EVALUATION OF RELAP5/MOD3.2 FOR AP1000 PASSIVE RESIDUAL HEAT REMOVAL SYSTEM

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ABSTRACT

The second side passive residual heat removal system is one of innovation designs of Chinese ACP1000 NPP, and it consists of the second side of steam generator, C-type heat exchanger and high accident cooling water tank. The purpose of this paper is to evaluate the capability of RELAP5/MOD3.2 code to simulate thermal-hydraulics behavior associated with experiments PRS-ST1 and PRS-TT1. The PRS experiments were simulations of the operation of the second side passive residual heat removal system when station block-out accident happened. The trends of RELAP5/MOD3.2 calculation were very similar to those observed in experiments, and the calculation results were in good agreement with experimental data. The discrepancies between the calculation and experiment were also identified in the water level of accident cooling water tank as well as EST injection flow rate. Much more attention should be paid to the nodalization of ACWT to model three-dimensional natural convection, as well as to modify flow pattern and heat transfer coefficient of direct-contact steam condensation in the future.

KEYWORDS
Passive, Nuclear safety, Thermal hydraulics, RELAP5

1. INTRODUCTION

Passive safety systems such as accumulators, condensation and evaporative heat exchangers, gravity driven safety injection systems and natural circulation systems have enormous potential to enhance reactors' safety, as well as eliminate the costs associated with the installation, maintenance and operation of active safety systems. As a result, passive safety systems are being widely used in numerous advanced water cooling reactors, including in ACP1000 that developed by CNNC(China National Nuclear Corporation) in recent years. ACP1000 incorporates a system to remove decay heat passively through the steam generators (SGs) in case of non-LOCA accidents, such as SBO (station black-out) etc. This is done by two natural circulation systems as shown in Figure 1. Firstly, the coolant transfer the decay heat to SGs by primary loop natural circulation, and then transfer heat from SGs to an accident cooling water tank (ACWT) outside the containment by condensing steam inside C-shape heat exchangers, the latter is defined as secondary side natural circulation in our researches. The water inventory in ACWT is sufficient for the long term heat removal (at least 72 hours) and can be replenished if necessary from an external source. In ACP1000, there are three independent passive residual heat removal systems, which means each SG connects to one C-shape heat exchanger, two emergency water-supply tanks (ESTs).

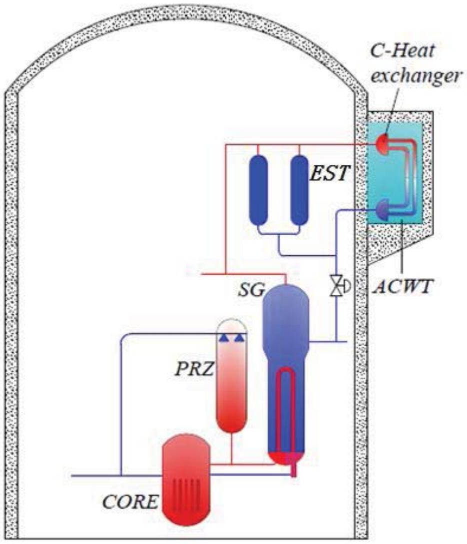

Figure 1. Schematic of ACP1000 passive residual heat removal system

It is specifically true that thermal-hydraulic phenomenon and related parameter ranges characterize the performance of passive systems, so experiments were conducted in NPIC (Nuclear Power Institute of China) to study the thermal-hydraulic phenomena occurring in ACP1000 passive residual heat removal system (PRHRS).

Meanwhile RELAP5/Mod3.2 code is a potential candidate for PRHRS analysis, an important step towards demonstrating the applicability of the RELAP5/Mod3.2 to PRHRS is to show its ability to predict the experiments. In this paper, the test facility RELAP5 model is established, and then code-predicted results are compared with steady-state experiment PRS-ST1 and transient experiment PRS-TT1, also the discrepancies are discussed associated with the nodalization, boundary conditions and thermal-hydraulics models.

2. DESCRIPTION OF FACILITY AND TEST

2.1. ESPRIT Facility

ESPRIT (Emergency Secondary Side Passive Residual Heat Removal System Integral Test Facility) facility is a scaled down model of one ACP1000 passive residual heat removal system, as shown in Figure 2. The scaling factors of ESPRIT facility for height and volume are 1/1 and 1/62.5, respectively. The design pressure is 8.6 MPa, the maximum heating power is 2 MW, and the height is approximately 60 m.

