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Analysis of Steam Condensation in a Finned Tube of Air-Water Combined Cooling System

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1. Introduction

After the Accident in Fukushima Nuclear Power Plants, intensive researches on a passive residual heat removal system are underway all around the world. The design base-operation time of an active pump driven safety system and cooling system is about 8 hours after an accidents. However, the passive cooling system is required to operate for 72 hours.

A Passive Auxiliary Feedwater System (PAFS) is one of the passive cooling systems of the existing power plant and the operating period is 8 hours because of the limited capacity of the cooling water tank. Therefore, to increase the operating period from 8 to 72 hours for an existing PAFS, the capacity of the cooling water tank should be increased up to 3-4 times.

To resolve the excessive increase of the cooling tank volume in water cooling systems, an air-water combined passive cooling system is proposed. In this combined cooling system, the core cooling during the initial stage of an accident having high decay power depends on the water cooling systems such as PAFS. For the later phase of an accident, an air-cooling system is applied to the core cooling. In the operation of the air-cooling system, the steam from the cooling water tank of the PAFS is condensed and recirculated to the cooling water tank by an air-cooling heat exchanger. In this way, the increase of the cooling water tank volume can be minimized.

2. System Description

Figure 1 shows a schematic diagram of an air-water combined cooling system. In the existing PAFS, the steam generated in the cooling water tank is discharged into the atmosphere. Therefore, the water level of the cooling water tank continuously decreases to the cooling limit of steam from the steam generator. In the air-water combined cooling system, the steam from the cooling water tank is condensed at the air-cooling heat exchanger and returned to the cooling water tank. The excessive steam that is not condensed at the air-cooling heat exchanger is discharged into the atmosphere through an orifice installed at the air-cooling heat exchanger (Fig. 2)

For complete passive cooling operation, neither the active valve nor the control system is installed in the cooling path from the cooling water tank to the air-cooling heat exchanger. The steam flow is induced by the differential pressure of the steam condensation. The tubes in the air-cooling heat exchanger are declined downward from a steam header to a condensate water header in the heat exchanger tube assembly. About a 3-10 degrees declination angle is recommended for a natural circulation.

The air-water combined cooling system consists of a heat exchanger and a motor fan for a forced circulation of air when on-site/off-site electricity is available. A four train air-water combined cooling system will be installed and each train has a cooling capacity of 50 %. Therefore, a single failure assumption and an air-craft crash can be considered.

The cooling capacity of the air-cooling heat exchanger depends on number of heat exchanger tubes. The steam condensation in the air-cooling heat exchanger takes place after steam is discharged from the cooling water tank of the PAFS. If the cooling capability of the heat exchanger is not sufficient, lots of steam that is not condensed in the air-cooling heat exchanger is discharged into the atmosphere through the orifice of the heat exchanger, and, the water level of the cooling water tank then decreases (Fig. 3).

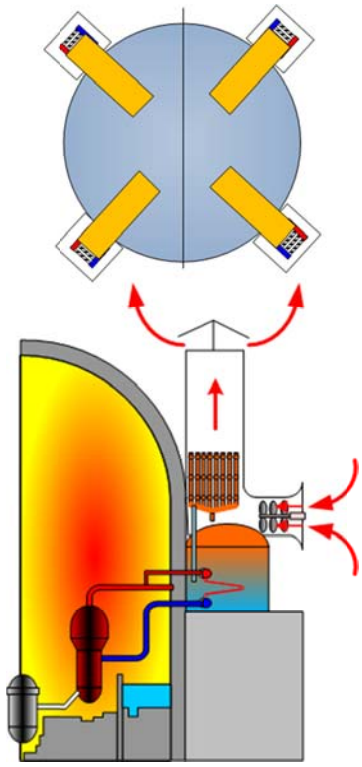

Fig. 1 Air-Water Combined Cooling System

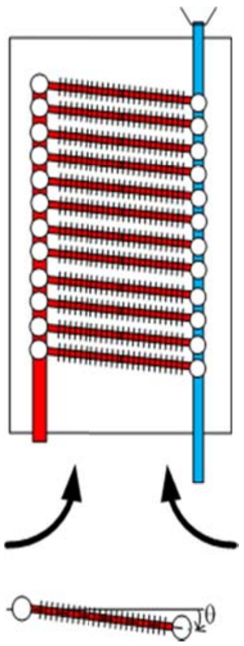

Fig. 2 Finned Tube

The water level can be preserved when all the steam from the cooling water tank is condensed at the air-cooling heat exchanger. However, in this case, the volume of the air-cooling heat exchanger may be excessively huge. It is necessary to optimize the capacity of the heat exchanger to limit the steam discharge and volume of the heat exchanger for the 72-hour system operation. The relationship between the capability of the heat exchanger and water level of the cooling water tank is shown in Fig. 4.

