Computers & Geosciences 63 (2014) 9–16

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Two- and three-dimensional Direct Numerical Simulation of particle-laden gravity currents

L.F.R. Espath [a], L.C. Pinto [a], S. Laizet [b], J.H. Silvestrini [a,*]

[a] Faculdade de Engenharia, Pontifícia Universidade Católica do Rio Grande do Sul, Av. Ipiranga 6681, 90619-900 Porto Alegre, RS, Brazil
[b] Turbulence, Mixing and Flow Control Group, Department of Aeronautics, Imperial College London, London SW7 2BY, United Kingdom

ARTICLE INFO

Article history:
Received 10 July 2013
Received in revised form
10 October 2013
Accepted 12 October 2013
Available online 21 October 2013

Keywords:
Particle-laden gravity current
Energy budget
Deposition of particles
Direct Numerical Simulation

ABSTRACT

In this numerical study, we are interested in the prediction of a mono-disperse dilute suspension particle-laden flow in the typical lock-exchange configuration. The main originality of this work is that the deposition of particles is taken into account for high Reynolds numbers up to 10 000, similar to the experimental ones. Unprecedented two- and three-dimensional Direct Numerical Simulations (DNS) are undertaken with the objective to investigate the main features of the flow such as the temporal evolution of the front location, the sedimentation rate, the resulting streamwise deposit profiles, the wall shear velocity as well as the complete energy budget calculated without any approximations for the first time. It is found that the Reynolds number can influence the development of the current front. Comparisons between the 2D and 3D simulations for various Reynolds numbers allow us to assess which quantities of interest for the geoscientist could be evaluated quickly with a 2D simulation. We find that a 2D simulation is not able to predict accurately the previously enumerated features obtained in a 3D simulation, with maybe the exception of the sedimentation rate for which a qualitative agreement can be found.

1. Introduction

Gravity currents are very common in nature, either in atmosphere due to sea-breeze fronts, in mountain avalanches of airborne snow or debris flows, or in the ocean due to turbidity currents and river plumes (Simpson, 1982). It is clear that the understanding of the physical mechanism associated with these currents as well as the correct prediction of their main features is of great importance for practical and theoretical purposes.

In this numerical study, we focus on particle-laden hyperpycnal flows (with negative-buoyancy) where dynamics can play a central role in the formation of hydrocarbon reservoirs (Meiburg and Kneller, 2009). Moreover, these particle-laden gravity currents are often extremely dangerous for the stability of submarine structures placed at the sea-floor like pipelines or submarines cables (Zakeri et al., 2008; Nisbet and Piper, 1998). We focus on the prediction of a mono-disperse dilute suspension particle-laden flow in the typical lock-exchange configuration where the deposition of particles is taken into account. We consider only flat surfaces using DNS (Direct Numerical Simulation). Our approach takes into account the possibility of particles deposition but ignores erosion and/or re-suspension. Note that in dilute suspensions, the particle volume fraction is considered relatively small, typically well below 1%.

Previous results for this kind of flows were obtained in laboratory experiments (de Rooij and Dalziel, 2001; Gladstone et al., 1998), using simplified theoretical models (Rottman and Simpson, 1983; Bonnecaze et al., 1993), or by numerical simulations (Necker et al., 2002, 2005; Nash-Azadani et al., 2011) for relatively small Reynolds numbers. It was shown that deposition, boundary conditions, initial conditions associated with the lock configuration, and particle sizes can have a strong influence on the main characteristics of such flows. Cantero et al. (2008) already performed DNS of planar gravity current in the Boussinesq limit for Reynolds number equal to 8950 and 15 000. However, the simulations were performed for density-driven gravity currents (no particle deposition) not for particle-laden gravity currents like in the present work. The authors carried out a detailed investigation about the effect of three-dimensionality and turbulent structures and their influence on the flow dynamics but only for gravity currents with no deposition.

