Liquid hydrogen droplet generation from a vibrating orifice

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Numerical studies of liquid hydrogen droplet generation in vapor helium from a vibrating orifice are conducted within the framework of incompressible Navier-Stokes equations for multiphase flow. The goal of the study is to unravel the basic mechanisms of droplet formation, so that shape and size can be controlled. The numerical model is validated by experiments, and the numerically predicted droplet shapes show satisfactory agreement with the experimental photographs of droplets. Parametric studies on the influence of injection velocity, nozzle vibration frequency and amplitude on the droplet shape are conducted. The model enables one to obtain a definitive qualitative picture of droplet shape evolution associated with the operating parameters, and may be used for quantitative analysis. In fact, the model could be used to aid the design of future experiments.

INTRODUCTION

One of the advanced propulsion systems for the next generation of space flights is a densified fuel consisting of atomic propellants, such as boron, carbon, or hydrogen [1]. Solid hydrogen particles are preferred for storing atomic propellants in these systems because they significantly reduce the fuel volume and weight in a launch vehicle, and, most of all, have the ability to stabilize and prevent the atoms from recombining. Atomic hydrogen propellant feed systems may require the production of hydrogen particles in cryogenic helium. Experimental and theoretical efforts are underway to investigate the formation of solid hydrogen particles in cryogenic helium. To create solid hydrogen particles in helium, droplets of liquid hydrogen at temperatures around 19 K are injected from a vibrating orifice into a dewar filled with vapor helium at 4 K. Apart from the physics of hydrogen droplet solidification, the shape and size of the ejected droplets and the way to control and optimize them are of particular interest. They pose a formidable task due to very small time scales and other experimental design challenges [2]. However, numerical studies offer a relatively easy, but powerful alternative to study their behavior.

The goal of the numerical simulations (within the framework of the incompressible Navier-Stokes equations for multiphase flow) is to unravel the basic mechanisms of droplet formation with a view towards controlling them. The numerical model is validated by comparing numerical results with experimental ones. Numerically predicted droplet shapes show satisfactory agreement with photographs of experimental droplets. Parametric studies on the influence of injection velocity, nozzle vibration frequency, and nozzle vibration amplitude on droplet shapes are conducted using the model developed.

PROBLEM FORMULATION AND SOLUTION TECHNIQUE

Formation of hydrogen particles in a helium bath involves a complex energy exchange process between hydrogen and the ambient helium, resulting in a reduction of hydrogen temperature and its consequent solidification [3, 4]. As a first step in modeling the process, however, we assume the system is isothermal, eliminating energy exchange between the phases as well as excluding hydrogen or helium phase changes. Also, for the liquid-hydrogen/vapor-helium system, we assume that the two phases are immiscible and non-interpenetrating. A volume-of-fluid two-phase fluid model [5], which solves for the volume fraction of each phase within each control volume, along with a piecewise-linear interface calculation approach [6], is implemented to track interfaces evolving in time between the two phases. A continuum surface force (CSF) formulation [7] is implemented to account for the surface tension along the interface between the two phases. A single momentum equation, with the surface tension as a source term, is solved throughout the computational domain. Dynamic meshing techniques [8, 9] are employed to simulate vibration of the generator orifice.

The computational domain in the study consists of two regions: a vibrating liquid hydrogen nozzle and a bath of vapor helium. Initially, the nozzle is filled with liquid hydrogen, and the helium bath is filled with helium vapor. Both fluids are initially at rest. At computation time zero, liquid hydrogen in the orifice undergoes a velocity jump from zero to a specified velocity. Simultaneously, the orifice vibrates with a velocity governed by a sinusoidal function. No-slip boundary conditions are applied on the walls of the computational domain. For computational purposes, (i.e., easy management of the dynamic mesh), the governing equation systems are solved in a general integral form using a finite volume method [10].

EXPERIMENTAL VALIDATION

An experimental setup, which consists of a vibrating orifice type generator in a cryogenic environment (shown in Fig. 1) and high-speed photography, is established to validate the numerical model. In the experiment, a vacuum jacketed liquid hydrogen reservoir is separated from the helium vapor filled environment by an orifice plate. The helium bath is a dewar with the inner diameter of 0.15 m and the height of 1.22 m. The length of the vibrating orifice is 0.15 m, and its inner diameter d is 1.0 mm. The orifice is attached to a mechanical oscillator vibrating sinusoidally with frequency 13 Hz and the amplitude 2.0 mm. The hydrogen injection rate through the orifice is regulated by use of a pressure gauge that controls the pressure difference at the liquid/vapor interface. The rate was estimated to be about 1.0 m/s based on measurements on the experimentally taken photographs.

