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Experimental analysis on passive residual heat removal in molten salt reactor using single cooling thimble test system

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An experimental setup has been designed and fabricated for the analysis of the passive residual heat removal system as applied to molten salt reactor. The main characteristic of this test facility is the presence of two natural circulation loops and a cooling thimble with double-wall barrier. The objective is to investigate the thermal performance of the drain tank cooling system, as well as further understand the heat transfer process. It is observed that the passive cooling system with single cooling thimble is capable of removing 2175 W at the desired temperature of 699 °C. Due to the large temperature difference, radiation heat transfer plays a significant role between the thimble and the bayonet tube. The contributions of several constituent thermal resistances in the heat flow path, together with the overall thermal resistance, have been obtained at various boundary conditions. It is also found that the operating mode is quite unstable with periodical oscillations at relative low temperature. From this study, valuable reference data and useful information are provided for practical applications.

1. Introduction

Priority should be given to safety problems in designing nuclear reactors. After reactor shutdown, it is essential to ensure the residual heat removal from the core and maintain temperature within safety limits under any of the normal or accidental conditions. Active cooling systems are dependent on external power supply and therefore are prone to failure when natural disaster happens, while passive cooling systems are more reliable due to their inherent safety features [1]. Passive residual heat removal system (PRHRS), whose principal function is to provide long term decay heat removal of fuel rods by transferring heat using natural circulation loops, are widely employed into advanced water cooled reactors [2]. Researches related to molten salt reactor (MSR) were first initiated by the Aircraft Reactor Experiment (ARE) [3] at Oak Ridge National Laboratory (ORNL). In 1960s, the Molten Salt Reactor Experiment (MSRE) [4] successfully operated for five years, which confirmed the practicality and reliability of this high temperature fluid fuel concept. MSR has the virtue of high thermodynamic efficiency, high neutron economy, large power density, high reliability and on-line refueling, which makes it to be re-evaluated as a candidate of Generation IV reactor technologies [5]. In case of accidental conditions, such as loss of power, mechanical failure of primary pumps, or loss of coolant or circulation in the secondary loop, the fuel salt is designed to enter the drain system in which the salt can be safely contained and cooled [6]. The MSRE used two pumps in the cooling system of fuel salt drain system. If this active cooling system is unable to work due to loss of electric power supply, the temperature build-up of liquid fuel may cause drain tank damage. Therefore, it is necessary to investigate a new PRHRS adapted to molten salt reactor.

As a kind of passive system, closed loop two-phase thermosyphons (CLTPT) or two-phase natural circulation loops have been investigated extensively in recent years. Zhang et al. [7] tested a two-phase natural circulation steam generator applied to solar collectors. The start-up transient behavior and thermal

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Nomenclature

A	surface area, m^2
D	diameter, mm
h	heat transfer coefficient, W/(m^2 °C)
h_{fg}	latent heat of evaporation, J/kg
ID	inner diameter, mm
L	tube length, m
M	mass flow rate of vapor, kg/s
OD	outer diameter, mm
P	pressure, kPa
Q	overall heat transfer rate, W
Q_r	radiation heat transfer rate, W
R	thermal resistance, °C/W
T	temperature, °C
V	volume flow rate of vapor, m^3/h
X	angle factor
σ	Stefan-Boltzmann constant, W/(m^2 K^4)
ε	emissivity
λ	thermal conductivity, W/(m °C)

