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Natural convection heat transfer characteristics of molten salt with internal heat generation

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ABSTRACT

Molten salt is a promising heat transfer fluid with its high heat capacity, high boiling point, and chemical stability. In liquid fueled molten salt reactors and spent fuel reprocessing unit, molten salt carries heat generating fuel itself in a liquid state. To investigate the natural convection heat transfer performance of molten salt, a vertical heater vertical cooler rectangular loop filled with chloride salt containing liquid fuel, NaCl-KCl-(Pu,^{238}U)Cl_3, is simulated using an open source CFD package, OpenFOAM under various heat input conditions; external heat flux, internal heat generation (IHG), and a combined heat input type condition. Different aspects of natural convection heat transfer according to heat input condition are found for same amount of total heat. The external heat flux condition generates a high temperature gradient near the heater wall with very thin thermal boundary layer due to the low thermal conductivity of molten salt. On the other hand, the IHG condition has a relatively flat temperature profile from its uniform volumetric heating. Due to the different behaviors of temperature evolution, local upward flow is formed only at the wall region under the heat flux condition, but global natural circulation flow is promoted under IHG condition. The combined type condition is largely dependent on how much heat exists in heat flux type, which strongly influences local heat and fluid phenomena in natural convection heat transfer. Molten salt has a high dependence on the heat input condition from its thermo-physical properties. Therefore, the distinct characteristics of molten salt and heat input conditions should be considered, when designing and analyzing the molten salt systems with both external and internal heating conditions.

1. Introduction

Molten salt has high advantages for heat transfer fluid with high volumetric heat capacity, high boiling point and low vapor pressure, and chemical stability. It is widely used in various systems in energy applications; for example, a coolant of nuclear reactors, solvent for reprocessing of spent nuclear fuel, and heat transfer medium for hydrogen production, chemical industry, and solar generation [1]. For nuclear applications, in particular, molten salt contains fissile materials, which acts as both fuel and coolant in liquid-fueled molten salt reactors (MSRs) and the fuel salt carrier in nuclear fuel reprocessing. Nuclear safety should be achieved by the prevention of the release of radioactive materials from nuclear materials with various safety systems. Two prior safety issues of the molten salt systems are decay heat cooling and freezing of molten salt. Passive decay heat removal can be designed to provide the sufficient cooling to prevent temperature increases, which threatens the integrity of the structures of systems at any time. Among the various methods for passive cooling, natural circulation is the widely used principle, as it is reliable thing driven by temperature differences and gravity.

The overall heat transfer performance in natural circulation flow is influenced by the fluid and its conditions. First thing is, the heat transfer performance is highly dependent on fluid properties. Table 1 lists the physical properties of various fluids including molten salt [2]. Compared with other fluids, both types of molten salt have high Prandtl (Pr) number, which determine the dominant heat transfer mechanism near wall, conduction or convection. High Pr fluids are expected to have a relatively thin thermal boundary layer due to the dominant convection heat transfer mechanism, and their temperature field are much more dependent on the wall condition [3]. In addition, the Pr number of a fluid is known to have considerable effect on the skin friction and heat transfer, which determines the overall flow field with buoyancy for natural circulation flow [4,5]. Several studies on natural circulation flow, laminar, and mixed convection heat transfer were conducted, and they commonly showed that flow structure was considerably influenced by geometry as the Pr of the fluid increased [6–10].

As it is quite difficult to achieve the actual conditions of molten salt

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Table 1
Transport properties of various fluids.

		T [K]	ρ [kg/m^3]	$\nu \times 10^6$ [m^2/s]	C_p [kJ/kg K]	k [W/m K]	β [1/K]	Pr
Liquid sodium [11]		800	828.0	0.274	1.260	62.90	0.0003	0.0045
Water at 1 bar		323	992.3	0.658	4.178	0.629	0.0030	4.342
Fluoride	FLiBe [1] (LiF-BeF_2) (66-34)	773	2036.0	7.318	2.400	1.016	0.0002	35
Chloride	NaCl-KCl-(Pu,^{238}U)Cl_3 [12] (45-25-30)	922	3075.5	2.150	1.256	0.692	0.0003	12

systems in experiments to evaluate the performance of natural convection, such as a high temperature and high heat generation, several approaches using molten salt simulant fluid or scaled experiments were developed. Bardet and Peterson suggested the scaling parameters and potential simulant fluid candidates for liquid salts [13] They chose heat transfer oils as the simulant fluids of fluoride salt, FLiBe by matching the Pr number of the fluid. Cammi et al. designed an experimental loop for natural circulation flow with internally heated fluids for molten salt and investigated the dynamics of natural circulation influenced by internal heat sources using Hitec®, a kind of nitride salt [14]. Shin et al. performed natural circulation experiments using DOWTHERM RP, a kind of heat transfer oil as molten salt simulant, focused on high Pr number fluid characteristics [15]. They validated the scaling laws developed based on the heat transfer characteristics of the high Pr fluid to simulate the actual operating conditions or decay heat removal system design of MSR.

