Imaging buoyancy driven flows

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Abstract A series of buoyancy driven flows are described and some experimental results using light attenuation imaging techniques are presented. This includes the challenge of measuring the entrainment and mixing in the flows. The data emerging from the analysis leads to new insight into the dynamics and mixing in turbulent buoyant plumes, buoyancy driven mixing in confined spaces and the dynamics controlling the separation of particles from two phase turbulent buoyant plumes.
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1 Introduction

Many problems in geophysical and environmental fluid dynamics involve turbulent buoyancy driven flows in which there is a considerable amount of mixing of fluids of different density, leading to a range of flow processes including tubulent buoyant plumes (Turner 1979; Woods, 2010), in which buoyant fluid issues from a localised source and rises through the ambient fluid and turbulent gravity currents (Turner 1979) in which dense fluid issues from a localised source and spreads along the base of the ambient fluid. In many of the plume like flows, the dynamics can be modelled using classical plume theory, in which the rate of mixing of ambient fluid is assumed to be proportional to the mean vertical speed of the flow and the surface area of the flow. This leads to very good agreement between model and theory for the entrainment rate into the plume and the bulk mixing rate.

However, various types of reaction arise in some of these flows, and this requires new models for the mixing within the flow, in terms of the intermingling and homogenisation of the different fluids, which will drive the reaction, as well as measureing the entrainment rate of ambient fluid into the flow (Landel et al. 2012; Rocco and Woods 2015). We present some results which identify simple approaches for measuring this mixing and dispersion, with the theoretical being presented in more detail in the two papers cited above. In two phase turbulent plumes, measurements of the separation between the fluid and the particles are also of enormous interest, for example for understanding the transport of microbes which may form small particles within air flows (Mingotti and Woods 2015), and also for modelling the transport of sand, clay and ash in geophysical particle laden flows. Here we present a series of new measurements of the separation of particles and fluid in the classical filling box flows, in which a two phase turbulent plume mixes the fluid within a confined space. We also touch on the use of imaging to explore the turbulent buoyancy driven mixing in a vertical tube (van Sommeren et al 2012). The theoretical analysis used to interpret and constrain these experimental data is presented in the main reference papers cited in the references; the aim of the present contribution is to illustrate the flow patterns and sturctures which arise in different situations.

2 Particle separation in turbulent plumes

As a simple model of particle transport and mixing in a turbulent plume, we explore the flow situation in which a dense stream of particle laden fluid is supplied to a confined ventilated space from above (figure 1).

The ventilation flow involves inflow of ambient fluid at high level and outflow of the mixed fluid at low level. The supply of particle laden fluid leads to formation of a turbulent buoyant plume which descends to the base of the space, mixing ambient fluid into the plume en route. In the lower region of the space, the downward flux carried by the plume exceeds the net downward ventilation flow, and so the entrainment and mixing into the plume leads to an upward flow in the background, which carries particles in suspension up through the ambient fluid. Owing to the finite fall speed of the particles, the particle laden layer of the ambient is of finite

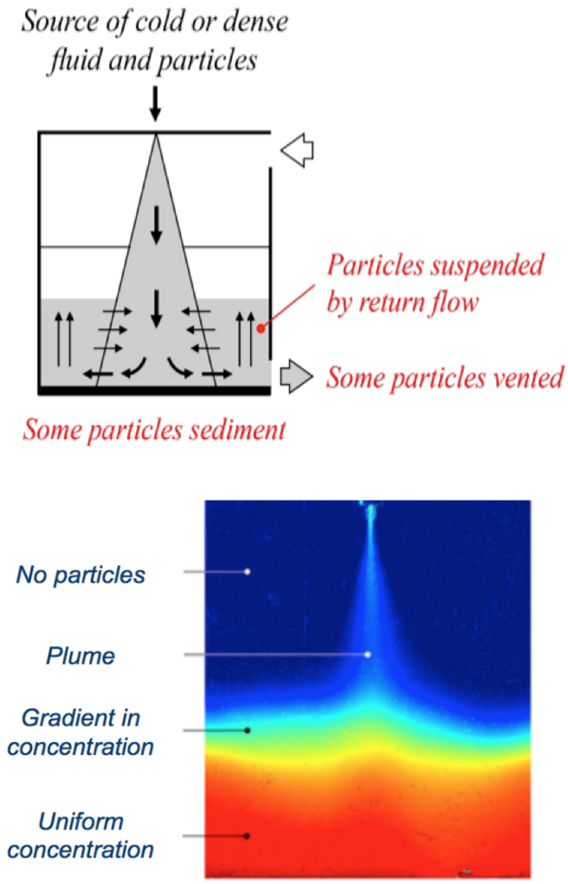

Fig. 1 Particle profile produced using light attenuation in the case of a plume of particle laden fluid descending into a ventilated reservoir. The reservoir is ventilated in the downwards sense. The layers observed in the figure correspond to a particle rich layer in the lower part of the vessel, and a particle free layer higher in the vessel.

