Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2012

Scaling Analysis of Reactor Cavity Cooling System for PMR 200

Yoon-Yeong Bae [a*], Sung-Deok Hong, [a] Yong-Wan Kim [a]
Korea Atomic Energy Research Institute, Daedeokdaero 989-111, Yuseong, Daejeon, Republic of Korea
[*] *Corresponding author:* yybae@kaeri.re.kr

1. Introduction

A government-sponsored research on the essential technologies pertinent to the development of the demonstration plant PMR 200, a VHTR demonstration plant, is being performed at the KAERI. The verification of the RCCS (Reactor Cavity Cooling System) performance is one of the key issues among the objectives included in the 3-year national nuclear research program, starting year 2012. It is customary, due partly to the limitation of financial resources and physical space, to perform a test in a reduced-scale test facility. In a process of scaling down, a distortion of physical phenomena is unavoidable since the matching of all pertinent non-dimensional parameters is practically impossible. Therefore, a scaling analysis is imperative in order to check the degree of distortion and applicability of the test results to the prototype design. A scale-down test are currently being performed in the ANL (1/2 scale), the University of Wisconsin (1/4 scale), and the Texas AM University (1/12 scale). This paper describes the requirement of the design PMR 200 and the result of scaling analysis of the RCCS in order to provide a basis for the design of the test facility to be built in the KAERI.

2. RCCS Design for PMR 200 [1]

The RCCS removes residual heat, which amounts to 0.3 – 0.6% of reactor full power, at both high and low pressure modes, by means of radiation and natural convection. Its operation has to be passive in order to eliminate any accident due to human error. The criteria for the RCCS design are the temperature at the reactor surface lower than 427ºC and at the reactor cavity concrete wall lower than 176ºC, respectively. The PMR 200 tentatively adopts a hybrid system, which includes both air and water-cooled loops placed side by side. The air system is supposed to provide full coverage of removing 100% of residual heat, while the water loop supports the air loop by giving a redundancy in any case of emergency. Fig. 1 shows the schematic diagram of the RCCS and the cross section of air and water ducts.

3. Scaling Analysis of RCCS

From a non-dimensionalization of governing equations for a single phase incompressible flow following non-dimensional parameter are identified [2].

Richardson Number $$Ri \equiv \frac{g\beta\Delta T_o \ell_o}{u_o^2} \quad (1)$$

Friction Number $$F_i \equiv \left(\frac{f\ell}{d} + K\right)_i \quad (2)$$

Modified Stanton Number $$St_i \equiv \left(\frac{4h\ell_o}{\rho C_p u_o d}\right)_i \quad (3)$$

Time ratio Number $$T_i^* \equiv \left(\frac{\alpha_s \ell_o}{\delta^2 u_o}\right)_i \quad (4)$$

Biot number $$Bi_i \equiv \left(\frac{h\delta}{k_s}\right)_i \quad (5)$$

Heat source Number $$Q_{si} \equiv \left(\frac{\dot{q}_s \ell_o}{\rho_s C_{ps} u_o \Delta T_o}\right)_i \quad (6)$$

Cavity radiation number $$N_r \equiv \frac{A\varepsilon\sigma T_o^4}{A_o \rho C_p u_o (T_o - T_r)} \quad (7)$$

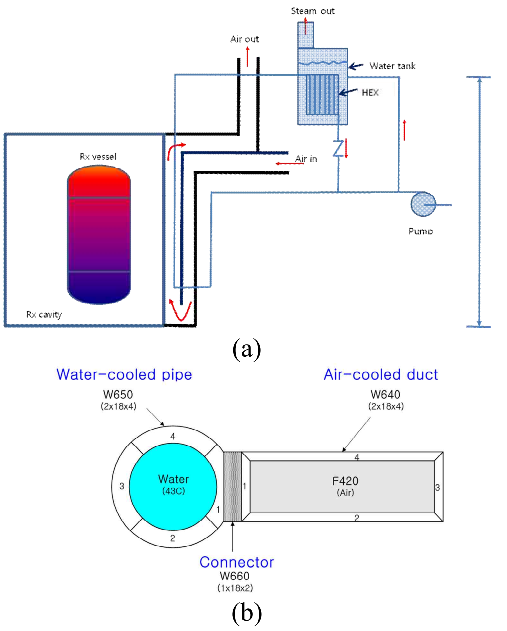

Fig. 1 Schematic diagram of PCCS experimental facility

Since both of natural convection and radiation are dominant phenomena in RCCS, in a modeling of test facility the non-dimensional parameters controlling those phenomena should be preserved as closely as possible in order to simulate the fluid-thermal phenomena occurring in prototype as correctly as possible. Generally, a model requires three similarities such as geometrical, kinematical and dynamical similarities. Since it is practically not possible to satisfy equalities of all non-dimensional parameters, it is customary to enforce the similarity requirements on some select ones. Among the similarity requirements Ri_R=1 * and N_{rR}=1 were selected as controlling non-dimensional parameters, since they were considered to dominate the heat transfer from reactor to RCCS and the following flow motion in the vertical air and water ducts. Besides Ri and N_r, friction number F also plays an important role since there is no driving force; and the buoyancy is balance only with the pressure drop in the natural convection system. The design of ducts should be carefully performed following the requirement of F_R=1.

