RESEARCH AND DEVELOPMENT OF ONE DIMENSIONAL TWO-PHASE SYSTEM CODE USED IN PT-SCWR

TIAN Ye [1], JIA Baoshan [1]

[1] Department of Engineering Physics, Tsinghua University, Beijing, China

Abstract

The main content of this paper is to build up a program to simulate the PT-SCWR moderator system. The system is a passive two phase natural circulation loop and can be parted into two parts: loop and heat exchanger. Along the whole loop, we chose the two-fluid model to describe the physical phenomenon, while some particular equations are added for different characteristic. Finally, we simulate the test loop to gain the computational result. The results show that the system is able to remove the redundant heat of moderator and can help to design the parameters of the test facility.

Key words: SCWR, Two-Fluid Model, Superheat.

1. Introduction

The Generation-IV nuclear energy system is still under design. As one of the recommended reactor types, the Supercritical Water-Cooled Reactor (SCWR) has its own features and advantages. AECL is designing a pressure tube supercritical water reactor (PT-SCWR) on the base of CANDU series. PT-SCWR uses supercritical light water as coolant, and heavy water as moderator. The moderator system is a passive natural circulation loop. The test loop of PT-SCWR moderator system is shown in Fig 1.

The moderator in Calandria is close to saturation. When the moderator flows out from the core and moves upward along the pipe, the single-phase heavy water (close to saturation) translates likely into steam bubbles at a certain superheat temperature because of the pressure lost. By the two-phase moderator flows and the pressure keeps reducing, the void fraction in pipe increases. Then the moderator arrives at the heat exchanger, and the steam and heavy water are parted by gravity naturally. Both steam and water release heat to the cooling water, so the steam changes into liquid again and goes back to the Calandria with cooled heavy water.

2. The physical model

The moderator system can be parted into two parts: loop and heat exchanger. Along the whole loop, we chose the two-fluid model[1], including basic mass, momentum, energy governing equations and closure laws, to describe the physical phenomenon, while some particular equations are added to the loop and heat exchanger parts for their different characteristics. Considering no energy transfers from outside to the loop, we take a basic assumption that the steam in pipe is always in saturation status to simply the model. So that this assumption takes place of the vapor energy conservation and subtract one equation from the six basic two-fluid model equations.

