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INTEGRAL AND LABORATORY MODELLING OF SEDIMENTATION FROM TURBULENT BUOYANT JETS

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Summary An integral model has been developed for turbulent, buoyant, particle-carrying jets injected at an angle to the vertical. The model allows particles to leave the jet where their fall-speed is greater than the entrainment speed of ambient fluid into the jet. The remaining particles drop-out once the jet reaches the free surface and spreads as a radial gravity current. The model is compared to laboratory experiments and shows excellent agreement.

INTRODUCTION

Marine outfalls and engine exhausts are examples of buoyant jets (or "forced plumes") injected at some angle to the vertical that may carry particles which subsequently drop out of the flow. The purpose of this work is to model such flows and describe the distribution of the sedimenting particles. In general, the particles can themselves affect the buoyancy but here we consider dilute suspensions, where the particle load has a negligible effect on the jet density. Initially we consider flow into a stationary, uniform ambient fluid, though the effects of ambient flow and stratification can be included later.

MODELLING

Jet model

Figure 1 shows a turbulent buoyant jet (in this case dyed, but with no particles). While the flow is unsteady and turbulent, it is common to work in steady mean flow properties using an integral model. Here we use "top-hat" profiles to describe the properties of the jet, and the basic angled plume model is as described in Lane-Serff et al. (1993)[1]. The local mean jet speed is denoted by U and the radius by R. These are dimensional values - it is usual to non-dimensionalise the equations using the source momentum and buoyancy fluxes.

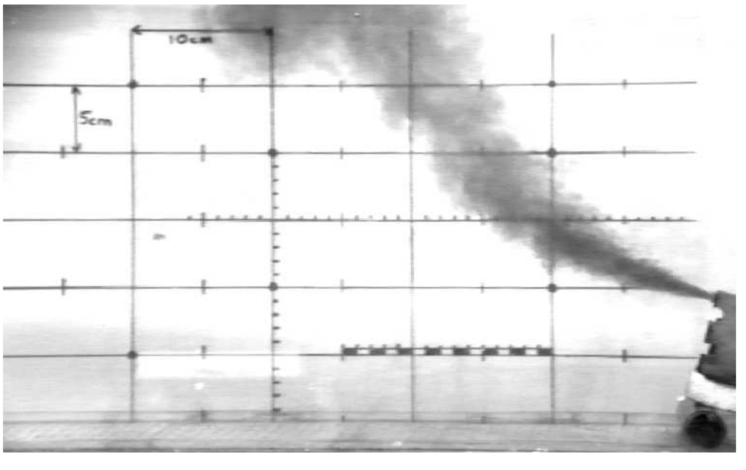

Figure 1. Angled turbulent buoyant jet (no particles), with the source angled slightly above the horizontal. The jet is dyed and the scale of the laboratory experiments is clearly marked. The free surface is just above the top of the picture and some of the spreading surface current can just be seen (especially towards the left).

The particles are assumed to have a single fixed (dimensional) fall speed W_S, and fall out of the jet where the component of fall speed normal to the jet boundary is greater than the entrainment speed of ambient fluid drawn into the jet αU. The model shows that an important parameter is the ratio of the fall speed to a typical entrainment velocity: $w_S = W_S/V_J$. As the jet turns towards the vertical and becomes a buoyant plume the sedimentation ceases. The proportion of sediment dropped in the near-source regions depends only on w_S (which can be regarded as a non-dimensional fall-speed) and the angle of the source. The results for a horizontal source are given in Figure 2a.

Spreading current model

When the buoyant fluid reaches the surface it spreads as a radial gravity current. We can estimate the particle-dropping from this part of flow using the model of Sparks et al. (1991)[2]. However, for our experiments we found that the scale for the predicted Gaussian distribution (R_G, say) is often comparable with or smaller than the radius of the plume at the surface, R_P. Thus we instead use a broader spread for our predictions by simply adding the initial gravity current spread estimate to the radius of the plume at the surface, i.e. $R_S = R_G + R_P$, and using a Gaussian distribution with this larger length-scale.

LABORATORY EXPERIMENTS

Experiments were conducted by injecting fresh water into tanks of salt water, using a simple gravity feed. Fine sand (of various measured size ranges) was mixed into the source water and kept in suspension by stirring. The fall velocity of the sand was determined empirically using tall cylinders of water and timing the falling particles (using video equipment for accuracy). The base of the tank was marked with a grid to determine the distance from the source. Once an experiment was finished, the sand was scraped into piles and collected using a syringe. This was filtered, rinsed with fresh water (to remove the salt), dried and weighed.