For the sake of model validation, parameters in the numerical computation are matched with the experimental operating conditions to our best knowledge, except that a small computational domain is used. The size of the computational domain is smaller than that of the helium bath for reasons of computational expediency. For computational purpose, the resolution involved an unstructured grid with initial 12,225 triangular elements. The dimensions of the computational domain and the relevant physical properties of the fluids are listed in Table 1. Also, instead of simulating a pendulously vibrated orifice that is equipped in the experiment, the entire nozzle is numerically vibrated transversely following a sinusoidal velocity.

Fig. 1 Vibrating orifice

Table 1 Simulation parameters

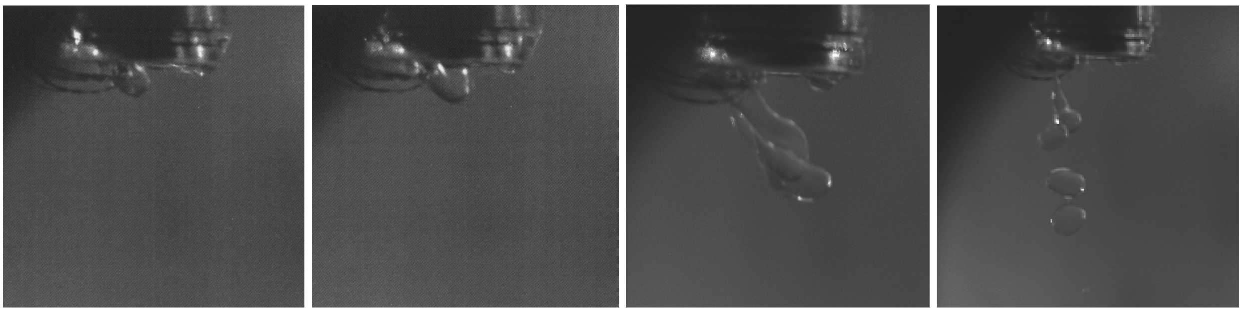
Vapor helium bath	Length (m)	0.04
	Width (m)	0.04
Liquid hydrogen nozzle	Length (m)	0.02
	Width (m)	0.001
Vapor helium [11]	Density (kg/m^3)	18.17
	Viscosity (kg/m·s)	1.276×10^{-6}
Liquid hydrogen [12]	Density (kg/m^3)	70.84
	Viscosity (kg/m·s)	1.392×10^{-5}
	Surface tension (J/m^2)	2.00×10^{-3}

Figures 2(a)-2(d) show the evolution of a droplet in the experiment. They each are double exposure images, where two individual frames separated by 10 ms are superimposed. In Figure 2(d), there is a second droplet ejected from the orifice following the first ones. Double exposure renders four objects in the figure. Diameters of the droplets in the figures are estimated to be between 1.5 and 2.0 mm.

Correspondingly, Figures 3(a)-3(d) show simulated droplet shapes at various elapsed times, which correspond to the individual experimentally taken photograph in Figure 2. The droplets inside the big circles in Figures 3(a)-3(d) are close-ups of the numerically predicted droplets for clarity of presentation.

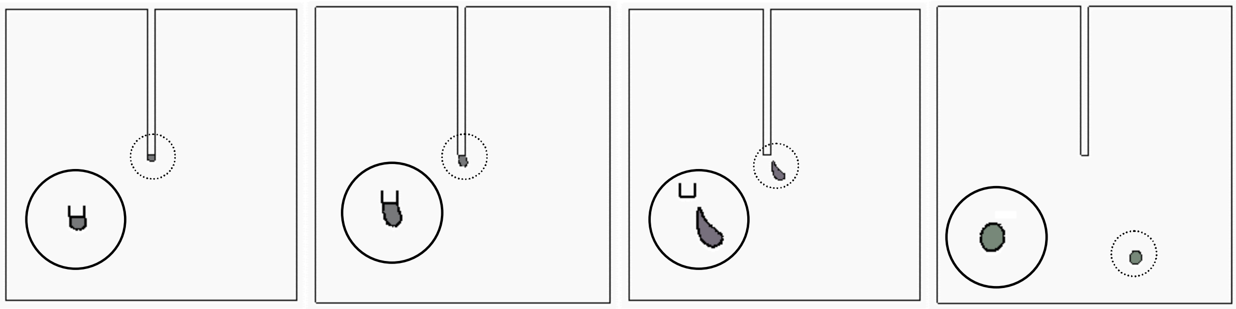
The diameter of the simulated droplet in Figure 3(d) is about 1.5-2.0 mm, which roughly agrees with the experimental result shown in Figure 2(d).

Notice that when operating the experiments, unlike running the simulations, it is very difficult to precisely control the orifice location or monitor its velocity under current experimental settings. Thus, the numerical simulation may not duplicate the experimental operating conditions as well as we would like. Nevertheless, droplet shapes that the model predicts catch the characteristic transients of droplet formation, and they are in relatively good agreement with experimental photographs.