The data acquisition system of ESPRIT records data from more than 200 instruments which include k-type thermocouples, flow meters, pressure transducers, and differential pressure transducers, its acquisition frequency is 10Hz.

The flow diagram of ESPRIT is shown in Figure 3, and the configuration includes a steam generator, two ESTs, a C-shape heat exchanger, a high position ACWT, water-supply system and several valves. During the operation, steam generated in SG flows into and condensed in the C-shape heat exchanger, and then condensation return to SG, so the flow and heat transfer in ESPRIT are typical natural circulation phenomena. There are eighty four U-Shape electrical heating rods installed in SG shown in Figure 4, which power is adjustable to the temporal evolution of heat transferred from reactor core. The U-shape heating rod has the same diameter with ACP1000 U-tubes, and the flow area and heat transfer area of ESPRIT SG boiling region are scaled 1/62.5 of ACP1000 prototype. The ESTs and ACWT has the same height with prototype, and the volumes of that is also scaled 1/62.5 of prototype. The steam line and C-shape heat exchanger are insulated by a U-shape water seal. Electrical operated valve HVS003 is used to simulate steam-discharging valve, which is controlled by SG pressure signal, opened when pressure is greater than 7.85MPa, and closed when pressure is less than 7.5MPa.

Figure 2. ESPRIT Facility

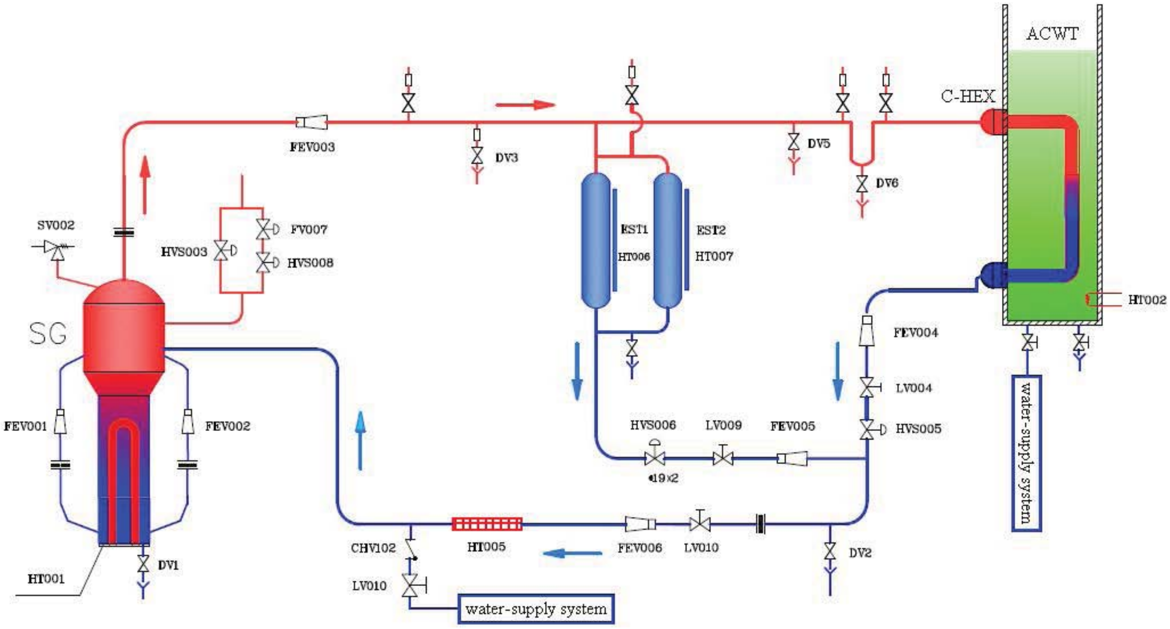

Figure 3. Flow Diagram of ESPRIT

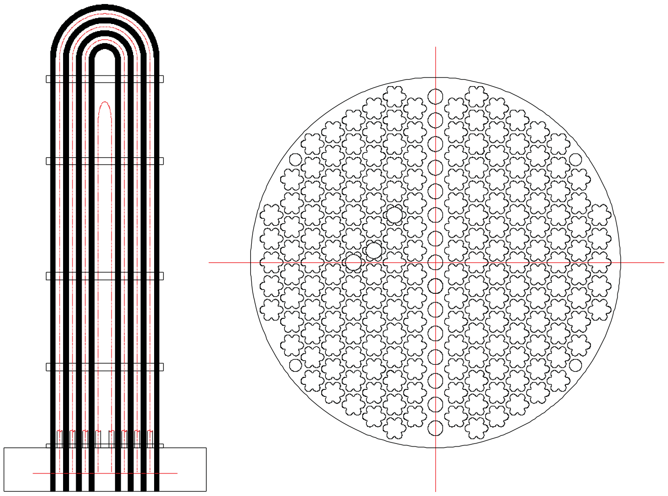

Figure 4. The Arrangement of U-Shaped Electrical Heating Rods

2.2. Steady-state Test

The steady-state PRS-ST1 was performed to access the stable heat removal capability of ESPRIT and to check the flow resistance difference between ESPRIT and ACP1000 passive heat removal system. The initial conditions of PRS-ST1 listed in table1 were established by water-supply system and HVS008. When the initial conditions achieved the requirements, HVS005 was opened instantaneously. Because the steam line was full of steam, and the C-shape heat exchanger and condensation line was filled with demonized water, so the fluid was driven by the large density difference along the loop. In this experiment, the heating power was maintained 426.9 kW (0.87% FP/62.5) unchanged until SG pressure and condensation temperature became stable.

