Scaling analysis of passive residual heat removal heat exchanger

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Abstract: When the station blackout accident happens on the pressurized water reactor nuclear power plant, the reactor core decay heat could be transferred to the second circuit by the natural circulation which between core and steam generator (SG). When the water level on the SG secondary side drops to the low level, the passive residual heat removal system (PRHR) will put into operation. In later time, the PRHR system plays a leading role in carrying out the core decay heat. Therefore, the heat exchange capacity of PRHR is an important factor which affecting the safety of the reactor. In order to verify the functionality of security systems on the new advanced pressurized water reactor technology, it is usually needed to carry out large-scale engineering verification tests. And in order to ensure that important phenomenon between prototype plant and test are similar, it is needed to carry out the scaling analysis. Taking the station blackout accident of passive nuclear power plant as research background, this paper uses H2TS method to take the scaling analysis. It focuses on the thermal-hydraulic behavior of PRHR system, and obtains the similar criterion between the prototype PRHR system and test PRHR system under the station blackout accident. It also carries out the distortion analysis. The conclusions gained are as follows. To ensure height ratio and flow area ratio of the passive residual heat removal heat exchanger (PRHR HX) are consistent with the integral system ratios, the geometric shape and arrangement type of heat transfer tubes are same with prototype, it is easy to establish similarity between test and prototype. It uses the same physical properties method to simulate the station blackout accident, the exchange capacity of the PRHR system has some distortion. But the heat exchange capacity of PRHR HX in the nuclear power plant has some design margin, you can adjust the heat exchanger pipe diameter and number to ensure PRHR HX is still able to meet the needs of core cooling function, even it has some distortion.

Keyword: scaling analysis; PRHR HX; station blackout; similar criterion

1 Introduction

After the Fukushima nuclear accident, the study of station blackout accident mitigation measures was widespread attention [1-8]. As the station blackout accident could result in serious consequences, the advanced nuclear technology has been modified or improved the appropriate safety systems in response to the station blackout accident. AP1000 is an advanced three-generation nuclear reactor; its safety system uses the passive safety design. For passive nuclear power plant, the loss of off-site power accident conditions is as same as the station blackout accident for tradition nuclear power plants. When the station blackout accident happens, the core decay heat is mainly exported through natural circulation of passive systems. The natural circulation process includes two parts. The first natural circulation between the core and SG is by evaporating the water inventory of the SG secondary side to remove the reactor core decay heat in the early accident. The second natural circulation between the core and PRHR system which heat sink is passive containment cooling system, the process will continue for a long time. Therefore, the second natural circulation will remove the most of core decay heat, it is an important means of core cooling. In order to verify the safety system ability of remitting the station blackout accident consequence, it usually needs to carry out large-scale engineering verification test. During the test design process, the scaling analysis work will carry out to ensure that the important phenomena between the test and prototype plant are similar.

The hierarchical two-tiered scaling analysis (H2TS) method is a methodology for dealing with complex,

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interacting physico-chemical processes via experiments, computer codes and/or dynamic analysis. The methodology uses concepts from the hierarchical theory developed for analyzing large, complex systems [9].

This paper takes the PRHR system of passive nuclear power plant as the research background, and uses the H2TS method to carry out the scaling analysis. It focuses on the natural circulation between the core and PRHR system during the station blackout. It could provide the guidance for the design or rehabilitation of the test facility.

2 System loop and accident sequence profile

AP1000 main loop consists of reactor core, pressurizer, steam generator and the main coolant pump. It sets up the passive core cooling system which include core makeup tank (CMT), accumulator, in-containment refueling water storage tank (IRWST) and PRHR HX [10].The main system apparatus shown in Fig.1.

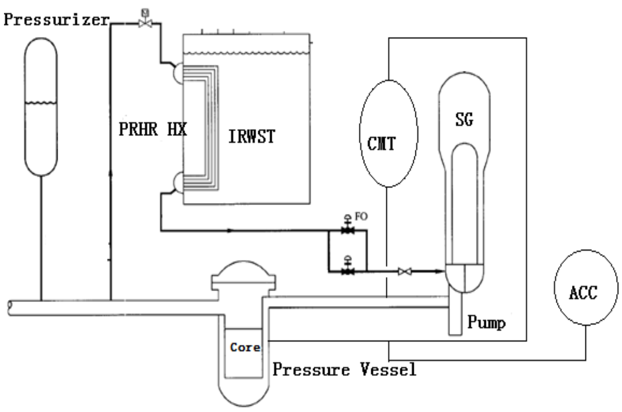

Fig.1 AP1000 main loop system and passive core cooling system.

