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Evaluation of stochastic particle dispersion modeling in turbulent round jets

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ABSTRACT

ODT (one-dimensional turbulence) simulations of particle-carrier gas interactions are performed in the jet flow configuration. Particles with different diameters are injected onto the centerline of a turbulent air jet. The particles are passive and do not impact the fluid phase. Their radial dispersion and axial velocities are obtained as functions of axial position. The time and length scales of the jet are varied through control of the jet exit velocity and nozzle diameter. Dispersion data at long times of flight for the nozzle diameter (7 mm), particle diameters (60 and 90 µm), and Reynolds numbers (10, 000–30, 000) are analyzed to obtain the Lagrangian particle dispersivity. Flow statistics of the ODT particle model are compared to experimental measurements. It is shown that the particle tracking method is capable of yielding Lagrangian prediction of the dispersive transport of particles in a round jet. In this paper, three particle-eddy interaction models (Type-I, -C, and -IC) are presented to examine the details of particle dispersion and particle-eddy interaction in jet flow.

1. Introduction

Particle and droplet dispersion in turbulent jet flows is an essential part of many important industrial processes. Typical examples include the dispersion of liquid fuel droplets in gas combustors and the mixing of coal particles by the injection jets of coal-fired power plants. The dispersion of the particles largely determines the efficiency and the stability of these processes.

Many computational studies on gas-particle turbulent jets have been performed. Direct numerical simulations (DNS) have been used to study gas-particle jets at relatively low Reynolds numbers (Chien, 1982; Li et al., 2011). However, DNS for a high Reynolds number flow is not computationally efficient. Therefore, simulation approaches are required that do not resolve all flow scales in three dimensions. Many gas-particle flows have been studied in which the subgrid-scale turbulence is modeled using large eddy simulation (LES) (Almeida and Jaberi, 2008; Yuu et al., 2001). LES provides good means to capture unsteady physical features in the turbulence. The accuracy and the reliability of LES predictions depend on several factors, such as the accurate modeling of the subgrid-scale phase interactions.

A promising alternative approach is the one-dimensional turbulence (ODT) model, which is able to resolve a full range of length scales on a one-dimensional domain that is evolved at the finest time scales (Kerstein, 1999; Kerstein et al., 2001). ODT has been applied to many different homogeneous and shear-dominating reacting (Echekki et al., 2001; Hewson and Kerstein, 2001; 2002; Lignell et al., 2012; Punati, 2012; Ricks et al., 2010) and nonreacting (Ashurst and Kerstein, 2005; Kerstein, 1999; Kerstein et al., 2001; Sun et al., 2014) flows including homogeneous turbulence, channel flow, jets, mixing layers, buoyant plumes, and wall fires.

Schmidt et al. (2004) extended the ODT model to the prediction of particle-velocity statistics in turbulent channel flow. Punati (2012), and Goshayeshi and Sutherland (2015a; 2015b) studied coal combustion and particle laden jets using ODT (using a version of the Type-C model noted below). In our previous study, one version of the ODT multiphase interaction model using an instantaneous (referred to as Type-I) particle-eddy interaction (PEI) model was presented to investigate particle transport and crossing-trajectory effects in homogeneous turbulence (Sun et al., 2014). Here, we extend this previous ODT study to shear flows and present two new PEI models to analyze the behavior of individual particles in jets at high Reynolds numbers (*Re*). One of the models applies continuous PEI (referred to as Type-C) and the other combines instantaneous and continuous interaction features (referred to as Type-IC).

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The remainder of this paper is organized as follow: first, a summary description of ODT is presented, with details of the PEI models given. This is followed by a presentation and discussion of the results of the Type-I, -C and -IC models, including comparisons to experimental results. Sensitivity of results to the single particle model parameter is discussed, and summary and concluding remarks are given.

2. Numerical description

2.1. ODT model

One-dimensional turbulence (ODT) is a numerical method to generate realizations of turbulent flows using a stochastic model of the turbulent cascade on a one-dimensional domain (Kerstein, 1999). The one-dimensional domain is formulated in the direction of primary velocity gradients and on which the governing equations for, e.g., mass, momentum, energy, and species conservation are solved. Most ODT applications, including that presented here, use Cartesian coordinates in which the *y, x* and *z* coordinates are the ODT domain-aligned, streamwise (direction for flow evolution), and spanwise directions, respectively.

The ODT model consists of two main mechanisms: diffusive advancement, and advective eddy events. The diffusive evolution on the 1D domain is governed by transport equations (described below) that omit the nonlinear advective terms, which are modeled by the eddy events. These diffusive equations dissipate velocity fluctuations and kinetic energy, though this process is only significant at diffusive scales, and the eddy events model the cascade of fluctuations to the dissipative scales. In general flows, nonlinear advection describes a vortex-stretching process that acts in three dimensions to transfer fluctuations to higher wave numbers and is costly to predict. In order to describe these nonlinear advective terms, ODT introduces the concept of the so-called “triplet map” that transfers fluctuations to higher wave numbers during eddy events. The triplet maps that make up the eddy events in ODT occur instantaneously. The rate of occurrence of this transfer by ODT eddy events is determined through a stochastic sampling of the evolving velocity field through a measure of the shear energy that is a function of the location on the domain and the eddy length scale (wavenumber). There are two approaches to evolve the ODT domain: (i) temporal evolution where each ODT realization is parameterized by (*y, t*) and represents a (possibly Lagrangian) time history, and (ii) spatial evolution, where each ODT realization is parameterized by (*y, x*). Even in predicting spatially developing flows like the jet in this case, most ODT simulations have been conducted using temporal evolution assuming a Lagrangian evolution of the flow domain to map results to the spatial evolution (Hewson and Kerstein, 2001).

