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Development of an algebraic-closure-based moment method for unsteady Eulerian simulations of particle-laden turbulent flows in very dilute regime

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ABSTRACT

An algebraic-closure-based moment method (ACBMM) is developed for unsteady Eulerian particle simulations, coupled with direct numerical simulations (DNSs) of fluid turbulent flows, in very dilute regime and up to large Stokes numbers St_K (based on the Kolmogorov timescale) or moderate Stokes numbers St (based on the turbulent macroscale seen by the particles). The proposed method is developed in the frame of a conditional statistical approach which provides a local and instantaneous characterization of the dispersed-phase dynamic accounting for the effect of crossing between particle trajectories which becomes substantial for $St_K > 1$. The computed Eulerian quantities are low-order moments of the conditional probability density function (PDF) and the corresponding governing equations are derived from the PDF kinetic equation in the general frame of the kinetic theory of gases. At the first order, the computation of the mesoscopic particle number density and velocity requires the modeling of the second-order moment tensor appearing in the particle momentum equation and referred to as random uncorrelated motion (RUM) particle kinetic stress tensor. The current work proposes a variety of different algebraic closures for the deviatoric part of the tensor. An evaluation of some effective propositions is given by performing an *a priori* analysis using particle Eulerian fields which are extracted from particle Lagrangian simulations coupled with DNS of a temporal particle-laden turbulent planar jet. Several million-particle simulations are analyzed in order to assess the models for various Stokes numbers. It is apparent that the most fruitful are explicit algebraic stress models (2ΦEASM) which are based on an equilibrium assumption of RUM anisotropy for which explicit solutions are provided by means of a polynomial representation for tensor functions. These models compare very well with Eulerian–Lagrangian DNSs and properly represent all crucial trends extracted from such simulations.

1. Introduction

1.1. Overview: Lagrangian versus Eulerian approaches

Dilute particle/droplet-laden turbulent flows are of central importance in many industrial applications as, for example, in combustion chambers of aeronautic engines or recirculating fluidized beds in chemical engineering. The highly-turbulent unsteady nature of these mixtures, in most cases confined in complex geometries, increases the complexity of their predictions and the modeling is still a challenge nowadays. In order for a model to be appropriate, two requirements must be satisfied: (i) the approach must be sufficiently accurate for providing right predictions in such complex situations and (ii) it must be usable for real applications at industrial scale. In very dilute regime, and for mixtures of interest to this study, particles have size smaller or comparable to the smallest lengthscale of the turbulence and the volume fraction and the mass loading of the dispersed phase are small enough to neglect collisions and turbulence modulation. For these flows, for which a point-particle approximation applies, the Eulerian–Lagrangian direct-numerical-simulation (DNS) approach is an uncontroversial accurate method. DNSs of the fluid turbulence are straightforwardly coupled with Lagrangian particle simulations by accurate interpolation of the fluid properties at the particle location (Riley and Paterson, 1974). The Eulerian–Lagrangian DNS method does not require further modeling efforts and it is easy to implement in existing single-phase DNS codes. For this reason, it has been extensively used over the years and nowadays it is considered as a reference when experimental data are not available. However, this approach is unfeasible in most real cases and its

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use unrealistic at industrial scale. For industrial applications the constraint is double: the computational cost of the DNS for such flows is prohibitively expensive; realistic industrial flow configurations involve a huge number of particles which, according to the Lagrangian method, have to be tracked separately with a consequent increase of computational costs. An alternative method for predicting unsteady turbulent particle-laden flows with a high level of accuracy is the Eulerian–Eulerian large-eddy simulation (LES) approach. This method seems indeed fulfill the two aforementioned requirements of high accuracy and reasonable computational cost (the reader is referred to Fox (2012) for a review about the LES approaches in multiphase flows).

In the Eulerian–Eulerian approach, the particles are described in an Eulerian framework as a continuous medium, and the two-phase governing equations are solved separately but coupled through interphase exchange terms. In the literature, several successful Eulerian models have been proposed to predict the dispersion of particles when the turbulence is modeled by using Reynolds-averaged Navier–Stokes (RANS) methods. Among these, we recall the phase-averaging (Elghobashi and Abou-Arab, 1983; Chen and Wood, 1985; Zhou, 2010) and the probability density function (PDF) (Reeks, 1991; Simonin, 1991a; Zaichik and Vinberg, 1991) approaches. As pointed out by Balzer et al. (1996), such PDF approaches are formally consistent with particulate Eulerian models based on the granular kinetic theory, which are extensively used in dense gas–solid flows when the particle dynamics is dominated by the particle–particle or the particle–wall collisions (see, e.g Gidaspow, 1994). In contrast, the unsteady (DNS/LES) Eulerian modeling of dilute particulate flows is a timely topic of research. In this paper we will focus on the unsteady Eulerian–Eulerian DNS approach as the baseline of the Eulerian–Eulerian LES approach (Moreau et al., 2010). The modeling suggested by this work should not be confused with the aforementioned two-fluid RANS approaches. Some unsteady (DNS) Eulerian models available in the literature are instead recalled below.

