

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

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**Abstract:** This study focuses on the influence of emission conditions – velocity and temperature – on the dynamics of a buoyant gas release in the atmosphere. The investigations are performed by means of wind tunnel experiments and numerical simulations. The aim is to evaluate the performances of a Lagrangian model simulating the dispersion of a plume influenced by thermal and inertial phenomena. Comparisons between experiments and numerical solutions are presented and critically discussed.

**Key words:** pollutant dispersion; Lagrangian models; plume rise; atmospheric turbulence

## 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. This last effect influences the plume behaviour in the stream-wise direction, producing the increase in its (time averaged) section. A correct modelling of both effects is required in order to estimate the concentration distribution of the pollutant emitted from the stack. In order to evaluate the impact of the pollutant sources on the air quality at the ground level, these release conditions have a great influence because they increment the dilution of pollutant and, consequently, may induce reduced concentrations.

Nowadays, a large number of studies have tested the accuracy of plume rise integral models by means of a comparison of the averaged trajectory of the plume centre of mass computed by numerical simulations and measured in small scale experiments (Hewett et al., 1971, 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 (Bowne and Londergan, 1983), 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 the 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 (Figure 1).

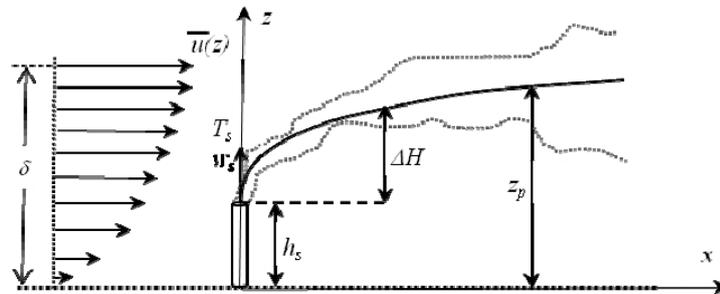


Figure 1: Buoyant plume in an atmospheric flow. The continuous line defines the mean trajectory of the plume centre of mass ( $z_p$ );  $\delta$  is the turbulent boundary layer depth,  $h_s$  is the stack height and  $\Delta H$  is the plume rise due to inertial and thermal effects;  $w_s$  e  $T_s$  are the velocity and temperature at the source, respectively.

### Similarity conditions

The reduced scale simulation of hot gas releases from a stack in an atmospheric neutral boundary layer (Figure 1) requires firstly that the pollutant dispersion takes place within a fully turbulent flow field, reproducing the dynamical characteristics of an atmospheric boundary layer. Further similarity criteria (Robins, 1980, Snyder, 1981) have then to be respected. In general, these are related to the following non-dimensional groups (the subscripts 's' and 'a' are related to the source and ambient air, respectively):

- 1  $h_s/\delta$  ratio between the stack height and the atmospheric boundary layer depth;
- 2  $d_s/\delta$  ratio between the stack diameter and the atmospheric boundary layer depth;
- 3  $R = w_s/u_\infty$  ratio between the gas velocity at the stack,  $w_s$ , and the flow field velocity at the boundary layer height,  $u_\infty$ ;
- 4  $Re_{jet} = w_s d_s / \nu_s$ , where  $\nu_s$  is the cinematic viscosity of the emitted gas at source conditions;
- 5 Froude number  $Fr = u_\infty / \sqrt{g d_s \frac{\Delta\rho}{\rho_a}}$  where  $g$  is the acceleration of gravity and  $\Delta\rho$  is the difference between density of the ambient air,  $\rho_a$ , and emitted gas,  $\rho_s$ ;
- 6  $T_s/T_a$  ratio between the temperature at the source and ambient temperature;

The experimental set up has to be designed in order to avoid the influence of  $Re_{jet}$  and  $d_s/\delta$ . The independence from  $Re_{jet}$  and  $d_s/\delta$  requires, respectively,  $Re_{jet} > 10^3$  (Hewett et al., 1971) and the measurement distance from the emission point  $x > 4\delta$  (Fackrell and Robins, 1982). In what follows we consider the plume dispersion for fixed ratio  $h_s/\delta$  and we focus on the influence of two parameters: the velocity ratio  $R$  and Froude number  $Fr$ .

