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Analysis of Condensation Phenomena in PAFS (Passive Auxiliary Feedwater System) Horizontal Heat Exchanger of APR+

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1. Introduction

APR+ (Advanced Power Reactor Plus) is the next generation nuclear power plant in Korea. It adopts PAFS (Passive Auxiliary Feedwater System) on the secondary system. It can replace the conventional active system for auxiliary feedwater injection to the steam generator, and it enable to supply the coolant by a passive system. It cools down the secondary system by heat transfer at a horizontal U-tube in PCCT (Passive Condensate Cooling Tank). High pressure steam flow from the steam generator is condensed in the horizontal heat exchanger. The water in PCCT is maintained at an atmospheric pressure, so that boiling heat transfer at the outside wall of heat exchanger and natural convection occur in PCCT pool. The heat exchanger and PCCT is higher than steam generator, so condensate can be drained and injected to feedwater system without any active system.

This study aims at design of the horizontal heat exchanger in PAFS. It should remove the heat generated in the steam generator. To satisfy this requirement, a system code analysis is conducted. The amount of condensation heat transfer is investigated by MARS (Multi-dimensional Analysis for Reactor Safety) code analysis.

2. MARS Calculation for APR+ PAFS

2.1 Design and Modeling of PAFS

To design PAFS heat exchanger, it is necessary to define the required heat removal rate and steam flow rate from steam generator. PAFS starts cooling down the steam generator at 300 seconds after TLOFW (Total Loss of Feed Water). From the safety analysis result of APR1400, the core decay heat at that time is about 110 MWth. Then the decay heat in APR+ can be estimated as follows.

$$Q = 110 \times \frac{1600}{1400} = 138 MWth \qquad (1)$$

The steam condition is the saturated steam at 7.4MPa, so that steam flow rate is calculated as 93.24kg/s.

Fig. 1 shows a design of U-tube bundle in PAFS heat exchanger. A bundle is composed of 60 tubes and the inner and outer diameter of the tube are 45.97mm and 50.8mm, respectively. It has three rows of inclined tubes and total length of that is about 8.1m.

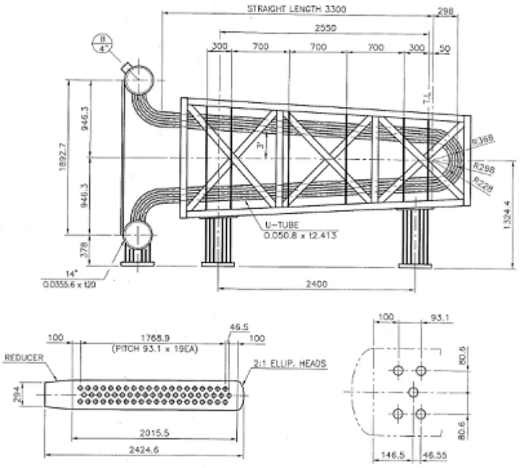

Fig. 1 Design of U-tube bundle

Fig. 2(a) and 2(b) are modeling diagram for MARS analysis of the horizontal U-tube and PCCT water, respectively. The capability of MARS code to predict the condensation phenomena in a horizontal heat exchanger has been proved with the analysis of NOKO test facility [1]. Similarly to the analysis of NOKO experiment, the U-tube was divided by 10 volumes and each volume contacted with pool water as shown in Fig. 2(b). Since PAFS in APR+ has four bundles, the modeling of single bundle in the analysis required a reduction of PCCT water volume to 1/4 of prototype, reserving the total height of the tank as 10m.

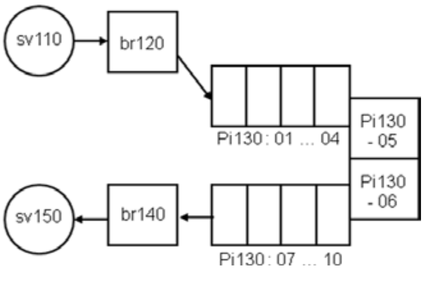

Fig. 2(a) Modeling of horinzontal U-tube

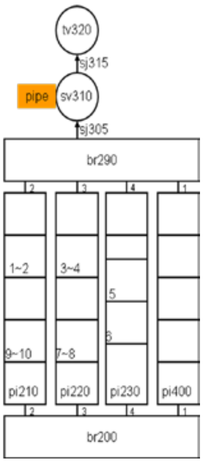

Fig. 2(b) Modeling of PCCT water

2.2 Analysis Results

According to the design and analysis model described above, MARS calculation was conducted for simulating the condensation phenomenon in horizontal U-tube heat exchanger. The injection steam flow rate was 23.31kg/s, which is 1/4 of that of prototype due to the single bundle modeling.

