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Preliminary Analysis of Scale Effect on Heat Removal Mechanism in Reactor Cavity Cooling System

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INTRODUCTION

The Reactor Cavity Cooling System (RCCS) maintains the concrete temperature below the design limit during normal operation. In an accident condition, the RCCS removes the residual heat, which amounts to 0.3 to 0.6 % of the full reactor power without additional electricity or water coolant supply. The criteria for the RCCS design are determined from the temperature limit of the reactor vessel material and concrete. Its governing heat transfer modes are the radiation across the reactor cavity and the buoyancy-driven internal convection in the riser ducts installed around the reactor cavity [1].

KAERI has conducted research on experimental verification of the RCCS coolability to make sure of the inherent safety of a VHTR [2]. A difficulty in the full-scale test of a huge RCCS requires a reduced scale test, and the scaling is imperative in this case. Since the radiation is independent on the scale effect and the convection is dependent on the scale effect, there is no scaling analysis methodology for similarity in both radiation and buoyance-driven internal convection. Therefore, the scaling criteria have to be developed to choose the most dominant non-dimensional parameters. ANL and the University of Wisconsin are performing 1/2-scale [3] and 1/4-scale tests [4] for GA-designed MHTGR, respectively. Bae et al. [5] proposed two cases to simulate the cases with the radiation and buoyancy-driven duct flow, respectively.

This paper presents the GAMMA+ analysis about the scale effect on RCCS heat removal mechanism to check the validity of Bae et al.'s [5] scaling analysis.

SCALING ANALYSIS FOR RCCS

An earlier scaling analysis [6] for the natural circulation of a PWR was based on the Richardson number without considering the radiation, which is the dominant heat removal mechanism in the RCCS. The RCCS consists of the reactor cavity, risers, and connecting ducts including a downcomer and chimneys. The reactor cavity and riser are isolated by the riser wall, where only heat is exchanged. Fig. 1 shows a schematic diagram of the heat removal mechanism for a RCCS.

The governing heat transfer modes in the RCCS heat removal mechanism are the radiation heat transfer from the reactor vessel and the internal convection by the buoyance-driven air flow in the riser duct.

It is very unlikely that there exists conspicuous dimensionless parameters that cover thermal behavior in both heat transfer modes. Bae et al. [5] suggested that the Planck number is a dominant dimensionless parameter in the reactor cavity, and the Richardson number in the riser. The Planck number and Richardson number are defined through the following equations.

$$Pl = \frac{k\Delta T}{W q''_W} \qquad (1)$$

$$Ri = \frac{g\beta\Delta T l}{u^2} \qquad (2)$$

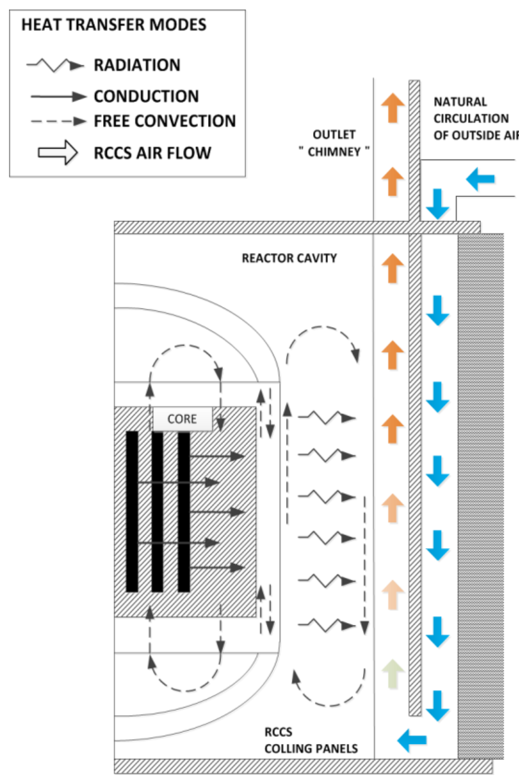


Fig. 1 Heat Removal Mechanism in RCCS

Their scaling analysis was performed based on the two parameters. For convenience of the experiment and the analysis of its results, the ratios of the temperature and temperature difference were set as $T_{oR}=1$ and $\Delta T_R=1$. Table 1 summarizes their results. All ratios of the parameters were obtained from the maintenance of the above dimensionless parameter similarities and energy balance in the riser. It was assumed that the convection heat transfer in the riser is fully developed internal turbulent convection, and the only heat transfer mode in the cavity is the radiation between the reactor vessel and the riser wall.

