Dynamic analysis of passive heat removal system for molten salt reactor

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Abstract: To get an insight of the transient behavior of Passive Residual Heat Removal System (PRHRS) for the molten salt reactor, a numerical study based on RELAP5 code was carried out. Ninety-nine control volumes are used for simulating the PRHRS. An auto gas blow-off device is installed in the system. In the model, the device is simplified by a trip valve. Heat flux boundary is given on the outer surface of the thimble and the atmosphere is served as a heat sink. At the initial state, helium is filled in the gas space. From the comparison of the correlations for prediction of decay power, Todreas & Kazimi formula is selected for calculation. The numerical results show the feasibility and efficiency of the PRHRS removing decay heat for the molten salt reactor. The discharging port is opened several times until the system pressure is no longer higher than the upper limit. A large increase of system pressure and water flow rate can be observed when water flows into the high-temperature tube. After discharging, the remaining gas mainly concentrates in the condenser and the downward channel after the condenser. The position of the discharging port was also studied.

Keyword: passive residual heat removal system; molten salt reactor; numerical analysis; RELAP5

1 Introduction

Two Phase Natural Circulation System (TPNCS) has already attracted great concern for wide applications in industry, especially in nuclear power plants, *e.g.* boiling water reactor and the new generation of pressured water reactor AP1000. Most designs of Passive Residual Heat Removal System (PRHRS) are two-phase natural circulation loops. Compared with common forced-circulation loops driven by an electric pump, natural circulation system has a never failed 'pump' that is pressure drop resulted from density difference. Nevertheless, the driving force is very sensitive to density difference and smaller than that in forced circulation loop. Therefore, the TPNCS needs more investigation to know about potential risks in operation.

Kuran *et al.* [1] performed startup experiments using Multi-Dimensional Integral Test Assembly facility in Purdue University. Condensation- and flashing-induced oscillations were observed in the start transient for steam dome pressure ranging from 55 kPa to 1 MPa. Oscillations would be more significant in the prototype design due to its longer chimney section. Zhao *et al.* [2] conducted a numerical investigation of transient behaviors of the open natural circulation system with a large tank as the heat sink using the homogeneous equilibrium model. Four types of operating behaviors including startup process, single-phase flow, transition stage, and approximate stable two-phase flow have been observed in their results. The system response is fast due to less than 200s for the system to achieve approximate stable single-phase flow. The largest oscillations of flow rate happened in the transition stage. It can be seen that two-phase flow loop is often companied by instabilities or oscillations, which has been mentioned in many papers [3-5].

Numerical analysis of PRHRS has been widely carried out using RELAP5 code, which was developed at the Idaho National Engineering Laboratory. Zhao *et al.* [6] investigated the capability and instability of external reactor vessel cooling using RELAP5 code. The effects of configurable parameters including containment free space pressure, cavity water subcooling, heat power, and cavity flooding level were analyzed. But the instabilities in the calculated results need further identification. Capability analysis of emergency passive residual heat removal system of CPR1000 was conducted with RELAP5 code by Zhang *et al.* [7]. The transient characteristics of the

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primary loop and the PRHRS were calculated in the event of station blackout accident. Many analyzes were based on RELAP5 [8-11]. From the validation of RELAP5 in natural circulation experiments [12], RELAP5 shows reasonable and acceptable results in system analysis.

Now, China initiates a project to investigate the Thorium Molten Salt Reactor (TMSR) technology [13]. The goal in the first stage is to design and construct a 2 MWth TMSR experiment. Finally, TMSR projects targets to achieve 100MWth. Therefore, it is necessary to evaluate residual heat removal system. In the past US MSR project in 1960's and 1970's, natural convection of molten-salt or NaK for removing residual heat was considered [14]. So in this paper, a system model was developed to study the PRHRS of the molten salt reactor. The goal of the paper is to investigate the transient process of the PRHRS when the decay power decreases. The transient processes of startup, water flowing into the hot tube and gas discharging were analyzed. The analysis can contribute to a better understanding of flow processes and give hints for design improvements to avoid undesired effects.

2 A brief introduction of the PRHRS

When molten salt reactor shuts down, molten salt will be discharged into the drain tank where the heat transfer tubes arranged in advance take decay heat away. Figure 1 shows the schematic of the PRHRS. The decay power is input from the surface of the thimble, so water boils in the annulus between the thimble and the center tube. The cooling water flows downward in the center tube, reverses at the bottom of the thimble and returns to the steam drum. The driving force is density difference due to boiling in the annulus. Steam in the drum goes up to the condenser, condenses to water. Then water flows back to the steam drum and the big natural circulation closes. We divide the whole loop into a condensing loop above the steam drum and a boiling loop below the steam drum.

