Experiment research and calculation method of natural circulation flow for AC600/1000

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Abstract. Passive safety concept is extensively used in the design for next generation advanced PWR nuclear power plant. The decay heat of reactor core can be removed through natural circulation flow of coolant following an accident. This not only increases reliability of engineered safety systems and reduces core melt frequency, but also simplifies systems and increases plant economy. Nuclear Power Institute of China (NPIC) has performed preliminary experiment research and relative theoretical analysis for passive characteristics of advanced PWR nuclear power plant AC600/1000. Three tests about natural circulation flow have finished as the following: residual heat removal through SG secondary side, core makeup tank behavior and wind flow of containment. The above mentioned three mechanism tests have verified natural circulation flow concept of AC600/1000. By the end of this year NPIC will finish other two single tests in order to research the following key technology of the passive safety systems: The natural circulation characteristics of tandem system of SG secondary side loop and air flow loop for emergency residual heat removal system (ERHRS) after station blackout accident; The water flow behavior in primary coolant system contained by core makeup tank, pressurizer, accumulator and reactor pressure vessel after small break accident; Computer code development and verification. Meanwhile, NPIC will cooperate with Karlsruhe Technology Center of Germany to research natural circulation characteristics of air in the annular channel between the steel shell and the concrete shell of containment. NPIC plans to build two large integral test facilities. One of which is used to research natural circulation flow and residual heat removal through primary loop, secondary loop and air flow loop from reactor core to ultimate sink —atmosphere after station blackout accident. It is also used to research the passive safety injection features for emergency core cooling system. The second integral test facility will be used to research the comprehensive heat removal behavior of passive containment cooling system. The paper will describe the utilization of natural circulation concept in the passive safety systems, experiment research performed by NPIC and computer codes as well for AC600/1000.

1. INTRODUCTION OF PASSIVE SAFETY AND NATURAL CIRCULATION CHARACTERISTICS FOR AC600/1000

1.1. Main design characteristics of AC600/1000

145 fuel assembly and 3658 mm active section core is used in AC600. 177 fuel assembly and 4267 mm active section core is used in AC1000. Neutron instrumentation system inserts into core from top of pressure vessel so that there is not any penetration in the bottom head of reactor pressure vessel. Steel water reflector is used to save neutron and to reduce neutron fluency on wall of reactor pressure vessel. Modularization construction, advanced digital instrumentation and control system are considered in AC600/1000 design. Passive safety systems including passive emergency residual heat removal, passive safety injection and passive containment cooling sub-systems are very important for AC600/1000 design.

No any penetration below top of reactor core is useful to reduce core melt frequency. Integral reactor top structure and large size reactor vessel are also used in AC600/1000 design. The inner diameters of reactor pressure vessels are 4000 mm for AC600 and 4340 mm for AC1000. Low power density of reactor core, low neutron leakage, 80% stainless steel +20% water reflector and large size reactor pressure vessel are able to assure 60 year life time of plant. Gray rods are used in AC600/1000 to achieve daily load follow. Linear power density of core is 134.2/140 W/cm for AC600/1000 respectively, much lower than current PWR nuclear power plant so that AC600/1000 reactor core has larger safety margin.
1.2. Passive safety features of AC600/1000

Natural circulation concept is used in the AC600/1000 passive safety system design. The system is actuated by gravity, natural circulation or pressurized gas. Following accident, AC600/1000 is able to maintain core cooling and containment integrity without operator’s intervention. This is an important safety requirement in the AC600/1000 design.

Emergency residual heat removal system (ERHRS) is used to remove decay heat from reactor core following accident. Secondary side of SG, emergency feedwater tank and air cooler establish a natural circulation cycle. Air coolers are located in a chimney. The heat transfer area is about 750m² for each air cooler. Emergency feedwater tank volume is 25m³ for each SG cycle.

FIG. 1. Secondary passive residual heat removal system.

Passive safety injection system of AC600/1000 (PSIS) is mainly used to mitigate the consequence of LOCA. The core cooling water is provided through use of the following four water sources: core make-up water tank (volume is 2 or 3 x 40m³), accumulator (volume is 2 or 3 x 40m³), refueling water storage tank and containment sump. Low pressure safety injection subsystem uses two or three active pumps, design flow rate of each which is 142 kg/s.

