Local Phenomena Scaling Analysis for Convection and Nuclear Boiling Heat Transfer Characteristics of Containment Vessel in i-SMR Integral Effect Test Facility

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1. Introduction

An innovative small modular reactor (i-SMR) is being developed as shown in Fig.1 [1]. Validation test program for i-SMR started in 2023 to produce data base for supporting the progress of the standard design approval (SDA) by 2028. One of scopes of the validation test program is an integral effect test with newly constructed thermal-hydraulic test facility. The scaling analysis with three-level scaling method [2] is being carried out to design the integral effect test facility. Global scaling ratios was determined as 1/2 height, 1/49 area and 1/98 volume of scaling ratios [1]. The scaled down test facility with 1/7 reduced diameter caused distortion of arrangement for main components. The reactor pressure vessel (RPV) and containment vessel (CV) should be separated as shown in Fig. 2. It can induce the scaling distortion of conduction heat transfer from RPV wall to CV condensate. The effect of conduction heat transfer should be considered in design of CV in the integral effect test facility.

This paper presents progress of local phenomena scaling analysis for design of CV considering heat transfer in CV condensate pool. Additional heat structure will be installed to compensate scaling distortion of separated RPV and CV, and design strategy will be described in this paper.

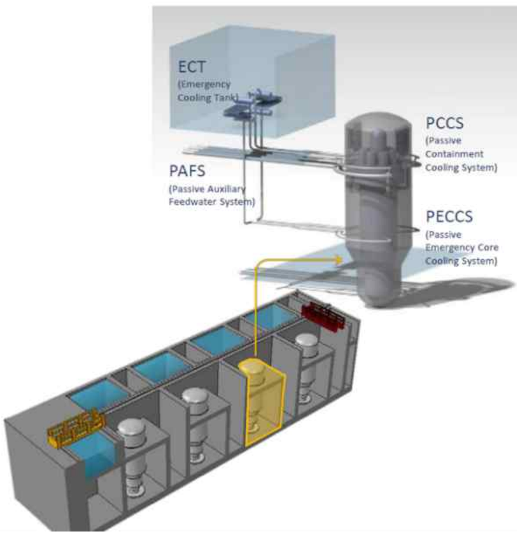

Fig. 1. Conceptual diagram of i-SMR [1].

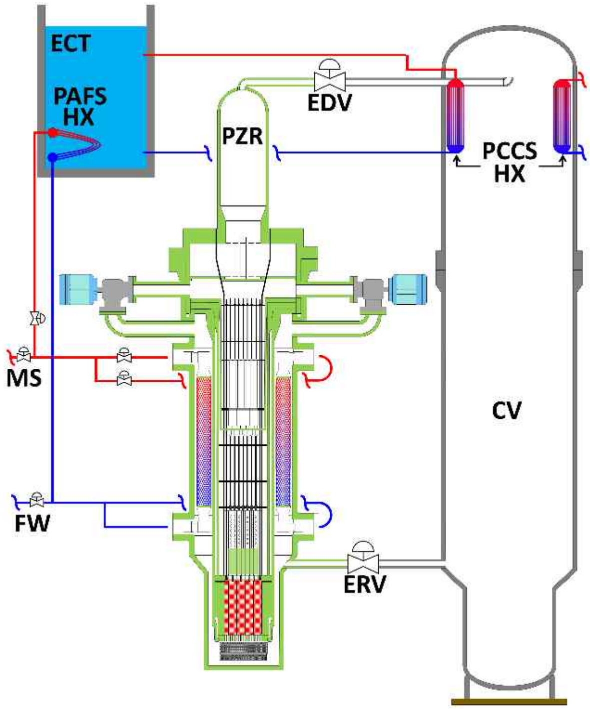

Fig. 2. Basic design of i-SMR integral effect test facility.

2. Local Phenomena scaling Analysis

A passive emergency core cooling system (PECCS) is one of passive safety systems in the i-SMR as shown in Fig. 1 [1]. When coolant discharged from the RPV during a loss of coolant accident (LOCA), it condenses in the CV and recirculates to the RPV by a gravity force. The PECCS uses CV condensate as an emergency coolant for recovery of reactor coolant system (RCS).

Design of the CV in integral effect test facility is important because water level of condensate determine recirculation flow rate for inventory recovery of RCS. Water level of CV condensate pool is significant variable for core cooling, therefore, two-phase flow in CV condensate pool needs to be reproduced in integral effect test facility. It can affect recirculation flow rate from CV to RPV, and is related with boundary scaling analysis. A boundary scaling analysis strategy of the CV was presented in previous study considering energy balance equations [1].

Especially, separated RPV and CV can result in thermal hydraulic distortion related to a conduction heat transfer. In an i-SMR prototype, there must be a bubbly flow in CV condensate pool by conduction heat transfer from RPV wall. Mixture level in bubbly flow can be higher than single phase water level without conduction heat transfer effect. And the bubble brings convection and nucleate boiling heat transfer in the CV condensate pool.

