Numerical Simulation of the Transient Flow Characteristics and Thermal Stratification Phenomena in the Passive Residual Heat Removal System of NHR-200-II

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Abstract. The NHR-200-II nuclear heating reactor is a multi-purpose small integral pressurized water reactor (iPWR) developed by the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University. The design of NHR-200-II features a reactor core with thermal power of 200MW, in-vessel hydraulically-driven control rods and passive residual heat removal (PRHR) systems, et.al. Passive residual heat removal experiments were conducted in a scaled integral test facility for NHR-200-II. The PRHR experiments in the scaled facility were simulated by a layered RELAP5 system model to study the flow characteristics of the PRHR system in different primary fluid temperatures and different valve states. The phenomenon of reversed flow occurred in some primary heat exchangers in the numerical simulations when the primary fluid temperature was higher than certain level, which was consistent to the experiments. The simulated uneven outlet temperature distribution of the primary heat exchangers was also consistent with the experimental data when the isolation valves for the steam generator was kept open. Thermal stratification effect in the headers of the PRHR system played an important role in the phenomenon of uneven outlet temperature distributions, and the layered RELAP5 model was proven to be an efficient method for preliminary estimation of thermal stratification effect in the headers.

Keywords: NHR-200-II · Passive Residual Heat Removal System (PRHRS) · RELAP5 · Natural Circulation

1 Introduction

Various advanced small modular reactors (SMRs) are currently under development in the worldwide, including the Westinghouse Small Modular Reactor (W-SMR) [1], NuScale [2], SMART (System-integrated Modular Advanced Reactor) [3], mPower [4] and IRIS [5]. NHR-200-II is also a new type of advanced SMR designed by the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University, the NHR-200-II reactor can be a safe, clean, affordable, and less carbon-footprint choice of nuclear power generation

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[6, 7], and the reactor can be used for district heating, power generation, process heat, desalination, et al.

NHR-200-II has several engineered safety systems [7]. The passive residual heat removal (PRHR) systems are key part of the safety features of the reactor. A series of passive residual heat removal experiments have been conducted in a scaled integrated test facility for NHR-200-II by INET [8, 9]. To explain the flow phenomenon in the experiments, it was necessary to establish a detailed numerical model to analysis the transient characteristics of the PRHR system in the scaled integral test facility of NHR-200-II.

In this paper, a layered RELAP5 model of the PRHR system was established, numerical simulations with different primary fluid temperatures were carried out, and the simulation results were discussed and compared to the experiments.

2 Design of the PRHRS Test Facility of NHR-200-II

The NHR-200-II reactor has two parallel intermediate circuits, and two parallel PRHR columns are connected to each intermediate circuit. For the sake of simplicity, only one of the PRHR columns was chosen for modeling. The schematic of the PRHR column was shown in Fig. 1. The PRHR column consists of seven primary heat exchanger (PHE) branches, a residual heat exchanger (RHE) branch and a steam generator (SG) branch. A hot header and a cold header that connecting all the branches are arranged above the top of reactor pressure vessel. The seven PHEs are placed inside the reactor pressure vessel, and the RHE is a finned tube heat exchanger that is installed in the air-cooling tower of NHR-200-II. PHEs are connected asymmetrically to the hot header and the cold header by T-shaped junctions, and the steam generator (SG) is connected to the headers by low resistance Y-shaped junctions. The RHE is connected between the hot leg and cold leg of the SG. The pressurizer (PRZ) is placed at the highest location of the loop.

The PRHR column removes heat from the core by three coupled natural circulation loops. The first natural circulation loop is the natural circulation of the primary fluid inside the reactor pressure vessel, the second natural circulation loop is the fluid circulation in the PRHR loop (Fig. 1), and the third loop is the natural circulation of air in the air-cooling tower.

An integral test facility was built to study the characteristics of the PRHR system of NHR-200-II. Design of the test facility was similar to the original PRHR system of NHR-200-II with some exceptions due to site and equipment limitations. The main differences between PRHR system in the integral test facility and the PRHR system of NHR-200-II were:

(1) The PRHR system in the integral test facility was a scaled model, the height ratio is about 1:5, the hydraulic diameter ratio is about 1:3 for most pipes, the system volume ratio is about 1:50, and the thermal power ratio of the integral test facility is about 1:20 to that of the prototype.
(2) Temperature and pressure of the PRHRS of the integral test facility were slightly lower than those of the prototype due to site limitations.
(3) The heat sink of the residual heat exchanger (RHE) in the test facility was water, instead of air in the prototype.

