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Reynolds-Averaged Two-Fluid Model prediction of moderately dilute fluid-particle flow over a backward-facing step

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ABSTRACT

In this work a Reynolds-Averaged Two-Fluid fully coupled model (RA-TFM) for modelling of turbulent fluid-particle flow is implemented in OpenFOAM and applied to a vertically orientated backward-facing step. Three particle classes with varying mass loadings (10–40%) and different Stokes number are investigated. Details of the implementation and solution procedure are provided with special attention given to challenging terms. The prediction of mean flow statistics are in good agreement with the data from literature and show a distinct improvement over current model predictions. This improvement was due to the separation of the particle turbulent kinetic energy k_p, and the granular temperature Θ_p, in which the large scale correlated motion and small scale uncorrelated motion are governed by separate transport equations. For each case simulated in this work, turbulence attenuation was accurately predicted, a finding that is attributed to separate coupling terms in both transport equations of k_p and ε_p.

1. Introduction

Modulation of turbulence is a complex two-way coupled phenomenon (Elghobashi, 1994) and can be caused by fluid-particle interaction and/or particle-wall interaction. Modulation can result in an increase in the fluid-phase fluctuating velocities (Gore and Crowe, 1989) due to particle vortex shedding (Peirano and Leckner, 1998), which is caused by a large particle Reynolds number, Re_p. Conversely, modulation of turbulence can result in the reduction of fluid-phase fluctuating velocities, i.e. attenuation. This behaviour is prevalent in fluid-particle flows due to high density ratios ($\rho_p \gg \rho_f$). This leads to the mean-feedback effect through drag - their primary coupling mechanism. Turbulence attenuation as a result of small heavy particles in the carrier flow is well established in the literature (Elghobashi and Truesdell, 2006; Gore and Crowe, 1989; Hetsroni, 1989; Kulick et al., 1994; Tsuji and Morikawa, 1984; Vreman, 2015; Yamamoto et al., 2001) and has been shown to be further influenced by the inhomogeneity of wall-bounded flow (Vreman, 2007).

To date there have been numerous experimental studies investigating small heavy particles in wall-bounded, high Reynolds number flow (Borée and Caraman, 2005; Caraman et al., 2003; Kulick et al., 1994; Tsuji and Morikawa, 1984). One valuable study is that of Fessler and Eaton (1999) in which mean and turbulence statistics of dilute (Elghobashi, 1994) fluid-particle flow were recorded in a vertically orientated backward-facing step. They report turbulence attenuation across three particle classifications (different Stokes number and mass loadings) and provide valuable insights into the particle behaviour in the free shear layer. Traditionally, the backward-facing step has been used as a benchmark for validation of single-phase turbulence models, as flow separation, reattachment and redevelopment are rife in engineering applications. Due to the complex nature of turbulence attenuation and the challenging physics in a backward-facing step configuration, its successful prediction has proven difficult (Chan et al., 2001; Mohanarangam and Tu, 2007; Mukin and Zaichik, 2012; Van Wachem et al., 2001; Yu et al., 2004).

There are two main approaches for predicting macroscale fluid-particle systems: the Eulerian–Lagrangian (E-L) method in which the fluid-phase is solved in an Eulerian frame and the particle-phase is solved with Lagrangian equations. Typically, all scales of motion are resolved except the boundary layers on the particle surfaces resulting in a high resolution of the flow field. It follows that E-L simulations are used for understanding fundamental phenomenon e.g. clustering (Capecelatro et al., 2015; Tanaka et al., 1996), and verifying experimental observations (Helland et al., 2002; Liu and Xu, 2009). Due to their expensive cost as each particle requires its own momentum equation, large particulate systems with high Reynolds number become inviable. This leads to the second approach: the Eulerian–Eulerian (E-E) methodology models both the fluid- and particle-phase as interpenetrating continua resulting in both phases acting as “fluids”. This reduces the com-

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Nomenclature

U_0	centreline velocity, [ms^{-1}]
C_D	drag coefficient, [-]
A_i	diagonal coefficients of the matrix
g	gravity, [ms^{-2}]
$\mathbf{n}$	unit vector normal to the wall, [-]
Re_p	particle Reynolds number, [-]
d_p	particle diameter, [m]
$\mathbf{u}_i$	velocity, [ms^{-1}]
$\mathbf{u}_w$	wall velocity, [ms^{-1}]
$\mathbf{u}_{p,\,w}$	particle slip velocity parallel to the wall, [ms^{-1}]
$\mathbf{u}''_p$	particle velocity fluctuation w.r.t PA velocity, [ms^{-1}]
$\mathbf{u}''^2_{p,i}$	particle Reynolds stress component in direction i, [m^{2}s^{-2}]
$\mathbf{u}'''_f$	fluid velocity fluctuation w.r.t PA velocity, [ms^{-1}]
h	pipe width, [m]
p_i	pressure, [Pa]
g_0	radial distribution coefficient, [-]
H	step height, [m]
t	time, [s]
k_i	turbulent kinetic energy, [m^{2}s^{-2}]