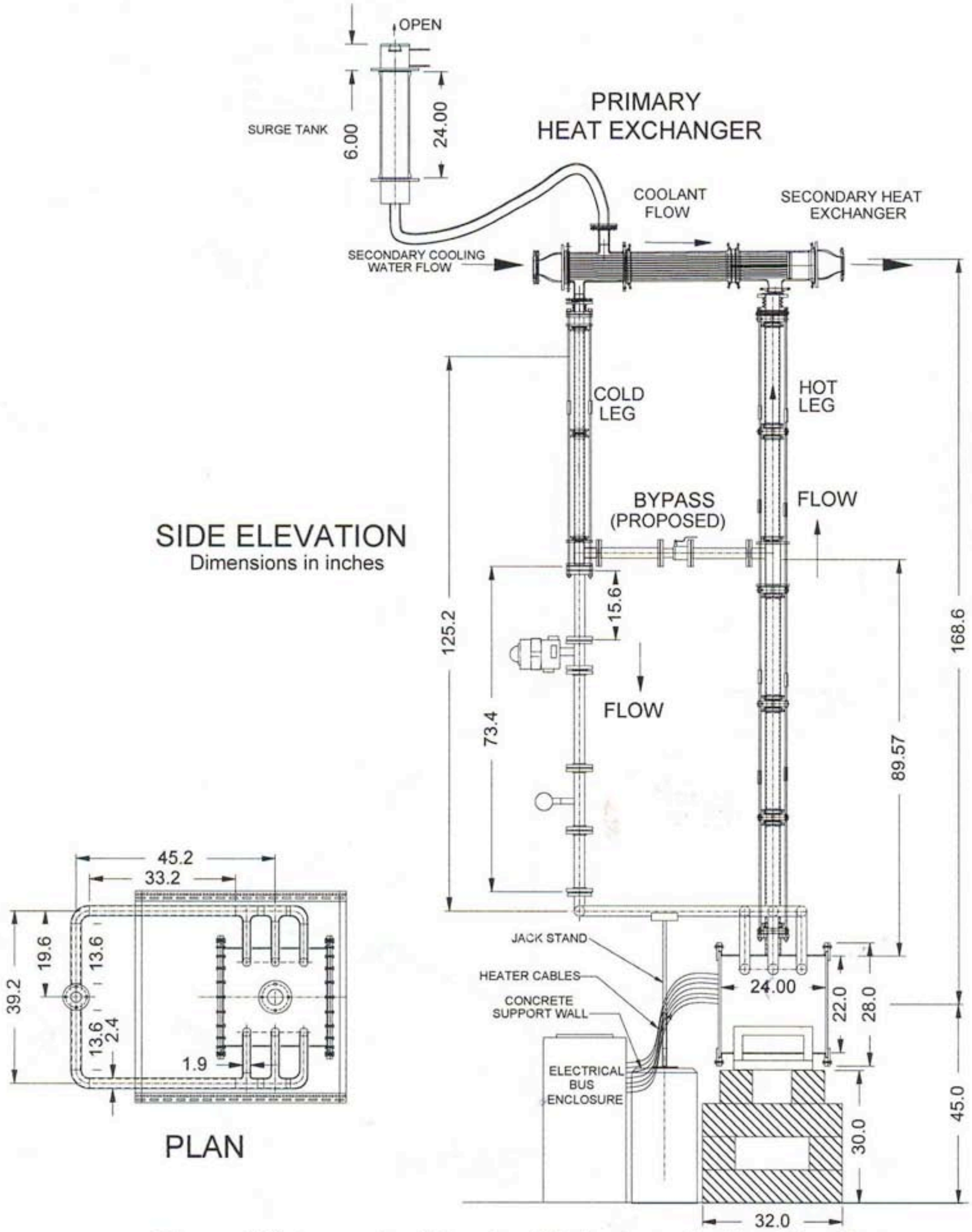

Figure1 PT-SCWR Moderator Cooling Test Loop

2.1 The loop model

The loop model includes the basic two-fluid model equations and closure laws. We also take the following assumptions:

1. One-dimension fluid in the loop;

2. Vapor phase is always in saturation status;
3. Liquid phase is superheated in two phase flow, and might be subcooled in one phase flow;
4. Do not consider the non-condensable gas.

In the rising section of the loop, the pressure of heavy water becomes lower as the fluid flows up, so the saturation temperature becomes lower. When the actual temperature of heavy water has reached the saturation temperature, heavy water in the fluid will not boil into steam immediately because of surface tension. This phenomenon delays the point of vaporization, and the temperature of heavy water in the vaporization point is a little higher than the saturation temperature. According to the process of boiling, the growth of bubble is the consequence of transition from sub-stationary state to stationary state. The simulation of the bubbles production and growth in superheat liquid is very complicated, including many influence elements, and we choose two aspects of them to derive the model.

One of the two aspects is to derive the relationship between the superheat temperature and the radius of bubble. If considering the vapor is ideal gas, as figure 2 shows, we have [2]:

$$\begin{cases} p_g + \int_0^H \rho_g g dH = p_\infty \\ p_f + \int_0^H \rho_f g dH = p_\infty \end{cases} \Rightarrow \int_0^H (\rho_f - \rho_g) g dH = p_g - p_f = \frac{2\sigma}{r^*} \tag{1}$$

r^* is the bubble radius

We substitute $dp_g = -\rho_g g dH$ into formula (1):

$$-\int_{p_\infty}^{p_g} \frac{\rho_f - \rho_g}{\rho_g} dp = \frac{2\sigma}{r^*}$$

As $\frac{\rho_f}{\rho_g} \gg 1$ so we have: $-\int_{p_\infty}^{p_g} \frac{\rho_f}{\rho_g} dp = \frac{2\sigma}{r^*}$

Because the vapor is ideal gas, the equation changes to:

$$-\int_{p_\infty}^{p_g} \frac{\rho_f RT}{Mp} dp = \frac{2\sigma}{r^*} \Rightarrow -\frac{\rho_f RT}{M} \ln\left(\frac{p_g}{p_\infty}\right) = \frac{2\sigma}{r^*}$$

$$\therefore p_g = p_\infty \exp(-\frac{2M\sigma}{\rho_f RTr^*}) \approx p_\infty (1 - \frac{2M\sigma}{\rho_f RTr^*}) \approx p_\infty (1 - \frac{2\sigma \upsilon_f}{p_\infty \upsilon_g r^*}) \tag{2}$$