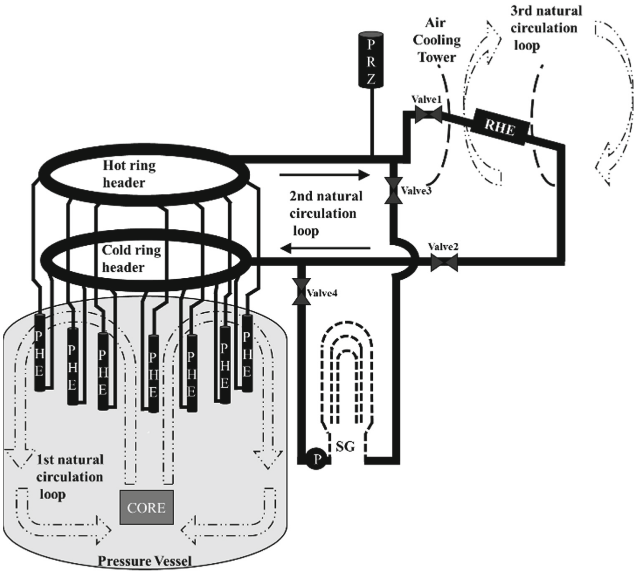


Fig. 1. Schematic Diagram of a PRHR system.

(4) The RHE was a smooth tube-array heat exchanger in the test facility, while the RHE was a finned-tube air cooler in the prototype.
(5) The number of PHE was six for the test facility due to space constraints, while there are seven PHE in the prototype.

The geometry information of key components of the integral test facility is summarized in Table 1.

Table 1. Geometry Information of Key Components in the integral Test Facility of NHR-200-II

Components name	SG	PHE	RHE	Cold ring header	Hot ring header
Elevation (m)	3.05 (center) (951P-953P)	0 (center)	1.427 (center)	2.198	2.432
Hydrulic diameter (mm)	118.0	60.0	76.0	92.0	92.0
Heat transfer area (m2)	9360	39.8	8.09	/	/
Tube/Pipe length (m)	3.79785 (length of heat transfer tubes)	1.6 (length of heat transfer tubes)	2.76 (length of heat transfer tubes)	8.69 (length of the circular pipe)	8.69 (length of the circular pipe)

In the PRHR system of Fig. 1, there are four valves to switch branches, i.e. Valve1 at hot leg of RHE branch, Valve2 at cold leg of RHE branch, Valve3 at hot leg of SG branch, and Valve4 at cold leg of SG branch. The pump of intermediate circuit was located behind the SG outlet, and the pump was used only on normal operating conditions. The PRHR system can be triggered by opening isolation Valve1–2 and closing the Valve3–4. However, possible failure in closing the Valve3–4 should be considered.

A series of scaled PRHR experiments were conducted with the primary fluid temperature kept constant during each experiment. This was achieved by controlling the reactor core at a low but constant fission power, and the core fission power was balanced by adjusting the cooling capacity of the PRHR system, so the primary fluid temperature was kept constant during each experiment.

The following conclusions were made depend on the experiment data:

(1) Reverse flow may occur in some PHE branches, and the heat removal capacity of the PRHR system was significantly lower when reverse flow occurred.
(2) The outlet temperatures of PHE branches were significantly different once the SG branch was not isolated.
(3) The outlet temperature of PHE branches were near equal if the SG branch was isolated.

To explain those observations, transient flow characteristics of the PRHR system was simulated with different combination of valve states (opening or closing) and different primary fluid temperatures.

3 Numerical Model of the PRHRS Test Facility

A REALP5 model was setup according to the geometry and hydraulic parameters of the PRHR system of the scaled integral test facility. The node diagram of the RELAP5 model was shown in Fig. 2. In this diagram, the six primary heat exchangers (PHEs) were named with starting numbers of 1–6, and the cold header and hot header were named starting with numbers 7 and 8 correspondingly.

Unlike other pipe components, the hot and cold headers in the test facility were closed circular pipes, and the pipe diameter of the headers was significantly larger than other pipe components, so possible local recirculation and thermal stratification may occur in the hot and cold headers. To capture the secondary flow phenomena in the headers, a layered model was used for the headers. The layered header model composed of three layers that arranged vertically, and the center layer was connected to its neighborhoods to simulate vertical flow mixing at low flow rates. The schematic diagram of layered model for the headers was shown in Fig. 3.

