Studying wind effect on the hydrodynamic behavior of lock-exchange density current

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ABSTRACT

In the present study, the two-dimensional lock-exchange turbidity current under the influence of wind flow is modeled using an open-source software. To solve this, the LES method has been used in order to observe turbulent phenomena more accurately. By developing the two-phase solver of the software so that the equations of the VOF method are coupled with the scalar equation of concentration, the three-phase problem is simulated as a phase of a mixture of dense fluid and pure water next to the air phase. The results show that an increase in wind speed reduces the buoyancy force driving the turbidity current and increases the entrainment, which means faster pollution of water areas. This increase in wind speed also increases the wall shear stress, with the difference that the amount of wall shear stress at low wind speeds is not significant. So this prevents a significant change in the deposition behavior of the current. Studying the current's sedimentation behavior, showed that at high wind speeds, the co-current wind flow corresponding to the turbidity current has more harmful effects than the reverse wind flow and its sediment accumulation is getting higher.

KEYWORDS

Wind flow, Turbidity current, Turbulent phenomena, Sedimentation, VOF method

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1. Introduction

Turbidity current is one of the kinds of Gravity currents in which the density difference is due to the presence of suspended particles in the flow [1]. Practically in all previous numerical studies on the turbidity current in the open channel, the effect of wind flow has been neglected and also the effect of wind flow on shallow waters with the help of satellite data and ground stations, has been studied.

Gkesoulir and Stamou [2] studied numerically and experimentally the effect of wind on a Settling tank, which is a means of separating sedimentable solid particles from wastewater, and found that as wind speed increased, sedimentation rate increased and density current velocity decreased. To save time, instead of modeling airflow (assuming three-phase flow), apply air velocity as a boundary condition above the ambient fluid. (Modeling in two phases). In the present work, by integrating the Volume of Fluid (VOF) method and the concentration scalar equation, the three-phase problem is reduced to the two-phase problem. In the new method, a momentum equation for two phases of air and dense mixture (containing pure water and fluid denser than water) and a concentration scalar equation for density current are solved, and the effect of this concentration equation is added to the modified density equation of the VOF method.

2. Methodology

VOF is one of the most popular volumetric methods of free surface simulation. This method is used for two or more incompressible and immiscible fluids and its purpose is to track and determine the position of the interface between these fluids. This method uses a scalar indicator function that is represented by α' (fluid volume fraction). To find the percentage of presence of each phase in the computational cell and determine the boundary between the phases, the following scalar equation is solved for the volume fraction [3].

$$\frac{\partial \alpha'}{\partial t} + \frac{\partial \alpha' u_j}{\partial x_j} = 0 \qquad (1)$$

The equation of continuity and momentum in the VOF method with respect to the effect of the interface (here the free surface) and the incompressible flow, is as follows [3]:

$$\frac{\partial u_j}{\partial x_j} = 0 \qquad (2)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho g \delta_{2i} + F_i^{ST} \qquad (3)$$

The source term F_i^{ST} is the surface tension force vector, which is calculated as follows [3]:

$$\mathbf{F}^{ST} = \sigma \kappa n_i \delta \qquad (4)$$

In this equation, σ is the surface tension, $\mathbf{n} = \nabla \alpha'$ vector perpendicular to the interface (from air to water) and κ free surface curvature obtained from the vector perpendicular to the surface as follows:

$$\kappa = \nabla . \left(\frac{\nabla \alpha'}{|\nabla \alpha'|} \right) \qquad (5)$$

The local properties of the fluid, μ and ρ in each cell, are the weighted mixture of the properties of both fluids [4]:

$$\mu = \alpha' \mu_w + (1 - \alpha')\mu_{air} \qquad (6)$$

$$\rho = \alpha' \rho_w + (1 - \alpha')\rho_{air} + \alpha' \rho_w \beta C \qquad (7)$$

In the last equation $\beta C = \left(\frac{\rho_m}{\rho_w} - 1\right)$, ρ_m is the density of the mixture of density current and ρ_w density of water. $C = \frac{\rho - \rho_w}{(\rho_m - \rho_w)}$ non-dimensional concentration is between zero and one and its value is obtained from the concentration advection-diffusion equation (according to the two-dimensional assumption and incompressibility) [5]:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = \alpha\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) - V_s \frac{\partial C}{\partial y} \qquad (8)$$

