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Cryogenics 45 (2005) 304–316
Cryogenics
www.elsevier.com/locate/cryogenics

Numerical study of the two-phase flow characteristics of slush nitrogen ☆

Jun Ishimoto [a,*], Ryusuke Ono [b]

[a] Department of Intelligent Machines and System Engineering, Hirosaki University, 3, Bunkyo-cho, Hirosaki, Aomori 036-8561, Japan
[b] Mayekawa Mfg. Co. Ltd., Advanced Technology Laboratory, 2000, Tatsuzawa, Moriya, Ibaraki 302-0118, Japan

Received 6 October 2004; received in revised form 3 December 2004; accepted 18 December 2004

Abstract

The fundamental two-phase flow characteristics of slush nitrogen in a pipe are numerically investigated to develop effective cooling performance for long-distance superconducting cable. First, the governing equations of two-phase slush nitrogen flow based on the unsteady thermal non-equilibrium two-fluid model are constructed and several flow characteristics are numerically calculated taking into account the effects of the slush volume fraction, the thermodynamic behavior of slush, and the duct shape. Furthermore, the numerical results are compared with previous experimental results on pressure loss measurement and visualization measurement in two-phase slush nitrogen flow along the longitudinal direction of the pipe. Results of this research show that it is possible to reduce the pressure loss by using a two-phase slush flow under the high Reynolds number condition and by applying the appropriate volume fraction of slush particles. The optimized thermal flow conditions for cryogenic two-phase slush nitrogen with practical use of latent heat for slush melting are predicted for the development of a new type of superconducting cooling system.

Keywords: Slush nitrogen; Two-phase flow; Multiphase flow; Superconducting cable; Internal flow

1. Introduction

Recently, development of a new type of cooling method for superconducting cable has become necessary. At present, single-phase subcooled liquid nitrogen flow is generally employed as the refrigerant for superconducting cable [1]. However, the presently used single-phase systems suffer from the disadvantageous requirement of a large-scale tank for liquid nitrogen storage due to low heat capacity. Furthermore, the production technology used by these systems requires large quantities of refrigerant to obtain sufficient cooling performance. To overcome these difficulties and to realize effective cryogenic cooling performance, a cooling system utilizing a cryogenic solid–liquid two-phase slush flow [2,3] has been developed and the heat transfer characteristics of this system have been partially reported [4,5].

Therefore, we propose a new type of cooling system which utilizes two-phase slush nitrogen flow as a refrigerant for long distance superconducting cables [1]. Solid–liquid two-phase slush nitrogen flow (slurry nitrogen flow) is composed of a mixture of dispersed fine solid nitrogen particles and liquid nitrogen, and is transported through a pipeline as smoothly as a single-phase fluid up to a high solid mass fraction. The characteristic features of such a cooling system are as follows:

1. Reduction in the pressure loss of working refrigerant flow in the transfer tube becomes possible because of

☆ Translation of article originally published in Cryogenic Engineering (Journal of Cryogenic Society of Japan) 2004; 39 (10): 463–474.
* Corresponding author. Tel./fax: +81 172 39 3680.
E-mail address: ishimoto@cc.hirosaki-u.ac.jp (J. Ishimoto).
URL: http://www.mech.hirosaki-u.ac.jp/ (J. Ishimoto).

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doi:10.1016/j.cryogenics.2004.12.001

Nomenclature

Asp	aspect ratio, $(=l/D)$
c_p	specific heat at constant pressure, $\mathrm{J/(kg \cdot K)}$
D	inlet width of duct, m
d	diameter, m
Ec	Eckert number
e^{ijk}	permutation symbol
Fr	Froude number
g_r^i	contravariant vector of gravitational acceleration, $\mathrm{m/s^2}$
g^{ij}	fundamental metric tensor
h	specific enthalpy, J/kg
l	duct length, m
N	number density, $\mathrm{1/m^3}$
Pr	Prandtl number
p	absolute pressure, Pa
R	radius, m
Re	Reynolds number
T	absolute temperature, K
t	time, s
u^i, u^j, u^k	contravariant velocity, m/s
α	volume fraction
Γ	phase generation density, $\mathrm{kg/(m^3 \cdot s)}$
η	longitudinal coordinate, m
λ	thermal conductivity, $\mathrm{W/(m \cdot K)}$
μ	dynamic viscosity, $\mathrm{Pa \cdot s}$
ν	kinematic viscosity, $\mathrm{m^2/s}$
ϕ	apparent viscosity parameter, $(=\mu_T/\mu_l)$
ξ	transverse coordinate, m
ρ	density, $\mathrm{kg/m^3}$
τ	integration time, s
Ω^i	contravariant angular velocity, rad/s
∇_j	covariant differential

Subscripts and superscripts

$()_{(ex)}$	exit section of the duct
$()^i$, $()^j$, $()^k$	contravariant component
$()_i$, $()_j$, $()_k$	covariant component
$()^{(i)}$	interface
$()_{(in)}$	inlet section of the duct
$()_l$	liquid phase
$()_p$	slush particle phase
$()_{pl}$	mixture
$()_S$	single-phase
$()_s$	saturation
$()_T$	two-phase
$()_{tr}$	triple point
$()_0$	initial stationary state
$()^{\sim}$	normalized variable

the decrease in the apparent viscosity of two-phase slush flow by appropriate manipulation of the slush particle size.

2. Until the superconducting state can be attained or when the breakdown (quench) of the superconducting state occurs locally, the temperature variation inside the flow duct for the refrigerant can be kept at the smallest possible value because the slush flow minimizes the effect of Joule heating which arises in the superconducting cable due to the latent heat of the melting of the slush nitrogen particles.
3. The cryogenic heat capacity (enthalpy) of slush refrigerant is greater than that of liquid refrigerant, and it is possible to reduce the required mass and storage capacity of refrigerant due to the inclusion of fine solid particles, i.e., density is increased.
4. Because of the enhanced liquid-phase self-cooling effect by the latent heat of the melting of the slush nitrogen particles, bubble generation can be better suppressed than in the conventional single-phase system, and thus the dielectric breakdown of a superconductivity state accompanying vapor phase formation can possibly be avoided.

With regard to the applied superconductive technology which utilizes cryogenic solid slush, slush nitrogen production and experiments on internal pipe flow are ongoing, and prototype experiments using a small-sized apparatus have been recently begun. Especially, the method of producing slush hydrogen (similar to slush nitrogen as cryogenic solid refrigerant) for use as fuel for reusable space shuttles or space planes, the use of cold neutrons as coolant [4] and the development of a densimeter or mass-flowmeter are proceeding as well for application to the transport and storage of hydrogen as a clean energy source [6,7]. In addition, theoretical analysis on slush hydrogen flow in vacuum insulation pipes has been partially conducted [8]. However, some problems remain in the numerical modeling and techniques, and their applicability to actual fluid transferring devices has not been sufficiently investigated.

As mentioned above, experimental and numerical study to date on the two-phase flow of cryogenic fluid has yielded only limited information on the basic hydrodynamic characteristics of two-phase slush nitrogen flow. Also, the application of such information to the development of a superconductive pipe-flow-cooling or heat exchange system utilizing the unique characteristics of two-phase slush nitrogen flow has not been undertaken. Furthermore, fluid transfer applications utilizing slush nitrogen in the cooling system are limited, and the formation method, transfer method, and heat