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Modeling heat transfer in dilute two-phase flows using the Mesoscopic Eulerian Formalism

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ABSTRACT

In dilute two-phase flows, the accurate prediction of the temperature of the dispersed phase can be of paramount importance. Indeed, processes such as evaporation or chemical reactions are strongly non-linear functions of heat transfer between the carrier and dispersed phases. This study is devoted to the validation of an Eulerian description of the dispersed phase – the Mesoscopic Eulerian Formalism (MEF) – in the case of non-isothermal flows. Direct Numerical Simulations using the MEF are compared to a reference Lagrangian simulation for a two-dimensional non-isothermal turbulent jet laden with solid particles. The objectives of this paper are (1) to study the influence of the thermal inertia of particles on their temperature distribution and (2) conduct an *a posteriori* validation of the MEF, which was recently extended to non-isothermal flows. The focus is on the influence of additional terms in the MEF governing equations, namely heat fluxes arising from the Random Uncorrelated Motion (RUM). Results show that mean and rms of particle temperature are strongly dependent of the thermal Stokes number. The mean temperature is satisfactorily predicted by the MEF, comparing to the Lagrangian reference. Under the conditions of the present study, the RUM heat fluxes have a marginal influence on the mean particle temperature. However, a significant impact was observed on the magnitude of particle temperature fluctuations. Neglecting the RUM heat fluxes leads to erroneous results while the Lagrangian statistics are recovered when it is accounted for in the regimes of low to moderate thermal Stokes number.

1. Introduction

A variety of industrial devices involve two-phase flows and many of them are non-isothermal. In combustion chambers, for example, fuel is injected in liquid state at a relatively low temperature into a hot, turbulent flow. Due to hydrodynamic forces, the liquid is atomized into droplets. The subsequent evaporation of the droplets' cloud is driven by heat exchange between the carrier and the dispersed phase. Moreover, temperature fluctuations may have a strong impact on the local evaporated fuel mass fraction as evaporation is a non-linear phenomenon. The resulting fluctuations of local equivalence ratio are known to have a negative impact on ignition, flame propagation or even combustion instabilities [1–3]. An accurate description of heat transfer to the dispersed phase is therefore necessary.

Very few studies have directly tackled the issue of particle temperature dispersion, which is mainly due to the lack of experimental data of non-isothermal two-phase flows [4]. Recent experimental techniques – such as rainbow thermometry – seem promising but further improvements are required [5]. An alternative is to use Direct Numerical Simulations (DNS): a few studies of non-isothermal academic configurations, coupled with lagrangian tracking of particles, have been carried out. The mechanism of two-phase heat and turbulent transport by particles was investigated in an decaying isotropic turbulence with an imposed temperature gradient in the fluid [6]: it was found that the particle temperature fluctuation and velocity are well correlated in the direction of the imposed temperature gradient. Jaberi [7] investigated the effects of the particle dynamical response time, τ_p, the Prandtl number, Pr, the Reynolds number, Re and mass-loading ratio, r_{ml}, on the statistics of particle temperature in a non-isothermal isotropic turbulence with stationary velocity and temperature fluctuations. They showed that particle temperature fluctuations decrease as τ_p, Pr, Re and r_{ml} increase. An extension of this work [8] showed that the response of particle temperature is different when the fluid and particle temperature decay in isotropic turbulence. In this case, the variance of the fluid and particle temperatures increase when the magnitude of $r_{ml} \times$ Pr increases.

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Shotorban et al. [9] studied the dispersed-phase temperature statistics in particle-ladden turbulent homogeneous shear flow in the presence of mean temperature gradient. They found that the particle temperature variance increases when the ratio of specific heat increases.

The Eulerian–Lagrangian (EL) approach is as a powerful tool to understand and simulate two-phase flows in academic configurations. However, the lagrangian tracking of individual particles for the simulation of a realistic industrial configuration is still beyond reach because of the large number of droplets. An alternative is to model the dispersed phase as a continuum, like the carrier: this approach is called Eulerian–Eulerian (EE). The equilibrium Eulerian approach, recently extended to non-isothermal flows gives promising results [10] but is adapted only to particles with sufficiently small dynamical and thermal inertia. The statistical approach proposed by Février et al. [11], called the Mesoscopic Eulerian Formalism (MEF), is able to reproduce local and instantaneous properties of particles embedded in a turbulent fluid flow [12]. The cornerstone of the MEF is the partitioning of the particle velocity field into two contributions: a continuous, self-coherent velocity shared by all particles called the mesoscopic field and a spatially uncorrelated contribution referred to as Random Uncorrelated Motion (RUM). This formalism showed its ability to simulate correctly turbulent two-phase flows in a complex geometry [13] and was recently extended to non-isothermal conditions [14]. *A priori* tests in a non-isothermal droplet-laden turbulent planar jet [15] show the ability of this approach to describe an evaporating dispersed phase interacting with a turbulent flow. The objective of the present work is twofold:

1. study the influence of the particles' thermal inertia in a configuration representative of a spray injection in a combustion chamber.
2. and propose an *a posteriori* validation of the MEF extended to non-isothermal flows.

