Survey of experiments and code development for the passive residual heat removal system of PWR in China

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Abstract Three different kinds of experiments and their typical results are surveyed for the passive residual heat removal system (PRHRS) of PWR performed in Nuclear Power Institute of China (NPIC) recent ten years. The typical results of MISAP, a special code for PWR passive residual heat removal system developed and assessed by NPIC, are also described briefly in this paper.

Keywords Passive residual heat removal system, Advanced PWR, Reactor thermal-hydraulics

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1 Introduction

The trend of nuclear power reactor development in industrialized countries speeds the emersion of new generator Nuclear Power Plant (NPP). With great improvements in reliability, economics and safety, they have a high efficiency of fuel utilization and a less release of radioactivity. At the design stage, a main consideration is given to utilization of passive safety systems and their inherent safety features. Some passive safety systems have been adopted by some advanced designs of NPP, for example, AP600, EP1000, AC600, and so on, and a lot of valid researches and experiments have been carried out in the world.

Since 1992, a series of experiments on the passive residual heat removal system (PRHRS) of PWR have been completed in Nuclear Power Institute of China (NPIC), and a special code for the secondary-side PRHRS of PWR, MISAP, has also been developed, and assessed using the experimental data. Some typical results will be surveyed in this paper.

2 Experimental research on the secondary-side PRHRS of AC600

2.1 Test facility

AC600 (Chinese 600MW advanced PWR) secondary-side passive emergency core residual heat removal system is an important part of Chinese advanced PWR passive safety system, and the simulating test facility of PRHRS of AC600 was built in NPIC according to some simulating laws in 1992. It was composed of the steam-water loop, the emergency feed-water loop, the safe discharge and relieving pressure system and so on. The flow diagram of the test facility of AC600 PRHRS is shown in Fig.1.

The simulating laws of AC600 PRHRS test facility are as follows:

(1) The corrected ratio of power to volume should be preserved in order to keep the similarity of the thermal hydraulical characteristic of the test facility to that of the prototype, and all major components of the prototype should have their corresponding simulator in the test facility. (2) In the test facility, the relative height difference between SG simulator and air-cooler simulator is adjustable and the test facility should have a wider range of working fluid parameters. (3) The same working fluid as that of the prototype was used in the test facility, and operated under the same fluid temperature and system pressure as those of the prototype.

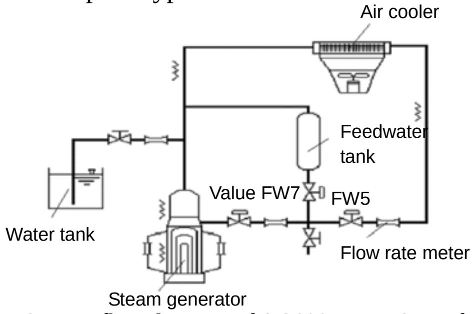

Fig.1 System flow diagram of AC600 PRHRS test facility.

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The main parameters of the AC600 PRHRS test facility are as follows: overall power-volume scaling factor is 1/390; total height of the test facility is 19 m, and relative height ratio is 1:1. The height difference between hot source and hot sink of this test facility is adjustable. The design pressure, design temperature and maximum heating power of the test facility is 8.6 MPa, 316 ^{o}C and 150 kW, respectively. The test facility is composed of main loop and emergency feed-water loop. The main components include steam generator simulator, air cooler, water tank, feed water tank, valves, etc.[1]

2.2 Typical steady-state experimental results

The steady-state experiments mainly verified the residual heat removal ability of the system by natural circulation and identified various affecting factors including the installing way of air-cooler, relative height between hot source and hot sink, system resistance, system pressure and wind speed of air-cooler.