In the integral effect test facility, an additional heat structure will be used in CV lower part to simulate conduction heat transfer of the prototype reactor [1]. Also, effect of convection and nucleate boiling heat transfer in CV condensate pool was considered in local phenomena scaling analysis. The hydraulic diameter in Eq. (1) needs to be determined to design of heat structure in the CV. Inner diameter of CV lower part (d_2) and diameter of heat structure (d_1) are design parameters.

$$D_{\hbar} = \frac{4A}{P} = d_2 - d_1 \tag{1}$$

The dimensionless gap diameter (D^*_{gap}) as shown in Eq. (2) is determined by the gap width, i.e., hydraulic diameter ($W_{gap} = 1/2D_{\hbar}$) and it needs to be over the criterion, 19.11 [3]. When this value cannot exceed the criterion value, 19.11, two-phase flow can be changed from bubbly flow to cap bubble flow. It induces another distortion in two-phase flow regime of CV condensate pool.

$$D^*_{gap} = \left(\frac{gW_{gap}\Delta\rho}{\sigma}\right)^{0.5} \tag{2}$$

To evaluate the heat transfer with model and correlation in CV condensate pool, Chen correlation [3] was used as shown in Eqs. (3) ~ (8). The two-phase heat transfer coefficient ($\hbar_{2\Phi}$) of Chen correlation is determined as summation of convection heat transfer coefficient ($\hbar_{CV}$) and nucleate boiling heat transfer coefficient ($\hbar_{NB}$).

$$\hbar_{2\Phi} = \hbar_{CV} + \hbar_{NB} \tag{3}$$

$$h_{CV} = F\frac{k_f}{D}0.023\left[\frac{G(1-x)D}{\mu_f}\right]^{0.8} Pr_f^{0.4} \tag{4}$$

$$F = \left[\frac{Re_{2\Phi}}{G(1-x)D/\mu_f}\right]^{0.8} \tag{5}$$

The effect of convection heat transfer can be affected with hydraulic diameter and two-phase Reynolds number ($Re_{2\Phi}$) as shown in Eqs. (4) and (5).

The nucleate boiling heat transfer coefficient ($\hbar_{NB}$) is a Forster-Zuber pool boiling heat transfer coefficient (h_{FZ}) times a suppression factor (S) as shown in Eq. (6) [3].

$$h_{NB} = Sh_{FZ} \tag{6}$$

$$h_{FZ} = f(k, c_p, \rho_f, \sigma, \mu_f, h_{fg}, \rho_g, \Delta T, \Delta p_{sat}) \tag{7}$$

$$S = \begin{cases} \left(1 + 0.12Re_{tp}\right)^{-1.14} & Re_{tp} < 32.5 \\ \left(1 + 0.42Re_{tp}^{0.78}\right)^{-1} & 32.5 \le Re_{tp} < 70 \\ 0.0797 & Re_{tp} \ge 70 \end{cases} \tag{8}$$

The Forster-Zuber pool boiling heat transfer coefficient (h_{FZ}) in Eq. (7) can be preserved when properties of fluid is maintained between model and prototype. In the integral effect test, pressure and temperature will be maintained. The effect of nucleate boiling heat transfer is determined by two-phase Re number (Re_{tp}) in the suppression factor (S) as shown in Eq. (8).

The convection and nucleate boiling heat transfer coefficient ratios ($\frac{h_{CV,m}}{h_{CV,p}}$ and $\frac{h_{NB,m}}{h_{NB,p}}$) between model and prototype can be expressed as Eq. (9) and (10).

$$\frac{h_{CV,m}}{h_{CV,p}} = \left(\frac{D_m}{D_p}\right)^{-1}\left(\frac{u_m}{u_p}\frac{D_m}{D_p}\right)^{0.8} = \left(l_R^{1/2}\right)^{0.8}(d_R)^{-0.2} \tag{9}$$

$$\frac{h_{NB,m}}{h_{NB,p}} = \frac{S_m}{S_p} = \left(\frac{1 + 0.12Re_{tp,m}}{1 + 0.12Re_{tp,p}}\right)^{-1.14} = \left(\frac{1 + 0.42Re_{tp,m}^{0.78}}{1 + 0.42Re_{tp,p}^{0.78}}\right)^{-1} \tag{10}$$

Table I shows the local phenomena scaling analysis results while changing the hydraulic diameter that can be implemented in the geometric shape of CV lower part. As a result, we selected 1/4.4 of hydraulic diameter for design of heat structure in CV lower part because the distortion of convection heat transfer coefficient is the least. Even the distortion is large in case with low velocity nucleate boiling, it is not dominant in the transient condition.

The selected hydraulic diameter does exceed the cap bubble criterion, 19.11, and it has value from 19.31 to 23.69 in range of 1 ~ 4 MPa. It is expected that a two-phase flow regime can be maintained.

Table I: Local phenomena scaling analysis results for hydraulic diameter of CV condensate pool

D_R	l_R	$\frac{h_{CV,m}}{h_{CV,p}}$	$\frac{h_{NB,m}}{h_{NB,p}}$			
		$\left(l_R^{1/2}\right)^{0.8}(d_R)^{-0.2}$	$\left(\frac{1+0.12Re_{tp,m}}{1+0.12Re_{tp,p}}\right)^{-1.14}$		$\left(\frac{1+0.42Re_{tp,m}^{0.78}}{1+0.42Re_{tp,p}^{0.78}}\right)^{-1}$	
			$u_f = 0.005\ m/s$	$u_f = 0.01\ m/s$	$u_f = 0.01\ m/s$	$u_f = 0.02\ m/s$
1/1	1/6.8	0.46	0.49	-	1.97	5.02
1/2	1/4.1	0.65	0.32	0.76	-	3.01
1/4	1/2.2	0.96	0.24	0.45	-	1.84
1/4.4	1/2.02	1.02	0.23	0.42	-	1.71

3. Conclusions

The local phenomena scaling analysis for design of CV in integral effect test facility was carried out. The 1/4.4 of hydraulic diameter was selected to reduce thermal hydraulic distortion for reproduction of two-phase heat transfer in the CV condensate pool. Also, the selected hydraulic diameter exceeds the cap bubble criterion. Even the design of CV in an i-SMR prototype is being modified, the local phenomena scaling analysis methodology is valid. It will be applied to modified design of CV and heat structure in integral effect test facility.

ACKNOWLEDGMENTS

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