One of the principal objectives of this numerical study is to investigate the complete energy budget in particle-laden gravity currents for various Reynolds numbers with a comparison between two- and three-dimensional simulations. The main features of the flow are related with the temporal evolution of the front location as well as the suspended sediment mass, sedimentation rate, the resulting streamwise deposit profiles.

* Corresponding author. Tel.: +55 51 3353 8307; fax: +55 51 3320 3525.
E-mail address: jorgehs@pucrs.br (J.H. Silvestrini).

0098-3004/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cageo.2013.10.006

Concerning the complete energy budget of the flow, each term is evaluated without simplification assumptions, with the potential energy and kinetic energy as well as the dissipation related to the potential and kinetic energy variation. Within this framework, an excellent estimation should be obtained for the potential energy and kinetic energy and for the dissipation, with the preservation of the total energy inside the computational domain.

The organisation of this paper is as follows. In Section 2, we present the flow configuration and governing equation. The energy budget is explained in Section 3 while the numerical parameters and flow parameters of each simulation are detailed in Section 4. Some suggestive flow visualisations are presented and discussed in Section 5. Then, in order to better understand the underlying properties of each flow, some temporal results are presented in Section 6, followed by a conclusion in Section 7.

2. Flow configuration and governing equations

The well-known lock-exchange flow configuration is used in this numerical work (see Fig. 1) where uniformly suspended particle sediments are enclosed in a small portion of the dimension domain $L_{1b} \times L_{2b} \times L_{3b}$ separated by a gate with clear fluid. When the gate is removed the particle–fluid mixture flows due to gravity with a mutual inverse interaction between the "heavy" particle-mixture flow and the "light" clear fluid. The motion is understood as the transformation from potential energy to kinetic energy. We assume a dilute suspension of single diameter particles and we do not take into account the influence of particle inertia and/or particle–particle interaction. It should be noted that the concentration affect the mixture viscosity, however this effect is neglected.

With the restriction imposed by the dilute suspension approach, this flow can be evaluated numerically by solving the incompressible Navier–Stokes and a scalar transport equation under the Boussinesq approximation. Also, these assumptions allow to relate the particle diameter with the settling velocity. To make these equations dimensionless, half of the box height is chosen (Fig. 1) as the characteristic length scale h and the buoyancy velocity u_b is chosen as the velocity scale. The buoyancy velocity is related to the reduced gravitational acceleration $u_b = \sqrt{g'h}$ where $g' = g(\rho_p - \rho_0)c_i/\rho_0$. The particle and clear fluid densities are ρ_p and ρ_0, respectively, with g being the gravitational acceleration and c_i the initial volume fraction of the particles in the lock. When introducing the velocity and length scales two dimensionless numbers appear in the equations: the Reynolds number defined as $Re = u_b h/\nu$ where ν is the kinematic viscosity of the fluid, and the Schmidt number $Sc = \nu/k$, where k is the mass diffusivity of the particle–fluid mixture. All other parameters and variables are made dimensionless using c_i, h or/and u_b. Thus, the dimensionless form for the governing equation and scalar transport equation are

$$\frac{\partial \underline{\mathbf{u}}}{\partial t} + \underline{\mathbf{u}} \cdot \nabla \underline{\mathbf{u}} = \frac{2}{Re}\mathbf{div}(\underline{\underline{\mathbf{s}}}) - \nabla p + c\underline{\mathbf{e}}^g \tag{1a}$$

$$\mathbf{div}(\underline{\mathbf{u}}) = 0 \tag{1b}$$

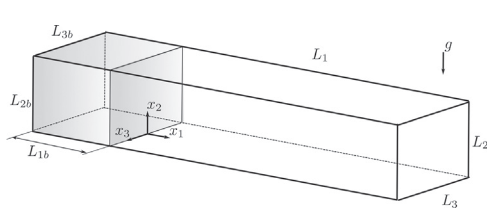

Fig. 1. Schematic view of the initial configuration of the lock-exchange flow problem.

