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Preliminary CFD Analysis of Refrigerant Cooled, Scaled Down RPV of OPR1000

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1. Introduction

To improve the safety and efficiency of nuclear power plants during operation, it is essential to evaluate various passive safety systems and new technology applications from different perspectives. However, the evaluation of new concepts in passive safety systems or 4th industrial revolution technology-based systems is challenging for existing large-scale integral effect test facilities due to their size, high-pressure/temperature conditions, and significant budget and manpower requirements. In addition, there is an ongoing and steady demand for skilled professionals in the field of nuclear safety, and to specialize in human resources in the nuclear safety field, there is a need for a comprehensive and practical educational program that utilizes manageable physical objects.

To overcome the limitations of existing large-scale thermal-hydraulic facilities, a reduced and manageable thermal-hydraulic platform is necessary. Therefore, the ultimate goal of this study is to develop a reduced thermal-hydraulic platform for the OPR1000, which is the most operated nuclear power plant in Korea, to improve its safety and operational efficiency and foster the future nuclear workforce. The reduced thermal-hydraulic platform was designed, called URILO-II (UNIST Reactor Innovation LOop-II), and will simulate thermal-hydraulic phenomena occurring in an OPR1000 for evaluating the new systems and education. The URILO-II was based on the OPR1000 and was reduced in height by 1/8, diameter by 1/10, and volume by 1/800. It uses the refrigerant R134a as working fluid to simulate normal, transient, and accident conditions of the reference nuclear power plant at lower operating pressure and temperature ranges [1,2]. However, the design of URILO-II requires a preliminary evaluation of the scale design due to its characteristic of using refrigerant as the working fluid and the relatively huge scale reduction compared to the typical integral effect test facilities (IETs). Therefore, this paper presents the preliminary validation of scaling design on the most crucial component of the URILO-II experimental apparatus, the RPV (Reactor pressure vessel), by conducting preliminary CFD evaluation.

2. Methods

2.1. Design characteristics for URILO-II

URILO-II uses refrigerant R134a as the working fluid and was designed using the fluid-to-fluid scaling analysis method. R134a has a density ratio equivalent to that of the reference nuclear power plant at 26.5 bar, and to ensure the same hydraulic phenomena, the operating pressure of URILO-II's hot-leg section was set to 26.5 bar, with a low pressure of 1/5.85 compared to the reference and the ability to perform experiments at temperatures of around 80°C. The RPV of URILO-II was designed based on Ishii's Three-level scaling method [3–5], and the detailed design is shown in Figure 1 and Table I.

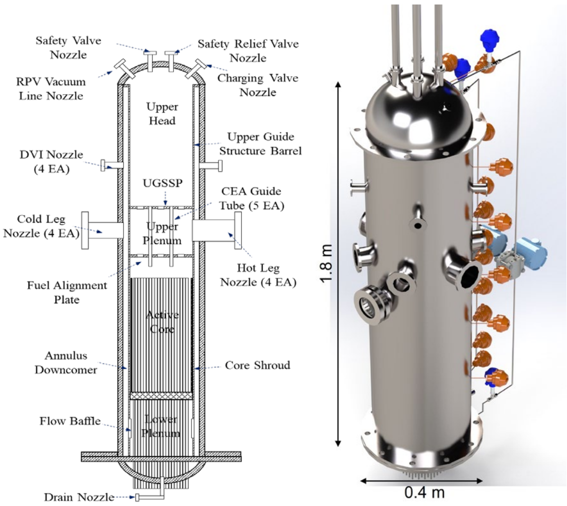

Fig. 1. RPV design of URILO-II, which reduced OPR1000 to 1/8 height ratio and 1/100 area ratio

Table I: RPV design value of URILO-II compared with OPR1000

Parameter	URILO-II (Ideal)	OPR1000
Fluid	R134a	Light water
Power [MW]	1.7	2,815
Pressure [bar]	26.5	155.1
Core flowrate [kg/s]	75.9	15,332.5
Core inlet temp. [°C]	61.0	296.0
Core outlet temp. [°C]	75.0	327.3
Pressure drops [kPa]	86.0	441.5

Since this experimental facility is still in the pre-construction phase and was intended to simulate the phenomena of the OPR1000 nuclear reactor using R134a as the working fluid, it is necessary to evaluate distortion in the scaling design. Although direct experimentation is the best way to compare results, since this apparatus is still in the pre-construction phase, a preliminary evaluation of the design methodology and results was conducted through computational analysis.

The purpose of this computational analysis is to evaluate whether the design operating conditions of the RPV, which were designed using the scaling method, including inlet/outlet temperatures, flow rate, and pressure drop, have been appropriately designed. For this purpose, the computational analysis interpreted the single-phase flow of R134a as the heat transfer conditions occurring at the simulated core and verified the pressure drop and outlet temperature distribution between the RPV inlet and outlet by comparing them.

2.2. Numerical methods

To solve the single-phase flow and heat transfer problem, the finite volume method was applied to divide the continuous equation into a finite number of volumes and calculate the characteristics of each volume to analyze the flow. The CFD analysis used the R134a material property for working fluid and applied boundary conditions of an inlet flow rate of 18.98 kg/s (total 75.9 kg/s) and inlet pressure of 26.5 bar from four cold legs, with the outlet condition set at the hot leg. In addition, the simulated core included 156 heaters, each with a heat flux of 767.3 kW/m2 as shown in Table II.

