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# PHYSICAL MODEL OF BUOYANT PLUME DEVELOPMENT

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**Abstract**: In this work we aim at investigating a negatively buoyant plume and providing quantitative estimates of the effect of a background rotation on the dynamics of the turbulent plume, with a focus on the intensity of the fluxes of ambient fluid entrained within the plume depending on the parameters that control the flow dynamics. The experiments were performed taking advantage of recent works on the dynamics of atmospheric downburst and on the analysis of the entrainment coefficient in plumes with varying dynamical states.

***Key words:** physical model, buoyant plume, particle image velocimetry.*

## INTRODUCTION

Axisymmetric turbulent forced plumes produced by horizontal, circular sources of constant buoyancy, momentum and volume fluxes have been the subject of considerable research over the last 70 years or so. Zeldovich (1937) and Morton (1959) developed the classic plume model assuming a conceptual point source of buoyancy flux alone, complete dynamical self-similarity, fully-developed turbulence, small density differences and negligible diffusion and radiation. The backbone of this theory has remained virtually unchanged, although validated by a limited number of experimental results focusing on the details of the internal flow. Although relatively few, these results have provided a quantification of some of the key dynamical quantities such as the entrainment coefficient. These quantities are however characterized by a non-negligible scatter, with differences that can exceed 20 to 25 %. Despite this scatter, the classic plume solutions provide a robust and reliable model for buoyant plumes in geophysical and industrial contexts and have been extended to account for stratified environments (Caulfield and Woods, 1998), non-constant source strengths (Scase et al., 2006), chemical reactions (Zhou et al., 2002), non-Boussinesq plumes (Rooney at al., 1996) and background rotation (Fernando et al., 1998 and

Yamamoto et al. 2011). The objective of this work is to study the effect of rotation on the turbulence within a buoyant plume experimentally, a subject that has been rarely tackled in the literature. The experiments are performed in rotating water tank producing negatively buoyant plumes emitted from a circular source, with varying plume density and background rotation. In particular, we obtained a detailed description of the velocity field within the plume thank to the particle image velocimetry technique. These measurements allow us to provide estimates of the entrainment coefficient (Ezzamel et al., 2015) of the plume depending on the intensity of the effects induced by the background rotating motion and depending on the relative role of buoyancy effects within the plume itself.

## THE EXPERIMENTAL SETUP

The laboratory experiments were performed in the Geophysical laboratory of the University of Torino (*TurLab*). The experimental apparatus was made up of a rotating platform, 6 m of diameter, on which a rotating tank is placed (maximum angular velocity around 20 rpm). The tank of 5 m in diameter was filled with 26-36 cm of fresh water mixed with tracer particles. For the data acquisition a 2-dimensional (2D) PIV (Particle Image Velocimetry) system was used. It recorded a sequence of images of a sheet produced by a vertical green laser with power 2-4 W (Ferrero et al., 2014). To improve the quality of the experimental data, different camera setups were used. To generate the vertical current, a new technique was adopted. A plastic drawer 13.5 cm high with a hole of 2.6 cm closed with a cap of concrete was filled with a salty water solution and settled at the tank water level. Once the solid body rotation was attained, the cap was removed and the vertical density current was generated (see Figure 1). A relevant drawback of this set-up is related to the 2D acquisition system: in some experiments, particularly in those with rotation, the intense horizontal oscillation of the flow field prevents the plume to stay on the laser sheet and hence to be detected by the PIV system. In this paper, we considered the experiments with the following tank rotation periods: T =295s, T =468 s, T =620s and T =∞ s.

