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Scaling Analysis for Conceptual Design of Steel Containment Vessel in i-SMR Integral Effect Test Facility

Jin-Hwa Yang*, Byoung-Uhn Bae, Hwang Bae and Kyoung-Ho Kang
Korea Atomic Energy Research Institute
989-111 Daedeokdaero, Yuseong-gu, Daejeon, 305-353, Korea
**Corresponding author: f1yjh@kaeri.re.kr*

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1. Introduction

Recently, an innovative small modular reactor (i-SMR) is being developed in Korea. It is an integral type pressurized water small modular reactor which has a steel containment vessel with fully passive safety systems (PSSs) as shown in Fig. 1. Main components of the reactor coolant system (RCS) consisting of a core, a pressurizer, reactor coolant pumps (RCPs), and a steam generator (SG) are contained in one pressurized reactor vessel (RV). The RV is installed inside a steel containment vessel (CV).

It has a plan to acquire a standard design approval (SDA) by 2028. Validation test program for i-SMR is being conducted to produce data base for the SDA. Among the test facilities, an integral effect test facility is being designed to carry out validation tests for combined effect of RCS and PSSs. In order to design and construct the integral effect test facility, scaling analysis for test facility is important. A three-level scaling method proposed by Ishii et al [1] is applied to design the integral effect test facility and a basic design for the test facility is being carried out. In this paper, the definition of the global scaling ratio for the basic design of the integral effect test facility and the considerations of the boundary scaling analysis in the CV are presented.

2. Passive Safety Systems of i-SMR

There are three passive safety systems in i-SMR as shown in Fig. 1 [2]. It includes a passive emergency core cooling system (PECCS), a passive containment cooling system (PCCS), and a passive auxiliary feedwater system (PAFS). It will be briefly introduced in this chapter, and the concerned passive safety systems for boundary scaling analysis in the CV are PECCS and PCCS.

2.1 Passive Emergency Core Cooling System (PECCS)

PECCS is newly suggested passive safety system for coolant injection in the i-SMR. PECCS maintains the pressure and thermal equilibrium between the RV and the CV during an accident transient. The emergency depressurization valve (EDV) and the emergency recirculation valve (ERV) installed on the upper and side parts of the RV perform a natural circulation between the RV and the CV.

There are 2 EDVs and 2 ERVs. During normal operation, EDVs and ERVs are closed. When the PECCS is actuated after accidents, RV's high energy steam is discharged into the CV through EDVs. The steam is condensed by PCCS heat exchanger (HX), and condensed water accumulates in the annulus between the RV and CV. When hydraulic head of the CV condensate pool becomes higher than that of the RCS after the CV condensed water level becomes high enough, the condensed water is recirculated back to the RV through the ERVs. With the coolant circulation through the PECCS, residual heat of the core transfers to the emergency cooling tank (ECT) by PCCS HX.

2.2 Passive Containment Cooling System (PCCS)

PCCS uses condensation heat transfer with nearly pure steam on outer wall of HX to cool the CV. The PCCS HX is located in the upper part of the CV. It is connected to the ECT with pipes. The fluid condition on the outer wall of HX is expected as high-pressure and high-temperature steam around from 1 to 4 MPa.

PCCS has 2 trains with each of 100% capacity, and each train is composed of one HX, connecting pipes and ECT. Normally, the water continuously circulates inside the PCCS. Under an accident condition, the steam inside CV condenses on the outer wall of HX, and the water inside HX tubes evaporates and flows out to the ECT. The PCCS operates continuously by gravity until the ECT depletes.

2.3 Passive Auxiliary Feedwater System (PAFS)

PAFS uses a two-phase natural circulation to remove decay heat from the core with helical type SG. Horizontal heat exchanger is submerged in the ECT. Flow path of secondary side of the SG is switched to the connecting pipes of the PAFS HX when the PAFS is activated after accidents.

2 trains of PAFs are implemented and each train has a capacity of 100%. Each train is composed of one PAFS HX, connecting pipes, and ECT. Each train of PAFS is capable of bringing the RCS to safe shutdown condition within 36 hours and maintaining that condition at least for another 36 hours. During normal operation, there is no water flow inside the system. When the PAFS is actuated, steam is transferred to the HX and condensed, then recirculated back to the steam generator.

