The evaluation process for leak detection systems using CFD analysis

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1. Introduction

If a small amount of leakage exceeds the operation limit conditions of a nuclear power plant, losses due to the nuclear power plant shutdown may occur, or accidents due to leakage may occur. Accordingly, developing a system of quickly detecting a small amount of leakage has been required, and research is being conducted on this. In developing such a system, it is necessary to understand the thermal-hydraulic characteristics of the system. Therefore, this study established a numerical analysis-based evaluation process to evaluate the leak detection system simulator, and applicability evaluation was performed.

2. Methods and Results

This section describes the leak detection system under development and its evaluation process based on CFD analysis. In addition, CFD analysis was performed to confirm the applicability of the evaluation process.

2.1 leak detection system

The schematic of the leak detection systems under development is shown in Fig. 1. A leak detection system, including transfer piping and collection units, is installed in parallel near major equipment and pipelines in the containment building. When steam naturally flows into the collecting unit when a leak occurs, the collecting system periodically supplies circulating air to move the high-humidity air that has flowed into the collecting unit through the transfer system to the humidity sensor. And then measures the humidity change to check for leaks(1). High-humidity air flowed in from the collection unit after pipe leakage was mixed with low-humidity circulating air and diffused during transport. Hence, the relative humidity of the high-humidity air decreases during transport. This study used computational fluid dynamics analysis to calculate this phenomenon before constructing the leak detection system.

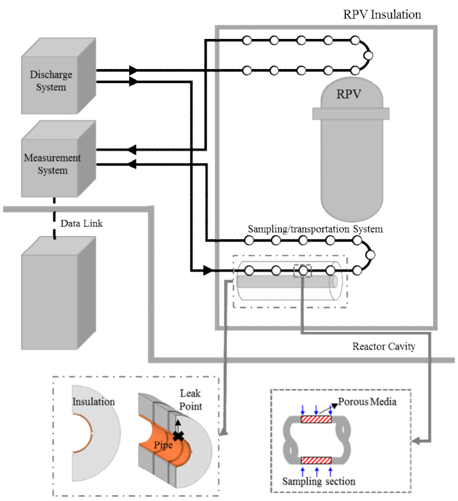


Fig. 1. Schematic of the leak detection systems

2.2 Evaluation process using CFD analysis

This study established an evaluation process that divides the analysis into two steps to analyze collecting and transporting leaks from pipes. The diffusion of humid air in the insulation after pipe leakage was analyzed first, and the temperature, pressure, and humidity data at the collector location were acquired. Afterward, the humid-air behavior analysis in the transfer piping with collection units was performed using the CFD analysis results previously performed as input conditions. This study performed a transient analysis considering compressibility using ANSYS Fluent (ver. 18), a commercial CFD code based on the finite volume method.

2.3 Analysis of humid air diffusion in pipe insulation

Critical flow may form at the leaked part when a leak occurs in a high-pressure pipe because the pressure difference between the inside and outside is very large. However, since the size of the leakage part in the small leak is very small, it is difficult to measure the thermal-hydraulic phenomenon inside the pipe and the outer cover through experiments. Therefore, as shown in Fig. 2 (a), CFD analysis was performed for leakage in the insulation area between the pipe and the outer cover. As a result of the preliminary experiment, it was observed that a considerable amount of steam was discharged through the gap between the outer cover of the pipe and the insulation. Therefore, to consider the effect of these gaps, the gaps between pipes and insulators, insulators and insulators, and outer covers were considered and analyzed. To define the leak condition, pressure 15.5 MPa and temperature 325K were used as the upstream condition of the pipe. At this time, it is assumed that leakage occurs through a 1 mm hole, and the critical mass flux, throat pressure, and temperature are calculated using the HEM model and applied to the inlet conditions. The numerical analysis method for the critical flow formed due to leakage in the pipe was verified by comparing it with the experiment (2). After the CFD analysis, the pressure, temperature, and mass fraction data of steam at the detection loop installation location were obtained. These were applied as input conditions at the inlet of the collection unit in the humid air behavior analysis in the detection loop.

