European Journal of Mechanics B/Fluids 62 (2017) 32–41

Contents lists available at ScienceDirect

European Journal of Mechanics B/Fluids

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

Effect of particle inertia on the transport of particle-laden open channel flow

Sanjeev Kumar Jha

School of Civil Engineering, University of Manitoba, Winnipeg, Canada

ARTICLE INFO

Article history:
Received 25 March 2016
Received in revised form
19 July 2016
Accepted 30 October 2016
Available online 12 November 2016

Keywords:
Two-phase flows
Partial two-fluid model
Particle inertia
Open channels
K-epsilon model

ABSTRACT

The particle inertia is a key feature affecting the transport of particle-laden, open-channel flows. In this paper, the influence of particle inertia is investigated by varying the size, density and concentration of particles in the flow. Under the framework of Reynolds-Averaged Navier–Stokes equations, a partial two-fluid flow model is developed. The partial-two fluid model offers simplification over complete two-fluid model by solving a mixture equation for the momentum equation for water. The governing equations consider particle–fluid interaction through a drag force, inter-particle collisions, dispersivity of the particles, and a *K*-epsilon turbulence closure. A range of particle size, density and concentration is considered in the sensitivity analysis. The results show that the particle size has significant influence on its velocity, distributed concentration in the water column and in reducing the turbulent kinetic energy. The variation in the density of particles in the flow show minor effect on the mean velocities of both phases and a slight reduction in the turbulent kinetic energy. Increase in maximum concentration of particles at the bed only affects the turbulent kinetic energy significantly; however, it does not have notable influence on the mean-velocities of both phases, and the distribution of particle concentration. The influence of particle inertia on the dispersivity of the particles in the flow is investigated by simulating the test cases of laboratory experiments. The comparison of results with the experimental data shows that the Schmidt number decreases with the increase in particle size in case of flow with high particle density. In cases of flow with low particle density, the maximum concentration of the particles at the channel bed governs the values of the Schmidt number required to match the experimental data.

© 2016 Elsevier Masson SAS. All rights reserved.

1. Introduction

Particles transported in natural channels vary in size, shape, density and in volumetric concentration. From two-phase flow perspective, the particles (disperse phase) have strong influence on the modulation of turbulence in the ambient water (carrier-phase) and hence on the evolution of the flow. The effect of particles on flow resistance and turbulence modulation are of paramount importance in the estimation of total volume of particles transported in natural channels [1]. In recent literature there are increasing applications of the concept of multi-phase flow to better characterize the hydrodynamics of the phases in particle-laden open channel flows [2–5]. Large-eddy simulation and Direct Numerical Simulation have been applied by many researchers to investigate the effects of particles on the structures of local turbulence in a fully developed channel flow. An important question arises how to relate the small scale interactions with the macroscopic flow behavior [6]. Several experimental studies have reported the existence of velocity lag between particles and water [7–9]. Those experiments conducted with various particle sizes and densities [10,11,7,12] revealed that the stream wise velocity of particles in open channels is less than that of the carrier fluid (water) even in the case of dilute flow. Aziz [13] showed that the suspended-particle load calculation can be overestimated by 37% in some cases, if the velocity-lag between the two phases (particles and water) is ignored. Cheng [14] showed that the velocity lag can become more prominent with the increase in volumetric concentration of particles in the flow.

The effect of particle size, density and volumetric concentration on the flow can be together addressed in terms of particle inertia. There is relatively less research reported in the literature in which the influence of particle inertia on the flow is explicitly addressed. Greimann and Holly Jr [15] proposed an analytical expression of the distribution of volumetric concentration of the particles which also included the effect of particle inertia assuming that interparticle interactions are negligible. They suggested a criteria based on the Stokes' number to determine when particle inertia

E-mail address: Sanjeev.Jha@umanitoba.ca.

http://dx.doi.org/10.1016/j.euromechflu.2016.10.012
0997-7546/© 2016 Elsevier Masson SAS. All rights reserved.

becomes necessary to be considered. They suggested developing a better model for the fluid eddy viscosity and turbulence quantities. Muste et al. [6] investigated the effect of fixed-size particle with two different densities and increasing volumetric concentrations in dilute flows. They reported that the local water turbulence and the velocity of the flow are influenced by the presence of the particles irrespective of the density of particles. Due to dilute nature of the flow, they ignored the inter-particle collisions in their analysis. With increasing volumetric concentration of the particles in the flow, they observed reduction in mean velocities of both water and particles. Turbulence intensities slightly decreased in the case of flow with heavy particles. Zhong et al. [16] proposed an analytical relationship to investigate distributions of particles in flows covering a wide range of particle inertia and volumetric concentrations. They observed that the diffusion theory is only applicable for small particle inertia and low volumetric concentrations. The basic equations based on turbulent diffusion theory such as Rouse equation and Hunt equation are known to have several limitations [17]. Zhang et al. [18] analyzed the effect of particle inertia on the particle dispersion in open channels based on two-phase flow mixture theory. The effect of particle inertia was studied by analyzing vertical dispersion, motion and flux properties based on the concept of drift velocity. Dispersion of particles with high inertia was found to be affected by particle turbulence and collisions. Turbulence of water–particle mixture was not significantly affected. Zhang et al. [18] applied their modeling framework to the experimental test case of Xingkui and Ning [19]. They compared their results with the volumetric concentration derived from Rouse equation and reported that by considering high-order inertia effect in the equations, the modeling results were significantly improved. They applied empirical relationship for turbulence closures and a better turbulence model was sought for, in the future studies.

