Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2018

Comparative Study between Two Reduced-scale Test Results for Air-Cooled RCCS Scaling Law

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1. Introduction

The air-cooled Reactor Cavity Cooling System (RCCS) is a key passive safety feature in a High Temperature Gas-cooled Reactor, because it can be operated without additional electricity and water coolant supply [1]. In the accident condition, it removes the residual heat, which amounts to 0.3~0.6 % of the full reactor power. It maintains the concrete temperature below the design limit during the normal operation. Its governing heat transfer mechanisms are the radiation across the cavity and the buoyancy-driven air flow in the riser ducts around the cavity as shown in Figure 1.

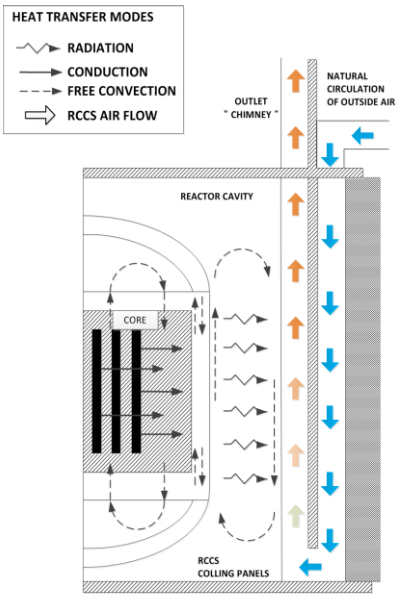


Fig. 1 Heat Transfer Mechanisms for RCCS

The chimney of the air-cooled RCCS is too high to perform a full scale-test, so a reduced-scale test is necessary to verify its performance. Since the radiation is independent of the scale effect and the convection is dependent, there is no scaling methodology satisfying similarities in both radiation and convection. Therefore, the scaling law for air-cooled RCCS has to be developed to choose the most dominant non-dimensional parameters. Korea Atomic Energy Research Institute (KAERI) [2] and Argonne National Laboratory (ANL) [3] performed the tests for the comparison with two reduced-scale test facilities to develop the scaling methodology. KAERI and ANL's test facilities are NAtural Cooling Experimental Faclity (NACEF) [2] and Natural convection Shutdown heat removal Test Facility (NSTF) [3], respectively. This paper summarizes the collaboration study between KAERI and ANL to develop the scaling law for air-cooled RCCS.

2. Methods and Results

2.1 Scaling Law & Test Matrix

An earlier scaling analysis [4] for natural circulation system was based on the Richardson number without considering radiation. Bae et al. [5] proposed two cases simulating the radiation across the cavity and the buoyancy-driven duct flow in the riser, respectively. In the case of radiation, the Plank number with width between reactor vessel and riser walls is dominant dimensionless parameter in the reactor cavity, and the Richardson number with the heated height in the riser.

Table 1 summarizes the scaling analysis results. All the ratios of the parameters were obtained to maintain the similarities of the aforementioned dimensionless parameters and energy balance in the riser duct flow.

Table 1 Scaling Analysis Results [5]

Ratio of variables	Ratio in terms of height scale		Rationale
	$Ri_R = 1.0$	$Pl_R = 1.0$	
T_R	1	1	Enforced
$\Delta T_{out-in\,R}$	1	1	Enforced
Ri_R	1	l_R^{-1}	$Ri = \frac{g\beta\Delta Tl}{u^2}$
Pl_R	$l_R^{0.5}$	1	$Pl = \frac{k\Delta T}{Wq''_w}$
u_R	$l_R^{0.5}$	l_R	
q''_{wR}	$l_R^{-0.5}$	1	
h_R	$l_R^{0.4}$	$l_R^{0.8}$	$(u_R)^{0.8}$
$(\Delta T_{W-F})_R$	$l_R^{-0.9}$	$l_R^{-0.8}$	$(q''_w / h)_R$
t_R	$l_R^{0.5}$	1	$t = l/u$
$(H_{upperplenum})_R$	$l_R^{0.5}$	$l_R^{0.25}$	From jet theory

Details of the facility designs, test matrix, and test results for the comparative study were outlined in Table

