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Steady characteristic investigation on passive residual heat removal system of Chinese advanced PWR

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Abstract Thermal-hydraulic characteristic investigation on passive residual heat removal system (PRHRS) of Chinese advanced PWR was conducted to provide input data for PRHRS design and to demonstrate the feasibility of unique design features. A total of 237 sets of test data at steady state have been obtained and the main influence factors on the two-phase natural circulation flow rate and residual heat removal capability were identified. On the basis of theory analysis, a correlation of two-phase natural circulation was obtained, and relative errors of 95% test data were less than ±16%. There is a considerable effect of the system status parameters on the threshold of height between heat source and heat sink, and its correlation of two-phase natural circulation system has been obtained. The steady characteristic research shows that PRHRS has the capability of removing the core decay power through natural circulation.

Key words Chinese advanced PWR, Passive residual heat removal system, Steady characteristics

CLC number TL33

1 Introduction

Since TMI and Chernobyl accidents, the safety of nuclear power plant (NPP) has been addressed extensively and strictly by both administrative authorities and the public. Especially, there are considerable concerns over the safety of an ordinary light water reactor. To improve the safety of the nuclear reactors, the safety authorities recommended the implementation of passive systems, an NPP safety technology that has been adopted in a number of new concept reactors, including AP600, EPP1000, SPWR, WWER1000 and MS600[1]. Adoption of the passive safety system improves the reactor's safety and reliability, but it has some problems that have not been solved perfectly by theoretical calculation. Therefore, tests are necessary for verifying the system design and assessing the safety analysis code.

The Chinese advanced Pressurized Water Reactor (CAPWR) uses passive safety systems. In this paper, we report the study on thermal-hydraulic characteristics of its passive residual heat removal system (PRHRS). It was conducted to provide the design parameters and to demonstrate feasibility of the design. A total of 237 sets of test data at steady state were obtained and the main influence factors, e.g. the system pressure, height between heat source and heat sink, system effective resistance coefficient, and wind velocity, on the two-phase natural circulation flow rate and residual heat removal capability were determined. The main operation parameters are shown in Table 1. The comprehensive test facility of PRHRS (Fig.1) was built by Nuclear Power Institute of China. Its mechanism, structure and design parameters can be found elsewhere[2].

Table 1 Parameters of the steady state test

Parameters	Values
Height between heat source and heat sink / m	7, 11, 15
Chimney height / m	8.8, 10.8, 12.8
Slope angle of air-cooler / rad	0, $\pi/3$
Pressure / MPa	1.3~8.2
Heating power / kW	60~140
Natural circulation flowrate / $kg \cdot h^{-1}$	110~298
Wind speed / $m \cdot s^{-1}$	0.65~4.3
Circumstance temperature / °C	29~35

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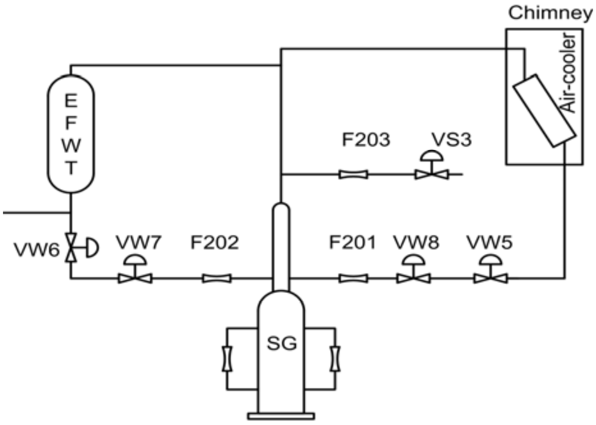

Fig. 1 Schematic diagram of PRHRS test facility for Chinese advanced PWR.

