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Numerical investigation on the effect of shrouds around an immersed isolation condenser on the thermal stratification in large pools

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ABSTRACT

This paper deals with the numerical investigation on thermal stratification phenomena in the Gravity Driven Water Pool (GDWP) of the Advanced Heavy Water Reactor (AHWR). Study has been performed at decay power level to simulate thermal stratification in GDWP for Station Black-Out (SBO) conditions. Thermal stratification in GDWP has been simulated using a three-volume pool nodalization approach. The study points to characteristic nature of progress of thermal stratification in the GDWP. Full potential of the pool water can be realised only if the entire inventory of water rises to saturation temperature. This can be achieved only by mixing of water. Thermal stratification prevents realisation of the full heat removal potential of the pool water volume particularly below the Isolation Condenser (IC). The single vertical shroud deployed in the pool is the simplest passive internal, which ensures participation of whole pool inventory. A parametric study on single and three-shroud configurations has been performed by varying shroud location or spacing and shroud height. The study indicates limited suppression of thermal stratification by single-shroud configuration compared to three-shroud configuration. The performance of both single and three-shroud configurations was found to be similar for the first three days. However, during a prolonged SBO, the three-shroud configuration was found to be superior due to enhanced mixing. Parametric study was conducted to arrive at an optimum spacing and shroud height for three-shroud configuration. Studies were also conducted to understand the influence of conductivity of shroud material and leakage through shroud on its performance.

1. Introduction

Natural circulation has many engineering applications including solar energy systems, building ventilation systems and cooling of electrical and electronic equipment. Natural circulation is very useful for heat removal from the core of a nuclear reactor during normal operation as well as following a Station Blackout (SBO). After reactor shut down, the reactor core continues to produce decay heat. Continuous cooling of the core even after reactor shutdown is a necessity to maintain core integrity. Reactors employ active and passive safety systems to remove decay heat. An active safety system requires external power source while a passive safety system functions without an external power source. The operating cost of passive safety systems is much lower than for active safety systems. A well designed natural circulation system having a large heat sink can fulfil the requirement of core cooling in the case of prolonged SBO without operator intervention ("IAEA-TECDOC-1624," 2009).

Passive system using a large pool of water with an immersed heat exchanger to remove decay heat from core is incorporated in many advanced reactor designs. An example of such a system can be seen in the AHWR being designed and developed in India, where decay heat is removed through IC immersed in a large pool of water called GDWP (Sinha and Kakodkar, 2006). The decay heat produces steam in the core, which rises to the IC where it gets condensed because of transfer of heat to the surrounding pool water. Heating of pool water followed by upward movement of heated water results in thermal stratification of the pool water. More details of AHWR are given in Section 2.

Thermal stratification in a natural convection system has been extensively studied experimentally and computationally by many researchers. Natural convection studies performed in a rectangular water pool heated from a single vertical wall or two opposite vertical walls from outside show that water layers at the top remain almost mixed (i.e. there are not very sharp temperature boundaries

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to discriminate hot and cold layers of water) and thermally stratified below (Gupta et al., 2008). Investigation of natural convection on large pools was performed in NOKO test facility experiments to examine heat transfer capability of an emergency condenser under different operating condition (Krepper et al., 2002). The steam produced with the help of electrical heaters inside a pressure vessel simulating reactor vessel is passed through horizontally placed emergency condenser. The tube bundle forming the condenser remains submerged in a horizontal cylindrical tank and tests were performed to investigate heating up process in the tank. The experimental results show that upper surface of the pool starts boiling much before the mean pool temperature reaches boiling point due to thermal stratification (Krepper et al., 2002).

Studies have been performed on the development of buoyancy driven flows due to heat loss from a vertical cylindrical tank filled with water of uniform temperature. Heat loss by the water through side walls resulted in buoyancy driven downward flow along the side walls and corresponding upward flow at the center (Fan and Furbo, 2012a). A strong downward flow along the side walls is observed when vertical temperature gradients are smaller than 2 K/m (weak thermal stratification). The heat loss from side walls results in significant reduction of downward flow rate once there is buildup of thermal stratification in the tank (Fan and Furbo, 2012b). Quantification of thermal stratification can be performed in different ways such as thermocline thickness and related methods, Wu and Bannerot stratification coefficient, stratification efficiencies based on the first and second law of thermodynamics, volume fraction extraction efficiency and MIX-number in Thermal Energy Storage (TES) tanks (Haller et al., 2009).

