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Fluid-to-Fluid Scaling Design for Integral Effect Test Facility of OPR1000 Using R134a

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1. Introduction

The thermal-hydraulic integral effect test (IET) facilities of a nuclear power plant (NPP) are utilized to evaluate the accident simulation, safety issues, or new technology by reproducing the thermal-hydraulic phenomena of the reference NPP in the reduced scale [1]. This is mainly used for licensing and code improvement, as it provides insight into the integral phenomenon of NPPs and can produce verification data. In Korea, a representative IET facility, ATLAS [2] scaled down from APR1400, a representative IET facility has been producing valuable data from the viewpoint of thermal-hydraulics through various accident experiments, and other IETs such as SNUF, URILO, VISTA [1], etc. have been developed. Although there has been a lot of research on IET development and experiment for advanced NPPs such as APR1400 and SMART, OPR1000 does not yet have an IET facility such that there is a lack of infrastructure for evaluating safety issues or new technologies.

OPR1000 is the backbone of the APR1000 which is under development as a 1000MW-class PWR NPPs, and steady demand is expected in the NPP market thanks to its efficiency and safety. For the evaluation of the integral effect of OPR1000 and the application of new nuclear technology, this study deals with the preliminary design for developing the OPR1000 scaled-down IET facility. As an important safety issue has already been performed well with the ATLAS, this IET is mainly aimed at reproducing the thermal-hydraulic phenomenon of OPR1000 and evaluating the applicability of advanced technologies (Passive auxiliary feedwater system, emergency core barrel duct, etc.). This study scales the reference OPR1000 in the low-pressure and low-temperature range using refrigerant as the working fluid, it was designed to have a relatively large reduction ratio with a height ratio of 1/8 and a diameter ratio of 1/12 to facilitate deformation application.

2. Methods and Results

In this section scaling methods used to design the model are described. The OPR1000's IET facility includes a primary system, a secondary system with a turbine and generator, and an emergency core cooling system. In this paper, we only deal with global scaling and describe the preliminary design of the reactor pressure vessel.

2.1 Fluid-to-Fluid Scaling

This IET uses a refrigerant as a working fluid to reproduce the thermal-hydraulic phenomenon of a reference NPP. When a refrigerant is used, it is possible to conduct experiments under very low pressure and temperature conditions compared to reference and have the advantage of being able to design on a small scale in terms of energy inventory. Among various refrigerants (R123, R410a, R134a, R1234fy), R134a was selected as the working fluid in consideration of toxicity, flammability, and environmental friendliness, and thermodynamic properties.

The main target experiments to be performed with this IET are forced convection with reduced power, natural circulation, loss of coolant accident (LOCA), station blackout, and loss of feedwater accident. Except for forced convection, in all accident experiments, transients due to natural circulation occur, and two-phase flow is dominant due to pressure change and energy accumulation. Therefore, the scale must match the similarity between natural circulation and two-phase flow to simulate important phenomena.

For scales using different fluids with reduced height and reduced pressure, Ishii's three-level scale method [3] and H2TS [4] scale method can be used. Among them, fluid-to-fluid scaling was performed based on Ihsii's three-level scaling method [3], which can be systematically scaled in single-phase forced circulation, single-phase natural circulation, and two-phase natural circulation. For single-phase forced circulation and natural circulation, dimensionless numbers are derived as shown in Table I by non-dimensionalization of the continuity, momentum, and energy equations with the assumption of one-dimensional and incompressible flow with neglecting viscous dissipations [5]. In addition, the dimensionless number of two-phase natural circulation is derived from the drift flux model and the integral effect of local response, and the similarity groups for R134a are summarized in Table 1 [5].

To match the natural circulation of two-phase flow, it is most important to set the liquid-gas density ratio of R134a to be the same as that of the reference NPP, because the density ratio is related to vapor size, quality, and void fraction. Since R134a has the same density ratio as water of 15.5 MPa at a pressure of 2.65 MPa, this pressure was selected as the operating pressure.

Based on the geometric ratio of 1/8 height ratio, 1/12 diameter ratio, and the thermodynamic properties of R134a at 2.65 MPa, the velocity and time are 2.8 times faster than that of the reference OPR1000 due to the reduction of the axial length. The power density is 1.71 times larger than that of the reference, and the core power is 2,383 times lower, so it is possible to simulate the reference with a small-scale power.

