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Laboratory experiments of turbulent plume and their fractal dimensions

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Turbulent plumes are ubiquitous in nature, some examples of which are volcanic plumes and black smokers. There have been many laboratory experiments on turbulent plumes, for example by Fernando et al. (1998) who studied the velocity and the width of the plumes and their parameter dependence. However, there have been few attempts to characterize the shape (e.g., the volume and the fractal dimensions) as a function of parameters such as the Reynolds number. There have been measurements of fractal dimension of the boundary of turbulent flows (Sreenivasan et al., 1989), and we can expect that similar characterization can be made for plumes as well. Here we report the preliminary results of laboratory experiments performed in order to study the evolution of the shape of the plumes as the Reynolds number is changed.

A water colored with a fluorescent dye and milk (density = 1.02 g/cc) is injected downward through an orifice (ID 1 mm) into a water contained in an acrylic tank with a cross-section of 16cmx16cm and a height of 25 cm. A light sheet is used as an illumination, and photographs are taken at time intervals of 1 second using a digital camera. The injecting velocity is controlled by the height of the reservoir fluid from which the colored fluid is injected. The resulting Reynolds number is in the range of 250-1260.

Entrainment rate of the plumes are calculated as the ratio of the volume at a distance 15cm from the exit of the orifice, to the cumulative volume of the fluid injected up to that time. We use a box counting method to calculate the fractal dimension of the sharp outer boundary of the plumes at a distance 15cm from the exit of the orifice.

Plume morphology and entrainment rates:

By varying the Reynolds number of the plumes, 3 regimes were found. For 250 le Re le 360, plumes meander and gradually spread outwards, which we define as the diffusive meandering regime. For 800 le Re le 1300, plumes take the form of a cylindrical cone, which we define as the cone regime. For the intermediate 360 le Re le 800, a plume initially consists of a head and a tail, but later transforms into a cone. Consequently, we define this as the transient regime. The time taken for the plume to descend a distance of 15 cm, decreases with Reynolds number and becomes approximately constant in the cone regime. We interpret this result to be due to the deceleration caused by large entrainment at high Reynolds numbers. On the other hand, entrainment rate was found to increase monotonically with Reynolds number.

Fractal dimension analysis:

We calculated the fractal dimension from the images, and found that in the diffusive meandering regime the fractal dimension is approximately constant of about 1.10, within the range of error bars. As the Reynolds number was increased, fractal dimension increased in a stepwise manner to a value of 1.17 in the transient regime, after which it decreased with Reynolds number. This Reynolds number dependent fractal dimension can be attributed to the change in the size of the predominant vortices. In the diffusive meandering regime, the typical size of the vortices are 2 cm, which decreases to 0.5-1cm in the transient regime. These vortices then disappear in the cone regime. Our experiments described above, suggests that it may be possible to estimate the Reynolds number from the images of the plumes, by identifying the regimes and calculating their fractal dimensions.

Fernando H.J.S., et al, Phys. Fluids, 10, 2369-2383, 1998.

Sreenivasan K.R., et al, Phil. Trans. R. Soc. London, 421, No.1860, 79-108, 1989.