The station blackout accident sequences of AP1000 are as follows [11]: When the station blackout happens, the secondary loop losses the feed water and the main pump idler turn. The system heat transfer capacity rapidly decline, main loop temperature rises, in a very short time, the steam generator and main loop reach the overpressure condition. The main loop pressure drops after the pressurizer relief valve open. When main loop pressure drops to the setting value or less, the valve is closed, then the main loop temperature rise again. During this process, the SG secondary side water level dropped gradually. When it drops to the low level, it will trigger the PRHR isolation valve to open, and the PRHR system puts into operation.

PRHR natural circulation and SG natural circulation export heat collectively from core, and it continues for a long time. When the reactor cold leg coolant appears low temperature signal, the CMT operates. The CMT operates in cycle mode, and the boron-containing cold water in CMT accelerates the core cooling, it flows slowly as for its temperature rises. Eventually, the core decay heat power and PRHR natural circulation reach the balance condition. The core decay heat is transferred out by the natural circulation between the core and PRHR system for a long period of time during the station blackout accident, the passive containment cooling system is its heat sink and the ultimate heat sink is the atmosphere. Therefore, there is sufficient capacity to achieve the core cooling function. Due to the importance of PRHR system, it needs the detailed scaling analysis for PRHR system when carrying out the test study of station blackout accident.

3 Scaling analysis for main loop natural circulation

Through the tireless efforts of Ishii *et al.*, they establish the foundation for the single-phase and two-phase simulation methods about the reactor natural circulation, and determine the fundamental equation and simulation ideas for PWR natural circulation scaling analysis methods [11]. The simple analysis for the natural circulation phenomena in the main loop are as follows.

When station blackout accident happens, the natural circulation which is established between the core and SG belong to single-phase natural circulation. For single-phase natural circulation, the heat transfer change in the core leads to local density changes, but that will not immediately have a great impact on the flow rate, so, it could ignore density partial differential terms of time and apply the Boussinesq hypothesis to single-phase natural circulation [12], the system control equations are as follows:

Mass conservation equation:

$$\rho_i u_i a_i = \rho_r u_r a_r \tag{1}$$

Momentum conservation equation:

$$\rho_r \sum_i (l_i \frac{a_r}{a_i}) \frac{\partial u_r}{\partial t} = \Delta \rho g l_{hc} - \frac{\rho_r u_r^2}{2} \sum_i \left[(\frac{\rho_r}{\rho_i}) \times (\frac{a_r}{a_i})^2 (\frac{fl}{d_h} + k) \right] \quad (2)$$

Energy conservation equation:

$$\frac{\partial \rho_i h_i}{\partial t} + \frac{\partial \rho_i u_i h_i}{\partial s} = (\frac{a_s}{a_i}) q_s - (\frac{a_s}{a_i}) \frac{\partial (\rho_s c_{vs} T_s)}{\partial t} \quad (3)$$

In above formulas, s is the loop along the way, h_i is the fluid enthalpy, c_{vs} is the specific heat capacity at constant volume, T_s is the solid temperature, q_s is the volume heat release rate, l_{hc} is the difference temperature between cold core and hot core, u_i is the fluid velocity, ρ is the density, a is the cross-sectional area.

Expressing the control equations in dimensionless form, we get the follows dimensionless similarity criterion numbers:

Richardson number：

$$\Pi_{Ri} = \frac{g \Delta \rho_0 l_{hc}^0}{\rho_r u_0^2} \quad (4)$$

Friction number：

$$\Pi_{Fi} = \sum_i (\frac{a_r}{a_i})^2 (\frac{\rho_r^+}{\rho_i^+}) \times (\frac{fl}{d_h} + K)_i \quad (5)$$

Heat source number：

$$\Pi_H = \frac{l_{hc}^0 q_s^0}{\rho_r^0 h_i^0 u_0} (\frac{a_s}{a_i}) \quad (6)$$

Heat capacity number：

$$\Pi_C = \frac{\rho_s c_{vs} T_s^0}{\rho_r^0 h_i^0} (\frac{a_s}{a_i}) \quad (7)$$

In above formulas, f is the friction coefficient, K is the local loss coefficient, d_h is the diameter, the superscript 0 means the value which under the initial moment, the superscript r means the value which at the inlet.

