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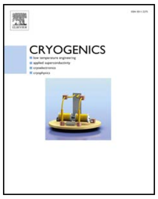

Research paper

Flow field and friction factor of slush nitrogen in a horizontal circular pipe

Tao Jin, Yijian Li[*], Shuqin Wu, Jianjian Wei

Institute of Refrigeration and Cryogenics/Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Zhejiang University, Hangzhou 310027, China

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ABSTRACT

Slush nitrogen is the low-temperature two-phase fluid with solid nitrogen particle suspended in the liquid nitrogen. The flow characteristics of slush nitrogen in a horizontal pipe with the diameter of 16 mm have been experimentally and numerically investigated, under the operating conditions with the inlet flow velocity of 0–4 m/s and the solid volume fraction of 0–23%. The numerical results for pressure drop agree well with those of the experiments, with the relative errors of ± 5%. The experimental and numerical results both show that the pressure drop of slush nitrogen is greater than that of subcooled liquid nitrogen and rises with the increasing particle concentration, under the working conditions in present work. Based on the simulation result, the flow pattern evolution of slush nitrogen with the increasing slush Reynolds number has been discussed, which can be classified into homogenous flow, heterogeneous flow and moving bed. The slush effective viscosity and the slush Reynolds number are calculated with Cheng & Law formula, which includes the effects of particle shape, size and type and has a high accuracy for high concentration slurries. Based on the slush Reynolds number, an experimental empirical correlation considering particle conditions for the friction factor of slush nitrogen flow is obtained.

1. Introduction

Cryogenic slurry is the low-temperature two-phase fluid with solid particle suspended in the liquid, such as slush hydrogen and slush nitrogen. Slush nitrogen has drawn much attention for its potential as the coolant for high temperature superconducting cables. Compared with subcooled liquid nitrogen, its lower temperature, higher heat capacity and density can contribute to lower storage and transport costs and help to reduce the risk of superconductor quenching [1–3].

So far, the experimental researches on slush nitrogen flow have mainly been focused on the cases in a horizontal pipe. With the help of PIV method, Takakoshi et al. [4] measured the particle velocity distribution profile of slush nitrogen in a horizontal pipe to observe the flow pattern evolution of slush nitrogen. Ohira et al. [5–7] studied the pressure drop of slush nitrogen flow in the horizontal circular, corrugated and converging–diverging pipes, and found that the pressure drop reduction phenomenon (i.e., the pressure drop for slurry flow can be lower than that of the subcooled liquid) could occur for slush nitrogen under some certain operating conditions. Jiang and Zhang [8] obtained the experimental empirical correlations for the friction factor of slush nitrogen flow in a horizontal pipe with the diameter of 10 mm, however, the pressure drop reduction phenomenon was not observed.

In recent years, numerical simulation has become an efficient way to predict the flow characteristics of slurry flow. The computational fluid dynamics (CFD) models employed for the pipe flows of ordinary solid–liquid mixtures have been improved and are applicable to determine the pressure gradient, volume fraction distribution and velocity profile [9,10]. Nevertheless, these approaches, usually with dispersed phase of sand, spherical glass beads and ash, etc. are valid for fine and uniform particles, but not suitable for cryogenic slurries due to their non-spherical and coarser particles with the average size of 0.5–2 mm [11,12]. Ishimoto et al. [13] 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 the horizontal circular and converging–diverging pipes, but this approach is only applicable for dilute slurry flow. Ohira et al. [14] constructed a 3-D numerical simulation code to clarify the flow and heat transfer characteristics of cryogenic slush nitrogen in a horizontal circular pipe, and the particle collisions were neglected. Based on the Euler-Euler approach, coupled with the granular kinetic theory, Jiang and Zhang [15] found that the particles gathered in the central region of the pipe for the slush nitrogen flow at a high velocity, due to the pulse behavior and inelastic collisions within the solid phase.