Table I. PRS-ST1 initial conditions

Item	SG Pressure (MPa)	SG water Level (m)	ACWT temperature (℃)	Power (kW)
Parameters	7.5	13.7	40.0	426.9

2.3. Transient Test

The purpose of the transient test PRS-TT1 was to investigate the system response during ACP1000 reactor SBO accident for 72 hours and to access system codes for the safety analysis of passive residual heat removal system. In the design of ACP1000, the start-up time of passive residual heat removal system is set 60.2s after reactor shutdown, so the heating power (Figure 5) was decreased from 1533.0 kW (3.13% FP/62.5) at 0 second to 80.0 kW (0.16% FP/62.5) at 72 hours in PRS-TT1 test. The initial conditions of PRS-TT1 are listed in Table 2, the transient was initiated by opening HVS005 and HVS006 valves, as the water in EST and heat exchanger drained down, the natural circulation began to establish.

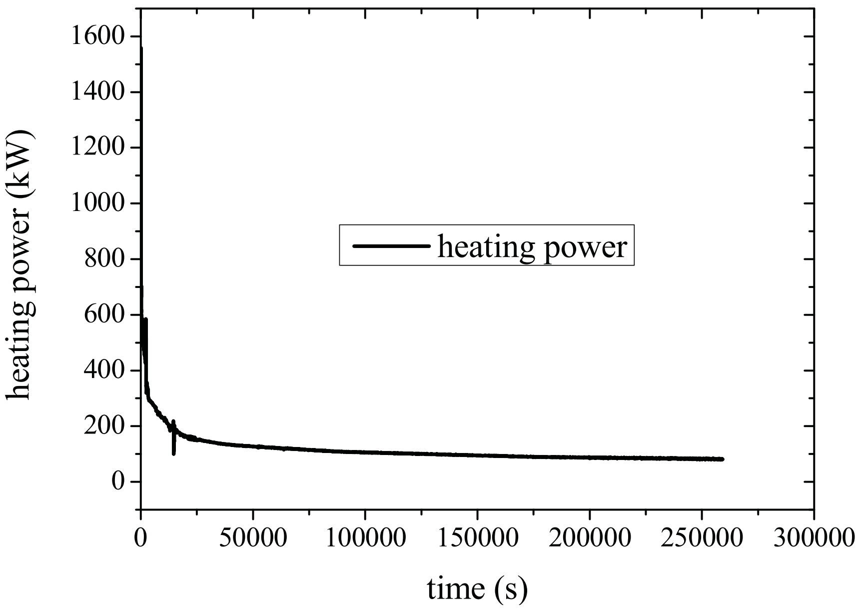

Figure 5. The Variation of Heating Power in PRS-TT1

Table II. PRS-TT1 initial conditions

Item	SG Pressure (MPa)	SG water Level (m)	ACWT, EST temperature (℃)	Power (kW)
Parameters	7.5	13.7	50.0	1533.0

3. RELAP5 NODALIZATION

The RELAP5 computer code developed as a highly generic best-estimate code has been used for simulation of ACP1000 passive residual heat removal experiments. As shown in Figure 6, ESPRIT facility were composed of 121 volumes, and the maximum length of SG boiling region, heat exchanger and EST were 1.5m, 0.4m and 0.6m respectively. The U-shape heating rods were modeled using 8 heat structures, and the rod bundle interphase friction model option was applied to the SG boiling region. Time-dependent volume TDV and time-dependent TDJ were used to simulate water-supply system, to control SG pressure and water level associated with V261.