Fig. 3 represents the distribution of liquid volume fraction in the horizontal tube. The liquid fraction increased as the steam flowed toward the exit and condensation occurred. However, the local liquid fraction was decreased around vertical region. Especially, the vertical pipe connected to the exit played a significant role in reducing the liquid fraction under 0.4, by draining the condensate water effectively.

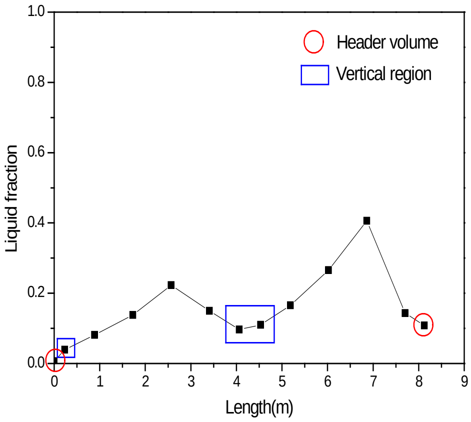

Fig. 3 Liquid fraction distribution

Figs. 4 and 5 show the calculation results of heat removal rate integrated along the length and thermal equilibrium quality, respectively. Even though the liquid fraction near the exit was less than 1.0, the accumulated heat removal rate was estimated over 34.5MW and the thermal equilibrium quality near the exit of tube was less than 0.0. That means the subcooled liquid exists in the horizontally stratified flow region. From those results, it is concluded that horizontal U-tube bundle in PAFS has a sufficient capability of cooling down the decay heat in APR+.

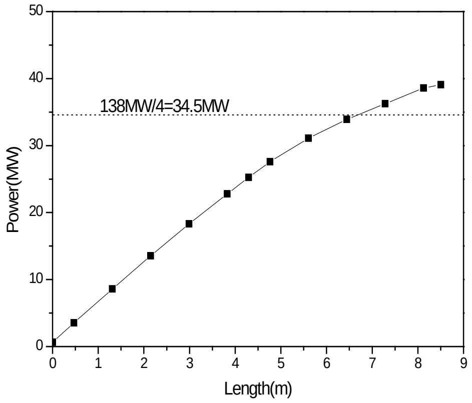

Fig. 4 Integrated heat removal rate

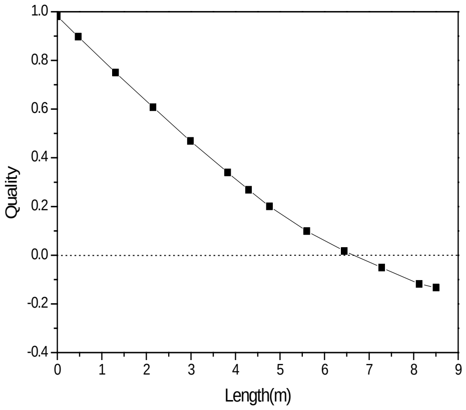

Fig. 5 Thermal equilibrium quality distribution

3. Conclusion

To supply the feedwater in the secondary side of APR+ by a passive system, PAFS adopts the horizontal U-tube heat exchanger, which utilizes the steam condensation in the tube and boil-off in PCCT pool water. In this study, MARS calculation results proved the capability of PAFS heat exchanger to cooling down the required decay heat without any passive system.

In the future, a separate effect test and an integral effect test will be performed to experimentally investigate the two-phase flow phenomena in horizontal U-tube and PCCT. Those experimental results will be used for more elaborate validation of computational analysis code.

REFERENCES

[1] A. Schaffrath et al., Experimental and analytical investigation of the operation mode of the emergency condenser of the SWR1000, Nuclear Technology vol. 126, pp. 123~142 (1999)