Considering the similar circumstances of slush nitrogen and slush hydrogen, studies on cryogenic slush hydrogen can help to understand the flow mechanisms of slush nitrogen. Slush hydrogen is considered to be the potential space vehicle propellant because of its improvements in density and heat capacity over liquid hydrogen [16]. In 1990s, Sindt

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[*] Corresponding author.
E-mail address: zjulyj@zju.edu.cn (Y. Li).

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and Ludtke [17] claimed that slush hydrogen with the solid fraction of 53% still had sufficient fluidity for pipe transportation. Recently, many researchers have carried out studies on modeling slush hydrogen flow by CFD methods [18–20]. To improve the modeling of cryogenic slurries, Gamma et al. [21] used the finite-volume Navier-Stokes CFD solver to attain a precise assessment of thermal fluid dynamics behavior of slush hydrogen for the Europe FESTIP program, considering various situations, namely linear pipelines flow, Venturi duct flow and in-tank storage. Based on Jiang and Zhang's model [15], the influence of gravity on the hydraulic and heat transfer characteristics of slush hydrogen in a circular pipe has been investigated [19]. Jin et al. [22] used the effective viscosity of slush hydrogen to modify the momentum exchange in the two-fluid numerical model where the pressure drop reduction phenomenon for slush hydrogen was replicated in the numerical analysis.

The earlier two-fluid models for cryogenic slurry were based on the hypothesis of constant diameter for solid particles, which neglected the influence of particle size distribution on the interfacial momentum and energy transfer. Jin et al. [23] built a two-fluid numerical model coupled with population balance modeling (PBM) for slush nitrogen flow, in which the particle size distribution was calculated with the population balance equations to consider the influence of particle size on the interfacial interactions. The results showed that the model had a high accuracy for predicting the pressure drop and the heat transfer coefficient.

At present, the experimental data for the flow characteristics of slush nitrogen are not sufficient and comprehensive, and the results from different researches are even in discrepancies, e.g., the discrepancy on the pressure drop reduction phenomenon, thus the experimental empirical correlations and numerical models both need further verification. In this study, an experimental apparatus for the flow test of slush nitrogen in a horizontal circular pipe with the diameter of 16 mm has been built up. The pressure drop is measured for slush nitrogen flow with the inlet velocity of 0–4 m/s and the solid volume fraction of 0–23%. The Euler-Euler two-fluid model coupled with PBM [23] will be further validated by the experimental results. Based on the experimental and numerical results, the flow pattern evolution of slush nitrogen in a horizontal pipe will be discussed. Meanwhile, the experimental empirical correlation for friction factor of slush nitrogen flow will be obtained.

2. Experimental and numerical methodology

2.1. Experimental apparatus and measurement method

The experimental setup for the flow tests of slush nitrogen in horizontal pipe, as shown in Fig. 1, mainly consists of slush nitrogen production system, flow test system, and measurement/control system. The freeze–thaw method is adopted for the production of slush nitrogen with the freeze–thaw cycle of 15 s - 15 s and the pumping rate of 9 L/s. The photo of slush nitrogen and the profile of particle size distribution are presented in Fig. 2, where the particle size varies from 0.4 to 3.0 mm with an approximate average value of 1.5 mm. The particle size distribution is obtained by photography and MATLAB image processing. The slurry images are converted to binary image and the particle properties (i.e., size and number) can be recognized by REGIONPROPS function. The solid fraction of the slush nitrogen is measured by a capacitance-type densimeter with the measurement error of ± 0.16%, and the liquid level meter of slush nitrogen is measured by a capacitance-type liquid level meter with the measurement error of ± 1%. More details about the capacitance-type densimeter and liquid level meter can be found in our earlier work [2].

