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Turbulent latent and sensible heat flux in the presence of evaporative droplets

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ABSTRACT

Direct numerical simulations of an Eulerian-based carrier phase are performed which are two-way coupled in momentum and energy to Lagrangian droplets within a Boussinesq-type incompressible formulation, where the droplets are allowed to evaporate and condense and are thus coupled to the vapor field of the carrier phase. Turbulent planar Couette flow is simulated under varying boundary forcings to understand the degree to which evaporating droplets modify vertical fluxes of energy in horizontally homogeneous systems. In particular, the separate influences on both sensible and latent heat are substantial but opposite in sign, and the local relative humidity can result in droplet-induced heat or moisture fluxes which counteract the prescribed background gradients. The influence of droplet Stokes number is also considered, where it is shown that both clustering and turbophoresis play important roles in determining the magnitude of the droplet-induced sensible and latent heat fluxes.

Introduction

In many industrial and natural environments, the addition of suspended solid or liquid particles within a turbulent carrier gas phase can result in significant modifications to the bulk statistics of velocity, temperature, and other scalar quantities throughout the system. For instance the phenomenon of turbulence modulation (Balachandar and Eaton, 2010), where solid particles modify carrier phase motions through momentum coupling, can for example result in altered velocity fluctuation profiles and Reynolds stresses in turbulent flows near walls depending on the size and concentration of the particulate phase (Kaftori et al., 1998; Righetti and Romano, 2004; Kulick et al., 1994). In applications ranging from industrial powder transport to the formation of riverbed ripples, this dynamic coupling mechanism between phases requires careful attention if bulk-scale models are to be faithfully developed (Crowe, 2000).

For numerically modeling particulate-laden flows where elements of the dispersed phase remain small compared to the smallest turbulent length scales of the flow, the Lagrangian point-particle approach has been used extensively in combination with direct numerical simulation (DNS) of the carrier phase to study particle dispersion and momentum coupling in a wide variety of isotropic (Elghobashi and Truesdell, 1993; Boivin et al., 1998) and wall-bounded (Zhao et al., 2013; Soldati and Marchioli, 2009; Dritselis and Vlachos, 2011) flows. Details regarding processes such as preferential concentration or clustering (Richter and Sullivan, 2014a; Bernardini et al., 2013; Sardina et al., 2012; Rouson and Eaton, 2001) and the effects of particle Stokes number (Lee and Lee, 2015; Richter and Sullivan, 2013; Ferrante and Elghobashi, 2003) have been continually uncovered, which in turn have provided insight into physical mechanisms which are often difficult to observe or measure experimentally.

Beyond momentum coupling, however, a dispersed phase, depending on its material properties, also possesses the ability to modify the thermodynamic characteristics of the carrier phase flow, which has important implications for instance in systems where droplet size evolution is critical, such as within combustion chambers (Miller and Bellan, 1999) or during cloud formation (Vaillancourt and Yau, 2000). Owing to the larger degree of complexity in considering both two-way dynamic and thermodynamic coupling, less attention has been focused on understanding the feedbacks and carrier phase modifications in the fully coupled system, particularly from an experimental perspective. Studies are beginning to emerge, however, which, as in the case of two-way momentum coupling, offer progress in understanding energy and mass coupling mechanisms in particulate systems.

Considering only heat coupling — i.e., non-evaporating particles whose temperature differences with the ambient drive sensible heat transfer between phases — Shotorban et al. (2003) performed DNS of transient homogeneous turbulent shear flow laden with small, two-way coupled particles. They monitored the temperature variance budget and turbulent heat fluxes under varying particle size, concentration, and specific heat ratio, and found a general decrease of

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carrier phase temperature variance and turbulent heat flux with the addition of particles. Similarly, Zonta et al. (2008) and Zonta et al. (2011) studied turbulent channel flow dispersed with low concentrations of small, thermally coupled inertial particles, and illustrated the dual function of particles: altering cross-channel heat fluxes through both a modification to the mean temperature gradient as well as the Reynolds stress ejection events near the wall.

Kuerten et al. (2011) find similar results for thermally coupled particles in a turbulent channel flow, generally finding an enhancement of nondimensional cross-channel heat transfer depending on the dispersed phase characteristics. They again highlight the dual influence of particles through momentum and thermal coupling by breaking the total heat flux into the laminar, turbulent, and particle-induced components — a process that was also used by Richter and Sullivan (2014b), who analyzed the heat flux budget for thermally coupled particles in turbulent planar Couette flow, and who demonstrated an efficient heat transfer mechanism where particles of Stokes number near unity collect in the ejection regions typically responsible for turbulent fluxes in unladen conditions.

Studies that consider full thermodynamic coupling, where droplet evaporation is included in addition to momentum and energy coupling, are fewer in number. Mashayek (1998) performed an extensive analysis of the effects of evaporating droplets in weakly compressible homogeneous shear flows, and illustrates the significant modifications to both kinetic and internal energy evolution in the system, which is different when considering evaporating versus non-evaporating droplets. Miller and Bellan (1999) similarly consider evaporating droplets in weakly compressible environments, focusing on the mixing between a laden and unladen stream of gas. Particle clustering and entrainment of relatively unsaturated gas results in a broadening of the droplet size distribution, while at the same time lowering the kinetic and thermal energy of the downstream gas phase.