Table I Scaling Analysis Results [5]

Ratio of variables	Ratio in terms of length scale		Rationale
	$Ri_R = 1.0$	$Pl_R = 1.0$	
$\Delta T_{out-in\,R}$	1	1	Enforced
u_R	$l_R^{0.5}$	l_R	
q''_{wR}	$l_R^{-0.5}$	1	
$(\Delta T_{W-F})_R$	$l_R^{-0.9}$	$l_R^{-0.8}$	$(q''_w / h)_R$
t_R	$l_R^{0.5}$	1	$t = l/u$
$(H_{upperplenum})_R$	$l_R^{0.5}$	$l_R^{0.25}$	From jet theory

GAMMA+ MODEL

In the 1/4 scale test facility, the height is a 1/4 of the PMR200 reactor cavity height, and the distance between the reactor vessel and the risers remains the same as the PMR200. Fig. 2 shows the input model and nodalization for GAMMA+ with various cavity heights.

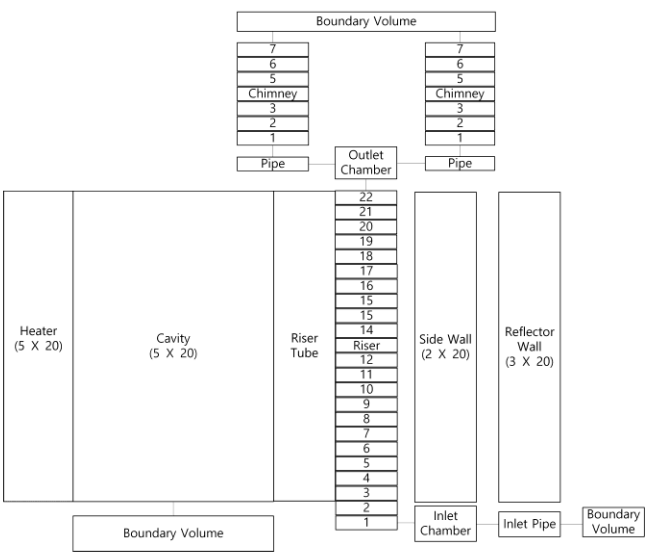


Fig. 2 GAMMA+ Nodalization

The fluid model for the buoyancy induced air flow in the riser duct consists of a flow from the inlet boundary, two inlet pipes, the inlet chamber, riser tubes, the outlet chamber, two outlet pipes, and two chimneys through to the outlet atmospheric boundaries. In this analysis, the inlet boundary condition is the constant mass flow rate used to estimate the applicability of the GAMMA+ heat transfer model and the scale effect on the RCCS heat transfer mechanism. This input model has a two-dimensional fluid model for a cavity with atmospheric conditions.

The solid model consists of a heated surface (representing the reactor vessel), six riser tubes, the side walls, and the reflective wall. The heated surface was modeled as a 2-D plate. The riser walls were modeled as hypothetical 3-D circular pipes by considering the radiation and convection heat transfer of the rectangular duct. The duct thickness is 5 mm. The cavity is encased by a heated surface, two side walls, and a reflective wall. The walls were modeled as 2-D plates. Their thickness was 30 mm. RCCS riser walls were categorized into two outer risers and four inner risers to calculate the view factors, as shown in Figure 3. It was assumed that there is no length-scale effect on the view factors.

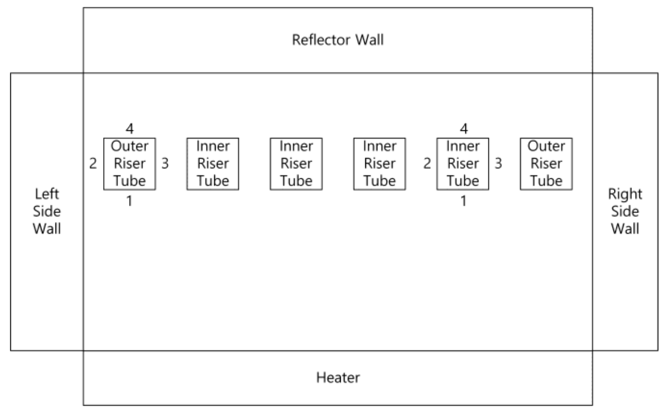


Fig. 3 Cross Sectional View of Risers & Cavity

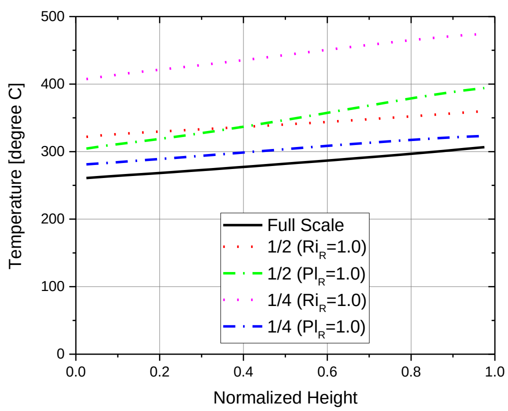
Table II shows the calculation cases based on Table I. In the case of two scaling criteria, the GAMMA+ analysis was performed to assess the scale effect on the heat transfer mechanism in RCCS. Churchill & Chu's [6] correlation was used for the convective heat transfer coefficients on the heater, side walls, reflector wall, and outer surfaces of the riser tube. The convective heat transfer correlation by considering the mixed convection was used for the convective heat transfer in the riser ducts.

