Numerical simulation of three-dimensional and bi-disperse particle-laden turbidity current in an experimental channel in the presence of an obstacle

Saba Teymouri a, Ehsan Khavasi b*

a Department of Mechanical Engineering, University Of Zanjan, Zanjan, Iran.
b Department of Mechanical Engineering, University Of Zanjan, Zanjan, Iran.
* P.O.B. 45371-38791. Zanjan, Iran, khavasi@znu.ac.ir

ABSTRACT

In the present study, the propagation of a continuous three-dimensional, in collision with obstacle and bi-disperse particle-laden turbidity current with a large eddy simulation method was modeled using the OpenFOAM numerically. Due to the presence of large number of suspended particles, the Eulerian-Eulerian method has been used and for each particle a concentration equation, which the particles settling velocity has been added to, is solved. The results show that before the obstacle, there is no significant change in the current velocity profiles in with and without obstacle state, but presence of an obstacle decreases the maximum velocity by 10%, also the amount of suspended particles on the obstacle decreases in channel width. In the final semi-stable state, the maximum concentration 15.3% is reduced in compared to without obstacle state. By increasing the particle diameter to 20 and 30 microns, maximum concentration is increased by 12.5% and 22.3%, the amount of suspended particles also decreases by 68% and 21%, respectively. As a result, particles with larger diameter precipitate more and rapidly. Changing the inlet concentration in the case of smaller diameter particle increases the amount of suspended particles by 11.2% and current will have more capability for carrying suspended particles.

KEYWORDS

Density continuous current, obstacle, turbidity, particles, LES.

* P.O.B. 45371-38791 Zanjan, Iran, khavasi@znu.ac.ir
Introduction

In this paper, hydraulic jumps, instability along the common boundary of two fluids, turbulent structures along the wall, the distribution of turbulent quantities and instabilities in the current are well illustrated. The Eulerian-Eulerian method for density current contains small particles is the best choice, because with the lowest possible computational cost, acceptable results are obtained.

In this paper, we tried to investigate the density current behavior and the sedimentation of particles in the encounter of topographic changes by putting obstacle. In the present study, a density current of bi-disperse particle-laden is simulated and the analysis emphasizes the effects of an obstacle to the dynamics and density current turbulence and the particle sedimentation. Current contains particles and the particles diameter effect on the current front location and the amount of suspended particles are studied.

Problem information

In the present study, the diffusion of density current bi-disperse particle-laden is modeled in a three-dimensional channel. The physical field specification in this study is been chosen in accordance with the conditions employed in Garcia experimental experiments [1]. In order to consider the slope effect 1%, gravity acceleration components are defined as \( g = (0.098055, -9.8, 0) \). This problem is considered to be quasi-steady state, and \( y' \) is about one in this study.

Governing equations

In this study, large eddy simulation method was used to simulate the current. This method is able to calculate three-dimensional and unsteady turbulent quantities instantaneously, so that the methods of Navier-Stokes equations are not able to calculate by RANS method [2].

The final equations governing for this current are filtered in this section. In this research, a three-dimensional box filter or "cubic root of cell volume" filter (which is equivalent to averaging over volume) has been used and to ensure better results along the wall, the Van driest damping function is proposed by Moin and Kim [3], has been used. With respect to the continuity equation, we can write [2]:

\[
\frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left( 2\nu_{SGS} S_{ij} \right)
\]  

Where \( S_{ij} \) is filtered strain rate. Using equation (1) in the momentum equation, the continuity, momentum, and concentration equations are presented in the following form [2]:

\[
\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} \left( u_i u_j \right) = \frac{\partial}{\partial x_j} \left( \nu \frac{\partial u_i}{\partial x_j} \right) + \frac{\partial}{\partial x_j} \left( 2\nu_{SGS} S_{ij} \right)
\]

\[
\frac{\partial c_n}{\partial t} + \frac{\partial}{\partial x_j} \left( u_j c_n \right) = \frac{\partial}{\partial x_j} \left( \alpha \frac{\partial c_n}{\partial x_j} \right) + \frac{\partial}{\partial x_j} \left( \alpha_{SGS} \frac{\partial c_n}{\partial x_j} \right)
\]

Where \( \rho \) and \( \nu \) are the density and viscosity of the environmental current (water). Also, gravity is in the opposite direction of \( y \) or \( i = 2 \). In the above equations, Boussinesq approximation is used for concentration.