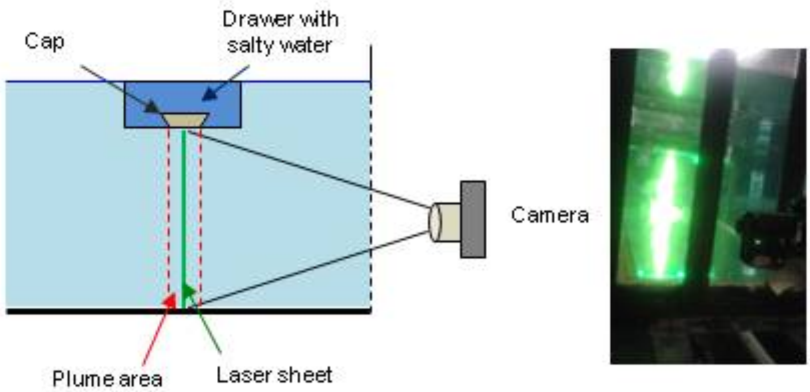
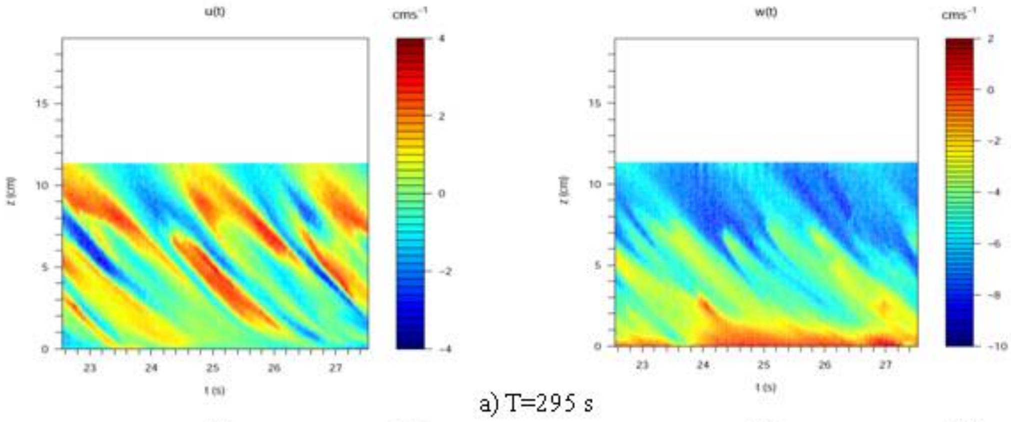


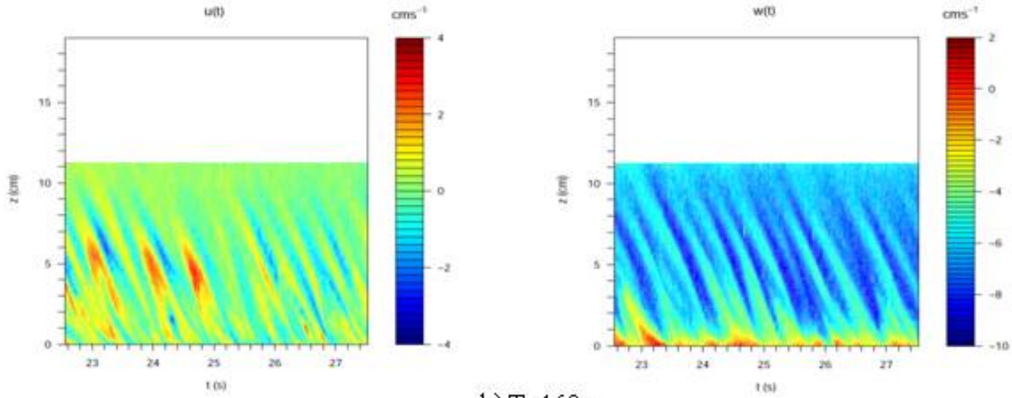

**Figure 1.** Left panel: a side view of the experimental setup. Right panel: an image of the plume produced during the data acquisition.

## RESULTS

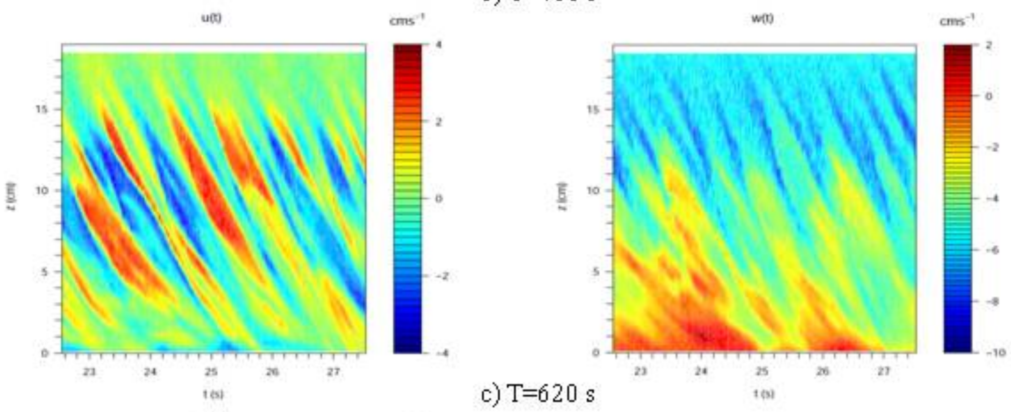
The analysis is performed using a two-dimensional cylindrical coordinates system (*r, z*) with axis of symmetry in the centre of the plume (0, 0) *cm*. The *z* range varies from the tank bottom to the drawer and the radial distance has the origin at the plume centre. The analysis is divided in two sections. The first accounts for the phenomenological description of the current, while the second considers the turbulent kinetic energy (TKE) development.



