Reduced Height Effect on the PWR’s Integral Test Facility during Long Term Cooling

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1. INTRODUCTION

The scale-down integral test models are widely used for nuclear power plant (NPP) integral test. With the Hierarchical, Two-Tiered Scaling (H2TS) method developed, a reduced height scale test facility could be design which can lower the cost and bring other benefits.

In a reduced height model, the gravity driven force and the fluid pressure could be different due to actual height changes, and it could make the test facility some behaviors different to the prototype. So the reduced height effect should be clearly addressed to ensure the model can simulate the transients in prototype correctly.

In this work, the effect caused by the reduced height design method will be analyzed, and it shows the pressure difference across the core is also scale-down by the reduced height ratio. And during the long term cooling phase, the local pressure in the simulator core is different from the prototype, and it can reduce the saturate temperature, which can be thought as conservative for the test.

2. SCALING ANALYSIS FOR REDUCED HEIGHT TEST FACILITY

Natural circulation (NC) is the most cooling mechanism in a passive safety system, and both a loop level and a component level scaling analysis are performed.

The basic relation for NC similarity can be obtained from scaling analysis, and it shows when the reduced height model works under the same system pressure, by adjusting the loop resistance and core power, the model can simulate the single natural circulation properly. This has been taken as the basic scaling requirement for a reduced height test system.

When the scaling is performed at the component level, as the reactor core, it can be seen that if we want to keep the similarity both at the loop level and component level, it must be satisfied:

\[
(l_1)_R = l_R \quad (a_1)_R = a_R \quad (F_1)_R = F_R \quad \dot{Q}_{a,R} = \left(\frac{a_1 l_1^2}{R}ight)_R
\]

The requirements above are meant to be satisfied when considering design a scaled down PWR integral test facility, and the system will satisfy the relation of \((u_0)_R = \left(\rho l^2\right)_R\). And according to the similarity laws for a specific component, the pressure drop across the section should be:

\[
(\Delta P)_R = \left(\rho l^2\right)_R l_R
\]

So the pressure drop across a specific component in the NC loop will be scaled down to the height scale ratio. During high pressure phases following a beginning of the LOCA, the change of the fluid pressure causing by water level gravity head decreasing may be neglect. But within the low pressure long term recirculation cooling phase, it may lead the fluid property bias from that of the prototype.

When perform the scaling analysis on the recirculation loop, it can be seen the fluid pressure in the core will be different, and it may cause the water property change from the prototype. For AP1000 condition, the saturate temperature will decrease about 10 degrees, with the height ratio change from 1 to 1/4. The decrease of saturate temperature should require more cooling capacity of the system, so from that point of view, the test result can be thought as conservative.

3. CONCLUSIONS

The work shows the pressure drop across the core will be scaled by the height scale ratio, which will cause the boiling occurring early in the core. Because the core exit quality and void fraction could be change the NC behavior heavily, a detailed analysis under the two-phase scenario needs to be performed for fully understand the reduced height effect.

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ABSTRACT

With the development of scaling analysis approach, the reduced height test facility, such as APEX and PUMA in US, and ATLAS in Korea, have been successfully used for the NPP safety test. In this paper, the distortion originated from the reduced height effect is analyzed for the long term cooling phase based on the Natural Circulation. First, based on the NC scaling performed at a loop level and a component level, it shows the pressure drop through a specific component is scaled down, which could change the fluid property especially during the long term cooling phase for its low atmospheric pressure. Then, the scaling analysis of long term cooling loop is performed by cutting the loop into the three control volume sections, and it shows the reduced height will change the pressure at the core, which causes the fluid property slightly bias from the similitude condition and is conservative for the test result.

1. INTRODUCTION

The scale-down integral test models are widely used for nuclear power plant (NPP) integral test, and the test itself has a great importance for NPP design certification and related safety analysis code benchmark. Earlier test facilities were commonly built as a full height system, which was based on a power-volume scaling analysis approach [1]. However, the power-volume scaling method can not deal with a comprehensive system well, and an improved approach for the natural circulation scaling problem was developed by Ishii and Kataoka [2]. As a systematic scaling approach was required for integral reactor thermal hydraulic test which includes a wide range of phenomena, the Hierarchical, Two-Tiered Scaling (H2TS) method was developed. Based on this scaling method, a reduced height scale test facility could be design which can lower the cost and bring other benefits [3], such as APEX and PUMA in US, and ATLAS in Korea. And recently, a new 1/3 height scale model called ACME (Advance Core-cooling Mechanism Experiment) for a large advanced passive safety NPP was proposed to be designed and built in China.

