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Comparison of the structure of computed and measured particle-laden jets for a wide range of Stokes numbers

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A B S T R A C T

Turbulent particle-laden jets have been the subject of interest for many years on account of their relevance to several practical devices like engines, combustors and gasifiers. While prior experimental studies have examined particle-laden flows at high Stokes number, experimental data on particle-laden jets with particle Stokes number of the order of one and lower have not been available until recently. This study presents results from computations of particle-laden jets for Stokes number ranging from 0.3 to 500 and their comparison with measured results. The mean gas-phase velocity is found by solving RANS equations with a k—ϵ model for turbulence. The particles are solved in a Lagrangian framework with the coupling between the carrier and dispersed phase modeled using a drag coefficient with a high-Reynolds number correction. Particle–turbulence interactions are modeled using a random-walk dispersion model. The influence of Stokes number on the spreading rate of the carrier and dispersed phase is examined. It is shown that for the range of Stokes numbers considered, the computed results agree with measured particle centerline velocities within about 20%. The changes in particle velocities predicted as Stokes number varies are consistent with measured changes in these variables. While no specific trends can be identified in the differences between computed and measured results that would relate the differences to Stokes number, several parametric studies are carried out to investigate the effect of jet inlet gas phase turbulence intensity, fluctuating particle velocity at the jet inlet, turbulence modulation and the dispersion model employed on jet spreading and centerline velocities.

1. Introduction

Turbulent jets are common in several devices like engines, combustors and gasifiers. These jets have been studied in detail by several researchers in the past [1–5]. As a result, we have a fairly good understanding of the behavior of turbulent jets. However, in most of these devices, the flow often includes a dispersed phase as well. For instance, internal combustion engines and gas turbines have turbulent drop-laden jets, while a gasifier often has a solid particle-laden turbulent jet. Addition of a dispersed phase significantly increases the complexity of the flow.

In a particle-laden turbulent flow, there can be different regimes of particle–turbulence interaction [6]. When the particle mass loading ratio (the ratio of particle mass flux to the carrier phase mass flux) and the volume fraction of the dispersed phase are low, the particles do not influence the structure of the jet significantly. This regime is referred to as a one-way coupling regime. The particles are affected by the turbulent flow field, but the particles themselves do not affect the turbulence. When the particle mass loading ratio is relatively high, but the volume fraction of the dispersed phase is low, there exists a two-way coupling regime. In this regime, the particles influence the turbulence and the turbulence affects the particle motion. In scenarios where both the particle mass loading ratio and the volume fraction of the dispersed phase are high, there exists a four-way coupling regime, where inter-particle interaction becomes important in addition to the turbulence–particle interaction. In this work, we will be studying particle-laden jets that are in the two-way coupling regime.

For particle-laden turbulent flow, the particle Stokes number (St) at the jet exit is an important parameter. The St is defined as the ratio the particle response time, τ_p to the flow response time τ_f, i.e.

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$$St = \frac{\tau_p}{\tau_f}. \quad (1)$$

For a spherical particle, the particle response time can be taken as the time constant of the particle in Stokes flow, i.e.

$$\tau_p = \frac{\rho_p d_p^2}{18\mu}, \quad (2)$$

where ρ_p is the particle density, d_p is the particle diameter and μ is the viscosity of the carrier fluid. The flow response time can be obtained from a characteristic length scale and a velocity scale of the flow. For example, in the case of a pipe flow, the pipe diameter D provides a characteristic length scale and the bulk velocity provides a characteristic velocity scale. The flow response time can then be expressed as

$$\tau_f = \frac{D}{U_b}. \quad (3)$$

Thus the St at the jet exit is given by

$$St = \frac{\rho_p d_p^2 U_b}{18\mu D}. \quad (4)$$

If the St is small, the particles would adjust quickly to any changes in the flow. If the St is large, the particles would take a longer time to adjust to the flow. In a two-way coupling regime, the particle St at the jet exit would influence the structure of the jet.

Several researchers have studied turbulent particle-laden jets through both experimental and computational techniques. Shuen et al. [7] have reported measurements and computations of particle laden jets. They have measured the mean velocities of the carrier and the dispersed phase using Laser Doppler Anemometry (LDA). In their work, they compare the effect of particle diameter d_p, the mass loading ratio Φ_m and the Reynolds number Re. However, no explicit discussions are provided about the development of the jet at different St. From their experimental conditions, the St is calculated to be between 100 and 500.

