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Large-eddy simulation of a dispersed particle-laden turbulent round jet

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Abstract

The numerical results obtained by large-eddy simulation (LES) of a particle-laden axisymmetric turbulent jet are compared with the available experimental data. The results indicate that with a new stochastic subgrid-scale (SGS) closure, the effects of the particles on the carrier gas and those of the carrier gas on the particles are correctly captured by the LES. Additional numerical experiments are conducted and used to investigate the effects of particle size, mass-loading ratio, and other flow/particle parameters on the statistics of both the carrier gas phase and the particle dispersed phase.

Keywords: Particle-laden jet; Dilute, two-phase flows; Turbulent jet; LES

1. Introduction

Among various predictive methods available for particle-laden or droplet-laden dispersed multiphase turbulent flows, the numerical methods based on large eddy simulation (LES) are very attractive as they provide the most optimum means of capturing the unsteady physical features in these flows [1–6]. The accuracy and the reliability of LES predictions is, however, dependent on several factors such as the accurate modeling of the subgrid-scale (SGS) phase interactions and the correct representation of the initial/boundary conditions for all phases. To ensure the accuracy of a given model, both verification and validation studies should be conducted as suggested by Boivin et al. [7]. Of high importance to the development and verification of LES SGS models are both *a priori* analysis of direct numerical simulation (DNS) data, and *a posteriori* analysis of LES results via comparison with the laboratory experiments.

Armenio et al. [8] investigated the effects of the SGS on particle motion. Their work indicates that using a filtered velocity field alone to advance the particles can lead to serious inaccuracies; thus the importance of the SGS closures is emphasized. Miller and Bellan [9] conducted a thorough *a priori* analysis of the SGS effects using DNS results for a transitional mixing layer, and they also concluded that neglecting the SGS velocity fluctuations in LES might lead to gross errors in the prediction of the particle drag force. This, in turn, will lead to errors in both the carrier-phase and the dispersed-phase. Miller [10] went on to investigate the effects of solid particles on an exothermic reacting mixing layer. He found that the preferential concentration of the particles in the high-strain braid regions of the mixing layer, can lead to local flame extinction. Several other researchers have also used DNS data for a better understanding of isothermal and non-isothermal reacting and nonreacting particle-laden turbulent flows. For example, Mashayek [11,12] and Mashayek and Jaberi [13] noted that the presence of particles effectively decreases the turbulent kinetic energy while increasing the anisotropy of homogeneous turbulent shear flows. These effects were shown to be magnified by increasing either the mass-loading ratio or the particle time constant. They also found that the autocorrelation coefficient of the velocity of the carrier

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Nomenclature

B_M	mass transfer number	u_i	ith component of fluid velocity vector, **U**
c_p	specific heat at constant pressure of fluid	u_{cl}	centerline axial velocity
D	jet diameter	u_m	mean axial velocity
d_p	particle diameter	u_{rms}	root-mean-square of axial velocity
E	total energy	$\overline{u'v'}$	Reynolds stress
f_1	coefficient related to particle velocity	u^*	fluid velocity at particle position
f_2	coefficient related to particle temperature	u_p	particle velocity
f_3	coefficient related to particle temperature	v_i	ith component of particle velocity vector, **V**
J_i^α	mass flux of species α in ith direction	W_α	molecular weight of species α
K	thermal conductivity	X_i	ith component of Lagrangian coordinate system
m_p	mass of particle	x_i	ith component of Eulerian coordinate system
N_s	number of species	x_p	particle location
P	pressure	Y_α	mass fraction of species α
q_i	heat transfer in ith direction	α_2	ratio of specific heat of the particle to that of the fluid
R^0	universal gas constant		
R	molecular weight gas constant	γ	ratio of specific heats of the fluid
r	radial position	η	coefficient related to particle energy
r_0	jet radius	μ	fluid viscosity
S_E	energy source term	ρ	fluid density
S_{ui}	momentum source term in ith direction	ρ_p	particle density
S_ρ	mass source term	τ_{ij}	Newtonian fluid stress tensor
T	fluid temperature	τ_p	particle time constant/Stokes number
T_p	particle temperature		
t	time		

gas in an isotropic two-phase flow increases with an increase in mass-loading ratio. Jaberi [14] and Jaberi and Mashayek [15] studied particle temperature in homogeneous turbulence. They found that the temperature intensity decreases with increasing particle time constant, thermal diffusivity and/or Prandtl number. Their results clearly indicate the importance of the thermal coupling effects and the SGS temperature interactions between phases in non-isothermal two-phase flows which should be included in the LES of such flows.

This study is intended to offer evidence that the LES and the corresponding SGS closures discussed and implemented herein are both applicable and accurate. This is accomplished through comparison with the experimental data of Gillandt et al. [16], who have generated phase-Doppler-anemometry (PDA) results for the near-field of a moderate Reynolds number round jet laden with heavy particles. Most of the reported experimental studies of particle-laden turbulent jets [17–21] consider the "far-field behavior" of the flow and/or do not measure both the carrier and dispersed phases concurrently. The goal of LES is, of course, to be able to predict the near and far flow field behavior of both phases, but it seems to be more prudent to focus first on the performance of the models in the near field. The desire to improve the applicability of LES to multiphase flows is complemented by the current limitations of experimental methods of flow measurement. For example, the PDA system [16,22] can measure the velocities of both the carrier gas and the particles, but the particles must be much larger than the tracers (to offer a definitive separation of scales). This results in a description of a flow which involves particles larger than those that may be observed in some industrial applications. In contrast, the LES methods described herein may be readily used for various particle sizes and Reynolds numbers. This work is somewhat similar to the investigation of a slit-jet by Yuu et al. [23]. However, there are important physical differences between planar and axisymmetric free jets and an additional emphasis is placed here on the effect of particle inlet conditions and SGS models.

The remainder of this paper is organized as follows: first, a description of the governing equations and computational methodology for both the carrier gas and particulate field is presented in Section 2. That is followed by a detailed discussion of the LES results, including the experimental validation in Section 3. Finally, the paper is completed by a summary and some concluding remarks in Section 4.

2. Formulation and computational methodology

In the hybrid Eulerian–Lagrangian two-phase large eddy simulation (LES) method, the "resolved" carrier gas field is obtained by solving the filtered form of the (compressible) Navier–Stokes, energy and scalar equations, together with the equation of state for pressure