For the air-cooling heat exchanger, an SUS304 finned tube was considered (Fig. 5). The tube is made of a 2 inch pipe, and SUS304 fins (1 mm thick, 12.7 mm high, and 4.23 mm pitch) are arc-welded to the surface of the pipe. A test facility to evaluate the heat transfer capability of a 12-tube air-cooling heat exchanger has been constructed.

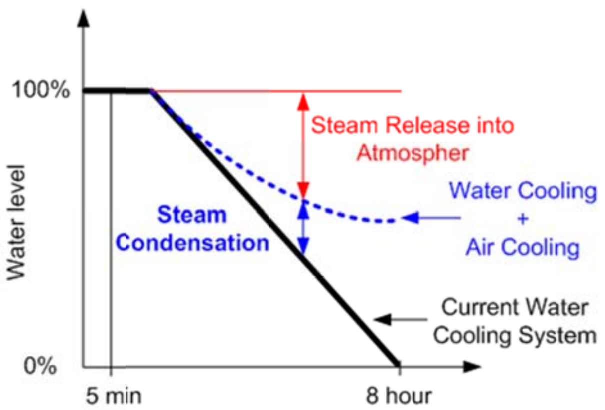

Fig. 3 Steam Condensation vs. Steam Discharge in an Air-Cooling Heat Exchanger

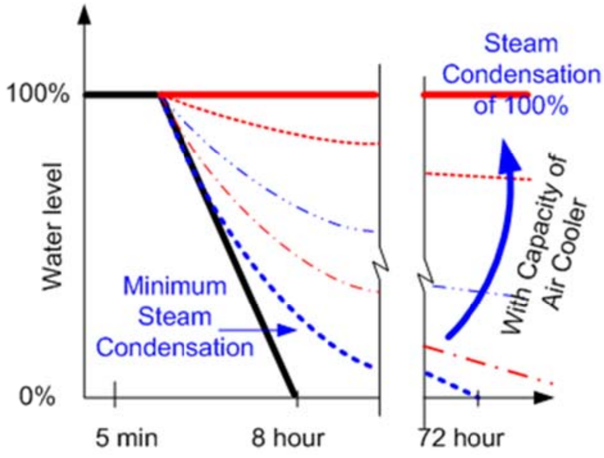

Fig. 4 Water Level vs. Capacity of an Air-Cooling Heat Exchanger for 72-hour Operation

3. Analysis of Heat Exchanger Tube

To analyze the heat transfer capability of a single heat exchanger tube, as shown in Fig. 5, a simulation of the steam condensation by air-cooling was performed using a CFX code. The boundary condition applied to the calculation is shown in Fig. 6, and the tube is horizontally declined 3 degrees downward. The steam enters from the left side of the tube, and the condensate flows to the right side of the tube. The outside surface of the tube is cooled by air and steam is condensed in the tube.

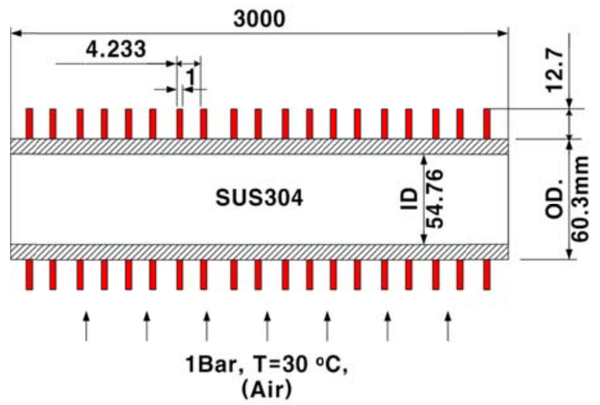

Fig. 5 Dimension of Finned Tube

A single tube was simulated as a slab model and thus, the tube bundle effect was not considered. The cold air enters from the bottom of the air-cooling heat exchanger, and the heated air at the surface of the tube flows upward by a buoyance force. In the calculation, a cross air-flow from both sides of the tube was not considered. Figure 7 shows the mesh distribution, and 22 million elements were used for the calculation.

