SIMULATION OF BUOYANT COULD BY LES

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1. Introduction

Buoyant flows play an important role in various technological and environmental issues. For example, dumping of dredged material directly into the sea, dispersal of pollutants, smoke, or volcano exhaust in atmosphere, formation of clouds etc. Large amounts of sediments and mud are often disposed off in designated areas of coastal waters for artificial land reclamation. The motion thus induced is a typical example of thermals. The study of thermals is important to assess the impact of such projects on the environment Many researchers[1,2,3,4,5,6] investigated motion of thermals.

In this paper, a 3-D numerical model is presented to simulate a buoyant thermal using the tools of Large Eddy Simulation. Eddy viscosity is calculated by using modified Smagorinsky model considering buoyancy effects. The model is verified against the existing experimental data of buoyant line thermals.

2. Governing Equations

For governing equations, 3-D Navier-Stokes equations are passed through a spatial filter and resulting effects of sub grid scale are modeled. We used well-known modified Smagorinsky model (taking buoyancy terms into account) for calculation of eddy viscosity. The governing equations so obtained are as following.

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

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

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

The U_i= velocity component in the x_i direction, P = pressure in excess of the hydrostatic pressure at reference density ρ_a, $\Delta\rho$ = density excess (=ρ-ρ_a), ρ = density of thermal fluid, g_i= acceleration due to gravity in the x_i direction, u_i' = non-resolved component of velocity, C = volumetric concentration of particles or dense fluid, c`= non-resolved concentration; $\overline{u_i'u_j'}$ = sub grid correlation terms between non-resolved velocity due to the grid-filtering, $\overline{u_i'c'}$ = sub grid correlation terms between non-resolved velocity and concentration and V_{si} = settling velocity of particles in the x_i direction and is set to zero for buoyant cloud case. $-\overline{u_i'u_j'}$ 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 = sub grid scale eddy viscosity; k = turbulent kinetic energy ; δ_{ij}= Kronecker delta function. The last term in Eq. (4) represents the normal stresses and can be absorbed in the pressure terms of the momentum equations. The sub grid scale eddy viscosity ν_t can be expressed by assuming that the sub-grid turbulent production includes a buoyancy term[8]. Therefore,

$$\nu_t = (Cs\,\Delta)^2\left(\left|\bar{S}\right|^2 - \frac{g_i}{\rho Sc_t}\frac{\partial\Delta\rho}{\partial x_i}\right)^{1/2} \tag{5}$$

where Δ= filter width, Cs = Smagorinsky constant and Sc_t = sub grid turbulent Schmidt number.

$$-\overline{u'_i u'_j} = \frac{\nu_t}{Sc_t}\frac{\partial C}{\partial x_i} \tag{6}$$

All boundaries are considered as a slip wall boundary and Boussinesq assumptions are assumed to be valid.

3. Methodology

Using operator-splitting technique, Eq. (2) can be written in a split form constituting advection diffusion equation and a pressure equation. The model is developed using cubic spline method for calculation of space derivatives and Crank-Nicolson methods for advancing the solution in time. Solving advection diffusion equation, three components of velocity u, v, and w are computed at intermediate level, which is without inclusion of pressure terms. Using these velocities, Poisson equation is solved for pressure. With the pressure and velocities known as above at intermediate level, the Poisson equation is solved for velocities at next time step. Equation (3), the mass transport equation is solved to update excess density at every time step.

4. Results and Discussion

The results of this model are verified against existing experimental data[6] for buoyant line thermals. The experimental conditions are for case S1, ε_0=0.036, and initial buoyancy W_o=0.000882 (m^3/s^2) and for case S2, ε_0=0.02 and W_o=0.0049(m^3/s^2). Where ρ_a is the density of ambient fluid, ε_0=(ρ-ρ_a)/ρ_a and ρ is the density of the thermal fluid. The Smagorinsky coefficient was taken to be 0.21 and turbulent Schmidt was 0.5. The non-dimensionalised half width $H^*=H/A_0^{1/2}$, non-dimensionalised buoyancy $B^*=B/(W_0/A_0)$ and non-dimensionalised velocity $V^*=V/(W^2_0/A_0)^{1/4}$ are plotted as a function of non-dimensionalised falling distance, $Z^*=Z/A_0^{1/2}$. H is the half width of the cloud, A_0 is the initial half volume per unit width, V is the mass center velocity of the cloud, and Z is the falling distance from source. The picture of buoyant cloud at time 10 seconds is compared with the simulated excess density contours along with velocity vectors in Fig. 1. The wake is seen in experimental picture as well as excess density distribution contours. The comparison of B^*, V^*, H^*, with experimental values are shown in Fig. 2,3 and 4. The simulated values for buoyancy, velocity, and half width are in good agreement with experimental values.

