Buoyant Plumes in Confined Space

by

Muhammad Eeqmal Eesfansyah Hassim[1], Amey S. Joshi[2], Sivapragasam Munusamy[3], Abu Seena[4], Dongdong Shao[5]

INTRODUCTION

Plume is a flow commonly encountered in nature and our daily life that is driven only by the density difference between the flow and the receiving environment. The source of the density difference can be the difference in temperature, e.g., smoke plume formed above the chimney stack, or the difference in the concentration of the dissolved mass, e.g., salt content or salinity (which is the case in our experiment), or the combination the above two effects, e.g., explosive plume formed in the volcanic eruption.

In an array of plumes with some horizontal spacing R, which is a typical configuration for the smoke stacks, each plume can only entrain ambient fluid in a limited area of R^2 if not interacting with the neighboring plumes. Besides, the vertical rise of the plume is often affected by the atmospheric stratification. These effects of the finite environment on the plume can be modeled by considering a single plume in an enclosed space, both laterally and vertically.

In the present preliminary experimental study, our group (Group C) is to set up a dense plume by injecting salt solution at a constant rate continuously into a small tank with constant rectangular cross section which is filled with fresh water. Dye is added to the source solution to

[1] University of Melbourne, Australia
[2] Bangalore University, India
[3] Bangalore, India
[4] KAIST, Korea
[5] Nanyang Technological University, Singapore

facilitate the observation of the development of the turbulent flow and the subsequent formation of a stable stratification in the environment due to the continuous mass input.

In the following sections, we will briefly review the previous studies on this particular flow, and then describe the experimental setup adopted in our study, which is followed by the major observations made in the experiment as well as some discussions.

‘FILLING BOX’ MODEL

Suppose we have a point source of buoyancy located on the floor of an enclosed space. Driven by the density difference, a rising plume is created within the initially uniform environment. When the front of the plume reaches the upper boundary which is solid and insulating, it spreads out horizontally and then advects downward as pushed by the subsequent flow. Once the front descends, it is entrained by the ascending plume at the same level. Due to the re-entrainment, the plume that reaches the top subsequently becomes even more buoyant than the previous front and hence the replacement is continuous. As a result, the front is pushed further downward and a stable stratification is formed gradually in the environment if vertical overturning does not occur. The whole process is termed ‘filling box’ in the literature. However, it is noted that our experimental setting is exactly an inverse of the case described above as we can find later. The reason for turning the flow upside-down is mainly for the convenience of the experimental operation.

In their original model on the ‘filling box’ problem, Baines and Turner (1969) studied the advance of the first front of the buoyant interface as well as the behaviour in the asymptotic state when the filling lasts for an infinite time. The basic assumption on the asymptotic state is that, since the buoyancy flux is constant, the density deficit and hence the reduced gravity in the ambient decrease linearly with time while the density gradient at all levels stay constant. Together with the conservation equation of the volume, momentum and buoyancy fluxes, the properties of the plume and environment can be resolved.

EXPERIMENTAL SETUP

The schematic of the experimental setup is shown in Fig. 1.

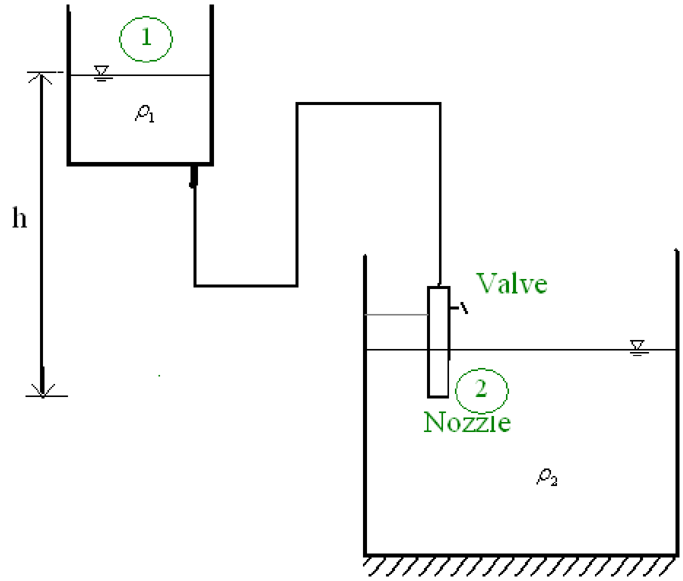


Figure 1 Schematic of the initial experimental setup

It consists of a rectangular glass tank of the dimension 200 mm x 200 mm x 300 mm (*L* x *W* x *H*). This glass tank is filled with fresh water. A cylindrical beaker containing salt water mixed with liquid artificial cochineal dye is elevated at a height *h* from the water surface level in the rectangular tank. The dyed salt water is driven into the rectangular tank by gravity through a nozzle. The flow rate can be controlled by a valve.