Subscripts

ag	air gap
b	bayonet tube
bi	bayonet inner
bo	bayonet outer
bw	bayonet wall
c	condenser
ci	condenser tube inner/condenser inlet
co	condenser tube outer
$cond$	conduction
$conv$	convection
f	two-phase fluid in the steam riser
h	heating section
t	thimble tube
ti	thimble inner
to	thimble outer
tw	thimble wall
wc	water in condensation tank

performance of the two-phase loop thermosyphon were studied experimentally. It was noticed that the horizontally arranged system exhibited relatively low two-phase heat transfer coefficients. Franco and Filippeschi [8] designed and realized a CLTPT device of small dimensions. Experiments were performed to understand the correlation between mass flow rate and heat flow rate. The maximum of mass flow rate was found to be strongly affected by the operating pressure and fluid property. Honda et al. [9] applied a natural circulation system to cool electronic components and investigated the heat removal performance and flow characteristics in FC-72. The system was characterized by a low thermal load due to its engineering application. Loop type heat pipe also arouses great interest among researchers [10]. Mochizuki et al. [1] proposed a loop type heat pipe based passive emergency core cooling system to dissipate residual heat from reactor with 1380 MW full load thermal capacity. It was analyzed that the overall thermal resistance of heat pipe was 1.44×10^{-5}°C/W. Xiong et al. [11] designed and tested a gravity assisted heat pipe with a particularly long evaporator to remove decay heat in the spent fuel pool. An overall heat transfer capacity of 10.5 kW was observed at normal operating condition. In general, the utilization of two-phase natural circulation loops to cool fuel salt in drain tanks is a possible method. All the above researches bring significant insight into the heat and mass transfer mechanisms of two-phase natural circulation loops. However, these data are obtained for specific applications and cannot be used in general cases.

ORNL proposed a conceptual design to cool the primary drain system in Molten Salt Breeder Reactor (MSBR) with coolant circulated by natural circulation to a water-cooled heat exchanger [6]. A variety of coolants were compared and studied. As a result, the fused salt, sodium-potassium (NaK) alloy and steam-water were recommended for further investigation. However, the fused salt selected as coolant had unavoidable defects of strong toxicity and handling problems, and research of NaK system remained incomprehensive. Ishiguro et al. [12] used a code named NETFLOW++ to study the feasibility of a PRHRS designed for the FUJI-233Um molten salt reactor, and a peak temperature of fuel salt was noticed since the decay heat was greater than heat removal at the beginning. This peak temperature and the time for reaching the peak are closely associated with cooling capacity of PRHRS. Hence, it is crucial to determine the heat removal ability of PRHRS at required boundary conditions. Wang et al. [13] built a two-dimensional model to calculate transient behavior of NaK heat pipe in PRHRS of MSR with finite element method. The heat removal ability of a PRHRS developed for MSRE was numerically studied by Sun et al. [14], but no verification experiment was conducted to demonstrate the accuracy and effectiveness of the calculation results. Overall, most of studies on PRHRS for molten salt reactor focus on conceptual designs and theoretical calculations; experimental investigations are rare in the open literature.

In a work presented by Forsberg [15], radiant heat transfer played an important role in passive removal of decay heat from the salt to a heat exchanger for the liquid-salt-cooled very high temperature reactor (LS-VHTR). Experimental studies were carried out by Bopche and Sridharan [16] to evaluate the contribution of thermal radiation in removal of decay heat generated by fuel rods in the absence of coolant water. This is similar to the high temperature heat pipe used in molten salt reactor. Since the temperature difference between fuel salt and coolant can be very large in the double barrier design [17], emphasis should be placed on radiant heat transfer.

Another important factor affecting the performances of natural circulation loops is instability. Instability is undesirable as it may induce severe mechanical vibration of components, which has to be considered for design and safe operation of systems [18]. There is a strong coupling relationship between fluid dynamics and heat transfer processes in two-phase flow systems. In terms of natural circulations in small and narrow channels, the self-sustained oscillations result from the feedback between the flow rate, the vapor generation rate and the pressure drop in a heating section [19]. A large number of experimental and numerical analyses on flow instabilities have been discussed in Refs. [20–22].

The aim of the present study is to test and verify key technologies related to passive heat removal in molten salt reactor and evaluate the thermal performance of the drain tank cooling system. A test loop with single cooling thimble has been fabricated for experimental investigations. Efforts are made to determine the heat transfer capability of the residual heat removal system under