Dynamics of Densimetric Plumes and Fire Plumes in Ventilated Tunnels

Lei Jiang, Pietro Salizzoni, Matheiu Creyssels

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.

The study of the release of a buoyant fluid within a layer of ambient fluid confined vertically and laterally is of major interest in industrial and environmental flows. In the thesis we investigate the dynamics of a release of buoyant fluid discharged within a tunnel and subjected to a forced mechanical ventilation. A peculiar aspect of these flows (see Fig.1) is the appearance of a backlayer of buoyant fluid, which forms after impingement of the release at the confinement surface (or at the ground), and whose front, driven by a pressure gradient, can move forward against the ventilation (depending on its intensity).

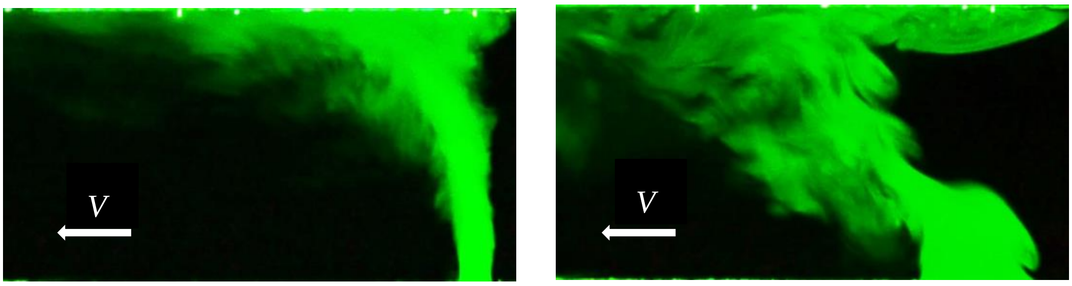

Figure 1 Flow visualisations of the buoyant release submitted to a critical ventilation velocity (from right to left): (left) forced release (momentum dominated); (right) lazy release (buoyancy dominated).

The focus is on the control of the propagation of this buoyant front by means of the forced tunnel ventilation. This issue is directly linked to industrial and transportation safety problems related to the dispersion of harmful gases in confined spaces. Examples include the leakage of high pressure natural gas from pipelines, the accidental releases of hydrogen or hydrogen sulfide, and the propagation of smoke from fires in road and rail tunnels as well as on underground escalators.

This problem has been notably addressed to assess the safety of twin-bore road tunnels, where the ventilation velocity, which blows all the smoke downstream, allowing the users to evacuate by the entrance, is usually referred to as the ‘critical velocity’. These practical implications are therefore related to a fundamental problem, that of defining the intensity of the ‘critical’ ventilation velocity depending on the geometrical and dynamical conditions at the source.

This thesis investigates experimentally, theoretically and numerically the critical ventilation velocity in longitudinal ventilated tunnels in case of a fire.

The fire is first modeled by a release of light gas in ambient air. In the experiments, the light fluid is an air/helium mixture. A simple mathematical model, based on the classical plume study, is formulated to interpret the variations of the critical velocity as a function of the source conditions (momentum and buoyancy fluxes and geometry). A good agreement is observed between the experimental results and the theoretical predictions for both the momentum-driven and buoyancy-driven releases. For momentum-driven plumes, the influence of the source radius and the non-Boussinesq effects (the effects due to large differences between the densities of the buoyant plume and the ambient fluid) are not negligible, and both the features can be well described by the model. For buoyancy-driven plumes, both the experiment and the model show that the non-Boussinesq effects are negligible.

Subsequently, the difference between a buoyant plume and a fire is studied, by combining experiments and numerical simulations. The reason for the appearance of the so-called 'super-critical' velocity, a ventilation velocity that becomes independent of the heat release rate when it becomes large, is discussed. It is shown that small fires can be reliably modeled as buoyant densimetric plumes released at ground level. The dynamics induced by larger fires require instead the modeling of large flames and hence a volumetric source of heat and buoyancy within the tunnel. In the simulation of fires, when the heat release rate is increased, the volume of combustion also increases, but the critical velocity remains nearly constant, which validates the appearance of the `super-critical' velocity.

The effect of tunnel inclination on the critical velocity is then studied. The influence of slope (defined as negative when the entrance of fresh air is at a lower elevation than the source) on the movement of smoke is mainly related to the role of the component of buoyancy along the tunnel axis. A positive slope helps the formation of the backlayer, while a negative slope helps reaching the critical condition. However, this effect depends on the source condition. Our experiments and numerical simulations on densimetric plumes suggest that the dynamical condition at the source affects the critical velocity of a buoyant plume: when the buoyant plume is momentum-driven, the influence of slope is small; when the buoyant plume is buoyancy-driven, the influence of slope is large. This behavior can be well described by a theoretical model based on the previous model of the critical velocity in a horizontal tunnel. These results have been extended to the case of fires by conducting numerical simulations and there is again a good agreement between the observed results and the theoretical model. In particular, the ratio of the critical velocities obtained for an inclined and an horizontal tunnel is independent of the power of the fire.

Finally, the effect of vehicular blockage on the critical velocity is studied experimentally and numerically. The vehicles are modeled by blocks of different sizes placed upstream of the buoyancy or fire source. It is shown that only the block close to the source affects the critical velocity, whereas the effect of other blocks of the same size located further upstream is negligible. As the fire-blockage distance becomes larger, the critical velocity changes and becomes close to the value in an empty tunnel. The relative position between the blocks and the fire source has large influence on the critical velocity. When the blocks are placed at the center laterally, the ventilation flow cannot reach the fire plume directly, a larger critical velocity is needed compared with that in a corresponding empty tunnel. On the other hand, when the blocks are placed at the sides laterally, the ventilation flow can directly impact the fire plume and a smaller critical velocity is needed, with a reduction ratio similar to the blockage ratio. It is also found that the changing of critical velocity ratio (ratio between the case with blocks and that in an empty tunnel) is mainly affected by the blocks, whereas the effect of the source condition (buoyant plume, small or large fire) is small.

For further information, please consult the thesis:

Lei Jiang, 2017. Dynamics of Densimetric Plumes and Fire Plumes in Ventilated Tunnels. École Centrale de Lyon.