International Journal of Heat and Mass Transfer 117 (2018) 143–153

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Influence of source conditions and heat losses on the upwind back-layering flow in a longitudinally ventilated tunnel

P. Salizzoni [a,*], M. Creyssels [a], L. Jiang [a], A. Mos [b], R. Mehaddi [c], O. Vauquelin [d]

[a] Laboratoire de Mécanique des Fluides et d'Acoustique, UMR CNRS 5509, University of Lyon – École Centrale de Lyon, INSA Lyon, Université Claude Bernard Lyon I, 36, Avenue Guy de Collongue, 69134 Écully CEDEX, France
[b] Centre d'Études des Tunnels, 25 Avenue François Mitterrand, Case n°1, 69674 Bron, France
[c] Université de Lorraine, CNRS, LEMTA UMR 7563, 54 518 Vandoeuvre-lès-Nancy, France
[d] Aix Marseille Université, CNRS, IUSTI UMR 7343, 13 453 Marseille, France

ARTICLE INFO

Article history:
Received 6 February 2017
Received in revised form 18 September 2017
Accepted 4 October 2017

Keywords:
Buoyant flows
Turbulent plumes
Back-layering
Tunnel ventilation
Heat transfer

ABSTRACT

We study experimentally the dynamics of a back-layering flow developing below the ceiling of a longitudinally ventilated tunnel, and induced by the presence of a steady source of buoyancy at the tunnel floor. Our aim is to identify the dependence of the longitudinal extent of the back-layering flow upwind of the source (and therefore against the tunnel ventilation velocity) as a function of the parameters characterising the buoyant release at the source and of those characterising the thermal losses at the tunnel ceiling. To this end purpose we performed experiments in two different reduced scale models, using helium and hot air as buoyant fluids. Based on the experimental results, we develop a semi-empirical model for the prediction of the (non-dimensional) extent of the back-layering flow. This can be expressed as a function of three non-dimensional parameters. The first one is the tunnel Richardson number Ri, expressing the ratio between the buoyancy effects induced by the source and the inertia effects of the tunnel ventilation. The second is its critical value Ri_c, obtained by imposing the so-called critical ventilation velocity, preventing the formation of a back-layer flow upstream of the source. The third parameter, referred to as λ_T^*, characterises the heat losses at the tunnel walls. The variability of the conditions imposed at the source, namely the momentum flux related to the injection of buoyant fluid, have negligible influence on the critical condition and therefore on the extent of the back-layering flow (which depends therefore on the buoyancy flux at the source, only). In contrast, the heat losses play instead a major role, which results in a relevant reduction of the back-layering flow that can be five times shorter than in the adiabatic case.

1. Introduction

The release of light fluid from a ground level source placed within a longitudinally ventilated tunnel results in the formation of a bent-over plume [1–3], inclined in the sense of the tunnel ventilation. Depending on the intensity of the ventilation velocity [4], the buoyant fluid can reach the tunnel ceiling and give rise to a horizontal gravity current (see Fig. 1a), referred to as back-layering flow, that develops against the ventilation.

The back-layering flow (Fig. 1b) is driven by the horizontal inertia force and by its buoyancy. The presence of a light fluid generates a static pressure gradient that tends to push forward the buoyant fluid, as happens for a gravity current produced by a dense fluid propagating horizontally against a rigid wall [5]. This occurs as long as the wall shear stresses, the shear stresses at the buoyant/non-buoyant fluid interface, and the dynamic pressure exerted by the ventilation velocity at the front of this current are not able to balance the force (per unit volume) related to this gradient and to the inertia of the buoyant fluid. The dynamics of this flow can also be significantly altered by the heat losses to the tunnel ceiling, which reduces the buoyancy of this gravity current.

The study of the dynamics of a back-layering flow is of interest for several engineering applications, related to the need of controlling spread of toxic airborne pollutants within enclosed ventilated spaces. Typical examples are given by the security issues related to the ventilation of (road and railway) tunnels [6–9], escalators [10] and mines [11].

In the studies conducted so far and aiming in characterising the extent of the back-layering length upwind of the source, hereafter referred to as l, most authors have attempted to define its dependence on a reduced number of control parameters, namely the tun-

* Corresponding author.
E-mail address: pietro.salizzoni@ec-lyon.fr (P. Salizzoni).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.017
0017-9310/

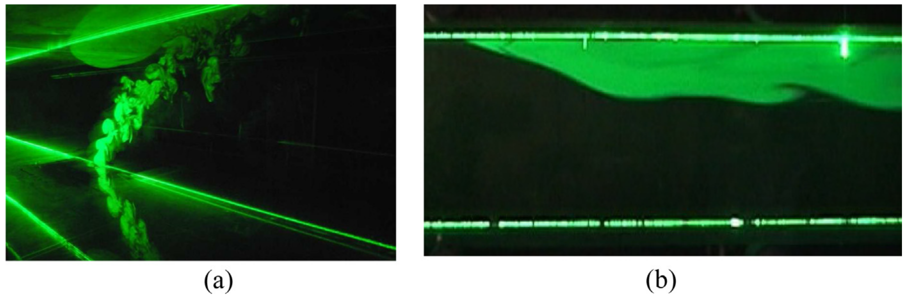

Fig. 1. Back-layering flow visualised on a vertical plane in the 'isothermal' model, and produced by a steady source of helium in a longitudinally ventilated tunnel. (a) Bent-over buoyant plume impinging on the ceiling. (b) Detail of the back-layering front. Tunnel ventilation is directed from left to right.