Besides, an external heating system is connected to the high temperature molten salt systems due to the high melting point of salt, preventing blockage of the flow channel. Especially for nuclear systems, reaction heat is generated from fuel dissolved in molten salt as internally heated fluid. Both internal heat generation and external heating should not exceed the maximum limit temperature for the molten salt system. Several investigations were performed for natural circulation with internally heated fluid to consider reaction heat generation limited to their geometries [16–18]. However, few studies have investigated the influence of heat input condition of molten salt containing liquid fuel material, as most studies have utilized existing correlations when predicting the temperature and heat transfer performance of molten salt systems.

With necessity to understand and analyze the effect of internal heat generation regarding liquid nuclear fuel or reaction heat, this paper deals with the physical understanding of natural convection heat transfer for the molten salt under the heat input condition, i.e., external heat flux, internal heat generation (IHG), and combined heat flux and IHG conditions. Among various types of molten salts widely used in nuclear fields, chloride salt is preferred option to get a harder neutron spectrum and higher solubility for the actinides than that of fluoride salt [19]. Therefore, chloride molten salt containing nuclear fuel, NaCl-KCl-(Pu, ^{238}U)Cl_3, is chosen as the working fluid to provide physical insights for the design and analysis of nuclear systems. In this study, the natural convection heat transfer characteristics of molten salt are investigated by numerical simulations using open source CFD package, OpenFOAM, and the effect of the heat input condition on the natural convection heat transfer determined by temperature and velocity field inside loop. It should be noted that we tried to use the original meanings of both terms of "natural convection" and "natural circulation" in this paper. Hereafter, two terms indicating local and global phenomena will be discussed when describing their characteristics of molten salt heat transfer.

2. CFD modeling

A single phase molten salt-filled rectangular loop was considered to analyze thermal-hydraulic characteristics of natural convection with IHG. To model the natural circulation flow due to the buoyancy force from temperature difference, a source term with Boussinesq approximation was added in momentum equation. To consider IHG, the volumetric heat source term in the energy equation was added. The mass, momentum, energy conservation equations are in equations (1)–(3).

$$\nabla\cdot\mathbf{V} = 0 \tag{1}$$

$$\rho\left\{\frac{\partial V}{\partial t} + (\mathbf{V}\cdot\nabla\mathbf{V})\right\} = -\nabla p + \rho\mathbf{g} + \mu\nabla^2\mathbf{V} + \rho_0\mathbf{g}\beta(T - T_0) \tag{2}$$

$$\rho C_p\left\{\frac{\partial T}{\partial t} + (\mathbf{V}\cdot\nabla T)\right\} + k\nabla^2 T + Q_s \tag{3}$$

where V is the velocity field, p is the pressure [Pa], ρ is the density [kg/m^3], μ is the fluid viscosity [Pa·s], β is the thermal expansion coefficient [1/K], T is the temperature field [K], T0 is the reference temperature [K], k is the thermal conductivity [W/m·K], and Qs is the internal heat generation [W/m^3]

2.1. buoyantBoussinesqSimpleFoam solver in OpenFOAM

The *buoyantBoussinesqSimpleFoam* solver in OpenFOAM was used to simulate the natural circulation of molten salt with IHG. It is a steady-state solver for buoyant and turbulent flow of incompressible fluids with a pressure-velocity SIMPLE corrector [20]. It adopts the Boussinesq approximation for density variation as shown in equation (4) under certain condition. IHG was modeled in fvOptions by adding the volumetric heat source term to the energy equation. For all simulations, k-epsilon turbulence model is used. Fig. 1 shows the typical structures of the *buoyantBoussinesqSimpleFoam*.

$$\rho = 1 - \beta(T - T_0)(\text{when } \beta(T - T_0)/\rho_0 << 1) \tag{4}$$

2.2. CFD setting of natural circulation loop for molten salt

The single phase molten salt-filled rectangular loop had configurations of vertical heater-vertical cooler (VHVC) with asymmetric position. Since natural circulation flow lies under stability problem from orientations of heater and cooler of loop, a VHVC loop was chosen to remove the stability issue of natural circulation flow, which is the most stable in natural circulation flow [21,22].

Fig. 2 and Fig. 3 shows the simulation domain of the molten salt-filled rectangular loop and grid configurations. The width and the height of loop are 1.42 m and 2.20 m respectively, and the diameter is 0.0269 m. Details regarding the dimension of loop are given in Table 2.

Various heat input conditions for each case are set as follows: i) external heat input; ii) internal heat generation (IHG); and iii) combined heat input considering both the external and internal cases (see Table 3). The external heat input is set as a constant heat flux on the