depth. The result of this flow regime is to disperse the particles through the fluid in the lower part of the space, and this leads to very efficient dispersal of the particles even though they are supplied from a localised source.

In order to test a model for this flow pattern, it is necessary to measure the particle concentration in the experimental system throughout space. To do this, we used a light attenuation technique in which the intensity of the light passing through the experimental system decreases as the concentration of particles increases (figure 1b). This approach enables non-invasive measurements of the particle concentration throughout the experimental system, and testing of the theoretical model for the particle transport and sedimentation on the base of the experimental system.

The modelling can be extended to the case in which the supply fluid contains both particles and dissolved salt so that the density is influenced by both the presence of particles and the salt.

As the particles sediment from the upward return flow, a particle free layer of mixed ambient and plume fluid develops, with a well mixed particle suspension below and a layer of clear ambient fluid above which is being supplied by the inflowing ventilation flow (figure 2).

In this case the measurable quantities arising from the experiments include the height of the partcle laden layer and also the height of the particle free layer, as shown in the cartoon (figure 2). Data for each of these properties is very similar to the model predictions. The use of light attenuation to measure particle loading of flows has tremendous application in a number of environmental flows; the above flow is one which arises in the top down ventilation of a hospital when microbes may be suspeded in the flow.

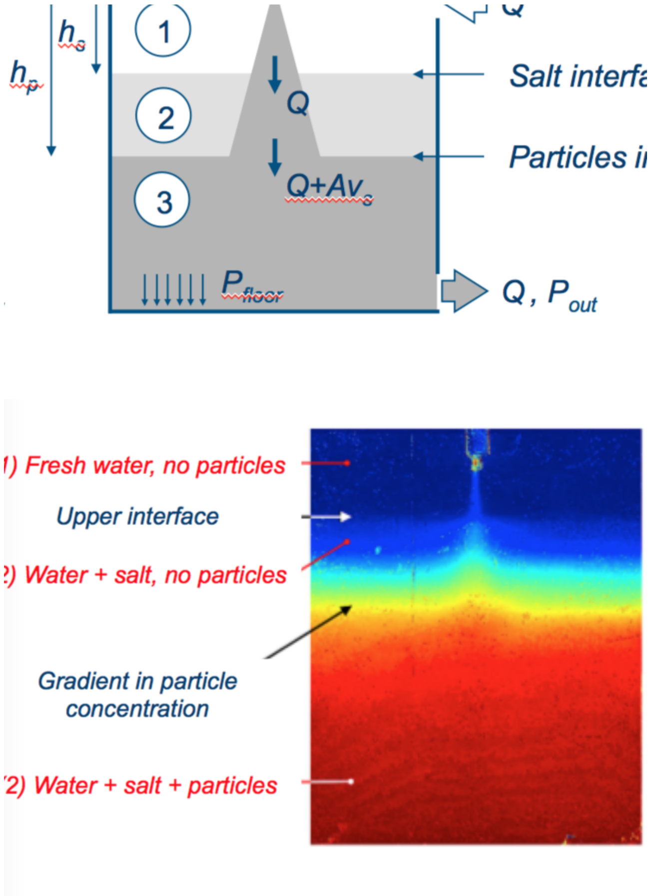

Fig. 2 Variation of the light intensity in the case of a particle laden plume of saline water flowing into a downward ventilated vessel. In this case three layers develop in the system. A fresh water layer, a saline layer and then a particle laden saline layer. After Mingotti and Woods 2015

3 Mixing in Turbulent Flows

A second use of light attenuation is in the measurement of the turbulent mixing within a flow. For example, a turbulent plume involves a series of eddies which advance through space, engulfing and mixing with the ambient fluid (figure 4). In this colour enhanced image, the colour represents the salinity of the system and hence reveals the history of the stirring and then mixing of the plume and ambient fluids as they homogenize. However, use of this data is difficult in building a model of the mixing. One approach to identify how rapidly the fluid from the source mixes with the flow in the ambient is to set up a steady plume flow, with no colour contrast between the source fluid and the ambient, and then, at a specific time, to add dye to the source fluid. The mixing at the leading edge of the dyed source fluid can be used to determine the dispersion coefficient.