By (1) (2): $$p_{\infty} - p_f = \frac{2\sigma}{r^*}\left(1 + \frac{\upsilon_f}{\upsilon_g}\right) \tag{3}$$

By the ideal gas law: $$\frac{dp}{dT} = \frac{i_{fg}}{T(\upsilon_g - \upsilon_f)} \Rightarrow \frac{1}{p}dp = \frac{i_{fg}M}{RT^2}dT \tag{4}$$

Integral the formula (4) from p_f to p_{∞} and from T_{sat} to T_g, we have:

$$\ln\left(\frac{p_{\infty}}{p_f}\right) = -\frac{i_{fg}M}{R}\left(\frac{1}{T_g} - \frac{1}{T_{sat}}\right) = \frac{i_{fg}M}{RT_gT_{sat}}(T_g - T_{sat})$$

$$(T_g - T_{sat}) = \frac{RT_{sat}T_g}{i_{fg}M}\ln\left[1 + \frac{2\sigma}{p_f r^*}\left(1 + \frac{\upsilon_f}{\upsilon_g}\right)\right] \approx \frac{RT_{sat}^2}{i_{fg}M}\frac{2\sigma}{p_f r^*} \quad \text{and} \quad \frac{Mp}{\rho} = RT$$

So: $$(T_g - T_{sat}) = \frac{2\sigma T_{sat}}{i_{fg}\rho_g r^*} \tag{5}$$

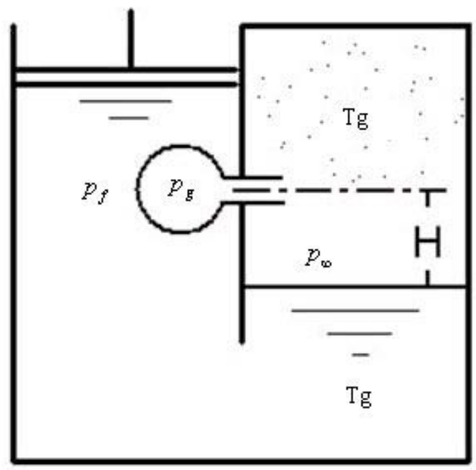

Fig 2 The schema of bubble growing

This equation shows the relationship between the superheat temperature and radius of bubble.

Another aspect is considering the bubble growth in the superheat liquid. Due to the experiment and calculate data by Scriven and Florchuetz [3], we have the bubble diameter relationships in the bubble growing process:

$$r = \sqrt{r_0^{\ 2} + D_f JaNu(\tau)} \tag{6}$$

In the equation, we define Ja: $\text{Ja}=\dfrac{c_f\rho_f(T_f-T_{sat})}{i_{fg}\rho_g}$ c_f is the specific heat of liquid, i_{fg} is the latent heat of vaporization, T_f is the temperature of superheated liquid. r_0 is the initial bubble radius, which is 0 in this model.

Define Nu: the dimensionless heat flux to the bubble, it is a function of Ja: $Nu = f(Ja)$, and Labuntsov supply a simple relationship: $Nu = 2 + (\dfrac{6\times Ja}{\pi})^{1/3} + \dfrac{12}{\pi}Ja$

$D_f = \lambda_f / c_f\rho_f$ λ_f is the liquid coefficient of heat conductivity.

We can calculate the superheat or the bubble critical diameter by the above model, as the following steps:

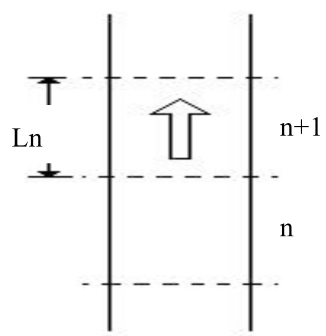

Figure 3 A segment of the loop

The figure 3 is a part of the rising section of the loop, which is parted to N segments. In the 'n' segment which the actual temperature is saturated, the bubble radius is 0. So in the 'n+1' segment, the bubble radius is $r_{n+1} = \sqrt{D_f Ja Nu(\tau)}$. In the equation, the τ is the time constant in flowing from 'n' segment to 'n+1', so $\tau = \dfrac{L_n}{V_l}$

According to equation (5), the superheat temperature is inversely proportional to the bubble radius, and to equation (6), the bubble radius is in direct proportional to superheat temperature. So we can get the superheat temperature and bubble radius by iterative computations.

