International Journal of Multiphase Flow 68 (2015) 100–120

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Effect of turbulence non-isotropy modeling on spray dynamics for an evaporating Acetone spray jet

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ARTICLE INFO

Article history:
Received 15 May 2014
Received in revised form 17 October 2014
Accepted 20 October 2014
Available online 25 October 2014

Keywords:
Spray turbulent dispersion
Stochastic modeling
Reynolds Stress Model
SST-k-ω
Turbulence non-isotropy
Acetone spray jet

ABSTRACT

The effect of turbulence closure on spray dynamics is studied for three dilute Acetone spray jets using an Eulerian–Lagrangian approach with two-way coupling. A stochastic random walk algorithm is employed to model the droplets' dispersion. Simulations using different turbulence closure models (i.e. the isotropic SST-k-ω, and the k-ϵ realizable models, and the non-isotropic Reynolds Stress Model (RSM)) are compared with the Sydney spray measurements for **SP2**, **SP6**, and **SP7** spray conditions (Gounder et al., 2012). The experimental mass flow rate, spray mean and rms data are injected for each available size bin during the numerical simulations. Overall, the simulations show good comparisons with the mean and rms spray measurements. The turbulence closure non-isotropy modeling shows relatively weak effect on the spray mean velocity and size profiles predictions, where the RSM predictions was slightly better at the centerline at $x/D = 10$ and $x/D = 20$ for the **SP2** mean axial velocity, with similar predictions to the **k** models for the **SP6** and **SP7**. The RSM, however, consistently predicts better rms axial and radial spray velocity distribution, which indicates more realistic droplet dispersion than the isotropic SST-k-ω and the k-ϵ. The RSM gas phase shear stresses show that close to the nozzle (i.e. at $x/D = 5$ and $x/D = 10$) the turbulence non-isotropy increases as we approach the centerline and is maximum at the shear layer location at $x/D = 5$. On the other hand, at the downstream locations at $x/D = 30$ the turbulence field non-isotropy increases at the jet edge. A conical region of large size mean droplets ($D10 > 26\mu$m) is observed around the **SP2** jet edge. This region disappears quickly for the **SP6** and **SP7** after the inflow section. The data analysis exhibits that the RSM predicts higher Stokes number than the SST-k-ω due to faster mixing time scales. For the impact on dynamics, at the centerline the SST-k-ω and k-ϵ models, predict higher droplets' slip velocity, higher drag force, and faster droplet's response than the RSM. The droplets' tendency for cross-stream dispersion is also found to vary with the turbulence model. The fan spreading phenomenon is observed at the down stream locations away from the nozzle. The results show that the spray turbulence is non-isotropic and lags the gas phase rms values, especially at the centerline. This discrepancy decreases downstream and towards the jet edge. The study shows the importance of non-isotropy modeling on the droplets dispersion and spray dynamics predictions.

Introduction

Spray injection is common in many practical systems, where liquid droplets are injected and atomized in a continuum gas-phase flow (Lefebvre, 1999). Of specific interest are the high Reynolds number turbulent flow devices such as cyclone separators, scrubbers, gas turbine and internal combustion engines.

In a typical numerical simulation for such devices, turbulence is unresolved and, therefore, is modeled. In reality, the injected droplets' path in such turbulent environment is expected to be altered by the gas phase flow turbulent fluctuations, which can be different for different turbulence closure models. For example, accounting for turbulence non-isotropy in different directions or assuming isotropic turbulence that are computed from a single velocity and length scales. As such, it is important to know how the gas phase flow turbulence modeling impacts the droplets' trajectories. In the current work, a stochastic approach is employed to model the droplets' dispersion by the gas phase flow fluctuations. The effect of the particles' dispersion on the gas phase flow fluctuations might also be important for unity Stokes number flows (Hardalupas and Horender, 2003). However, only the effect of the flow field on the droplets' dispersion is considered here.

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.10.009

Turbulent spray simulations are challenged by the demand to resolve a wide range of scales on a computationally affordable coarse mesh. For example, during the computations large amount (order of a billion) of spray droplets can exist with size distribution that ranges between 0.1–100 μm. Such scales are much smaller in size compared to the computational mesh (order of a *mm*). As such, an Eulerian–Lagrangian framework is usually employed, where the spray injected particles are tracked in a Lagrangian frame of reference (El-Asrag et al., 2014). Such an approach is convenient as it separates the different scales and therefore alleviates the restriction on the computational mesh size. It is then important to accurately model the coupling between the different frames of reference to account for the spray–flow interactions.

To model such spray–flow interactions, a two-way coupling approach, known as particle source in cell (PSI) (Crowe et al., 1977), is implemented. Where the gaseous flow equations, solved in the continuum phase, are coupled with the liquid injected droplets through source terms. As the droplets travel along their trajectories they undergo mass, energy and momentum exchanges with the surrounding gas phase. The gas flow also induces aerodynamic forces on the droplets such as drag and surface tension. To simplify the analysis, three Sydney evaporating Acetone spray jets with low Weber number (estimated to be less than 0.1 (Gounder et al., 2012; Masri and Gounder, 2010; Chen et al., 2006)) are studied, where breakup and coalescence can be assumed negligible.

