Nuclear Engineering and Technology xxx (2017) 1–12

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Heat transfer and flow characteristics of a cooling thimble in a molten salt reactor residual heat removal system

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A R T I C L E I N F O

Article history:
Received 18 January 2017
Received in revised form
21 June 2017
Accepted 21 July 2017
Available online xxx

Keywords:
Cooling Thimble
Flashing Flow Instability
Heat Transfer Rate
Molten Salt Reactor
Natural Circulation

A B S T R A C T

In the passive residual heat removal system of a molten salt reactor, one of the residual heat removal methods is to use the thimble-type heat transfer elements of the drain salt tank to remove the residual heat of fuel salts. An experimental loop is designed and built with a single heat transfer element to analyze the heat transfer and flow characteristics. In this research, the influence of the size of a three-layer thimble-type heat transfer element on the heat transfer rate is analyzed. Two methods are used to obtain the heat transfer rate, and a difference of results between methods is approximately 5%. The gas gap width between the thimble and the bayonet has a large effect on the heat transfer rate. As the gas gap width increases from 1.0 mm to 11.0 mm, the heat transfer rate decreases from 5.2 kW to 1.6 kW. In addition, a natural circulation startup process is described in this paper. Finally, flashing natural circulation instability has been observed in this thimble-type heat transfer element.

1. Introduction

With today's rapid development in China, energy shortage and environmental pollution problems are becoming increasingly serious. Because of this, nuclear power has attracted more attention from society because it is clean and highly efficient. However, after the Fukushima accident, individuals worldwide maintain a vigilant and critical perspective toward the development of nuclear power, and China is no exception. Today, nuclear power is an essential energy source because of its prominent advantages. Although the pressurized water reactor is the most common type of reactor worldwide, it has potential safety risks because of its high-temperature and high-pressure boundaries. In contrast with pressurized water reactors, molten salt reactors (MSRs) have the advantages of low pressure, small size, high breeding efficiency, and little residual radioactivity [1].

The molten salt reactor concept was put forward in the early 1960s. In 1965, the Oak Ridge National Laboratory (ORNL) successfully designed and set up the MSR experiment (MSRE) [2,3], and successfully operated it for 4 years. By the end of 1969, it had fully demonstrated the feasibility of using molten fuel and a molten heat transfer medium [4]. Research into MSRs was set aside in 1972, and since then the United States has focused on the liquid metal fast breeder reactor. Japan studied the FUJI series of MSRs beginning in the 1980s, and that study is continuing today.

Beginning in the 21st century, MSR studies have gradually made their way back into the international agenda, and MSR has been proposed as the generation IV nuclear reactor. The United States proposes the fluoride salt-cooled high-temperature reactor (FHR), which has many things in common with an MSR. The FHRs use solid nuclear fuel, cooled with low-pressure molten fluoride. The goal of FHRs is to reliably and economically generate large amounts of electric power and high-temperature process heat [5]. After the Fukushima accident, Japan accelerated the pace of research process on the FUJI series of MSRs. FUJI is a thermal reactor that uses the fuel FLiBe mixed with U/Pu/Tu. The moderator is graphite, which does not need changing during the reactor core's lifetime [6]. To achieve the efficient transmutation of the transuranium elements in light water reactor spent fuel, Russia proposed to use transuranium elements instead of the U–Pu circle as a nuclear fuel to build a molten salt actinide recycler and transmuter (MOSART) [7]. France is developing a molten salt fast reactor, in which the fuel circle uses two launching modes, the ^{233}U launch and the transuranium elements launch [8]. The technological and experimental studies of both MOSART and molten salt fast reactor have goals of decreasing the generation of highly toxic radioactive waste while

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http://dx.doi.org/10.1016/j.net.2017.07.026
1738-5733/

simultaneously generating electric power. China is also putting effort into an MSR. The Shanghai Institute of Applied Physics and Chinese Academy of Sciences plans to build a 100-MW thorium MSR by 2030.

The residual heat removal system is an important component of an MSR [9,10]. After the MSR shuts down, the fuel salt is drained into the drain salt tank through a frozen valve. Two primary plans exist to cool the fuel salt in the drain salt tank: external cooling of the drain salt tank and internal cooling using heat transfer elements. The representative method for the external cooling plan is reactor external vessel cooling (REVC), which is a mitigation strategy for a severe accident. For a reactor core meltdown, the decay heat of melt can be removed from the bottom head by two-phase natural circulation in the REVC channel; in this way, in-vessel retention is realized. Currently, this cooling method has been applied practically in the AP1000 and APR1400 [11].

For the external cooling plan design for the MSR, in reference to the REVC method of the AP1000, the drain salt tank is placed in the pool and the heat is removed by natural convection of the water outside the drain salt tank. However, if this method is used, the fuel salt at the center of the drain salt tank may not be sufficiently cooled because of the tank's very large volume, and the continuous generation of decay heat may make the temperature of the molten salt rise to a level greater than the fuel salt temperature limit. The drain salt tank is also equipped with a heater to prevent the fuel salt from solidifying during the heat removal process. When the heater runs, the pool-type residual heat removal system remains in operation, working against the efforts to maintain the molten salt temperature. Another disadvantage is that the heat dissipation power can be difficult to control.

