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Experimental study on the sub-atmospheric loop heat pipe passive cooling system for spent fuel pool

Zhenqin Xiong [a], Cheng Ye [b], Minglu Wang [a], Hanyang Gu [a, *]

[a] School of Nuclear Science and Engineering, Shanghai Jiao Tong University, No.800 Dongchuan Road, Shanghai 200240, China
[b] Shanghai Nuclear Engineering Research & Design Institute, Shanghai 200233, China

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ABSTRACT

As one kind of the natural circulation cooling system, loop heat pipe is promising in improving the safety of the nuclear power station since it is passive and has no electricity driven components. A novel heat pipe cooling system is designed for passively removing the residual heat released by the spent fuel stored in the spent fuel pool (SFP) under the accidental conditions such as the station blackout. This system is characterized by its large-diameter and long-length evaporator. Its working fluid is water and it's sub-atmospheric. To test such system's heat transfer performance and get to know its thermo-fluid dynamics, a test facility for a simplified heat pipe made of one evaporator tube and one condenser has been developed. The heat transfer rate of the simplified heat pipe is obtained in a wide range of conditions covering the potential working conditions in spent fuel pool. Moreover, it's found that heat pipe with such a large-diameter and long-length evaporator is vulnerable to be unstable. The periodic state mode is more likely to happen when the heat source temperature, the air velocity or the volumetric filling ratio is low. Furthermore, the effects of hot water temperature, the air velocity and the filling ratio of the water in the circulation system have been analyzed.

1. Introduction

Storage of the irradiated nuclear fuel in water pools has been standard practice since nuclear reactors first began operation more than half a century ago (Johnson, 1977). Spent fuel assemblies release the decay heat continuously. It is vital to effectively cool the spent fuel pool (SFP) for the safety of the whole nuclear power plant, especially in the accidental conditions. The reliability of the nuclear power plant safety systems for the commercial power plants has come under question since Fukushima nuclear disaster happened in 2011. A series of measures aimed at strengthening the safety system have been proposed. A novel concept of developing a long-term completely passive cooling system for the whole nuclear power plant, which works even in the conditions beyond design basis accidents, attracts the attention of researchers around the world (Sviridenko, 2008). Completely passively cooling spent fuel pool is one of the key technologies for the long term passive cooling system (Merzari and Gohar, 2012; Ye et al., 2013).

As shown in Fig. 1, the SFP is cooled by an active cooling system in present commercial nuclear power plant. Water in the pool is pumped to a heat exchanger. Thereby, it is cooled by the cooling water provided by the active water chilling system. This cooling system might be unavailable when the station black-out accident happens. The reliability of the system would be improved if this active cooling system is replaced by a passive cooling system.

The integrity of the spent fuel stored in the SFP should be guaranteed all the time to prevent the leakage of irradiation. It is threatened if boiling crisis happens on the surface of the spent fuel. Therefore, to keep the integrity of the spent fuel stored in the SFP, the temperature of the water in the pool needs to be cooled to be lower than the saturate temperature, about 100 °C. Ambient air is the final heat sink for the SFP. Therefore, the temperature difference between the ambient air and the water in SFP is in the range of 20–60 °C. To achieve high heat transfer efficiency in this range of temperature difference, technology based on the two-phase loop heat pipe is proposed to passively cool the SFP by the authors (Ye et al., 2013). As shown in Fig. 2, a novel completely passive spent fuel pool cooling system was designed for the spent fuel pool, using the high-efficiency heat pipe cooling technology that is available in an emergency condition such as the station blackout.

* Corresponding author. Tel.: +86 21 34204917; fax: +86 21 34205182.
E-mail addresses: zqxiong@sjtu.edu.cn (Z. Xiong), Guhanyang@sjtu.edu.cn (H. Gu).

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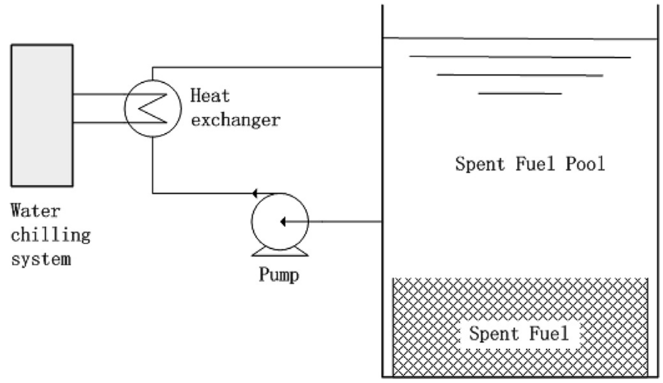

Fig. 1. Conventional active cooling system for SFP.

