*Transactions of the Korean Nuclear Society Spring Meeting*
*Jeju, Korea, May 12-13, 2016*

# The Results of the Third NACEF Test for the RCCS Verification

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## 1. Introduction

KAERI has been performing 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 demonstration plant of the 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 [3-5]. Here described are the results of the third 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 Richardson number remains the same as the prototype.

## 2. Description of Test Facility

Fig. 1 shows the natural cooling phenomena in the 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.

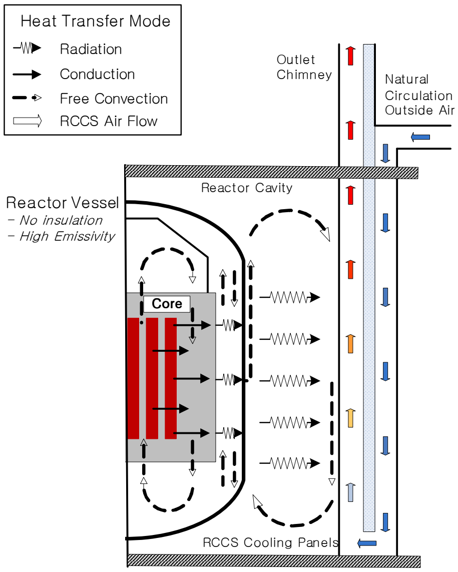

Fig. 1. Natural cooling phenomena in the RCCS

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 [3-5]. Figs. 2 & 3 show the 3-D figure of the NACEF and the plan view of its test section, respectively. Six riser tubes were provided in the NACEF compared to 220 in the prototype.

Fig. 2. 3-D figure of the NACEF

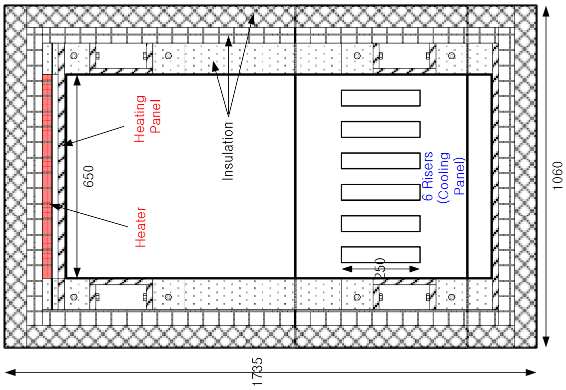

Fig. 3. Plan view of the NACEF test section

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 Third Test

The third 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 [6, 7] 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 about a half of the prototype, $v_R = l_R^{\frac{1}{2}} = (4/17)^{\frac{1}{2}} = 0.485$ (the square root of the scale) when the Richardson number remains the same in both scales and the air temperature increment is the same as the prototype. When the ratio of the Richardson number ($Ri_R$) of this mockup to the prototype is unity, the heat flux in the mockup needs to be about twice of the prototype, $q''_R = l^{-\frac{1}{2}} = (4/17)^{-\frac{1}{2}} = 2.06$. Based on this analogy, 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 up to 6,500 s, the power input was applied to 19.8 kW in stepwise manner. Afterwards, the power input was then controlled to adjust the total loss coefficient to be the same as that (7.96 based on a riser) of the prototype by monitoring the natural convection air flow rate and total differential pressure along the air flow passage. Along with the power input, a damper opening was adjusted to obtain appropriate test conditions, such as the air temperature increment and the scaled air velocity. At 52,000 s, the power input was set at 21.3 kW to maintain the same air temperature increment (98°C) in the riser as the prototype. Thereafter, the desired test conditions were obtained as the scaling analysis. The removed power and heat flux by the risers due to natural convection were estimated to be 13.4 kW and 5.16 kW/m$^2$, respectively.

Table II: Test conditions and measured values

| | PMR200 values | Scaled values | Measured values |
|---|---|---|---|
| $\Delta T_{riser}$ (°C) | 98 | 98 | 100 |
| $q''$ (kW/m$^2$) | 2.54 | 5.23 | 5.16 |
| Mass flow rate per riser (kg/hr) | 170.1 | 82.5 | 79.7 |
| $Ri_R$ | 1 | 1 | ~ 1 |
| Total loss coef. based on a riser | 7.96 | 7.96 | 8 |

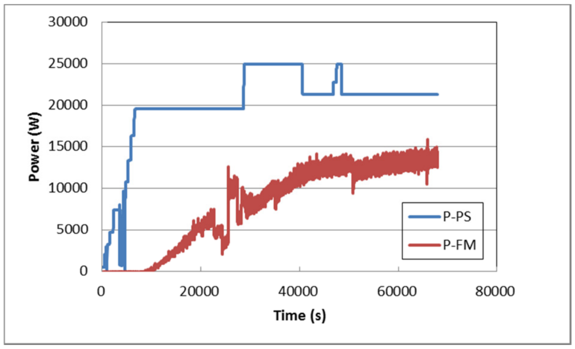

Fig. 4. Applied power (P-PS) and removed power (P-FM)

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, 67,900 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.

