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Experimental study on heat transfer performance between fluoride salt and heat pipes in the new conceptual passive residual heat removal system of molten salt reactor

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ABSTRACT

In order to improve the passive safety performance of molten salt reactor, a new conceptual design of passive residual heat removal system (PRHRS) has been proposed using heat pipe technology. In this paper, an experimental system has been constructed to verify the PRHRS design of molten salt reactors. An eutectic salt mixture of 46.5 mol%LiF-11.5 mol%NaF-42 mol% KF compositions called FLiNaK is selected as working fluid. Tests on the natural convection between the fluoride salt and a vertical array of heat pipes in the drain tank have been conducted. The temperature field of fluoride salt in the tank with different heat pipe spacing is analyzed. Comparisons have been made on the heat transfer characteristics between the natural convection with a single heat pipe and the vertical array of heat pipes. In addition, the empirical correlation for the Nusselt number is obtained within the range of Rayleigh numbers from 5.7×10^6 to 1.31×10^7. A good agreement between the proposed correlation and the experimental data is obtained with the deviation of −2.9%–1.7%. This work could provide valuable experimental data and suggestions for the design and analysis of PRHRS of MSR.

1. Introduction

The molten salt reactor (MSR) is the only reactor which can use liquid fuel instead of solid fuel. It has some unique advantages including good neutron economy, better inherent safety, more efficient and sustainable form of nuclear power associated with online fuel processing (Leblanc, 2010). With the growing demand on new generation reactors, MSRs have attracted a lot of attention and become one of the 6 candidates of the Generation IV reactors.

The passive residual heat removal system (PRHRS) has become more and more important in the design of MSR, especially after the nuclear disaster at the Fukushima Dai-ichi Nuclear Power Plant. Most studies on MSRs are at the stage of conceptual design and focus on the reactor core and its primary loop analysis. However, the traditional residual heat removal system which adopted in MSRE cannot satisfy the need of passive safety. That system is driven by two electric pumps and it would stop working once the pumps lose power. Some researchers have paid their attention on the design of PRHRS for MSRs. T. Ishiguro et al proposed a PRHRS in the FUJI-233Um MSR system (Ishiguro et al., 2014). In this design, a closed cooling circuit without pumps or blowers was designed, and many water tubes directly passed through the drain tank. Studies were carried out on its passive cooling performance and the tolerance on the thermal shock. Sun et al (Sun et al., 2014) improved the residual heat removal system in 10 MW MSRE and proposed a conceptual design of PRHRS using bayonet cooling thimbles. Based on this design, they carried out a series of experimental and numerical researches to verify its feasibility (Wu et al., 2016a,b; Chen et al., 2016). A new conceptual design of PRHRS was proposed by Wang et al. which adopted high-temperature heat pipe technology (Wang et al., 2013a). A series of studies were conducted on the performance of this design under the accident of MSR (Wang et al., 2013a,b). Results showed that the heat pipes performed well during the start-up and the residual heat of fuel salt could be removed rapidly and effectively.

Fluoride salt is used as fuel or coolant in the design of MSRs. Thus its heat transfer characteristics are of great importance. It is very difficult to conduct experiments using fluoride salt due to its special properties, such as hygroscopicity, chemical activity and high melting point. Only a limited amount of experimental research on heat transfer using fluoride salt can be found in the open literature. Most of them were conducted on the forced convection of fluoride salt (Grele and Gedeon, 1954; Hoffman and Lones, 1955; Cooke and Cox, 1973; Silverman et al., 1976; Ignat'Ev et al., 1984; Yoder et al., 2014). However, it should be noted

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Nomenclature

T	molten salt temperature (°C)
H	molten salt altitude (m)
T_{local}	local average salt temperature (°C)
T_{bulk}	salt bulk temperature (°C)
T_w	surface temperature of the evaporator (°C)
H_{hp}	height of heat pipe on the side wall of the drain tank (m)
H_T	altitude of temperature measuring points (m)
H_{max}	the maximum salt altitude in the drain tank (m)
Q	heat transfer power (W)
Q_{ave}	the average heat transfer power of a heat pipe in the vertical array
A	surface area of a heat pipe evaporator (m^2)
L	length of the heat pipe (m)
D	outer diameter of the heat pipe evaporator (m)
P	heat pipe spacing in the vertical array
L_c	characteristic length (m)
g	gravitational acceleration (m/s^2)
c_p	specific heat capacity (J/(kg·k))
h	heat transfer coefficient (W/(m^2·k))
Nu	Nusselt number $Nu = hL_c/k$
Ra	Rayleigh number $Ra = g\beta L_c^3 T\rho^2 c_p/\mu k$
Symbols	
ρ	density (kg/m^3)
μ	viscosity (Pa·s)
k	thermal conductivity (W/(m·K))
β	thermal expansion coefficient (1/K)
Subscripts	
hp	heat pipe
e	the evaporator of heat pipe
rad	radiation heat transfer
i	the number of five-junction K-type thermocouple probe
j	the number of temperature measuring point in the thermocouple probe