From the trial runs conducted with this setup, it was observed that the flow system produced jet-type flow because of the head difference between the water levels. This was immediately rectified with a suitable adjustment of the initial setup. The modified configuration is shown in Fig. 2.

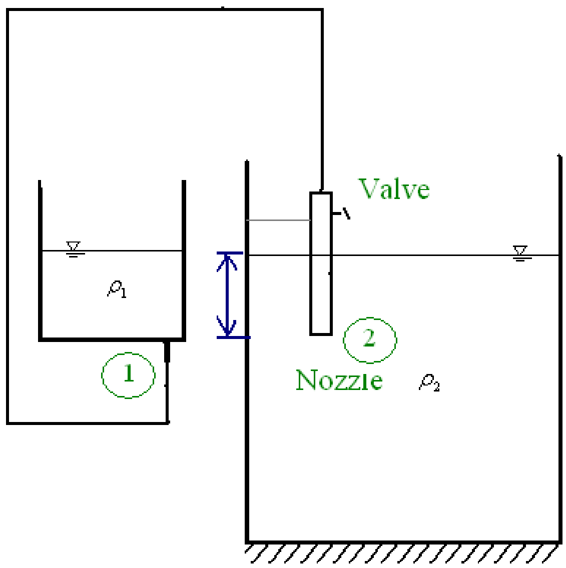


Figure 2 Schematic of the final experimental setup

The cylindrical beaker was lowered so that its water level was in-line with that in the rectangular tank. With such a configuration, the flow is driven by the density difference between the saline solution in the beaker (ρ_1) and fresh water in the rectangular tank (ρ_2), in which $\rho_1 > \rho_2$.

However, during the trial runs, it was found that the valve associated with the nozzle was not tightly sealed which caused entrapment of air in the tube and thus block of flow. Therefore, the nozzle was replaced by a small pipette.

OBSERVATIONS AND DISCUSSIONS

The results reported in this section are from the experiments conducted with the final setup as shown in Fig. 2. The observed plume is shown in Fig. 3. A laminar plume exits the tip of the pipette (the exit is slightly above the top of the field of view). Based on dimensional analysis, the downstream variation of Reynolds number is found to follow $Re=B^{1/3}z^{2/3}/\nu$, where B is the buoyancy flux which is constant for a simple plume in unstratified environment, z is the vertical distance from the exit and ν is the kinematic viscosity of the fluid. Thus, the Reynolds number increases downwards, implying that the laminar plume is in a transition to turbulent plume. Presumably, the transition is triggered by the shear-induced instability as the velocity gradient at the inflection point in the velocity profile of the plume is very significant. The turbulent plume expands vertically downwards in a conical shape, which features two trains of rolling-up eddies on the sides of the cone, entraining the ambient water into the flow.