In a thermally stratified storage tank, water layers of highest temperature remain on the top (nearly well mixed), from where, hot water is supplied for different processes in industries and households. TES tanks are required to develop high degree of thermal stratification (Abdoly and Rapp, 1982; Ghaddar et al., 1989) for which many design studies have been performed (Fernández-Seara et al., 2007). Strong thermal stratification is desirable for TES systems. But in the case of nuclear reactors, strong thermal stratification introduces early fatigue in many critical components which compromises in structural components service life (Bieniussa and Reck, 1999; Qiao et al., 2014). In the case of passive safety systems, during the process of decay heat removal, effective temperature difference between primary (steam flowing through condenser pipes) and secondary (pool water) and hence heat transfer reduces with the development of thermal stratification. This results in deterioration of heat removal capability of the Isolation Condenser System (ICS) (Gupta and Jaluria, 1982). Thus thermal stratification in the pool is a problem to be addressed to maximize the efficacy of a given amount of water in the pool (Opanasenko et al., 2012).

Full potential of the pool water can be realised only if the entire inventory of water rises to saturation temperature. This can be achieved only by mixing of water. Literature survey suggests a number of possible ways to mix a thermally stratified pool. Active systems like impellers (Ramsay et al., 2016) and circulation pumps can be used for mixing of pool water during normal operation. While, in the absence of a driving power source, passive internals can be arranged in the pool to channelize the pool water circulation. The circulation mixes the pool water and lowers the average temperature in the pool. One example of channelized flow is the system designed for cooling the Test Blanket Module (TBM) in the International Thermonuclear Experimental Reactor (ITER) (Giancarli et al., 2012; Kumar et al., 2008). The long circulation path provided by the channelization causes good mixing to its highly conductive molten coolant (Lead-Lithium).

2. Description of main heat transport system (MHTS) and ICS of AHWR

The Advanced Heavy Water Reactor (AHWR) is a vertical pressure tube type boiling water reactor, which uses heavy water as a moderator, and light water as a coolant (Sinha and Kakodkar, 2006). The core of the reactor is cooled down by two phase natural circulation flow. The coolant rises from the core through tail pipes (risers) into the four steam drums, where gravity separation of steam from saturated water takes place. Each steam drum is capable to remove one fourth of the heat generated in the core. The separated water in the steam drum is mixed with the feed water and returned through down comer to a common inlet header during normal operation of the reactor (Nayak et al., 2009). The common inlet header supplies coolant water to 452 channels through individual feeder lines. The coolant density difference between down comer and riser develops natural circulation between the steam drum and the reactor core (together known as MHTS). The required mass flow rate of coolant through the core is obtained by placing the steam drum at a suitable height with reference to the core of the reactor (see Fig. 1).

The AHWR relies on passive safety systems for enhancing reactor safety particularly during SBO. Passive safety systems maintain high reliability due to the elimination of all the events associated with the non-availability of pumps used in active heat removal systems. During normal operation of the reactor, high quality steam is supplied to the turbine and then to the main condenser to condense low pressure steam. In the case of planned shutdown (for reactor maintenance) and unplanned shutdown (e.g. SBO, grid failure etc.) steam gets diverted to the IC through a steam supply line connected to a single IC unit (see Figs. 1 and 2a). The condensate is collected back in the steam drum through condensate return line. The condensate return line from a pair of IC has two type of valves active and passive (see Fig. 1). The IC condensate return line connected to each steam drum is generally closed by valves. Normal system operating pressure is 70 bar and the passive valve present in the condensate return line starts opening at 76.5 bar and gets fully opened at 79.5 bar. The active valve can be operated manually and opens automatically on a high-pressure signal set at 80 bar.

The GDWP situated at the top in AHWR is used as a heat sink during passive decay heat removal. It has a total capacity of 8000 m^3, which is divided into 8 sectors, each having capacity of 1000 m^3 (see Fig. 2a). Each sector consists of an IC installed at a height of 0.8 m from the bottom of the pool. One single IC unit consists of 180 vertical 2″ Sch 80 pipes of length 1.6 m each connected with the common inlet and outlet headers known as top and bottom headers respectively (see Fig. 2b). The ICs has been designed for a pressure of 85.0 bar and a temperature of 300 °C. Geometric details of the GDWP and installed IC are given in Tables 1 and 2 respectively.

3. Earlier studies related to thermal stratification in GDWP

In the process of decay heat removal, the condensation of steam inside IC takes place. Thus, the pool water in contact with the IC tubes gets heated and moves towards the free surface by virtue of buoyancy force. In this process, layers of relatively hot water keep on piling over the colder layer of water. Thus, the pool gets thermally stratified. Thermal stratification affects efficient participation of the pool inventory in the heat transfer process. Using RELAP, (Verma et al., 2013), simulated the GDWP without shrouds using a single volume pool nodalization. While (Kumar et al., 2017) simulated the natural circulation in the pool by dividing GDWP without shroud into three volumes, which are connected to each other with the help of cross flow junctions as shown in the