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Coupled Lagrangian impingement spray model for doublet impinging injectors under liquid rocket engine operating conditions

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Abstract To predict the effect of the liquid rocket engine combustion chamber conditions on the impingement spray, the conventional uncoupled spray model for impinging injectors is extended by considering the coupling of the jet impingement process and the ambient gas field. The new coupled model consists of the plain-orifice sub-model, the jet-jet impingement sub-model and the droplet collision sub-model. The parameters of the child droplet are determined with the jet-jet impingement sub-model using correlations about the liquid jet parameters and the chamber conditions. The overall model is benchmarked under various impingement angles, jet momentum and off-center ratios. Agreement with the published experimental data validates the ability of the model to predict the key spray characteristics, such as the mass flux and mixture ratio distributions in quiescent air. Besides, impinging sprays under changing ambient pressure and non-uniform gas flow are investigated to explore the effect of liquid rocket engine chamber conditions. First, a transient impingement spray during engine start-up phase is simulated with prescribed pressure profile. The minimum average droplet diameter is achieved when the orifices work in cavitation state, and is about 30% smaller than the steady single phase state. Second, the effect of non-uniform gas flow produces off-center impingement and the rotated spray fan by 38°. The proposed model suggests more reasonable impingement spray characteristics than the uncoupled one and can be used as the first step in the complex simulation of coupling impingement spray and combustion in liquid rocket engines.

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1. Introduction

Doublet impinging injectors are frequently used in bipropellant hypergolic liquid rocket engines for rapid atomization and mixing in a short distance. The oxidizer and fuel react as soon as the two jets collide and break up into droplets. A stable liquid sheet is formed in the perpendicular direction

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when two laminar jets impinge on each other. Large droplets shed from the rim of the sheet.[1,2] Thickness distribution of the sheet and droplet sizes could be calculated with the potential flow method and the instability theory.[3] But in the regime of liquid rocket engines, turbulent jets break up immediately around the impingement point, and in this case analytical theory on laminar sheets fails to predict the spray characteristics well. Under this circumstance, the research on spray characteristics of doublet impinging injectors, such as mass flux, mixture ratio, and droplet size, was mainly done experimentally.[4–6] In terms of the chamber combustion efficiency, the mass flux and the mixture ratio distributions play important roles.[7] A uniform mass flux distribution increases the combustion efficiency as well as the combustion instability. High trust level liquid rocket engines may contain hundreds of pairs of doublet impinging injectors, where efficiency and stability are balanced by the appropriate distribution of these injectors. Individual injector test is usually taken under atmosphere conditions to get the mass flux distribution of the injector, which is then used to design the injector distribution patterns.[8] However, the high chamber pressure and the large velocity in the thrust chamber make the spray characteristics of the impinging injectors different with those under the atmosphere conditions.[9] More specifically, the high gas density and viscosity under high pressure and temperature conditions will lead to better atomization, as well as enhance the interactions between the gas phase and the liquid phase. Furthermore, axial gas flows may displace the impingement point, and non-uniform radial gas flows could distort the liquid jets, leading to an off-center impingement, which forms a deflected spray fan. As a result, the distribution of mass flux is away from expectation.

The numerical simulation is an effective tool in predicting the injector performance of liquid rocket engines. Surface tracking methods, such as volume of fluid method and level set method, are widely used in simulating the breakup process of impinging liquid jets. Single pairs of doublet impinging injectors with various jet velocities and liquid properties were numerically studied by many researchers.[10–12] The calculated sheet patterns and droplet sizes well agree with experiment. Despite its wide use in simulating individual injectors, the surface tracking method is not feasible for the computation with hundreds of injectors. As a complementation, the Lagrangian method works well in the spray simulation. In a Lagrangian method, droplets are described by Lagrangian formulations, and the gas phase is governed by Eulerian formulations.[13] The coupling of the two phases is achieved by exchanging terms of mass, momentum and energy. The primary atomization process is realized by various injector modes, such as plain-orifice nozzle, swirling nozzle, and air blaster. And the secondary atomization is described by TAB (Taylor Analogy Breakup) models, KH/RT (Kelvin-Helmholtz/Rayleigh-Taylor) models or wave models,[1] depending on the droplet Weber number. Besides, in dense sprays where droplet collisions become significant, different collision models are introduced with collision Weber number ranging from 0 to 100.[14,15]

Up to now, no appropriate Lagrangian atomization model is established for the simulation of doublet impingement spray in the liquid rocket engine. The severe obstacle is that the impingement process is difficult to model. Thus the problem exists where and how to introduce the propellant droplets to start the Lagrangian calculation. The available solution to this problem is to specify the droplet parameters at the impingement point,[16,17] where droplet velocities, diameters, and distributions are obtained from the individual injector experiments, and then these parameters are assigned as a fixed numerical boundary in the spray simulation. By this way, the position of the source of the droplets (i.e. the impingement point) is determined by geometry parameters and holds constant during the simulation. In this manner, the droplet calculation process begins at the impingement point, and thus the impingement process is excluded from the simulation. This method could be categorized as an uncoupled model, because the influence of the gas flow on the impingement process, especially the motion of the liquid jets, is ignored. The displacement of impingement point and off-center impingement introduced by the gas flow could not be predicted. Moreover, the engine start-up phase could not be solved reasonably either, because the drastic change of the chamber conditions during start-up will lead to a corresponding change in the spray characteristics, which could not be described with the uncoupled method.

To overcome the shortcoming of the uncoupled method, the current study tries to build a coupled Lagrangian spray model, which could describe the jet-jet impingement and predict the effect of the rocket engine chamber conditions on the impinging spray. Correlations are used to calibrate the model and the comparison with experiment could be used as verification. Finally, the spray characteristics under liquid rocket engine operating conditions are investigated using this new model, which could be used as the first step to the overall coupled computation of spray and combustion in liquid rocket engines.

2. Numerical model

As illustrated in Fig. 1, the numerical procedure begins with the injection of the large droplets from the orifices. The motion of continuous liquid jet is represented by that of the large droplets with the equal diameter and velocity to the jet. Large droplets break into small child droplets after the jet-jet impingement under specific rules. The combustion of the droplets changes the chamber conditions, which then in turn affects the jet motion, jet-jet impingement and the droplet motion, thus showing coupled behavior. Fig. 1 also shows the comparison between the coupled model and the conventional uncoupled

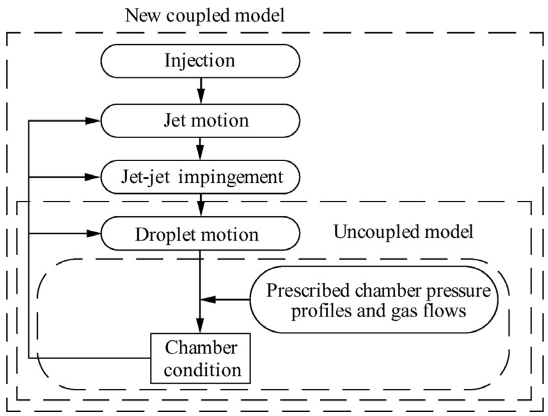

Fig. 1 Comparison between coupled model and uncoupled model.

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