### Experimental equipment and measure techniques

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 (Irwin, 1981). The measures of velocity are performed through a  $X$ -wire anemometer. In particular, the measures provided the time averaged profiles of longitudinal velocity and the standard deviation of the velocity components. The estimation of the turbulent kinetic energy dissipation rate is performed from the time gradient of the instantaneous velocities assuming the turbulence local isotropy and 'frozen turbulence' hypotheses. These are all the parameters required as input data for a dispersion Lagrangian model.

The gas was released from a stack model placed in a transversal air flow and it produced an ascending sloping plume (Figure 1). The source diameter is  $d_s=0.027$  m and the stack height from the ground is  $h_s=0.04$  m; the boundary layer depth  $\delta$  is equal to 0.54 m. The temperature range of the smokes going out the stack varies between 348 and 423 K. The gas velocity at the source varies between 2 and 7  $\text{ms}^{-1}$ , whereas the velocity at the edge of the boundary layer  $u_\infty$  varies between 0.7 and 1.5  $\text{ms}^{-1}$ . In these conditions, 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. The measures were performed by evaluating the temperature value averaged over two minutes. Two other thermocouples were placed at the stack outlet and upwind the source.

### NUMERICAL MODELLING

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:

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

$$dX_i = (\langle u_i \rangle + U_i')dt \quad (2)$$

where  $U_i'$  is the Lagrangian velocity fluctuation related to the Eulerian mean velocity  $\langle u_i \rangle$  and  $d\zeta_j$  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).

The coupling between the Lagrangian model and the integral plume rise model is performed by imposing in the equation (2) the equality between the Eulerian mean velocity  $\langle u_i \rangle$  and the velocity of the plume centre of mass.

More precisely, the plume is considered as made up some puffs that are constituted by a set of particles; at each time step we evaluate the velocity of the puffs by means of the integral model and we associate it to the corresponding particles. The plume rise, besides influencing the height of the centre of mass, generates some turbulence increasing the plume size. In order to take into account this effect, Webster and Thomson (2002) propose to add a random displacement at each time step in equation (2). The approach is similar to that of the ADMS model (Robins et al., 2009) and adopts a second mass conservation equation in which the entrainment due to the ambient air turbulence is neglected. Such equation allows us to evaluate an equivalent plume radius  $b_0$  depending on time and due to the relative motion between the plume and the external air only ( $u_{ent}^{rise}$ ). Now, we consider an additional spread  $r_i=(r_x, r_y, r_z)$  with zero mean and variance  $\sigma^2$  depending on the variation of  $b_0$  between two time steps:

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

and, finally, the equation (19) assumes the following form:

$$dX_i = (\langle u_i \rangle + U_i) dt + r_i \quad (4)$$

The formulation of this model is based on two implicit assumptions whose ambiguity deserves to be discussed. First of all, we cannot univocally split the plume width into a part due to the external turbulence and a part due to  $u_{ent}^{rise}$ , because the two effects are not linearly additive. Moreover, adding the random displacement  $r$ , that is a Wiener process, to the trajectories of the particles (2), that is a second order Markov process, is an empirical procedure which is in contrast with the theoretical bases of the Lagrangian models (Gardiner, 1983).

## VALIDATION OF THE MODEL

In the dispersion modelling we assume negligible diffusion and radiation effects, so that the temperature  $T$  (and the mass) of each fluid particle remains constant. Numerical profiles of temperature are compared with the non-dimensional experimental temperature values:

$$T^* = \frac{\rho_a c_a^p (T - T_a)}{Q_s} \delta^2 u_\infty \quad (5)$$

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).

We have performed a quantitative evaluation of the accuracy of the numerical results by means of some statistical indices according to Hanna and Chang (2003). The systematic error is evaluated by the Fractional Bias (FB) and Mean Geometric (MG), whereas the local error is given by the Normalised Mean Square Error (NMSE) and Geometric Variance (VG). The statistical analysis of the results is completed by the Dispersion Plot, and the Quantile-Quantile Plot.