FIG. 2. Passive safety injection system for AC600.
The containment of AC600/1000 is a two-shell structure. Between inner steel shell and outer reinforced cylindrical concrete shell, there is a baffle to form an annular wind duct. Containment top water storage tank capacity can meet the requirement of 72 hours for steel shell cooling after large LOCA. In the top of containment, there is a cooling water distribution to make the heat removal more efficient and quick in the early phase of an accident. For long term cooling, peak pressure of the containment is not larger than 90% of containment design pressure. For severe accident, containment pressure is below failure pressure. Containment spray system is eliminated in the AC600/1000 design.

2. MAJOR EXPERIMENT RESEARCH RELATED TO SAFETY FOR AC600/1000

2.1. Experiment Research Plan

Experimental studies about passive safety characteristics for AC600/1000 are divided the following three steps:

1) Mechanism demonstration tests include emergency residual heat removal test through natural circulation flow of SG secondary side, core make-up tank performance test and wind tunnel test for passive containment cooling. Above three mentioned tests finished by the end of 1996.

2) Part function demonstration tests include emergency residual heat removal test through natural circulation flow of SG secondary side and atmosphere loop and thermal hydraulic transient behavior test research during small break LOCA for core make-up tank, pressurizer, accumulator and reactor pressure vessel. Above two mentioned tests will be finished by end of this year. Meanwhile, NPIC will cooperate with Karlsruhe Technology Center of Germany to do air natural circulation flow test for AC600/1000 passive containment cooling system.
Comprehensive function demonstration tests. NPIC plans to construct the following two large test facilities: a. Integral thermal hydraulic test facility. It is a tandem system of primary coolant cycle, secondary side cycle of SG and air flow cycle, which can be used to research station black out accident, small break LOCA and computer code development. b. Integral containment cooling test facility. It is used to simulate and research comprehensive characteristics of passive containment cooling system for AC600/1000.

2.2. Experimental study of secondary-side passive emergency residual heat removal system for AC600/1000

The main purpose of the experimental study is to demonstrate capability of decay heat removal, to determine behavior of the system and components, to find start-up characteristics and procedures and to obtain a database for developing computer codes for AC600/1000 passive emergency residual heat removal system.

The total 166 sets of experimental data are identified. The test results illustrate that short disturbances of wind speed, power and valve opening have no significant impact on natural circulation flow, implying that the system seems to tolerate these disturbances. A correlation of two-phase, natural circulation flow rate is derived from constitutive equations by use of lumped system parameters were obtained. The empirical coefficients m and n were obtained by non-linear regression of 83 test data. Compared with 166 sets of the measured data, the deviation of 98.8% of the data points is within ±15%.

<table>
<thead>
<tr>
<th>TABLE I. STEADY STATE TEST PARAMETER RANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Elevation difference between air cooler and SG/L_{ab}</td>
</tr>
<tr>
<td>Slope angle of air-cooler/θ</td>
</tr>
<tr>
<td>Pressure/P</td>
</tr>
<tr>
<td>Heating power/qc</td>
</tr>
<tr>
<td>Natural circulation flowrate/W</td>
</tr>
<tr>
<td>Wind speed/V</td>
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FIG 4. Schematic diagram of ERHRS test facility.
It is noted from transient research that AC600/1000 ERHR system is able to remove decay heat. Three start-up modes are available to trigger natural circulation flow. Computer code ERHRAC simulating natural circulation flow characteristics of ERHRS for AC600/1000 has been developed based on the test data.

2.3. Full pressure core make-up tank test

Passive core make-up water tank is used so as to eliminate high pressure safety injection pumps. Transient characteristic research of core make-up water tank in the case of small LOCA were performed. The break sizes are: 2, 6, 12, 18, 30 mm respectively. Thermal hydraulic behaviors of pressurizer and draining flow rate measurement from core make-up water tank to primary coolant system following small LOCA were researched and carried out in the test. A total of 80 sensors were used to measure temperatures, liquid level and flow rate.