Results of the steady state experiment show that, for this test facility and under the experimental parameter range, when air temperature is 6~23 ^{o}C, relative height between the cold and hot centers is 11 m and wind velocity in the chimney is more than 1.5 m/s，about 100 kW power (corresponding to 2% full power of AC600) can be taken by natural circulation, at this time the system flow rate is about 190~230 kg/h. It is also shown that the heated power is a main factor to affect the natural circulation flow rate, but the installing way of air-cooler has no effect on the steady-state natural circulation flow rate.

2.3 Typical transient experimental results

The main purpose of transient experiments is to research the characteristic of system's startup mode and the transition characteristics from the startup to the steady-state natural circulation. Three kinds of startup modes have been studied: the liquid column startup mode (i.e. cold startup mode), the small-flow-rate startup mode (i.e. hot startup mode), and the feed water startup mode. The typical experimental results of transient experiments are shown in Figs.2~5.

The experimental results show that the steady state natural circulation flow can be built by the three

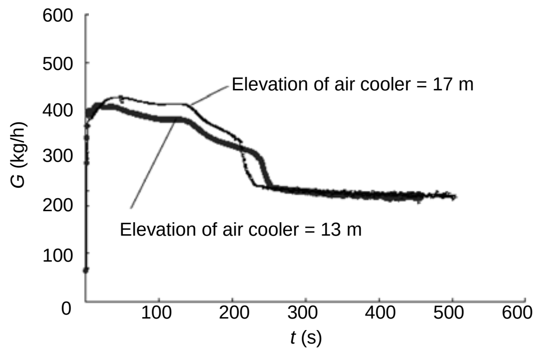

Fig.2 Effect of elevation on system flow rate under liquid –column startup mode.

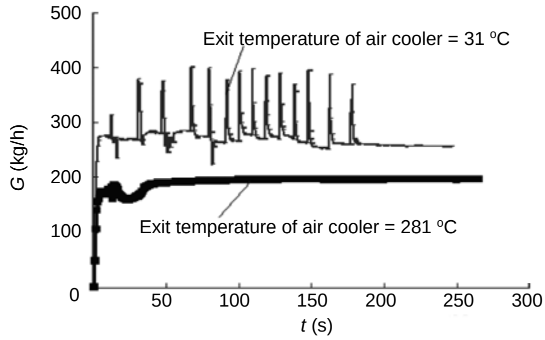

Fig.3 Effect of exit-temperature of air cooler on system flow rate under liquid column startup mode.

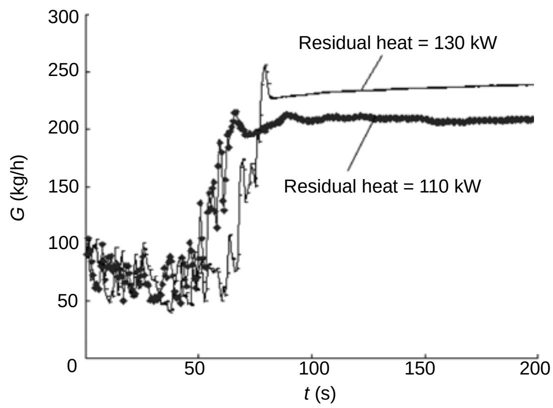

Fig.4 Typical results of system flow rate under small-flow-rate startup mode.

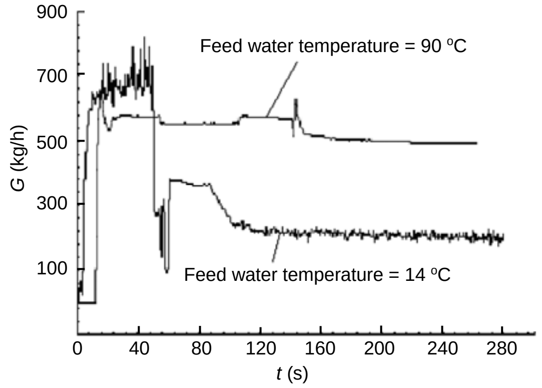

Fig.5 Typical result of feed water flow rate under feed water startup mode.

kinds of startup modes, but the stability and instable time would be affected by the startup mode, boundary condition and installing way of the equipment. Among the three kinds of startup modes, the transient characteristic of the small-flow-rate startup mode is the best.