For example, in figure 5, we illustrate the advance of the front of dyed fluid in a plume flow, using colour enhanced images of the flow. It is seen that the dyed fluid is stretched out at the front of the flow; this can be modelled as a dispersion process relative to the mean flow, thereby providing a parameterisation of the mixing rate within the flow (eg Rocco and Woods, 2015). This mixing model also then leads to a fluid residence time distribution, which is of especial importance in modelling reactions in the flow, since the degree of reaction will vary depending on the specific residence time.

4 Mixing in a confined system

The light attenuation approach is also of importance in measuring the mixing in flows in confined systems. For example, the buoyancy driven flow in a confined tube which arises when a steady flux of dense fluid is added to the top of a tube containing less dense fluid. In this case, the dense fluid migrates down the tube, generating a turbulent mixing flow with the original fluid. This leads to a gradual dilution of the salinity in the flow with distance from the top of the tube. A time series of images of the density distribution in the tank can be used to determine both the stratification which develops and also the rate of deepening of the stratification (figure 6). This deepening is in fact self-similar, with the unstable buoyancy gradient retaining the same profile and strength at all times, since this drives the mixing. In order to achieve this scaling, the magnitude of the buoyancy at the top of the tube and the depth of the buoyant fluid within the tube both increase at the same rate. In order to conserve the total mass of buoyant fluid supplied to the tank, this then requires that the depth of the layer increases as $t^{1/2}$ (figure 6) (cf van Sommeren et al 2012).

5 Summary

A series of flow problems involving turbulent mixing in stratified fluids have been presented and the use of the light attenuation method to measure the evolving density field has been described. This enables new models of the stirring and mixing in these turbulent flow to be developed and tested, as described in more detail in the references below.

References

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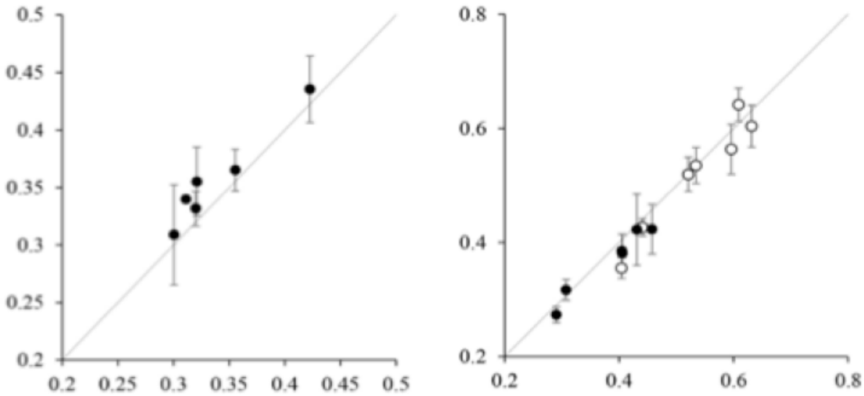

Fig. 3 Comparison of the depth of the upper fresh-saline interface and the lower particle-laden - particle-free interface in terms of the model prediction and the experimental measurements obtained from the images (after Mingotti and Woods 2015).

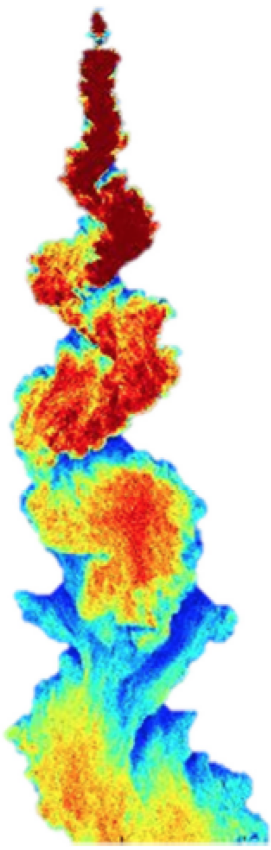

Fig. 4 Image of the salinity structure in a tubulent two dimensional plume, showing how the mixing leads to a gradual dilution of the flow and also that there is a considerable level of stratification in the flow associated with the turbulent eddies.