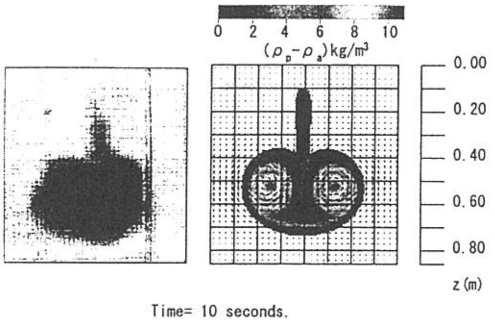

Fig. 1. Comparisons of simulated contours of excess density with picture of the buoyant cloud at 10 seconds for case S1.

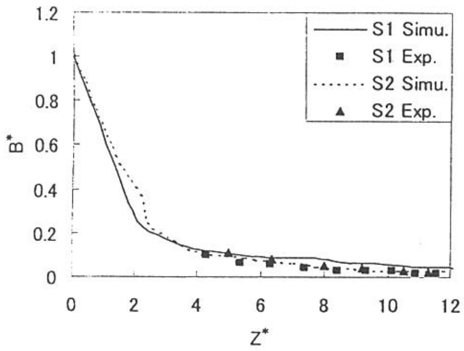

Fig. 2. Non-dimensionalised Buoyancy B^* as a function of Z^*

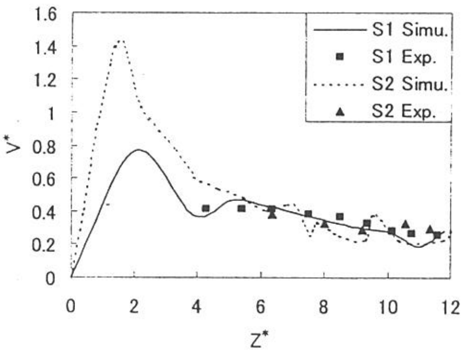

Fig.3. Non-dimensionalised mass center velocity V^* as a function of Z^*

The model is capable of reproducing the experimental values of buoyancy up to a considerable extent as shown in Fig.2. The non-dimensional mass center velocity is plotted as the function of falling distance in Fig.3. The simulated values of velocity for both the cases are in good agreement with the experimental values. In the accelerating phase the velocity for case S2 is higher, which is quit natural, as the density is higher than case S1. The non-dimensional half width of the cloud is plotted as a function of falling distance in Fig.4. All values seem to be falling on a single curve. Therefore, showing the linearly growing nature of the thermal width. However, the simulated values are in marginal agreement with the experimental values.

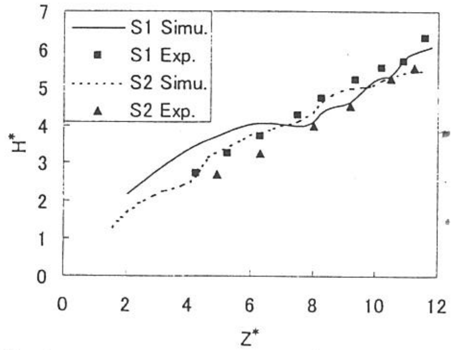

Fig. 4. Non-dimensional half width H^* as a function of Z^*

4. CONCLUSIONS

A three-dimensional model has been developed to simulate the motion of buoyant clouds. Utilizing several assumptions, model formulates a relatively efficient solution. The results of the model were compared with the experimental results of a two-dimensional study. The comparison shows the main flow characteristics including shape, non-dimensional half width H^*, average buoyancy B^* and mass center velocity V^* of the buoyant cloud are in reasonable agreement with the experimental results taking Smagorinsky constant Cs=0.21 and turbulent Schmidt number Sc_t =0.5

However, further studies are recommended in order to verify the results of the model against experimental data of axisymmetrical buoyant and particle clouds.

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