All experimental data from the AC600 PRHRS test facility have been employed to develop the code MISAP1.0.

3 Experimental researches of PRHRS in Chinese advanced PWR

3.1 Test facility

The PRHRS test facility for Chinese advanced PWR came from reconstructing the test facility of AC600 secondary-side PRHRS. A chimney about 12 m in height was established in order to simulate natural air convection in the chimney of the prototype. The chimney's height can be changed to research the effect of the chimney's height on the process of PRHRS. A wind-door was adopted in the entrance of air-cooler to simulate the inlet resistance of chimney. At the same time, some changes have also been made in the loop and the emergency feed-water tank (EFWT). The flow diagram of PRHRS test facility for Chinese advanced PWR is shown in Fig.6.

More than 30 transient experiments have been carried out while the residual heat in the core changed from 8% to 2% full power. And more than 280 sets of steady state experiments have also been carried out and they are employed to analyze the effect on the threshold of relative height between hot source and hot sink and to assess the new code version MISAP2.0.

The startup modes include warm and cold patterns when the emergency feed-water is on or off respectively. If there is a tiny flow rate to keep a little natural circulation in both steam-water circulation loop and natural air convective loop before the startup of transient experiment, this type of startup mode is called the warm startup. On the contrary, if the initial condition is cold, or there is no flow in both team-water circulation loop and natural air convective loop, this type of startup mode is called the cold startup.

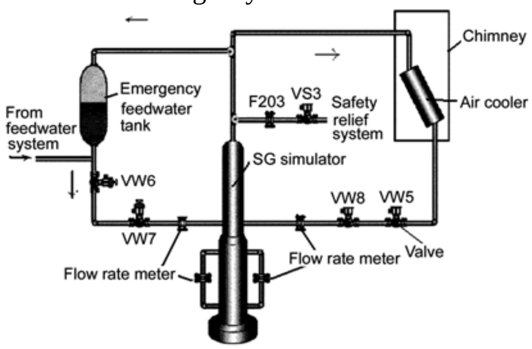

Fig.6 The flow diagram of PRHRS test facility for Chinese advanced PWR.

3.2 Results

3.2.1 Steady-state experiments

The study results show that the relative height between hot source and hot sink does not always influence the ability of heat removal in this system. In Reference[2], a set of equations has been established to calculate the maximum ability of heat removal and the relative height threshold between hot source and hot sink. The comparison with experimental data shows this prediction method to be reasonable.

3.2.2 Transient experiments

The typical results of the cold and warm startup experiments with emergency feed-water are shown in Fig.7. The pressure increases before the natural air convection in chimney is established when the residual heat is larger than that absorbed by cold water in air-cooler and EFWT. But the pressure begins to drop not only because of the less residual decay heat but also because of the air flow rate reaching its maximum, and finally the pressure reaches a plateau at the end of the emergency feed-water injection. As shown in Fig.7, there is no remarkable difference between cold and warm startups.

The system pressure increases faster and can reach higher value when feed-water loop is off. But the pressure decreases at last and does not exceed its top limit no matter which startup style is adopted.

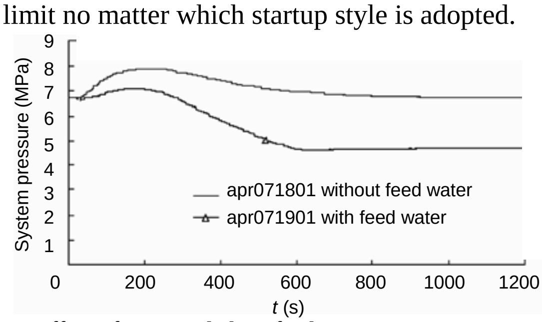

Fig.7 Effect of open and close feed water on system pressure.