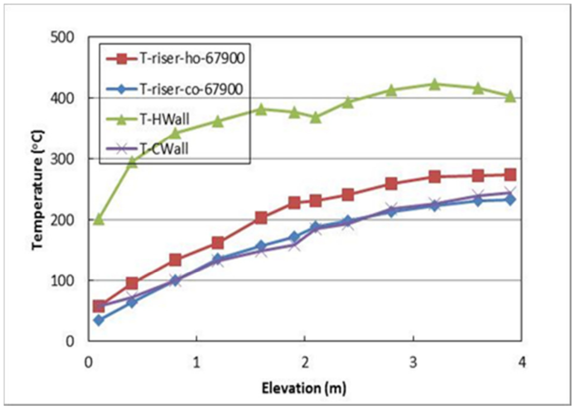

Fig. 5. Temperature distribution in test walls (t = 67,900 s)

Fig. 6 shows 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. Mass flow rate caused by natural convection was measured. At 52,000 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 total mass flow rate in the 6 risers was 478.5 kg/hr and that in a riser was 79.7 kg/hr. A sudden fall of the mass flow rate at 25,000 s was caused by a deliberate decrease of the damper opening to check its performance.

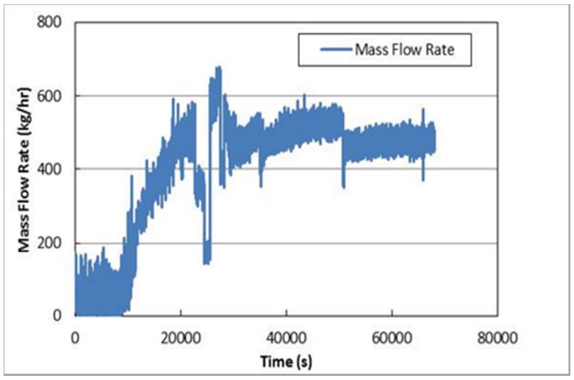

Fig. 6. Mass flow rate in the north chimney

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 (11 °C) were about 1.9 m/s.

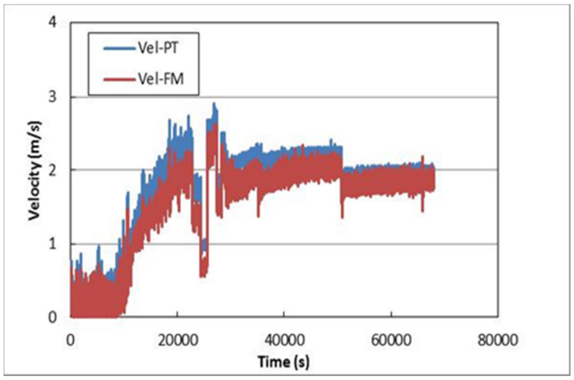

Fig. 7. Air velocity induced by natural convection

Fig. 8 shows the air temperature increment in a riser tube. The air temperature increased with an increase in the input power but with a decrease in the damper opening. A sharp increase at about 25,000 s was caused by a sudden decrease of the damper opening. After 52,000 s, the time of the last damper adjustment, the temperature increment finally reached a quasi-steady state and the value (100 °C) was more or less similar to the required test condition (98 °C).

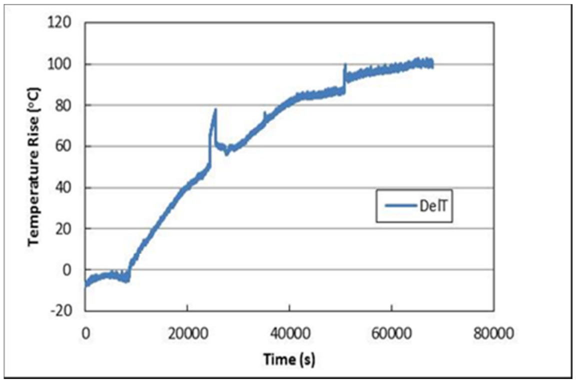

Fig. 8. Air temperature increment in a riser tube

Fig. 9 shows 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 = 67,900 s).

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

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

where, $\dot{m}$ : mass flow rate, $c_p$ : specific heat of air, $\Delta T_z$ : 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 [8].

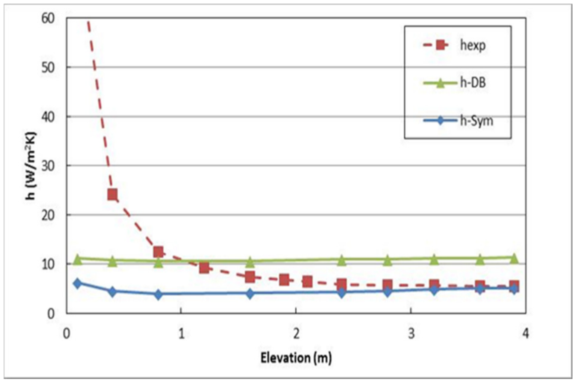

Fig. 9. Heat transfer coefficients along a riser (t = 67,900 s)

In the fairly well developed region (above 2 m), the heat transfer coefficients from the test appear lower than the Dittus-Boelter correlation, but are similar to the Symolon correlation. This indicates that the heat transfer phenomena are close to the mixed convection rather than the forced convection.