For a passive safety system, natural circulation (NC) originated from the gravity driven force is the most important mechanism for the emergency core cooling, so the system level design is mainly based on the natural circulation (NC) scaling analysis. Due to the gravity driven force depends on the liquid level, in a reduced height model, the gravity driven force and the fluid pressure could be different due to actual height changes, and it could make the test facility some behaviors different to the prototype. If the system pressure is high, the pressure difference originated by water level change is small and could be neglect. However, when the system pressure is low, especially during the gravity injection and long term cooling phases, the water level change caused by the scaled height may affect the local pressure. And some researchers think that a full height choice is better than reduced height when considering design a scale down system [4,5]. Therefore, this reduced height effect should been clearly addressed to ensure the model can simulate the transients in prototype correctly.

The extensively scaling analysis has been done before for the test facility design, and the system level design are heavily relayed on the entire loop level NC scaling analysis [6]. The scaling analysis at a component level should be performed following a loop level analysis to address the scaling requirement of component design for a reduced height system. In this work, based on the previous scaling analysis method and results, the effect caused by the reduced height design method will be discussed. First, the similarity of kinetic and dynamic at the entire loop level is delineated to see how a reduced height model loop can duplicate the NC transient taken within the prototype, and then the core is taken as an individual component from the loop to perform the scaling analysis, and this will show that the pressure difference across the core is also scale-down by the reduced height ratio. For the similarity requirement, the pressure change may cause the fluid property bias from the prototype. Based on the scaling analysis at the loop level and the core level, the NC scaling for a long term cooling phase with the low atmospheric pressure is done by this work. In this stage, the entire long term cooling recirculation loop is divided into the three control volumes and the pressure drop is deduced...
for each section, which can confirm the local pressure in the simulator core is different from the prototype. In order to evaluate the reduced height effect on the fluid property, key fluid property parameters of different height ratio choices are evaluated based on the long term cooling phase condition. The result could support the distortion evaluation and test data analysis.

2. BASIC SCALING LAWS OF NC LOOP

NC is the most cooling mechanism in a passive safety system, and many papers once focused on the NC scaling analysis. For the NC scaling analysis, the single-phase scenario is relatively simple, but it gives the basic understanding for NC scaling rules. In this work, we only focus on the single-phase, and both a loop level and a component level scaling analysis will be performed to see how the reduced height system can duplicate the NC behavior not only for the entire loop but also for a specific component from the loop, such as core. First, the NC loop scaling is performed.

Fig. 1 shows a schematic view of NC loop in a typical PWR

![Fig. 1 Natural circulation loop in a typical PWR](image)

Fig.1 Natural circulation loop in a typical PWR

Fig.1 shows a schematic view of NC loop in a typical PWR, as it shows, the fluid density decreases from $\rho_0$ to $\rho_1$ through heating from the core, and then increases from $\rho_1$ back to $\rho_0$ by the heat removal though the SG. For the simplicity, the heat loss is not considered in. The fluid mass continuity in the entire loop can be expressed by:

$$\rho_i u_i a_i = \rho_{i+1} u_{i+1} a_{i+1}$$

(1)

where $u$ is the fluid velocity, $a$ is the flow cross area, and subscript $i$ means the ith component in the loop.

And the momentum balance of the loop fluid is written as:

$$\frac{d\rho_i u_i}{dt} \sum \left[ \frac{a_i}{a_i} l_i \right] = \beta \rho_i \Delta T_i L_{th} - \frac{\rho_i u_i^2}{2} \sum \left[ \frac{f_i}{d_i} l_i \right] \left( \frac{a_i}{a_i} \right)^2$$

(2)

where $l$ is the length, $\beta$ is thermal expansion coefficient, $\Delta T$ is the temperature difference, $f$ is the friction loss factor, $d_i$ is the hydraulic diameter, and $K$ is the form loss. The subscript $c$ denotes core entrance, and $th$ means thermal height.

Through the normalization by the initial or boundary conditions, the normalized equations of Eq.1 and Eq.2 can be obtained, and this process are presented in many papers so we don’t copy them here. As a similarity requirement, the buoyant force should match with the resistance force, and Richardson number and Friction number should be equal for the prototype and model, which are:

$$\Pi_{E,R} = \left( \frac{\rho_i g \Delta T_i L_{th}}{u_0} \right)_R = 1$$

(3)

and

$$\Pi_{F,R} = \left[ \sum \left( \frac{f_i}{A_i} \right) \rho_i u_i^2 \right]_R = 1$$

(4)

The subscript 0 means the initial value. And $F_i = \left( \frac{f_i}{d_i} + K \right)$ is the friction factor of ith section. Scaling analysis generally use the length ratio $l_{i,R}$ instead of thermal height ratio $L_{th,R}$ for they are basically the same value when each component length ratio is identical, $l_{i,R} = L_{th,R}$.