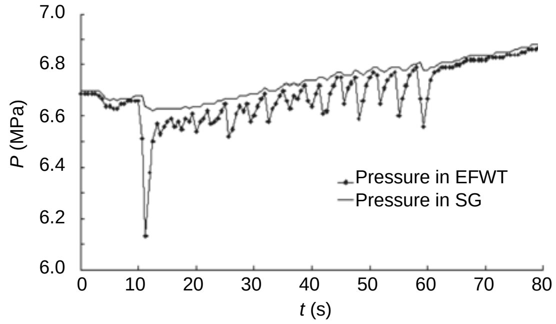

Fig.8 Pressure fluctuation in emergency feed water tank when water-hammer occurs.

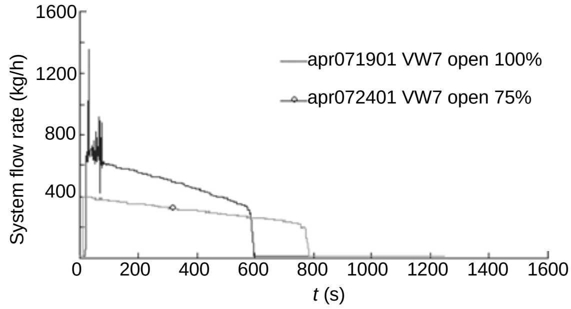

Fig.9 Effect of resistance of feed water loop.

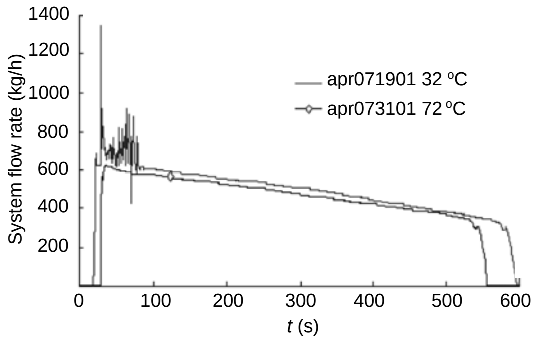

Fig.10 Effect of temperature of feed water on water hammer.

The water hammer tests show that the water hammer occurs in EFWT when a great deal of steam, which is rushing into EFWT through the pressure balance pipe after the feed-water valve is opened, condenses quickly. But if the temperature of feed-water is higher than 52 ºC or the resistance of feed-water loop is large enough, no water hammer can be observed, as shown in Figs.8~10.

3.3 Conclusions

Based on the experiments, semi-empirical model related to the relative height between hot source and hot sink has been established, and it can be applied to system arrangement design for PRHRS of Chinese advanced PWR. Transient experiment also provides some basic experimental data for the system startup mode of the prototype. Furthermore, a way to call off potential water hammer has been identified.

4 Fundamental investigations about secondary side PRHRS of PWR

4.1 Test facility

Because the basic thermal-hydraulical characteristics need to be researched in different system arrangement solutions, the test facility is not established according to strict scaling laws. Of course, the test facility is still composed of primary loop, secondary side PRHRS and main feed-water system. The primary loop is a natural circulation loop which includes heating section and SG. The PRHRS includes emergency condenser, storage water tank and emergency feed-water tank. A flow diagram of the test facility of PWR PRHRS is shown in Fig.11.[3]