Many publications studied spray turbulence interactions. Chen and Pereira (1998)] studied the effect of the gas phase temperature fluctuations on the droplets' evaporation. They showed that the inclusion of the gas temperature fluctuations has a strong effect on the vaporization of individual droplets, but has a negligible effect on global spray ensemble-averaged droplet properties such as the velocity, diameter, and mass flux. Kourmatzis et al. (2013)] studied experimentally the effect of turbulence, evaporation and heat release on the dispersion of droplets in dilute spray jets. The dynamics and dispersion characteristics are analysed by conditioning results on the droplet Stokes numbers. They defined the droplets dispersion tendency by the ratio of radial root mean square (rms) velocity to axial mean velocity for the tracer particles. The droplets' dispersion was found to vary significantly between reacting and non-reacting flows. However, dispersion was found to be largely unaffected by evaporation but is dependent on the carrier velocity and axial location within the spray.

Hardalupas and Horender (2003), Sahu et al. (2014) showed also experimentally and numerically in a shear layer that particle centrifuging occurs due to the flow vortical structures, which increases the local particle concentration. Droplet clustering was also observed for large class sizes. This clustering was found to increase towards the spray edge. They also reported that the droplet velocity fluctuations are isotropic close to the spray axis with an increase in anisotropy towards the spray edge due to the memory effect. This finding is opposite to the current work results as will be shown in Section "Results". The non-isotropy was observed by measuring the spatial correlation coefficients between the axial droplet velocity fluctuations component and the gas phase velocities. The measurements showed that the more the droplets travel away from the centerline, the higher the correlation between the droplet axial velocity and the gas phase axial velocity fluctuations. This behavior was found to be independent of the droplet size class. Correlations of the cross-stream velocity fluctuations, on the other hand, were found to decrease with distance from the centerline.

The Sydney spray non-reactive experiments (Gounder et al., 2012; Masri and Gounder, 2010; Chen et al., 2006) have been recently simulated by few authors. De et al. (2011)] simulated two evaporating Acetone spray jets (i.e. **SP1** and **SP2**) and three ethanol reactive jet flames (i.e. **ETF1**, **ETF4**, and **ETF7**) using a fully stochastic separated flow (FSSF) approach. They used the k-ϵ model for turbulence closure and a thermal model for spray evaporation with an infinite conductivity in the liquid phase. They investigated the effect of the gas-phase velocity, temperature and mixture fraction fluctuations on mass and heat transfer. A one step finite rate Eddy-Dissipation-Model (FR-EDM) is employed for chemistry-turbulence closure. The temperature and mixture fraction fluctuations are found to have minor effect, especially for non-reactive spray jets, compared to the gas-phase velocity fluctuations that contribute most to mass and heat transfer.

In the current work three Sydney evaporating Acetone spray jets with different inflow conditions (i.e. **SP2**, **SP6**, and **SP7**) are simulated (Gounder et al., 2012) Three common RANS turbulence closure models are compared to investigate the turbulence closure non-isotropy effect on spray dynamics and dispersion characteristics. The two equation models (i.e. k-ϵ and SST-k-ω) assume isotropic turbulence, while the RSM solves 7 equations for the full shear stress tensor. The evaporating Acetone spray jets simulations are assessed with the experimental data (Chen et al., 2006; Gounder et al., 2012; Masri and Gounder, 2010) without the complexity of combustion.

The paper is organized as follows. In Section "Numerical setup" the numerical setup is described for the spray jets. The numerical approach used for particle dispersion is then highlighted in Section "Numerical approach". Next, the three turbulence models results are compared with the experimental profiles and the results are discussed in Section "Results". Finally the conclusions are presented in Section "Conclusion".

Numerical setup

The Sydney spray experimental setup is explained in detail elsewhere (Gounder et al., 2012; Masri and Gounder, 2010; Chen et al., 2006) and is reviewed here briefly. The experimental apparatus is shown in Fig. 1. The liquid spray jet is injected upstream through a nebulizer and advected downstream to the nozzle exit and mixed by air (i.e. the carrier [$\dot{m}_{car}$] in Fig. 1). Due to the relatively long passage and high saturation vapor pressure of Acetone, some of the liquid spray evaporates and mixed air and vapor/liquid Acetone is injected at the nozzle exit (i.e. $x/D = 0$). Air is also injected through a secondary co-flow pilot stream with velocity 1.5 m/s and the whole setup is placed in a wind tunnel of air coflow of 4.5 m/s. For non-reactive Acetone spray jets, measurements for eight different variations (i.e **SP1** to **SP8**) of the carrier and the

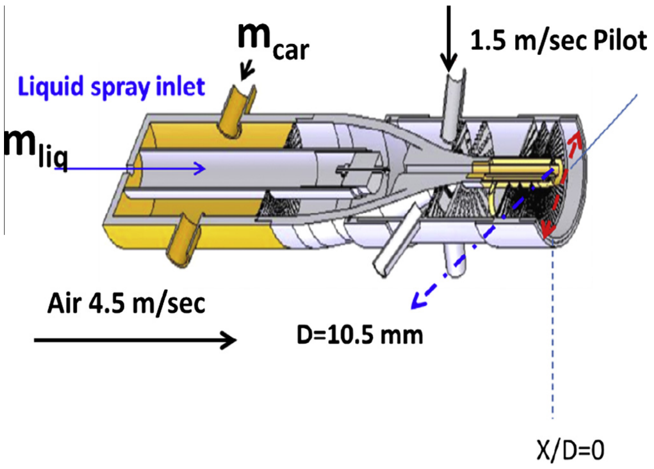

Fig. 1. Spray burner experimental setup Website (2014)]. Where m_liq and m_car are the liquid mass flow rate and the carrier air mass flow rate, respectively.