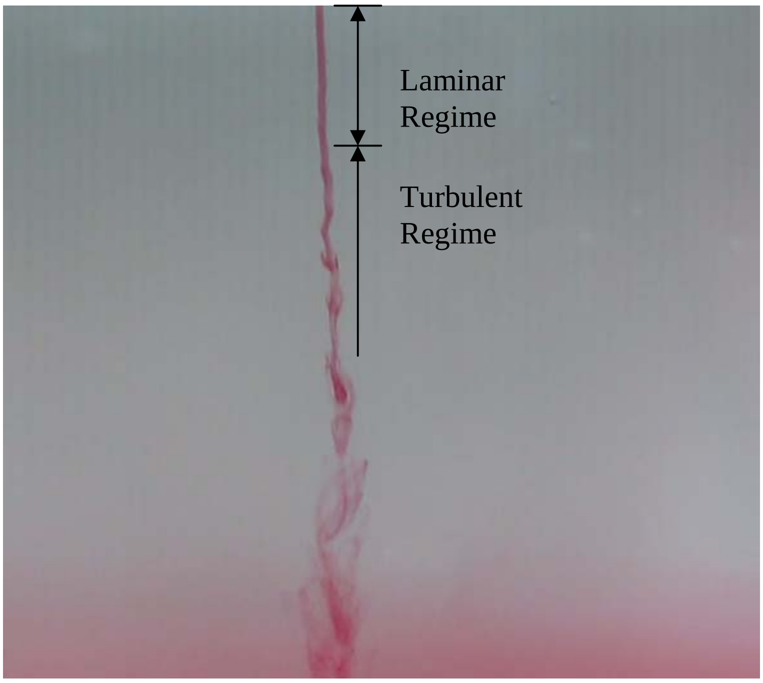
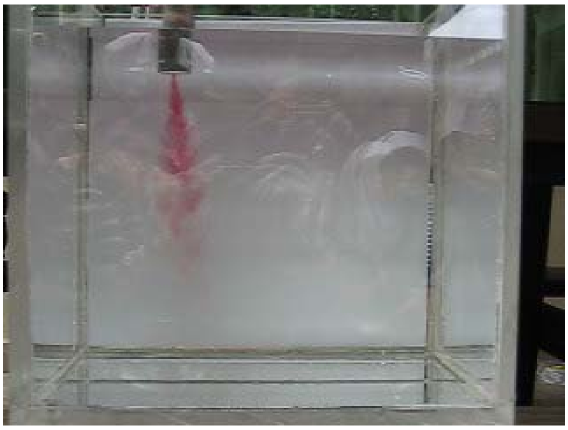
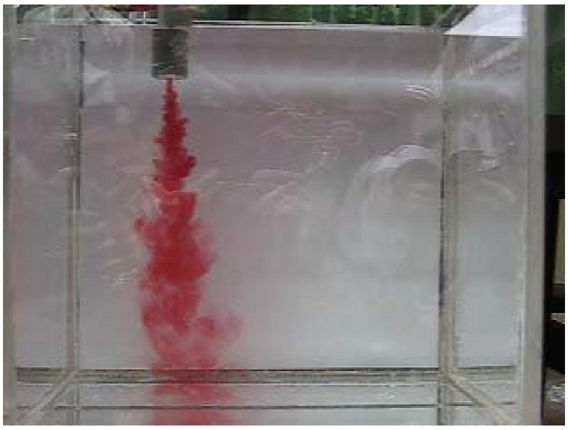


Figure 3 Typical picture of the flow development

The heavier solution starts to deposit on the bottom of the tank, and eventually fills up the entire tank through the ascending of the dense layer interface. As noted in the previous section, this process is exactly the inverse of the ‘filling box’ process. A series of photos extracted from the video record are presented in Fig. 4, indicating the time history (flow stars at t = 0s).



(a) t = 5s



(b) t = 10s

(c) t = 15s

(d) t = 30s

(e) t = 40s

(f) t = 55s

Figure 4 Time history of ‘filling box’ process

An interesting phenomenon was observed during the experiments as shown in Fig. 5. As can be seen from the figure, the plume leaving the nozzle features a series of blobs. This anomaly could be possibly due to the Kelvin-Helmholtz instability.

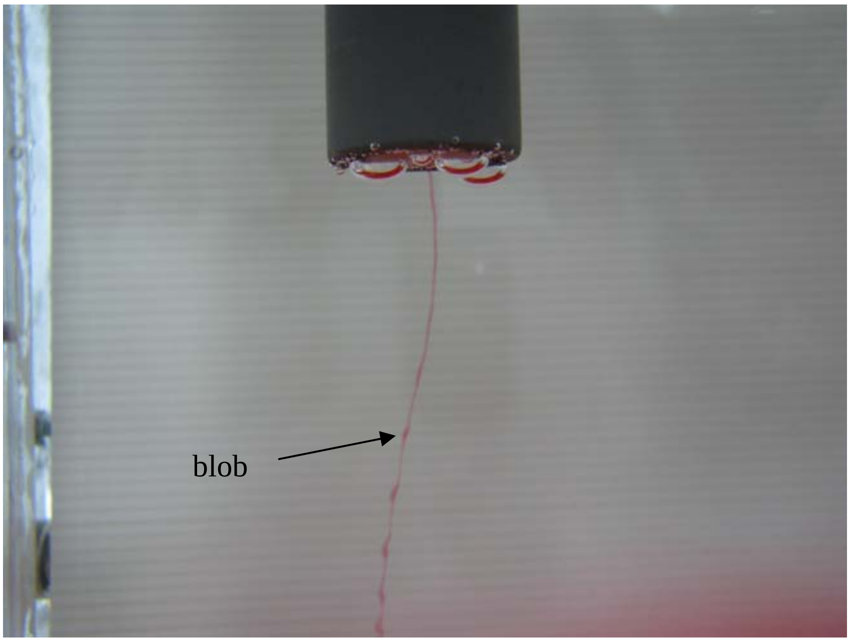


Figure 5 Blobs in the starting flow

In summary, a turbulent plume was set up and observed in a laboratory tank. The entrainment process was observed and the filling box mechanism understood. However, due to the constraint in time and availability of the facility, we were not able to carry out a quantitative measurement of the plume. Thus, verification of the prediction of the existing models on the various plume features was not attempted.

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