2.4 The behavior of humid air in the detection loop

In the leak detection system, the detection loop is composed of several collection units attached with porous sintered material to collect leak flow and a transfer tube for transporting the leak flow (Fig. 3). Since the flow rate of the fluid flowing into the collection unit varies depending on the characteristics of the porous sintered material, an experimental verification analysis was preceded to verify the flow characteristics in the porous sintered material (3). Then, by applying the characteristics of these porous sintered materials, the behavior of wet air in the collection loop was analyzed. Through this, the change in relative humidity after the transfer was evaluated according to the distance and angle of the leak location and the collection unit. In this analysis, the transfer tube was assumed to be straight. Since the transfer tube of the detection loop was installed in a complex structure, straight and elbow pipes are combined. When humid air passes through the pipe elbow, the humidity profile spreads longer than straight lines, so the analysis was additionally performed to calibrate the humidity profile.

To confirm the applicability of the evaluation process using the established CFD, analysis was performed using the same conditions as the experiment (Table 1). When the relative humidity change of the measurement

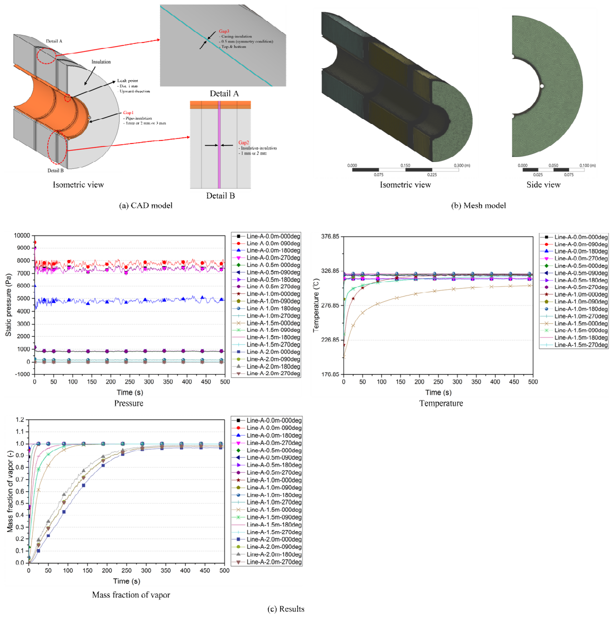


Fig. 2. Pipe insulation CFD model and analysis results

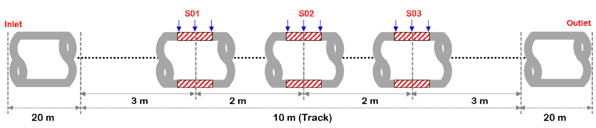
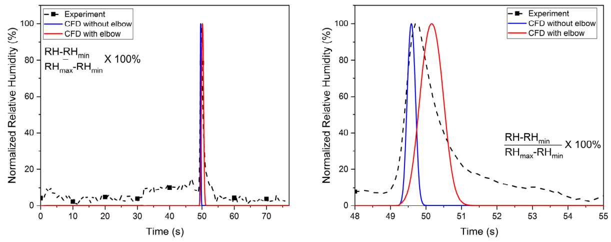


Fig. 3. Schematic of the detection loop

Table I Operating conditions

Upstream pressure	Discharge velocity	Operating time			
		Flushing time	Vacuuming time	Pressure recovery time	Discharge time
70 bar	11 m/s	30 s	1 s	15 s	30 s



(a) t = 0 ~ 75.7s (full time) (b) t = 48 ~ 55s

Fig. 4. Comparison of the normalized relative humidity profile at end of the detection loop

part at the end of the detection loop was normalized, and the experiment and CFD analysis results were compared, high-humidity air tended to occur at a similar time (Fig. 4). This study modeled the transfer tube as only the straight pipe, but the experimental equipment used an elbow pipe. As the high-humidity air passes through the elbow pipe, the high-humidity air can spread longer. When considering the effect on the elbow pipe, the CFD analysis results showed a similar trend to the experiment.

3. Conclusions

In this study, we established an evaluation process using CFD analysis for the leak detection system under development and confirmed its applicability. As a result of CFD analysis, a relative humidity profile similar to the experiment was revealed, and the effect of the elbow pipe was also confirmed to be necessary. The results of this study will be used to build and understand leak detection systems in future work.

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