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Numerical analysis on spatial universality of similarity technique inside molten salt reactor system

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ABSTRACT

To compensate the difficulties in the study on a thermal-hydraulic system in a full scale, a similarity technique has been developed to predict the thermal characteristics of fluid in the full-scale system under smaller and simpler conditions. Then the feasibility of using simulant fluid for various MSR systems are numerically tested based on the similarity technique in this study. The utilization of thermal-hydraulic code with the simulant fluid, DOWTHERM RP, reproduces the system design values and the Nusselt numbers for the representative MSR systems including MSFR, MOSART, and MSBR. The steady state results confirm the applicability of similarity technique using DOWTHERM RP to simulate the thermal-hydraulic phenomena in MSR systems. The evaluated Nusselt numbers from the analysis results well agrees with the theoretical Nusselt numbers for all the MSR systems. Thus, it is concluded that the numerical analysis using the similarity technique well reproduces the steady-state heat transfer performance of the molten salts regardless of system configuration and specifications. In addition, the spatial consistency between global characteristics and local characteristics evaluated from the similarity techniques is tested. From the transient analyses results under the loss of flow accident, it is found that the local characteristics of molten salt evaluated by the similarity technique can well reproduce the global thermal-hydraulics of molten salt in existing MSR systems.

1. Introduction

To compensate the difficulties in the study on a thermal-hydraulic system in a full scale, a similarity technique has been developed to predict the thermal characteristics of fluid in the full-scale system under smaller and simpler conditions [1,2]. Generally, the small-scale model based on the similarity rules is established for a certain full-scale prototype of a thermal system, and then it is expected to that the model effectively predicts the behavior of the full-scale prototype. Mostly in the major scaled models, a dimensional analysis is used to determine dominant dimensionless parameters that can reproduce the behavior of a given system. Several studies on different thermal-hydraulic systems have been conducted using similarity technique: natural convection on a horizontal plate [3], heat transfer in microchannels [4,5], transport processes in fluidized beds [6,7], or development of heat transfer solutions based on the Prandtl number of fluid [8,9], etc.

In the nuclear engineering, especially for the developing advanced nuclear reactors, it is important to study the fundamental phenomena inside the reactor system and, simultaneously, to perform the thermal-hydraulic system analysis, while the real-scaled experiments are impossible to do. In that sense, the present study employs the similarity technique to investigate the thermal-hydraulic behaviors inside one of the most promising advanced nuclear reactors, Molten Salt Reactors (MSRs).

MSR has its uniqueness in the use of liquid salt for both fuel and coolant, which provides enhanced safety and reliability, reduced waste generation, effective use of uranium or thorium ores, resistance to proliferation, and improved economic competitiveness. After the first proposal of MSR concept by Oak Ridge National Laboratory (ORNL) [10], several MSRs have been proposed in thermal and fast neutron spectrum [11–15]. In the 21st century, the MSRs in the fast spectrum using fluoride salts have been investigated mainly in the EURATOM Framework Programs, and the MOST project which revisited and emphasized the potential of MSR in the fast spectrum as a “non-moderated” concept [16]. Later, two representative designs of fast spectrum concepts were developed: Molten Salt Fast Reactor (MSFR) and MOlten Salt Actinide Recycler & Transmuter (MOSART). The MSFR concept employs a fast breeder reactor with a large negative power coefficient using the thorium fuel cycle [17,18], while in contrast, MOSART was developed as an efficient burner of TRU waste from spent LWR fuel [19,20]. Additionally, other molten salt systems for nuclear energy have been

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Nomenclature

C_p	heat capacity [J kg^{-1} K^{-1}]
D	diameter of circular tube [m]
Fr	Froude number [–]
g	acceleration of gravity [m s^{-2}]
Gr	Grashof number [–]
L	characteristic length [m]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
Q	volumetric flow rate [m^3 s^{-1}]
Q_p	mechanical pumping power [kg m s^{-1}]
Q_h	heating power [W]
Re	Reynolds number [–]
T	temperature [K]
U	fluid velocity [m/s]

Greek symbols

ΔP	pressure drop across the system [Pa]
ΔT	temperature difference scale [K]
α	thermal diffusivity [m^2 s^{-1}]
β	thermal expansion coefficient [K^{-1}]
ν	kinetic viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}]

Subscripts

m	model
p	prototype

investigated worldwide, such as a solid-fueled fluoride high-temperature reactor in US [21] and a Thorium Molten Salt Reactor Nuclear Energy System (TMSR) in China [22].