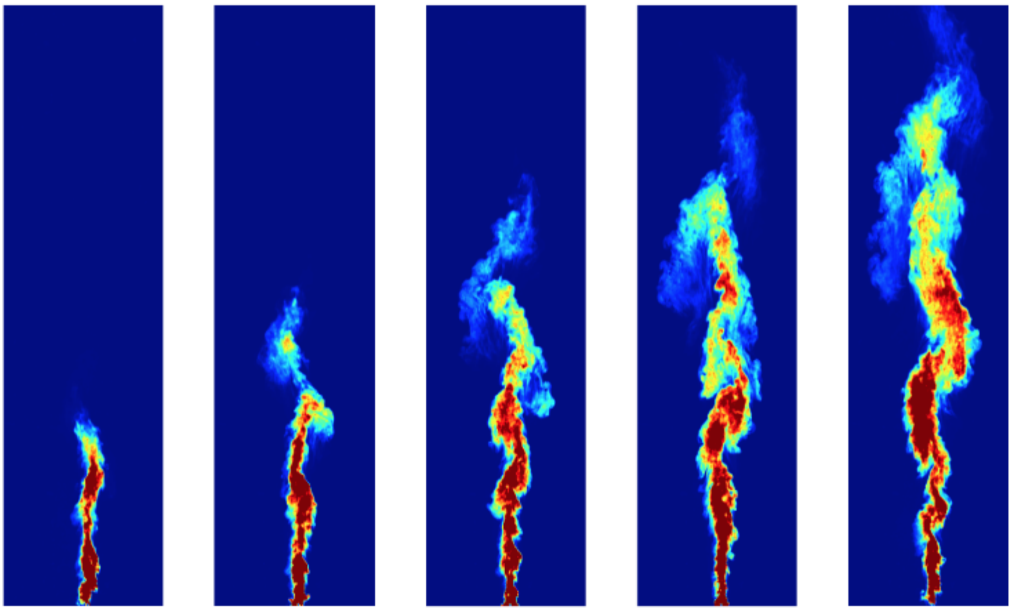

Fig. 5 Image of the evolving tongue of dyed fluid migrating into the plume further downstream in the tank. This data can be used to predict a dispersion coefficient for the mixing (see Rocco and Woods 2015).

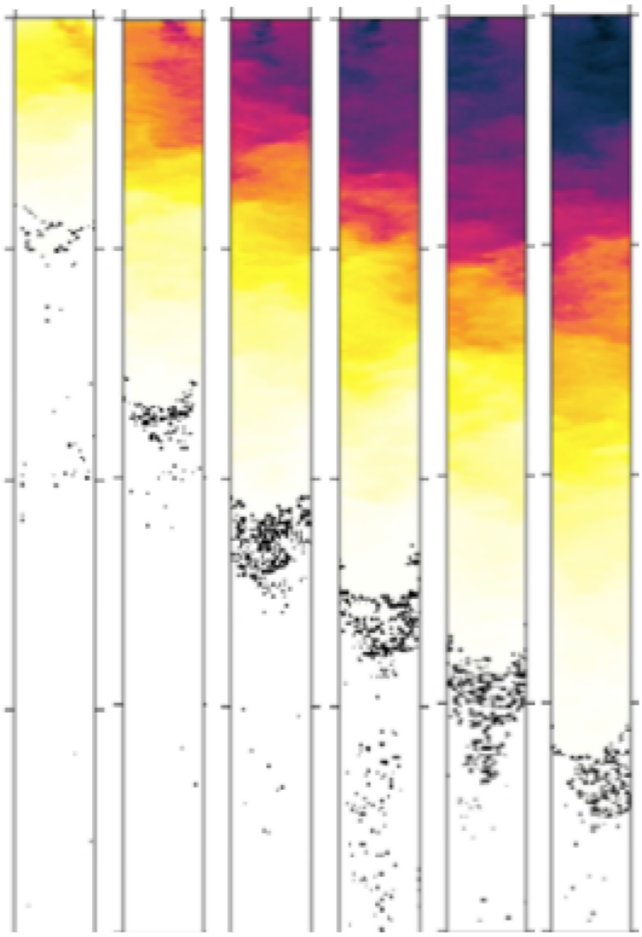

Fig. 6 Series of images showing the advance of a continous source of saline water supplied to the top of a tank. The images, at equal time intervals, illustrate the gradual increase in salinity at the top of the tank and also the gradual slowing of the advancing front with time, as expected for a self-similar deepening of the saline region.