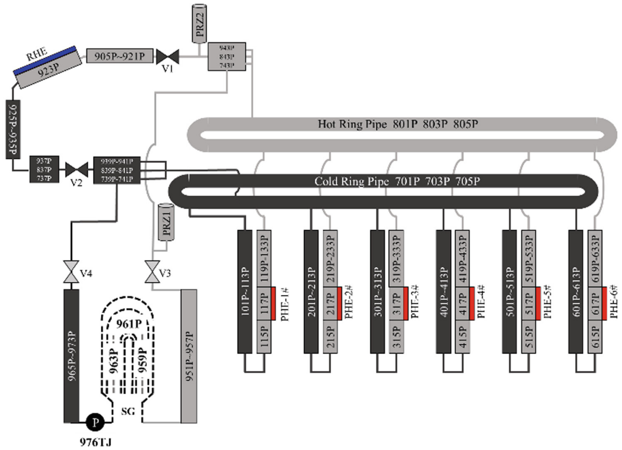
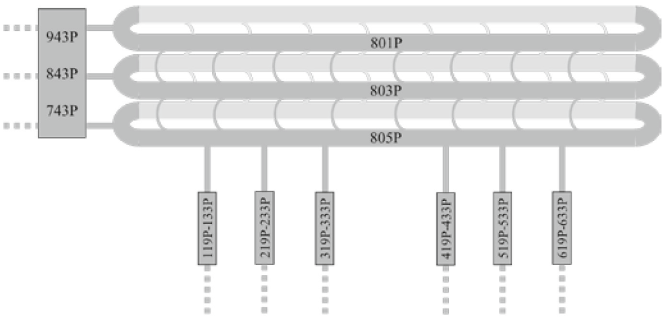
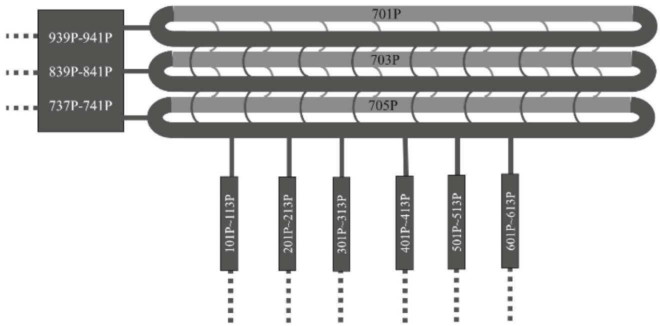


Fig. 2. The Overall Figure of Node Diagram of PRHRS.



(a) Schematic of the hot header.



(b) Schematic of the cold header.

Fig. 3. Node Diagram of Hot and Cold Header with Layered Model.

4 Numerical Simulations and Analysis of Results

All numerical simulations were divided into four stages through the control of the target flow rate of pump (976TJ) and the control of the valves of V1 ~ V4.

(1) In the first stage (0–100 s), the PHE and SG branches were put into operation, where the valves of V1 and V2 were closed and the valves V3 and V4 were opened. The SG branch and PHE branches were driven by the pump 976TJ. The mass flow rate of the pump was ramped from zero to a maximum of approximately 32 kg/s. At this stage the pressurizer PRZ1 was put into operation.
(2) In the second stage (100–600 s), the pump 976TJ was gradually stopped but the RHE branch was failed to put into operation (the valves of V1 and V2 were failed to open). The loop was in natural circulation mode between the six PHE branches and the SG branch.
(3) In the third stage (600–2700 s), the RHE branch was successfully put into operation by opening the valves of V1 and V2, however, the isolation valves of V3 and V4 were assumed failing to close in this stage. In this stage, the PHE branches, the PHE branch and the SG branch were all running. The purpose of this stage was to simulate the case of isolation failure of the SG branch.
(4) In the fourth stage (2700–5000 s), the SG branch was switched off by closing the valves of V3 and V4. In this stage, the loop was in natural circulation mode between the six PHE branches and the RHE branch.

The temperatures were set to 298.15 K for the RHE secondary fluid, and 453.15 K for the SG secondary fluid.

15 different primary fluid temperatures in PHEs were set in 15 cases. The primary fluid temperatures simulated were 327.15 K, 353.15 K, 368.15 K, 383.15 K, 398.15 K, 413.15 K, 427.15 K, 443.15 K, 458.15 K, 473.15 K, 488.15 K, 503.15 K, 522.15 K and 527.15 K.

The mass flow rates of each branch during different stage were shown in Fig. 4. The flow directions in Fig. 4 were specified as follows. For PHE branches, the flow rates were positive when fluid flows from cold header to hot header. For the RHE branch and SG branch, the flow rate was positive when the fluid flows from hot header to cold header.

In the first stage (0–100 s), due to the existence of hot and cold headers, the steady-state flow rates of each PHE branch were slightly different (Fig. 5).

