EXPERIMENTAL STUDY ON PARTICLE DISTRIBUTION IN LOCK-EXCHANGE GRAVITY CURRENTS

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Summary Laboratory experiments were conducted to investigate the spatio-temporal evolution of solute-driven gravity currents with low-density particles. Phase Doppler Particle Analyzer (PDPA) enables the non-intrusive and synchronous measurements of velocity and grain size in the currents. The results show that the flow structures ,especially turbulence stratification, have strong effects on the particles distribution.

INTRODUCTION

Gravity currents are driven by buoyancy between the fluids of different densities ,which are widespread both in natural and industrial systems[1].When density difference is caused by a suspension of particles, they are termed as particle-driven gravity currents, which are present in a wide range of hydraulic, geological, oceanographical and environmental processes, and act as major agents of sediment transport in lakes, rivers and oceans.While the driving force behind these flows is quite simple, the flow phenomena can be rather complex.Both experimental and theoretical approaches have been adopted to elucidate the physical processes[2], which reveal an interplay between particle dispersion and dynamics of the current. Upward directed turbulence competes with gravitational settling in keeping particles in suspension, while the driving buoyancy force changes with time and position along the current by particle concentration. Various methods have been considered for measuring time series in one or more parameters within particulate gravity currents.In this work, we address the spatio-temporal evolution of particle-laden gravity current by use of Phase Doppler Particle Analyzer. PDPA is a non-intrusive, laser-based measurement technique based on measuring the Doppler signal scattered by particles as they cross the measuring volume. It allows the simultaneous measurement of size and velocity of particles, droplets, or bubbles. To our knowledge, PDPA has never been applied to the study of transportation and sedimentation of particles in gravity currents. In order to use optical diagnostic techniques, we replaced the pure particle-laden gravity currents by solute-driven gravity currents with low-density particles.

EXPERIMENTAL SETUP AND PROCEDURE

A series of nominally identical experimental flows generated in a rectangular Perspex flume,with a dimension of 200 mm wide, 400 mm deep and 2590 mm long. A Perspex gate with latex seal around its edges was positioned vertically at a distance x_0 = 200 mm away from the left end of the channel to form a lock. Both compartments were filled with tap water to the same depth of h_0 = 100 mm. In order to match the refractive index while maintaining density difference, aqueous solution of potassium phosphate and glycerol were used for the heavier and lighter fluid ,respectively. Several classes of polydispersed spherical solid glass beads (ρ_p = 1.65 g/cm^3)were added into the denser fluid uniformly(volumetric concentration ˜ 0.1 %). The measurement volume was located at the center line of the flume. All the experimental flows were produced with identical initial condition, and the release time of the lock gate was set to $t = 0$ for each flow.The distance from the lock gate x, the height above the flume floor y and time t after release are nondimensionalized by the lock length x_0, total fluid depth h_0 and a time scale $t_0 = x_0/(g'h_0)^{1/2}$(reduced gravity:$g' = g\Delta\rho/\rho_a$),respectively.After the lock gate was suddenly removed, the denser fluid quickly accelerated and formed a current along the bottom of the flume.There was an initial slumping phase during which the front advanced at a constant velocity, and then a self-similar phase in which the front velocity decreased as $t^{-1/3}$. The transition from the first to the second phase was indicated to occur at about 10 lock lengths when a disturbance which was generated at the end wall overtook the front.This work was focused on the slumping phase.

RESULTS

The experimental data are presented as time series of the evolving vertical structure shown in figure 1.From the stream-wise velocity profile, the flow can be divided into three segments:lower flow segment,velocity maximum segment,upper flow segment [3].Here,the velocity maximum occurs around $y^* = 0.15$.This stratification is induced by dynamics of the flow, which is determined by the frontal instability [4]. Root-mean-square values of velocity (figure 1(c),(d))are used to approximate the turbulence intensity as well as the Reynolds stresses $\tau_R = -\overline{u'v'}$ (figure 1(e)) and the turbulent kinetic energy $k = 0.5(\overline{u'^2 + v'^2})$(figure 1(f)).$Dmn = \sum {d_i}^m / \sum {d_i}^n$ are used to statistically analyze the grain size.$D10$ is the median grain size(figure 1(g)).$D43$ is the volume mean grain size and can give prominence to large particles(figure 1(h)).Obviously, the velocity maximum segment is typically weakly turbulent.The vertical velocity and RMS