1.1 System characteristic parameters

1.1.1 System equivalent diameter and system equivalent area[3]

System equivalent diameter

$$D_e = \frac{4V_{loop}}{S_{wet}} = \frac{4\sum_i A_i L_i}{\sum_i \pi D_i L_i}$$

where V_{loop} and S_{wet} are total volume and wetted area of the system, respectively, L_i, D_i and A_i *are* the length, equivalent hydraulics diameter and flow area of every section, respectively. System equivalent area

$$A_e = \frac{V_{loop}}{\sum_i L_i} = \frac{\sum_i A_i L_i}{\sum_i L_i}$$

1.1.2 System effective resistance coefficient[4]

System effective resistance coefficient

$$K_{eff} = \sum \frac{A_e^2}{A_i^2}\left(\frac{f_i L_i}{D_i} + K_i\right)$$

where f_i and K_i represent friction coefficient and form loss coefficient, respectively.

1.1.3 System characteristic velocity[5, 6]

According to inherent characteristic for PRHRS of Chinese advanced PWR, system characteristic velocity of $D_e^3\rho_r^2 g\beta q_s L_{th} / (A_e\mu^3 C_P)$ for single-phase natural circulation could not meet the need of two-phase natural circulation. Therefore, the parameter group U_m, regarded as system characteristic velocity is defined as

$$U_m = \left(\frac{D_e L_{th}}{A_e^2}\right)\left(\frac{q_s \rho_g}{\Delta\rho \rho_f h_{fg}}\right)$$

where q_s, ρ_f, ρ_g, h_{fg} and L_{th} are respectively heating power, saturated liquid density, saturated steam density, latent heat of evaporation and height between the heat source and heat sink , and $\Delta\rho = \rho_f - \rho_g$.

1.1.4 Height between heat source and heat sink[7]

Height between the heat source and heat sink (Fig. 2) is connected to the cold center of heat sink (air cooler) and heat center of heat source (steam generator).

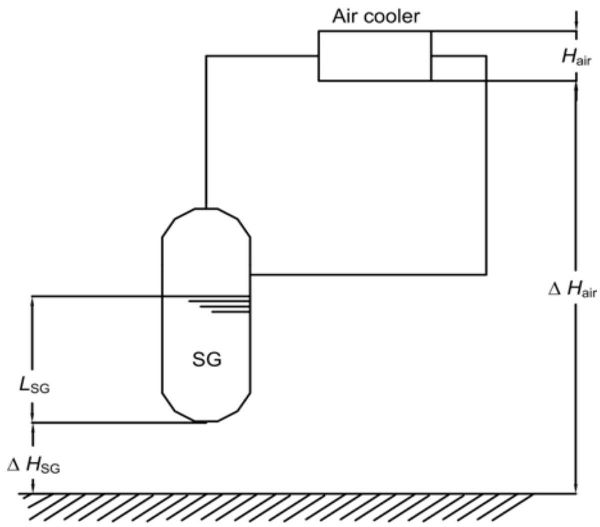

Fig. 2 Schematic diagram of height between heat source and heat sink.

Height of the cold center of heat sink is approximately defined as

$$L_{thair} = H_{air}/2 + \Delta H_{air}$$

where ΔH_{air} is the height between bottom of air cooler and datum plane, H_{air} is height of air cooler. Height of the center of heat source is approximately defined as

$$L_{thSG} = L_{SG}/2 + \Delta H_{SG}$$

where ΔH_{SG} is the height between bottom of steam generator and datum plane, L_{SG} is liquid level of steam generator. Height between the heat source and heat sink is defined as

$$L_{th} = L_{thair} - L_{thSG}$$

1.1.5 Modified Reynolds number for natural circulation system

Height between heat source and heat sink may be defined as system characteristic length, so modified Reynolds number can be expressed as

$$Re_{\mathrm{m}} = \frac{U_{\mathrm{m}} L_{\mathrm{th}}}{\nu} = \left(\frac{D_{\mathrm{e}} L_{\mathrm{th}}^{2}}{A_{\mathrm{e}}^{2}}\right)\left(\frac{q_{\mathrm{s}} \rho_{\mathrm{g}}}{\Delta\rho \rho_{\mathrm{f}} h_{\mathrm{fg}} \nu}\right)$$

where U_{m} and ν represent system characteristic velocity and liquid kinematic viscosity, respectively.

1.2 Theoretical solution

On the basis of basic assumption, analytical solution of two-phase natural circulation can be obtained through continuity equation, momentum equation and energy equation for two-phase natural circulation.