The overall thought of modeling ACWT was to simulate three-dimensional natural convection in water pool as far as possible. The nodalization of ACWT is shown in Figure 7, and the main flow path is very similar to a natural circulation associated with cross flow. The water from volume 135 was heated up or boiling in volume 137 and volume 138, then flowed into volume 142, in which the water and vapor were separated by buoyancy. Finally vapor flowed into atmosphere, and water returned to volume 135 through volume 141 and volume 136. In order to simulate local natural convection, the same height volumes were connected by cross flow junctions.

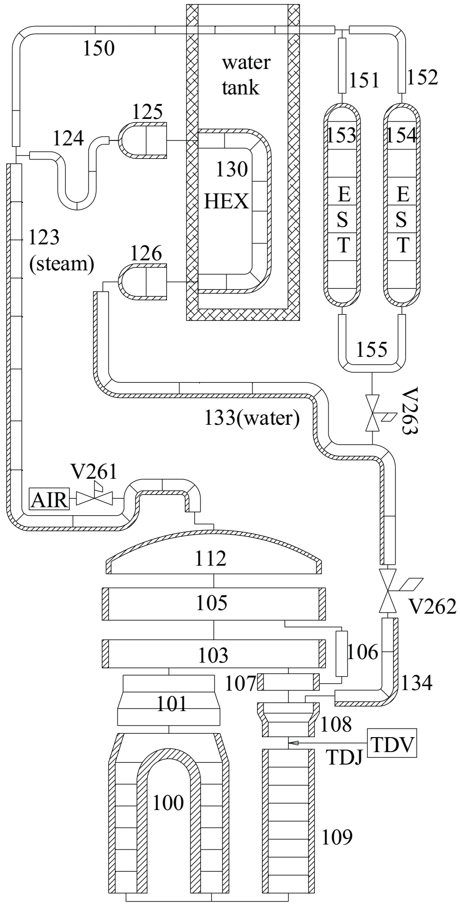

Figure 6. RELAP5 Nodalization of ESPRIT

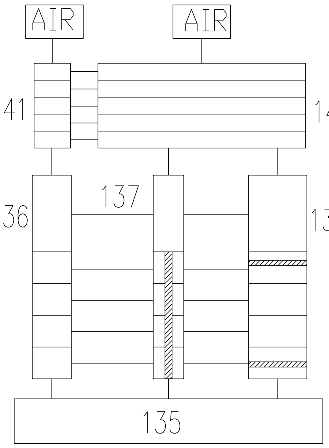

Figure 7. RELAP5 Nodalization of ACWT

Although all the pipe and components of ESPRIT was covered with thermal insulation cotton, environmental heat losses from all metal structures exposed to atmosphere were not ignored, and were simulated using the heat structure components. The third kind boundary condition was used as right boundary condition of heat structures, where the heat transfer coefficient as a function of surface temperature was obtained from a general table, and the sink temperature was air temperature 16 degree centigrade measured during experiments. The heat loss of ESPRIT generally involved air natural convection heat transfer and radiation heat transfer. The heat transfer coefficient $h(T_w)$ were calculated by

$$h(T_w) = \frac{\Phi_{NC} + \Phi_{Rad}}{(T_w - T_f)} \tag{1}$$

Where Φ_{NC} is heat flux of natural convection, Φ_{rad} is heat flux of radiation, T_w is wall temperature, T_f is sink temperature.