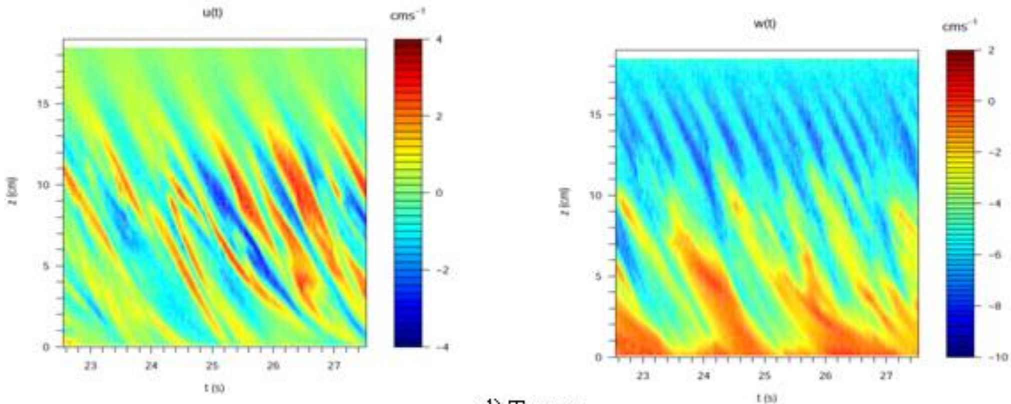
a) T=295 s



b) T=468 s



c) T=620 s



d) T=∞ s

**Figure 3.** Temporal evolution of the radial u (left) and vertical w (right) velocity components in the centre of plume for the different experiments

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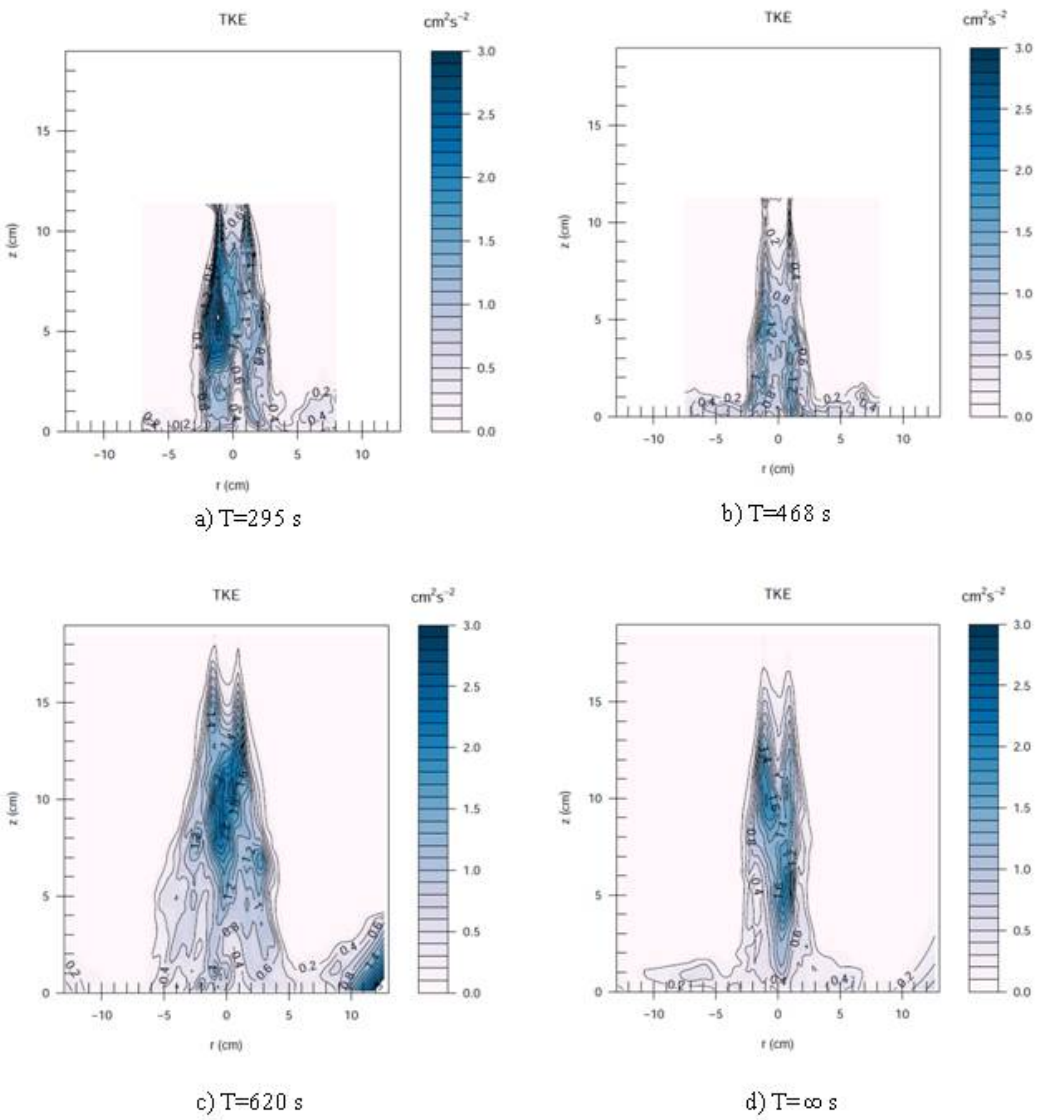