If the property similitude condition can be met, the most important relation for NC scaling can be obtained from Eq.3, which are $(u_0)_R = l_{i,R}^2$ and $(h_0)_R = l_{i,R}^{-1}$. Therefore, in a reduced height system, the event occurs faster than the prototype.

When the facility works under the same pressure of the prototype, the fluid property similitude can be realized, and the temperature rise cross the core should be identical. The relation as shown below is satisfied under steady state,

$$\rho_0 d_0 a_0 C_p \Delta T_0 = Q_0$$

(5)

where $C_p$ is heat capacity and $Q$ is the core power. Hence, the core power ratio needs to set as:

$$\hat{Q}_{0,R} = \left( \frac{1}{a_i} \right)^2$$

(6)

Therefore, when the reduced height model works under the same system pressure, by adjusting the loop resistance and core power to satisfy Eq.4 and Eq.6, the model can simulate the single natural circulation properly. This has been taken as the basic scaling requirement for a reduced height test system.

3. SCALING ANALYSIS OF CORE

The above scaling laws is obtained through the entire loop level scaling analysis, if the scaling is performed at the component level, as the reactor core, the most important component for the NC loop as a heat source to generate the buoyant force, the similarity laws for the core need to be specified and the loop system level scaling can not deal with a component issue, so a component level scaling analysis should be performed. The following part will take the core as a specific component, and the control volume method will be used.

Under a single-phase NC, the momentum equation for the control volume of the core can be expressed by:

$$\frac{d}{dt}(\rho_i u_i l_i) = \Delta P_i + \Delta P_c - \left( \frac{\rho_i u_i^2}{2} \right) \left( \frac{d_i}{d_i} + K \right)$$

(7)

where $\Delta P_c$ is the pressure drop cross the core, which equals the sum of the momentum change, acceleration loss, gravity and friction loss, within the control volume. The
The gravity number, the ratio of the gravity of the fluid in the core and the inertia force:

\[ \Pi_G = \frac{\rho c_{\text{gravity}}}{\rho u_0} \]

The friction number, the ratio of the friction force and the inertia force:

\[ \Pi_f = F_{\text{friction}} / F_{\text{inertia}} \]  

The pressure drop number, the ratio of pressure drop across the core and the inertia force:

\[ \Pi_{\Delta p} = \frac{\Delta P_{\text{core}}}{\rho u_0^2} \]

Under a steady state, the pressure drop across the core can be expressed by:

\[ \Delta P_{\text{core}} = \left(1 - \frac{\beta \Delta T}{2} \right) \rho_0 g l_c + \frac{\rho g l_c}{2} F_{\text{fluid}} - \Delta \left(\rho_0 u_0^2\right) \]

The similarity numbers can be drawn from this normalized equation.

The pressure drop number can be rewritten as:

\[ \Pi_{\Delta p} = \Pi_{\text{gravity}} + \Pi_{\text{ inertia}} - \Pi_s \]

Therefore, if the Pi numbers \( \Pi_{\text{gravity}}, \Pi_{\text{inertia}} \) and \( \Pi_s \) can be respectively kept in the same values, \( \Pi_{\Delta p} \) will be the same.

The scaling analysis on a different component within the loop will get the same results.

From the analysis above, it can be seen that if we want to keep the similarity both at the loop level and component level, it must be satisfied:

\[ (l_1)_R = l_R \quad (a_1)_R = a_R \quad (F_1)_R = F_R \quad (\dot{Q})_{0,R} = a_R l_2^2 \]

So it can be seen from Eq.17, the pressure drop across a specific component in the NC system will satisfy the relation of \( (u_0)_R = (l_1^2) \) _R_.

Based on the scaling analysis of the NC loop above, the scaled NC system will satisfy the relation of \( (u_0)_R = (l_1^2) \) _R_.

And according to the similarity laws for a specific component, the pressure drop across the section should be:

\[ (\Delta P)_R = \left(\rho_0 u_0^2\right)_R = l_R \]

Therefore, if the Pi numbers \( \Pi_{\text{gravity}}, \Pi_{\text{inertia}} \) and \( \Pi_s \) can be respectively kept in the same values, \( \Pi_{\Delta p} \) will be the same.

The scaling analysis on a different component within the loop will get the same results.