2.1.1. Diffusive advancement

In the Lagrangian frame of reference, choosing (*y, t*) as independent variables, the governing equations are derived from the Reynolds transport theorem and advanced in time along the ODT line (Lignell et al., 2012). Since there is no mass source term, no non-convection mass flux, and uniform properties inside the grid control volumes in one dimension, the finite-volume equation applied on the grid cells for the continuity equation is

$$\rho \triangle y = \text{constant}, \tag{1}$$

where the density ρ is constant for the nonreacting flow considered here. The diffusive advancement evolves scalar equations of momentum (per mass) component U_i using a conservative finite volume method written here for a given cell:

$$\frac{dU_i}{dt} = -\frac{1}{\rho \triangle y}(\sigma_{i,e} - \sigma_{i,w}), \tag{2}$$

where $\sigma_{i,j}$ is the viscous stress. The subscripts *e* and *w* represent east and west faces of the control volume. The viscous stresses for the three velocity components are represented as

$$\sigma_i = -\mu \frac{dU_i}{dy}, \tag{3}$$

where μ is viscosity. The spatial derivative appearing in this equation is evaluated at cell faces using a finite difference approximation between the two neighboring cells.

2.1.2. Eddy events

Turbulence is characterized by a three-dimensional vortex stretching process that is modeled in ODT through a representative sequence of eddy events as introduced at the beginning of this section. This model has two key components, the triplet-map representation of the length-scale cascade and the model for the rate of triplet maps. Turbulent eddies are sampled randomly on the domain as a function of the eddy location, represented by their left bound, y_0, and by their size, *l*, with the triplet map occurring over the region $[y_0, y_0 + l]$ for the given sample. The triplet map spatially compresses the fluid property profiles within $[y_0, y_0 + l]$ by a factor of three. The original profiles are replaced with three copies of the compressed profiles, with the middle copy spatially inverted. This mapping is described by

$$f(y) = y_0 + \begin{cases} 3(y - y_0) & \text{if } y_0 \le y \le y_0 + 1/3l, \\ 2l - 3(y - y_0) & \text{if } y_0 + 1/3l \le y \le y_0 + 2/3l, \\ 3(y - y_0) - 2l & \text{if } y_0 + 2/3l \le y \le y_0 + l, \\ y - y_0 & \text{otherwise.} \end{cases} \tag{4}$$

where *f*(*y*) and *y* are the original fluid location and the post-triplet-map location, respectively. The fluid outside $[y_0, y_0 + l]$ is unaffected. The triplet map is measure preserving and all integral properties (e.g., mass, momentum, and energy) or moments thereof are constant during a triplet map. Specifically, the kinetic energy is conserved, which is a desirable property because eddy events physically model the inviscid advection process. Immediately after the triplet map, kernel transformations are introduced that redistribute energy among the velocity components (Wunsch and Kerstein, 2001). The transformations are meant to model the velocity randomization and so-called return to isotropy effect in turbulent flows. The kernel can be considered as a wave function that adds or subtracts energy from the eddy based on the amplitude of the wave. An eddy event maps the velocity component *i* as follows:

$$U_i(y) \longrightarrow U_i(f(y)) + c_i K(y), \tag{5}$$

where the kernel $K(y) \equiv y - f(y)$ is the displacement induced by the triplet map and integrates to zero over the eddy interval. c_i is the kernel coefficient of $K(y)$ and is specified to ensure conservation of energy among momentum components. This form is written for constant density flows, as studied here. A variable density formulation is also available (Ashurst and Kerstein, 2005).

The procedure to sample and accept an eddy follows that described in Lignell et al. (2012), and a summary description is provided here. The eddy rate density for an eddy occurrence at location y_0 and length *l* is denoted as $\lambda_e(y_0, l, t)$ and is dimensionally $\tau_e^{-1} l^{-2}$ where τ_e is an eddy time scale given in Eq. (10). The rate of all eddies at a given time is $\Lambda(t) = \iint \lambda_e(y_0, l, t) dy_0 dl$, and the eddy PDF is defined as $P(y_0, l, t) = \lambda(y_0, l, t)/\Lambda(t)$. (In the following, the y_0, *l*, and *t* functional dependencies will be presumed.) Ideally, eddies would be sampled from this PDF, with occurrence times sampled with Poisson statistics with mean rate Λ. However, this is inconvenient and computationally expensive since the two dimensional eddy distribution would have to be constructed at each timestep, with a correspondingly complex sampling procedure involving numerical inversion. Instead, we use a thinning method (Lewis and Shedler, 1979) coupled with the rejection method (Papoulis and Pillai, 2002). In a thinning process,