$$\frac{\partial c}{\partial t} + (\underline{\mathbf{u}} + u_s \underline{\mathbf{e}}^g)\nabla c = \frac{1}{Sc\,Re}\nabla^2 c \tag{1c}$$

where $\underline{\mathbf{e}}^g = (0, -1, 0)$ is the unit vector in gravity direction and the non-dimensional quantities $\underline{\mathbf{u}}, p, c, \underline{\underline{\mathbf{s}}}$ represent the fluid velocity, pressure, particle concentration, and strain rate tensor fields, respectively. The particle settling velocity u_s is related to the particle diameter by the Stokes settling velocity law (Julien, 2010).

For the initial condition, a weak perturbation is imposed on the velocity field at the lock-exchange interface in order to mimic the disturbances introduced in the flow when the mixture is released. Free-slip boundary conditions are imposed for the velocity field in the streamwise and spanwise directions while no-slip boundary conditions are used in the vertical direction. For the scalar field, no-flux conditions are used in the streamwise and spanwise directions and in the vertical direction at the top of the domain. In order to take into account the particles deposition in the vertical direction at the bottom of the domain, the following outflow boundary condition is used:

$$\frac{\partial c}{\partial t} + u_s e_2^g \frac{\partial c}{x_2} = 0 \tag{2}$$

It allows particles to leave the computational domain mimicking a deposition process. It should be noticed that no re-suspension is allowed, as well as no erosion.

3. Energy budget of the flow

Following previous studies (Winters et al., 1995; Necker et al., 2005), we present in this section a framework for the analysis of the energy budget. It is possible to better understand particle-laden gravity currents by investigating the temporal evolution of the potential energy and the kinetic energy. The main difference between density-driven gravity currents and particle-laden gravity currents is that dissipation occurs not only at the macroscopic scale with the strain rate but also at the microscale scale around each particles.

In order to accurately investigate the temporal evolution of the different energy components, we consider the full budget equation for the kinetic energy. A similar approach, with simplifying assumptions, can be found in Necker et al. (2005). The main difference between the present work and the work of Necker et al. (2005) is that we compute the exact energy equation (8) without any assumptions over the dissipation terms.

The energy budget for an incompressible flow with particle concentration in the dilute suspension approach can be extracted from the governing equations and scalar transport equation. The total energy can be split into the kinetic energy and potential energy, and distinguish the dissipation associated to the strain rate in the macroscopic advective motion and the dissipation that occurs in the microscopic Stokes flows around the particles.

The time derivative of the kinetic energy equation is derived from the inner product between the momentum equation (1a) with $\underline{\mathbf{u}}$ and is expressed as

$$\frac{\mathrm{D}\left(\frac{1}{2}\underline{\mathbf{u}} \cdot \underline{\mathbf{u}}\right)}{\mathrm{D}t} = -\mathbf{div}(p\underline{\mathbf{u}}) + \frac{2}{Re}\mathbf{div}(\underline{\underline{\mathbf{s}}} \cdot \underline{\mathbf{u}}) - \frac{2}{Re}\underline{\underline{\mathbf{s}}} : \underline{\underline{\mathbf{s}}} - u_2 c \tag{3}$$

where $\mathrm{D}(\cdot)/\mathrm{D}t$ is the material derivative. Integrating Eq. (3) over the entire domain Ω gives

$$\frac{dk}{dt} = -\int_\Omega \frac{2}{Re}\underline{\underline{\mathbf{s}}} : \underline{\underline{\mathbf{s}}}\, d\Omega - \int_\Omega u_2 c\, d\Omega \tag{4}$$

where Ω represents the entire computational domain and $k(t) = \int_\Omega \frac{1}{2}\underline{\mathbf{u}} \cdot \underline{\mathbf{u}}\, d\Omega$. Note that any integral of a divergence field over the domain is zero because there is no transport across the boundaries.