The mixed convection behavior in this test is also claimed by Figs. 10 and 11. The comparisons of the heat transfer coefficients in the well-developed region in this test (RCCS-3) with two mixed convection correlations in the figures confirm that heat transfer is deteriorated due to the upward mixed convection.

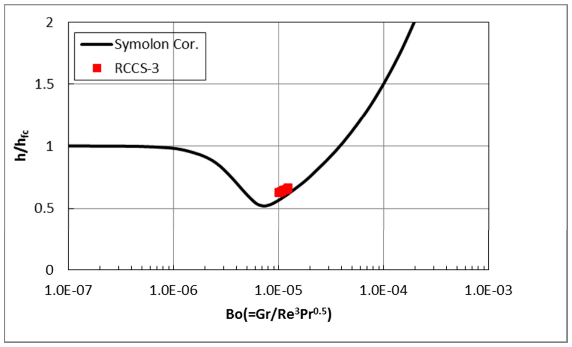

Fig. 10. Comparison of heat transfer coefficients with the Symolon correlation [9]

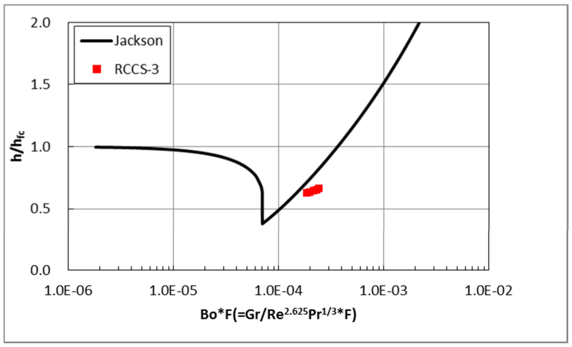

Fig. 11. Comparison of heat transfer coefficients with the Jackson correlation [10]

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.

## 4. Conclusions

The third natural cooling test was performed 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 regime is in the mixed convection region. Although the RCCS in the prototypic PMR200 is expected to well remove the decay heat during the LPCC accident, a careful consideration in the design of the RCCS is needed since the flow regime is neither forced convection nor natural convection. More experiments will be performed to confirm natural cooling phenomena by varying test conditions obtained from precedent scaling analyses such as the loss coefficient in the system, mass flow rate and/or input power, etc. The experimental data obtained from these tests will be used for the validation of system codes such as the GAMMA+ code, which will be in turn used for the reactor design.

## ACKNOWLEDGEMENTS

This study was supported by Nuclear Research & Development Program of the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science, ICT and Future Planning (2012M2A8A2025682)

## REFERENCES

[1] Y. Y. Bae, et al., Scaling Analysis of Reactor Cavity Cooling System for PMR 200, Trans. KNS Spring Meeting, Jeju, Korea, May 17-18, 2012.

[2] Y. Y. Bae, et al., Scaling Analysis of PMR200 Reactor Cavity Cooling System, Proceedings of the HTR 2012, Tokyo, Japan, Oct. 28 – Nov. 1, 2012, Paper HTR2012-7-020.

[3] J. H. Kim, et al, Results of the Preliminary Test in the 1/4-Scale RCCS of the PMR200 VHTR, Trans. KNS Autumn Meeting, Pyeongchang, Korea, Oct., 30-31, 2014.

[4] J. H. Kim, et al., The Test Results of the NACEF RCCS Test Facility, Trans. KNS Spring Meeting, Jeju, Korea, May, 7-8, 2015.

[5] J. H. Kim, et al., The Results of the Second NACEF Test, Trans. KNS Autumn Meeting, Gyeongju, Korea, Oct., 29-30, 2015.

[6] H. S. Lim, GAMMA+1.0 Volume I: User's Manual, KAERI/TR-6167/2015, KAERI, 2015.

[7] H. S. Lim, General Analyzer for Multi-component and Multi-dimensional Transient Application GAMMA+1.0 Volume II: Theory Manual, KAERI/TR-5728/2014, KAERI, 2014.

[8] A. F. Wibisono, et al., Numerical Investigation on Water Deteriorated Turbulent Heat Transfer Regime in Vertical Upward Heated Flow in Circular Tube, International Journal of Heat and Mass Transfer, Vol. 83, pp. 173-186, 2015.

[9] P. Symolon, et al., Mixed Convection Heat Transfer Experiments in Smooth and Rough Vertical Tubes, Trans. ANS, Vol. 92, pp.387-390, 2005.

[10] IAEA, Heat Transfer Behaviour and Thermohydraulics Code Testing for Supercritical Water Cooled Reactors (SCWRs), IAEA-TECDOC-1746, pp. 159-200, 2014.