Table II Scaling Analysis Results [5]

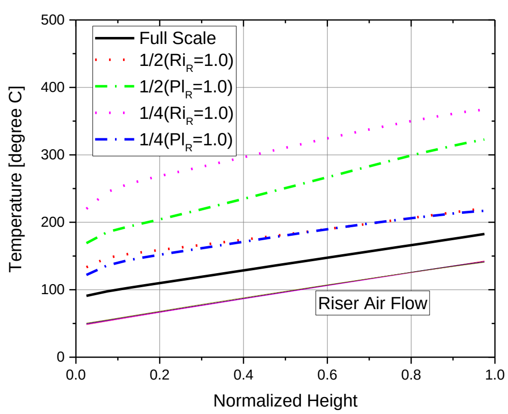
Variables	Full Scale	1/2 Scale		1/4 Scale	
		Ri_R=1	Pl_R=1	Ri_R=1	Pl_R=1
l [m]	16 m	8 m	8 m	4 m	4 m
ΔT_{out-in} [℃]	98℃	98℃	98℃	98℃	98℃
T_{in} [℃]	44℃	44℃	44℃	44℃	44℃
$\dot{m}$ [kg/s]	0.249	0.176	0.124	0.124	0.063
q'' [kW/m^2]	2.4	3.39	2.4	4.8	2.4

RESULTS AND DISCUSSION

A GAMMA+ analysis was conducted to check the validity of the scaling laws in the previous sections. Figure 3 shows the temperature profiles of the heater and riser tube wall as a function of the normalized axial position. In the case of $Ri_R=1$, Tables I and II show the velocity and heat flux are proportional to $l_R^{0.5}$ and $l_R^{-0.5}$, respectively. The heater surface temperature values at the 1:4 scale case of $Ri_R=1.0$ are higher than those at any other cases. In the case of $Pl_R=1$, Tables I and II show that the heat flux is always equal to that at the full-scale case and the velocity is proportional to l_R. However, the heater temperature values in the case of 1/2 scale are higher than those of a 1:4 scale. This trend cannot be obtained from Table I. The sudden increase of the riser duct temperature in the cases of 1:1 and 1:2 results on a height-directional temperature gradient. In the case of 1:4, there is no sudden increase in the riser duct temperature because of the axial conduction. Figure 3 shows that the heater temperature $Pl_R=1$ case with a 1:4 scale is the closest to that at the full scale condition.



(a) Heated Surface Temperature

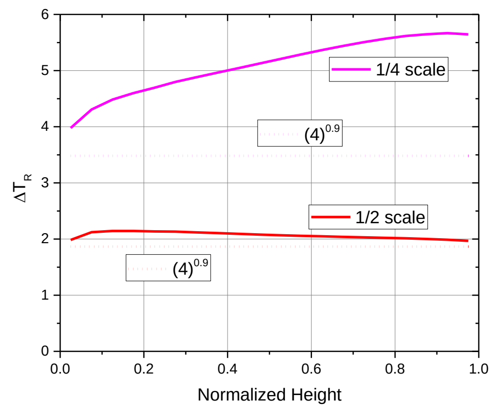


(b) Riser Wall Temperature & Air Flow Temperature

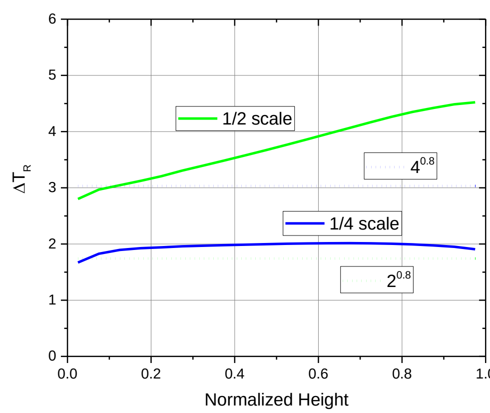
Fig. 3 Temperature Profiles of Heated Surface, Riser Wall, and Riser Duct Air

Generally, the scale-down ratio decreases the mass flow velocity in the riser duct and the convective heat transfer coefficient in the riser duct. Therefore, the temperature profiles of the riser wall and the heated surface in the 1/2 scale always has to be between the temperature profiles in the full scale and the 1/4 scale. But GAMMA+ analysis results show that the temperature profiles of the riser wall and the heated surface in the 1/2 scale are higher than those in the 1/4 scale at the $Pl_R=1.0$ condition.