1.2.1 Basic assumptions

The basic assumptions of (1) one dimension model, (2) incompressible flow, (3) negligible effect of pressure, (4) steady flow, (5) being liquid in the outlet of air cooler and (6) negligible loss of viscous dissipation are adopted.

1.2.2 Analytical solution

Based on the assumptions, governing equations of two-phase natural circulation can be written as[8, 9]

continuity equation

$$\frac{\partial W}{\partial Z} = 0 \tag{1}$$

momentum equation

$$\Sigma\left(\frac{\rho_i U_i^2}{2}\right)\left(f_i \frac{L_i}{D_i} + K_i\right) = (\rho_{\mathrm{l}} - \rho_{\mathrm{g}}) L_{\mathrm{th}} g \tag{2}$$

where U_{i} is flow velocity in every section. Energy equation

$$W(h_{\mathrm{g}} - h_{\mathrm{l}}) = q_{\mathrm{s}} \tag{3}$$

where W, h_{i} and h_{g} are respectively flow rate, saturation steam enthalpy and fluid enthalpy in the outlet of air cooler. From Eqs.(1) and (2), one gets

$$\frac{W^2 K_{\mathrm{eff}}}{2 A_{\mathrm{e}}^2 \bar{\rho}} = (\rho_{\mathrm{l}} - \rho_{\mathrm{g}}) L_{\mathrm{th}} g \tag{4}$$

where $\bar{\rho} \approx (\rho_{\mathrm{f}} + \rho_{\mathrm{g}})/2$ is system density meaning time values.

With a thermal expansion coefficient[10], one has

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P \tag{5}$$

Eq.(5) can be expressed as

$$\rho_{\mathrm{l}} = \frac{\beta \rho_{\mathrm{f}} (h_{\mathrm{f}} - h_{\mathrm{l}})}{C_{\mathrm{P}}} + \rho_{\mathrm{f}} \tag{6}$$

Combining Eqs.(3), (4) and (6), we have

$$\frac{W^2 K_{\mathrm{eff}}}{2 A_{\mathrm{e}}^2 \bar{\rho}} = \left[\frac{\beta \rho_{\mathrm{f}} \left(\frac{q_{\mathrm{s}}}{W} - h_{\mathrm{fg}}\right)}{C_{\mathrm{P}}} + \rho_{\mathrm{f}} - \rho_{\mathrm{g}}\right] L_{\mathrm{th}} g \tag{7}$$

Eq.(7) can be expressed as

$$W^3 + \left(\frac{\beta \rho_{\mathrm{f}} h_{\mathrm{fg}}}{C_{\mathrm{P}}} - \Delta\rho\right) L_{\mathrm{th}} g \frac{2 A_{\mathrm{e}}^2 \bar{\rho}}{K_{\mathrm{eff}}} W - \frac{\beta \rho_{\mathrm{f}} q_{\mathrm{s}}}{C_{\mathrm{P}}} L_{\mathrm{th}} g \frac{2 A_{\mathrm{e}}^2 \bar{\rho}}{K_{\mathrm{eff}}} = 0 \tag{8}$$

Let

$$B = \left(\frac{\beta \rho_{\mathrm{f}} h_{fg}}{C_{\mathrm{P}}} - \Delta\rho\right) L_{\mathrm{th}} g \frac{2 A_{\mathrm{e}}^2 \bar{\rho}}{K_{\mathrm{eff}}}$$

$$C = -\frac{\beta \rho_{\mathrm{f}} q_{\mathrm{S}} L_{\mathrm{th}} g}{C_{\mathrm{P}}} \cdot \frac{2 A_{\mathrm{e}}^2 \bar{\rho}}{K_{\mathrm{eff}}}$$

Eq.(8) can be written as

$$W^3 + BW + C = 0 \tag{9}$$

Form loss has a key action on natural circulation system, so K_{eff} is a weak function of W. It is assumed that B and C have nothing with W. On the other hand, while heating power, system pressure, height between heat source and heat sink, and system resistance are definite, natural circulation flow rate is also definite. So Eq.(9) has only real root, and its solution is

$$W = \sqrt[3]{-\frac{C}{2} + \sqrt{\left(\frac{C}{2}\right)^2 + \left(\frac{B}{3}\right)^3}} + \sqrt[3]{-\frac{C}{2} - \sqrt{\left(\frac{C}{2}\right)^2 + \left(\frac{B}{3}\right)^3}} \tag{10}$$

