal airflow able to prevent this backflow in a tunnel has been investigated in terms of fire heat release rate (HRR) dependency. The term 'critical' has been associated with the situation corresponding to the limit between the two flow patterns presented in Fig. 1. In particular, this state is identified by the rising of a small recirculating bubble immediately upstream the region where the buoyant plume impinges the tunnel ceiling.

Although a consistent scatter in different numerical and experimental data of this 'fire in tunnels' literature, it is usually stated that the 'critical' longitudinal airflow varies with the cubic root of the HRR for small values of the HRR and becomes almost constant for higher values. The reason for this behaviour can be attributed to different dynamical aspects whose relative influence is not fully understood.

In this paper, we propose to revisit this issue by analysing the dynamics of a release of buoyant fluid within a ventilated tunnel. Our aim is to focus on the influence of the source parameters (size, velocity and density) on the critical condition, rather than globally consider the source through its buoyancy flux only (or its equivalent HRR). A dimensional analysis of the problem is first proposed to identify the non-dimensional parameters governing the flow dynamics (Section 2). Parametrical tests are then performed on an air-helium reduced scale tunnel (Section 3) in order to determine the dependencies between these non-dimensional

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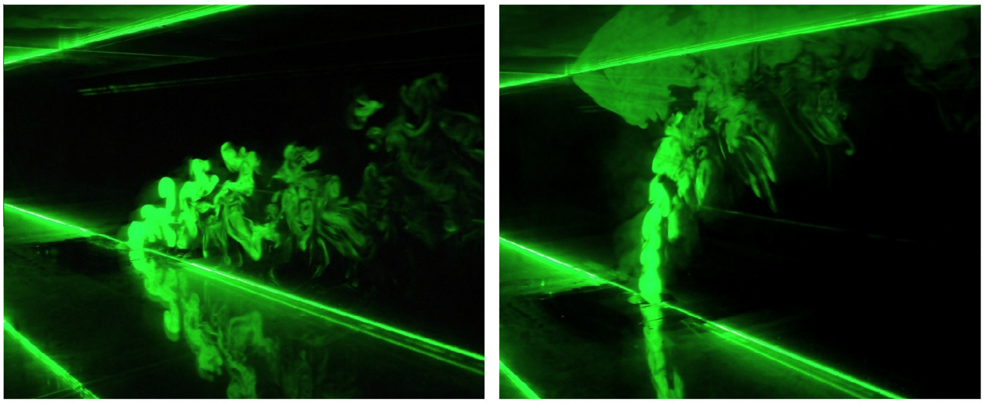
(a) (b)

Fig. 1. Flow visualisation within the reduced scale tunnel, with a ventilation blowing from left to right. (a) Buoyant release fully blown downstream the source; (b) stratified layer flowing against tunnel ventilation.

parameters (Section 4). We finally discuss the implications of our findings for safety issues in tunnels (Section 5).

2. Dimensional analysis

We consider the release of a buoyant gas within an indefinitely long tunnel with a rectangular cross-section (height H and width L) and longitudinally ventilated. The buoyant source is circular and placed at the floor, at the centre of the tunnel. The buoyant release is due to the injection of light gas into an ambient fluid with a reference density ρ_0. The interaction between the buoyant plume and the longitudinal airflow within the tunnel can induce a backlayering flow developing close to the tunnel ceiling. The longitudinal extension of this back flow, referred to as ℓ (see Fig. 2), depends on the condition imposed at the injection source (velocity W_i, density ρ_i and diameter D_i), on the velocity U of the longitudinal airflow in the tunnel, on the tunnel geometry and on the physical properties of the fluid, i.e. its molecular diffusivity D_m and its viscosity ν (for the sake of simplicity we neglect an eventual difference between the viscosities of the two fluids) and on the module of the gravitational acceleration g. In a general form we can therefore write:

$$\ell = f(U, W_i, \rho_i, \rho_0, \nu, D_m, g, D_i, L, H) \qquad (1)$$

Eq. (1) shows the dependence of ℓ on ten dimensional parameters, with three independent dimensions (time, length and mass). In accordance with the Vaschy – Buckingham theorem we can then express the dependence of the non-dimensional backlayering length on seven non-dimensional governing parameters, that fully characterise the physics of the phenomenon. Eq. (1) can therefore be rewritten as:

$$\frac{\ell}{H} = f\left(\Gamma_i, \mathrm{Re}, \mathrm{Sc}, \frac{\rho_i}{\rho_0}, \frac{U}{W_i}, \frac{D_i}{H}, \frac{L}{H}\right) \qquad (2)$$

where $\mathrm{Re} = W_i D_i/\nu$ is the source Reynolds number, $\mathrm{Sc} = D_m/\nu$ is the Schmidt number and Γ_i is the so-called 'plume Richardson number' (e.g. 4) at the source, defined as:

$$\Gamma_i = \frac{5}{16\alpha}\frac{g\Delta\rho D_i}{\rho_0 W_i^2} \qquad (3)$$

where $\Delta\rho = \rho_0 - \rho_i$ and $\alpha = 0.1$ is a reference top-hat plume entrainment constant [8]. The value of Γ_i allows us to classify different plume typology [6]. The condition $\Gamma_i = 1$ identifies a 'pure' plume, with an initial dynamical equilibrium between momentum and buoyancy. A plume is then referred to as 'forced' when $\Gamma_i < 1$, i.e. with an excess of momentum flux compared to the buoyancy flux, and as 'lazy' [4] when $\Gamma_i > 1$, i.e. with a deficit of momentum flux compared to the buoyancy flux.

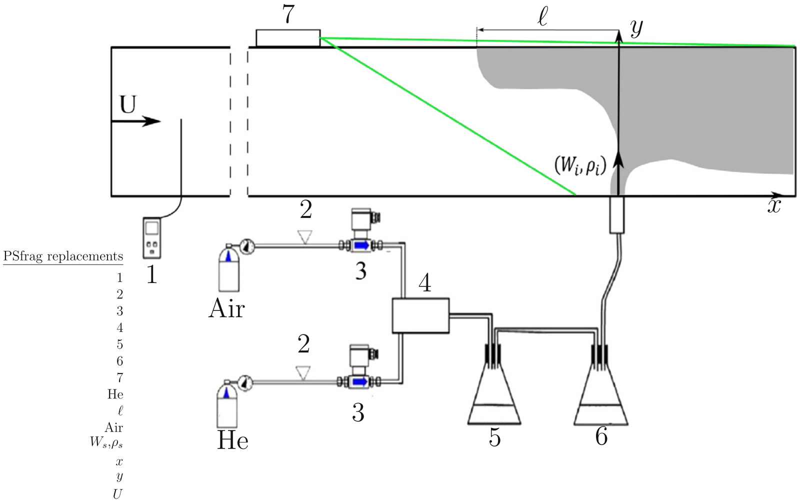

Fig. 2. Experimental set-up of the reduced scale tunnel. Hot wire anemometer (1), manometers (2), flow metres (3), mixing chamber (4), solution of hydrochloric acid (5), solution of concentrate ammoniac (6), laser source (7).