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Analysis of flow characteristics of cryogenic liquid in porous media

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ABSTRACT

Fluid flow related to heat transfer with a change in phase is an important phenomenon because many industrial processes rely on them for material processing and energy transfer. Examining fluid flow associated with heat transfer with a change in phase involves multiphase flow analysis, which can be utilized in various applications. In particular, studying the flow phenomena of a cryogenic liquid subjected to evaporation can help better understand cryogenic liquid behavior in a porous structure. In present study, the flow phenomena of a cryogenic liquid in a porous structure, glass wool, were examined. We conducted an experimental investigation of the behavior of a cryogenic liquid in porous media with various densities in order to understand how the cryogenic liquid behaves in a porous structure. The present study examined the thermophysical properties of glass wool media with different bulk densities and investigated its permeability under different injection pressures. The experimentally determined thermophysical properties and permeability were used to explain the experimental results. In two distinct experiments, temperature and pressure were measured to find the phase state of the flow and the tendency of propagation of the liquid-saturated region in glass wool media with different bulk densities. The results revealed that the nonlinearity of the pressure distribution over distance increased as the bulk density of the glass wool increased, and the rate at which the pressure gradient increase became conspicuously greater with accretion in injection pressure. Numerical simulation was conducted to further understand a cryogenic liquid's flow behavior in porous media, and the simulation results were compared with the experimental results. The numerical simulation results were in good agreement with the experimental results.

1. Introduction

Heterogeneous materials are generally composed of domains of different materials or of the same materials in different phases. Despite differences in their mechanical characteristics, foams, composite materials, sandstone, soils, and concrete are common examples of man-made or natural heterogeneous materials [1]. The geometrical microstructure of composite materials can be classified according to the following features: the nature of connectivity, the characteristic relative sizes and shapes, and the arrangement of structural elements. The connectivity of structural elements categorizes composite materials according to the existence of a phase that apparently "encapsulates" other phases. One of these groups can be defined as skeletal composites, in which at least two phases are present with one phase providing a monolithic frame to contain other phases. A more complicated structure is includes entangled materials such as cellulose-reinforced polymers, metallic wools, and glass wools [2]. These materials contain networks connecting them to penetrated and porous structures. The process of flow through porous media is of interest in a wide range of engineering fields, and extensive research has been performed on flow and heat transfer through porous media, covering a broad range of different fields and applications, such as ground water hydrology, petroleum reservoir and geothermal operations, and building thermal insulation [3]. The fluid flow related to heat transfer with a change in phase is important because many industrial processes rely on these phenomena for material processing and energy transfer. Examining fluid flow related to heat transfer with a change in phase involves multiphase flow analysis which can be adapted to various applications such as the analysis of stratified and dispersed flow, evaporation, and condensation [4,5].

The flow phenomena of cryogenic liquids subjected to evaporation are essential for understanding the behavior of cryogenic liquids in porous structures. The structure and material properties

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Nomenclature

A	cross-sectional area of the plate [m^2]
c_p	specific heat capacity [J/kg K]
C_{ij}	inertia loss term
D_{ij}	viscous loss term
E_a	energy of phase a [J/s]
e	thermal effusivity [W/m^2 K $s^{0.5}$]
k	thermal conductivity [W/mK]
k_{eff}	effective heat conduction coefficient [W/mK]
k_p	permeability [m^2]
K	absolute temperature [°C]
L	flow length [m]
$\dot{m}_{bc}$	mass change from b phase to c phase [kg/s]
Nu_L	Nusselt number
Pr	Prandtl number
Δp	pressure difference between two locations [Pa]
Ra	Rayleigh number
Q	mass flow rate [mm^3/s]
S_i	source term for the ith (x, y, or z) momentum conservation equation
v_a	velocity for phase a [m/s]
$\lvert v \rvert$	magnitude of velocity [m/s]
$\vec{v}_{dr,a}$	drift velocity for phase a [m/s]
$\vec{v}_m$	mass-averaged velocity [m/s]
α_a	volume fraction for phase a
α_b	volume fraction for phase b
ρ	density of the material [kg/m^3]
ρ_a	density for phase a [kg/m^3]
ρ_m	mixture density [kg/m^3]
μ	viscosity [Pa s]
μ_a	viscosity for phase a [Pa s]
μ_m	mixture viscosity [Pa s]

