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Numerical investigation on liquid sheets interaction characteristics of liquid-liquid coaxial swirling jets in bipropellant thruster

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ABSTRACT

Spray atomization process of a liquid-liquid coaxial swirl injector in bipropellant thruster has been investigated using volume of fluid (VOF) method coupled with large eddy simulation methodology. With fine grid resolution, detailed flow field of interacted liquid sheet has been captured and analyzed. For coaxial swirling jet, static pressure drop in the region between the liquid sheets makes two liquid sheets to approach each other and merge. A strong pressure, velocity and turbulent fluctuations are calculated near the contact position of two coaxial jets. Simulation results indicate that additional perturbations are generated due to strong radial and axial shear effects between coaxial jets. Observation of droplet formation process reveals that the Rayleigh mode instability dominates the breakup of the ligament. Droplet diameter and distribution have been investigated quantitatively. The mean diameter of the coaxial jets is between that of the inner and the outer jets. Compared with the individual swirling jets, wider size distributions of droplets are produced in the coaxial jets.

1. Introduction

Bipropellant thruster is an executing mechanism in space vehicle, which provide motive power in the orbital attitude maneuver of a space vehicle. In a bipropellant thruster, injection system is one of its key components and its atomization performance directly affects the performance, lifespan and reliability of the thruster. A coaxial injector consist of an inner orifice surrounded by a concentric annular outer orifice, is preferred in bipropellant thruster due to its advantages: high mixing efficiency and better quality of atomization at lower injection pressure.

Coaxial injectors are employed with different combination of propellant phase, such as gas-gas, gas-liquid and liquid-liquid. When the propellants are liquid phase, liquid-liquid coaxial swirl injectors are widely used. In coaxial swirl injectors, propellants are discharged from the inner and outer orifice, respectively, in the form of coaxial swirling sheets. At downstream of the orifice exit, the inner and outer liquid sheets interact and mix with each other. The interaction of the liquid sheets influences the atomization process, thus the spray characteristics of coaxial swirl injectors could be quite different from single swirling injectors.

Over the past decades, a series of meaningful studies are carried out to investigate the characteristics of coaxial swirling sprays (Hautman, 1993; Hardalupas and Whitelaw, 1996). Seol et al. (1998) investigated the interaction of inner and outer liquid sheets of a dual-orifice at low injection pressure. They observed that the spray interaction was affected by the ambient pressure around the spray. Sivakumar and Raghunandan (1998a,b) studied the interaction between two thin coaxial sheets, which were formed by coaxial swirl injectors. The merging and separation processes were visualized by still photographic technique. The results indicated that the hysteresis phenomenon influenced the spray characteristics of combined spray. In a different attempt, Sivakumar et al. (2003) revealed that the merging process results an increase of SMD by 40–50%. Moreover, Kim et al. (2006) investigated the influence of recess on spray characteristics of a liquid-liquid swirl coaxial injector. It is revealed that the interaction between two conical liquid sheets influences the spray characteristics intensely and they were determined to be close to the side having larger momentum between inner and outer spray.

In general, these studies focus on the effects of injector geometric parameters, injection conditions and liquid properties on spray characteristics such as discharge coefficient, spray angle, breakup length and mean droplet size. These investigations are significative to reveal the atomization characteristics of coaxial swirling sprays. However, the detailed structure of the interacted coaxial liquid sheets, development of surface instability, ligament and droplet formation mechanism are still insufficient and need to be further investigated.

With the development of interface tracking methods and the improvement of computing performance, numerical simulations have been carried out to predict the breakup process of liquid

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jet and provide an effective tool for the detailed study of liquid atomization mechanism. Menard et al. (2007) investigated the primary breakup of a turbulent liquid jet with the use of a coupled level set-VOF-ghost method, detailed information about the dense region of spray was described. Desjardins (2008) used a combined level set/VOF method to compute the primary atomization of a straight liquid jet. De Villiers (2004) applied LES-VOF method to a round jet and investigated the atomization process under the influence of nozzle flow. Pai et al. (2008) simulated the primary breakup of cross flows, and the detail of atomization was well resolved with 100 million grids. Siamas et al. (2009) simulated a swirling annular two-phase jet using an adjusted VOF method. The flow field and Kelvin-Helmholtz surface instability has been investigated. Herrmann (2008, 2010) and Hermann et al. (2010) discussed the effect of grid resolution on droplet size distribution of a turbulent liquid jet in crossflow, as well as examined the effect of gas to liquid density ratio on primary breakup characteristics. Shinjo and Umemura (2010, 2011) characterized the liquid surface instability that results in primary atomization with the use of a detailed numerical simulation. The dynamics of ligament and droplet formation were investigated based on the simulation results. On the whole, using high performance computer system and with fine grid resolution, the ligament and droplet formation process can be captured correctly which is hard to be observed in experiment investigation, allowing a detailed study of liquid atomization mechanism.