There are several plans for internal cooling, one of which is to use a thimble-type heat transfer element designed by ORNL, which was successfully operated for 4 years. There have also been several new designs for the residual heat removal systems in recent years. One such design, developed by Wang et al. [12], immerses the drain salt tank in a secondary coolant molten salt pool, and sodium–potassium alloy (NaK) heat pipes are placed across the drain salt tank to transfer the heat from the fuel salt in the drain salt tank to the secondary coolant molten salt. Another design, developed by Ishiguro et al. [6], consists of a drain tank, a closed water circuit, and an air cooler. Heat transfer pipes with a diameter of 30 cm pass vertically through the drain salt tank. The water in the heat transfer element goes through the drain salt tank and transfers heat to the air cooler. At the outlet of the air cooler, the collected cooling water circulates back to the drain salt tank [6]. In the current study, we use a furnace to simulate the high temperature environment of molten salt. The design of Wang et al. [12] is relatively complicated, containing fuel salt and NaK liquid alloy. The dimensions of the heat transfer element designed by Ishiguro et al. [6] are relatively large, which makes furnace design challenging. Furthermore, both the designs of Wang et al. [12] and Ishiguro et al. [6] are purely theoretical. By contrast, the ORNL design has been operated successfully for 4 years, which fully proves the feasibility of a thimble-type heat transfer element. Therefore, in the current research, the experimental heat removal loop is based on the ORNL design. In the ORNL residual heat removal system, the cooling thimbles are directly inserted into the drain salt tank to remove the sensible heat and decay heat of the fuel salt. A schematic diagram of the residual heat removal system designed by ORNL is shown in Fig. 1. From the figure, it is evident that this type of residual heat removal system is not passive. If the entire system loses electricity, the water pump will shut down, and the heat of the high temperature water in the condenser cannot be removed, resulting in failure of the residual heat removal system.

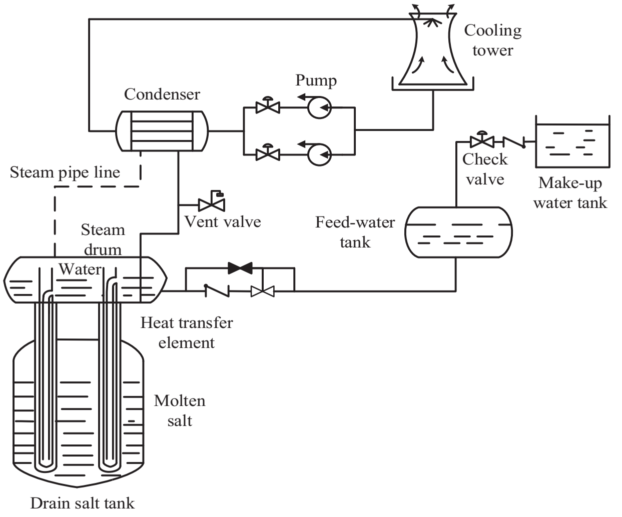

Fig. 1. Schematic of the MSR residual heat removal system. MSR, molten salt reactor.

Natural circulation instability is an important factor that affects the performance of natural circulation loops. The instability phenomena vary in different experimental natural circulation loops owing to variation in experimental structures, including the pipe diameter, the height of the experimental loop, the system pressure, and the heat flux [13,14]. The major flow instability phenomena observed by scholars include density wave oscillations, flashing instability, and geysering instability. Prasad et al. [15] conducted experiments under both forced and natural circulation conditions to study density wave oscillations, classifying them into two types. Type I instability is a low frequency oscillation that occurs at low pressure and low mass flow rate. This type of instability is dominated by gravity effects in the unheated riser section; the hydrostatic head is very sensitive to flow rate fluctuations. Type II instability, occurring at high power and low inlet subcooling, is attributable to the interaction between the mass flux, two-phase flow pressure loss, and void formation. Flashing instability often occurs when the structure of the experimental loop is high, and both system pressure and heating power are low, which implies large saturation temperature differences between the inlet and the outlet of the rising section. At low heating power, the coolant may not reach saturation conditions in the heating section. However, because of the strong variation of saturation temperature across the system, flashing can occur in the rising section [16,17]. Furuya et al. [18] regard flashing instability as a type of density wave instability [18]. However, Tanimoto et al. [19] and Shi et al. [20] consider that flashing instability has its own characteristics that are different from other instabilities. Geysering instability occurs for a certain range of inlet subcooling temperatures [21,22]. In general, the driving force is insufficient and the main stream flows slowly or is stagnant. Additionally, the slug developed from the heating section will be condensed into water in the rising section. Duffey and Rohatgi [23] divided the geysering into three phases: oscillation, venting, and reflux. Jiang et al. [16] investigated the geysering phenomenon in detail and found that the mass flow rate oscillates with high peak values such as pulses without a regular period. The energy released by the pressure wave resulting from the condensation of subcooled vapor causes strong mechanical vibrations in the system [16].

In the current research, an experimental natural circulation loop is designed and built with a single cooling thimble by reference to the design of ORNL. The heat transfer and flow characteristics are analyzed for the MSR cooling thimble. The influence of the cooling thimble gas gap width on heat transfer is analyzed using

Please cite this article in press as: Z. Yang, et al., Heat transfer and flow characteristics of a cooling thimble in a molten salt reactor residual heat removal system, Nuclear Engineering and Technology (2017), http://dx.doi.org/10.1016/j.net.2017.07.026