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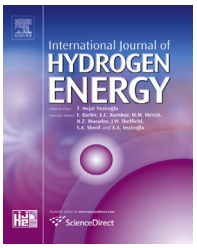

Numerical prediction of flow characteristics of slush hydrogen in a horizontal pipe

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ABSTRACT

Slush hydrogen has lower temperature, higher density and higher heat capacity than those of liquid hydrogen, and is considered as a potential propellant for novel aerospace rockets with decreased spacecraft size and weight. In this study, an improved three-dimensional numerical model based on Euler–Euler two-fluid model has been built to predict the flow characteristics of slush hydrogen in a horizontal pipe. In this model, an effective viscosity of mixture, which takes the particle shape and size into consideration, is adopted to modify the drag law for interphase momentum exchange, and the wall boundary conditions for the solid phase are based on Johnson–Jackson model which involves the friction and collision between the particle and the wall. The performance of the model has been verified by the comparison between the calculated results and the experimental data from the literatures and considered to be effective for slush hydrogen flow. The improved model is then used to analyze the effects of inlet velocity, solid fraction, particle size on the flow characteristics, including pressure gradient, solid volume fraction distribution and velocity distribution and abundant to predict the flow pattern shift. Moreover, the numerical results indicate that the pressure drops for subcooled liquid hydrogen, under some operating conditions, are greater than those of slush hydrogen, which are presented in some published experimental work.

Introduction

Slush hydrogen is the cryogenic suspension of solid hydrogen particles and subcooled liquid hydrogen, which has been considered as a potential propellant for novel aerospace rockets with decreased spacecraft size and weight due to its higher density and heat capacity than normal-boiling-point liquid hydrogen [1–4]. An important concern for the application of slush hydrogen is the transfer characteristics, especially for high concentration slurries. Earlier experimental studies of NASA National Aerospace Plane (NASP) project showed that the slush hydrogen with 50% solid fraction could well flow through pipelines, valves, turbo-pumps and other flow components [5,6]. Another kind of cryogenic suspension, slush nitrogen, also have attracted attention for its potential as the coolant for high temperature

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superconductive cables [7–9]. Ohira K [8] found that the pressure drop reduction phenomenon (i.e., pressure drop for subcooled liquid nitrogen is greater than that of slush nitrogen) emerged clearly for high velocity flow from experimental results of slush nitrogen flow in horizontal pipe. With the development of computational technology, CFD (Computational Fluid Dynamics) method is becoming an effective way to predict the multiphase flow. In 1990s, a numerical code, called FLUSH, was developed to calculate the pressure drop and solid fraction loss for steady-state and one-dimensional flow of slush hydrogen through the pipe system in the frame of the NASP project and achieved good agreement with the preliminary experimental results [5]. Gamma et al. [10] used the finite-volume Navier-Stokes CFD solver to get a precise assessment of thermal fluid dynamics behavior of slush hydrogen for the Europe FESTIP program and took in consideration several situations, namely linear pipelines flow, Venturi duct flow and in-tank storage. However, so far the numerical model for slush hydrogen is still not effective for fully understanding the cryogenic flow mechanism.

The CFD models employed for the pipe flows of ordinary solid–liquid mixtures have been improved and applicable to determine the pressure gradient, volume fraction distribution and velocity profile. Nevertheless, these approaches, usually with dispersed phase of sand, spherical glass beads, ash, etc., are valid for fine and uniform particles, but not suitable for cryogenic slush hydrogen, since the latter carries non-spherical and coarser particles with an average size of 0.5–2 mm. Moreover, the modeling of cryogenic slurry flows should consider the interphase heat transfer and heat leak, which results in solid fraction loss. Ishimoto et al. [11] developed a two-dimensional model based on the unsteady thermal non-equilibrium Eulerian–Lagrangian approach to predict the flow characteristics of slush nitrogen flow in horizontal circular and converging-diverging pipes, but this approach is not applicable for the dense slurry flow. Several three-dimensional CFD simulations based on steady Euler–Euler approach have also been conducted to determine the flow and heat transfer features of slush nitrogen [12,13] and slush hydrogen [14]. However, more attention needs to be paid to the effects of coarser cryogenic particles on the phase interaction for momentum and energy exchange, which are different from that of fine ambient particles.

In the present study, an improved three-dimensional (3-D) computational model is built up and the basic equations are adopted for predicting the flow characteristics of slush hydrogen in a horizontal pipe. The novelty of the model resides in the consideration of the large-size solid hydrogen particles. By introducing the mixture effective viscosity, which is dependent on the characteristics of the solid particles, the effects of particles on the interfacial momentum exchange are taken into account. The wall boundary conditions for solid phase based on the Johnson–Jackson correlations [15] are employed to simulate the friction and collision between the particle and the wall, and the effective empirical parameters are adopted. The proposed model is validated by various sets of experimental data over a large scale operating conditions in the literatures, in terms of slurry type, mean flow velocity, particle size and solid concentration, and shows fairly good performance. Thus, the model is adopted to calculate and analyze the effects of inlet velocity, solid fraction, particle size on the flow features, including pressure gradient, solid volume fraction distribution and velocity profiles.

Mathematical model

The Euler–Euler two-fluid approach allows for the modeling of multiple separate, yet interacting phases. In the 3-D numerical modeling of cryogenic slush hydrogen, the flows are considered incompressible and steady and each particle is inelastic with uniform and constant size and shape. The thermo-physical property values at the triple point adopted in the simulations for slush hydrogen are given in Table 1 [16]. The energy exchange between two phases is accounted, yet the variation in the properties and mass due to the temperature and pressure changes have not been considered, nor does the vaporization.

Governing equations

Conservation of mass

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla\cdot\left(\alpha_q \rho_q \vec{v}_q\right) = \dot{m}_{pq} - \dot{m}_{qp} \tag{1}$$

where the subscripts *p and q* denote for either "s" referring to the solid phase or "l" referring to the liquid phase, respectively, and *p* is the contrary phase of *q*.

Conservation of momentum

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q \vec{v}_q\right) + \nabla\cdot\left(\alpha_q \rho_q \vec{v}_q \vec{v}_q\right) = -\alpha_q \nabla p + \nabla\cdot\bar{\bar{\tau}}_q + \alpha_q \rho_q \vec{g} - \nabla p_s + \vec{F}_{L,q} + \vec{F}_{VM,q} + \vec{F}_{D,q} + \left(\dot{m}_{pq}\vec{v}_{pq} - \dot{m}_{qp}\vec{v}_{qp}\right) \tag{2}$$

where p_s is the solids pressure composed of a kinetic term and a second term due to the particle collisions, as given by $p_s = \alpha_s \rho_s \Theta_s + 2\alpha_s{}^2 \rho_s \Theta_s d_s g_{0,ss}(1+e_{ss})$. e_{ss} is the restitution coefficient for collisions between particles, taken as 0.7–0.99 for different types of particles. d_s is the particle diameter put as 0.5–2 mm for slush hydrogen. Θ_s is the granular temperature and $g_{0,ss}$ is the radial distribution function. The lift force due to solid–liquid velocity gradients is expressed as

Table 1 – Thermo-physical properties of hydrogen at triple point.

Thermo-physical property	Unit	Solid hydrogen	Liquid hydrogen
Pressure	MPa	–	0.00736
Temperature	K	13.957	13.957
Density	kg/m^3	86.59	77.05
Dynamic viscosity	Pa·s	–	2.58E-05
Specific heat	kJ/kg·k	2.6	7.0197
Thermal conductivity	W/(m·K)	0.129	0.104
Latent heat of fusion	kJ/kg	62.8	–

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