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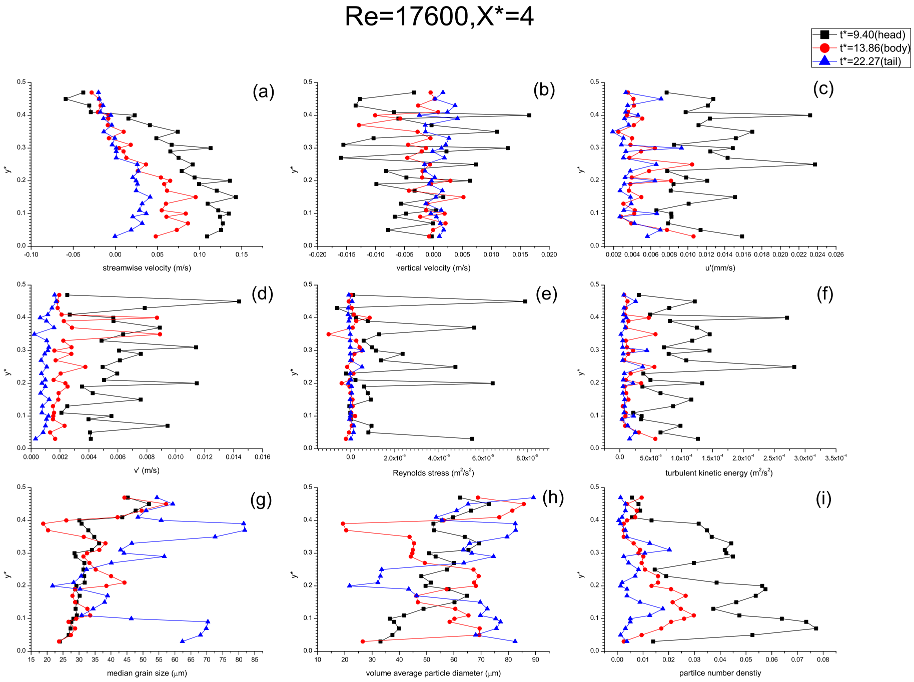

Figure 1. The vertical profiles of (a) streamwise velocity, (b)vertical velocity (c) RMS streamwise velocity,(d)RMS vertical velocity, (e)Reynolds stress, (f)turbulent kinetic energy, (g) median grain size,(h) volume average grain size and (i) particle number density at various times after the passage of the front at $x^* = 4$.In this case,the density difference$\Delta\rho/\rho_0 = 4\%$, the median grain size of the added polydispersed particles is 40.17um.

in this zone is rather small(figure 1(b)),which implies that the particles are more likely to be still in the vertical direction. Compared with the profile of particle number density(figure 1(i)), there are two peaks around the $y^* \approx 0.13$ at the front.This phenomenon indicates that the velocity maximum segment separates the upper and the lower regions and suppresses the particles upward and settling motion. In the upper flow segment, it clearly shows that the $D43$ is increased while the turbulent is intense,which means the turbulence has the potential to inhibit the setting of coarse particles and that coarse particles accumulate in these zones. The upper part of the head is the source of relatively coarse sediment that is transported backward from the head by vortricity and subsequently settles downward into the body and tail of the flow. This explains the median grain size increases in the body and tail. In the lower flow segment, finer grain size appears in the lower flow segment of the head as well as the foreside of the body. The inverse grading seen within the body may be linked to coarse particles in the head being swept upwards and backwards, then falling back into the body of the current. Meanwhile, the larger particles, which are initially in this region and around velocity maximum segment, settle to the lower layer near the floor.Because the coarsest particles concentrate at a height below the velocity maximum, they will lag behind the head during transport.

CONCLUDING REMARKS

A lock-exchange experiment tank and PDPA were used to generate turbulent gravity currents with low-density particles and to study the interplay between particle distribution and flow dynamics.The highest turbulence intensity was found at the upper and lower boundaries , while the coarse sediments accumulated in these zones. The level of maximum downstream velocity coincides with the lowest turbulence intensity, and suppress the particles exchange between the upper and the lower segments.After the head, the grain size exhibits an inverse grading due to the evolution of turbulence stratification.

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