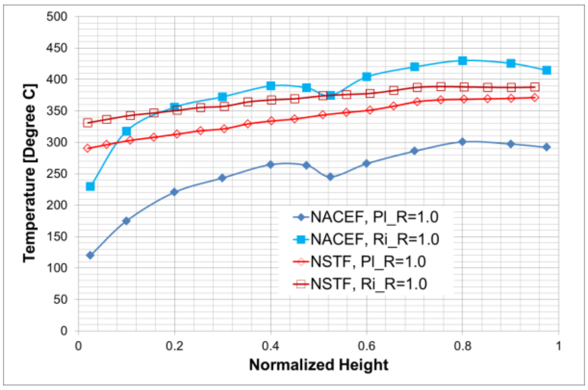
2. The reference condition for the test matrix was obtained from the results of analysis [3], conducted using a system code GAMMA+ for the low pressure conduction cooling event in PMR200. The test matrix was founded to validate the suggested scaling laws with constant heat flux. Two test facilities differ in the ratio between the heated riser height and total height. Both facilities have a similar cross-sectional dimension of the riser duct and the same heated plate per a riser duct. Because of the different facility height ratio and the weather condition between KAERI and ANL, the test matrix was focused on the scaling effect of the heated riser length with constant heat flux. The test period was 2 hours for the steady-state target power and flow rate. The target power was not the electric power from heaters but the hear removal rate through the riser duct flow. The heat removal rates were calculated from the measured mass flow rate in the riser duct and the temperature difference between the inlet and outlet of the riser duct. The inlet temperature of the outlet chimney was defined as the outlet temperature of the riser duct with considering the thermal mixing at the outlet plenum.

Table 2 Summary of RCCS Facilities, Test Matrix and Test Results for Comparative Study
(p: test plan, r: test results)

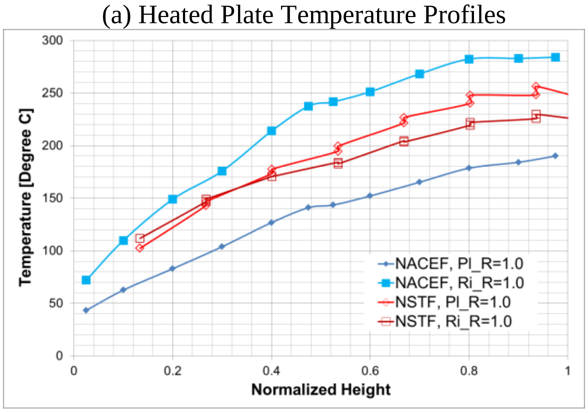
	PMR 200	ANL (NSTF)		KAERI (NACEF)	
Total Height [m]	55.2	26.2		13	
Total Riser Height [m]	17	7.5		4.5	
Heated length of Riser [m]	17	6.82		4.05	
Number of Ducts	220	12		6	
Flow Area of a Riser Duct [cm^2]	4×24	4.41×24.47		4×24	
Thickness of Riser Duct [mm]	5.0	4.41		5.0	
Total Width of Heated Plate [m]	-	1.29		0.64	
Width of Heated Plate per duct [m]	-	0.108		0.107	
Length Ratio	1.0	0.401		0.238	
Scaling Analysis	-	Ri_R	Pl_R	Ri_R	Pl_R
Mass Flow per duct [g/s]	47	p: 30 r: 30	p: 19 r: 19	p: 23 r: 23	p: 11 r: 11
ΔT between Inlet & Outlet of Riser[℃]	98	p: 98 r: 94	p: 98 r: 97	p: 98 r: 99	p: 98 r: 100
Heat Removal Rate per Duct[kW]	4.67	p: 3.0 r: 2.8	p: 1.9 r: 1.9	p: 2.3 r: 2.2	p: 1.1 r: 1.1

2.2 Comparison with NACEF & NSTF Test Results

Figures 2 show the comparison between the test results from KAERI and ANL facilities at Ri_R=1.0 & Pl_R=1.0 conditions. The comparison for Pl_R=1.0 case indicated that the mixed convection in the riser duct should be considered in extrapolation of the heat removal behavior of RCCS from the scale-down test results. In addition, the scale effect on the natural convection in the cavity had to be estimated to extrapolate the heated panel temperature profile from the scale-down test results. The governing characteristic length for the cavity convection had to be determined from the comparative study between the test results and the system code analysis results.