In the second stage (100–600 s), as primary fluid temperature increased, the temperature difference between PHE and SG decreased gradually, so the flow rates of each branch decreased gradually (Fig. 6). The stability behavior of the PRHR system depended on the primary fluid temperature. The loop was stable when the primary fluid temperature was lower than 458.15 K, i.e. the SG secondary fluid temperature. The flow rates of PHE branch and SG branch oscillated and gradually decayed to zero when the primary fluid temperature was higher than 458.15 K.

In the third stage (600–2700 s), all the branches of the PRHR system were running, including the SG branch, the RHE branch and the PHE branches.

The PRHR system in this stage was found to be stable as the primary fluid temperature were between 327.15 K and 383.15 K. Steady flow rates of each branch under different primary fluid temperatures were shown in Fig. 7.

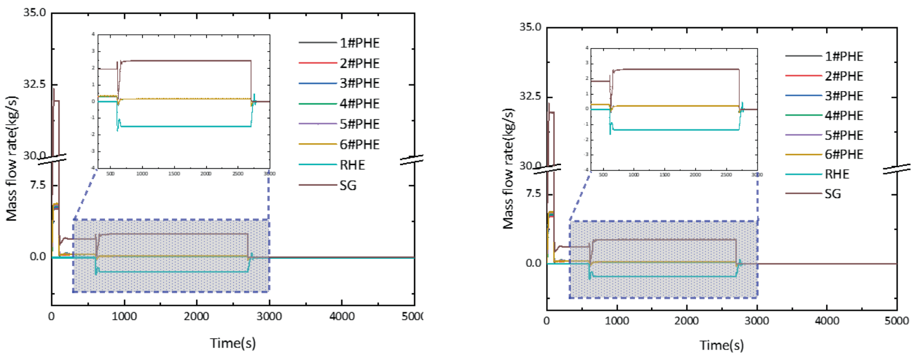
The flow rates in each branch of the PRHR system oscillated with decreasing magnitude when the primary fluid temperature is 458.15 K.

The flow rates of each branch of the PRHR system became steady after an initial unstable period for the primary fluid temperature range from 473.15 K to 533.15, and the flow rates of 2#PHE, 3#PHE, 4#PHE and RHE branches were positive, while flow rates of other PHE branches, i.e. 1#PHE, 5#PHE, 6#PHE, were negative (Fig. 8).

In the fourth stage (2700–5000 s), the steam generator was isolated from the PRHR system. The PRHR system became stagnated when the primary fluid temperature was in the range of 327.15 K to 458.15 K. In the primary fluid temperature of 473.15 K to 527.15 K, the flow in the PRHR system became steady-state with reverse flow in some PHE branches (Fig. 9), and the reverse flow occurred in the 1#PHE, 4#PHE, 5#PHE and 6#PHE. The flow rates of each branch increased with primary fluid temperature. The flow rates in the reversed PHE branches were basically the same value, while the flow rates in the positive PHE branches were different (Fig. 9).

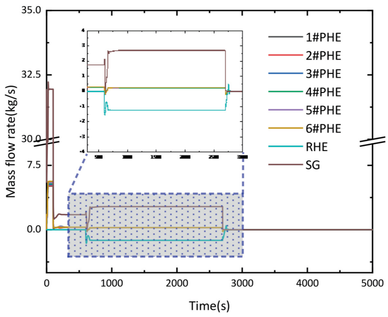
Thermal stratification effect in the hot and cold ring headers and corresponding Y-junctions was shown in Fig. 10 and Fig. 11, where the temperature contours of the headers and the Y-junctions were plotted for primary fluid temperature of 522.15 K. It was clearly shown in Fig. 10 and Fig. 11 that the layered header model can capture some detail of local flow phenomena in the headers and Y-junctions, such as thermal stratification or local recirculation.

It was observed in the scaled PRHR experiments that the outlet temperatures of the six PHE branches were significantly uneven if the SG branch was not isolated, while the outlet temperatures were nearly equal if the SG branch was isolated. In the numerical simulations, the phenomenon of uneven outlet temperatures of PHE branches were successfully captured in the third stage (600–2700 s in Fig. 12), and the outlet temperatures of PHE branches were nearly equal in the fourth stage (2700–5000 s in Fig. 12). The numerical simulations agreed the experimental data quantitively.