The organization of the paper is as follows: the two solvers and modeling equations are described in Section 2; the configuration and boundary conditions are then presented in Section 3; finally the results are presented in Section 4 with detailed validation of the dynamics and temperature of the dispersed phase.

2. Description of the solvers and modeling equations

These simulations are carried out by two different codes developed at CERFACS and CORIA:

- A dilatable low-Mach solver (Asphodele – CORIA) with lagrangian tracking of individual particles.
- A compressible code (AVBP – CERFACS), where the MEF has been implemented.

2.1. Carrier phase flow solvers

Numerical methods used for the carrier-phase flow solvers have been already described in the litterature [16–18] and are only summarized here. Boundary conditions are treated in Section 3.2. AVBP solves the compressible Navier–Stokes equations. A third-order in time and space, finite-element scheme TTGC [19] is used for the carrier and dispersed phase. Asphodele is a DNS structured low-Mach solver. It uses a fourth-order finite-difference scheme for the gas and a third-order explicit Runge–Kutta scheme with a minimal data storage method [20] for both carrier and dispersed phases. A third-order interpolation is employed for the determination of gaseous phase properties at the location of a particle.

2.2. Eulerian/Lagrangian formulation

As described by Reeks [21], it is possible to take into account many forces to characterize the particle dynamics. However, because of the high density ratio between dispersed and gas phases, only the drag force, which is prevalent, has been retained. Additionally, several usual assumptions have been made: some of them are given in the following, but details may be found in a reference paper of Sirignano [22]. First, the spray is assumed to be dispersed and each particle is unaware of the existence of the others. Any internal heterogeneity or particle rotation is neglected and an infinite heat conduction coefficient is assumed in the particle. As a consequence, the particle temperature remains uniform but evolves with time. As a first approach and because of the dispersed nature of the flow, a one-way coupling has been considered. By denoting $\mathbf{V}_p$ and $\mathbf{X}_p$ the velocity and position vectors of a particle, respectively, the following relations are used to track particles throughout the computational domain:

$$\frac{\mathrm{d}\mathbf{V}_p}{\mathrm{d}t} = \frac{1}{\tau_p}(\mathbf{U}(\mathbf{X}_p, t) - \mathbf{V}_p) \tag{1}$$

$$\frac{\mathrm{d}\mathbf{X}_p}{\mathrm{d}t} = \mathbf{V}_p \tag{2}$$

The vector $\mathbf{U}(\mathbf{X}_p, t)$ represents the gas velocity at the particle $\mathbf{X}_p$. The right hand side term of Eq. (2) stands for a drag force applied to the particle and τ_p is the kinetic relaxation time:

$$\tau_p = \frac{\rho_p d_p^2}{18\mu_f} \tag{3}$$

where d_p is the particle diameter, ρ_p is the dispersed phase density and μ_f is the gas viscosity. The heating of each particle is characterized through

$$\frac{\mathrm{d}T_p}{\mathrm{d}t} = \frac{1}{\tau_\theta}(T(\mathbf{X}_p) - T_p) \tag{4}$$

where the characteristic relaxation time τ_θ is defined as:

$$\tau_\theta = \frac{P_r}{12}\frac{C_p}{C_f}\frac{\rho_p d_p^2}{\mu} = \frac{3}{2}\mathrm{Pr}\alpha\tau_p \tag{5}$$

where the gas and particle constant heat capacities are denoted C_f and C_p, respectively. Pr is the Prandtl number. The particle-to-fluid heat capacity ratio is $\alpha = C_p/C_f$.

2.3. Eulerian/Eulerian formulation: the Mesoscopic Eulerian Formalism

2.3.1. General presentation

The MEF was originally presented by Février et al. [11]: using Direct Numerical Simulations, they observed that two arbitrarily-close particles may have drastically different velocities. In other words, the ratio of the two-point correlation between particle velocities and the particle kinetic energy does not reach unity when the distance goes to zero (c.f. their Fig. 3). Based on this observation, the cornerstone of the MEF is a statistical-average operator, $\langle \bullet \mid \mathcal{H}_f \rangle$ that corresponds to the average over all particle realizations for a fixed carrier-fluid realization $\mathcal{H}_f$. This operator splits the particle velocity, u_p, in two contributions: a continuous, self-coherent velocity, $\tilde{u}_p = \langle u_p \mid \mathcal{H}_f \rangle$, shared by all particles called the mesoscopic field and a spatially uncorrelated contribution, δu_p, referred to as Random Uncorrelated Motion. One has

$$u_p(t) = \tilde{u}_p(x_p(t), t) + \delta u_p(t), \tag{6}$$

where $x_p(t)$ is the position of the particle at time t. Similarly, one can decompose the particle temperature T_p into its mesoscopic, $\widetilde{T}_p$, and uncorrelated, δT_p, components:

$$T_p(t) = \widetilde{T}_p(x_p(t), t) + \delta T_p(t). \tag{7}$$