Helium is filled in the system at the initial state so that the system pressure is atmosphere pressure. When the heat transfer tubes are put into service, water temperature increases and vapor is generated. Helium will be discharged from the discharging port if the system pressure increases above the upper limit.

Table 1 Design parameters of the PRHRS

Parameters	Value
Number of heat transfer tubes	6
Height of the heat section (m)	1.5
Wall thickness of the heat transfer tubes (mm)	1.5
Height difference between the steam drum and the condenser (m)	2.0
Initial water temperature (℃)	20
Volume of the steam drum (m^3)	0.22
Total amount of water (kg)	82.2
Heat transfer area of the condenser (m^2)	2.5
Volume of the water tank (m^3)	1.59

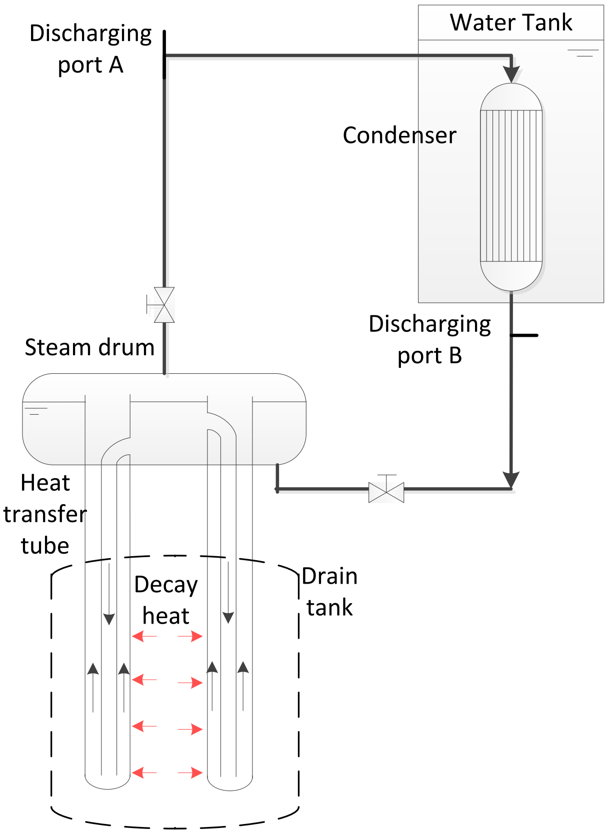

Fig. 1 The PRHRS of molten salt reactor.

3 RELAP5 model

In RELAP5, the natural circulation system is composed of control volumes and junctions. The volumes are similar to the grid in CFD software and the junctions are used to connect the volumes. Figure

2 shows the nodalization of the PRHRS. There are 99 volumes and 99 junctions in the system model. 201B, 202P and 203B simulate the steam drum. The condenser is modeled by 303P and the water tank is modeled by 307P. 101A and 100P simulate the annulus and the center tube, respectively. 301P, 302P, 304P, 305P and 306SV model the associated pipes between the condenser and the steam drum.

The system boundary is given in 101A and 308TDV. Heat flux is specified in the heat boundary at the left side of 101A and 308TDV gives a constant atmosphere pressure. It should be noted that heat transfer also occurs between the annulus and the center tube. Other components are assumed to be adiabatic.

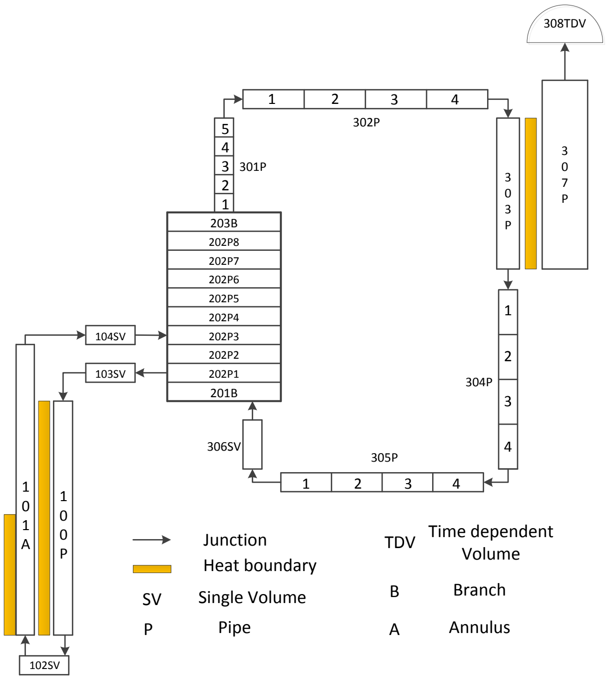

Fig. 2 Nodalization of the PRHRS.