As the various MSR concepts have been developed, numerical analyses in both steady-state and transient conditions are required to provide a fundamental understanding of system characteristics and safety performance. Toward that end, many researches have done their efforts to develop an analysis code including liquid fuel effects for various molten salt systems. The first numerical model was developed by Shimazu [23] for MSBR: it analyzed the expected consequences of nuclear excursions by lumped calculations using reactor kinetics equations and heat transfer equations. Subsequently, Krepel et al. [24,25] developed DYN1D-MSR and DYN3 D-MSR codes for MSBR and MSRE, that the neutron diffusion equation and a one-dimensional flow model were combined. Meanwhile, Yamamoto et al. [26] and Suzuki and Shimazu [27] coupled neutron diffusion equations with heat transfer equations in fuel salt and graphite to analyze the steady-state and transient behaviors in SMSR. For the analysis of MOSART design, Wang et al. [28] extended thermo-hydraulic and neutronic models of existing SIMMER-III code in steady-state conditions, and Nicolino et al. [29] and Zhang et al. [30] coupled thermo-fluid and neutronic dynamics of MOSART in transient conditions. On the other hand, relatively few studies have reported analysis results of MSFR. Based on the previously developed lumped calculations [31], Brovchenko et al. [32] developed a decay heat calculation tool for MSFR. Rouch et al. [33] performed a thermal-hydraulic analysis of MSFR using FLUENT CFD code, in which the energy released by the fission reaction and the decay heat were adapted to the model in terms of a constant heat source. However, the previous numerical analyses for MSRs have two limitations: the first is the limitation in model geometry and the other is the time-scale capability for transient analysis. These limitations result in significant disadvantages in transient analyses, as the reliability of the analysis results depends on the accuracy of the modeled system configuration and analysis time.

As an initial step to developing reliable numerical code for MSRs, the present paper aims to test the feasibility of a thermal-hydraulic system code to analyze both the steady-state characteristics of molten salt fluids and the transient phenomena that occur over the entire MSR system. The considered MSR systems have the specifications of the representative MSRs: MSFR, MOSART, and MSBR. The numerical platform for the molten salt simulant fluid was developed by modifying a Multi-dimensional Analysis of a Reactor Safety-Liquid Metal Reactor (MARS-LMR) code developed by KAERI [34]. The complex but practical configuration of entire MSR system was modeled in MARS-LMR code which gives more physically reliable analysis results over a long-time scale. Finally, the feasibility of thermal-hydraulic analysis using simulant for the various MSR system concepts is focused in this study. The similarity techniques evaluated through the entire system and at the local point of the system are compared to verify the universality. The analyses are performed for the steady-state and transient behaviors of the simulant, which simulate the normal operation and the loss of flow accident, respectively.

2. MSR system configurations

The high degree of configurational flexibility gives various design concepts for MSR systems for both single- and dual-fuel salt designs. Optimized from the various MSR concepts in early studies, the international research teams employ two practical MSR designs for the major single-fluid core and heat transfer component options: integral type and loop type. The integral type system locates a core, a pump, and a heat exchanger within the reactor vessel. On the other hand, the loop type system separates the pump and heat exchanger from the core. In this section, the detailed information for the reference MSR systems is described.

2.1. Molten Salt Fast Reactor (MSFR)

The recent MSFR design is a 3000 MW_{th} reactor with three different circuits [18]. It employs the integral type system, where the heat exchanger between the fuel salt and the secondary salt is located within the reactor vessel. The fuel salt then flows up through the core and goes down through the flow path between core shield and vessel, where the heat exchanger surrounding the core cools the fuel salt and where the primary pump is located. The heat exchanger and pump are located in a subcritical section of the core vessel to avoid neutron damage. The fuel salt is composed of lithium fluoride and thorium fluoride with 22.5 mol% of heavy nuclei. The mean operating temperature of fuel salt is about 948 °C with a maximum temperature of 1023 °C. The preliminary design of the primary circuit is a single compact cylinder with height of 2.25 m and diameter 2.25 m. The radial reflectors are about 50 cm thick including a fertile blanket; a B_4C layer of 20 cm thick encloses the reflectors. The salt drainage system is located at the bottom of the vessel, enabling a safe shut down in case of an accident. The fuel salt flows from the bottom part to the top part of the center core, and returns through 16 sets of pumps and heat exchangers surrounding the core. The total fuel salt volume is 18 m^3: half is for the core and half for the external fuel circuit. The resulting hydraulic diameter of the return flow path is 0.295 m. The total flow rate of fuel salt is 18932.2 kg/s,