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Forced convective heat transfer of slush nitrogen in a horizontal pipe

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ABSTRACT

In the present study, the flow and heat transfer characteristics of slush nitrogen in a horizontal pipe of 10.0 mm in diameter were investigated experimentally and theoretically. The flow velocity was in the range of 0.9–3.4 m/s, and the solid volume fraction was up to 30.0%, and the slush Reynolds number ranged from 1.89×10^4 to 1.01×10^5. The Eulerian–Eulerian multiphase model incorporated with the kinetic theory of granular flow was employed to investigate the forced convective heat transfer of slush nitrogen by taking into account of the heat and mass transfer between the solid and liquid phases. It was found that the pressure drop of slush nitrogen was higher than that of subcooled liquid nitrogen and increased with the solid volume fraction due to the existence of solid particles, and it showed different dependences on the flow velocity in the heterogeneous and pseudo-homogenous flows. Due to the latent heat involved in the solid–liquid phase change, the local heat transfer coefficients of slush nitrogen were higher than that of subcooled liquid nitrogen. The heat transfer between solid and liquid phases was enhanced as the solid volume fraction increased, leading to higher local heat transfer coefficient and lower and more stable fluid temperature of slush nitrogen. Although the dependences of the local heat transfer coefficient on the velocity and solid volume fraction were similar in both the homogeneous and heterogeneous flows, the distribution of the fluid temperature on the cross-section was found to vary with the flow patterns because of the non-uniform distribution of solid particles. The heat transfer correlation was proposed based on the experimental results for predicting the heat transfer performance of the heterogeneous and pseudo-homogenous slush nitrogen flows with various solid volume fractions.

1. Introduction

The application of slush nitrogen as a coolant for high-temperature superconducting (HTS) devices attracted considerable interests recently. Slush nitrogen contained small solid nitrogen particles suspending in liquid nitrogen, leading to higher density and lower temperature (about 63 K) than liquid nitrogen. Solid nitrogen was capable of absorbing more heat due to the latent heat, improving the heat capacity of slush nitrogen and keeping the fluid temperature very stable, and therefore the efficiency and stability of the cooling systems were significantly improved with slush nitrogen. Though slush nitrogen has been studied from various aspects, for examples production [1], density measurement [2,3], flow and heat transfer in horizontal pipes [4,5], its effective application to the HTS devices cooling was still difficult right now because the flow and heat transfer characteristics and the associated mechanisms of slush nitrogen were not clearly understood so far.

Slurry flows, such as sand-water and coal-water slurries, in horizontal pipes were generally categorized into four flow patterns: homogeneous flow, heterogeneous flow, moving-bed flow and stationary-bed flow on the basis of the solid distribution on the pipe cross-section [6]. However for slush nitrogen flow in the horizontal pipe, only three flow patterns were distinguished, which were pseudo-homogeneous flow, heterogeneous flow and bedload flow [7]. The dependence of pressure drop on the velocity was in accordance with typical slurry flows, but the solid distributions of slush nitrogen were different due to the relatively large particle sizes. Solid nitrogen particles created by the freeze–thaw method had the average diameter of 1.0 mm, and generally required very strong suspension force [6], resulting in the difficulty to suspend the particles completely even at the velocity as high as 3.5 m/s. On the other hand, the pipe diameter of 10.0–15.0 mm was small compared with the particle size, and the particle–wall interactions were stronger in slush nitrogen flow than that in slurry flow with the small ratio of particle-to-pipe diameter [8], resulting in the significant migration of the particles toward the center of the pipe. Therefore slush nitrogen in this case was defined as pseudo-homogeneous flow. In addition, the deposition of large solid particles at the bottom at low velocity easily blocked the narrow pipe, leading

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Nomenclature

C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$	empirically assigned constants in the turbulence model
C_L	lift coefficient
C_{VM}	virtual mass coefficient
D	pipe diameter, m
d_p	particle diameter, m
e_{ss}	particle–particle restitution coefficient
e_w	particle–wall restitution coefficient
G_k	production of turbulent kinetic energy
g	gravitational acceleration, m/s^2
g_0	radial distribution function
h_{local}	local heat transfer coefficient, W/(m^2 K)
h_{sl}	interphase heat transfer coefficient, W/(m^2 K)
$\boldsymbol{I}$	unit tensor
I	turbulent intensity
k	turbulence kinetic energy, m^2/s^2
k_{Θ_s}	diffusion coefficient of granular temperature
$\dot{m}_{qi}$	rate of mass transfer from q phase to i phase, kg/(m^3 s)
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
Re	Reynolds number
Re_p	particle Reynolds number
T	temperature, K
$\boldsymbol{U}$	velocity, m/s
u'_s	particle fluctuating velocity, m/s

