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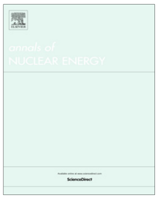

The study of passive cooling system assisted with separate heat pipe for decay heat removal in spent fuel pool

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ABSTRACT

The nuclear energy plays an important role in world energy production, and the safety of nuclear power plant has drawn increasing attention as well, where the decay heat removal system is an essential part of nuclear plants to ensure its passive safety. This paper aims to propose the way to achieve entirely passive cooling for spent fuel pool. A separate heat pipe assisted passive cooling system with a large cooling capability of 16 MW is discussed, which focuses on passive cooling in the condenser section by mean of natural draft air cooling. After comparing several condenser section configurations, the optimization of the cooling system is discussed to meet the demands of both high-efficiency heat transfer and economic feasibility. In order to find an overall optimal solution for the passive cooling system with the minimum cost, the multi-objective optimization method is employed to investigate a set of system parameters.

1. Introduction

Nuclear energy plays an important role in energy production by supplying about 11% of the world net electricity generation in 2012 (International Energy Outlook, 2016). Compared with the conventional thermal power generation, nuclear power could increase the energy intensity of power plant and reduce the unit cost of power and the emission of pollution such as carbon dioxide, sulfur dioxide, smoke, dust, nitric oxide, etc. In recent years, the development of nuclear power has drawn an increasing attention. Pressurized water reactor (PWR) is the most commonly used reactor in nuclear power plants, where the high pressure water is pumped to the reactor core for active cooling. The active cooling system could malfunction if power sources are cut off by accident. The accident happened in Fukushima plant exposed the potential risk of the system. As a typical 3rd PWR technology, the AP1000 system improves the safety level of a power plant significantly by using passive cooling design. Compared with the conventional PWRs, the major safety advantage of the passive plants is providing long-term core cooling and decay heat removal without offsite or onsite power sources, which is very important when some unpredictable accidents cut off the power supply (Schulz, 2006).

Previous research mainly focused on the passive cooling for the reactors in nuclear plants (Kunitomi et al., 1996; Cho et al., 2000; Nayak and Sinha, 2007; Wang et al., 2013). Besides the reactors, the spent fuel pool needs to be cooled as well, where the spent fuel rods are stored after being unloaded from the nuclear reactor, and continuously generate a lot of decay heat. In a conventional cooling system, the water temperature in the pool is supposed to be below 50 °C when the active cooling equipment operates. In case the active cooling system stopped working in an accident, the decay heat would be dissipated through water boiling in the spent fuel pool, which would cause the exposure of rods to air as the water boiled away gradually. As a result, the spent fuel rod components would be damaged and the spent fuel would leak out. So it is necessary to develop passive cooling technologies for the decay heat removal in the spent fuel pool.

A heat pipe assisted by gravity could work passively to transport heat from the evaporator section to the condenser section. The heat transfer occurs by phase change, which leads to high heat transfer capability. Since the driving force is commonly provided by gravity, which eliminates the need for electric power and operators entirely, the heat pipe could provide passively cooling continuously. The heat pipe heat exchanger (HPHE) has been widely used in various industry sectors for a long time. Rassamakin et al. proposed to apply the aluminum alloy extruded heat pipes in solar collectors (Rassamakin et al., 2013). S.H. Noie-Baghban designed an HPHE and constructed for the heat recovery in a hospital (Noie-Baghban and Majideian, 2000). Hassam evaluated a heat

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pipe exchanger on heat recovery and renewable utility (Chaudhry et al., 2012). However, few studies focus on the large-scale heat pipes utilized for the heat removal in a spent fuel pool.

Different from the conventional heat pipes, the separate heat pipe could achieve a long distance and large scale capacity of heat transfer, which is suitable for the passive cooling in the spent fuel pool. Therefore, the application of HPHE is a potential way to improve the safety level in a nuclear power plant. Kaminaga et al. presented the use of HPHE in the emergency core cooling system (ECCS) as the safer system with high runtime reliability for the nuclear reactors (Kaminaga et al., 1998). Various concepts and designs about the passive decay heat removal system based on the heat pipe technologies were also developed. Mochizuki et al. proposed a completely passive cooling system using the separate heat pipe for removing the decay heat of the nuclear reactor when the electrical power could not run the cooling system. Their separate heat pipe system was designed for a 27 MW cooling load (Mochizuki et al., 2012). In the solution of Mochizuki et al., the heat pipe was only applied to maintain the natural circulation of the medium inside heat pipe. However, the driving force of the air crossing the condensation section is not mentioned, and it is critical to drive the cooling air flow naturally to achieve an entirely passive air cooling.