(a) Heated Plate Temperature Profiles



(b) Riser Front Wall Temperature Profiles

Fig. 2 Comparison with Test Results

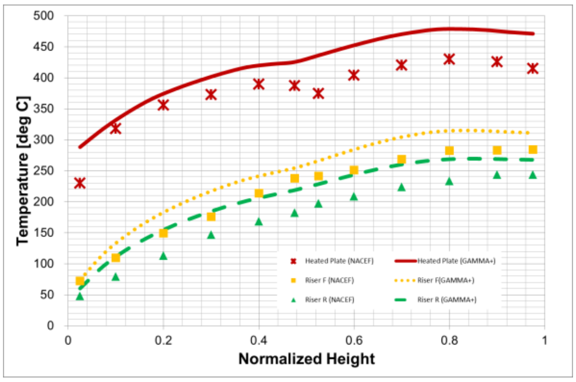
Ri_R=1.0 case of NSTF is expected to be mainly forced convection with some potential mixed convection effects, while the other test cases will have more significant mixed convection impacts. Since the previous convection flow regime map and mixed convection correlation were developed based on a circular pipe flow test results, Shin et al. [6] performed the separate test for the riser convection.

2.3 Separate Test for Riser Duct Convection

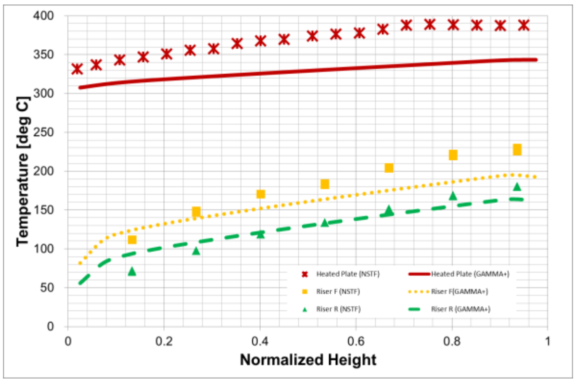
Shin et al. [6] designed and constructed a facility for the heat transfer experiments of vertical upward air flow, purely driven by buoyancy due to heat addition from wall, inside a single riser. 47 experimental runs, including the test matrix conditions from NSTF and NACEF, were conducted. Heat transfer rate decreased with increasing buoyancy around the specific conditions. Two new correlations for turbulent mixed convection inside the vertical rectangular duct were developed by fitting the experimental data: one for temperature difference [6] and the other for heat flux [7]. The average differences between the developed correlations and the experimental data were 4.34% and 5.69 %, respectively. The new correlations based on temperature difference and heat flux can be adopted for the RCCS system analysis and the scaling analysis, respectively.

2.4 Post-test Analysis

Kim et al. [8] conducted post-test analysis using GAMMA+ to simulate KAERI and ANL test results. The various mixed convection correlations for the riser duct flow and natural convection correlation in the cavity were employed to simulate the test results. The mixed convection appeared in the riser duct seems to be the most important phenomenon to be considered in a simulation of the integral test results using a system analysis code. Using the height-based enclosed cavity convection correlation for the cavity convection and the correlation developed based on the Shin et al.'s experimental data [6], the heated plate temperature were predicted within ±10% error range at all test conditions at the NSTF and NACEF. Figures 3 show the comparison with the simulated and measured temperature profiles at Ri_R=1.0 cases from NACEF & NSTF. The differences between them are reasonable, considering the non-uniform flow distribution in the riser ducts, the uncertainties of the developed correlations and the heat removal rate.



(a) NACEF



(b) NSTF

Fig. 3 Test Results & GAMMA+ Analysis Results for Ri_R=1.0 Cases

Based on the GAMMA+ analysis, the computational fluid dynamic (CFD) analysis was focused on the heat transfer phenomena in the riser duct. Kim et al. [7] used the in-house CFD code, and performed several trial calculations to select a suitable turbulence model for simulating KAERI and ANL test results. Commercial CFD codes were used to simulate the entire system. ANL successfully simulated the Ri_R=1.0 case of NSTF, using the Realizable two layer k-ε model (RKE model). In the Pl_R=1.0 case of NSTF, with the additional employment of the algebraic heat flux model, the simulated temperature profile matched the measured temperature profile well in shape, but was significantly higher in magnitude.