2 Correlation of two-phase natural circulation

It is difficult to determine friction coefficient and form loss coefficient, because the fluid in upward and downward section for the PRHRS is regarded as saturated steam and liquid, respectively, and the air cooler undergoes phase change from saturated steam to liquid. By analyzing the system characteristic parameters (Fig. 3), the modified Reynolds number can be introduced, and one can decide that system effective resistance coefficient is

$$K_{\text{eff}} = A_1 Re_{\text{m}}^{A_2}$$

where A_1 and A_2 the relevant experimental coefficient.

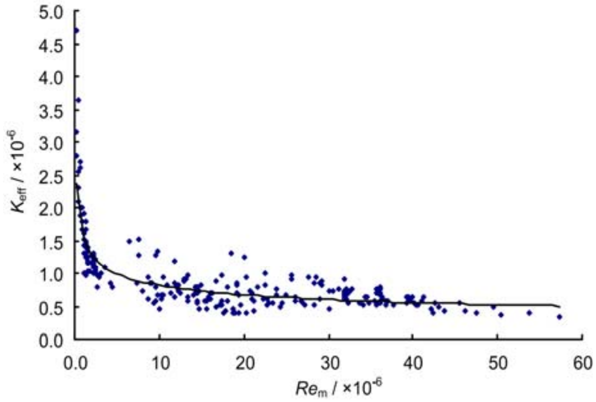

Fig.3 System effective resistance coefficient vs. modified Reynolds number.

Based on the model of system effective resistance coefficient, 237 sets of experimental data were used to analyze steady characteristic of the two-phase natural circulation. The correlation of system effective resistance coefficient can be written as

$$K_{\text{eff}} = 7.45 \times 10^{7} / Re_{\text{m}}^{0.28} \tag{11}$$

It was found that 90% of the deviations to the 237 sets of experimental data were within ±40% (Fig.4).

With the calculated K_{eff} using Eq.(11), steady flow rate of the two-phase natural circulation could be calculated with Eq.(10) and 95% of the data deviate within ±16% (Fig.5) from the 237 sets of experimental data.

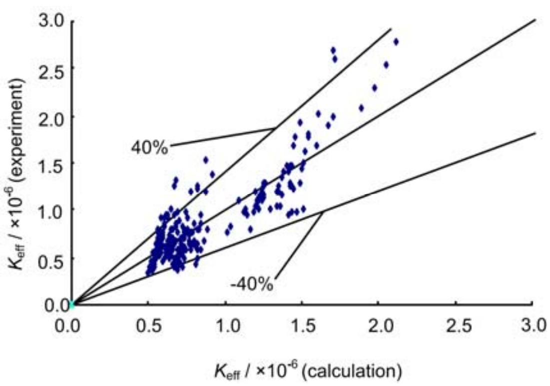

Fig.4 Experimental and calculated system effective resistance coefficient.

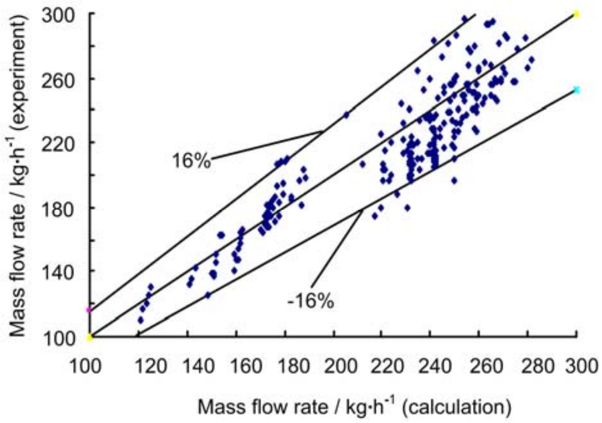

Fig.5 Experimental and calculated mass flowrate of two-phase natural circulation.

3 System analysis

3.1 The threshold of height between heat source and heat sink

For a given system, status parameters (such as system pressure and valve form loss coefficient) and system boundary conditions (such as circumstance temperature and chimney height), wind velocity provided by chimney is limited. So the secondary outlet air temperature of air cooler is confined by heat exchanging capability of air cooler.