2.2 The heat exchanger model

The heat exchanger is made of many tubes, and the geometry is complicated. The steam separation in the input area is also hard to simulate by physical models. So we take a simplified model as Figure 4 shown.

The cool water flows from left to right in the tube, and the two phase heavy water flows in an opposite direction between the tube and shell. When the heavy water flows into the heat exchanger, the bubble rises up and separates from liquid naturally. So an interface of vapor and water is formed by gravity. Above the interface, the saturated steam condenses on the cooling tube, and flow down to the water. Below the interface, the heavy water gets cooling by convection heat transfer. Finally, the cooled heavy water (including the condensate) flows back to Calandria.

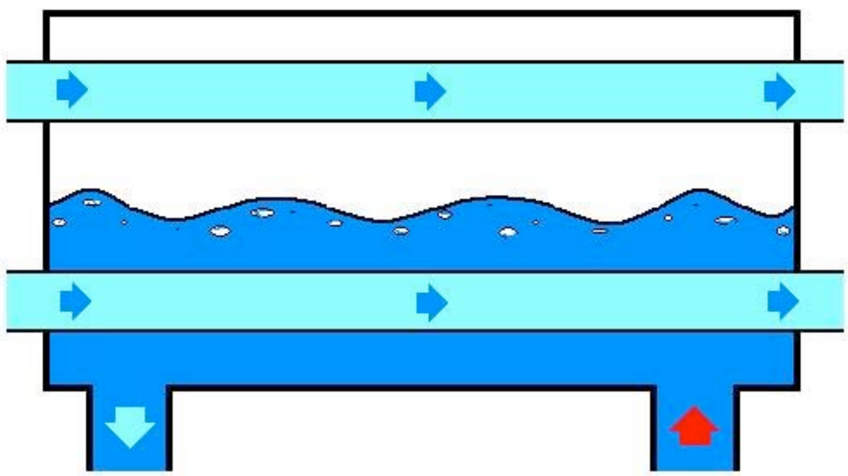

Figure 4 The heat exchanger simplified model

As the figure shows, we take two tubes above and below the interface to represent all the tubes. So we can use one standard tube in the steam part to simulate the saturated steam condensation and one tube in water part to simulate convection heat transfer of heavy water. And some assumptions are added:

1. The steam and water separated immediately at the input area and form one phase flow on the both side of interface;
2. The steam only condenses on the wall of cooling tube, do not consider the condensate on the interface;
3. A water film will be formed when steam condenses on the tube, the physical property is considered as constant in film;

4. Ignore the convection heat transfer in film, only consider heat conducting;
5. In film the temperature is logarithmic distribution;
6. Ignore the sub cooled in film, the condensate enthalpy is considered the same as saturated water;
7. The steam is saturated;
8. Ignore the noncondensable gas;
9. The steam condenses on the film at zero velocity, and no viscosity force;
10. The tubes in heat exchanger is evenly distributed,
11. The condensate will fall into the water when the film is thick enough, but do not consider the momentum changes in vertical direction.

3. Algorithm of model

The model of moderator system is only one dimension, so we can use finite difference method to discretize the equations. We segment the loop into many tiny calculating units. In each unit, we define momentum parameters (including velocities) in the center and other parameters (including mass, energy, property, etc.) in the unit edge. The concrete discretizations of equations are not listed in this paper.

4. The code development and validation

In order to demonstrate the capabilities of the model and numerical procedure developed, we choose one set of experiment data of the test loop to be compared with the simulation results of the loop code.

The experiment data are from some early experiments measurement results of the test loop [4], including the mass flow rate, temperature at the inlet and outlet of the Calandria under different power levels. Considering that the system is a natural circulation loop, the boundary conditions are only reactor power, the physical parameters of cool side of the exchanger tube including temperature, flow rate and pressure. In the reference [4] experiment, the parameters of cool side of the exchanger tube are not changed, the parameters in test loop changed by adjusting the power, mainly the temperature and the flow rate. These two physical parameters are able to show most important information of the loop, so we choose this experiment to validate our loop code. The experiment data are shown in figure 5.

