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Direct numerical simulations of a planar jet laden with evaporating droplets

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Abstract

A direct numerical simulation (DNS) study is conducted on the various aspects of phase interactions in a planar turbulent gas-jet laden with non-evaporative and evaporative liquid droplets. A compressible computational model utilizing a finite difference scheme for the carrier gas and a Lagrangian solver for the droplet phase is used to conduct the numerical experiments. The effects of droplet time constant, mass-loading and mass/momentum/energy coupling between phases on droplet and gas-jet fields are investigated. Significant changes in velocity, temperature, density and turbulence production on account of the coupling between the liquid and gas phases are observed in non-isothermal jets with evaporating droplets. Most of these changes are attributed to the density stratification in the carrier gas that is caused by droplet momentum and heat transfer.

Keywords: Droplet-laden turbulent jet; Two-phase planar jet; Droplet evaporation; DNS

1. Introduction

Multiphase flows occur in a wide range of engineering applications. Ink jet printers, spray combustors, and fire prevention systems are obvious examples of physical situations for which the understanding of multiphase transport phenomena are very important. This work is focused on a specific class of multiphase flows, that of dilute turbulent free shear flows laden with a dispersed medium, either solid particles or evaporating droplets. It is an effort to understand the complex mass/momentum/energy interactions between gas and droplet phases in a two-phase planar jet.

The general features of the "developed" single-phase planar and round turbulent jets are well-established. Hinze [1], Pope [2], Bernard and Wallace [3] and others have discussed these flows in detail, noting the general characteristics of the self-preserving portion of the flow. The near-fields of shear layers and jets are mainly controlled by the Kelvin–Helmholtz instabilities and are strongly dependent on the inlet flow conditions and external forcing [4]. Stanley and Sarkar [5] studied two-dimensional shear layers and jets, noting the impact that external forcing has on the jet development. They found that, although the downstream growth was nearly unaffected by forcing at the inlet, the near-field was modified. They reported some interesting results related to the symmetry of 'weak' and 'strong' jet flows due to forcing. The simulations performed herein would be classified as strong using their convention.

The effects of temperature/density on the growth and stability of free jets were studied by Kennedy and Chen [6]. They found that "cold jets" tended to be significantly more stable than "hot jets". They also indicated a modification of the mean velocity profile, where the cold jets profile were 'narrower' and had a "more gradual taper of velocity" than their hot counterparts. These are explained by Colucci [7], who used the linear stability theory to show that with a lower density at the shear zone the jet is more

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Nomenclature

B_M	mass transfer number
c_p	specific heat at constant pressure of fluid
c_L	specific heat of droplets
D	jet diameter
d_p	particle diameter
E	total energy
f_1	coefficient related to particle drag
f_2	coefficient related to particle heat and mass transfer
f_3	coefficient related to particle heat and mass transfer
h_α	specific enthalpy of species α
h_α^0	enthalpy of formation of species α
J_i^α	mass flux of species α in ith direction
K	thermal conductivity
Le_α	Lewis number of species α
L_v	latent heat of evaporation
m_p	mass of particle
Ma	Mach number
N_s	number of species
P	pressure
Pr	Prandtl number
q_i	heat transfer in ith direction
R^0	universal gas constant
R	molecular weight gas constant
Re	Reynolds number
r	radial position
r_0	jet radius
S_E	energy source term
S_{ui}	momentum source term in ith direction
S_ρ	mass source term
T	fluid temperature
T_p	particle temperature
T_m	mean gas temperature
T_{rms}	RMS of gas temperature
t	time
u_i	ith component of fluid velocity vector
u_i'	deviation from the mean velocity in ith direction
u_{cl}	centerline axial velocity
u_m	mean axial velocity
u_{rms}	root-mean-square of axial velocity
$\overline{u'v'}$	Reynolds stress
v_i	ith component of particle velocity vector
W_α	molecular weight of species α
X_i	ith component of Lagrangian particle position
x_i	ith component of Eulerian coordinate system
Y_α	mass fraction of species α
γ	ratio of specific heats of the fluid
η	coefficient related to particle energy
μ	fluid viscosity
ρ	fluid density
ρ_p	particle density
σ_{ij}	Newtonian fluid stress tensor
τ_p	particle time constant
$\dot{\omega}_\alpha$	scalar source/sink term

stable. He also found that the convective wave speed is biased towards the higher density stream. In summary, if the higher speed stream is of lower density than the lower speed stream, the Kelvin–Helmholtz instabilities will be attenuated. Add to that the effects of the particle drag, etc. and there are interesting modifications to the jet structure.

Despite challenges involved in measurements and computations of particle laden turbulent flows, there have been a significant number of published works on these flows [8–11]. For example, Crowe et al. [12] used numerical and experimental data to show that particle dispersion in free shear flows is controlled by large-scale vortical structures, and not so much by local diffusion due to particle concentration gradients. Armenio and Fiorotto [13] studied the importance of the different forces acting on particles. The intent was to determine which, if any, could be neglected in favor of computational efficiency. They found that the most important force is that due to particle drag.

Jaberi [14] conducted a study of fluid–particle thermal interactions in a particle-laden homogeneous turbulent flow. His findings indicate that the temperature of both the carrier gas and the dispersed phase are dependent upon various properties, such as the particle time constant and the mass-loading ratio. Mashayek [15–17], Miller and Bellan [18,19], and Miller [20] also used DNS to study the temperature field and the phase (heat, mass and momentum) interactions in droplet-laden homogeneous shear and temporal mixing layer turbulent flows. An important finding was that in homogeneous shear flows solid particles decrease the turbulent kinetic energy and increase the anisotropy of the flow, but the evaporation effect is usually in the direction of decreasing the anisotropy. Several different models for evaporation models were compared by Miller et al. [21]. They found that the non-equilibrium Langmuir–Knudsen model is the most accurate one. This model is used here.

As noted above, the main objective of this work is to study the droplet–carrier gas interactions in dilute, two-phase isothermal and non-isothermal planar jets with and without droplet evaporation. For reasons that are not discussed here, the calculations are based on an Eulerian–Lagrangian model and utilize a particle-source-in-cell (PSIC) methodology. This may not be considered a true DNS because the flow around each individual particle or droplet is not fully computed. However, a careful analysis of the results indicates that for the dilute systems and small (low Reynolds number) droplets studied here the point-