Although height between heat source and heat sink is large enough to make natural circulation flow rate big enough, heat exchanging capability of air cooler is too poor to make primary saturated vapor cooled to be saturated water or subcooled water completely. So two-phase flow instability of natural circulation system presents.

Typical test results of the threshold of height between heat source and heat sink is shown in Fig. 6. When outlet flow of air cooler is two-phase flow, two-phase flow instability of natural circulation system occurs. So when saturated steam from steam generator is condensed into saturated water by air cooler, height between heat source and heat sink is the threshold of height between heat source and heat sink. Since the threshold height between heat source and heat sink is not a constant, there is a considerable effect of system status parameter and system boundary condition on the threshold of height between heat source and heat sink.

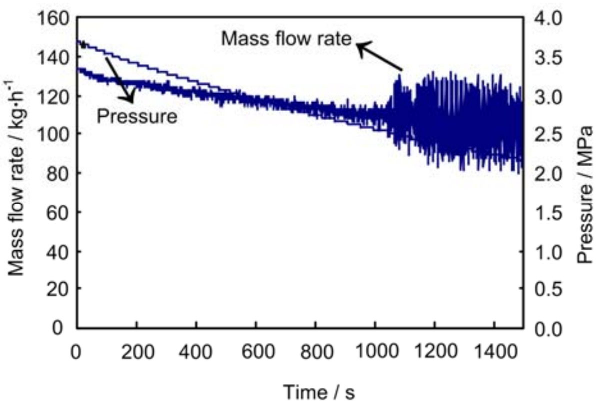

Fig.6 Typical test of the threshold of height between heat source and heat sink

For primary side of air cooler, residual heat removal capability may be written as follows

$$W(h_g - h_f) = q_s \tag{12}$$

The threshold height between heat source and heat sink can be calculated from Eqs.(10)~(12).

3.2 Effect of height between heat source and heat sink on residual heat removal capability

As shown in Figs. 7 and 8, if height between heat source and heat sink is less than the threshold height, residual heat removal capability and the system natural circulation flow rate increase with the height between heat source and heat sink, because of increased driving force of natural circulation. But residual heat removal capability is not always influenced by height between heat source and heat sink in the steam-water system with air cooler, which differs from normal natural circulation system.

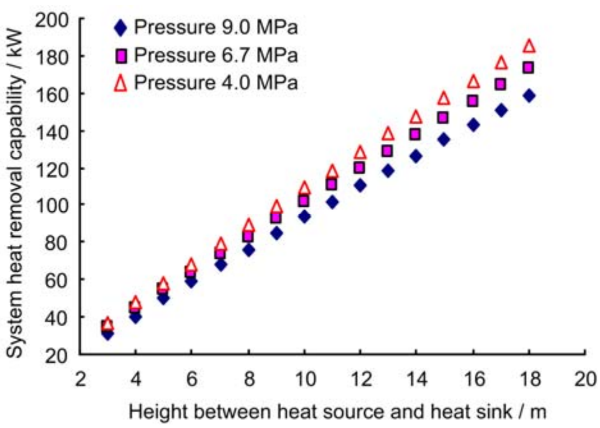

Fig.7 Residual heat removal capability *vs.* height between heat source and heat sink.

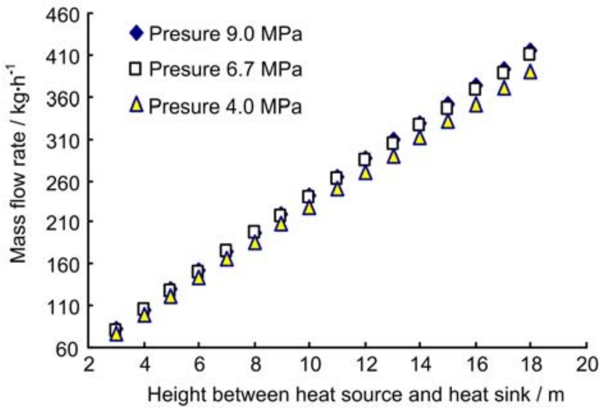

Fig.8 Mass flowrate of natural circulation *vs.* height between heat source and heat sink.