of the porous media has strong effect on the flow behavior of liquids, especially for cryogenic liquids, which are heavily affected by the ambient temperature as well. To investigate flow behavior in porous media, the material properties of a porous structure must be determined first. Permeability is a key parameter for analyzing such flow behavior. Various aspects of the permeability of fibrous porous media have been reviewed extensively by various authors, and a number of different tests have been performed over the past few decades. A study conducted by Klinkenberg [6] demonstrated that the permeability of a material to a gas is a function of the mean free path of the gas molecules. Marmoret et al. [7] investigated the air permeability of anisotropic glass and determined the intrinsic permeability and anisotropic factors of industrial fabrics. In other experiments for measuring permeability, Ladd [8], Olson [9], and Langfelder et al. [10] attempted to determine how air permeability changes with fluid contents for compacted media. In addition, Barden et al. [11] studied the relationship between air and water permeability of compacted unsaturated cohesive soil. They measured the permeability of soil to air and water, which is considered to be affected by the geometrical factors of soil. In addition, the thermophysical properties of a porous medium are important parameters that determine the flow behavior of cryogenic liquids since the flow behavior is mainly influenced by the ambient temperature. Various studies related to phase transitions of cryogenic liquids have previously been conducted by different researchers and extensively reviewed. Velat [12] studied the flow and heat transfer processes that occur in horizontal two-phase flow during chill-down, experimentally demonstrating the existence of several phase transitions during the chill-down phase. Xu et al. [13] examined the two-phase flow of solid hydrogen particles and liquid helium. They employed a three-dimensional two-phase mixture model along with the standard $k-\varepsilon$ mixture turbulence model. Van Sciver et al. [14] numerically and experimentally investigated cryogenic multiphase flows. They measured the multiphase flow of propulsion cryogens using a cryogenic flow visualization apparatus and implemented a robust model to simulate the flow phenomenon in cryogenic multiphase flows. However, most studies have focused on numerical simulations, rather than on experimental work, leaving the validity of the simulations questionable.

In this study, the flow behavior of a cryogenic liquid in porous media was examined by conducting two distinct experiments: one using a square-section cylinder and the other using a rectangular duct. An experimental feasibility test was initially performed using a square-section cylinder to study the density effect of porous media. The experiment using a rectangular duct imitated liquefied natural gas (LNG) insulation panels in a Mark III-type LNG cargo containment system (CCS). When an insulation panel is damaged, a cryogenic liquid such as LNG would leak into a porous medium, such as the glass wool inside the panel. The pressure distributions and temperature of the cryogenic liquid in the glass wool structure were evaluated to investigate the leakage phenomenon. The simulation parameters, such as permeability and thermophysical properties of glass wool, were obtained from experiments, and the validity of the simulation was verified by comparing the simulation results with experimental results.

The present paper reports the thermophysical properties of glass wools with different bulk densities in terms of the temperature dependence and permeability under different applied pressures. The characteristics of the two main experimental results are then discussed, and the simulation results for a cryogenic liquid flow in porous media are compared with the experimental results.

2. Background and theory

2.1. Introduction of LNG CCSs and a model of LNG leakage phenomena

LNG can be easily transported using LNG carriers; LNG is liquefied at cryogenic temperatures until its volume becomes 1/600 of its vapor phase volume. LNG carriers are largely classified as either Moss-type or membrane-type ships, and the CCSs for membrane-type ships are mainly divided into NO 96 or Mark III systems, designed by Gaz Transport and Technigaz (GTT), France, as shown in Fig. 1.

In an NO 96 system, a thin sheet of high nickel alloy, Invar, is used as the primary barrier. The secondary barrier is composed of the same material as the primary barrier and has similar thickness. The insulation system consists of two layers of plywood boxes, which are filled with a granular insulation material, perlite. The boxes have parallel internal members (bulkheads), which are also made of plywood sheets. The secondary barrier is located between a primary box and a secondary box. As it is essential for the internal surfaces of the plywood boxes to be flat to support the Invar membrane, mastic resin rope is laid on the bottom surfaces of the secondary boxes adjacent to the hull, as shown in Fig. 2. In a Mark III system, the primary barrier consists of a corrugated membrane made of an austenitic stainless steel sheet. The secondary barrier is a layer of triplex, which is a thin aluminum foil with glass fiber cloth glued to each side. The insulation of the primary and secondary barriers are made of polyurethane foam. A