In a conventional power plant, the hyperboloid natural draft cooling tower is widely used for the heat removal of cooling water from the condenser. The natural draft dry cooling tower could operate passively without the electric power source. Zhuang proposed to use the longitudinal finned heat pipe in a dry cooling tower to improve the efficiency (Zhuang, 2004). The performance evaluation of a dry-cooling system for the power plant was conducted as well (Conradie and Kroger, 1996). Zhai and Fu investigated the cooling performance of the cooling towers in windy days (Zhai and Fu, 2006). Hooman presented a set of scaling laws for a dry natural draft cooling tower by modeling the heat exchanger and tower supports as a porous medium (Hooman, 2010). Merzari and Gohar presented a small passive air cooling heat pipe system for the spent fuel pool (SFP), the maximum heat load was about 0.5 kW (Merzari and Gohar, 2012). Ye et al. proposed a loop-type heat pipe cooling system with a cooling capacity around 16 MW (Ye et al., 2013).

This paper also aimed to achieve the passively cooling for a spent fuel pool, which could provide passive decay heat removal just by the separate heat pipe. In general, the entirely passive cooling system relies on the natural convection in both the evaporator and the condenser section. Although some research on the condenser section has been conducted before, the detailed analysis on the air ventilation in condenser section is insufficient (Muraoka et al., 2001; Annamalai and Ramalingam, 2011). Therefore, in this paper, the study will be focused on the separate heat pipe assisted passive cooling in the condenser section by means of natural draft air cooling, that is, the ambient air passing through the condenser section shall be driven just by the buoyancy draft, and the system is designed to achieve high efficiency heat transfer and economic feasibility simultaneously. In order to optimize the solution for passive cooling systems with minimum cost, a multi-objective optimization method is employed to investigate a set of system parameters.

2. The passive cooling system assisted with separate heat pipe

2.1. The concept of passive cooling system

To prevent it from boiling, the water in spent fuel pool needs to be maintained in a temperature range from 50 to 90 °C. Considering the spent fuel rod unloaded in an emergency, the maximum heat needed to be removed could reach 16 MW. During normal operation periods of the nuclear plant, water temperature in spent fuel pool is lower than the boiling point of the medium in the heat pipe; the cooling system does not engage. In the case of an accident, the water temperature in the pool would exceed the set point of the cooling system and the passive cooling system starts to operate, transfers the decay heat to the ambient, maintains the pool temperature in the set range, and eventually prevents the water boiling in the pool. The setting point of the passive cooling system is the boiling point of the medium in the heat pipe.

The normal operating temperature of the heat pipe is around from 50 to 70 °C, while the ambient temperature is around 10–35 °C. With such small temperature difference, it is a challenge to dissipate a large amount of heat. The cooling system is designed to prevent the water in spent fuel pool from boiling, and all decay heat could be drawn by the natural ventilation in the condenser section. The heat pipe used in this system is characterized by a large-diameter and long tube heat exchanger (Ye et al., 2013; Xiong et al., 2015).

The principle of the separate heat pipe assisted passive cooling system for the spent fuel pool is shown in Fig. 1. The cooling system is composed of an evaporator section and a condenser section. The evaporator section is immersed in the spent fuel pool; the condenser section is installed in the cooling tower or exposed in an open space. The longitudinal plate finned tube is employed in the evaporator section while the round-finned tube is employed in the condenser section for the purpose of enhancing the heat transfer efficiency.

When water in the pool is heated by the spent fuel rods and flows across the tube bundle in the evaporator section due to the buoyancy effect, natural convective circulation occurs in the pool. Furthermore, the decay heat is transferred to the medium (Ammonia was selected as the heat pipe medium) inside the heat pipe, then it is dissipated out on the condenser section with the natural convective environmental air, where the gas-state medium is cooled to be liquid state and the condensed liquid flows back to the evaporator section by gravity. As described above, the heat is continuously removed from the spent fuel pool to the environment in an entirely passive way.

2.2. The configuration of the condenser section

While the temperature of the spent pool increases, the temperature of the working fluid inside the heat pipe increases if a constant heat source for the condenser section is employed, and the load of heat dissipation also increases. When the pool temperature reaches 80 °C, the corresponding removed heat load for each tube should reach around 20 kW.

In the condenser section, the natural ventilation of environmental air could be achieved through various ways. One way is to utilize the dry natural draft cooling tower, which can improve the buoyancy effect of the cooling air, the alternative option is to place the condenser section in the open space without a cooling tower. The cooling tower is assumed to provide the driving force for the cooling air with about 1 m/s inlet velocity (Kuppan, 2000; Mochizuki et al., 2014). As shown in Fig. 2, there are two configurations of the condenser section: the heat pipe bundle installed around the vertical inlet opening of the cooling tower as ring type or installed in an open space as a horizontal plate. Table 1 shows some parameters about heat pipe heat exchanger for passively removing the 16 MW heat of spent fuel pool.

In the evaporator section, the external heat transfer coefficient of the tube in the evaporator section $h_{ou,e}$ is assumed as 200 W/(m^2 K). In the condenser section, the heat exchanger bundle consists of numbers of round-finned tubes with aluminum fins and