The rationale for the current study is to apply multi-phase flow theory with better closures for the eddy viscosities of water and particles, stresses due to inter-particle collisions and interaction forces between the two phases in elucidating the interaction between particles and water and observe the changes in velocity profiles and concentration distribution due to changes in size, concentration and density of particles. This study extends two-phase flow approaches presented in [20]. In that paper, hierarchy of models were proposed based on the complexities involved in solving governing equations and also the closures required to deal with turbulence. Two modeling frameworks were developed for simulating the dilute transport of suspended sediment in open channels: (i) a Partial two-fluid model (PTFM) in which the mixture equation was obtained by combining the mass and momentum equations of both phases; (ii) a Complete two-fluid model (CTFM), which solves the two-phase flow equations for both phases. The mean flow variables of both phases and turbulence statistics of the carrier phase were validated against the experimental data of Lyn [21], Muste and Patel [7], and Muste et al. [8]. The results obtained from solving CTFM were no better than the PTFM when simulating transport of dilute suspended sediment in open channels. The drag force was found to be relatively more important than other interaction forces such as lift and virtual mass. The value of the Schmidt number (the ratio between the eddy viscosity of the flow and the diffusivity of particles) was considered smaller than one. Additional terms in the K-epsilon model were found to have no significant effect on the model results. It is worth pointing that in [22] flows with non-uniform sediments in open channels was studied, which included a range of different size of sediments simultaneously present in the flow. The diffusivity of particles was found to decrease with increasing particle concentration in the flow. The particles with larger diameter tend to promote more turbulence intensity through the particle's wakes, thus the diffusion is enhanced [5]. In the current study, only uniform particles are considered, similar to what was presented in [20] in cases of dilute flows. The aim in this paper is to apply the general framework for modeling dilute and nondilute flows as presented in [23] to study the influence of particle concentration, size and density in modifying the mean velocity profiles of both phases and the distribution of particle concentration.

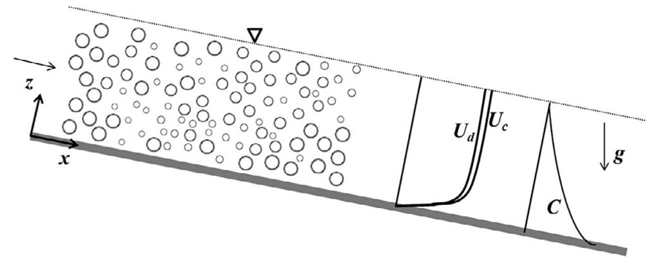

Fig. 1. Schematic of particle-laden, open-channel flow. x and z denote the direction along the flow and normal to it respectively. U_c and U_d represent mean velocity of the carrier phase (water) and the disperse phase (particles) respectively. g is acceleration due to gravity.

2. Theoretical models

2.1. One-dimensional two-fluid model

The governing equations for a two-fluid model can be obtained by ensemble and time averaging of the exact conservation equations of mass, momentum and energy for both carrier and disperse phase [20,24–26]. Following Jha and Bombardelli [23], the general governing equations for one-dimensional uniform and fully developed, particle laden, open channel flow, as shown in Fig. 1, are presented in Table 1. In the equations α, ρ, U, W, and F denote the volume fraction, density, mean velocity in the streamwise (x) direction, mean velocity in the wall-normal (z) direction, and interaction forces respectively. The subscript 'c', 'd', and 'm' indicate carrier phase, disperse phase, and a mixture of both phases respectively. t refers to time coordinates and S_b refers to the slope of channel. T refers to laminar deviatoric stresses and also stressed due to turbulent fluctuations. Stresses due to interparticle collisions are denoted by ς. d_p is the diameter of the particle, and ν is the kinematic viscosity of water. Eqs. (T2), (T3) and (T5) contain terms like $\overline{\alpha'_d\, w'_d}$, $T_{xz,m}$, $T^{\mathrm{Re}}_{xz,m}$, $T_{xz,d}$, $T^{\mathrm{Re}}_{xz,d}$, and $\varsigma^{\mathbf{Re}}_{xz}$. The closures for these terms are listed in Eqs. (T8)–(T15). The variables with an overbar indicate the mean components and the lower case letters with the superscript ' indicate fluctuations in the variable. In Eq. (T8), the diffusivity of the disperse phase is defined as $D_d = \frac{\nu_{T,c}}{Sc}$, where $\nu_{T,c}$ is the eddy viscosity of the carrier phase, and Sc is the Schmidt number. Hsu et al. [27] proposed the additional term, S_K and S_ε, in the equations for turbulent kinetic energy (K) and its dissipation rate (ε). S_K can be divided into two parts: S_{K1} represents the correlation between the fluid and particle velocity fluctuations and S_{K2} represents the production of turbulent kinetic energy due to the drag force [27,28]. T_P is the particle time scale and T_L is the flow time scale respectively. The expression for particle time scale was adapted from Hsu et al.'s expression for a non-linear drag force [29]. Similar to Enwald et al. [30], in Eq. (T14), τ is the granular temperature, which can be defined as $\tau = 2\,K_d/3$; K_d is the turbulent kinetic energy of the disperse phase; $\alpha_{d,\max}$ is the maximum packing concentration which has the value of 0.53 as an upper limit; e is the coefficient of restitution of particle collision.

2.2. Boundary conditions

The Neumann boundary condition was applied to the mean velocity of carrier phase and disperse phase in the flow direction

Download English Version:

https://daneshyari.com/en/article/4992403

Download Persian Version:

https://daneshyari.com/article/4992403

Daneshyari.com