The above figures show the pressure curves of CMT for all 5 break sizes. It is evident that there exists a pressure oscillation phase during pressure drop down, especially for $\phi$30mm break size and lasts from 50s to end of draining. In general, the blow down phase is longer, steam condensation in CMT is more. The draining behaviors of CMT are complex and change with break size. The draining mass flow rate increases rapidly at the beginning and has a low oscillation phase before stable draining phase. All break sizes have obviously a high flow rate peak. After about 500s, all flow fluxes are nearly the same.
FIG. 6. Schematic diagram of CMT test rig.

FIG. 7. Pressure variation in CMT.

FIG. 8. Condensed steam vs. time in CMT.

TABLE II. TEST INITIAL CONDITIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2</th>
<th>6</th>
<th>12</th>
<th>18</th>
<th>30</th>
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<tbody>
<tr>
<td>Initial water storage</td>
<td>kg</td>
<td>1028</td>
<td>1031</td>
<td>1030</td>
<td>1037</td>
<td>1032</td>
</tr>
<tr>
<td>System pressure</td>
<td>MPa</td>
<td>14.81</td>
<td>14.97</td>
<td>14.33</td>
<td>14.16</td>
<td>15.15</td>
</tr>
<tr>
<td>Upper temp. of RPV</td>
<td>°C</td>
<td>315</td>
<td>322</td>
<td>324</td>
<td>306</td>
<td>312</td>
</tr>
<tr>
<td>Bottom temp of RPV</td>
<td>°C</td>
<td>257</td>
<td>259</td>
<td>257</td>
<td>295</td>
<td>309</td>
</tr>
<tr>
<td>Pressure at water injection</td>
<td>MPa</td>
<td>12.39</td>
<td>12.20</td>
<td>12.11</td>
<td>12.11</td>
<td>12.33</td>
</tr>
</tbody>
</table>

2.4. Wind channel test for passive containment cooling system

The wind channel test will research air flow resistance characteristic and effects of air channel shape and air inlet location on natural circulation flow.

The influence of environment wind and surrounding buildings on the natural convection flow had been especially considered. Moreover, the velocity field at the lower turning of air baffle
and the surface wind pressure distribution of containment were needed for design. The main purposes of the test were: a) To verify the feasibility of passive containment cooling system design. Main emphasis was put on the influence of the environmental wind; b) To supply a database for preliminary design and design improvement, especially the experimental data of velocity field in annuli and pressure drop of each section. The velocity field in the low baffle end zone was calculated and tested.

The model tests (1/10 in scale) with different flow deflectors were done to study the way of improvement. Both test and calculated results indicated that there were an enclosed vortex in the stagnant bottom and an obvious separate bubble formed at the rear of the baffle. The flow deflectors could reduce the separate bubble. Another model test was run in 0.2—0.5 m/s water velocity. A larger vortex at the upper stream of flying object protect shielding and a smaller bubble at the downstream of it were proved by both test and calculation.

A pressure distribution test in the surface of containment was done in a low velocity wind tunnel with various wind speeds, air entrances, yaw and pitch angles. The test shows that the pressure is positive in the area of $-35^\circ \leq \theta \leq 35^\circ$. The influence of wind on natural convection of containment was also done with a 1/50 integral model. The test results revealed that natural convection flow rate was enhanced in general by outside wind and horizontal wind ($\alpha = 0$) had the better effect than $\alpha < 0^\circ$ or $\alpha > 0^\circ$. The position of chimney might influence the air flowing around the containment. The distance between containment and chimney should be larger than 4 times of chimney diameter. However, smoke wind tunnel test showed no exhausted hot air was re-circulated under any condition.

![Diagram of containment structure](image)

**FIG. 9. Diagram of containment structure.**

![Flow field near flying protect shielding](image)

**FIG. 10. Flow field near flying protect shielding.**
2.5. Summary

1) The studies of passive ERHR system, CMT injection system and passive containment cooling system prove that the design of all these passive systems are feasible and reliable in principle and can meet basically the required safety functions.