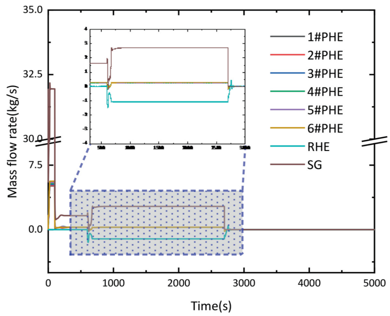


(a) 327.15K **(b) 353.15K**

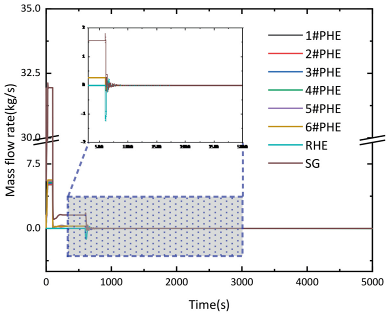
Fig. 4. Mass Flow Rate of Each Branch at Different Primary Fluid Temperature.



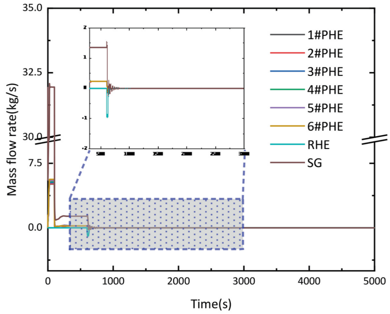
(c) 368.15K



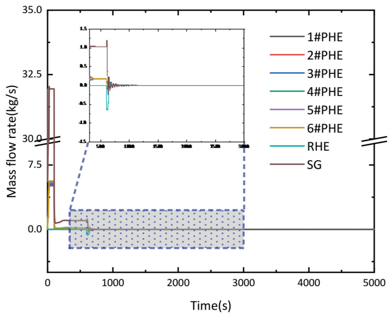
(d) 383.15K



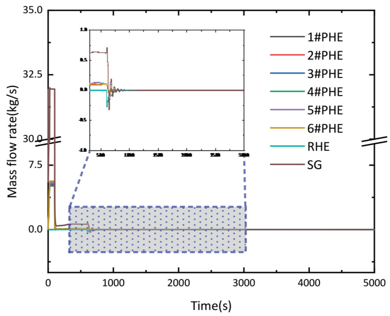
(e) 398.15K



(f) 413.15K

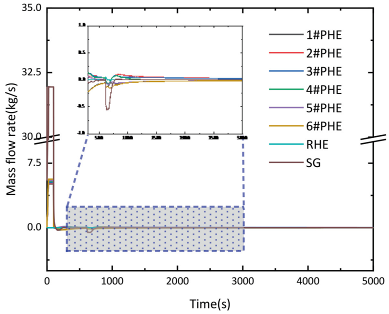


(g) 427.15K

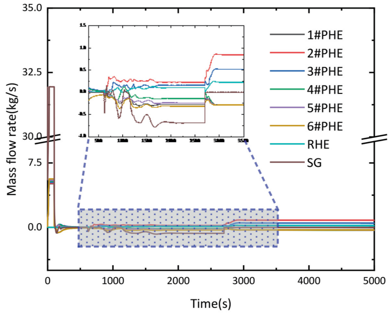


(h) 443.15K

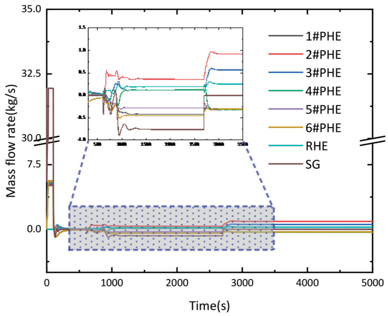
Fig. 4. (*continued*)