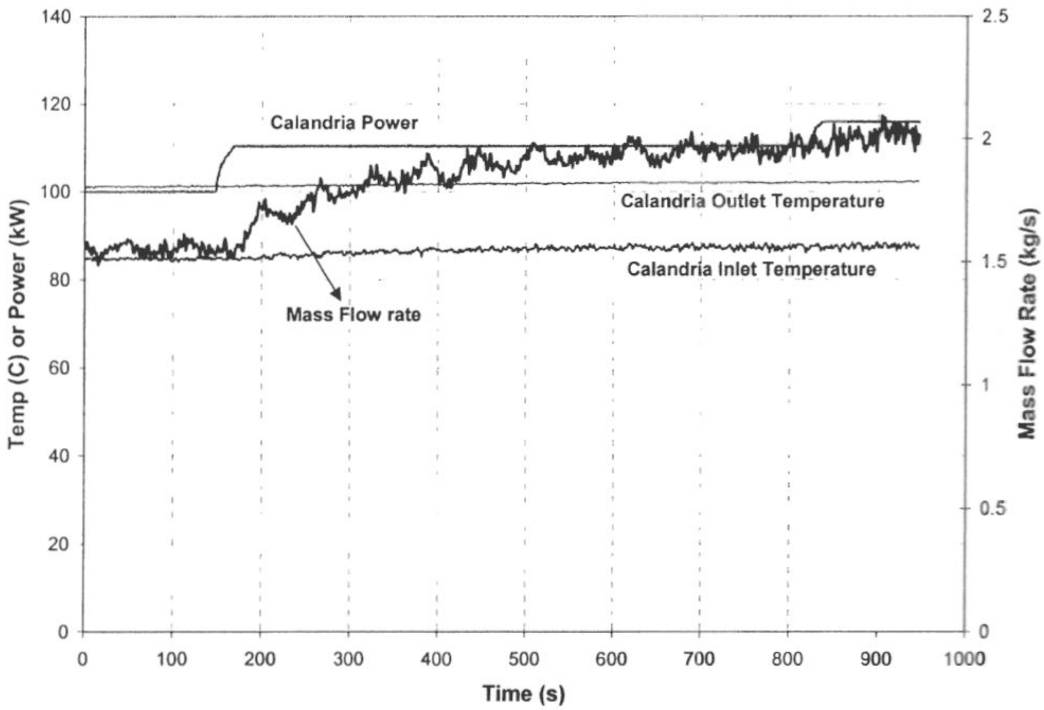

Figure 5 The experiment data of the test loop

As the figure shows, at the time t=0s the loop is in steady state, and begins variation by increasing the power level at t=150s. Finally the loop return to the steady state at t=700s. The compared data of experiment and simulation results are shown in table 1.

Table 1 The compared data of experiment and simulation results

Power	Parameter	Experiment data	Simulation data	Relative error
100kW	Flow rate（kg/s）	1.6	1.66	3.75%
	Temp outlet（℃）	101.1	101.1	-
	Temp inlet（℃）	84.8	86.15	1.59%
110kW	Flow rate（kg/s）	2.0	2.08	4%
	Temp outlet（℃）	102.3	102.3	-
	Temp inlet（℃）	87.7	89.1	1.60%

The max relative error of simulation results and experiment data is 4%, considering the surging of flow rate and the assumptions of the simulation model, the compared result is acceptable.

5. Some simulation results

The operation condition of the system can be parted to steady state and transient state. In actual operation, the system can be considered in the steady state when the reactor runs a period of time without changing the boundary conditions. But if the power changed or accident happened, the system will be in transient state. The following results are in transient state.

5.1 The power variation condition

At the time t=0, the reactor power increased from 0.27MW to 0.30MW immediately, the parameter conditions are shown in figure 6 and figure 7.