A local Eulerian characterization of the dispersed phase was suggested by Maxey (1987) who using a Taylor expansion of the particle-motion equation in powers of Stokes number provided an expression for the particle-velocity field in terms of fluid velocity and its derivatives. In this approximation, only one equation for the particle concentration must be resolved and the dispersed phase would not require additional modeling. This approach was extended by Ferry and Balachandar (2001) in order to account for the added mass, Saffman lift and Basset history forces and evaluated by DNSs of homogeneous isotropic turbulence (HIT) (Rani and Balachandar, 2003) and homogeneous turbulent mean-sheared flows (Shotorban and Balachandar, 2006). In the literature, it is often referred to as equilibrium Eulerian approach or fast Eulerian method. Successfully assessed for small particle inertia, this approach fails for Stokes numbers, based on the Kolmogorov lengthscale, St_K, approaching unity (Rani and Balachandar, 2003; Shotorban and Balachandar, 2006). An alternative unsteady approach was suggested by Druzhinin (1995) who used a spatial average of the particle equations over a lenghtscale much greater than the particle diameter and of the order of the smallest lenghtscale of the flow. The resulting system of closed Eulerian equations for the particle volume fraction and the particle velocity was tested in DNSs of particle-laden circular vortex and HIT of bubbles and particles, in one-way and two-way coupling (Druzhinin and Elghobashi, 1998, 1999). In the frame of the modeling of polydispersed flows, we also recall the multi-fluid method of Laurent and Massot (2001), which assumes a monokinetic description of the particle velocity. Also these approaches are restricted to small particle inertia. For large Stokes numbers, alternative effective models are described in Sections 1.2 and 1.3.

1.2. An unsteady Eulerian approach for large Stokes numbers

Recently, Février et al. (2005) showed that in order for an Eulerian approach to be able to model the dispersed phase composed of particles having response times larger than the Kolmogorov timescale, it should account for the effect of crossing between particle trajectories. This effect involves many different velocities in the same volume of control violating the assumption of the uniqueness of the particle velocity distribution. By introducing a new operator of ensemble average over a large number of particle realizations conditional on a given fluid flow realization, local statistics of the dispersed phase may be derived in the framework of the conditional PDF approach. The novel conditional statistical approach (Février et al., 2005), known as mesoscopic Eulerian formalism (MEF), is based on the idea that the particle velocity may be partitioned in two contributions: (i) an Eulerian particle velocity field, referred to as mesoscopic field, which is spatially correlated and shared by all the particles and which accounts for correlations between particles and between particles and fluid and (ii) a spatially-uncorrelated particle velocity component, referred to as random uncorrelated motion (RUM) contribution, associated with each particle and resulting from the chaotic particles' behavior. In the Eulerian transport equations, the RUM contribution is characterized in terms of Eulerian fields of particle velocity moments; the larger is the particle inertia the more important is RUM. According to MEF, the assumption of the uniqueness of the particle velocity distribution is no longer a constraint since this model accounts separately for correlated and chaotic contributions which characterize the particle velocity property at large Stokes numbers. The existence of a spatially-uncorrelated velocity due to the crossing of particle trajectories was already pointed out by Falkovich et al. (2002); modeling this contribution is crucial in order for an Eulerian model to be effective in dilute regime. In the literature, MEF was used by IJzermans et al. (2010) and Meneguz and Reeks (2011) for characterizing the particle segregation by a full Lagrangian method (FLM) and by Gustavsson et al. (2012) who analyzed the relationship between caustics, singularities and RUM. Vance et al. (2006) used MEF to investigate the spatial characteristics of the particle velocity field in a turbulent channel flow with and without interparticle collisions. Simonin et al. (2006) compared such an approach with a two-point PDF method (Zaichik et al., 2003), pointing out the ability of the latter to capture the behavior of the dispersed phase as modeled by the MEF decomposition. In this study, we will use the conditional PDF approach in the framework of a moment method and we will focus on the closures of the system of equations derived from.

1.3. The conditional PDF approach and the question of the closures

According to the conditional PDF approach (described in Section 2), the PDF kinetic equation is closed at the same level than the Lagrangian equation governing the discrete particle variables, such as the drag law formulation in the dynamic equation. Unfortunately, a closed kinetic equation for the PDF does not completely solve the closure problem since this evolution equation in phase space creates an infinite set of coupled moment equations in real space. So any finite set of moment equations has to be supplemented by closure models of the unknown moments written in terms of the computed ones. Depending on the closure, models may be provided by using a Grad's moment method (Grad, 1949) or by means of quadrature-based moment methods (QBMMs) or kinetic-based-moment methods (KBMMs) (McGraw, 1997; Marchisio and Fox, 2005; Fox, 2008; Fox et al., 2008; Desjardins et al., 2008; Passalacqua et al., 2010; Kah et al., 2010; Yuan and Fox, 2011; Vié et al., 2011; Chalons et al., 2012). Grad's, QBMM