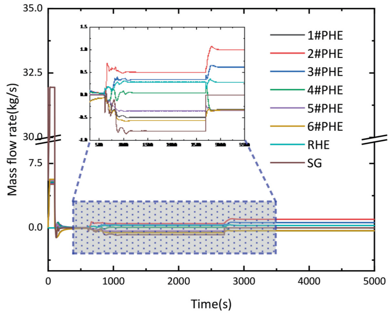
(i) 458.15K



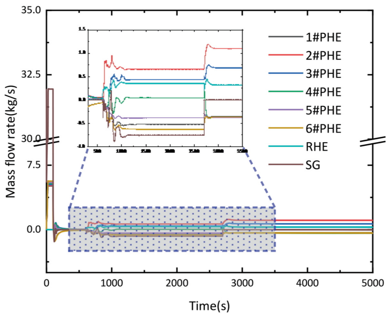
(j) 473.15K



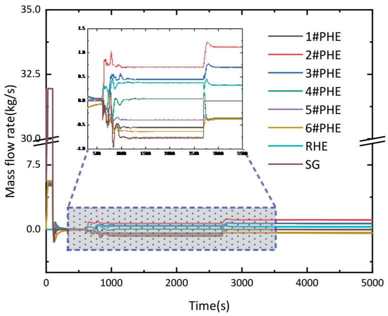
(k) 488.15K



(l) 503.15K

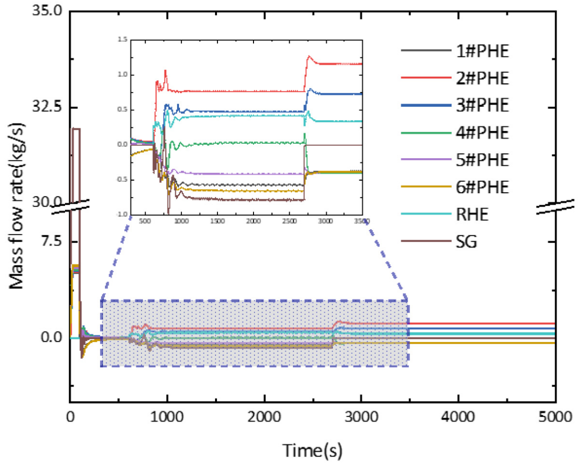


(m) 522.15K



(n) 527.15K

Fig. 4. (*continued*)



(o) 533.15K

Fig. 4. (*continued*)

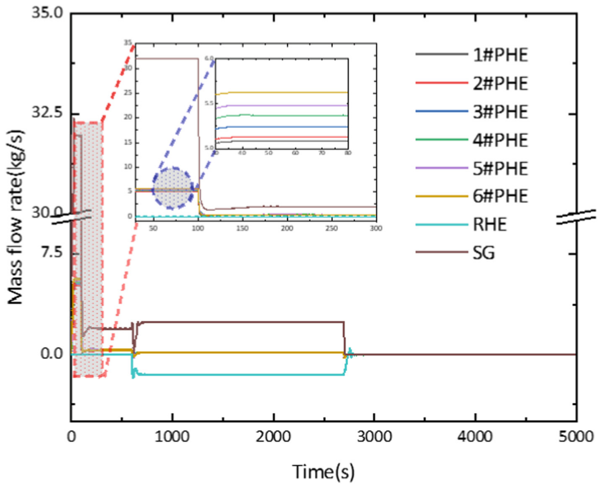


Fig. 5. Mass Flow Rate of Each Branch at Primary Fluid Temperature of 327.15 K.

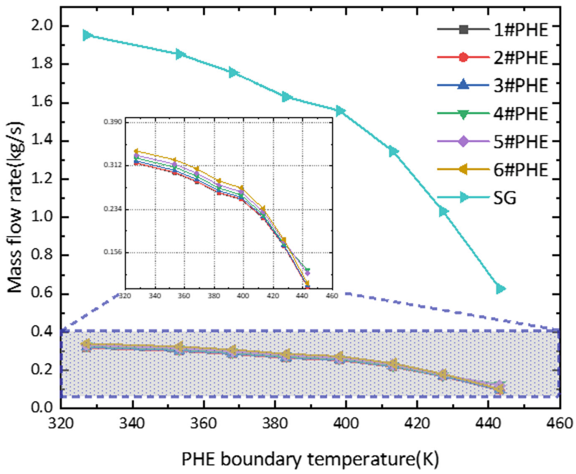


Fig. 6. Steady Mass Flow Rate at the Second Stage (PHE 327.15–443.15K, t = 500.0 s).

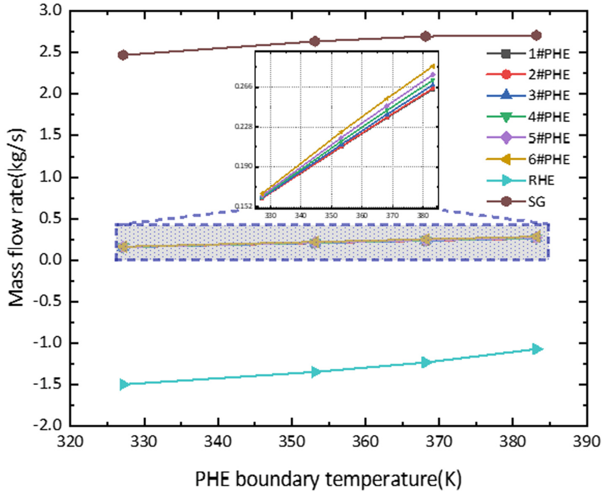


Fig. 7. Steady Mass Flow Rate at the Third Stage (PHE 327.15–383.15 K, t = 2000.0 s).