that the working principle of a PRHRS is to incorporate and use passive safety measures, such as gravity or natural convection, to remove the residual heat and keep the reactor system safe. But little experimental data on natural convection heat transfer of fluoride salt is available. Yoder et al (Yoder et al., 2014) carried out experiments on the natural convection between fluoride salt FLiNaK and a vertical cylinder in a nickel crucible. They acquired natural convection heat transfer data in fluoride salt at temperatures up to 700 °C and performed visual observation of the salt during tests. Srivastava et al (Srivastava et al., 2017) conducted studies on the natural convection of fluoride salt LiF-ThF_4 in the molten active fluoride salt loop (MAFL). In Srivastava's research, various steady-state and transient natural circulation experiments at different power level have been performed, and the correlation given for natural circulation flow in a loop was compared with the steady-state experimental data. The lack of experimental data on the natural convection of fluoride has seriously impeded the development of MSR. More experimental studies are needed to be conducted on the natural convection heat transfer characteristics of fluoride salt.

Considering few experimental data on the natural convection of fluoride salt, an experimental system using fluoride salt FLiNaK has been constructed based on the conceptual PRHRS proposed by Wang et al. (2013a), and some previous work has been done(Liu et al., 2018). In this paper, experiments have conducted on the natural convection heat transfer between fluoride salt FLiNaK and a vertical array of heat pipes with different heat pipe spacing in the drain tank. The molten salt temperature field in the drain tank is measured and analyzed. The natural convection heat transfer between the salt FLiNaK and the heat pipe array is investigated. The correlations on the natural convection between the molten salt and heat pipe array are obtained. This work is aimed at providing experimental data for the further design of new PRHRS of MSR. In addition, this experimental research will also provide the reliable guidance and practical experiences for follow-up experiments using FLiNaK, further demonstrating the feasibility of designed PRHRS.

2. Experimental system description

The schematic diagram of the new conceptual passive residual heat removal system (PRHRS) is shown in Fig. 1. The most innovative point is that high temperature heat pipes are adopted in this design. As shown in Fig. 2, high pipes are sealed tubes which contain two-phase natural circulation of liquid metal driven by capillary force, and thus they have excellent heat-transfer capability (Grover et al., 1964). Heat pipes are inserted into the drain tank from its side wall, and they have an inclination of 10° to make the condenser higher to ensure good working performance. The residual heat of fuel salt can be discharged through heat pipes passively. Based on this design, the preliminary analysis on the performance of this conceptual PRHRS in the accident of MSR have been done (Wang et al., 2013a). The results show that the heat pipes have good working performance and the new conceptual PRHRS can remove the decay heat in the system rapidly and effectively.

In this study, an experimental system has been built to demonstrate the feasibility of the new conceptual PRHRS, as shown in Fig. 3. A series of experiments would be conducted on this system. The main system parameters are shown in Table 1. The fluoride salt FLiNaK (46.5 LiF–11.5 NaF–42 KF, mol%) is used in this experimental system. The molten salt system and argon system are major components of the experimental system. The molten salt system is constructed using stainless steel 316 which has good performances in both the corrosive resistance and high-temperature tolerance. Two drain tanks are the test sections. One of drain tanks (Drain Tank-2) has high-temperature heat pipes inserted from the side wall. The detailed description of the drain tanks is explained in Section 2.2. Expansion bends are installed to afford the thermal stress at high temperature. Two freeze pipes are 30 cm long stainless steel pipes in the same diameter of salt pipes. The flow of molten salt is controlled by freezing or thawing the plug of salt in the freeze pipes. In order to provide preheating and heat protection, all tanks and salt pipes in the molten salt system are entwined with electric heating wires and wrapped with fiberfrax insulation. The argon system provides high purity (99.999%) argon gas to protect the salt FLiNaK. In addition, after the salt melt in the storage tank, the argon gas supplied

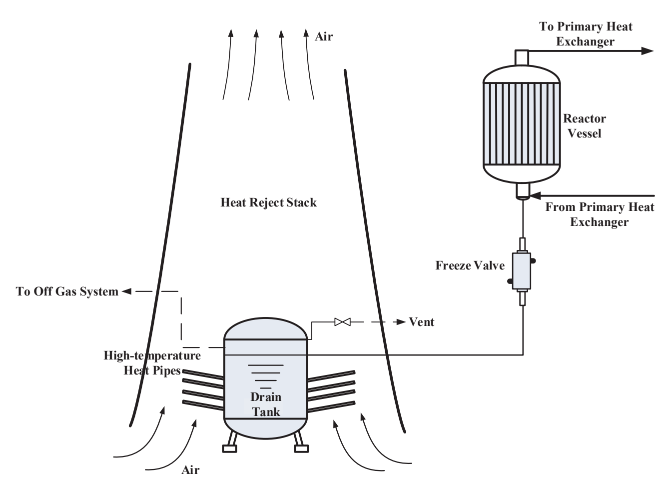

Fig. 1. The schematic diagram of the new conceptual PRHRS.