The driving force of motion is the density difference, this type of currents after a while is stopped and depreciated with the loss of particles due to sedimentation and zeroing its density difference. To correct this equation, the settling term is added to the concentration equation, the Stokes relationship has been used to get the settling velocity. This relationship is as follows:

\[
v_s = \frac{9}{18} \frac{\rho - \rho_w}{\rho} \nu
\]

In this equation, the fluid viscosity is \( \mu \) that considered to be approximately equal to the water viscosity and the effect of particles on it is ignored and \( D \) is the average diameter of the particles.

\[
\frac{\partial c_n}{\partial t} + \frac{\partial}{\partial x_j} \left( u_j c_n \right) = \frac{\partial}{\partial x_j} \left( \alpha \frac{\partial c_n}{\partial x_j} \right) + \frac{\partial}{\partial x_j} \left( \alpha_{SGS} \frac{\partial c_n}{\partial x_j} \right)
\]

As seen in equation (5), the particles diameter influences the particle settling velocity and the settling velocity on the concentration equation. Particles diameter is based on the average diameter for kaolean particles that usually used for turbidity current experiments [4,5]. The dynamics of dynamic Smagorinsky method presented by Lilly [6] is used to solve the equations.

To solve this problem, Open FOAM with open source code is used, which is specific for Linux environment and in C++. The used solver is prepared by adding two concentration equation and the settling velocity parameter to the Piso FOAM solver. Also, a 12-core computer with a processor of 3.6 GHz and a 16-GB RAM was used to perform simulations. Each run takes about 5-6 days.
Sedimentation in turbidity current

The amount of suspended particles is calculated from the following equation [7]:

\[ q_s = \int_0^\infty u(y)c(y)dy \]  

(7)

Figure 1 shows the amount of suspended particles for channel without and with obstacle along the channel's length and width. The amount of suspended particles decreases along the plain channel, without obstacle due to the deposition of particles but in the channel with obstacle, the two-part current and lateral deviation by the obstacle increase the sediment and thus reduce the amount of suspended particles on the obstacle.

![Figure 1: The amount of suspended particle for plain channel without obstacle (dashed line) and channel with obstacle (line) a) along the channel (x) at z = 0 and b) in Width of the channel (z) at x = 71.5h.](image)

Figure 2 shows the effect of increasing diameter on amount of suspended particles. According to the figure, it can be said that the amount of suspended particles decreases with increasing particle diameter. In other words, larger particles will sediment sooner and fine particles are transported to more distances by flow. The amount of suspended particle decreases by increasing the particles diameter for 30 and 20 microns in diameter by 68% and 21% respectively.

![Figure 2: The amount of suspended particles for R1, R2 and R3 along the channel](image)

Figure 3 shows two states that the entrance concentration of the particle with a smaller diameter and the particle with a greater diameter is not equal. In the case where the entrance concentration of the particle with a smaller diameter is greater (linear curve), the amount of suspended particles is increased by 2/11% and the flow has more suspended load capacity.

![Figure 3: The amount of suspended particles for R4 and R5 along the channel](image)

Figure 4 shows the amount of suspended particles in the middle of the channel (z = 0) and near the side wall (z = 0.11). The amount of suspended particles in the middle and near the wall are nearly equal before the obstacle but with approaching the obstacle and the flow becomes dual, in the middle of the channel, the amount of suspended particles decreases further. After passing the obstacle and creating the front head, the particles are deposited on the sides and in the middle of the channel, the amount of suspended particles increase.

![Figure 4: The amount of suspended particles in the middle of the channel (line) and near the walls (dashed line)](image)

Conclusions

Density current after passing the obstacle and collision with the channel floor, with a change of phase from the supercritical region to sub-critical, has a hydraulic jump. The velocity profiles almost coincide with each other before the obstacle, it is indicating that before the obstacle the current behavior is almost the same as the channel without obstacle. Also, the presence of obstacle has reduced maximum velocity of current by 10%. Also, the difference in maximum particles velocity after the obstacle is greater.

The general figure of the concentration profile in the presence of obstacle is similar to the no obstacle state and the difference is generally at the current height. In the final steady state, after current through the obstacle, the maximum concentration in compared with the no
obstacle state by 15.3%. The concentration and the mount of suspended particles increases and decreases with increasing particles diameter, respectively and particles are transported to a greater distance by current. When the entrance concentration of the particle with a smaller diameter is greater, the amount of suspended particles is greater and the current has a more suspended load capacity. By decreasing the entrance concentration, the particle deposits later. By decreasing the concentration, the instabilities on the common boundary increase and make it more intense in the environmental fluid entrainment and turbulence in the dense layer. Since turbulence is the main mechanism of suspension of particles, thus reducing concentrations, increasing the amount of suspended particles and decreasing sediment rates.

References