4. ANALYSIS AND DISCUSSION

4.1 PRS-ST1 Test Simulation

In this simulation, V262 was opened when all initial conditions were established. Figure 7 shows the comparison between code-predicted results and PRS-ST1 experimental data. ACP1000 passive residual heat removal system is a typical natural circulation system without pressurizer, which can achieve the steady-state under two equilibrium conditions, including the system driving head matches with flow resistance, as well as heat transfer through C-shape heat exchanger matches with heating power. Obviously, the initial conditions diverged from the equilibrium conditions dramatically, so a long time parameters adjustment occurred before system achieved steady-state. As shown in Figure 8, the SG pressure decreased rapidly due to the heat transfer through C-shape heat exchanger, the reason for this phenomenon was that the temperature difference inside and outside heat transfer tube under high pressure condition was higher than that under low pressure. At the initial phase of PRS-ST1, the heat transfer quantity through C-shape heat exchanger was greater than SG heating power, and SG pressure began to decrease towards equilibrium state as a consequence. Because the heat exchanger and condensation pipe was full of cold water before test start-up, therefore, the condensation was speeded up and reached the maximum velocity within minutes. When the cold water totally drained into SG, the mass flow rate of condensation began to decrease. About 15000s later, the system achieved the final steady-state.

It is apparent that the code-predicted behavior of the PRS-ST1 matched well with the experiment the experimental data. However there was also minor discrepancy between code-predicted and measured condensation temperature. From 500s to 3000s after PRS-ST1 test start-up, the code-predicted intensity of natural convection in ACWT was greater than that of real situation. As a result, the code-predicted water temperature outside heat transfer tubes was smaller than that of real situation, which leaded RELAP5 less predicted the condensation temperature during this period. At final stage, the heat transfer mode in ACWT was nucleate boiling, and pool boiling had absolute predominance in the heat transfer quality, so the discrepancy of condensation temperature became small.