The uneven outlet temperatures of the PHE branches in the third stage can be explained by the reverse flow in some PHE branches and the thermal stratification effects in the headers. Significant thermal stratification occurred in the third stage, since the fluid from SG branch can flow into the lower part of the cold header or hot header through the low-resistance Y-junctions in the headers. In the fourth stage, since the valves of the SG branch closed, the thermal stratification phenomenon in the headers became insignificant, and the outlet temperatures of PHE branches became the same value.

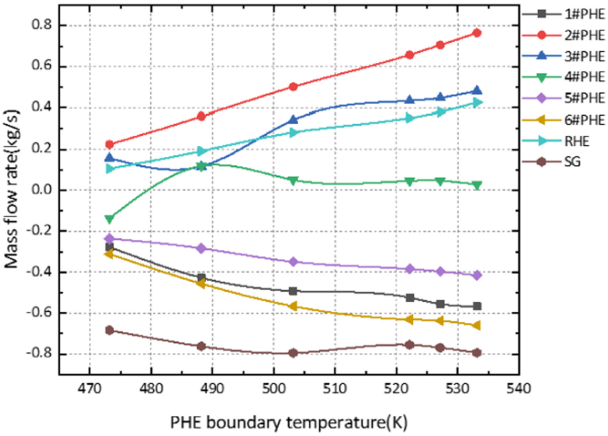


Fig. 8. Steady Mass Flow Rate at the Third Stage (PHE 473.15–533.15 K, t = 2000.0 s).

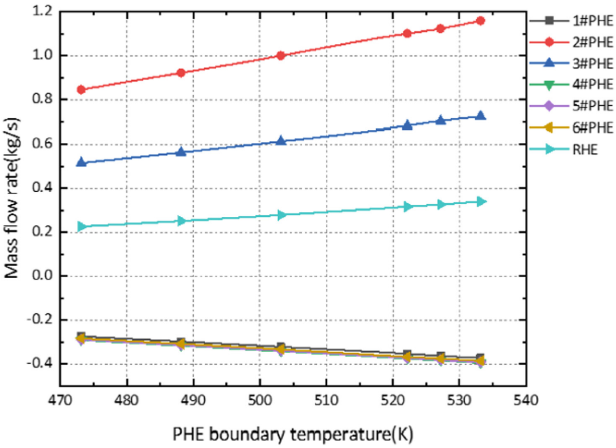
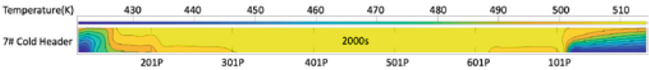
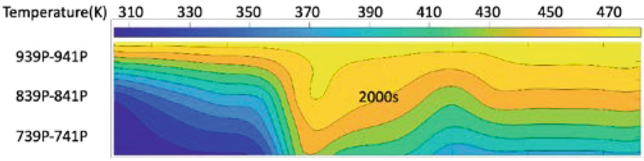


Fig. 9. Steady Mass Flow Rate at the Fourth Stage (PHE 473.15–533.15 K, t = 4000.0 s).

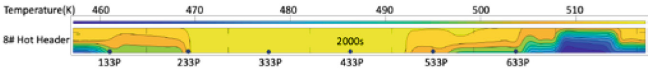


(a) Temperature of Cold Header -2000s.

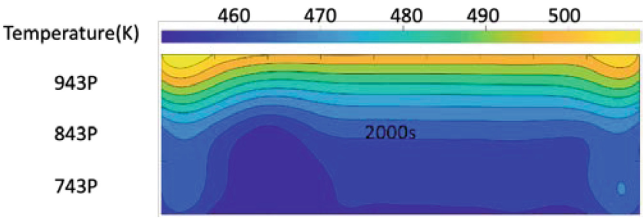


(b) Temperature of Y-Junction of Cold Header (939P-941P/839P-841P/739P-741P) -2000s.

Fig. 10. Thermal Stratification of Cold Header and Y-Junction.



(a) Temperature of Hot Header -2000s.



(b) Temperature of Y-Junction of Hot Header (943P/843P/743P) -2000s.

Fig. 11. Thermal Stratification of Hot Header and Y-Junction.

5 Conclusions

In this paper, a layered RELAP5 model was developed for the PRHR system of a scaled test facility for the NHR-200-II reactor. Numerical simulations were carried for both the PRHR scenario of SG branch isolated and the PRHR scenario of SG branch not isolated. The main conclusions include:

(1) For the case of SG branch not isolated, the numerical simulations shown that the outlet temperatures of all PHE branches were significantly uneven (600–2700 s in Fig. 12), and for the case of SG branch isolated, the outlet temperatures of PHE branches were nearly equal (2700–5000 s in Fig. 12). In both cases, the numerical results were qualitatively consistent with the experimental observations.