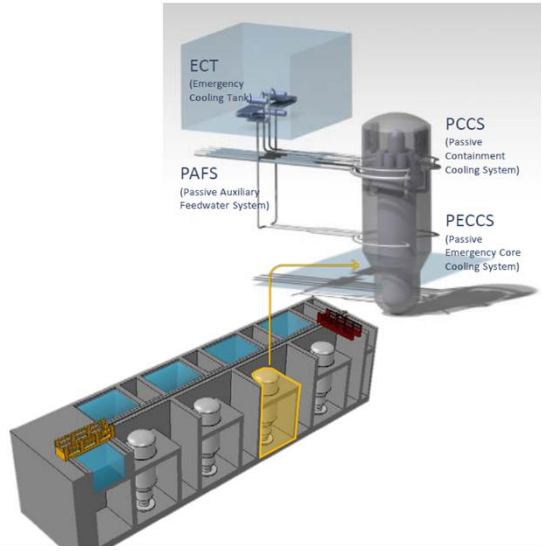

Fig. 1. Conceptual diagram of i-SMR [2].

3. Global Scaling Analysis

The scaling analysis method applied to the basic design of the integral effect test facility is the three-level scaling method [1]. In the case of an integral effect test facility, conditions of infrastructure must be considered. The conditions of infrastructure includes the space of the building where the integral effect test facility is installed and the electricity capability equipped in the building.

To reflect the characteristics of the prototype reactor as much as possible and maintain the configuration of the passive safety systems, the height scaling ratio and area scaling ratio were determined to be 1/2 and 1/49 of the prototype reactor, respectively. As a result, the global scaling ratio for volume of integral effect test facility was determined to be 1/98.

Fig. 2 presents a diagram of integral effect test facility. Components that cannot be placed according to the results of global scaling analysis are adjusted. It maintains integral type helical SG, but separates RCPs and CV. Because the CV of scaled down test facility cannot contain RV inside, and the location of RCPs is overwrapped with pressurizer. EDV and ERV will be changed as pipes to connect between the RV and the CV. The shape of the RV internal structure will be preserved as much as possible in consideration of the differential pressure for each section in the RCS. Passive safety systems, such as PECCS, PCCS, and PAFS, should appropriately reduce the driving force of natural circulation and gravity according to the global scaling ratios.

Physical variables can be derived according to the three-level scaling method [1]. The global scaling ratios of the main physical variables are summarized in Table 1. The basic design of the RCS, the secondary system, and the PSSs of the integral effect test facility will be carried out following the global scaling ratios, and boundary scaling analysis for mass and energy transfer and local scaling analysis to preserve local phenomena will be performed [3].

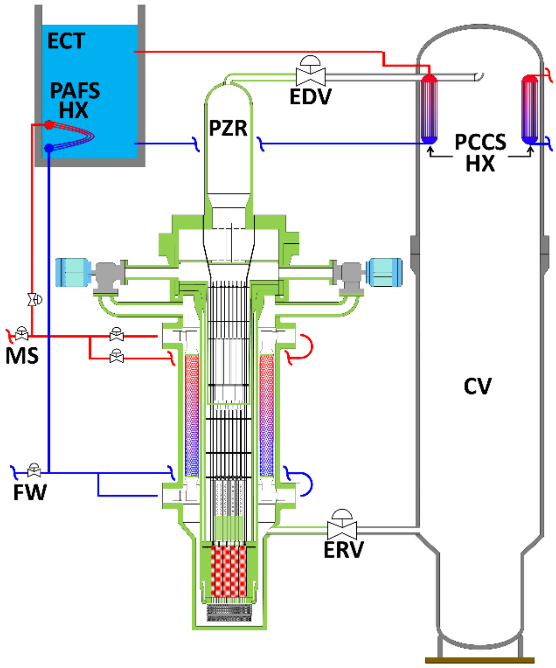

Fig. 2. Conceptual diagram of i-SMR integral effect test facility.

Table I: Global scaing ratios for i-SMR-IET.

Parameter	Symbol	Scale Ratios	
Length, height, elevation	l_{oR}	l_{oR}	$1/2$
Diameter	d_{oR}	d_{oR}	$1/7$
Area	α_{oR}	d_{oR}^2	$1/49$
Volume	v_{oR}	$l_{oR}\alpha_{oR}$	$1/98$
Core ΔT	ΔT_{oR}	1	1
Velocity	u_{oR}	$l_{oR}^{1/2}$	$1/\sqrt{2}$
Time	τ_R	$l_{oR}^{1/2}$	$1/\sqrt{2}$
Gravity	g_R	1	1
Power/volume	$\dddot{q}_R$	$l_{oR}^{-1/2}$	$\sqrt{2}$
Heat flux	$\ddot{q}_R$	$l_{oR}^{-1/2}$	$\sqrt{2}$
Core power	q_R	$\mathrm{\alpha_{oR}} l_{oR}^{1/2}$	$1/69.3$
Rod diameter (core)	$d_{rod,oR}$	1	1
No. of rods (core)	n_R	$\mathrm{\alpha_{oR}}$	$1/49$
Flow rate	$\dot{m}_R$	$\alpha_{oR} l_{oR}^{1/2}$	$1/69.3$
Subcooling, Δi	$\Delta i_{sub.R}$	1	1
Subcooling, ΔT	$\Delta H_{d,R}$	l_{oR}	$1/2$
Pump head	$\Delta H_{d,R}$	l_{oR}	$1/2$
Friction number	F_R	1	1
Pressure drop	ΔP_R	l_{oR}	$1/2$