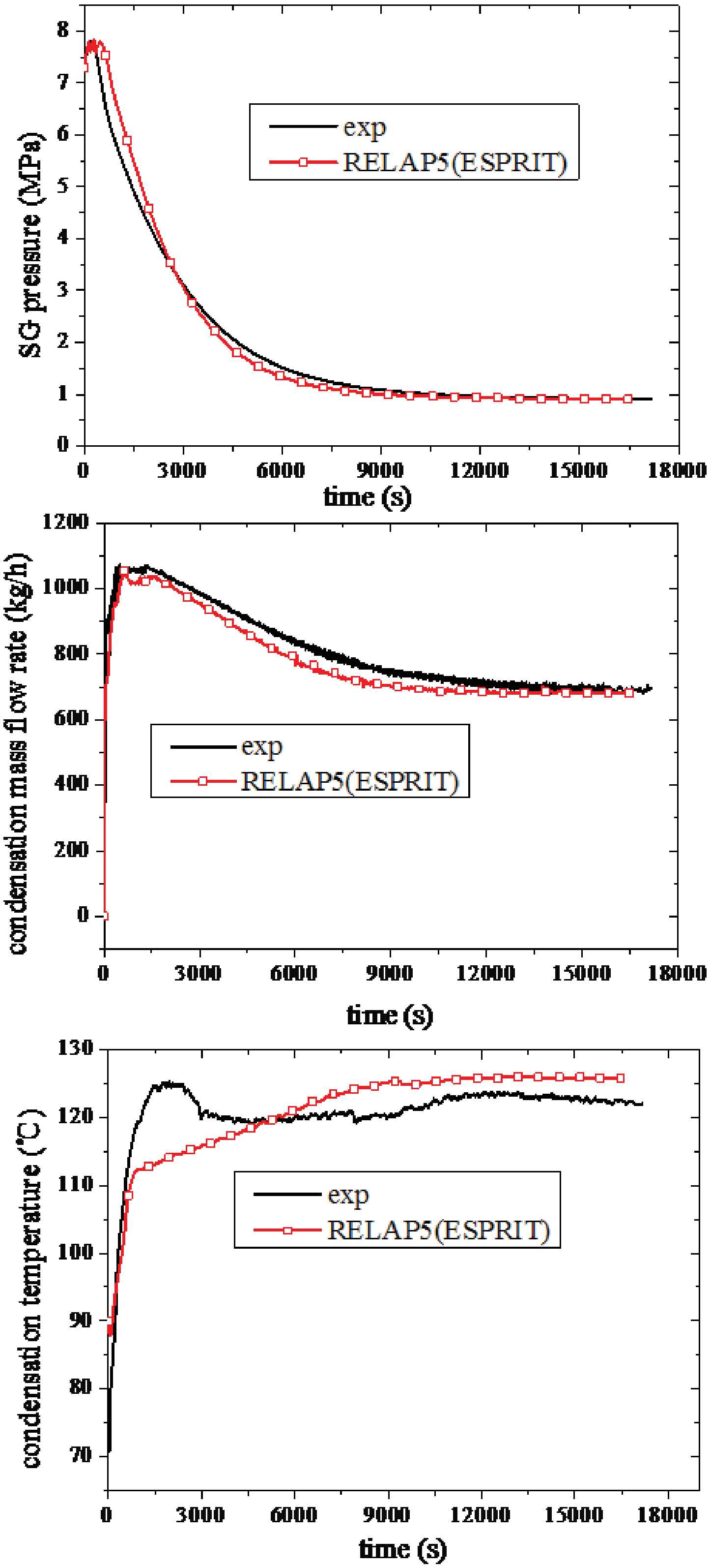

Figure 8. Code-predicted Results and Experimental Data of PRS-ST1

4.2 PRS-TT1 Test Simulation

In this simulation, the valve V262 and V263 were opened at same time to initiate the transient test. The code-predicted and measured pressure, condensation flow rate and ACWT water level are presented in Figure 9. It is shown that the SG pressure decreased from 7.85MPa to about 0.3 MPa in 72 hours, and water inventory of ACWT was sufficient for 72 hours operation during SBO accident. Because there was two-phase mixture existed in condensation pipe, the measured condensation mass flow rate by Venturi flow-meter showed big oscillation. A nearly 1m discrepancy of ACWT water level can be observed in Figure 10, the acceptable reason was that the heat transfer at the air-water interface in ACWT was not simulated in this RELAP5 model. The area of air-water interface was about 2.5m^2, so the heat transfer at this interface should be modeled in future researches.