(a) (b) (c) (d)

Fig. 2 Snapshots of droplet formation (experiment)



(a) (b) (c) (d)

Fig. 3 Snapshots of droplet formation (simulation)

PARAMETRIC STUDIES

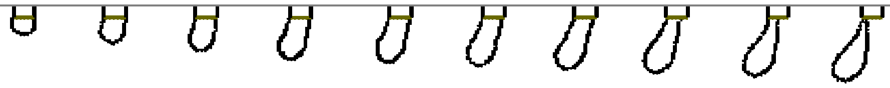
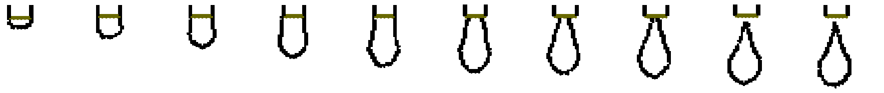
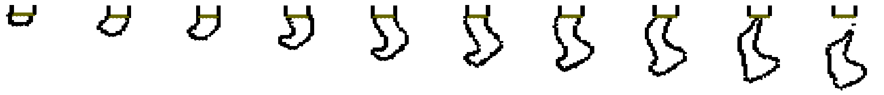
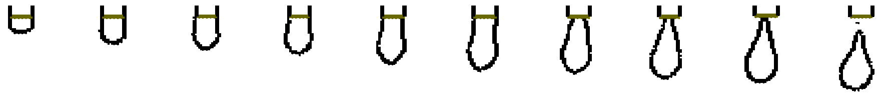
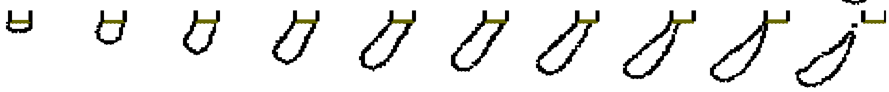
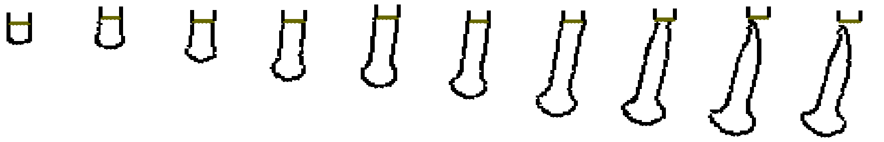
When liquid hydrogen is injected into vapor helium from a vibrating orifice, the liquid deforms, and, if the deformation is sufficiently large, the liquid breaks into droplets. Parametric studies on the influence of nozzle vibration frequency ω and amplitude A, and hydrogen injection velocity $\vec{v}$ on the droplet deformation are conducted. The studied cases, along with their operating parameters, and the corresponding droplet shape evolutions at different elapsed times are listed in Table 2. Only droplets at their early stages, before detaching from the orifice, are presented in the studies, due to the fact that initial droplet shape is important for completely characterizing drop dynamics in the flow, and it also plays an influential role in determining the final size and shape of a droplet.

Cases 1, 2 and 3 in Table 2 study the influence of orifice vibrating frequencies on the droplet shape; Cases 1, 4 and 5 study the influence of orifice amplitudes; and Cases 1, 6 and 7 study the influence of hydrogen injection velocities. Systematic analysis of the droplet shapes in Table 2 through Weber numbers and orifice-vibrating velocities show that the degree of droplet deformation is largely governed by surface tension stresses, inertial forces and the gravitational force. The orifice vibrating amplitude and frequency influence droplet shape by way of instant vibrating velocities, which determine the inertial force in the vibrating direction and the deformation of the droplet in that direction. The hydrogen injection velocity governs the droplet size considerably and determines the inertial force in the vertical direction. The frequency and amplitude of the vibrations and the injection velocity have to be carefully tuned to obtain a droplet of desired shape and size.

SUMMARY AND CONCLUSIONS

Numerical modeling of liquid hydrogen droplet generation from a vibrating orifice is developed and validated. Parametric studies on the influences of operational conditions on the droplet shape and size are conducted. It has been demonstrated that the computational model enables one to obtain a definitive qualitative picture of droplet shape evolution associated with the operating parameters. The computational model may also be used for quantitative analysis or parametric studies, and, in fact, the model could help design future experiments.

Table 2 Droplet shape evolution

Case	ω (s^{-1})	A (mm)	$\vec{v}$ (m/s)	10 snapshots of initial stages of droplet formation and detachment
1	**50**	**1.6**	**1.0**	
2	**5**	1.6	1.0	
3	**500**	1.6	1.0	
4	50	**0.32**	1.0	
5	50	**3.2**	1.0	
6	50	1.6	**2.0**	
7	50	1.6	**0.5**	

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