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Particle-laden flows forced by the disperse phase: Comparison between Lagrangian and Eulerian simulations

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ABSTRACT

The goal of the present work is to assess the ability of Eulerian moment methods to reproduce the physics of two-way coupled particle-laden turbulent flow systems. Previous investigations have been focused on effects such as preferential concentration, and turbulence modulation, but in regimes in which turbulence is sustained by an imposed external forcing. We show that in such regimes, Eulerian methods need resolutions finer than nominal Kolmogorov scale in order to capture statistics of particle segregation, but gas and disperse phase velocity variances can be captured with resolutions comparable to the Kolmogorov length. The work is then extended to address the question whether Eulerian methods are suitable in scenarios in which the continuum field of interest (temperature or momentum) is itself primarily driven by particles. To this end we have extended our analysis to the problem of turbulence driven by heated particles (Zamansky et al. PoF 2014) and have assessed capabilities of Eulerian methods in capturing particle segregation, as well as statistics of the temperature and velocity fields. Separate investigations are developed for cases with and without buoyancy driven turbulence. For each case corresponding Lagrangian calculations are developed and convergence of statistics with respect to the number of particles is established. Then the statistically-converged Lagrangian and Eulerian results are compared. Results show that accurate capture of segregation by the Eulerian methods always requires resolutions much higher than the nominal Kolmogorov scale. In scenarios for which a continuum phase is forced by particles, results from Eulerian methods show some sensitivity of predicted continuum statistics to the mesh resolution. This sensitivity was found to be largest for the case of a temperature field forced by hot particles, but without presence of buoyancy. In this case a Eulerian method with nominal Kolmogorov resolution was found to be insufficient for capture of temperature statistics. When additional coupling between particles and continuum phase is introduced by including the buoyancy effects, this sensitivity is suppressed in the temperature field, but some sensitivity to the Eulerian mesh resolution were detected in the momentum fields.

1. Introduction

Turbulent particle- or droplet-laden flows play a key role in numerous applications, including natural processes such as droplet clouds, dust storms, and protoplanetary disks, as well as industrial applications such as fuel sprays in internal combustion engines, fluidized beds, particle-based solar receivers, and pharmaceutical sprays. Understanding the key processes underlying the coupled dynamics of particles and fluids in such systems requires development of models capable of reproducing their physics. In most of these systems the particle-laden mixture is under turbulent conditions and can induce preferential concentration in the particle field (Squires and Eaton, 1991b; Elgobashi and Truesdell, 1992; Eaton and Fessler, 1994; Fessler et al., 1994): inertial particles are ejected from vortex cores and tend to accumulate in low vorticity zones. This phenomenon is characterized by the particle Stokes number, which is the ratio between the particle inertial relaxation time to the Kolmogorov time scale of the turbulence (Eaton and Fessler, 1994).

Previous investigations indicate that preferential concentration is strongest for systems with Stokes number of order unity (Eaton and Fessler, 1994). Very small particles with small Stokes number essentially follow the flow streamlines, and cannot be effectively centrifuged outside of vortex zones; in the limit of very large Stokes number, the particle phase is hardly influenced by the flow field and

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thus effects of preferential concentration is suppressed. Preferential concentration plays a key role in various processes including enhancement of particle–particle collision (e.g. leading to faster particle agglomeration or drop coalescence Sundaram and Collins, 1997; Wang et al., 1998) and turbulence modulation (Gore and Crowe, 1989; Elgobashi and Truesdell, 1993; Fessler et al., 1994; Boivin et al., 1998, Pouransari and Mani). In some scenarios preferential concentration plays a primary role even in generation and sustaining turbulence (Zamansky et al., 2014; Mizukami et al., 1992). Therefore, when it comes to modeling of particle-laden flow phenomena, one key concern is the capability of the model to capture preferential concentration.

Early numerical models attempted to couple Lagrangian particle methods with traditional Eulerian fluid turbulence simulations (Riley and Patterson, 1974; Elgobashi and Truesdell, 1992; Squires and Eaton, 1991a; 1991b). In the most simple limit, trajectory of the particles can be determined by use of the Stokes drag formula given the following assumptions:

- The particles are smaller than the Kolmogorov length scale ($d < \eta$): particle-resolved DNS is not necessary, and a Point-Particle approximation can be adopted Maxey and Riley (1983).
- The density ratio between the particles and the gas phase is large ($\rho_p >> \rho_g$): the drag force is dominant over all other forces (added-mass, history, lift).
- The Reynolds number of the particles is smaller than one ($\mathrm{Re}_p < 1$): the Stokes drag formulation can be used, i.e the momentum relaxation time of the particle is $\tau_p = \rho_p d^2/18\mu_g$, where ρ, μ, and d denote density, viscosity, and particle diameter respectively, and subscripts "p" and "g" represent particle, and fluid (gas) respectively.
- Dilute regime: the volume fraction is small ($\alpha_p < 10^{-3}$) and thus particle-particle collisions would have negligible impact on primary dynamics.
- Small mass loading($\alpha_p\rho_p/\rho_g < 10^{-2}$): the mass ratio is small enough to avoid momentum two-way coupling between the two phases.
- Monodisperse solid spherical particles: all particles have the same size that does not change with time.

  We add to this list another assumption relevant to a subclass of cases with heat transfer:
- Negligible heat capacity for the particle ($c_{p,\,particle} \ll c_p$): the heat absorbed by the particles is immediately transferred to the gas phase: there is no need to solve the temperature equation of the particles.

