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

A scaling study of the natural circulation flow of the ex-vessel core catcher cooling system of a 1400MW PWR for designing a scale-down test facility

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1. Introduction

A scaling study on the steady state natural circulation flow along the flow path of the ex-vessel core catcher cooling system of 1400MWe PWR is described. The scaling criteria for reproducing the same thermalhydraulic characteristics of the natural circulation flow as the prototype core catcher cooling system in the scale-down test facility is derived and the resulting natural circulation flow characteristics of the prototype and scale-down facility analyzed and compared.

The purpose of this study is to apply the similarity law to the prototype EU-APR1400 core catcher cooling system and the model test facility of this prototype system and derive a relationship between the heating channel characteristics and the down-comer piping characteristics so as to determine the down-comer pipe size and the orifice size of the model test facility. As the geometry and the heating wall heat flux of the heating channel of the model test facility will be the same as those of the prototype core catcher cooling system except the width of the heating channel is reduced, the axial distribution of the coolant quality (or void fraction) is expected to resemble each other between the prototype and model facility. Thus using this fact, the down-comer piping design characteristics of the model facility can be determined from the relationship derived from the similarity law.

2. Geometry of the Prototype and Model Facility of Core Cater Cooling System

The core catcher is in a rectangular shape with a dimension of 6 m x 16 m. The core catcher is geometrically symmetric along a longer axis. The lower wall has an inclination angle of 10^o to facilitate the steam venting during the cooling process. The lowermost part of the core catcher body is made flat. The decay heat sensible heat from the molten corium is to be released to the cooling channel by a boiling heat transfer and to the top by a radiation heat transfer. The cooling channel is made of a single channel between the core catcher body and inside wall of the reactor cavity. The width of the gap between the core catcher body and concrete body is about 10 cm. A large number of short columnar structures are placed between the core catcher body and reactor cavity wall, which is used to support the static and dynamic loading on the core catcher body. As shown in Fig.1, down-comer piping embedded in the cavity concrete are provided to enhance the two-phase natural circulation.

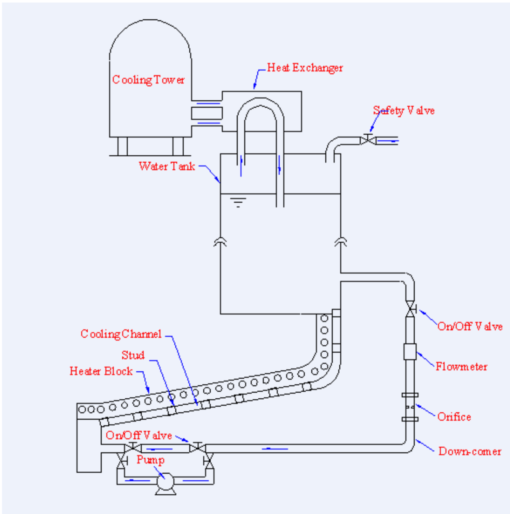

Figure 1. Schematic Diagram of the Conceptual Design of the Model Test Facility of the EU-APR1400 Core Catcher Cooling System

3. Reduction of Ishii & Kataoka's [1] Scaling law to the Current Study

To simplify the analysis the following assumptions are made:

1. The cooling channel gap between the cor e catcher body and concrete body is the s ame for the horizontal and slanted portio n of the heating channel, and that for the vertical portion of the heating channel ma y be the same as that for the horizontal or may be bigger.
2. The molten corium in the core catcher ha s a single and homogeneous layer, and m aintains 40MWt decay power, which is a bout 1% of core power.
3. The upward and downward heat power fr

om the molten corium is the same. Therefore, the heat power loaded to the cooling channel is 20MWt uniformly.

4. The two phase flow in the natural circulation loop is a steady.
5. The inlet coolant is saturated.

For the pressure drop in the loop, the pressure drop along the heated channel of the same flow area can be expressed as [2]:

$$\Delta P_o = \rho u_o^2 \left\{ K_h + \frac{f}{2d_o} \left[\frac{1+\frac{\Delta\rho x_e}{\rho_g\, 2}}{\left(1+\frac{\Delta\mu x_e}{\mu_g\, 2}\right)^{0.25}} \right] (\ell_o) + \left[\frac{x_e^2}{\alpha_e}\frac{\rho}{\rho_g} + \frac{(1-x_e)^2}{(1-\alpha_e)} - 1 \right] + K_e \left(1 + \frac{\Delta\rho}{\rho_g} x_e^{1.5}\right) \right\} + g\rho_o \ell_o - \Delta\rho g[\langle\alpha\rangle_o(\ell_o)] \quad (1)$$

Where ℓ_o is the total length of the heated section and the mean void fraction is given approximately by $\langle\alpha\rangle_o = f\left(\frac{x_e}{2}\right)$.