Table I: R134a Scaling results of OPR1000's IET

Parameter	Scaling law	Scaling ratio
Working fluid	R134a	-
Axial Length	l_{oR}	1/8
Flow Area	a_{oR}	1/144
Volume	$l_{oR}a_{oR}$	1/1152
Velocity	$l_{oR}^{1/2}$	1/2.8
Time	$l_{oR}^{1/2}$	1/2.8
Rod Power density	$\left(\frac{\rho_g h_{fg}}{\Delta\rho C_{pf} l_{oR}^{1/2}}\right)_R \left(\rho_s C_{ps}\right)_R$	1.71
Core Power	$q'''_{oR} l_{oR} a_{soR}$	1/2383
Δ T	$\left(q'''_o l_o^{1/2} / \rho_f C_{pf}\right)_R$	1/2.1
Mass rate	$\rho_{fR} l_{oR}^{1/2} a_{oR}$	1/282
Subcooling	$\left(h_{fg}\rho_g / \Delta\rho\right)_R$	1/9.11
Pump head	l_{oR}	1/8
Pressure drops	l_{oR}	1/8
Density ratio	$(\Delta\rho/\rho_g)_R$	0.996
Two-phase similarity groups		
Phase change no.	$\left(\frac{q'''_o \delta l_o^{1/2}}{d\rho_f h_{fg}}\right)_R \left(\Delta\rho / \rho_g\right)_R$	1.01
Subcooling no.	$\left(\Delta h_{sub}\right)\left(\Delta\rho / h_{fg}\rho_g\right)_R$	1.02
Exit quality ratio	$\left(\Delta\rho / \rho_g\right)_R^{-1}$	0.98
Friction no.	$\left(\left(\frac{fl}{d}\right)\frac{1+x\left(\Delta\rho / \rho_g\right)}{\left(1+x\Delta\mu / \mu_g\right)^{1/4}}\right)_R$	1.0
Orifice no.	$\left(K_i\left(1+\frac{x^{3/2}\Delta\rho}{\rho_g}\right)\right)_R$	1.0
Drift flux no.	$\left(\frac{x_e\rho_f\Delta\rho}{\rho_g\left(\Delta\rho\alpha_o-1\right)}-1\right)_R$	0.98
Froude no.	$\left(\rho_f / \Delta\rho\alpha_o\right)_R$	1.02
Single-phase similarity groups		
Richardson no.	$\left(\beta\Delta T_{SP} l_o / u_{oSP}^2\right)_R$	1.0
Heat source no.	$\left(\frac{q'''_o l_o}{u_{oSP}\rho_s C_{ps}\Delta T_{SP}}\right)_R$	1.01
Pump no.	$\left(gH_d / u_o^2\right)_R$	1.0
Time ratio no.	$\left(l_o\delta^2 / u_{oSP}a_s\right)_R$	0.57
Biot no. (turbulent)	$\left(h\delta / k_s\right)_R$	1/31
Stanton no. (turbulent)	$\left(hl_o / \rho C_p u_o d\right)_R$	1/53

For the similarity of two-phase flow natural circulation, the phase change, the ratio of heat transfer of solids, and phase change heat transfer can be matched by selecting the appropriate hydraulic diameter and conduction depth. The subcooling number matches the similarity with the inlet temperature of the IET facility, and the drift flux number, Froude number, and exit quality number are matched if the density ratio of R134a is matched. Friction number and Orifice number can be matched independently by applying appropriate flow resistance. Therefore, in the case of two-phase, similarity with the reference nuclear power plant was secured.

In the case of single-phase, the Richardson number, which is the ratio of driving force due to buoyancy and inertia in natural circulation, is very important, and similarity was matched by reducing the temperature rise by 2.1 times. The heat source number, which means the ratio of the amount of energy generated compared to the axial energy distribution in the solid, and the pump number, which means the pressure drop, also matched those of the reference. However, the Biot number and Stanton number, which mean the energy distribution of solids and fluids, were severely distorted because of the low heat transfer rate of R134a. Therefore, it is difficult to match the energy distribution of the fluid in a single phase with single-phase heat transfer alone. However, it can be achieved only by allowing a phase change in the heat transfer region. That is, in the core, even though it is a single-phase experiment, the energy distribution of the fluid can be matched only by allowing subcooled boiling.