Particle-laden jet measurements of Modarress et al. [8] indicate that the fluctuations of the carrier phase decrease with increase in Φ_m. These measurements, however, are for $St > 10$. It is known that particles can either augment or attenuate turbulence depending on the St [6]. Fleckhaus et al. [9] report similar findings, but their St is about 70. Moreover, the standard deviation in the particle size is not mentioned in the work of Modarress et al. [8]. In the study of Fleckhaus et al. [9], the standard deviation is about 25%. Owing to the squared dependence of the St on the d_p, the effect of St might be masked in these measurements due to the polydispersity of the dispersed phase. Mostafa et al. [10] report measurements of particle-laden jets with the standard deviation of the particles being about 5%. This can be considered monodisperse. However, the St investigated in this study is of the order 10. Refs. [11–15] are other measurements on particle-laden jets. However, none of them report the behavior of the jet when St is of the order unity and lower. Moreover, the measurements are not for truly monodisperse particles (standard deviation <5%).

Eaton and Fessler [16] report that particle behavior can be significantly different depending on the St. They report that St of the order unity, in particular, shows a strong tendency to concentrate preferentially, while no such effects are observed for higher St. This necessitates the need to study the accuracy of particle–turbulence models under a wide range of St to determine the validity of the models. There might be applications where the St is of the order unity. The predictive capabilities of the particle–turbulence model should be studied before they are used in the design of such devices. For instance, in typical industrial furnaces, the St is of the order 1 [17]. Recently, Lau and Nathan [18] have reported detailed measurements of the velocity and concentration of the dispersed phase in particle-laden jets for St of the order unity and lower. This gives us an experimental benchmark to test existing models and identify their shortcomings if any.

In this work, the structure of a turbulent particle-laden jet is studied for a wide range of St numbers ranging from 0.3 to ~500 through computations and the computed results are compared with the measurements available. The sensitivity of the structure of the jet to parameters such as the turbulence intensity of the gas phase at the jet exit and the particle velocity fluctuations at the jet exit is examined. The effect of Pope's correction [3], turbulence modulation and the dispersion model employed is also studied. The rest of the work is organized as follows: an overview of the computational method employed in this work is presented followed by specific details of the computational setup. This is then followed by results and discussion where the computed results are compared with measurements. Subsequently, a detailed study is carried out to determine the sensitivity of the structure of the jet to the various parameters mentioned earlier. The paper closes with summary and conclusions.

2. Computational method and conditions of study

The computations are done with an in-house numerical code [19] that solves the Reynolds Averaged Navier Stokes (RANS) equations with a k–ϵ model for turbulence. This code has been widely employed in our earlier works for spray and jet computations [4,5,20–24]. Axi-symmetry of the jet is assumed in the current study. The particles are solved in a Lagrangian framework employing the Lagrangian-Drop Eulerian-Fluid (LDEF) approach of Dukowicz [25]. The coupling between the carrier and dispersed phase is modeled using a drag coefficient with a high-Reynolds number correction [26]. Particle–turbulence interactions are modeled using a random-walk dispersion model proposed by Gosman and Ioannides [27]. The volume fraction of the dispersed phase in all cases is less than 1%. The correction proposed by Pope [3] to account for vortex stretching in a round jet is included.

The axisymmetric domain has dimensions 100 (axial) × 30 (radial) cm and the domain is resolved by a 196 × 98 stretched grid. The orifice has 6 cells radially. The grid employed for our computations is shown in Fig. 1. Increasing the resolution was found to have no significant effect on the results. Fig. 2 shows the non-dimensional centerline velocity decay of the particles for two different grid resolutions. It can be seen that both centerline velocity curves are close to each other. We have used the 196 × 98 grid for all our computations. Further, the high and the low St cases show certain differences in their decay. This will be discussed in detail in the next section. Table 1 shows the conditions at the jet exit. The range of St studied varies from 0.3 to 533.8. The St is varied by changing the particle diameter, d_p, particle density, ρ_p and/or the bulk jet exit velocity U_b. The first three cases are compared with the measurements of Lau and Nathan [18], while the other cases are compared with the measurements and computations of Shuen et al. [7].

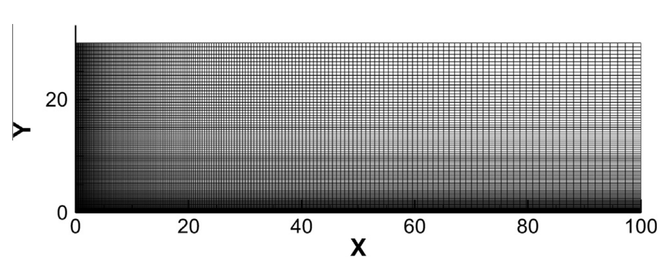

Fig. 1. The axisymmetric computational grid.