Large Eddy Simulation (LES) of Gravity Currents

Kyushu Institute of Technology, Member JSCE, ○Akhilesh Kumar JHA
Kyushu Institute of Technology, Member JSCE, Juichiro AKIYAMA

1. INTRODUCTION

One fluid flowing into another fluid of different density under the influence of gravity, the examples of which abound in reality, is termed as gravity current. The importance of studying various aspects of the motion of a gravity current needs no overemphasis[1]. Huppert and Simpson[2] described the denser fluid released into less dense ambient fluid as collapse of a series of equal area rectangles and proposed a constant Froude number for the moving front, Fis = 1.19 as long as the ratio of the height of front to the depth of ambient fluid, $H/h \leq 0.075$ and $Fis = 0.5(H/h)^{-1/3}$ otherwise. The motion of gravity current on horizontal bed has been hitherto simulated with mixed results[3,4,5].

This study examines experimentally and numerically the motion of 2D gravity currents on a horizontal bed. The focus is to understand how velocity, buoyancy, height of the front and densimetric Froude number vary in relation to each other as the front moves forward. A Large Eddy Simulation (LES) model is developed with cubic spline for space and Crank-Nicolson scheme with fractional step for time. The numerical results are compared with substantial experimental data and important conclusions are drawn about applicability of the numerical model and motion of the front.

2. MODEL DESCRIPTION

Applying the grid-filter to the incompressible Navier-Stokes equations and mass transport equation, the governing equations for the mean-flow and mass transport are obtained as

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho_a}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j^2} + \frac{\partial}{\partial x_j}\left(-\overline{u_i' u_j'}\right) + g_i \frac{\Delta\rho}{\rho_a} \tag{2}$$

$$\frac{\partial C}{\partial t} + (U_i + V_{si})\frac{\partial C}{\partial x_i} = \frac{\partial}{\partial x_i}\left(-\overline{u_i' c'}\right) \tag{3}$$

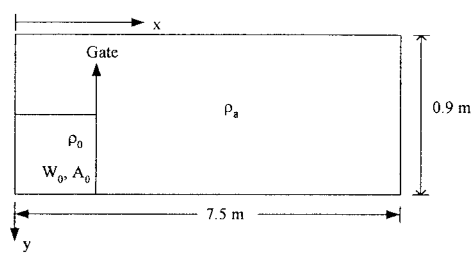

Fig.1 Experimental setup

where U_i= velocity component in the xi direction, P = pressure in excess of the hydrostatic pressure at reference density ρ_a, ρ = total density, $\Delta\rho$ = density excess ($=\rho-\rho_a$), g_i= specific body force in the x_i direction, u_i' = fluctuating velocity, $\overline{u_i' u_j'}$ = subgrid correlation terms between fluctuating velocity due to the grid-filtering, $\overline{u_i' c'}$ = subgrid correlation terms between fluctuating velocity and concentration, C = volume concentration of particles or dense fluid, c'= fluctuating concentration; V_{si} = settling velocity of particles in the x_i direction, $-\overline{u_i' u_j'}$ can be expressed as

$$-\overline{u_i' u_j'} = \nu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij} \tag{4}$$

where ν_t = subgrid scale eddy viscosity computed by a modified Smagorinsky model[6]; k = turbulent kinetic energy; and δ_{ij}= Kronecker delta function. Eqs.(1-3) are solved by operator splitting[6]. The pressure is computed by solving the Poisson equation by SOR method so as to satisfy Eq.(1). The governing equations are numerically integrated by evaluating space derivatives by a cubic spline and advancing the solution in time by the Crank-Nicolson scheme with fractional step

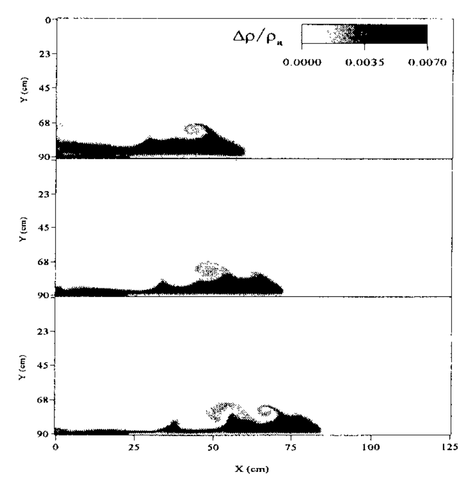

Fig.2 Computed front motion for GP2-1

3. EXPERIMENATAL AND NUMERICAL RESULTS

Experiments were conducted in a plexiglass flume(Fig.1). Results for two cases, GP2-1: Total initial buoyancy

