PLUME RISE AND SPREADING IN BUOYANT RELEASES IN THE ATMOSPHERE: REDUCED SCALE EXPERIMENTS AND STOCHASTIC MODELING

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INTRODUCTION

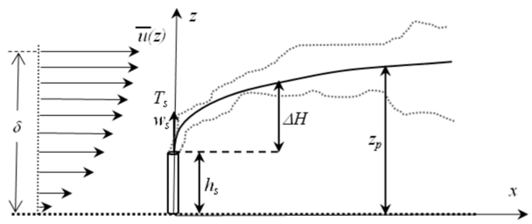
Gas emissions from incinerators, power station stacks and many other pollutant sources are characterised by higher vertical velocity and temperature than the ambient air. These source conditions have two main effects on the plume dynamics and pollutant dispersion: 1) they influence the trajectory of the plume centre of mass producing the plume rise phenomenon; 2) they provide a local production of turbulence that results in higher mixing with the ambient air with respect to that due to the atmospheric turbulence only.

Nowadays, a large number of studies have tested the accuracy of plume rise integral models by means of a comparison between numerical solutions and averaged trajectory of the plume centre of mass measured in small scale experiments (e.g. Contini and Robins, 2001). On the contrary, there are few works that systematically compare the concentration fields produced by buoyant plumes. Among these we cite Webster and Thomson (2002), who simulate the light gas release in the Kincaid experimental campaign, Anfossi et al. (2010) who perform the simulation of dense gas dispersion in the Thorney Island experiment. To our knowledge, the studies providing comparisons between dispersion models and small scale experiences in wind tunnel are rare (e.g. Schatzmann, 1979). The aim of this work is to fill this gap. To this purpose we have designed an experimental campaign and used its results to evaluate the accuracy of a Lagrangian dispersion model.

WIND TUNNEL EXPERIMENTS

The experiments were performed in the wind tunnel of Laboratoire de Mécanique des Fluides et d'Acoustique (LMFA) at the Ecole Centrale de Lyon (ECL). We reproduced a physical model of a small scale stack emitting hot air in a transversal air flow .

Experimental set -up



An adiabatic atmospheric boundary layer flow was obtained by means of vortex generators and a roughness distribution placed, respectively, at the wind tunnel inlet and on the ground. The measurements of velocity are performed through a *X*-wire anemometer.

The gas was released from a stack model of diameter d_s=0.027 m and height h_s=0.04 m; the boundary layer depth δ is equal to 0.54 m. The temperature range of the smokes going out the stack varies between 348 and 423 K.

We focus on the influence of two parameters:

- $R = w_s / u_\infty$ ratio between the gas velocity at the stack, w_s, and the flow field velocity at the boundary layer height, u_∞;

- the Froude number $Fr = u_\infty \Big/ \sqrt{g d_s \frac{\Delta\rho}{\rho_a}}$ where g is the acceleration of gravity and $\Delta\rho$ is the difference between density of the ambient air, ρ_a, and emitted gas, ρ_s;

The Froude number values are in the range 2.9-9.5 and the velocity ratio *R* varies from 1.8 to 6. The plume temperature profiles at varying distance from the source (from 0.25 m to 2.0 m) were measured by a thermocouple placed on a moving truck.

MODELLING

Plume rise

The plume rise is simulated by an integral model solving the mass, momentum and enthalpy balance equations, similarly to the Gaussian model ADMS (Robins et al., 2009). The variables that describe the plume dynamics are obtained by space and time averaging on the transversal sections of the plume. The effects due to the external air entrainment inside the plume are parameterised by the entrainment velocity that linearly depends on the ambient turbulence and the relative motion between the plume centre of mass and the external velocity. The model assumes a plume with circular cross-section, uniform properties within it and no retroaction on the atmospheric turbulence dynamics.

The integral model is coupled to the Lagrangian model SLAM with the aim to simulate the plume rise effects on the dispersion of the pollutants emitted from the stack. The temporal evolution of the velocity and position X_i of each particle is described through the following differential stochastic equations:

$$dU_i' = a_i\left(X_i, U_i', t\right)dt + b_{ij}\left(X, U_i', t\right)d\zeta_j \qquad (1)$$

$$dX_i = \left(\langle u_i \rangle + U_i'\right)dt \qquad (2)$$

where is the Lagrangian velocity fluctuation related to the Eulerian mean velocity and is an incremental Wiener process (Gardiner, 1983) with zero mean and variance dt; a_i and b_{ij} are, respectively, the deterministic and stochastic-diffusive acceleration components, which are determined according to the well-mixed condition (Thomson, 1987).