In the present study, a code based on a Volume of Fluid (VOF) interface tracking method coupled with a large-eddy simulation (LES) model is developed for computing the spray atomization process of a liquid-liquid swirl coaxial injector in bipropellant thruster. The present research mainly focuses on the detailed flow field of coaxial jets and the ligament formation process, thus to reveal the effect of interaction phenomenon on the primary breakup of liquid-liquid coaxial swirl jets. Further, the Droplet diameter and distribution of liquid-liquid coaxial swirling jets are investigated quantitatively.

2. Simulation setup

2.1. Governing equations

In the present calculation, the fluid is considered as incompressible Newtonian and isothermal. The mass continuity and momentum equations are as follows:

$$\frac{\partial u_i}{\partial x} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}} \frac{\partial^2 u_i}{\partial x_j \partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + F_s + G \tag{2}$$

where u_i and u_j are the velocities, ρ is the density, p is the pressure, *Re* is the Reynolds number of the flow, μ is the kinetic viscosity, τ_{ij} is the sub-grid scale(SGS) stress, F_s is the surface tension, and G is the force of gravity.

SGS stress can be approximated by the SGS model. The Smargorinsky model (Harris and Grilli, 2012) is the most widely used model that can be written as

$$\bar{\tau}_{ij} = 2\upsilon_t \bar{S}_{ij} - \frac{1}{3}\delta_{ij}\bar{\tau}_{kk} \tag{3}$$

where $\upsilon_t = C_s \Delta^2 (2\bar{S}_{ij}\bar{S}_{ij})^{\frac{1}{2}}$ is the SGS viscosity, $\bar{S}_{ij} = \frac{1}{2}(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i})$ is mean strain rate tensor, the constant C_s is 0.18.

The interface between gas and liquid phase is synchronously computed with the VOF method (Ubbink, 1997), which employs the volume fraction of one of the phases as an indicator function to mark the different fluids. The liquid volume fraction γ is defined as

$$\gamma = \frac{\iiint_{cell} \gamma(x, y, z) dxdydz}{\iiint_{cell} dxdydz} \tag{4}$$

The flow field can be divided into three regions:

$$\begin{aligned} &\gamma = 0 \quad \text{for a cell completely in the gas} \\ &\gamma = 1 \quad \text{for a cell completely in the liquid} \\ &0 < \gamma < 1 \quad \text{for a cell of the interface of liquid and gas} \end{aligned} \tag{5}$$

The indicator function follows a transport equation of the form

$$\frac{\partial \gamma}{\partial t} + \nabla \cdot (\bar{u}\gamma) = 0 \tag{6}$$

The local density and viscosity in a computational cell are given in terms of the liquid volume fraction by

$$\rho = \gamma \rho_l + (1 - \gamma)\rho_g \tag{7}$$

$$\mu = \gamma \mu_l + (1 - \gamma)\mu_g \tag{8}$$

where subscripts l and g respectively represent the liquid and gas phases. The interface is treated as a vicissitudinous zone, such that its exact shape and location are not specifically known. The surface tension force in Eq. (2) cannot be directly calculated. Brackbill et al. (1992) addressed this problem with the continuum surface force (CSF) model. Employing the CSF model, we represent surface tension force as a continuous volumetric force

$$F = \int_{s(t)} \sigma k' \vec{n}' \delta\left(\vec{x} - \vec{x}'\right) dS \approx \sigma k \nabla F \tag{9}$$

where the interface unit normal vector $\vec{n}$ and the curvature of the interface κ are given by

$$\vec{n} = -\nabla F, \ \kappa = \nabla \cdot \left(\frac{\vec{n}}{|\vec{n}|} \right) \tag{10}$$

2.2. Numerical scheme

The present code is developed based on the open source computational fluid dynamic toolbox called OpenFOAM (2012). The exploitation of OpenFOAM (2012) is based on the cell center-based finite volume method and provides an integrated range of discretization schemes to solve each term in the governing equations. In the present investigation, Crank–Nicholson method with second-order accuracy is used for the time discretion of governing equations. For general field interpolations, a linear form of central differencing scheme is implemented. Convective fluxes are discretized with the Gauss linear scheme. For pressure velocity coupling, the pressure implicit split operator (PISO) algorithm is addressed.

2.3. Flow configuration and boundary condition

In bipropellant thruster, fuel and oxidizer are injected into the combustion chamber separately by two coaxial injectors. As shown in Fig. 1, the inner injector has two twisty slots while the outer injector has three twisty slots. During the injection process, propellant flows through the twisty slot, thus tangential velocity is endued to the fluid in orifice and spray cone emerges due to the centrifugal force.

Propellant injected into quiescent air is considered in the present investigation. The atomization process of individual jets and coaxial jet are investigated. The flow conditions are set as shown in Table 1 and physical properties of the propellant are listed in Table 2. The inner path is fuel injector and the liquid is Monomethyl Hydrazine (MMH). Meanwhile, the outer path is oxidizer injector and the liquid is Mixed Oxides of Nitrogen (MON). The boundary conditions include uniform pressure inlet, uniform pressure on the cylindrical outlet and no-slip walls.