The CAP1400 NPP SFP has been chosen as the prototype reactor. The maximum heat released by the spent fuels in the pool is approximately 16 MW. To remove such large amount of heat, heat pipe system made up of thousands of pipes as the evaporators and thousands of pipes as the condensers is designed. The pipes of the evaporators are placed around the pool's interior wall and immersed in the pool. A condensation section with a chimney for air cooling is placed outside of the auxiliary building. The pipes of the condensers are installed at the bottom of the chimney. Water is selected as the heat pipe working fluid, which transfers heat from water in the pool in the form of the latent heat of vaporization. The gas-state water goes through the connecting pipeline and is cooled to be the liquid state in the condensation section. Finally, water falls in the downcommer to the inlet of the evaporation section and thereby the circulation of the fluid inside the heat pipe is formed. The heat pipe used in this system is characterized by a large-diameter and long-length evaporator. Its diameter is 65 mm and its immersed length is 7.6 m since SFP's depth is large. The normal operation condition for the heat pipe is that the water in the pool is 80 °C and the ambient air temperature is 30 °C.

The heat pipe proposed for the SFP is one kind of two-phase loop thermosyphon. Such kind of heat pipe has many industrial applications owing to its simplicity and high heat transfer capability and received extensive attention from researchers (Franco and Filippeschi, 2013; Khodabandeh and Furberg, 2010; Sureshkumar et al., 2013). However, the thermo-fluid dynamics of two-phase loop heat pipe is complex and presents some challenges. Franco and Filippeschi (2012) summarized the experimental work on loop type heat pipe of small dimensions. They compared the heat transfer performance of type A (the evaporator internal diameter much larger than the bubble diameter) and type B (the evaporator diameter is about 4–5 times larger than bubble diameter) (Franco and Filippeschi, 2010). It is concluded that for type A the thermal performance is mainly influenced by the flow regime in the evaporator section, while for type B the thermal performance are influenced by the fluid-dynamics of the whole loop. The loop heat pipe with a small evaporator (138 × 20.8 × 10 mm^3) is carefully tested (Wang et al., 2012). Instability phenomenon is not only indicated by checking the transient wall temperature but also directly reflected by the boiling structure obtained by visualization method. By increasing the heat flux, the boiling structure transits from intermittent Taylor bubble to continuous bubbly flows and instability occurs. Zhao et al. (2011) investigated the performance of a loop heat pipe with an outer diameter 27 mm and 45 mm long evaporator at liquid-nitrogen temperature range for the low temperature applications of loop heat pipes. It's found that the heat transport capacity is mainly affected by the flow resistance and the thermal resistance was reduced by using an improved condenser.

To evaluate the heat pipe cooling system's capacity to remove the heat in the working condition of the SFP and gain insight into such a system, a test facility for the heat pipe system has been developed and experimental study has been carried out. Since the heat load is huge in the SFP for CAP 1400, the heat pipe system which is composed of 1594 sets of condensers and evaporators are used. On average, 10.04 kW heat shall be removed by one set of the evaporator and condenser. For simplicity, a simple heat pipe made of a single set of an evaporator and a condenser was chosen in our test. Analysis is focused on the heat transfer rate and transient states of the system under a wide range of conditions concerned for the application in SFP.

2. Experimental apparatus of the heat pipe

The experimental setup for testing the performance of the heat pipe is shown in Fig. 3. The heat pipe tested is only a segment of the passive cooling heat pipe system for SFP to reduce the cost. It consists of an evaporator, a riser, a condenser, a down-comer and a horizontal tube. All these components are fabricated with stainless steel.

The evaporator is 8.3 m high. Its inner diameter is 65 mm and the thickness of the wall is 5.5 mm. The riser is 1 m long. The condenser is made of ten 2 m-long pipes. These pipes decline by 1.53°. Thereby, the fluid inside the condenser goes down through the down-comer smoothly. The down-comer is 9 m long vertical pipe and the horizontal tube is 2.2 m long. The inner diameter of both the down-comer and the horizontal tube is 25 mm. The evaporator section is shown in Fig. 4.

The fluid inside the heat pipe is pumped by surface tension force and gravitational force due to the density difference between the

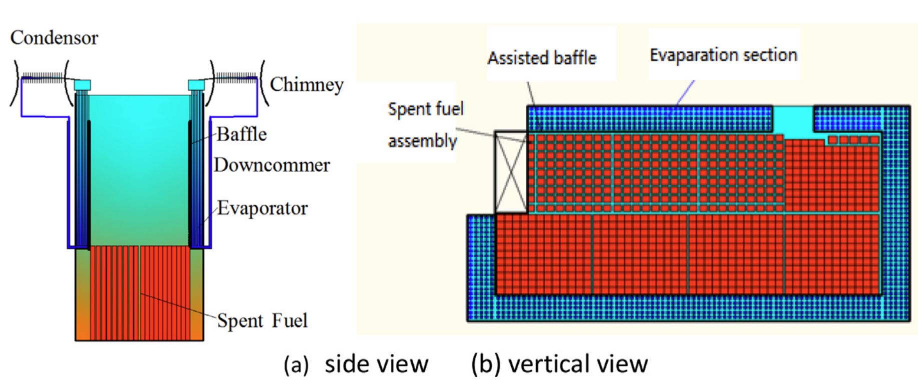

Fig. 2. The sub-atmospheric passive cooling system for spent fuel pool (Ye et al., 2013).