3.1 Nodalization sensitivity analysis

Figure 3 shows the mass error with different control volumes. It can be seen that the mass error increases to a large value when the number of volumes of heat transfer tube is 40, while the mass error in other conditions is very close to zero. So the nodalization of heat transfer tube with 20 volumes is selected. The mass flow rates with different volumes in the condenser are depicted in Fig. 4. H20_C5 means that heat transfer tube has 20 volumes and condenser has 5 volumes. The amplitude of H20_C5 is larger than other conditions where the mass flow rates are very close. So the scheme with 20 volumes for the heat transfer tube and 10 volumes for the condenser is a better choice for numerical analysis.

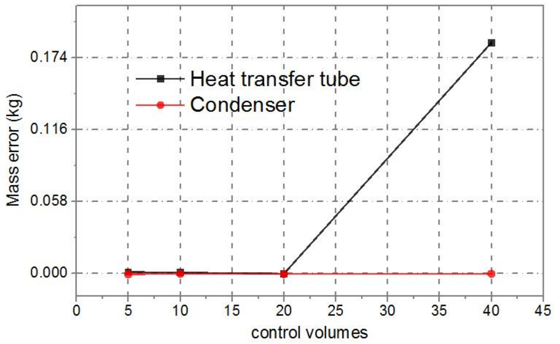

Fig. 3 Mass error with different control volumes.

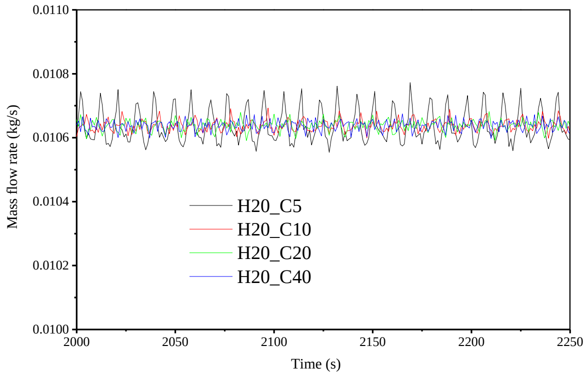

Fig. 4 Nodal schemes with different volumes in the condenser.

4 Results and discussion

4.1 decay power

To predict the decay power of the 2MWth molten salt reactor, an appropriate correlation should be selected. The typical correlations are Todreas&Kazimi formula, ANS formula and Shure formula [15]. Todreas&Kazimi formula is presented in the following:

$$\frac{P}{P_0}=0.066(\tau^{-0.2}-(\tau+\tau_0)^{-0.2}) \qquad (1)$$

Where P is the decay power τ seconds after shutdown, P_0 is the power in operation before shutdown, and τ_0 is the continuous running time of the reactor.

ANS recommended the following correlation for the prediction of decay power.

$$\frac{P}{P_0}=5\times10^{-3}a(\tau^{-b}-(\tau+\tau_0)^{-b}) \qquad (2)$$

Where a and b are the factors provided by ANS. Shure formula is similar to the correlation given by ANS. But Shure gave different values for a and b.

The experimental results were obtained from the molten salt reactor experiment conducted in Oak Ridge National Laboratory [16]. Figure 5 shows the comparison between the correlations and the experimental data. The largest deviations of ANS and Shure formula both exceed 20% while the deviation of Todreas & Kazimi formula is within 10%. So Todreas & Kazimi correlation is selected for the calculation of decay power.

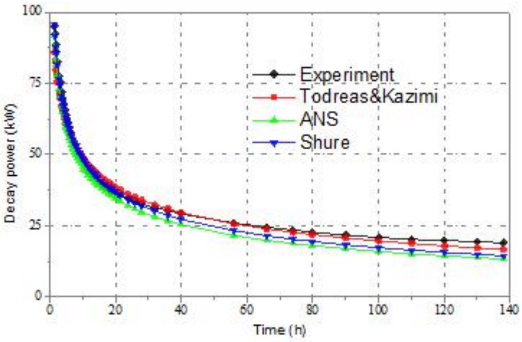

Fig. 5 Decay power correlations.