Precooled helium gas is used to pressurize the tank to 0.1–0.3 MPa, and thus to transfer slush nitrogen into the flow test pipe, where the flow tests are carried out. The flow velocity of slush nitrogen is calculated from the liquid level change, which is measured by the capacitance-type liquid level meter. The flow rate is controlled by the cryogenic control valve equipped at the end of the flow test pipe, which consists of three segments. The length of the upstream pipe is 500 mm to ensure the full development of the flow. The downstream segment of 300 mm is used to reduce the heat leakage at the flow outlet. The test segment is a 900-mm-long stainless steel pipe with the inner diameter of 16 mm and the outside diameter of 19 mm. The test pipe is wrapped with multi-layer thermal insulation blankets and is equipped with an outer pipe for vacuum insulation to minimize the heat leakage with the vacuum degree of 10^{-3} Pa. The pressures at the inlet and the outlet of the test pipe are respectively introduced by two capillaries, and a differential pressure transmitter is installed to measure the pressure drop of the slush nitrogen flow. The measuring range of the differential pressure transmitter is 0–35 kPa and its accuracy is ± 0.5%.

2.2. Numerical modeling

An Euler-Euler two-fluid model based on population balance equations has been built to predict the flow characteristics of slush nitrogen in a horizontal pipe, which was introduced in details in our earlier work [23]. The conservation equations for solid and liquid phases of slush nitrogen are given as

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

$$\frac{\partial}{\partial t}(\alpha_q\rho_q\vec{v_q}) + \nabla\cdot(\alpha_q\rho_q\vec{v_q}\vec{v_q}) = -\alpha_q\nabla p + \nabla\cdot\bar{\bar{\tau}}_q + \alpha_q\rho_q\vec{g} + \vec{R_{pq}} + (\dot{m}_{pq}\vec{v_p} - \dot{m}_{qp}\vec{v_q}) \tag{2}$$

$$\nabla\cdot(\alpha_q\rho_q h_q) - \nabla\cdot(\alpha_q\rho_q\vec{v_q}h_q) = \bar{\bar{\tau}}_q : \nabla\vec{v_q} - \nabla\cdot\vec{q_q} + h_{pq}(T_p - T_q) + \dot{m}_{pq}h_{melt} \tag{3}$$

where the subscripts q represents either s (solid phase) or l (liquid phase), and p is the opposite phase of q. α is the solid volume fraction, ρ is the density, $\vec{v}$ is the flow velocity, $\dot{m}_{pq}$ is the interphase mass exchange, $\vec{g}$ is the gravitational acceleration. p is the local pressure shared by two phases, $\bar{\bar{\tau}}_q$ is the shear stress for liquid phase, p_s is the solids pressure. $(\dot{m}_{pq}\vec{v_p} - \dot{m}_{qp}\vec{v_q})$ is the momentum transfer arising from the interphase mass exchange, $\vec{R_{pq}}$ is the interphase momentum exchange, which consists of lift force, virtual mass force and drag force.

The solid–liquid drag force is expressed by

$$\vec{F_D} = K_{sl}|\vec{v_l} - \vec{v_s}| \tag{4}$$

where $\vec{v}$ is the flow velocity, K_{sl} is the fluid–solid exchange coefficient, expressed by Huilin-Gidaspow correlations [24], and C_D is the drag coefficient, which is given by

$$C_D = \max\left[\frac{24}{Re_p}(1 + 0.15Re_p^{0.687}),\ 0.44\right] \tag{5}$$

where Re_p is the particle Reynolds number, defined by $Re_p = \rho_l d_s|\vec{v_s} - \vec{v_l}|/\mu_m$. ρ_l is the density of liquid phase, d_s is the particle diameter and μ_l is the viscosity of liquid phase. μ_m is the slush effective viscosity, derived by Cheng and Law [25]

$$\mu_m = \mu_l\exp\left\{\frac{2.5}{\beta}\left[\frac{1}{(1-\alpha_s)^{\beta}} - 1\right]\right\} \tag{6}$$

where α_s is the solid fraction of slush nitrogen. β is the sole empirical parameter to account for the shape, size and type of solid particle, ranging from 0.95 to 3.9, which can take the value of 1.5 for slush nitrogen [22].

The momentum equation of the solid phase is closed by the granular temperature equation. For a granular phase, the wall shear force can be obtained from the Johnson-Jackson correlation [26]