EFFECT OF NON-CONDENSABLE GAS ON THE PERFORMANCE OF PASSIVE CONTAINMENT COOLING SYSTEM IN VVER-1200 DESIGN

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Abstract

As a result of catastrophic events on the nuclear power plant "Fukushima" in Japan, there are a lot of concerns about the safety issues of evolutionary NPP design which rely on passive safety systems to provide the ultimate heat sink and deal with design basis accident (DBA) and beyond design basis accident (BDBA). However, the passive safety systems which use natural forces in operation is lack of practical operating experience and their performance reliability depends on the environmental, physical, nuclear, or chemical phenomena, to a greater extent than active systems. The passive containment cooling system's performance might be deteriorated by non-condensable gases that come from the containment and from the gases produced by cladding/steam interaction during a severe accident. These non-condensable gases degrade the heat transfer capabilities of the condensers in the passive containment cooling systems since they provide a heat transfer resistance to the condensation process. The paper presents the cooling capacity analysis of PRHR/C in VVER-1200 design using RELAP5 Mod3.2 to confirm the performance of conceptual design as well as to assess the efficiency of steam condensation outside heat exchangers within the presence of non-condensable gas. Comparison results are also presented and analyzed.

1. INTRODUCTION

Condensation heat transfer is a primary concern in passive systems used in advanced plants to increase the inherent safety such as the Passive Containment Cooling System (PCCS) of AP1000, VVER-1200 design, the Isolation Condensation System (ICS) of ESBWR design, and the Passive Residual Heat Removal System in AP1000, APR1400, VVER-1200. The principle working of PCCS in VVER-1200 design is based on using an air heat heat exchanger (HEX) which is connected with a pool located on the top of the containment. Natural circulation and heat removal capability are generated when air HEX receives heat from the containment: this occurs through liquid heating and stratification that produces a difference between densities in the rising and descending leg of the pool-type HEX [1]. Therefore, steam vented in the containment following DBA or BDBA will condense on the containment condenser tube surfaces to provide pressure suppression. In these systems, condensation heat transfer in the outer surface of vertical tubes is the main heat transfer mechanism, and non-condensable gases can be present during the accident scenarios. When condensation occurs at the interface of a liquid film on the wall of a vertical tube, a non-condensable gas will accumulate and form a non-condensable gas layer. This increases the non-condensable gas concentration at the interface between the liquid film and gas, which in turn reduces the condensation heat transfer rate. A lower condensation heat transfer rate causes the performance of the heat exchanger to deteriorate, which affects the heat removal capacity in accident conditions and impacts plant safety.

Many experimental/numerical studies have been performed to examine condensation heat transfer efficiency in the presence of a non-condensable gas inside a vertical tube [2-9]. Accordingly, these results has been only used to support the design of a passive system with steam condensation in the inner surface of vertical tubes. It should be also noted that these experimental test have very small scale in purpose of phenomena investigation or correlation development. To obtain appropriately experimental validation of Passive
Containment Cooling System in VVER-1200 V491 Design with steam condensation in the outer surface of vertical tubes, OKBM Afrikantov has developed a large-scale test facility and performed experimental investigations to support code validation at full-scale analysis of safety system as well as to prove the effectiveness and serviceability of the cooling loop for removing heat from the protective envelope [10]. The present paper provides some calculation results of above experimental test facility using RELAP5 Mod 3.2 Code to investigate the performance of cooling loop with an elevated concentration of non-condensable gases and with pure steam. The calculation results are also compared with experimental data to show the predictive capability of condensation heat transfer models implemented in RELAP5 MOD3.2 code.

2. DESCRIPTION OF EXPERIMENTAL TEST FOR VALIDATION OF THE COOLING LOOP

The construction of the full-scale cooling loop design which removes heat from the protective envelope were completed in 2008 at OKBM Afrikantov (Russia) and this test facility has been selected as benchmark data of this study. The arrangement of the cooling loop corresponds to a real cooling loop of PCCS in VVER-1200 V491 design. The design information of full-scale cooling loop and those of the protective envelopetank (which model the containment) can be obtained in details in [10], [11], respectively. The operation of test facility is illustrated in Fig. 1 and briefly introduced as follows: Steam generated from electrical steam generator flows into separators to lower its moisture content, flows along steam lines into the bottom part of the protective envelope, and then flows to the outer surface of heat exchanger tubes. The condensate water is collected into a collector which is positioned beneath the tank. In the cooling loop, water flows from the evaporator tank in to the heat exchanger (condenser) and receives heat to increase its temperature, partially evaporates, and then flows into steam receiver in which steam is separated and discharged along a pipeline into the atmosphere.