As shown in Fig.9, the threshold of height between heat source and heat sink increases with system pressure. When height between heat source and heat sink is up to the threshold height, outlet flow of air cooler is two-phase flow and the natural circulation system is instable. The system pressure will increase until the system is stable. This is called the characteristic of self-adaptation and self-coupling in two-phase natural circulation system.

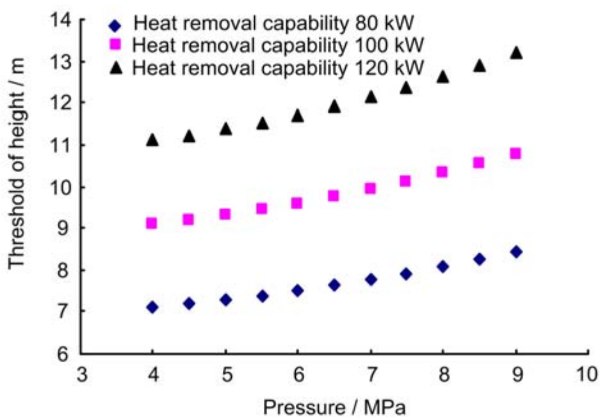

Fig.9 Residual heat removal capability *vs.* the threshold of height between heat resource and heat sink.

3.3 Effect of system pressure on residual heat removal capability

As shown in Fig.7, there are few changes for residual heat removal capability as system pressure increases, but general trend is that residual heat removal capability decreases with increasing system pressure. As shown in Fig.8, there are few changes for natural circulation flow rate under increased system pressure, but general trend is that natural circulation flow rate increases with the system pressure. The driving force of natural circulation becomes larger under higher system pressure, because of greater density difference between steam and water and system effective resistance coefficient. General effect is that it needs more natural circulation flow rate to remove the same quantity of heat because latent heat of evaporation decreased with increasing system pressure.

3.4 Effect of system effective resistance coefficient on natural circulation flowrate

As shown in Fig.10, when the system effective resistance coefficient is smaller, natural circulation flow rate deceases considerably as the system effective resistance coefficient increases. When the system effective resistance coefficient is up to 3×10^6, natural circulation flow rate does not always change as the system effective resistance coefficient increases.

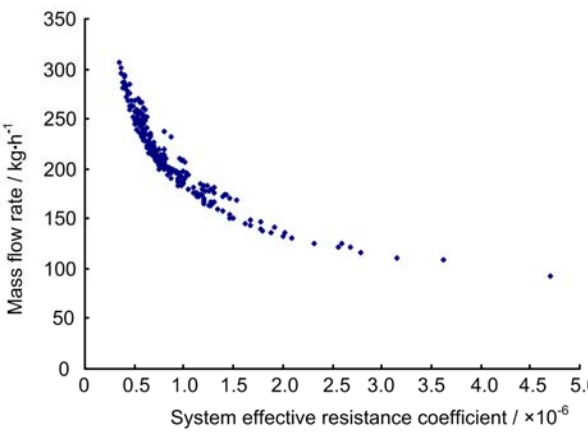

Fig.10 Mass flowrate of natural circulation *vs.* system effective resistance coefficient.

The characteristic is different from single-phase natural circulation system. There are two reasons. One is that height between heat source and heat sink increases as the system effective resistance coefficient increases with reduced water level of steam generator. The other is that the density difference between steam and water increases as the system effective resistance coefficient increases because the water temperature in down-comer drops. Both will increase the driving force of natural circulation. The driving force of natural circulation increases slightly when the system effective resistance coefficient is smaller. The driving force of natural circulation increases simultaneously with the system effective resistance coefficient when the equivalent system resistance coefficient is up to a specific value.

3.5 Effect of wind velocity on residual heat removal capability

Air momentum equation in chimney may be written as follows

$$(\rho_{\mathrm{chi}} - \rho_{\mathrm{cho}})gL_{\mathrm{ch}} = \frac{k_{\mathrm{ch}}W_{\mathrm{a}}^2}{2\rho_{\mathrm{ch}}A_{\mathrm{ch}}^2} \qquad (13)$$

where ρ_{chi} and ρ_{cho} are air density of inlet and outlet of chimney, respectively, L_{ch} is chimney height, W_{a} is air flowrate in chimney, k_{ch} is general resistance coefficient of chimney, A_{ch} is cross section area of chimney, ρ_{ch} is the air average density of inlet and outlet in chimney.