(2) The primary fluid temperature has a significant impact on the PRHR system. The phenomenon of reversed flow occurred in some PHE branches when the primary

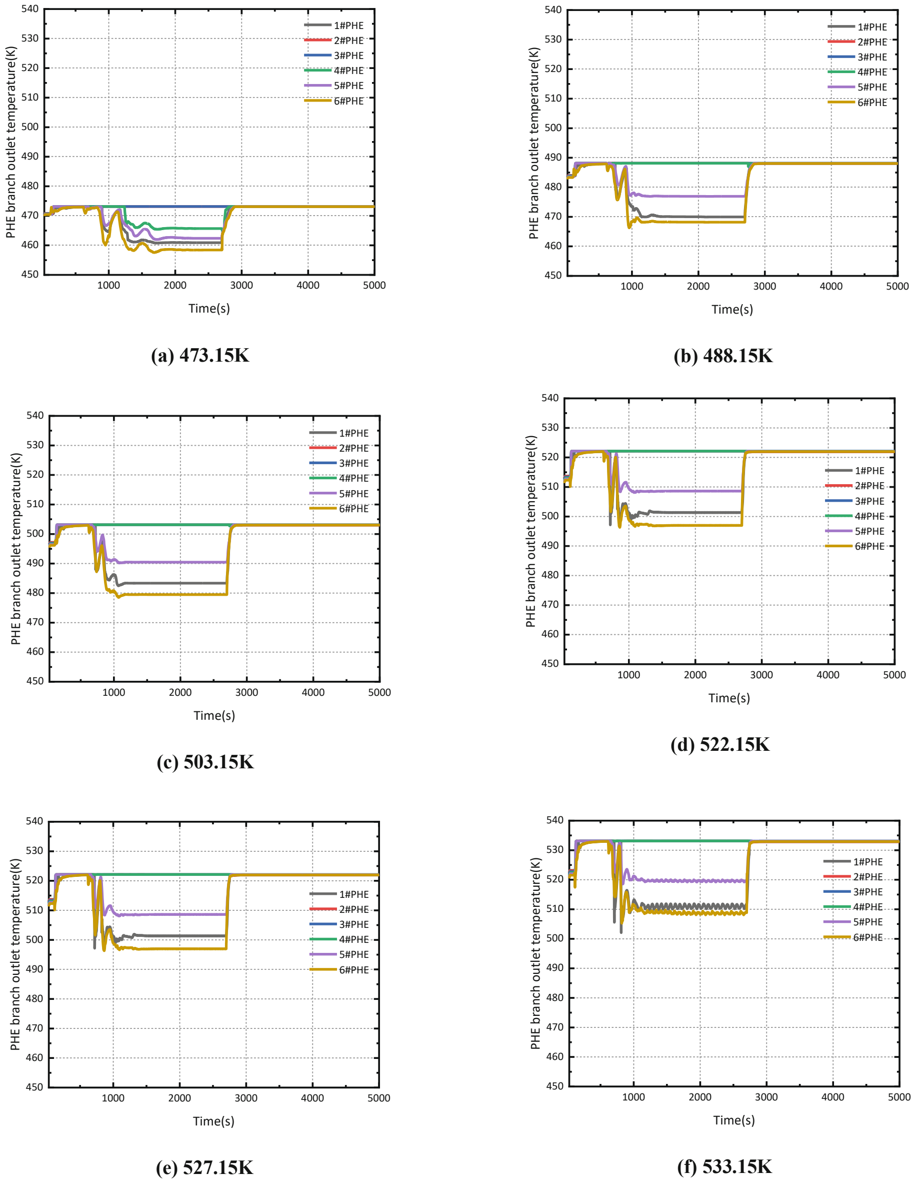


Fig. 12. PHE Branch Outlet Temperature Dispersion (PHE 473.15–533.15 K).

fluid temperature was higher than 473.15 K (Fig. 8 and Fig. 9), which was also consistent with the experiment observations.

(3) The uneven outlet temperatures of the PHE branches when the SG branch was not isolated can be explained by the reverse flow in some PHE branches and the thermal stratification effect in the headers. The layered RELAP5 nodalization for

the hot and cold headers can be used as a preliminary estimation method of the thermal stratification effect, however, detailed 3-dimensional CFD methodology is still necessary to accurately capture the phenomenon of thermal stratification in the hot and cold headers of the PRHR system.

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