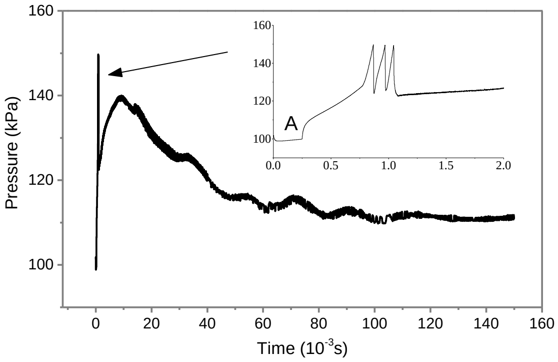

Fig. 6 Variation of pressure.

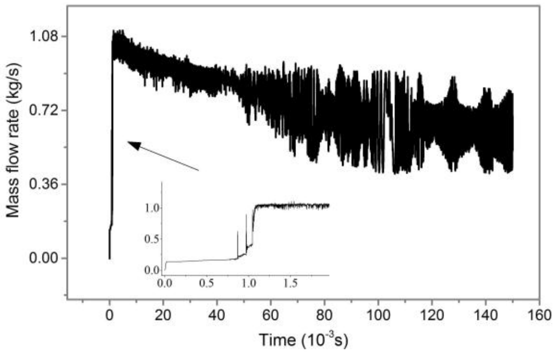

Fig. 7 Variation of Mass flow rate.

4.2 Startup

It is assumed that the molten salt reactor shuts down after the normal operation for 1000 hours. Then the PRHRS is started. Figure 6 and Figure 7 show the variation of system pressure and mass flow rate, respectively. Water is deeply subcooled at the initial state, so the decay heat is used to increase the water temperature until steam is generated. Part A in Fig. 6 represents the single phase stage. Water flow rate is very stable in this stage, which can be seen in Fig. 7. Then steam is generated in the annulus and flows into the steam drum. The drum pressure increases fast for the existence of non-condensable gas. Steam can only reach the condenser through diffusion and thus steam flow rate in the pipe above the steam drum is almost zero. When the drum pressure increases to the setting value (150 kPa), the gas is discharged from the discharging port. A sharp decrease of pressure can be seen in Fig. 6. Correspondingly, water flow rate increases sharply for flashing in the annulus. The sharp pressure drop often happens several times until the steam can circulate in the condensing loop and be condensed. As the decay power decreases, water is heated in the tank. At about 8×10^3s, a part of the water boils and heat transfer is enhanced in the condenser. Thus the pressure starts to decrease. After discharging, the system becomes stable and the decay heat can be removed smoothly.

4.3 Water flowing into the hot tube

As decay heat decreases, the number of heat transfer tubes used in the drain tank can be altered by changing the water level in the steam drum because the inlets of the center tube are at different elevations. So changing the water level means changing the number of heat transfer tubes, which leads to the change of the heat power and molten salt temperature indirectly. If the water level is lower than the inlet of the center tube, the heat transfer tube would be dried out finally. Then when we want to put this tube into use, the temperature of the tube surface is much higher than water saturation temperature. So water boils violently when flowing into the tube. It is necessary to investigate the process that water flows into the hot tube.

Figure 8 shows the variation of pressure and water flow rate. The pressure increases fast and fluctuates. However, water flow rate fluctuates around zero for about 50 seconds, which means water cannot be injected into the center tube easily. That is due to violent boiling of water at the inlet of the tube. Then when water flows into the annulus, more steam is generated and the pressure increase sharply to 220 kPa, which is 2.2 times larger than the initial value. Due to sufficient capacity of the condenser, the steam is consumed and the pressure decreases to a balanced value. The water flow rate is also accelerated by the violent boiling in the annulus. Figure 9 shows the variation of the surface temperature. It can be seen that the surface temperature decreases fast. When the high-temperature surface is cooled, water flow rate decreases gradually. After that, the system tends to be stable and no violent oscillations occur.