Figures 4 show the relative temperature difference between the riser duct and riser air alongside the normalized axial position. If the convective heat transfer is a fully developed forced turbulent heat transfer, the ratios of the temperature difference values are the same as those in Table I. If the ratio is larger than that of Table I, the mixed convection decreases the convective heat transfer coefficient in the riser duct. If the ratio is smaller than that of Table I, the mixed convection increases the convective heat transfer coefficient in the riser duct.



(a) $Ri_R=1.0$



(b) $Pl_R=1.0$

Fig. 4 Temperature Difference Profiles between Riser Air and Riser Wall

In the case of $Ri_R=1.0$, the convective heat transfer coefficient of 1/2 scale is close to the fully developed forced convective heat transfer. The convective heat transfer coefficient of 1/4 scale is always lower than the fully developed force turbulent convective heat transfer coefficient. Its decreased effect of the mixed convection increases as the riser air flows. In the case of PlR=1.0, the impairment of the convective heat transfer is observed at the 1/2 scale. On the contrary to 1/2 scale, the mixed convection enhances the heat transfer at the 1/4 scale. The heat transfer coefficients at the 1/4 scale are always rather larger than those at the 1/2 scale.

Fig. 5 shows theoretical prediction [7] of general features of mixed convection heat transfer in vertical tubes with the GAMMA+ analysis condition. The mixed convection effect can be generalized to provide the following simple equation of the manner in which the ratio of buoyancy-influenced to the buoyancy-free convective heat transfer coefficients varies with the buoyancy parameter $Gr/Re^{2.7}\,Pr^{0.5}$ [7]

$$\frac{h}{h_f} = \left| 1 - \frac{10^4 Gr}{\mathrm{Re}^{2.7}\,\mathrm{Pr}^{0.5}} \right| \qquad (3)$$

In the full-scale case, the heat transfer regime is always a pure forced turbulent convection. In the scale-down cases, the convection in the riser duct is the turbulent mixed convection. The thermal impairment is predicted in all scale-down cases except the case with 1:4 and $Pl_R=1.0$. Therefore, the mixed convection in the riser duct is very important to extrapolate the heat removal behavior of RCCS through the scale-down test, because the Reynolds number is not large enough to presume the pure forced turbulent convection in the riser duct.

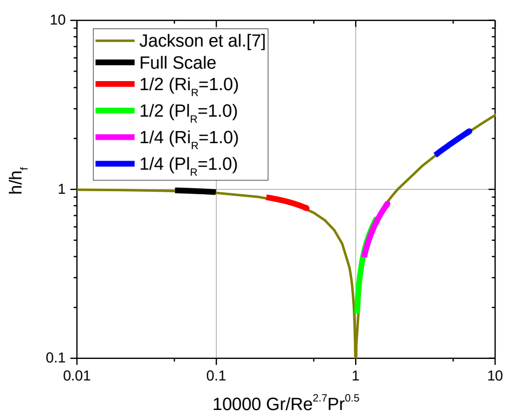


Fig. 5 Theoretical prediction of General Features of Mixed Convection Heat Transfer in Vertical Tubes with the GAMMA+ Analysis Conditions

CONCLUSION

In this paper, a GAMMA+ analysis was conducted to check the validity of the scaling law for the RCCS heat removal mechanism. The analytical results show that the scaling based on the Planck number is useful to extrapolate the reactor vessel temperature from the scale-down test results.

Because the heat transfer regime of the scale down tests is different from that of the full scale condition, it requires a careful approach to analyze the convective heat transfer in the riser duct.

In the present study, the comparison among the test results at ANL, KAERI, and UW will provide the information to develop and confirm the scaling criteria selected for an RCCS coolability demonstration. In particular, Seoul National University will develop a mixed convection heat transfer correlation for the riser duct under various RCCS experimental conditions.

NOMENCLATURE

g	gravity
Gr	Grashof number based on the riser duct hydraulic diameter
H	height of upper plenum
h	heat transfer coefficient in the riser duct
k	thermal conductivity of riser air
l	heated length, cavity height
$\dot{m}$	air mass flow rate in the riser duct
Pl	Plank Number
q''	heat flux on the heater
Re	Reynolds number
Ri	Richardson number
T	temperature
t	time
u	riser air flow velocity
W	radiation distance between heater and riser wall

Greek Letter

β	thermal expansion coefficient of riser air

Subscript

F	air flow in the riser duct
f	forced convection
in	inlet of the riser
out	outlet of the riser
R	ratio between model and prototype
W	wall of the riser duct

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