### Model I

We performed some simulations using the Lagrangian model SLAM with its original formulation, i.e. the particle trajectories are governed by the equation (2). The results reported in Figure 6 regard the  $Fr=4$ ,  $R=2$  configuration. It is worth noting a significant discrepancy between the measured and numerical profiles varying the distance from the source. Even though the computation of the centre of mass is almost the same, the modelled dispersion intensity is significantly underestimated along the whole plume length. The statistical indicators reported in Table 1 and the graphics in Figure 7 show a substantial overestimation of the numerical results and the ineffectiveness of the model to reproduce this phenomenon. It is clear that the dynamics of the plume is not correctly simulated and some mechanisms influencing the plume dispersion are neglected.

Table 1: Statistical indices of the simulations without additional spread of  $Fr=4$ ,  $R=2$ .

FB	NMSE	MG	VG
-0.52	4.62	0.79	2.31

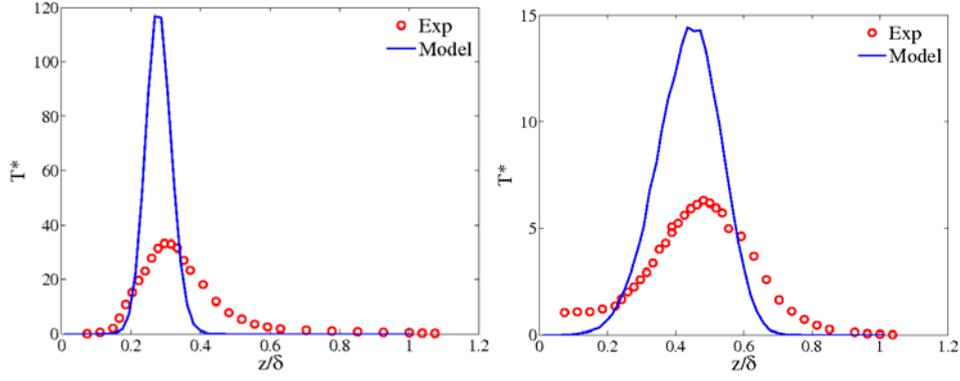


Figure 2: Comparison of vertical profiles at increasing distance from the source in  $Fr=4$ ,  $R=2$ ; simulations without additional spread (Model I); (a)  $x/\delta=0.463$ ; (b)  $x/\delta=1.852$ .

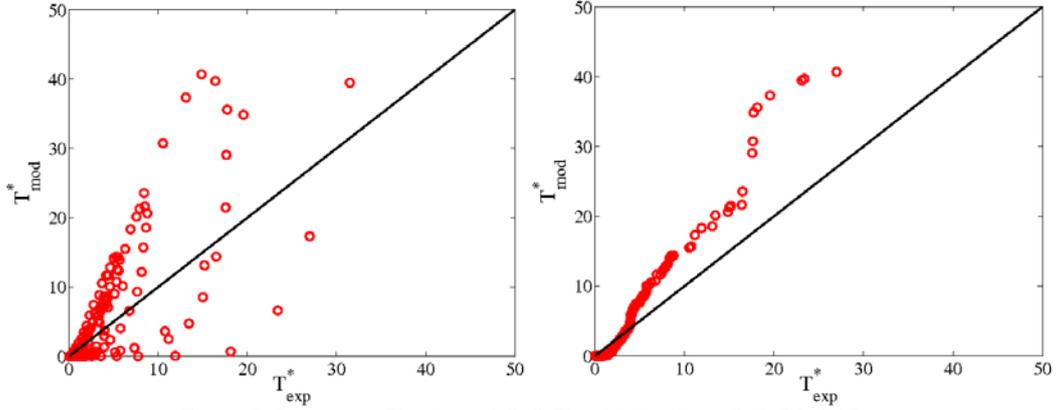


Figure 3: Dispersion Plot (a) and Q-Q Plot (b) for  $Fr=4$ ,  $R=2$  (Model I).

## Model II

The trajectory of the particles is governed by equation (4) where we added a new dispersion term due to the local generation of turbulent fluctuations produced by thermal phenomena; these effects are modelled as a function of the temporal variation of the plume transversal size (§3.2). Figure 4 reports non-dimensional profiles at  $Fr=4$ ,  $R=2$  and shows that the results computed by the modified model are more accurate and their agreement with the experiments is better.