Greek letters

α	volume fraction
β	drag coefficient, kg/(m^3 s)
ϕ	specularity coefficient
Θ_s	granular temperature, m^2/s^2
ε	dissipation rate of turbulent kinetic energy, m^2/s^3
λ_s	solid bulk viscosity, Pa s
μ	viscosity, Pa s
ρ	density, kg/m^3
γ_{Θ_s}	collisional dissipation of energy, kg/(m s^3)
$\boldsymbol{\tau}$	viscous stress tensor, Pa
ϕ_{sl}	fluctuating energy exchange between two phases, kg/(m s^3)
σ_k, σ_ε, σ_{sl}	turbulent Prandtl numbers

Subscripts

l	liquid
o	outer wall of the pipe
s	solid
tp	triple point
sl	slurry
t	turbulent
w	wall

to stable moving bed and stationary bed very difficult to form, and therefore only the bedload flow was observed in the experiments.

The frictional loss in slush nitrogen flow was the combination of the viscous friction in laminar sublayer formed near the pipe wall and the mechanical friction due to the particle–wall interactions, and therefore pressure drop of slush nitrogen was higher than that of subcooled liquid nitrogen under the same conditions [4,7]. However, Ohira et al. [5] reported the pressure drop of slush nitrogen in the pseudo-homogeneous flow was lower than that of subcooled liquid nitrogen flow because the turbulent diffusion in the liquid layer near the pipe wall was suppressed. Similar phenomenon of pressure drop reduction was also reported in the study with slush hydrogen [9], but was not found in other studies with slush nitrogen so far.

Slush nitrogen was considered to have higher cooling capacity because it absorbed more heat due to the latent heat when solid particles melted. In the experiments by Matsuo et al. [4], the heat transfer of slush nitrogen was found superior to that of subcooled liquid nitrogen at the low Reynolds number. But as the Reynolds number increased, the influence of solid particles on heat transfer became smaller because the flowing time was too short for the solid particles to absorb enough heat to be melted. Meanwhile, Ohira et al. [5] found that the heat transfer of slush nitrogen was deteriorated in the case of the pseudo-homogeneous flow, and it was considered being caused by the liquid layer with the low turbulent diffusion near the pipe wall, reducing the thermal convection toward the pipe center. Ikeuchi et al. [10] investigated the heat transfer characteristics of slush nitrogen during its melting under the condition close to actual flow speed and heat load in the application, and found that solid nitrogen melted quickly in the early stage of cooling.

With respect to the theoretical study, the Eulerian–Lagrange approach and Eulerian–Eulerian approach were both utilized to investigate the slush nitrogen flow in pipes, and the latter approach which assumed solid particles as a continuous phase, interpenetrating and interacting with the fluid phase within each control volume, was considered more appropriate for the concentrated slush nitrogen flow with solid volume fraction up to 30.0%, because of its capability of comprehensively considering the interactions of particles as well as the lower computing expense in this case. Ohira et al. [11] applied the Eulerian–Eulerian approach to the flow and heat transfer of slush nitrogen in the pipe with the diameter of 15.0 mm. Though the pressure drop reduction phenomenon was also found in the modeling, the liquid film near the pipe wall which was thought of as the reason for the pressure drop reduction in the experimental study could not be obtained. In order to consider the particle–particle and particle–wall interactions, the kinetic theory of granular flow developed from the kinetic theory of gases [12–14] was introduced to the Eulerian–Eulerian multiphase model by Jiang and Zhang [15]. Because the interactions of solid particles and pipe wall were considered, the radial migration of solid particles toward the center of the pipe was achieved in the modeling, which agreed better with the photographs of slush nitrogen flow taken in the experiments [5] than the numerical results by Ohira et al. [11]

So far, the investigation of the flow and heat transfer characteristics of slush nitrogen was insufficient, and the results of different groups were more or less divergent, which was possibly caused by the remarkable dependence of the slush characteristics on the flowing conditions or by the measurement uncertainty. Therefore more efforts were required to reach a through understanding of slush nitrogen for the future applications. In the present study, the pressure drop and heat transfer coefficients of slush nitrogen under various conditions were measured in the experiments. Meanwhile, the forced convective heat transfer of slush nitrogen in the horizontal pipe was modeled with the Eulerian–Eulerian approach incorporated with the kinetic theory of granular flow, and the influences of flow velocity, solid volume fraction, flow patterns, etc. on the heat transfer of slush nitrogen were investigated. Furthermore, heat transfer correlation of slush nitrogen was proposed based on the experimental and theoretical results.