In order to take into account the effect of buoyancy generated turbulence, Webster and Thomson (2002) propose to add a random displacement at each time step in equation (2). We consider an additional spread $r_i=(r_x,r_y,r_z)$ with zero mean and variance σ^2 depending on the variation of b_0 between two time steps:

$$\sigma^2 = \frac{b_0^2\left(t+\Delta t\right) - b_0^2\left(t\right)}{4} \qquad (3)$$

and, finally, the equation (2) assumes the following form:

$$dX_i = \left(\langle u_i \rangle + U_i'\right)dt + r_i \qquad (4)$$

RESULTS

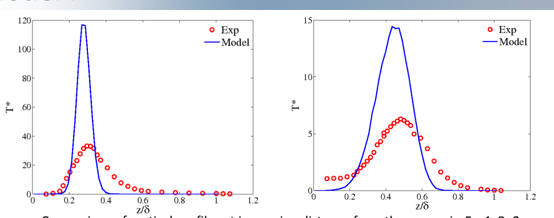
Numerical profiles of temperature are compared with the non-dimensional experimental temperature values:

$$T^* = \frac{\rho_a c_a^p \left(T - T_a\right)}{Q_s}\delta^2 u_\infty$$

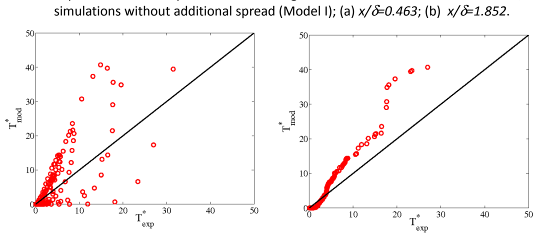
where Q_s is the thermal power at the source. In what follows we compare experimental results with numerical solutions that are computed by means of two different models:

1) a 'classic' Lagrangian model coupled to a plume rise model (***Model I***).
2) a Lagrangian model that includes both a module simulating the plume rise and a module reproducing the additional spread induced by the production of local turbulence due to thermal effects (***Model II***).

Model I

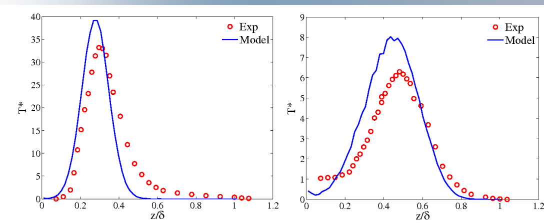


Comparison of vertical profiles at increasing distance from the source in *Fr=4, R=2*; simulations without additional spread (Model I); (a) *x/δ=0.463*; (b) *x/δ=1.852*.

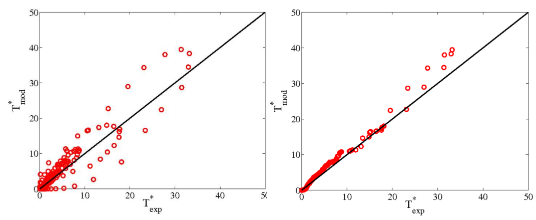


Dispersion Plot (a) and Q-Q Plot (b) for *Fr*=4, *R*=2 (Model I).

Model II



Comparison of vertical profiles at increasing distance from the source in *Fr=4, R=2*; simulations with additional spread (Model II); (a) *x/δ=0.463*; (b) *x/δ=1.852*.



Dispersion Plot (a) and Q-Q Plot (b) for *Fr*=4, *R*=2 (Model I).

CONCLUSION

We observe a significant discrepancy between numerical solutions and experimental data regarding the plume spread when we use the original model (2); the systematic underestimation of the plume spread means that we neglect the effects of the mechanisms of local turbulence production. Such effects are taken into account through an empirical strategy (4). The new simulations are able to correctly reproduce the increasing of turbulence due to thermal and inertial effects, significantly increasing the accuracy of the numerical results.

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