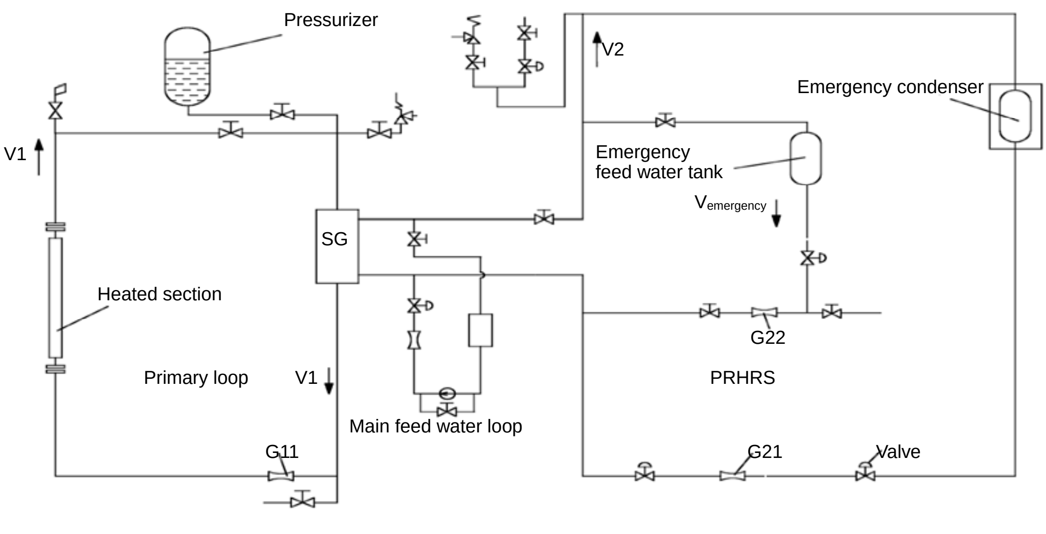

Fig.11 Flow diagram of fundamental test facility of PWR PRHRS.

The experiments include the steady state and transient ones. The steady-state experiments mainly research residual heat removal ability of the system with the affecting factor analysis, and the factors include system pressure, system resistance, relative height between hot source and hot sink, and liquid level in the emergency condenser. On the other hand, the transient experiments include researching the transient character with tiny flow rate startup mode or zero flow rate startup mode. For each of startup mode, two styles of water injecting way, i.e. the full pressure injection and the injection with compressed nitrogen, were used.

4.2 Results of steady-state experiments

The results of steady-state experiments show that the ability of residual heat removal is directly proportional to the natural circulation flow rate in the secondary side passive residual heat removal system with superheated or saturated steam; the smaller the total resistance in the loop, the bigger the ability of residual heat removal; the greater the relative height between condenser and heat exchanger, the bigger the ability of residual heat removal; and the effect of the system pressure in secondary side is not so apparent.

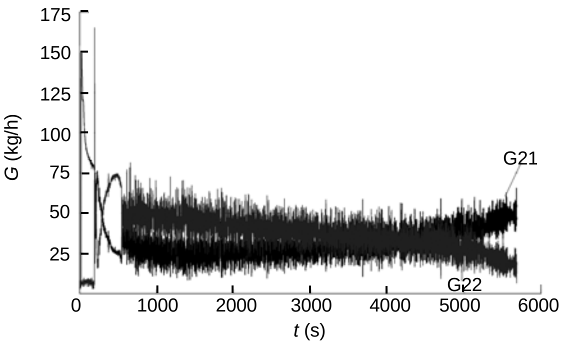

Fig.12 Relationship between G21 and G22 under full-pressure feed water startup mode.

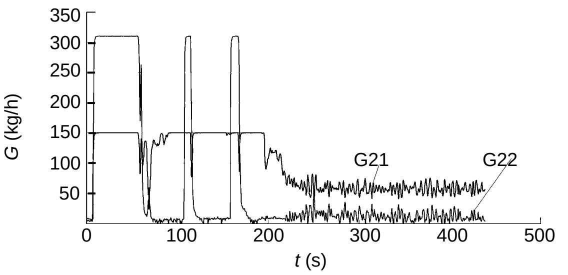

Fig.13 Relationship between G21 and G22 under compressed nitrogen water-injection startup mode.