4. Boundary Scaling Analysis

After determination of the global scaling ratio, the boundary scaling analysis should be conducted. It needs to consider the boundary conditions such as the break flowrate released from the RV to the CV, the condensation in the CV wall and the PCCS HX, and the recirculation flowrate injected back to the RV through the ERV. Natural circulation phenomena in the PECCS is shown in Fig. 3 and important physical variables for the boundary scaling analysis in the CV can be expressed in Eq. (1).

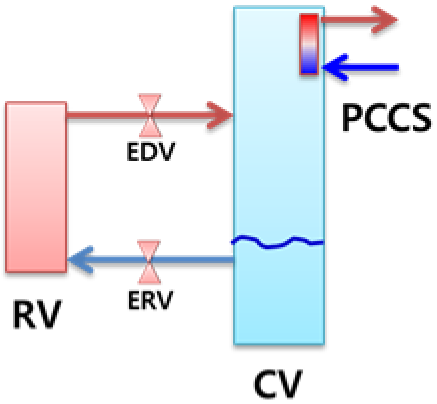

Fig. 3. Conceptual diagram of boundary scaling analysis for containment vessel.

$$\frac{dE}{dt} = (mh)_{EDV} - (mh)_{ERV} - Q_{HS} + Q_{Rad.} \quad (1)$$

Energy released from the RV through the EDV is presented as $(mh)_{EDV}$, and energy released or injected through the ERV is shown as $(mh)_{ERV}$. The Q_{HS} means the change in energy removed through the PCCS heat exchanger and wall condensation inside the CV. The $Q_{Rad.}$ is effect of radiation heat transfer from the high-temperature RV to the CV in normal operation.

4.1 Mass Flowrate through EDV and ERV

Because the EDV and ERV which are vessel-mounted valve cannot be simulated in the integral effect test facility, proper valves which can perform the similar function are necessary. Assuming an inadvertent operation of the ERV accident, the coolant discharged through the ERV at the beginning of the accident, recirculates back to the RV after condensed water level of the CV pool overcomes that of the RV.

In the prototype reactor, discharge and injection take place at one point on the ERV, but it is not possible to maintain a similarity in the integral effect test facility. Because the thermal-hydraulic phenomena in break simulation, such as a choking, is different with a safety injection using difference between hydraulic head of the CV and RV, the ERV should be divided into two different pipes.

4.2 Condensation on CV wall and PCCS HX

Steam condenses on the CV wall and outside of the PCCS HX, and temperature of cooling water injected from the ECT increases as passing through inside of tube as shown in Fig.3. The energy which is dissipated by condensation (Q_{HS}, heat sink in the CV) of the CV wall and the PCCS HX should be considered.

4.3 Radiation Heat Transfer

Radiation heat transfer effect ($Q_{Rad.}$) from the high temperature RV wall to the low temperature CV wall should be considered in the integral effect test facility. Because the initial wall temperature of the CV can affect condensation in the beginning of the accident. Therefore, the initial wall temperature of the CV will be increased using tracing heater to simulate the effect of radiation heat transfer in normal operation condition.

5. Conclusions

The global scaling ratio of the i-SMR integral effect test facility was determined, and the concerns for boundary scaling analysis of the steel containment vessel were described. Based on the result of global scaling analysis, main components was arranged and the conceptual diagram of the integral effect test facility was prepared. Boundary scaling analysis of the energy transfer in the CV was considered in terms of mass flowrate through EDV and ERV, condensation on CV wall and PCCS HX, and radiation heat transfer. The results of global scaling and boundary scaling analysis will be applied to design of the i-SMR integral effect test facility and local scaling analysis will be conducted for similarity for local phenomena.

ACKNOWLEDGMENTS

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REFERENCES

[1] M. Ishii et al., “The three-level scaling approach with application to the Purdue University Multi-Dimensional Integral Test Assembly (PUMA)", *Nuclear Engineering and Design*, 186, 177–211, 1983.
[2] J. H. Yang et al., “Scaling analysis and basic design of metal containment vessel in i-SMR integral effect test facility", Korean Society for Fluid Machinery Winter Meeting, Jeju, Korea, Nov. 29 – Dec. 1, 2023.
[3] Choi et al., “Scaling Analysis Report of the ATLAS Facility”, KAERI/TR-5465-2014, Korea Atomic Energy Research Institute, 2014.