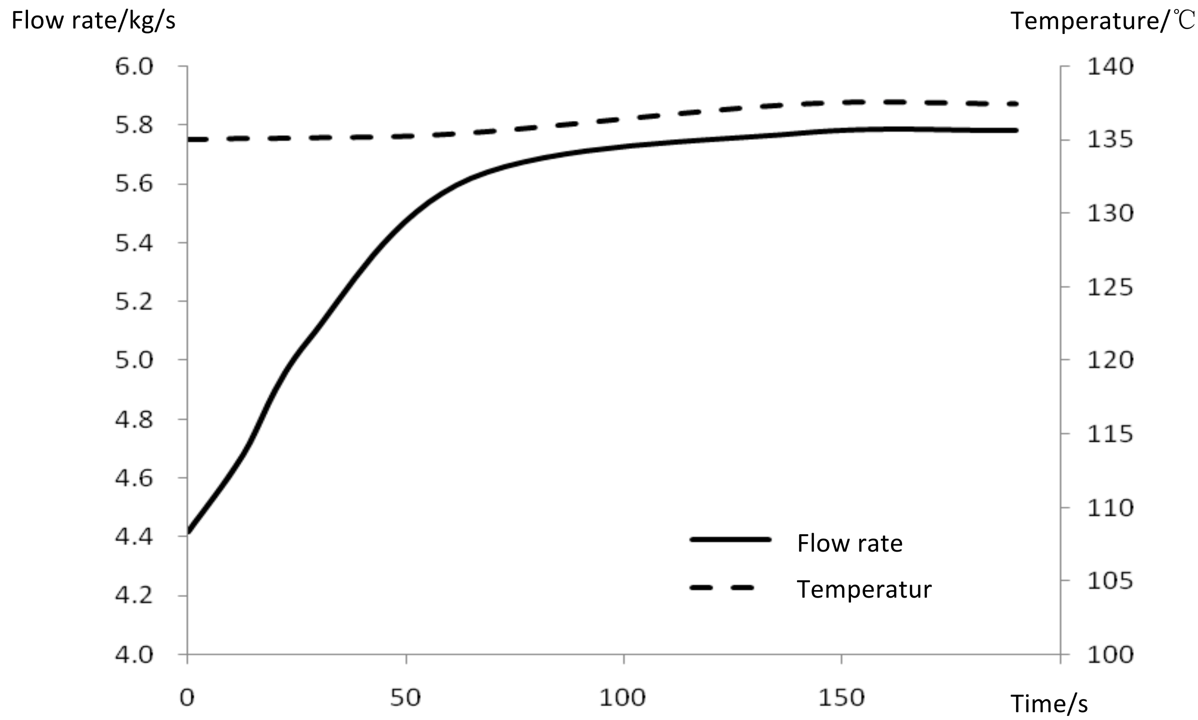

Figure 6 The flow rate and temperature of loop

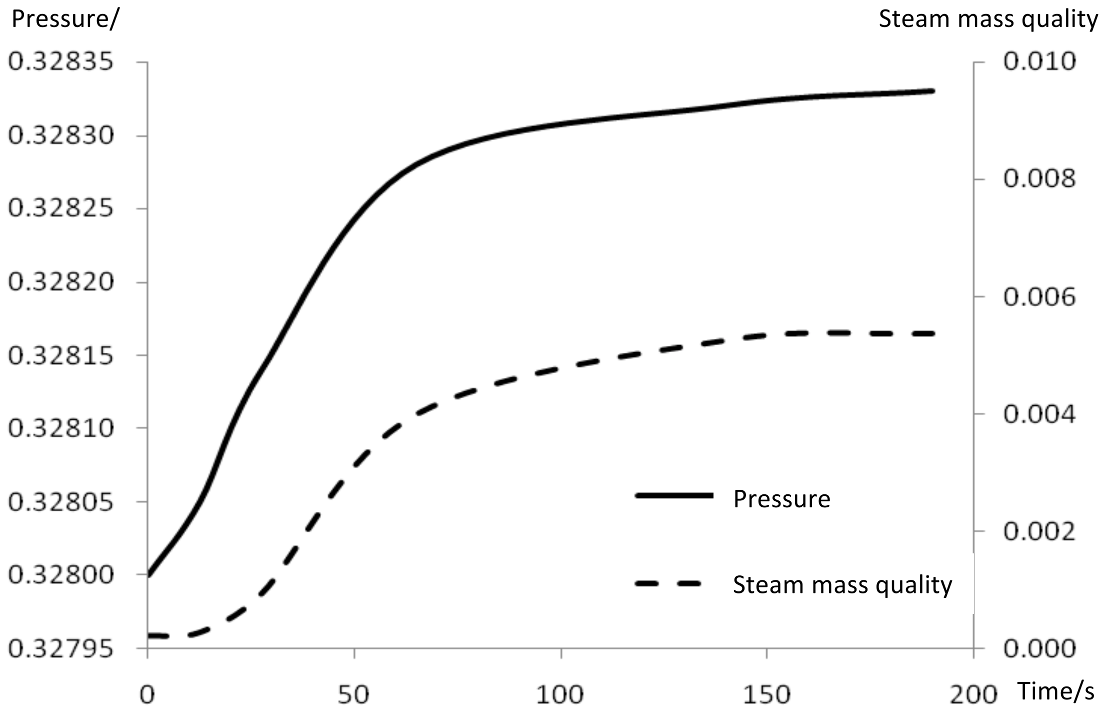

Figure 7 The pressure and steam mass quality

5.2 The parameters of cooling water changed condition

The parameters of cooling water including flow rate and temperature are important elements in the system operation condition. If the cooling water changed as the figure 8 shown, the variation of the loop physical parameter are shown in figure 9 and figure 10.