Here one needs to apply the similarity law to the prototype EU-APR1400 core catcher cooling system and the model test facility of this prototype system and derive a relationship between the heating channel characteristics and the down-comer piping characteristics so as to determine the down-comer pipe size and the orifice size of the model test facility. As the geometry and the heating wall heat flux of the heating channel of the model test facility will be the same as those of the prototype core catcher cooling system except the width of the heating channel is reduced, the axial distribution of the coolant quality (or void fraction) is expected to resemble each other between the prototype and model facility. Thus using this fact, the down-comer piping design characteristics of the model facility can be determined from the relationship derived from the similarity law.

From the geometric similarity,

$$\left(\frac{\alpha_{o,P}}{\alpha_{dc,,P}}\right)^2 = \left(\frac{\alpha_{o,m}}{\alpha_{dc,m}}\right)^2$$

we can obtain the down-comer pipe diameter of the model facility and from the Friction Number similarity the following equation is derived.

$$\left(\sum_i \mathbf{F_i}/\mathbf{A_i^2}\right)_m = \left(\sum_i \mathbf{F_i}/\mathbf{A_i^2}\right)_P$$

$$\frac{\left\{ \Sigma_i \left(\frac{f}{d}\ell_{TP,o}\right)_i \left[\frac{1+\Delta\rho x/\rho_g}{(1+\Delta\mu x/\mu_g)^{0.25}}\right]_i \left(\frac{a_o}{a_i}\right)^2 + \left(K_h + K_e(1+\Delta\rho x^{1.5}/\rho_g)\right)\left(\frac{a_o}{a_i}\right)^2 \right\}_P}{\left\{ \frac{0.184\ell_{dc,P}}{d_{dc,P}} \left(\frac{d_{dc}}{\mu_f}\right)_P^{-0.2} \left(\frac{m_{dc}}{a_{dc}}\right)_P^{-0.2} + (K_h + K_e + \Sigma_i K_i) \right\} \left(\frac{a_o}{a_{dc}}\right)_P^2}$$

And similar equation can be derived for the model test facility, too.

4. Results and Conclusion

If all the necessary numerical values of $Q_{ratio,p}$, $x_{e,p}$, $d_{o,p}$, $d_{dc,p}$, $\alpha_{dc,m}$, $\alpha_{dc,P}$, $\left(\phi_{\ell_o}^2(x)\right)_i$, are substituted into this equation, the orifice loss coefficient $K_{o,m}$ can be found as a function of $\left(Q_{ratio,p}/x_{e,p}\right)$. The result is given in Fig.1.

From this Figure, if the orifice K is kept as shown in Fig.1, the hydraulic similarity of the two-phase natural circulation flow between the prototype facility and the model test facility could be maintained.

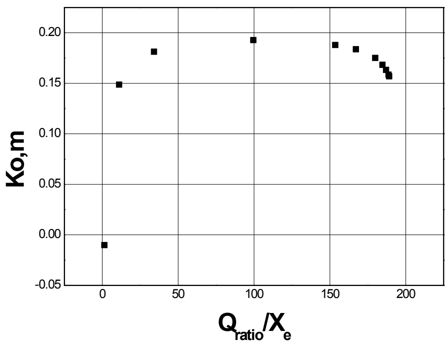

Fig. 1. Downcomer Orifice K value as a function of $Q_{ratio,p}/x_{e,p}$

REFERENCES

1. CONF-820962—4, Scaling Criteria for LWR's under Single-phase and Two-phase Natural Circulation, M. Ishii and I. Kataoka, Joint NRC/ANS Meeting on Basic Thermal Hydarulic Mechanisms in LWR Analysis, Sept. 14-15, 1982, Bethesda, MD., U.S.A.