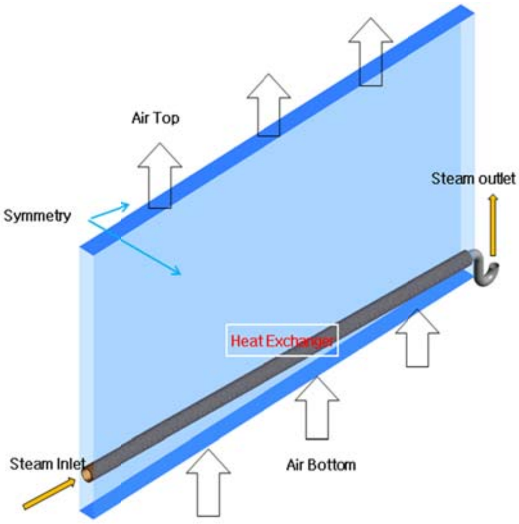

Fig. 6 Boundary Conditions

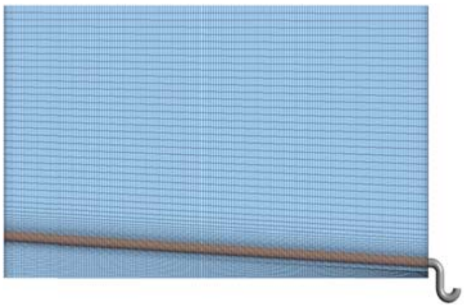

Fig. 7 Mesh

The calculated air temperature and velocity distributions around the tube are shown in Fig. 8 and Fig. 9, respectively. High--temperature steam enters the inlet of the tube (left hand side). However, the air near the inlet region is not sufficiently heated. Therefore, the air velocity driven by a buoyance force at the inlet region is relatively lower than that at the outlet region of the tube.

This phenomenon can take place more actively in the test facility. Furthermore, the multiple bundle effects of the heat exchanger can be generated by a 4-layer 3-tube arrangement of the test facility. However, the bundle effects were not considered in the calculation and therefore, the air flow distribution in the calculation may be quite different from that at the test facility.

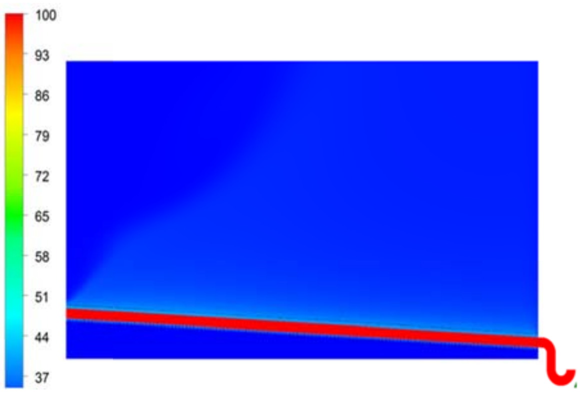

Fig. 8 Iso-Temperature Contour

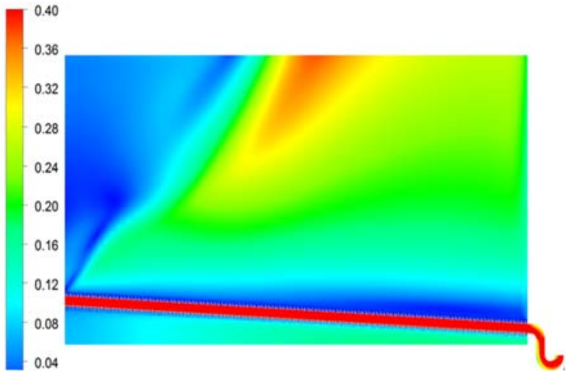

Fig. 9 Air-Velocity Contour

4. Conclusions

To design an air-water combined cooling system, the steam condensation characteristics of an air-cooling heat exchanger tube was calculated using a CFX code. The results show that the air velocities around the tube at the steam inlet/outlet regions are quite different with each other. Therefore, dense installation of thermocouples at the tube bottom region is required to measure the steam condensation in the tube. Otherwise, the detection and measurement of steam condensation at the steam inlet region may be very difficult.

The velocity distribution of air is not uniform and the distributions of air temperature and velocity around the heat exchanger tube are strongly asymmetric. Therefore, the temperatures at the inlet, middle, and outlet regions do not indicate the average temperatures of the corresponding regions, and some difficulties in the derivation of the average tube heat removal rate are expected. In the design of the measurement system of the test facility, the problems mentioned above should be considered.

Acknowledgement

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