**Figure 4.** Turbulent kinetic energy for the four experiments.

**Phenomenological description**

To provide a description of the vertical current behaviour, the temporal evolution of the radial and vertical velocity components (*u, w*) along the vertical axis of the plume is reported in Figure 2. The *w* component, (right panels in Figure 2) describes pulsed vertical structures of about -8 cm $s^{-1}$ (the blue stripes in the plots). The stripes, with a temporal amplitude of about 0.2 s, are clearly distinguishable and cover most of the *z* range for the experiment with a rotation period of T = 468 s, panel (b) in Figure 2. In contrast, the experiments with faster (T = 295 s), slower rotation period (T = 620 s) and in absence of rotation (T=∞ s) show noisier and generally less intense blue stripes (around -7 $cms^{-1}$). The most intense structures generally ended at mid $z$ and, near the tank bottom, the vertical velocity is close to zero (see the red areas in the plots). The cause is the rebound of the plume on the tank bottom. Information about the propagation of momentum along the current could be obtained from the stripe steepness. Except for the experiment with T = 295s, whereby the steepness remains the same and sometimes decreases approaching the bottom, it shows a common behaviour. The momentum propagation velocity increases approaching the tank bottom. A similar behaviour is observed for the $u$ component (left panels in Figure 2).

**Turbulent Kinetic Energy**

The analysis of the turbulent structures throughout the TKE is useful to establish where the entrainment occurs. As known, the turbulent entrainment takes place across the interface between turbulent/non-turbulent flow and governs the mixing rate and the spread. In addition, at the interface, mass, scalar quantities and momentum exchanges occur. The entrainment seems to be influenced by the small-scale eddy motion. The 2-dimensional TKE fields, calculated as $\frac{1}{2}(\sigma_u^2 + \sigma_w^2)$, are reported in Figure 3 for the different experiments. The TKE reaches its maximum (about 3 $cm^2s^{-2}$) in the intervals between 4 and 8 cm. At lower levels, the TKE distribution covers a large radial area and its intensity decreases also for the presence of the tank bottom. It can be observed an asymmetric behaviour of the plume near the tank bottom, even in the case without rotation. Figures 3 (a, b and d) show that, in presence of strong rotation or in absence of rotation, the turbulence distribution is narrower respect to the case with slow rotation (Figure 3c) in which the turbulence is less concentrated in the central area of the plume and it tends to cover a large radial interval (r ~ −5 / +5cm).

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