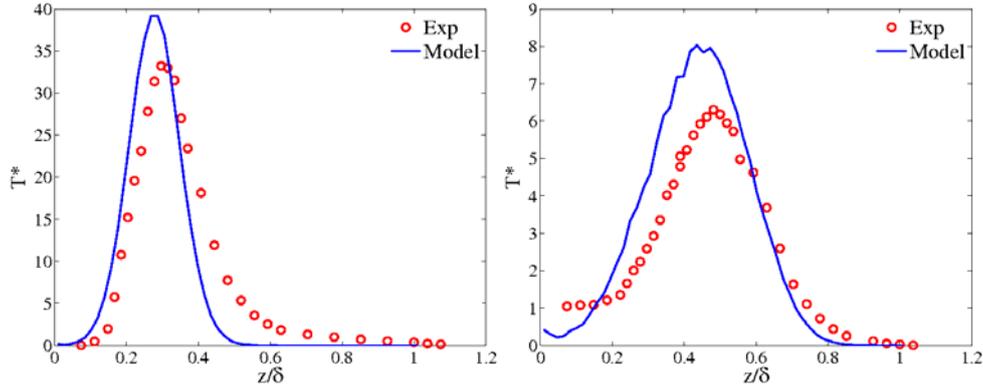


Figure 4: Comparison of vertical profiles at increasing distance from the source for  $Fr=4$ ,  $R=2$ ; simulations with additional spread (Model II); (a)  $x/\delta=0.463$ ; (b)  $x/\delta=1.852$ .

Table 2: Statistical indices of the simulations with additional spread for  $Fr=4$ ,  $R=2$ .

FB	NMSE	MG	VG
-0.133	0.322	0.911	1.503

The new simulations allow a significant improvement of all the statistical indices (Table 2) with respect to those previously obtained through the old model, where the particle trajectories are governed by the equation (2).

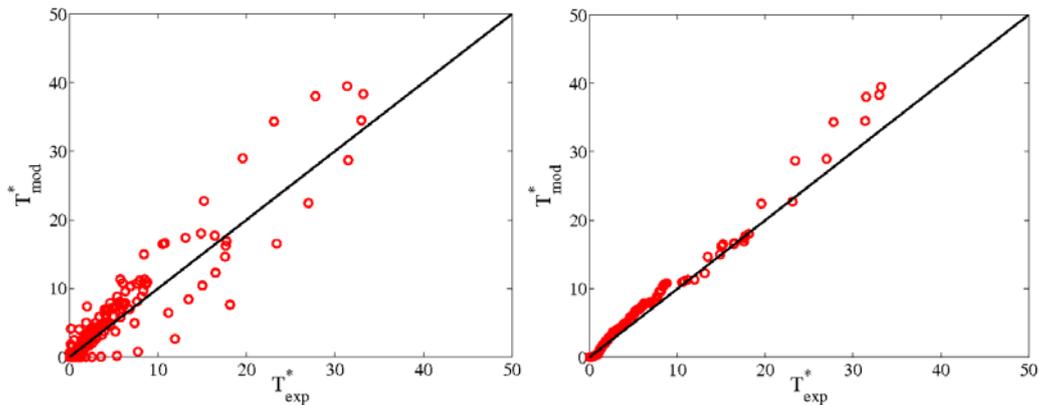


Figure 5: Dispersion Plot (a) and Q-Q Plot (b) for  $Fr=4$ ,  $R=2$  (Model II).

The Q-Q plot (Figure 4b) shows a distribution of the values close to the 1-1 line with a low dispersion of the data; that means that there is a good statistical agreement between numerical and experimental results. Figure 10a shows a not negligible dispersion of the data. This distribution is due both to the error coming from the estimate of the plume spread, and to the error provided in the computation of the centre of mass. It is worth noting (e.g. in Figure 4a) that low errors in the estimation of  $z_p$  cause a not perfect overlapping of the numerical and experimental profiles of  $T^*$  and that can produce not negligible local error.

## CONCLUSIONS

The dispersion of a plume characterised by thermal and inertial phenomena was experimentally and numerically studied. The phenomenon was investigated varying conditions at the stack, i.e. velocity and temperature. The numerical simulations were performed by two stochastic Lagrangian models and the reliability of the solutions was evaluated. 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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