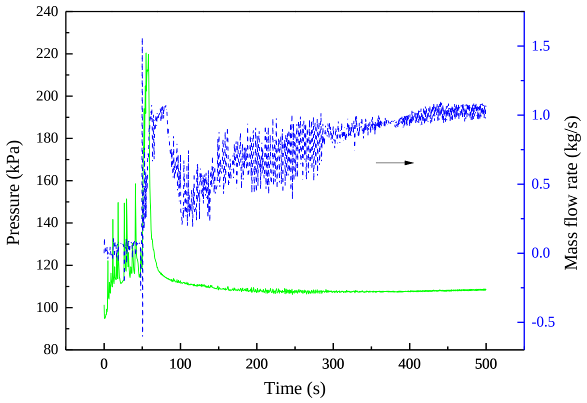

Fig. 8 Pressure and mass flow rate.

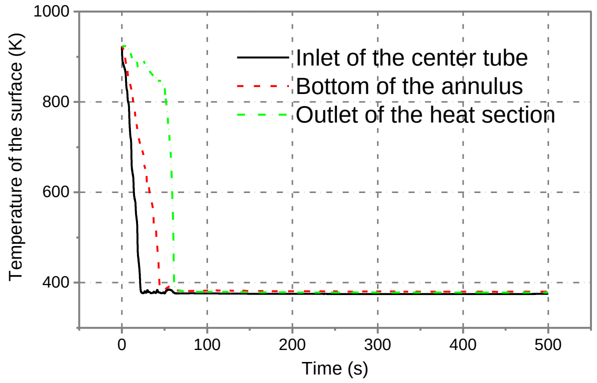

Fig. 9 Temperature of the tube surface.

4.4 Discharging port

Port A and Port B are both available for gas discharging. The auto gas blow-off component starts when the system pressure increases over 150 kPa. Then the mixture of helium and steam is discharge into a filtering system automatically. The comparison of gas discharging between port A and port B is shown in Fig. 10. Before discharging, the pressures of port A and port B are identical. When port B is opened, the pressure drop is about 25 kPa, the amplitude of which is much larger than that in port A condition. The blow-off device starts many times at port A while it only starts three times at port B. The non-condensable gas in the condenser cannot be easily discharged from port A since steam flows anticlockwise in the condensing loop. It seems that discharging at port A does not have a severe impact on system operation since after about 10×10^3s, the trends of the pressures become very similar.

It should be noted that the gas space is filled with helium at the initial state. After discharging, only a small fraction of helium stays in the system. Almost all the non-condensable gas concentrates in the condenser and 304P (in Fig. 2). It is not easy and needed to discharge all the non-condensable gas. The mass fraction of helium is similar in the two conditions after 10×10^3s, which implies that discharging port does not have a strong influence on long-term operation of the PRHRS.

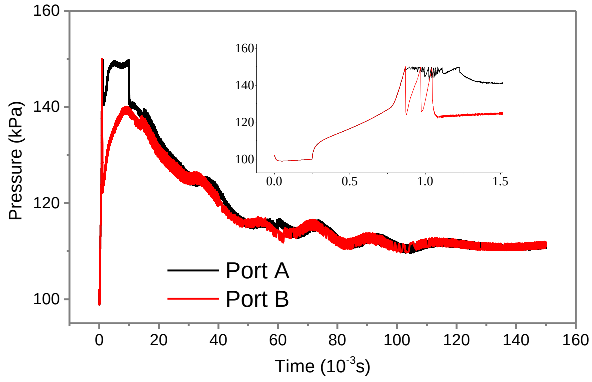

Fig. 10 Discharging at different ports.

5 Conclusions

A numerical investigation of the PRHRS of molten salt reactor was conducted. Todreas & Kazimi formula is considered as a better choice for the prediction of decay power. The numerical results show the feasibility and efficiency of the PRHRS removing decay heat for the molten salt reactor. The heat removing process can be roughly divided into three stages: single phase flow, gas discharging and stable two-phase flow. In gas discharging process, the system pressure increases to the upper limit and the discharging port is opened automatically. It should be noted that the port opening may be repeated several times.

A large increase of system pressure and water flow rate can be observed when water flows into the high-temperature tube. Violent boiling occurs and water cannot be injected into the tube immediately. The temperature of the tube surface decreases sharply. About 100~200 s later, the system becomes stable again. There is not much difference between port A and port B in discharging except that port A is opened more frequently. After discharging, some non-condensable gas still stays in the system and almost all of it concentrates in the condenser and the downward tube after the outlet of the condenser. This work is aimed to evaluate availability of PRHRS. Therefore, further study will be needed for evaluating availability of PRHRS to large power molten-salt reactor.

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