Table 1 Scaling values, single phase

Single phase, Shifted time					
Scaling parameter	Case 1	Case 2	Case 3	Case 4	Case 5
l_{oR}	0.2500	0.2500	0.2500	0.2500	0.5000
ΔT_{oR}	0.2500	0.5000	1.0000	1.0000	1.0000
δ_R	1.1225	0.8909	0.7071	1.0000	0.8409
d_R	1.1225	0.8909	0.7071	1.0000	0.8409
ξ_{RxR}	1.1225	0.8909	0.7071	1.0000	0.8409
a_{oR}	1.2599	0.7937	0.5000	1.0000	0.7071
u_R from T^*_{iR}=1	0.2500	0.3536	0.5000	0.5000	0.7071
q_{oR}	0.2500	0.7071	2.0000	2.0000	1.4142
q''_{oR}	0.2500	0.7071	2.0000	2.0000	1.4142
T_{oR} (in K) from N_{rR}=1	0.7071	0.9170	1.1892	1.1892	1.0905
h_R laminar	1.0000	1.0000	1.0000	1.0000	1.0000
h_R turbulent	0.3299	0.4353	0.5743	0.5743	0.7579
h_R natural	1.1892	1.4142	1.6818	2.8284	1.2968
Ri_R	1.0000	1.0000	1.0000	1.0000	1.0000
N_{rR}, radiation /advection	1.0000	1.0000	1.0000	1.0000	1.0000
Re_R	0.2806	0.3150	0.3536	0.5000	0.5946
$Ra_s{}^*{}_R$	0.3969	0.4454	0.5000	2.0000	0.7071
Pr_R	1.0000	1.0000	1.0000	1.0000	1.0000
St_R	0.2939	0.3455	0.4061	0.2872	0.6373
Ti^*_R	0.7937	0.8909	1.0000	0.5000	1.0000
Bi_R ($=h\delta/k$)	Depends on flow regime				
Q_S	1.0000	1.0000	1.0000	1.0000	1.0000
N_{tR}	0.2500	0.2500	0.2500	0.2500	0.5000
t_R	1.0000	0.7071	0.5000	0.5000	0.7071

The result of analysis, scaling ratios of various variables and parameters for several cases, are summarized in Table 1. Since a real time simulation is not of our interest, the analysis were done based on a shifted time simulation with allowance of t_R ($=l_R/u_R$) being not of unity.

For all cases Ri_R=1 and N_{rR}=1 were enforced as basic requirements. For case 1 l_{oR}=0.25 and ΔT_{oR}=0.25 were given as additional requirement; and for cases 2 and 3 ΔT_{oR} was increased to 0.5 and 1.0, respectively, while retaining l_{oR}. Case 4 is a variation of case 3 with additional requirement of exact geometric similarity in the radial direction. Case 5 is another variation of case 3 with an increased of ΔT_{oR} to 1.0. The values of the geometric similarity variables such as the solid thickness δ_R, the duct diameter d_R, the wetted parameter ξ_{RxR}, the duct area a_{oR} falling between 0.71 and 1.12, are largely different from the vertical linear scale l_{oR}, implying that the geometric similarity is seriously violated. The velocity scale u_R also shows wide variations and approaches unity as l_{oR} and ΔT_{oR} do. Among the heat transfer mechanism the natural convection is the most important one. Its similarity can be check by inspecting the modified Rayleigh number Ra_s*. Pr_R=1 is automatically satisfied, since the same fluid will be used in the test as that in the prototype.

The requirement ΔT_{oR}=1.0 shown in cases 3-5 provides a convenience of a direct application of the test data to the prototype

Case 5 preserves Ra_s* most closely; however, it requires relatively a large test facility. Case 4 includes an additional requirement of retaining the prototype radial dimensions. This additional requirement did not result in a severe distortion of thee prototype.

Although additional requirement of retaining horizontal dimensions is imposed on case 4, it does not show any conspicuous difference from the other cases.

3. Conclusions

A scaling analysis was performed on the RCCS for PMR200. The enforced basic requirements were both of the Richardson number and cavity radiation number being unity. Among the cases examined case 4 of vertical scale l_{oR}=0.25, horizontal scale d_R=1.0, temperature increase scale ΔT_{oR}=1.0, was found to be reasonable in terms of cost and experimental convenience.

REFERENCES

[1] B.H. Cho, Preliminary thermal sizing of major equipments in the hybrid RCCS/water cooling loop of PMR 200 MWt, NHDD-RD-CA-11-004 (Rev. 00), in Korean, 2011

[2] M. Ishii, I. Kataoka, Scaling laws for thermal-hydraulic system under single phase and two-phase natural circulation, Nuclear Engineering and Design, Vol. 81 pp. 411-425, 1984.

* Subscript R implies $\psi_R = \frac{\psi(\text{model})}{\psi(\text{prototype})} = \frac{\psi_m}{\psi_p}$