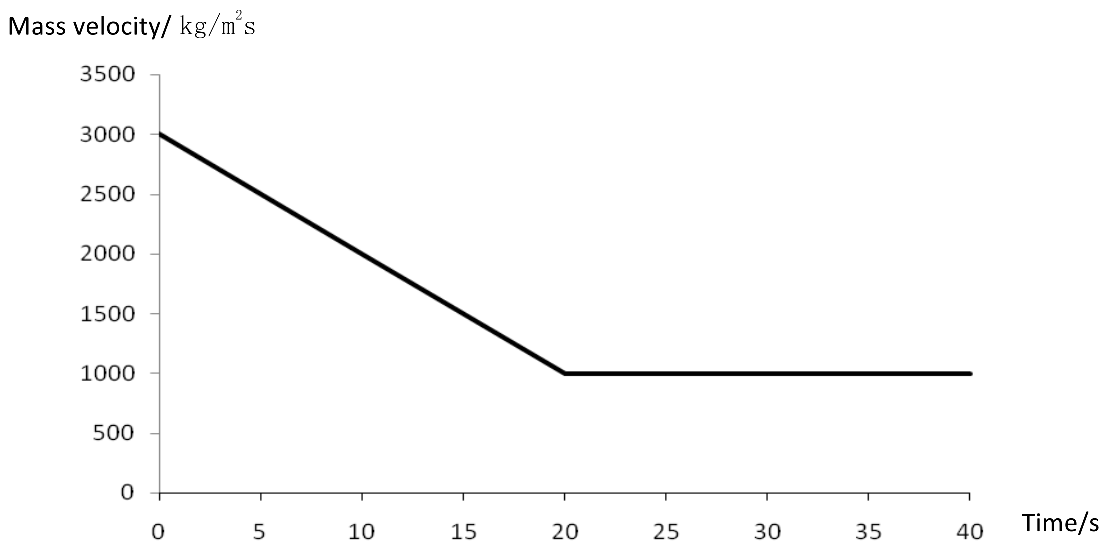

Figure 8 The change condition of cooling water mass velocity

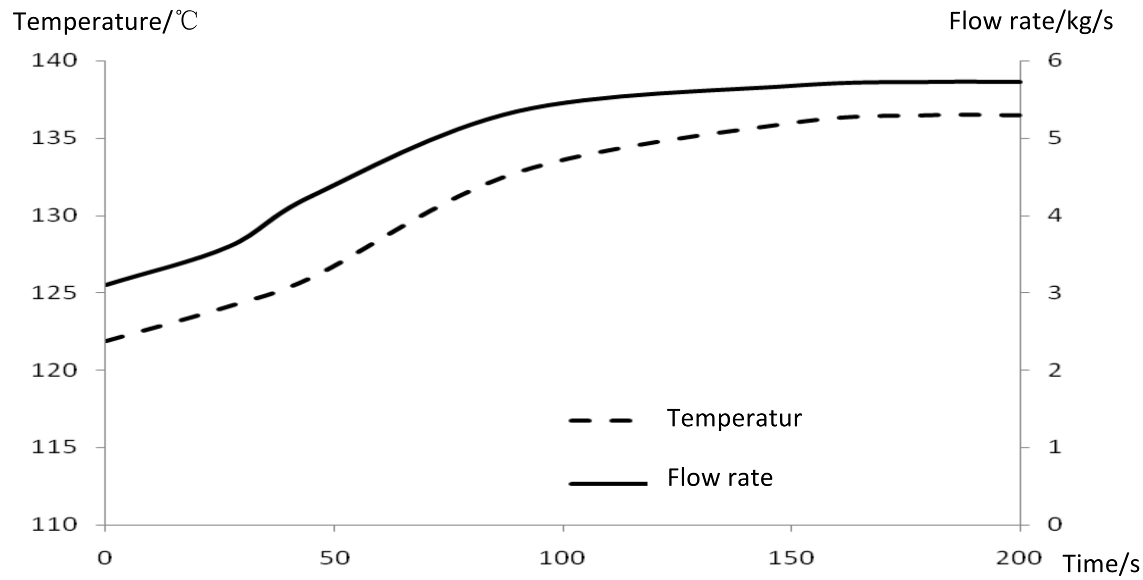

Figure 9 The flow rate and temperature of loop variation by time

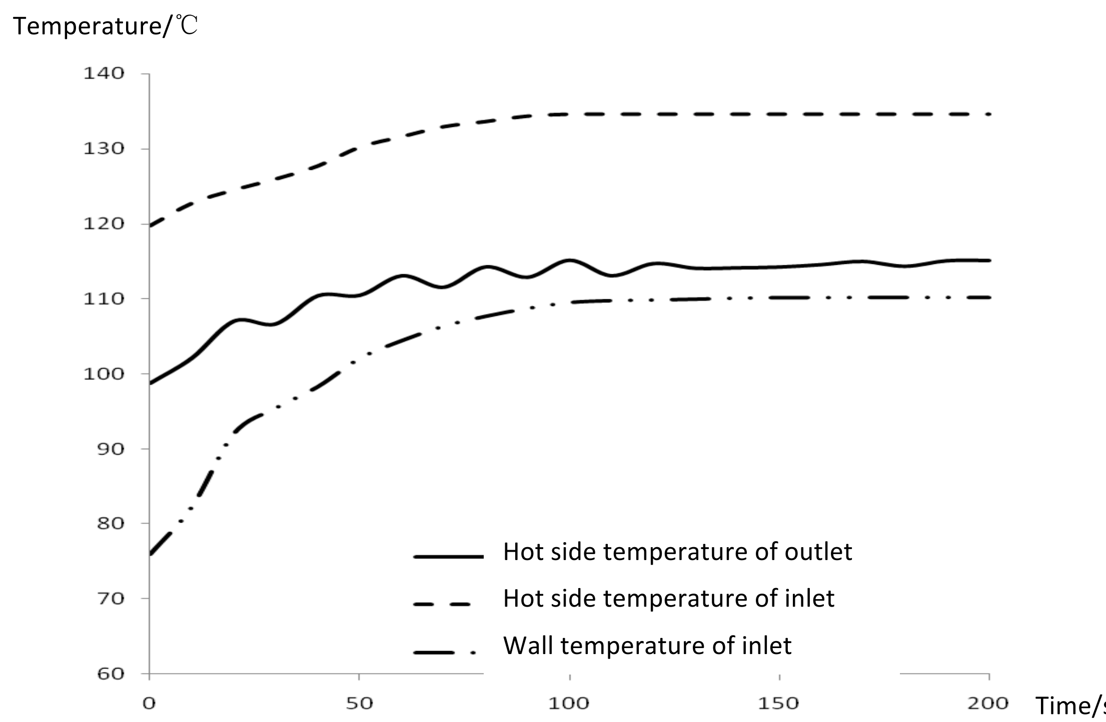

Figure 10 The temperature of exchanger variation by time

As the figures show, at the time t=180s, the system returns to steady state.

6. Conclusion

By analyzing the features of PT-SCWR moderator system, this paper builds up a program to simulate it and gets some simulation results. The results show that the system is able to remove the redundant heat of moderator and can help to design the parameters of the test facility.

7. Reference

[1] ZHAO Zhaoyi and ZHU Ruian, Thermo Hydraulics in Reactor Engineering, Beijing Tsinghua University press, 1992.

[2] XU Jijun and LU Zhongqi, Boiling Heat Transfer and Two-Phase Fluid, Beijing Atomic press, 2001.

[3] O.E.Ivashnyov, N.N.Smirnov, “Thermal growth of a vapor bubble moving in superheated liquid”, Phys. Fluids, Vol.16, No3, March 2004.

[4] S.K.Yang and H.F.Khartabil, “Flashing-Driven Passive Moderator Cooling Tests for CANDU Reactors”, ICONE 14 (2006).