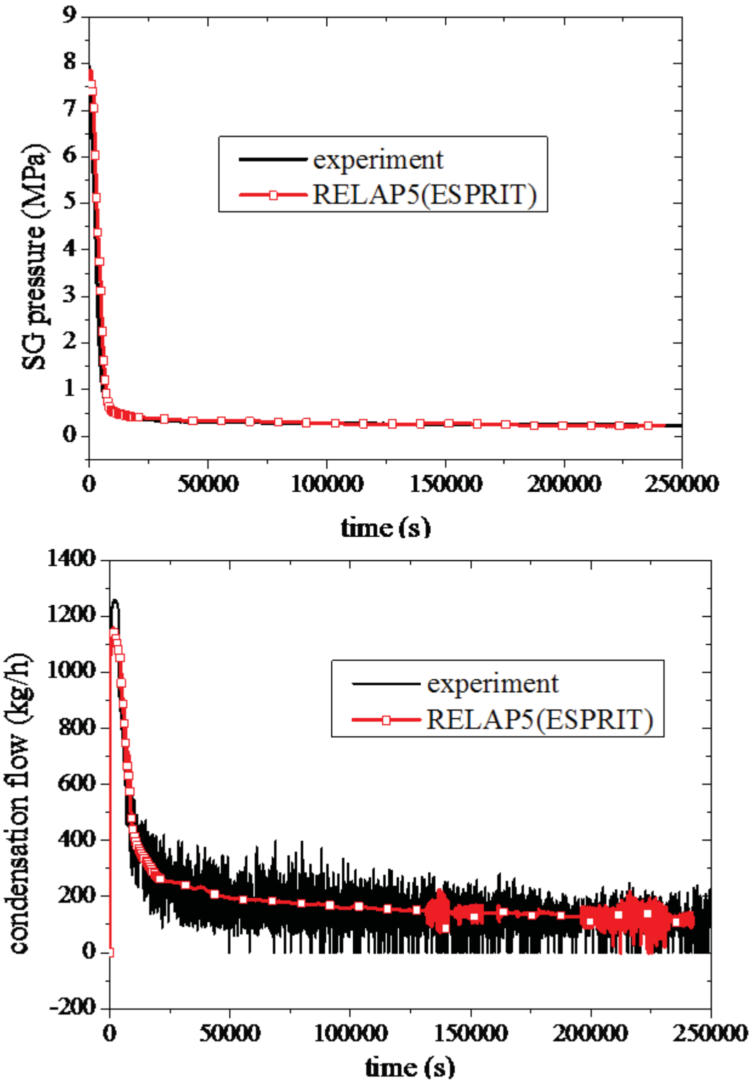

Figure 9. Code-predicted Results and Experimental Data of PRS-TT1

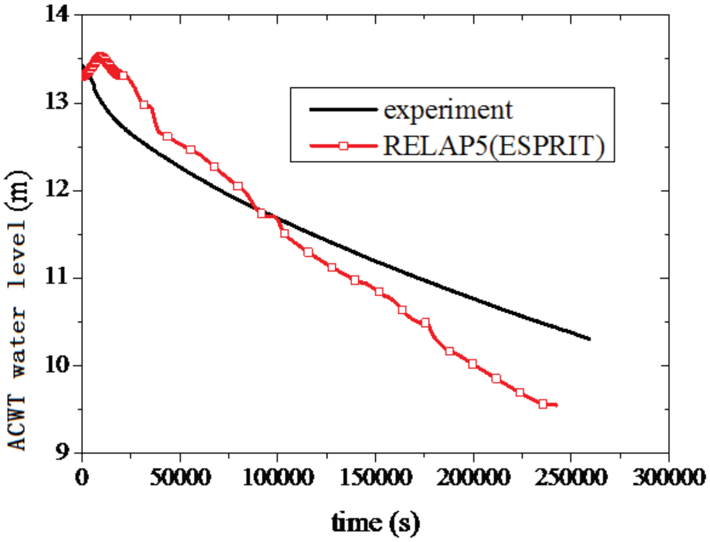

Figure 10. Code-predicted Results and Measured ACWT Water Level

The major discrepancy between code-predicted results and experimental data was EST injection flow as shown in Figure 11. The code-predicted EST injection flow rate was smaller than experiment at most injection time, so the code-predicted injection time was about 500s longer than experiment. Also some small and large injection flow oscillations occurred in RELAP5 simulation.

Simulating the direct-contact steam condensation in a water tank is always a weakness or defect of system analysis code [1-3]. The thermal-hydraulics phenomena of high speed steam jets into subcooled water pool are very complex, the flow pattern and two-phase interface area are very different from boiling or countercurrent flow [4-6]. According to the simulation experience, we should pay much attention on the nodalization of EST and modification of direct-contact steam condensation model.

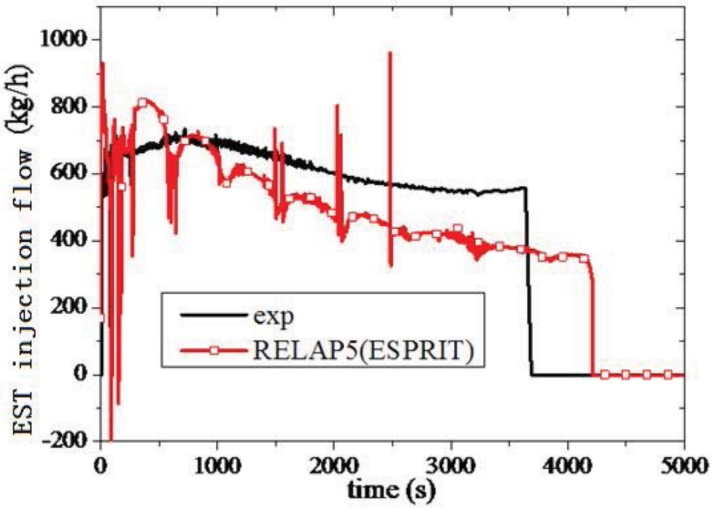

Figure 11. Code-predicted And Measured EST Injection Flow

5. CONCLUSIONS

In this work, a nodalization for ESPRIT facility using the RELAP5/MOD3.2 code has been presented as a contribution to the assessment of such code for ACP1000 passive residual heat removal system analysis. Steady-state test PRS-ST1 and transient test PRS-TT1 were simulated and compared with experimental data. The comparison indicates that RELAP5 code successfully calculated the overall primary behavior occurring in steady-state and transient testes, and important parameters were in consistent with measured data.

Some little and big discrepancies were also observed in the simulation, including EST injection flow and ACWT water level etc. It is concluded that much more attention should be paid to the nodalization of ACWT to model three-dimensional natural convection, as well as to modify flow pattern and heat transfer coefficient of direct-contact steam condensation in the future.

ACKNOWLEDGMENTS

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