Under such conditions Lagrangian point particle methods have been tested against experiments and were shown to be able to capture the preferential concentration phenomena fairly accurately Squires and Eaton (1991a); Elgobashi and Truesdell (1992). In a typical simulation, the number of numerical particles would be equal to the number of physical particles. Following the aforementioned simplifications, the equations for the Lagrangian particles are limited to their position $\mathbf{X}_p$ and velocity $\mathbf{V}_p$:

$$\frac{\mathrm{d}\mathbf{X_p}}{\mathrm{d}t} = \mathbf{V_p}, \tag{1}$$

$$\frac{\mathrm{d}\mathbf{V_p}}{\mathrm{d}t} = \frac{\mathbf{u_g}(t,\mathbf{X_p}) - \mathbf{V_p}}{\tau_p}, \tag{2}$$

where $\tau_p = \frac{\rho_p d^2}{18\mu_g}$ is the relaxation time of the particles and $\mathbf{u}_g$ is the gas phase velocity.

In the context of mesoscopic DNS simulations, the Lagrangian particle tracking is the reference. However, it still has some limitations. First, if one is aiming to capture the statistics of the disperse, e.g. the local Number Density Function, NDF (number of particles per unit volume), many realizations are needed to develop converged statistics. Additionally, in the limit that the average number of particles per CFD cell is large, Lagrangian methods can become very expensive due to extreme computing clock time needed to track all particles as well as complexities associated with the computational load balancing on parallel machines (Garcia, 2009).

Eulerian particle methods have been explored as an alternative to the Lagrangian particle tracking method (Druzhinin and Elghobashi, 1998; Ferry and Balachandar, 2001; 2002; Kaufmann et al., 2008; Masi and Simonin, 2014; Masi et al., 2014; de Chaisemartin, 2009; Laurent et al., 2012; Vié et al., 2015). The goal of such methods is to solve the statistics of the disperse phase, i.e. the NDF. Inspired by approaches in kinetic theory of gases (Chapman and Cowling, 1939), the NDF $f(t,x,v_p)$ is defined as the number of particles per unit volume, with certain velocity, v_p, averaged over many realizations. This NDF satisfies a Population Balance Equation (PBE) (referred to as the Williams–Boltzmann equation in the context of sprays (Williams, 1958)):

$$\frac{\partial f}{\partial t} + v_{p,i}\frac{\partial f}{\partial x_i} + \frac{\partial}{\partial v_{p,i}}\left(\frac{u_{g,i} - v_{p,i}}{\tau_p} f\right) = 0. \tag{3}$$

For an sufficiently large number of realisations of Eq. (2), Eq. (3) is the equivalent of Eq. (2), but written in Eulerian framework. However, to avoid to solve the NDF in the full phase space, moment methods are develop (see for instance Simonin, 1996), which aim to integrate the PBE over the velocity space to obtain equation on moments, i.e. integrals over the velocity space. The resulting moment equations are (Simonin, 1996)):

$$\frac{\partial C}{\partial t} + \frac{\partial C u_{p,j}}{\partial x_j} = 0, \tag{4a}$$

$$\frac{\partial C u_{p,i}}{\partial t} + \frac{\partial C\left(u_{p,i}u_{p,j} + \sigma_{ij}\right)}{\partial x_j} = C\frac{u_i - u_{p,i}}{\tau_p}, \tag{4b}$$

where $C(t,\mathbf{x})$ is the local number density of the particles, $u_{p,\,i}(t,\mathbf{x})$ is the mean velocity of the particles at the position $\mathbf{x}$, and $\sigma_{ij}(t,\mathbf{x})$ is the covariance matrix of the velocity distribution:

$$C = \int f(t,\mathbf{x},\mathbf{v_p})\mathrm{d}\mathbf{v_p}, \tag{5}$$

$$u_{p,i} = \frac{1}{C}\int v_{p,i} f(t,\mathbf{x},\mathbf{v_p})\mathrm{d}\mathbf{v_p}, \tag{6}$$

$$\sigma_{ij} = \frac{1}{C}\int \left(v_{p,i} - u_{p,i}\right)\left(v_{p,j} - u_{p,j}\right) f(t,\mathbf{x},\mathbf{v_p})\mathrm{d}\mathbf{v_p}. \tag{7}$$

The system of Eq. (4) needs a closure for the covariance matrix of the NDF, based on the underlying physics. A schematic of the possible closure assumptions is depicted in Fig. 1. The two quantities that drive the choice of the model are the particle Stokes number St_k based on the Kolmogorov time scale and the volume fraction (Laurent et al., 2012). These two quantities control the broadness and shape of the NDF in the velocity space. The Stokes number indicates the occurrence of particle trajectory crossings, i.e. the possibility of multivalued particle velocity at a given space-time instant. For small Stokes number, the particles dominantly follow the fluid and deviation of their velocity from fluid velocity is perturbative (but could be sufficient to induce considerable preferential concentration). It has been shown that for $\mathrm{St}_k < 1$ a monokinetic assumption, that is all particles at the same location have the same velocity (Laurent and Massot, 2001), is indeed valid (Balachandar and Eaton, 2011), i.e. only one velocity can describe the particle field per location in physical space. In this range, the covariance matrix can be neglected, and Eq. (4) is closed without any modeling requirement. As classified by Balachandar (2009), three approaches of increasing complexity exist in this range of Stokes number: