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The Results of the Fourth NACEF Test for the RCCS Verification

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1. Introduction

KAERI has been conducting natural convection tests in the NACEF (Natural Cooling Experimental Facility) to verify the proper functioning of the inherent passive natural cooling in the reactor cavity cooling system (RCCS) in the PMR200, a VHTR under development by the institute. The RCCS is the only ex-vessel passive safety system that should ensure the safety of the PMR200, and its performance needs to be verified [1, 2]. For the difficulty of the full-scale test, a 4/17-scale RCCS facility, NACEF, was constructed at KAERI and a few tests have satisfactorily been performed [3-6]. Here described are the results of the fourth test which aims at the evaluation of heat transfer in the RCCS mockup with the scaled air velocity in the risers and the scaled air temperature increment during passing through the risers, when the Planck number remains the same as the prototype.

2. Description of Test Facility

Fig. 1 shows the natural cooling phenomena in the air-cooled RCCS. The decay heat during an accident transfers from the fuels to the graphite block by conduction and in turn to the reactor vessel by radiation and convection. The reactor vessel needs to be cooled down below the design temperature to prevent its failure by the natural cooling of the RCCS heated mainly by radiation from it.

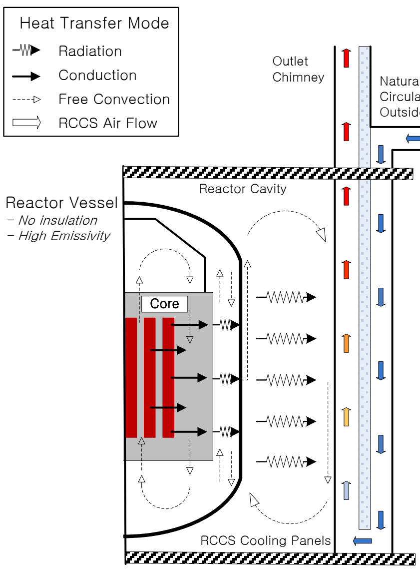

Fig. 1. Natural cooling phenomena in the air-cooled RCCS

A 4/17-scale mockup of the RCCS (NACEF) was designed and constructed at KAERI, of which the height is 4/17 of the prototype and the distance from the reactor vessel to the RCCS risers remains the same as that in the PMR200 [3-6]. Figs. 2 and 3 show the photograph of the NACEF (chimneys are not shown) and the cross-sectional view of its test section, respectively. Six riser tubes were provided in the NACEF compared to 220 in the prototype.

Fig. 2. Photograph of the NACEF

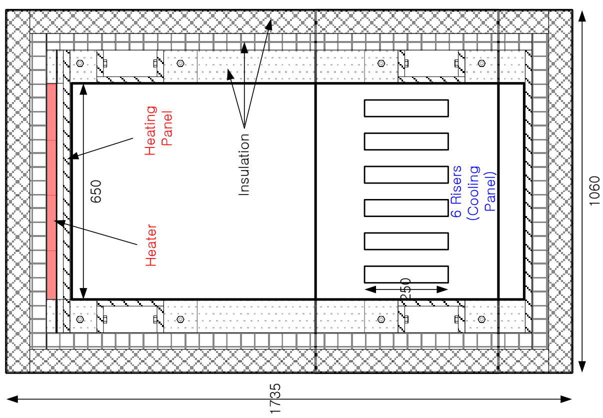

Fig. 3. Cross-sectional view of the NACEF test section

The hot panel, the mockup of the reactor vessel, is 4 m high and 0.65 m wide, and two chimneys are 8 m high. The ceramic mold heaters of 52 kW are equipped on the hot plate. Two flow meters of 0 ~ 1500 Nm^3/hr are installed in the downstream of the two chimneys of 0.4 m in diameter. Table I shows the instrumentations installed in the NACEF.

Table I: Instrumentations in the NACEF

Sensor	**Spec.**	**Manufac-turer**	**Model**	**No.**
Flow meter	0 ~ 1500 Nm^3/hr	SAGE	SRP-07	2
Diff. P	0 ~ 625 Pa	Rosemount	3051S	2
TC	0 ~ 1200 °C	OMEGA	0.5 mm K-type	174
Static P.	-1 ~ 1 barg	KELLER	PR-23RY	1
Velocity (Pitot tube)	0 ~ 44 m/s	DWYER	160F	1
Diff. P	0 ~ 25 Pa	DWYER	MS-121	1

3. Results of the Fourth Test

The fourth natural cooling test was performed in the NACEF. The purpose of this test is the evaluation of the scaling effect of the PMR200 RCCS. The scaled factors are first the buoyancy driven natural cooling air velocity in the risers and second the air temperature increment during passing the risers. The buoyancy driven air velocity in the riser and the air temperature increment during passing the riser were calculated by using the GAMMA+ code [7, 8] for the LPCC (Low Pressure Conduction Cooling) in the prototypic PMR200. However, these values would be distorted in the NACEF which is 4/17-scale of the PMR200 RCCS due to the difference in the height. The air velocity (also, mass flow rate) estimated in the 4/17-scale NACEF from a scaling analysis [2] is 4/17 of the prototype, $v_R = l_R = 4/17$ (the same as the scale) when the Planck number remains the same in both scales and the air temperature increment is the same as the prototype. When the ratio of the Planck number (Pl_R) of this mockup to the prototype is unity, the heat flux in the mockup needs to be the same as the prototype, $q''_R = 1$. Based on this similarity, the test conditions have been determined as shown in Table II. The measured values in the test are also presented.

Fig. 4 shows the applied electrical power input (P-PS) and the removed power (P-FM) by risers measured by a flow meter. In the early stage, the power input was increased to 10.9 kW in stepwise manner and then to 13.6 kW. At 48,100 s, it was decreased to 10.9 kW and then to 10.1 kW at 53,300 s to obtain the pre-determined heat removal rate of 6.7 kW, which was equivalent to the panel area (2.6 m^2) times the heat flux of 2.57 kW/m^2. The heat removal rate was calculated from the measured flow rate and air temperature increment (100°C) during passing the risers which was the primary requirement in the test. Beforehand, the total loss coefficient across the whole air flow passage was set by the damper adjustments to 31.0 which was close to the required value, 33.8. This value could be calculated from the natural convection air flow rate and total pressure drop across the whole flow passage. The removed power and heat flux by the risers due to natural convection in the test were estimated to be 6.8 kW and 2.61 kW/m^2, respectively.

Table II: Test conditions and measured values

	PMR200 values	Scaled values	Measured values
ΔT_{riser} (°C)	99	99	100
q“ (kW/m^2)	2.57	2.57	2.61
Mass flow rate per riser (kg/hr)	170	40	41
Pl_R	1	1	~ 1
Total loss coef. based on a riser	7.96	33.8	31.0

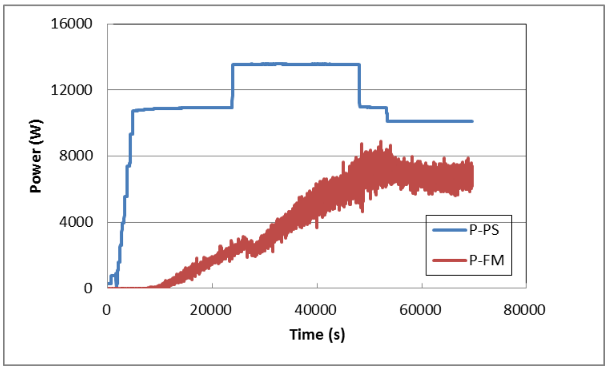

Fig. 4. Applied power (P-PS) and removed power (P-FM)

Fig. 5 shows the temperature distribution in the hot and cold panels and in the riser walls facing the hot and cold panels at a quasi-steady state, 69,000 s. The dip of the hot panel temperature at 2 m elevation is caused by heat loss to the flanges which has no heaters equipped.

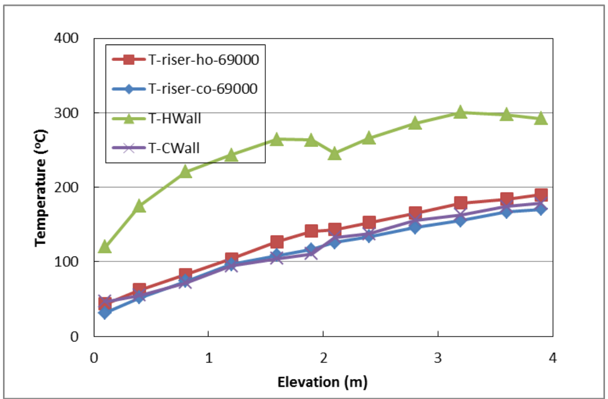

Fig. 5. Temperature distribution in test walls (t = 69,000 s)

Fig. 6 shows the mass flow rate measured in the north chimney by a flow meter. In the previous test [4], the air flow was found to have entered from the north chimney and escaped to the south chimney along with the air flow induced by natural convection from the risers. Therefore, the south chimney was closed and only the north chimney was opened from the beginning of the test in order to prevent the flow reversal from a chimney. The mass flow rate caused by natural convection was measured. At 26,000 s and 54,000 s, the damper was adjusted to obtain the required air velocity and air temperature increment in the riser tubes and then maintained at the position. The mass flow rate in the 6 risers was 245 kg/hr, which was equivalent to 41 kg/hr for a riser.

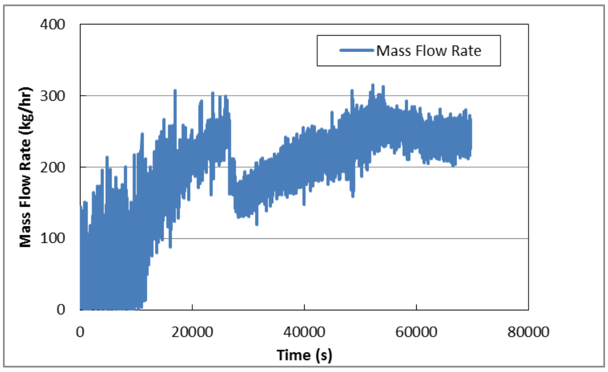

Fig. 6. Mass flow rate in the north chimney

Fig. 7 shows the air velocity induced by natural convection. The velocity measured by a Pitot tube installed in the lower section of a riser (Vel-PT) is in a good agreement with that calculated from the flow rate measured by a flow meter (Vel-FM). Both values estimated at the riser entrance temperature (15 ℃) were about 1.0 m/s.

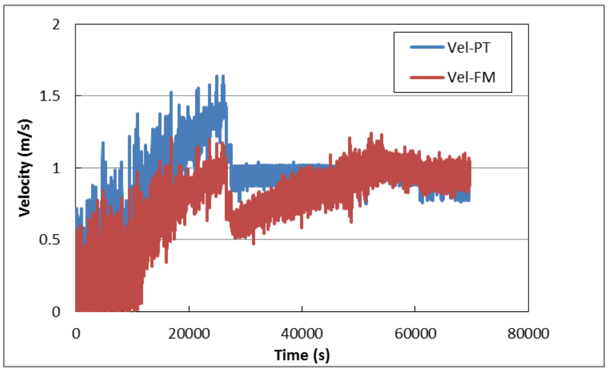

Fig. 7. Air velocity induced by natural convection

Fig. 8 shows the air temperatures at the inlet of a riser (TL-3) and outlet of the upper chamber (TU-6) and their difference (DelT). TU-6 was used for the average (bulk) air temperature at the riser outlet where the heated air was expected well mixed. The temperature increment across the riser tube ends reached 100°C after 62,000 s, which was close to the required test condition of 99°C.

Fig. 9 shows the heat transfer coefficients of natural convection in a riser at a quasi-steady state estimated with the scaled air mass flow rate and air temperature increment (t = 69,000 s).

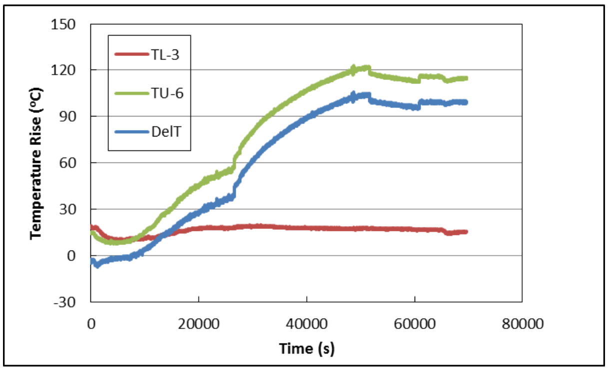

Fig. 8. Air temperature increment in a riser tube

The heat transfer coefficients were estimated based on the area-averaged riser wall temperature since each wall temperature is different from each other.

$$\bar{h} = \frac{\dot{m} c_p \Delta T_z / \Delta z}{\sum_{i=1}^{4} P_i \Delta T_{w,i}} \qquad (1)$$

where, $\dot{m}$: mass flow rate, c_p : specific heat of air, ΔT_z : air temperature increment along a certain height (Δz), P_i : width of i-th side of a riser, $\Delta T_{w,i}$: temperature difference between the i-th wall of a riser and the bulk of air

These heat transfer coefficients (hexp) are compared with two existing correlations. One is the Dittus-Boelter forced convection correlation (h-DB) and the other is the Symolon correlation (h-Sym) which is known to be a well-predicting mixed convection correlation [9].

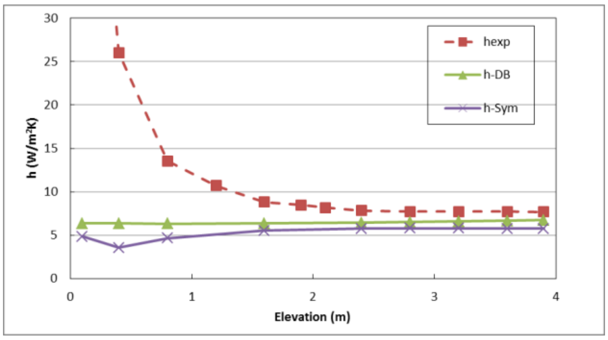

Fig. 9. Heat transfer coefficients along a riser (t = 69,000 s)

In the fairly well developed region (above 2 m), the heat transfer coefficients from the test appear to be 8.0 ~ 8.5 W/m^2/K which are rather higher than not only those estimated from the Symolon correlation but also those estimated from the Dittus-Boelter correlation. In the lower elevation than 2 m, the heat transfer coefficients obtained from this test are very much affected by the entrance effect and appear very high.

Figs. 10 and 11 show other comparisons of the heat transfer coefficient in the well-developed region in this test with two mixed convection correlations. The figures also show that the heat transfer coefficients in this test are rather over-estimated, even taking into account of the buoyancy effect in the mixed convection.

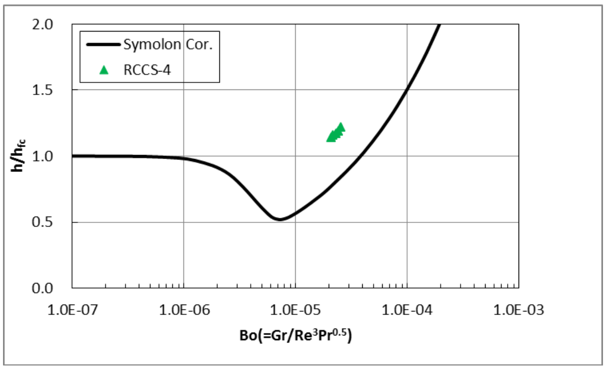

Fig. 10. Comparison of heat transfer coefficients with the Symolon correlation [10]

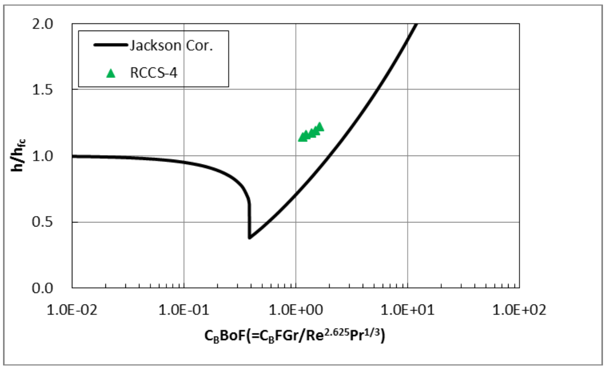

Fig. 11. Comparison of heat transfer coefficients with the Jackson correlation [11]

The discrepancy in the heat transfer coefficients between this test and the correlations seems to be probably caused by the uncertainty in the determination of the bulk temperature of the air flow in the riser tubes. The heated air temperature was measured at two points, of which one was the center of the riser tube exit and the other was the center of the exit plane of the upper chamber (TU-6) where the air flow was expected to become homogeneous [refer to Fig. 8]. The test data show that the former was about 20°C lower that the latter. Since the latter was used as the bulk temperature of the heated air for the estimation of the heat transfer coefficients, it would produce the higher values of the heat transfer coefficients due to the larger air temperature increment (ΔT_z) in the riser tube and the smaller temperature difference (ΔT_w) between the riser wall and the bulk air [Refer to Eq. (1)]. The better estimation in the bulk temperature would result in the better agreement between the heat transfer coefficients from the test and those from the correlations. Further investigations are needed to explain this discrepancy in the heat transfer coefficients.

4. Conclusions

The fourth natural cooling test was conducted in the NACEF facility, the 4/17-scale RCCS mockup of the PMR200. Natural convection cooling by buoyant force formed in the risers at scaled conditions. The heat transfer coefficients at the condition of Pl_R =1 appear rather higher than those estimated from both the mixed and forced correlations. The experimental data obtained from the test will be used for the validation of the system codes such as the GAMMA+ code, which will be in turn used for the reactor design. Although the RCCS in the prototypic PMR200 is expected to well remove the decay heat during the LPCC accident, a careful consideration is required in the interpretation of the measured heat transfer into a prototypic value due to the difference in the flow velocity between the prototype and the 4/17-scale mock-up.

ACKNOWLEDGEMENTS

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