W_0=4900 cm^3/s^2, initial area, A_0=1296 cm^2, a=36 cm and ε_0 = $(\rho-\rho_a)/\rho_a$ =0.040 and GP2-2: W_0=6860m^3/s^2, A_0=1296 cm^2, a=36 cm and ε_0 =0.014. The density currents were generated by opening the gate that separated the ambient fluid from the denser mixture. For numerical simulation of these cases, the physical domain was divided into computational cells of 0.01m x 0.01m. The Smagorinsky constant, Cs=0.16 and the turbulent Schmidt number, Sct = 0.1 were used. All boundaries are set no-slip.

Fig.2 presents a sequence in the motion of the front as computed by the numerical model for the GP2-1 case. The computed results for front velocity, front height and front buoyancy are shown in Fig.3. The superscript * means front location X, front velocity U, front height H and front buoyancy B non-dimensionalized by front height, buoyancy and area at a location beyond which the front is well developed, uninfluenced by the largely inactive part of the current behind the front and it moves on its own. The agreement between experimental data and computed results is overall reasonable. Fig.3 shows that the front velocity remains largely unchanged for some distance and shows rather steep slowdown thereafter. The height of the gravity currents drops continuously. The computed front height shows some numerical oscillation, which may be overcome by refining the grid in space and time. The computed buoyancy remains almost unchanged, which is similar to experimental data except the last data point.

Fig.4 shows computed and observed front densimetric Froud numbe F_i given by Eq.5 with F_{is} given by Huppert and Simpson[2].

$$F_i = \frac{U_f}{\sqrt{BH}} \qquad (5)$$

It may be seen that both experimental data and the computed results cluster around the line given by Huppert and Simpson[2] but don't exactly follow that. It is understood that the densimetric Froude number remains more or less constant for a given front height under a given depth of ambient fluid, even though the front velocity and height changes as the front advances. More detailed investigation is required to gain further insight into these.

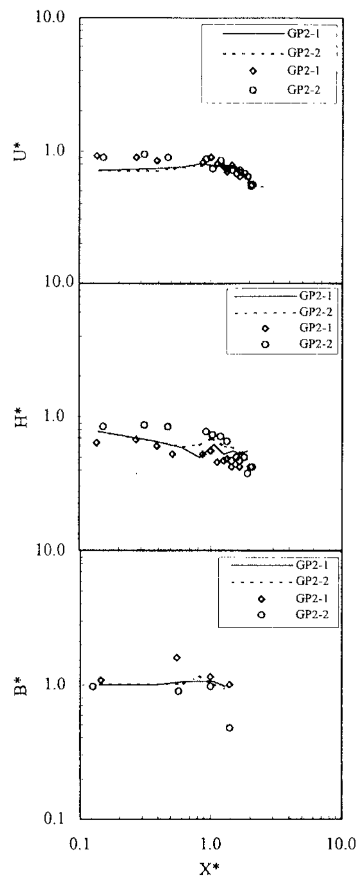

Fig.3 Comparison of computed results with experimental data.

4. CONCLUSIONS

The motion of gravity currents on a horizontal bed, produced by releasing denser fluid into a less dense fluid by opening a gate, is simulated by a Large Eddy Simulation (LES) model. The numerical model uses cubic spline for space and Crank-Nicolson scheme with fractional step for time. The Smagorinsky method, modified to include effects of buoyancy, is used to compute the eddy viscosity. The simulated results are compared with experimental data for front height, front propagation speed and front buoyancy. The computed densimetric Froude number is compared with experimental value as well as that available from existing studies.

It is concluded that the numerical model presented herein can reasonably simulate the motion of a 2D gravity current. On the motion of gravity current it is observed that the front velocity and height shows a steep decrease after a particular point in space. However, the densimetric Froude number remains more or less unchanged for a given front height. These would be studied in further detail in our future works.

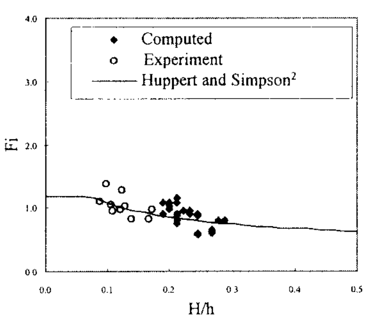

Fig.4 Densimetric Froude no. of front.

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