To make the natural circulation phenomena between the test and prototype to be similar, it should meet the follow criteria:

$$(\Pi_{Ri})_R = (\Pi_{Fi})_R = (\Pi_H)_R = (\Pi_C)_R = 1 \quad (8)$$

Suppose the test and prototype plant use the same physical property parameter, thus eliminating the physical parameters in above dimensionless number. According to the formula (8), we can obtain the following relationships [13]:

Velocity ratio:

$$(u)_R = l_R^{1/2} \quad (9)$$

Time ratio：

$$(\tau)_R = l_R^{1/2} \quad (10)$$

Core power ratio：

$$(Q)_R = (ua)_R = V_R * l_R^{-1/2} \quad (11)$$

Usually, the height ratio between test and prototype is determined by the experimenter according to the test requirements, and the power ratio can be determined by the test run parameters. According to the above three formulas, it can be considered the integral height ratio $(l)_R$, velocity ratio $(u)_R$, time ratio $(\tau)_R$ and cross-sectional flow area ratio $(a)_R$ are determinate.

4 Scaling analysis for PRHR system

The PRHR system consists of pipes, valves and PRHR HX, in which PRHR HX is a key component to implement its system functions. The PRHR HX consists of the inlet chamber head, the outlet chamber head and C-type tube bundle. The C-type tubes are placed in the in-containment refueling water storage tank. All the C-type heat transfer tubes in the PRHR HX have the similarity, these tubes constitute some thermal hydraulics channels which have a high degree of geometric similarity. So, it can choose a single heat transfer tube for the study during the scaling analysis, and the arrangement type of heat transfer tube is consistent with the prototype. Thus, it is easy to ensure the similar relationships.

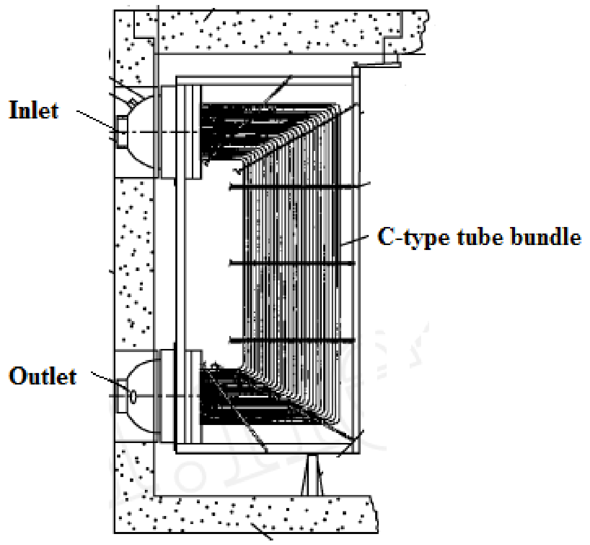

Fig.2 The passive residual heat removal heat exchanger.

PRHR HX is a part of the test system, in order to ensure that it has similarities with the prototype device, it should meet the height ratio, velocity ratio and flow area ratio of the system.

$$(l_{\text{PRHR}})_R = l_R \quad (12)$$

$$(a_{\text{PRHR}})_R = (N * a_{tube})_R = a_R \quad (13)$$

For formula (13), the total flow area of PRHR HX tube bundle is equal to the product of a single heat transfer pipe flow area and quantity, and the PRHR HX flow area ratio is equal to the flow area ratio of the system. As the flow area ratio of the system has been determined, it could determine the number of heat transfer tubes by changing the single tube flow area. In the actual test design process, the choice for inner and outer diameter of the heat transfer tube according to the GB17395.

$$(N)_R = \frac{a_R}{(a_{\text{tube}})_R} \qquad (14)$$

In summary, it can determine the height, flow area, quantity of the heat transfer tubes by the formula (12), (13), (14). The arrangement type of heat transfer tubes is consistent with the prototype PRHR HX. Thus, it can determine all the geometric parameters of the PRHR HX.

5 Analysis of scale distortion

Although it is easy to establish the similar relationship when the geometry of heat exchanger is similar with the prototype, but there has some distortion due to the decrease of geometry size. This part analyses the distortion of the heat exchange capacity.

The relationship of heat exchange capacity is as follow.

$$(q)_R = (hA\Delta T)_R \qquad (15)$$

Where, h is the convective heat transfer coefficient, A is the heat transfer area, ΔT is the temperature difference between the inside and outside of tubes.
According to the D-B formula, the relationship of convective heat transfer coefficient is as follow.

$$(h)_R = (\frac{Nu\lambda}{d})_R = (\frac{\mathrm{Re}^{0.8}\lambda}{d})_R = (\frac{u^{0.8}\lambda}{d^{0.2}\upsilon^{0.8}})_R \qquad (16)$$

Where, Nu is the Nusselt number, λ is the thermal conductivity of the fluid, d is the diameter of the heat transfer tube, Re is the Reynolds number, u is the fluid velocity, υ is the kinematic viscosity.