nel ventilation velocity U, a characteristic length scale of the tunnel (usually its height H or the hydraulic diameter), and the source heat release rate Q_s, or, equivalently the buoyancy flux $B_s = \frac{g}{C_P \rho_0 T_0} Q_s$ (C_p is the specific heat and ρ_0 and T_0 are reference density and temperature values of the ambient fluid). In this framework, the back-layering length can therefore be expressed as

$$l/H = f(B_s, U, H) \tag{1}$$

which according to the Vaschy-Buckingham theorem implies (three independent parameters and two units) a non-dimensional dependence in the form

$$l/H = f(Ri) \tag{2}$$

where $Ri = \frac{B_s}{U^3 H}$ is referred to here as the 'tunnel' Richardson number.

A first model of the length of a back-layering flow was presented by Thomas [12], who suggested a dependence in the form:

$$\frac{l}{H} \propto Ri \frac{T_0}{T_s} \tag{3}$$

with T_0 and T_s the temperature of ambient air and of the buoyant source, respectively. Note that in his definition of the 'tunnel' Richardson number, Thomas [12] used the tunnel width as a characteristic length, instead of the tunnel height.

The experiments by Vantelon et al. [13], performed in a ventilated tunnel at the 1/30 scale and equipped with a gas burner, led to a relevant modification of (3), and to an expression of the back-layering length in the form:

$$\frac{l}{H} \propto Ri^{0.3} \tag{4}$$

The dependency of l/H on $Ri^{1/3}$ was subsequently confirmed by Saito et al. [14], whose results were however significantly different from those presented by Vantelon et al. [13]. A similar relation was also indicated by Deberteix [15], based on experiments in a reduced scale tunnel:

$$\frac{l}{H} = 7.5\left(Ri_*^{1/3} - 1\right) \tag{5}$$

and adopting a different Richardson number defined as $Ri_* = \frac{T_s - T_0}{T_0} \frac{gH}{U^2}$.

Finally, based on experiments in a reduced scale tunnel with a gas burner, Li et al. [16] suggested that the length of the back-layering flow could be modelled as:

$$\frac{l}{H} = \begin{cases} 18.5 \ln\left(0.81 Ri_*^{\frac{1}{3}}\right) & \text{for } Q^* \leqslant 0.15 \\ 18.5 \ln\left(0.43 \frac{\sqrt{gH}}{U}\right) & \text{for } Q^* > 0.15 \end{cases} \tag{6}$$

with $Q^* = \frac{Q_s}{\rho_0 C_P T_0 \sqrt{gH^5}}$ a non-dimensional heat release rate, and with a Richardson number Ri_* which is the same adopted by Deberteix [15].

In order to have a global overview on the results obtained in previous studies, we have collected these in a single graph, which is presented in Fig. 2, where we plot the non-dimensional back-layering length l/H as a function of the tunnel Richardson number Ri. The plot includes data in a variety of experimental conditions in which the back-layer flow could be produced by isothermal buoyant plumes [17], gas burners [13,16] as well as smoke plumes due to burning tires [12].

When considering results obtained with given experimental conditions, the data suggest a one-to-one dependence $l/H = f(Ri)$. However, when observing the big picture, it is evident that the plot shows a significant dispersion of the experimental data. This can be attributed to two main features. Firstly, the rate at which l/H increases as a function of Ri, is very different for the different datasets. Secondly, the different sets of data are characterised by different values for $l/H = 0$, a condition that we refer here as 'critical', since it corresponds to that imposed by the so-called 'critical velocity' U_c [6,7,18]. Considering the set of data of Vantelon al. [13], the difference in the critical condition (compared to other set of data) is likely to be due to a different definition of the reference position at which the back-layering front is brought to rest by the ventilation. In the case of the set of data of Megret [17], this is instead likely to be due to conditions (initial momentum, diameter) imposed at the source.

It is therefore evident that, in a general way, we cannot identify a clear dependence of l/H on Ri only. It is indeed worth noting that a direct relation between l/H and Ri implies a description of the system in which it is implicitly assumed that the source conditions can be fully characterised by the buoyancy flux B_s only, therefore neglecting any further information about its radius, temperature (or density) and velocity. These latter parameters, as well as a gen-

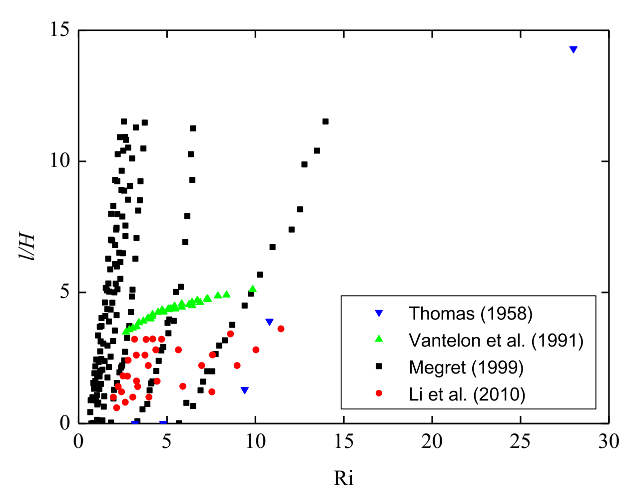

Fig. 2. Overview of previous literature results.