In this relation, V_s is the Stokes settling velocity, which is calculated from the following equation [6]:

$$V_s = g D_p^2 \frac{\rho_p - \rho_w}{18\mu} \qquad (9)$$

3. Results and Discussion

In order to observe the effect of increasing Re_{Air}, for simulations of agree wind flow, the head positions of the density current is investigated (Figure 1). As reported by Gkesoulir and Stamou [2], the trend is that as Re_{Air} increases, the head position becomes further backward.

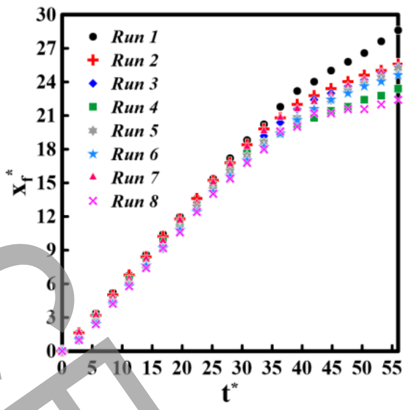

Figure 1. Current head position diagram for wind flow simulations with $Re_{Air} = 0$ to $Re_{Air} = 68800$

It was observed that the mean and maximum values of entrainment increase with increasing wind flow velocity in both categories of agree and disagree wind simulations. It was observed that for run 8 (highest wind speed and agree wind flow), the average value and maximum value increased by 463% and 921% respectively compared to run 1 (without wind flow) and also for run 11 (highest wind speed and opposite wind flow), the average value increases by 391% and the maximum value by 352% compared to run 1.

It was observed that with increasing wind speed and consequently increasing the lift force in the particles (the dominance of this force over the force of gravity on the particles), the particle re-suspension becomes more. It was observed that for run 8, the average value increased by 143% and for run 11, the average value increased by 175% compared to run 1. No specific trend was observed regarding the maximum wall shear stress. It should be noted that although the upward trend is observed in values of the wall shear stress, but except at the highest wind flow velocity (run 8), the absolute values of this stress are not significant and therefore should not have much effect on the sedimentation process as it can be seen in figure 2.

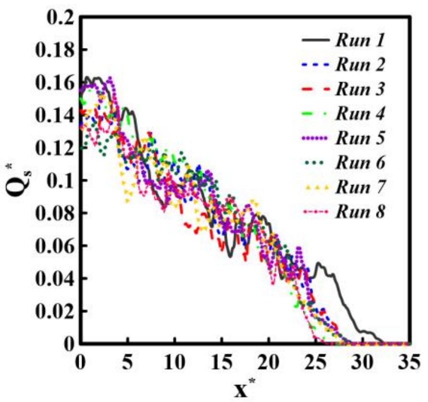

Figure 2. Sedimentation profile diagram for density current simulations in the presence of agree wind flow

Conclusions

The present work is a two-dimensional numerical simulation of lock-exchange density current in the presence of wind flow. This simulation was performed using the Large Eddy Simulations (LES) turbulence model and its results are summarized below:

It was observed that with increasing Reynolds number of agree wind current, the density difference between the ambient fluid and the dense fluid and consequently the driven buoyancy force decreases and as a result the head position falls back.

Effect of wind flow on entrainment was investigated. It was observed that the mean and maximum values of entrainment increase with increasing wind flow velocity in both categories of agree and disagree wind simulations.

Effect of wind flow on the shear stress of the wall was investigated. It was observed that the average amount of shear stress increases with increasing wind speed in both categories of agree and disagree wind flow simulations; As a result, as the wind speed increases and the lift force on the particles increases, the particle resuspension increases. It should be noted that although the upward trend is observed in the shear stress values of the wall, but except at the highest wind flow velocity, the absolute values of this stress are not significant and therefore should not have much effect on the sedimentation process.

Effect of wind flow on current deposition behavior was investigated. As mentioned in the previous section, due to the low values of wall shear stress, no significant difference was observed between the sedimentation profiles.

4. References

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