The total heat transfer area is equal to the product of a single heat transfer tube heat transfer area and quantity. The formula is as follow.

$$(A)_R = (Ndl)_R \qquad (17)$$

Since the physics property of the test is same as the prototype, so the temperature difference between inside and outside of the tubes are also same. Through the formula (16), (17) and (15), we can obtain the follow formula.

$$(q)_R = (hA)_R = \frac{a_R * l_R^{1.4}}{d_R^{1.2}} \qquad (18)$$

Comparing the formula (18) to the formula（11）, we can obtain the follow formula.

$$\frac{(q)_R}{(Q)_R} = \frac{a_R * l_R^{1.4}/d_R^{1.2}}{(au)_R} = \frac{l_R^{0.9}}{d_R^{1.2}} \qquad (19)$$

The formula (19) shows that the ratio between heat exchange capacity and core power is connected with the height ratio and the diameter ratio.

The Fig.3 shows that the ratio between heat exchange capacity and core power changes with the height ratios under different diameter ratios according to the formula (19), when this ratio is no less than 1, the heat exchange capacity has no distortion. If the heat transfer tube diameter ratio is equal to 1, it is more conducive to meet the similarity of pipe resistance and thermal resistance. In this case, the ratio between heat exchange capacity and core power is only connected with the height ratio, so the heat exchange capacity has no distortion on the full-height test facility. But, there will be a certain distortions of heat exchange capacity on no full-height test facility. Taking into account that the PRHR heat exchange capacity has a certain margin in the design, the PRHR heat exchange capacity of distortion is acceptable when the height of test facility decrease just a few. If the height of test facility decreases a lot, it can decrease the diameter of heat transfer tubes and increase the number to reduce the distortion of heat exchange capacity, making the design of the heat exchanger can meet the test requirements.

The detailed scale distortion will be summarized in Table 1.

In summary, the PRHR HX is designed to meet the requirements in part 3 under the station blackout accident, as long as the height ratio between test and prototype is not too small, the distortion of heat exchange capacity of the PRHR HX is acceptable.

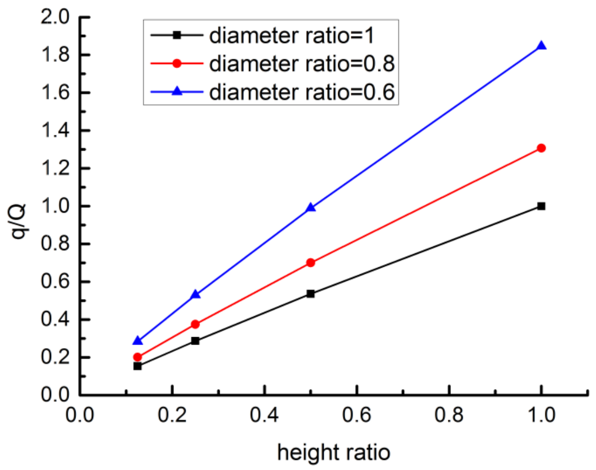

Fig.3 The ratio between heat exchange capacity and core power changes with the height ratio under different diameter ratios.

Table 1 The distortion under the different height ratios and diameter ratios.

Distortion		Diameter ratios 1	0.8	0.6
Height ratios	1	no distortion	no distortion	no distortion
	1/2	46%	30%	2%
	1/3	73%	63%	47%
	1/4	85%	80%	62%

6 Conclusion

In this paper, it carries out the scaling analysis for the thermal hydraulics behavior of the PRHR HX and obtains the corresponding similarity criteria. The conclusions are as follows:

(1) If it uses the same physical properties to simulate the prototype plant, the design of PRHR HX should ensure that the height ratio and the flow area ratio are consistent with the integral system ratios, and the arrangement type of heat transfer tubes is consistent with the prototype. Thus, it can ensure the similarity of natural circulation which between the test facility and the prototype.

(2) If the height ratio and the tube diameter ratio are equal to 1, it not only can guarantee the similarity of resistance characteristics, but also can avoid the distortion of heat exchange capacity.

(3) If the height ratio is less than 1, you can reduce the heat transfer tube diameter to increase the heat transfer capacity of the PRHR HX. So, it can guarantee the distortion of heat exchange is acceptable within a certain range.

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