Recently, Russo et al. (2014) outlined an incompressible formulation of thermodynamically coupled droplets in turbulent channel flow. They found significant modifications to the mean temperature and moisture profiles, and, using the same breakdown of heat transport as used by Kuerten et al. (2011), demonstrated a substantial increase in the bulk nondimensional cross-channel Nusselt number after adding thermodynamically coupled droplets — an effect driven by particle/ambient temperature differences, which is enhanced when the droplets are allowed to evaporate. Subsequent studies by Bukhvostova et al. (2014b) and Kuerten and Vreman (2015) illustrate the influence of relative humidity and particle collisions, respectively.

The current study aims to extend this overall understanding of energy and flux modification by simulating droplet-laden turbulent planar Couette flow and evaluating the components of the wall-normal fluxes of sensible and latent heat. Our focus is broadly motivated by droplets suspended over marine surfaces, and specifically whether or not their presence can enhance or attenuate upward energy fluxes. Since evaporating droplets ultimately provide the link between sensible and latent heat transfer, understanding the basic yet highly coupled effects of evaporative cooling and enhanced moisture transport on total energy transfer are necessary for fully assessing their ability to modify energy transport.

As will be noted throughout, the simulations presented herein are generally similar to those of Russo et al. (2014) and Bukhvostova et al. (2014b), but extends the analysis to probe specific thermodynamic feedback mechanisms between the droplets and the surrounding flow. We focus particularly on the breakdown of total enthalpy flux into the sensible and latent components, with emphasis on the difference between droplet effects on each component independently versus the overall droplet effect on the sum — a breakdown with implications on accurate model development. We first present a numerical model in Section 2 which solves a two-way coupled set of equations where droplets and the surrounding turbulent flow are coupled in momentum, energy, and water vapor mass. We then present the results of a series of direct numerical simulations, where boundary forcings are varied in a systematic way that highlight unique cross-phase thermodynamic couplings present in the system. It is in this regard that the current study differs significantly from that of Russo et al. (2014), and a breakdown of both sensible and latent energy flux is provided in Section 3.1. Section 3.2 shows the variation of cross-channel enthalpy fluxes as a result of boundary forcing and Section 3.3 illustrates the influence of droplet size on these findings. Finally, Section 4 summarizes our conclusions.

Numerical model

The current study aims to better understand thermodynamic coupling in turbulent flows under the influence of small (smaller than the Kolmogorov length scale of the flow), relatively high-density saline water droplets. Thus, this work employs the combined Eulerian–Lagrangian strategy of performing DNS of the carrier phase (air) while representing spherical saline water droplets as point particles, each dynamically and thermodynamically coupled to the surrounding flow. The numerical model is therefore similar to those of Mashayek (1998), Miller and Bellan (1999), and Russo et al. (2014).

Carrier phase

The equations governing conservation of energy, moisture, momentum, and mass of the ambient (carrier phase) fluid are solved via DNS. In the context of moist air, we invoke a Boussinesq-type approximation by assuming that the addition of water vapor does not appreciably modify the carrier phase density. Thus, $\rho_{gas} \approx \rho_a$, where ρ_{gas} is the total gas mixture density (air plus water vapor) and ρ_a is the dry air density. This approximation also assumes that temperature variations in the system are not large enough to produce appreciable density variations. For the conditions specified in the following simulations, these approximations hold true within 1%. Note that, since their primary motivation includes combustion processes (where these approximations do not necessarily hold), the Eulerian–Lagrangian simulations of both Mashayek (1998) and Miller and Bellan (1999) utilize a fully compressible formulation and do not make this constant density assumption. Russo et al. (2014) meanwhile, use an incompressible formulation similar to that used in the current study. The similarities and differences will be discussed in more detail below. We also note that given the small temperature and humidity ranges specified in the present simulations (and in accordance with the standard Boussinesq assumption), we assume that temperature and/or humidity-dependent thermodynamic properties such as viscosity or thermal diffusivity are unnecessary. In certain conditions these effects can be significant (Zonta et al., 2012; Zonta and Soldati, 2014), but Russo et al. (2014) for example show that the influence of a humidity-dependent thermal conductivity is small in similar setups.

Mass conservation under these assumptions therefore yields a divergence-free condition for the carrier phase velocity field:

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

which is enforced by solving a pressure Poisson equation at each Runge–Kutta stage.

Again under the incompressible approximation and neglecting buoyancy forces, momentum conservation of the carrier phase yields:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_a}\frac{\partial p}{\partial x_i} + \nu_a \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{1}{\rho_a} S_i^m, \tag{2}$$

where $\nu_a = \mu_a/\rho_a$ is the carrier phase kinematic viscosity and S_i^m is the momentum coupling source due to the presence of the particles, to be defined in Section 2.3.