4.3 Results of transient experiments

The typical results of transient experiments are shown in Figs.12 and 13, where G21 is flow rate through the condenser and G22 is flow rate of feed-water. When the main feed-water of the system is lost, temperatures of both primary and secondary loops in SG can be decreased due to the heat absorbed by cold water from emergency feed-water tank and the heat removal in emergency condenser. In this process, the flow rate of primary loop increased during initial stages, so it is advantageous to some important facilities such as core and SG.

The startup mode with full pressure injection is not a good manner because the time for water injection is very long; on the contrary, the startup mode with injection by compressed nitrogen is a good manner for PRHRS because the flow rate is stable during the injection.

4.4 Conclusions

The experimental results show that the ability of residual heat removal is directly proportional to the natural circulation flow rate, and the startup mode with injection by compressed nitrogen is a good manner for PRHRS.

5 MISAP code and its calculating results

5.1 Introduction of MISAP code

MISAP code is a special code used to analyze steady state and transient performance of the secondary side passive residual heat removal system in PWR and developed by the cooperation of Xi'an Jiaotong University and NPIC. FORTRAN 77 and the module structure are used, the experimental data from the test facilities mentioned above are employed to develop and assess MISAP code.

MISAP[4] code has the following main functions: (1) calculation of steady state and transient thermo-hydraulic performance of SG; (2) calculation of all kinds of accidental conditions under NPP's breakout of main steam pipe and loss of main feed water; (3) calculation of system's transient thermo-hydraulic performance of secondary passive residual heat removal system; (4) calculation of the performance of heating power of SG and transient performance of cooling capacity of air-cooler.

5.2 Assessment of the steady state characters

According to the requirement of experimental research of PRHRS in Chinese advanced PWR, the valid calculation should be carried out when some parameters, such as the height of chimney, water level of SG, and system resistance, are changed. The calculation shows that the main parameters, including system flow rate, system power, outlet temperature of SG and air-cooler, air flow rate, and outlet temperature of air side, coincide with experimental data well, with a relative error of less than 10%.

5.3 Assessment of the transient characters

The typical result on the comparison of calculation with experiments is shown in Fig.14, from which it is concluded that the code can simulate the basic trend of transient experiment, but the quantitative description is still not satisfactory.

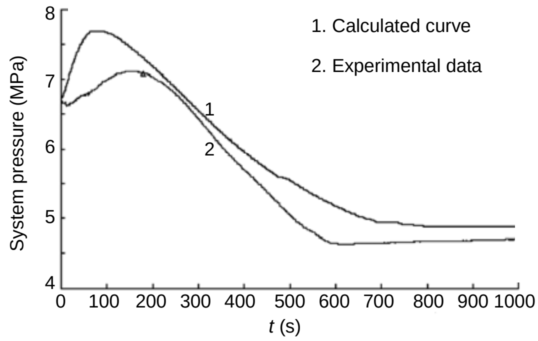

Fig.14 Comparison of calculated results with experimental data of system pressure for cold startup mode.

5.4 Conclusions

The calculating results show that MISAP code simulates the steady state experiment very well, and it is able to simulate the transient process of all startup modes. However, the quantitative description is not so good in the initial term of the transient or when flow fluctuations occur in the system.

6 Conclusions

The experimental results obtained in NPIC show that the main factors affecting the ability of passive residual heat removal system include the relative height between heat source and heat sink, the total resistance of loop system, and the temperature difference in the cold center and hot center. Some other parameters also affect the ability of the residual heat removal in different PRHRS. The startup performance of PRHRS is affected apparently by the installing way of the system equipment. Increasing water temperature and pressure of injecting system can restrain the water hammer, shorten the instable time of PRHRS, and make the transient characteristic of PRHRS better. The steady state characteristic of PRHRS can be predicted very well by MISAP code, but the quantitative calculation of MISAP code for the transient character of PRHRS is not so good, because the steam condensation model of MISAP code needs to be improved.

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