Air energy equation in chimney may be written as follows

$$q_{\mathrm{s}} = W_{\mathrm{a}}(H_{\mathrm{ao}} - H_{\mathrm{ai}}) \qquad (14)$$

where H_{ai}, H_{ao} are inlet and outlet air enthalpy respectively.

According to the air momentum equation and air energy equation, the followings can be learned. (1) Wind velocity of air natural convection is determined by chimney height, general resistance coefficient of chimney, air inlet and outlet temperature. (2) Wind velocity of air natural convection will affect heat removal capability of air cooler. (3) Heat removal capability of air cooler will meet the demand when chimney height is larger than a specific value.

In the test, the chimney height was 8.8 m, 10.8 m and 12.8 m, respectively, and the range of wind velocity of air natural convection was 1.65~4.3 m·s^{-1}. As shown in Fig.11, when the wind velocity is no less than 1.8 m·s^{-1}, air inlet temperature is 29~35°C and height between heat source and heat sink is 7m, the heat of 100 kW can be removed by natural circulation.

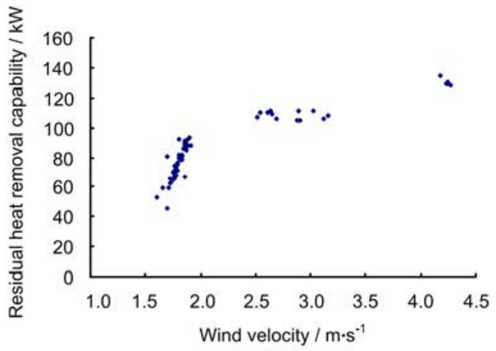

Fig.11 Residual heat removal capability *vs.* wind velocity.

4 Conclusions

The study on PRHRS of Chinese advanced PWR can be concluded as follows.

(1) The characteristic research shows that the PRHRS has the capability of removing the core decay power through natural circulation.

(2) On the basis of theory analysis, a correlation of two-phase natural circulation has been obtained. The relative errors of 95% experimental data were less than ±16%.

(3) There is a considerable effect of system status parameters (such as system pressure and valve form loss coefficient) and system boundary conditions (such as circumstance temperature and chimney height) on the threshold of height between heat source and heat sink, and its correlation for the two-phase natural circulation system has been obtained.

(4) When the system effective resistance coefficient is smaller, natural circulation flowrate and residual heat removal capability are decreased considerably as the system effective resistance coefficient is increased. When the system effective resistance coefficient is up to 3×10^6, natural circulation flowrate is not always changed as the system effective resistance coefficient is increased. This is called the characteristic of self-adaptation and self-coupling in two-phase natural circulation system.

References

1 Juhn P E, Kupitz J, Cleveland J, *et al.* Nucl Eng Des, 2000, **201:** 41-59.

2 Xiao Z J, Zhuo W B, Zheng H, *et al.* Nucl Eng Des, 2003, **225:** 305-313.

3 Zvirin Y, Jeuck P R, Sullivan C W, *et al.* J Heat Transf, 1981, **103:** 645-652.

4 Vijayan P K, Mehta S K, Date A W. Int J Heat Mass Transf, 1991, **34:** 2219-223.

5 Su G H, Jia D N, Fukuda K, *et al.* Nucl Eng Des, 2002, **21:** 187-198.

6 Huang Y P, Jia D N. Nucl Sci Eng (in Chinese), 1997, **17**: 202-207.

7 Ishii M, Kataoka I. Nucl Eng Des, 1984, **81:** 411-425.

8 Creveling H F, Depaz J F, Baladi J Y, *et al.* J Fluid Mech, 1975, **67:** 65-84.

9 Reyes J N. IAEA program of technical cooperation, 1995: 1-6.

10 Chen B D, Xiao Z J, Zhuo W B, *et al.* J Eng Thermophys (in Chinese), 1999, **20:** 17-21.