2) Some undesired thermal hydraulic phenomena were found and identified in these studies. For example, the flow vortex in the containment air duct, and "water hammer" of ERHR test may have bad impacts on its safety functions and should be avoided in the next step tests and AC600/1000 design.

3) All data obtained have been already used for design improvement and next R&D program planning.

3. ANALYSIS CODE DEVELOPMENT AND CALCULATION FOR NATURAL CIRCULATION BEHAVIOR OF AC600/1000

3.1. Theoretical analysis and research for AC600/1000 passive containment cooling behavior

PCCAC-2D is a two dimension computer code which has been already used in the design of AC600/1000 passive containment cooling system. PCCAC-3D is a three dimension computer code which will be finished by the end of next September. PCCAC-2D, 3D can be used to predict the pressure and temperature of mixing gas inside the containment following the accident of primary pipe rupture or main steam line rupture. The heat removal characteristics from inside containment to atmosphere through the water film on the out surface of steel shell and natural circulation flow of air can be also simulated and calculated by PCCAC-2D or PCCAC-3D.

It follows from preliminary calculation results that the maximum pressure 0.37 Mpa of mixing gas in the containment will occur in 1123S after double ended rupture accident of cold leg pipe. The maximum temperature 138°C will occur in 14S after the accident.
The maximum pressure 0.34MPa of mixing gas in the containment will occur in 16.8S after double ended rupture accident of hot leg pipe. The maximum temperature 143°C will occur in 6.8S after the accident. The maximum pressure 0.387MPa of mixing gas in the containment will occur in 395.3S after main steam line rupture accident. The maximum temperature 153°C will occur in 3S after the accident.

The flow fields of coolant in the containment indicate that main flow vortex will be established at 0.9S following accident, will be in equilibrium at 5.2S and will be destroyed at 24.8S because of the end of blow down. The temperature fields of coolant in the containment show that high temperature area is in around and above the break and low temperature area is in the bottom near steel shell at the beginning of the accident. Then the temperature fields become uniform after main flow vortex equilibrium. The natural circulation mass flowrate of air in the channel between steel shell and concrete shell of containment varies with time and reaches maximum 168 kg/s at 8000S. After 72 hours, the spray water will be ended and the natural circulation mass flowrate will reach 120 kg/s. It can be noted from the preliminary analysis and calculation that AC600 passive containment cooling system is able to remove decay heat of reactor from inside to outside of containment.
3.2. Station blackout accident calculation for AC600/1000

ERHRAC is a special computer code for AC600/1000 design. ERHRAC can be used to calculate the natural circulation flowrates of three cycles (primary coolant cycle, secondary side cycle of SG and air flow cycle). The links connecting those three cycles are the steam generator and air cooler, establishing a tandem system.

In the unlikely event of a station black out accident, the flowrate through reactor core rapidly reduces. The changeover of coolant flow in primary coolant loop from the forced circulation
to the natural circulation is initiated automatically when main pump coast down is ended. In the secondary side loop, from steam generator the steam passes on to an air cooler, in which its heat is transferred to the air and steam is condensed to water. Then condensed water returns back to the steam generator by gravity to establish a natural circulation flow cycle.

Natural circulation flow rate is: 4% rated flowrate for each primary coolant loop and 3% rated flowrate for each secondary side loop of SG respectively. Air flowrate is about 290Kg/s for each air cooler.

FIG. 16. Primary coolant flowrate per loop.

FIG. 17. Natural circulation flowrate for secondary side loop of each SG

FIG. 18. Air flowrate per air cooler
4. CONCLUSION

Compared with current PWR NPP in China, AC600/1000 has the following 4 key advantages:

(1) The safety and reliability of nuclear power plant can be increased through use of passive safety systems and advanced I&C systems.

(2) Advanced core design and fuel management are used in AC600/1000 to increase availability factor and operation life time of NPP, to reduce generation cost and to improve economic efficiency.

(3) System simplification and modularization technology can shorten construction period of NPP and reduce total capital cost.(4) AC600/1000 utilizes proven design technology and verified engineering experiments so that a prototype NPP is not required.

AC600/1000 is much safe, simple and economic NPP. AC-600/1000 will be next generation NPP of China.