Fig. 1. Schematic diagram of a passive system for removing heat from a protective envelope: 1) evaporator tank with a steam receiver; 2) feed line; 3) tank modeling the protective envelope; 4) exchanger-condenser; 5) discharge pipeline; 6) tanks with air; 7) pipelines feeding warming steam into the modeling tank; 8) electricity generator with a steam separator; 9) tank with a salt solution; 10) pump; 11) secondary cooler; 12) condensate collector; 13) air blow-off pipe [10, 11]

3. CALCULATION SETUP FOR OKBM AFRIKANTOV TEST FACILITY

Fig. 2 shows the RELAP5/MOD3.2 code nodalization scheme for the OKBM experiments. The RELAP5/MOD3.2 nodalization used for this simulation contained two loops as described in Fig. 2: The cooling loop and the protective envelope loop. Main components can be seen from this figure: 100 (Atmospheric, cooling loop), 102 & 104 (evaporator tank, cooling loop), 119-124 (Heat Exchanger Tubes, cooling loop), 202 (condensate collector, protective envelope loop), 204 (containment modelling tank, protective envelope loop), 215 (electrical steam generator, protective envelope loop). Experimental test cases with different gas (air) content in the modelling tank and total power of the electricity generators ranging from 0.5 to 1.8 MW
(controlled by electrical heater inside steam generator) are selected for calculations using RELAP5/MOD 3.2 in the present study. The gas content is setup by partial pressure in the modeling tank prior to discharging steam from steam generator to the modeling tank with following cases: 0, 150, 200, 250 and 300 kPa. For each test case, steam is discharged into the modelling tank with total power of the electricity generator 1.8 MW. Then the power of the electricity generator is lowered to 1.5, 1.0, and 0.5 MW and the parameters is allowed to stablized over a time of 1 hour at each power level [10].

Fig. 2. Nodalization Scheme for OKBM Afrikantov Test Facility

4. RESULTS AND DISCUSSION

Comparison results of the coolant temperature at the entrance (CV 135) and the exit (CV 110) of the cooling loop between RELAP5/MOD3.2 calculations and experimental data are shown in Fig. 3 (a). In this case, the initial air pressure in the tank modelling the protective envelope prior to heating was equal to atmospheric pressure (100 kPa). In can be seen that the calculation results have quite similar trends with the experimental data. The deviations may be accounted for differences in the initial condition of water temperature in the evaporator tank. However, the trend of coolant mass flow rate in the cooling loop is quite different. The experimental evidence of periodic oscillations of the cooling flow rate due to the onset of steam formation in the ascendending section of the discharge pipeline when coolant temperature reach 343 °K was not captured in the calculation results. It is reported that the oscillations of the flow rate along the cooling loop was observed only in a particular of regime with the transition of the total power of the electrical steam generator to 0.5 MW. As shown in Fig. 3 (b), this behavior was repeated at all power level (1.8 MW, 1.5 MW, 1.0 MW, 0.5 MW). The oscillations of the flow rate are related with a decrease of the average flow rate and an increase of the transit time of a volume of coolant through the heat exchanger tube and the discharge pipeline into the evaporator tank, which results in a delay of the back effect of the coolant temperature changes [10]. Most important parameter here is the pressure inside the protective envelope which indicates how efficient is the steam condensation. Fig. 3 (c) shown quite similar trends but very big deviations between RELAP5/MOD3.2 calculations and experimental data of the pressure inside the protective envelope. It can be explained by the weakness of condensation heat transfer models implemented in the code as already raised by some authors [2-4, 9]. They have suggested that the effect of the interfacial shear stress was not sufficiently considered in the correlations using the Reynolds number.
Figs. 3 (d), (e), and (f) clearly show the effect of non-condensable gas (air) on the efficiency of steam condensation when the initial air pressure inside the protective tank is increased. The presence of even a small quantity of non-condensable gas in the condensing vapor has a profound influence on the resistance to heat transfer in the region of the liquid-vapor interface. The non-condensable gas carried with the vapor towards the interface where it accumulates. The partial pressure of gas at the interface increases above that in the bulk of the mixture, producing a driving force for gas diffusion away from the surface.

Fig. 3. Typical calculation results of Temperature, Mass flow rate in the cooling loop and Pressure in the protective envelope with RELAP5 MOD3.2
5. CONCLUSIONS

The capability of the RELAP5/MOD3.2 code to investigate the performance of cooling loop of PCCS in VVER-1200 V491 design with an elevated concentration of non-condensable gases was assessed in this study. Overall, the RELAP5/MOD3.2 captured quite well the effect of the initial air pressure inside the containment to the performance of the PCCS. However, the current RELAP5/MOD3.2 code strongly underestimated the condensation heat transfer coefficient which lead to a strong overestimation of the pressure level.

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