2.5 Improved Scaling Law

All the results show that the mixed convection in the riser duct is very important to extrapolate the thermo-fluid behavior from the test results. Since the heat transfer coefficient in the riser did not show any monotonic trend, the heat transfer coefficients ratio cannot be expressed by the length ratio as Table 1. The buoyancy number based on the heat flux is used to consider the scale effect on the mixed convection. From Table 1, the ratio of the buoyancy number between model and prototype becomes

$$\left(Bo_q\right)_R = \left(\frac{Gr_q}{Re^3\,Pr^{0.5}}\right)_R = \frac{q''_R}{u_R^3}$$

The ratio of the buoyancy number can be expressed by the length ratio from the test conditions from Table 1. The ratios for Ri_R=1.0 and Pl_R=1.0 are proportional to l_R^{-2} and l_R^{-3}, respectively. Figure 4 shows the predicted mixed convection effect of the calculated $\left(Bo_q\right)_R$ by turbulent mixed convection based on the heat flux [7].

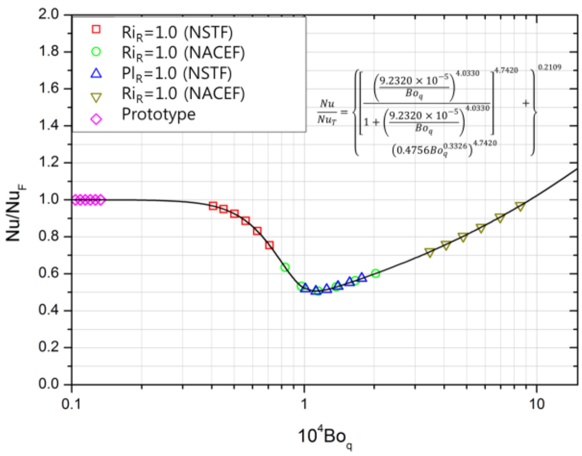


Fig. 4 Mixed Convection Effect of the Calculated Buoyancy Number Based on the Shin et al.'s Correlation [7]

Additionally, the post-test analysis results show that the cavity fraction across the cavity in the scale-down tests is smaller than that in the prototype condition. The higher wall temperature results in the larger radiation fraction on the heated plate. Therefore, the assumption that the cavity convection fraction on the heated plate in the scale-down test is the same as that in the prototype is conservative enough to extrapolate the heated wall temperature. Table 3 shows the improved scaling laws for air-cooled RCCS with considering the mixed convection effect in the riser duct and extrapolating the reactor vessel temperature. The function of the buoyancy number is shown in Figure 4.

Table 3 Improved Scaling Law

Ratio of variables	Ratio in terms of height scale		Rationale
	$Ri_R = 1.0$	$Pl_R = 1.0$	
T_R	1	1	Enforced
$\Delta T_{out-in\,R}$	1	1	Enforced
Ri_R	1	l_R^{-1}	$Ri = \frac{g\beta\Delta T l}{u^2}$
Pl_R	$l_R^{0.5}$	1	$Pl = \frac{k\Delta T}{Wq''_w}$
u_R	$l_R^{0.5}$	l_R	
q''_{wR}	$l_R^{-0.5}$	1	
$(Bo_q)_R$	l_R^{-2}	l_R^{-3}	
h_R	$l_R^{0.4} f(Bo_{q,m})$	$l_R^{0.8} f(Bo_{q,m})$	$(u_R)^{0.8}$
$(T_W - T_F)_R$	$l_R^{-0.9} f(Bo_{q,m})^{-1}$	$l_R^{-0.8} f(Bo_{q,m})^{-1}$	$(q''_w / h)_R$
$(T_h^4 - T_W^4)_R$	$l_R^{-0.5}$	1	Radiation dominant $q''_w \propto q''_{rad}$
t_R	$l_R^{0.5}$	1	$t = l/u$
$(H_{upperplenum})_R$	$l_R^{0.5}$	$l_R^{0.25}$	From jet theory

3. Conclusions

The test matrix for the comparative study was focused on the scale effect of the heated riser height. Comparison with the test results and the post-test analysis results showed that the mixed convection in the riser duct and the radiation similarity were very important to estimate the scale effect. It is recommended that the buoyancy number based on the heat flux is used to consider the mixed convection effect for the air-cooled RCCS scaling law. The improved scaling law can be applied to demonstrate the passive safety of the air-cooled RCCS.

ACKNOWLEDGMENTS

This study was supported by Nuclear Research & Development Program of the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP).
(2014M2A8A2074090 & 2017M2A81014758).

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