From the analysis above, it can be seen that if we want to keep the similarity both at the loop level and component level, it must be satisfied:

\[ (l_1)_R = l_R \quad (a_1)_R = a_R \quad (F_1)_R = F_R \quad (\dot{Q})_{0,R} = a_R l_2^2 \]

The requirements above are meant to be satisfied when considering design a scaled down PWR integral test facility.
show, the recirculation loop is divided into 3 control volume sections. The first control volume section consists of Sump Line, DVI line, and the pressure vessel downcomer, and the stored energy release due to downcomer metal structure is neglect for the simplicity and also because the AP1000 PIRT ranked it as “Low Importance”[7]. The reactor core is taken as the second control volume section which can be regarded as a bubble riser. And the last control volume section is the combination of the hot leg and ADS4 pipes above the core to perform the vent function.

\[ \Delta P_i = \Delta \left( \rho u^2 \right) - (\rho g h) - \left( \frac{\rho u^2}{2} \right) \]

(18)

And this agrees with the scaling requirement when designing an injection or vent lines for a scale down facility.

For the control volume section specified in Fig.3, the pressure at the core entrance can be written as:

\[ P_e = P_a + \rho_c gh - \left( \frac{\rho_c u^2}{2} \right) F_1 \]

(19)

The pressure at the core exit can be expressed by:

\[ P_c = P_e - \rho_c gh - \left( \frac{\rho_c u^2}{2} \right) F_2 \]

(20)

Above, the acceleration term does not exist for the constant flow area. And the pressure drop cross the core and the third section can be written as:

\[ \Delta P_c = \rho_c gh + \left( \frac{\rho_c u^2}{2} \right) F_2 \]

(21)

And

\[ \Delta P_3 = P_t - P_e = \rho_0 gh - \rho_c gh + \left( \frac{\rho_c u^2}{2} \right) F_1 + \left( \frac{\rho_c u^2}{2} \right) F_2 \]

(22)

It can be deduced that from Eq.21 and Eq.23, \( (\Delta P)_h = (\Delta P)_m = l_s \), which agree with Eq.17. So it can be obtained that:

\[ P_{e,m} = P_a + \frac{1}{3} \left( \rho_0 gh - \left( \frac{\rho_0 u^2}{2} \right) F_1 \right) \]

(23)

And

\[ P_{c,m} = P_a + \frac{1}{3} (\Delta P)_r \]

(24)

Therefore, the fluid pressure in the core will be different, and it may cause the water property change from the prototype. And in order to evaluation the reduce height effect on the fluid property, the key fluid parameters needs to be shown under different height ratio.

5. FLUID PROPERTY VARIATION EVALUATION

For evaluation the property change due to the reduced water level, the typical long term cooling condition is needed. Here we take the AP1000 as the model. For AP1000, the distance from flood-up level to the core entrance is approximately 7m, and we take the 60 degree as the sump water temperature to see the reduced height effect on the fluid properties including saturate temperature, heat capacity, latent heat and saturate temperature. The parameters changing with the height ratio are shown in Fig. 4, 5 and 6.

It can be seen from the results, the property parameter difference will increase with the height ratio decreasing. And it suggests that the height scale has effect on the water property similitude, but the property change is not so obvious.

However, it also should be noticed that the saturate temperature will decrease about 10 degrees, with the height ratio change from 1 to 1/4, which will cause the boiling occurring lower along the core axis. The decrease of saturate temperature should require more cooling capacity of the system, so from that point of view, the test result can be thought as conservative.

\[ \frac{T_m}{T_a} \]

Fig.4 The saturate temperature of the fluid at the core entrance versus height ratio

\[ \frac{C_p}{C_{p,a}} \]

Fig.5 The heat capacity of the fluid at the core entrance versus height ratio

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6. CONCLUSIONS

The scaling analysis of single-phase natural circulation both at the loop level and the component level were performed to get the basic scaling laws when considering to build a reduced height test facility. It shows that the reduced height can keep the dynamic similarity of the prototype and model during a high pressure transient through carefully choosing the friction factor of each component and keeping the length and flow area scale ratio unchanged for all the components in a loop. But the reduced height will decrease the pressure drop across any component by the height scale ratio, which may cause the fluid property change.

The long term cooling scaling analysis shows the reduced height effect on the fluid property change is not so obvious. But the saturate temperature is lower due to height reduction, which will cause the boiling occurring early in the core. However, the analysis in this work in based on the single-phase circulation, and if we consider a two-phase circulation scenario, the analysis will become comprehensive and a lot of factors should be considered in. Especially, the core exit quality and void fraction could be change heavily due to the saturate temperature decrease, which will cause the distortion of the two-phase NC simulation. Therefore, a detailed analysis under the two-phase scenario needs to be performed for fully understand the reduced height effect.

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