RESULTS

From the model, the total deposition is found by summing the near source deposition and the Gaussian distribution from the surface gravity current (Figure 2b-d). The near-source depositon is typically within a jet-length of the source (i.e. non-dimensional distance x = 1 on the figures), while for our experiments the jet reached the surface at approximately x = 2 (different for each experiment depending on the water depth and other parameters).

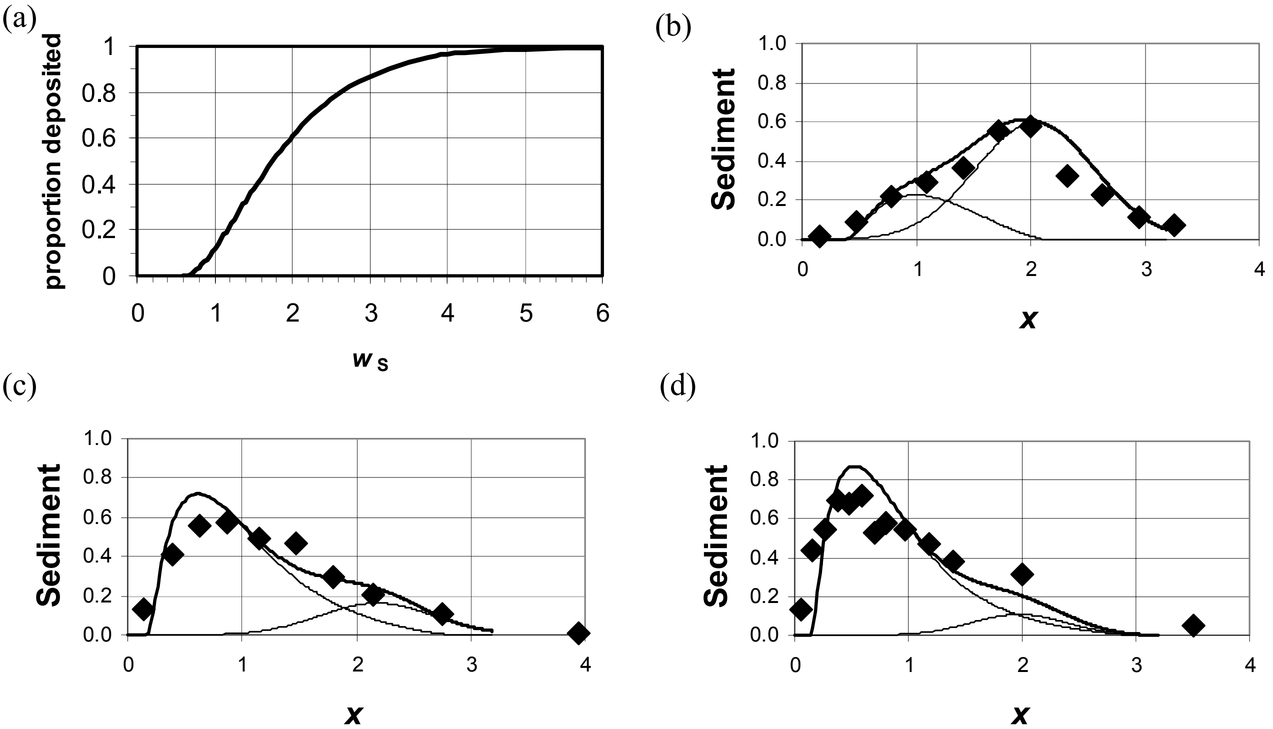

Figure 2 (a) Proportion of sediment dropping out in the near-source region as a function of the non-dimensional fall speed w_S for a horizontal source. (b-d) Theoretical predictions (for horizontal sources) for the sediment dropping out near the source and once the jet has reached the surface (thin lines for the two components, thick line for the sum) with symbols for the experimental measurements, with w_S = (b) 1.21, (c) 2.62 and (d) 3.13.

CONCLUSIONS

As can be seen from the figures, there is remarkably good agreement between the theoretical predictions and the laboratory results. By writing the parameter w_S in terms of the source conditions $w_S = W_S/\sqrt{(\alpha g'_0 D)}$, we find the powerful result that the proportion of sediment deposited in the near-source region is independent of the source flow rate (provided it is large enough that $Fr_0 > 1$).

Further ongoing work (with collaborators in UMIST and Dundee) includes adding the effects of ambient flow (both in the model and laboratory experiments), conducting larger-scale experiments and by developing CFD to include particles in the turbulence modelling. A selection of these results will be presented at the meeting.

References

[1] Lane-Serff, G.F., Linden, P.F., and Hillel, M. "Forced, angled plumes." *J. Hazard. Mater*. **33:** 75-99, 1993.

[2] Sparks, R.S.J., Carey, S.N. and Sigurdsson, H. "Sedimentation from gravity currents generated by turbulent plumes." *Sedimentology,* **38:** 839-856, 1991.