Table II: Boundary and initial conditions

Location	Type	Value
Cold leg	Mass flowrate inlet	18.98 kg/s
Hot leg	Pressure outlet	26.5 bar
Core	Heat flux	767.3 kW/m^2
Fluid domain	Fluid type	R134a
	Initial temperature	61 °C
	Initial pressure	26.5 bar

3. Results and Discussion

The internal temperature distribution of the Reactor Pressure Vessel (RPV) was analyzed through Computational Fluid Dynamics (CFD) simulations to verify the design adequacy by comparing it with the design specifications of the inlet temperature of 61℃ and outlet temperature of 75℃ and to understand the internal temperature distribution trend. The temperature distribution was confirmed under 100% operating condition, with an output of 1.7MW, an inlet temperature of 61℃, and a flow rate of 75.9kg/s. The outlet temperature at the hot leg was analyzed to be 76.1℃, which was 1.1℃ higher than the design specification of 75℃. Figure 2 shows the distribution of the internal working temperature, where the working fluid at 61℃ enters the downcomer, flows down, passes through the lower plenum and the core inlet, and is heated in the mock core before flowing out to the hot leg, revealing the trend of the temperature distribution.

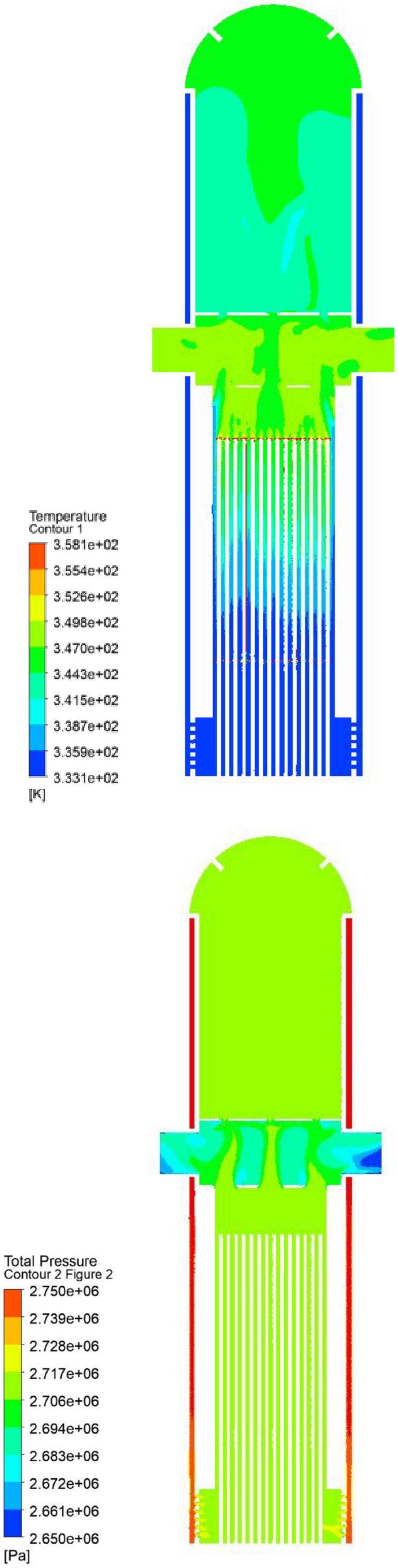

Fig. 2. CFD analysis results of URILO-II RPV, temperature distribution (Upper), pressure distribution (Bottom)

In the core, the temperature of the working fluid was analyzed to be 82°C at the uppermost part of the heating section, which is higher than the boiling temperature of the working fluid, which is 80°C. Therefore, it was found that the designed RPV has a possibility of local boiling occurrence. This is attributed to the fact that the heat transfer coefficient of R134a single-phase flow is about 1/10 of that of water, leading to local boiling. Although the main purpose of the URILO-II experimental facility is to simulate the two-phase flow of OPR1000, it is necessary to consider the distortion caused by single-phase flow heat transfer during the experimental condition selection for the RPV of URILO-II.

Regarding the pressure analysis, the internal pressure distribution trend was analyzed by comparing the pressure drop at the low and high-temperature regions with the design specification of pressure drop. The overall pressure drop of the RPV was calculated to be 8.77m, which is 14.6% higher than the design value of 7.65m (1/8 of the OPR1000 RPV head loss of 61.2m). Therefore, it was found that the designed RPV may have a higher pressure drop than the ideal design. The pressure distribution trend is shown in Figure 2, and it was identified that the flow area changes at the core inlet and outlet plenums significantly contribute to the pressure drop. Therefore, as the pressure drop is higher than the ideal scaling design value, experimental conditions and analysis should be selected regarding transient experiments that involve single-phase natural circulation without forced convection.

4. Conclusions

In conclusion, this study presented the preliminary validation of the RPV scaling design for a scaled-down thermal hydraulic platform, URILO-II, by CFD. The design of URILO-II was an IET that was reduced in 1/8 height scale from OPR1000 and used the refrigerant R134a as a working fluid. As a result of the CFD analysis, the core outlet temperature of the designed RPV was 76.1°C, 1.1°C higher than the ideal scale design value, which was similar to the similar design overall. However, because the heat transfer coefficient of the R134a single-phase flow was low, about 1/10 of that of water, a fluid temperature distribution higher than the boiling point appeared at the top of the core, and it was identified that local boiling was highly likely to occur in that region. It was also found that the designed RPV could have higher pressure drops than the ideal scaling design values. Therefore, in transient experiments involving single-phase natural circulation without forced convection, a slightly higher pressure drop characteristic should be considered. The results of this analysis will be used for the construction and experiment of URILO-II, and URILO-II will evaluate the applications of various passive safety systems and new technologies, and educate future nuclear students through comprehensive and practical training programs.

ACKNOWLEDGMENT

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