2.2 Preliminary Design of OPR1000's IET

Considering the scaling result in Table I and the mass and energy inventory ratio, the normal operating condition of the IET facility was derived as shown in Table II. At the pressure of 2.65 MPa, the full power is 1.18MW, the core inlet temperature is 61C, and the outlet temperature is 75C. In this study, the actual output of IET is planned to have 0.118 MW, which is 10% of the full power, so this IET can simulate decay heat after a reactor trip.

Table II: Normal operating condition for OPR1000's IET facility using R134a

Parameter	<u>P</u>rototype	<u>M</u>odel	Ratio (<u>M</u>/<u>P</u>)
Fluid	Water	R134a	-
Pressure	15.5MPa	2.65Mpa	1/5.85
T_{sat}	344.9°C	80.3°C	1/2.19
Power	2815 MW_{th}	1.18 MW_{th}	1/2383
Core inlet Temp.	296°C	61°C	-
Core outlet Temp.	327.3°C	75°C	-
Δ T	31.3°C	14°C	1/2.1
Subcooling	314.4 kJ/kg	34.5 kJ/kg	1/9.1
Core mass rate	14,892.5 kg/s	52.7 kg/s	1/282

The primary system of OPR1000's IET facility consists of a reactor pressure vessel, reactor coolant pump, pressurizer, steam generator, hot-leg and cold-leg, and the most important RPV is designed as shown in Figure 1. It was designed by preserving the flow area and axial elevation of the existing OPR1000. Another feature was that the pitch of the core heater was increased so that the hydraulic diameter of the subchannel was 3.5 times. This was due to matching the two-phase flow similarity with the low heat transfer rate of the refrigerant. So, the geometry of the heater was 9.7mm of outer diameter, 20mm of pitch, and p/d of 2.1.

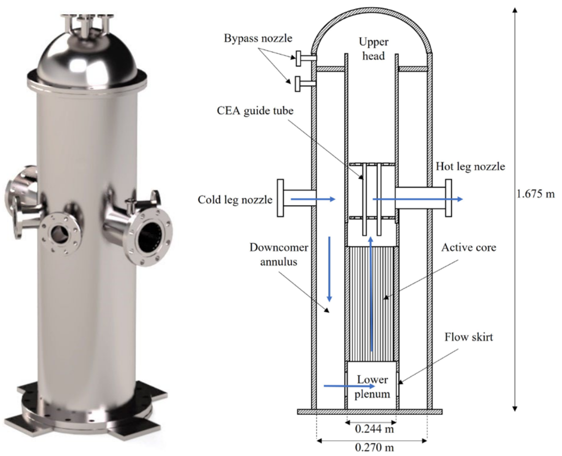

Fig. 1. The design of the scaled-down reactor pressure vessel and the core of OPR1000

3. Conclusions

This paper describes the preliminary design study for developing the scaled-down thermal-hydraulic IET of OPR1000. To simulate the reference at reduced pressure, R134a refrigerant was selected as the working fluid. Similarity groups were matched for scaling for force circulation, single-phase natural circulation and two-phase natural circulation. The two-phase flow had all the similarities, but in the case of a single phase, it was found that there was a serious distortion in the fluid energy distribution due to the low heat transfer rate of R134a. To overcome this, this IET tried to fit the energy distribution in a method that allows subcooled boiling in a single-phase experiment. Although the basic design of the RPV has been performed, additional designs for other major components and secondary systems will be carried out, and the experimental conditions will be selected through boundary mass and energy flow analysis.

Nomenclature

a	flow cross-section area	[m2]
d	hydraulic diameter	[m]
f	friction factor	[-]
l	axial length	[m]
u	velocity	[m/s]
T	temperature	[℃]
h_{fg}	latent heat of vaporization	[kJ/kg]
C_p	specific heat capacity	[kJ/kgK]
Δh_{sub}	subcooling	[℃]
q'''	power density	[kW/m3]

Greek Letters

α	void fraction	[-]
β	volumetric coefficient of expansion	
δ	conduction depth	[m]
ρ	density	[kg/m3]
μ	viscosity	[Pa-s]
χ	vapor quality	[-]
Δ	the difference	[-]

Subscripts

f	fluid phase
g	vapor phase
fg	phase change from fluid to vapor
o	reference values at heated section
oR	ratio of model to prototype at heated section
s	solid section
R	ratio of model to prototype
SP	single-phase

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