Greek letters

α_i	volume fraction, [-]
$\alpha_{p,\,max}$	maximum particle volume fraction, [-]
β	momentum exchange coefficient, [kgm^{-3}s^{-1}]
ε_i	turbulent kinetic energy dissipation, [m^{2}s^{-3}]
Θ_p	granular temperature, [m^{2}s^{-2}]
κ_p	particle fluctuation energy, [m^{2}s^{-2}]
$\kappa_{\Theta s}$	diffusion coefficient for granular energy, [kgm^{-1}s^{-1}]
μ_i	shear viscosity, [kgm^{-1}s^{-1}]
$\mu_{i,\,t}$	turbulent shear viscosity, [kgm^{-1}s^{-1}]
ν_i	kinematic viscosity, [m^{2}s^{-1}]
$\nu_{i,\,t}$	turbulent kinematic viscosity, [m^{2}s^{-1}]
ρ_i	density, [kgm^{-3}]
$\overline{\boldsymbol{\sigma}}_f$	fluid phase stress tensor,[kgm^{-1}s^{-2}]
$\overline{\boldsymbol{\sigma}}_p$	particle phase stress tensor, [kgm^{-1}s^{-2}]
τ_d	particle relaxation time, [s]

Subscripts

1	RA-TFM
2	MPM
f	fluid
i	general index
p	particle
x	x direction
y	y direction
z	z direction

Superscripts

$''$	PA particle velocity fluctuation
$'''$	PA fluid velocity fluctuation

Special notation

$\langle\cdot\rangle$	Reynolds averaging operator
$\langle\cdot\rangle_i$	phase averaging operator associated with phase i

putational cost considerably with the fully resolved scales of E-L being modelled. This approach then relies on constitutive relations to close the governing equations.

Numerous two-fluid (E-E) models have been derived using a one-step averaging process (Anderson and Jackson, 1967; Drew and Lahey, 1993; Ishii, 1975; Soo, 1990) e.g. volume- or time-averaging. Within this methodology, kinetic theory is used to close the particle-phase stress that appears in its momentum equation. This approach has been applied by many authors (Benavides and van Wachem, 2008; Dasgupta et al., 1994; 1998; Elghobashi and Abou-Arab, 1983; Hrenya and Sinclair, 1997; Peirano and Leckner, 1998; Viollet and Simonin, 1994; Zheng et al., 2001) with varying degrees of success. Recently, Fox (2014) has shown that a two-step process is required in order to derive a Reynolds-Averaged multiphase turbulence model. In the aforementioned models, the multiphase models are derived analogously to a single-phase model using time- or volume-averaging techniques that can lead to ill-formed equations e.g. time averaging results in a diffusive term in the continuity equation.

In addition to this, a conceptual error has been highlighted. The statement $k_p = 3\langle\Theta\rangle_p$ is often found in these models which is inaccurate. This is due to the particle turbulent kinetic energy k_p, and the phase averaged (PA) granular temperature $\langle\Theta\rangle_p$, belonging to two different realisations of the flow. This distinction was first highlighted by Février et al. (2005) in which particle velocities are decomposed into correlated k_p large-scale motion and uncorrelated $\langle\Theta\rangle_p$ small-scale motion. Both quantities are a result of separate models. It was shown that the correlated motion k_p arises due to the hydrodynamic (macroscale) model and the uncorrelated motion $\langle\Theta\rangle_p$ arises due to the kinetic (mesoscale) model.

The two-step derivation of Fox (2014) has been shown to circumvent these issues. Beginning at the kinetic (mesoscale) equation (Garzó et al., 2012), phase-space integration is applied to find the hydrodynamic (macroscale) moment equation which is then Reynolds-Averaged to form the Reynolds-Averaged Two-Fluid Model (RA-TFM) after the appropriate closure modelling has been applied. This approach results in separate transport equations for the particle turbulence kinetic energy k_p and the PA granular temperature $\langle\Theta\rangle_p$. Through the derivation of k_p the particle turbulent kinetic energy dissipation ε_p, is defined which appears as a source term in the transport equation of the PA granular temperature, $\langle\Theta\rangle_p$. This cascade of energy from correlated motion to uncorrelated motion is a crucial distinction. This leads to the particle fluctuation energy being written as $\kappa_p = k_p + 1.5\langle\Theta\rangle_p$. Février et al. (2005) found that even for non-collisional flow, separate transport equations for k_p and $\langle\Theta\rangle_p$ were essential, a direct result of the energy cascade outlined previously. Given these recent advances in the field, the modelling of previously challenging turbulent fluid-particle interactions in the Eulerian–Eulerian framework become clearer and their successful prediction more likely.

The overarching motivation of the present work is to increase the current understanding of the modelling of turbulent fluid-particle interaction in a complex flow field. We confine ourselves to turbulence attenuation of small heavy particles in a vertically orientated backward-facing step. The particles have material densities much larger than the fluid ($\rho_p \gg \rho_f$) and diameters smaller than the Kolmogorov length scale over the moderately dilute range $\mathcal{O}(10^{-4})$.

The RA-TFM of Fox (2014) is implemented in OpenFOAM and applied to the aforementioned flow configuration. The model predictions are compared against benchmark experimental data of Fessler and Eaton (1995, 1999). In addition, predictions are also compared against the model of Peirano and Leckner (1998) to highlight the importance of separating correlated and uncorrelated motion. Analysis is carried out on the mean particle streamwise velocities and the fluctuation intensity of both the particle and fluid phases. Applying the RA-TFM to wall-bounded flow requires physical wall boundary conditions for the particle turbulent quantities, k_p, ε_p and $\langle\Theta\rangle_p$. To this end the Johnson and Jackson (1987) boundary conditions were recently extended for the RA-TFM by Capecelatro et al. (2016b) and are implemented and applied here to describe the particle-wall interaction.