Experimental simulation study of transition transients between forced circulation and natural circulation with reactivity feedback

CHEN Hanying[1]**, GAO Puzhen**[1]**, TAN Sichao**[1]**, and WANG Zhongyi**[1]

1. Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin, 150001, China (chenhanying@hrbeu.edu.cn)

Abstract: To get an insight of the transition process between natural circulation and forced circulation in nuclear power system, an experimental simulation study considering reactivity feedback was carried out. The experimental simulation of reactivity feedback process was conducted by coupling the point kinetics model with an electrically heated experimental loop. Areal-time power control system was established to simulate the nuclear reactor's power change transients caused by the reactivity induced by temperature change. The experiment results show that: in the transition transient from forced circulation to natural circulation, the decrease of power in the initial stage of the transition can restrain the fast increase of the mean temperature of fuel; in the transition transient from natural circulation to forced circulation, enough negative reactivity should be inserted in time to avoid the power increase peak.

Keyword: natural circulation; reactivity feedback; point kinetics model; neutronics-thermal- hydraulics coupling

1 Introduction

The natural circulation is now widely used in advanced nuclear reactor designs to improve the safety and simplify the structure of the reactor. However, most of the nuclear reactors, even ones designed to primarily use natural circulation as the main method of fluid circulation, have pumps that can circulate the fluid in the case that natural circulation is not sufficient. In the transition transients between natural circulation and forced circulation, the fuel and coolant temperature will experience drastic fluctuation, and cause reactor power change. The insufficient cooling of the reactor fuel and the sudden increase of the core power during these transients may cause nuclear reactor accident. Therefore, it is important to investigate the operation condition and the reactivity feedback process of nuclear reactors during transition transient between natural circulation and forced circulation.

Most of the open research literature about the transition transient between natural circulation and forced circulation refer to calculation simulation study, such as Tian *et al.*[1], Hao *et al.*[2], Yu *et al.*[3] and Cui[4]. Some other scholars have conducted experimental simulation studies on the reactivity feedback transient of reactors. Kok *et al.*[5][6] implemented a simulated void-reactivity feedback in an experimental thermal–hydraulic loop to study the two-phase flow dynamics in boiling water reactor. Marcel *et al.*[7] built a downscaled GENESIS facility including an artificial void reactivity feedback system for simulating the neutronic-thermal-hydraulic coupling to investigate the stability performance of the Economic Simplified Boiling Water Reactor (ESBWR). Furuya *et al.*[8]developed the SIRUS-N facility to investigate regional and core-wide stability of natural circulation BWR. T'Joen *et al*.[9] developed a scaled model of the high performance light water reactor (HPLWR)incorporated an artificial neutronic feedback to study the coupled thermo-hydraulic-neutronic stability of the reactor. Shi *et al*.[10] built a BWR-type natural circulation test loop to perform the nuclear coupled startup transient tests for Purdue Novel Modular Reactor (NMR). In these calculation studies, the artificial void reactivity calculation based on point kinetics model is coupled with the experimental electrically-heated loops to simulate the transient with nuclear reactivity feedback in reactors. However, all these studies focus on the flow instability in natural circulation systems. The

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transition transients between forced circulation and natural circulation are not investigated in these studies.

In the present study, we established an experimental loop with natural circulation ability and installed instruments on it to measure the thermal-hydraulic parameters. The real-time reactivity feedback simulation calculation based on point kinetics model was conducted using the measured data. A power control system was designed to control the heating power of the experimental loop according to the real-time neutron kinetics calculation results. The transition transients between forced circulation and natural circulation considering reactivity feedback can be experimentally simulated using this neutronics-thermal-hydraulics coupling system. The transition experimental simulation from natural circulation to forced circulation was conducted and vice versa.

2 Experimental apparatus

2.1 Experimental loop

The schematic diagram of experimental apparatus is shown as Fig. 1. The experimental system consists of a heating section, a pressurizer, a circulation pump, a condenser, stainless steel tubing and valves, a power supply, measuring instruments, data acquisition and power control system. The circulation fluid is distilled water.

The heating section is a stainless steel circular tube with inner diameter of 14 mm, width of 1mmand length of 1600mm. The length of the riser is 3000 mm and the inner diameter is 40 mm. The length of the downcomer is 4700mm and the inner diameter is 20 mm. The length of the lower horizontal tube is 2700mm and the inner diameter is 18.6 mm.

All these tubes are made of stainless steel. The condenser is a shell-and-tube heat exchanger located on the top of the loop. The condenser has 31 heat exchange tube. The length of the heat exchange tube is 1510mm and the diameter of the tube is 19mm.The heating section is heated electrically by a DC power supply.

The pressurizer is a cylinder stainless steel vessel connected with the downcomer of the loop. The internal diameter of the pressurizer is 309mm and the height of the pressurizer is 1200mm.The lower space of the pressurizer is filled with water and the upper space of the pressurizer is filled with compressed nitrogen gas. A water level gauge is installed to the pressurizer. The highest operation pressure of the experimental loop is 2 MPa. The circulation pump in the loop is used to build a forced circulation and the natural circulation is established by switching off the circulation pump and opening the bypass valve.

2.2 Data acquisition and power control system

The temperature of heating wall is measured by N-type thermocouples attached to the surface of it. The thermocouples are installed by the vertical distance of 100mm with each other. The water temperature is measured by sheathed thermocouples located in the middle of the tube. Three sheathed thermocouples are installed in the inlet and outlet of the heating tube and the outlet of the condenser. The accuracy of thermocouples is ±1.5℃ from 0℃ to 375℃ and ±0.4% of the centigrade temperature measurement from 375℃ to 1000℃. The flow rate of the loop is measured by a electromagnetic flowmeter (KROHNE OPTIFLUX4300F/IFC300F) with the accuracy of ±0.5%. All the measured data is recorded by a National Instrument DAQ system (sampling frequency is 1000 Hz).

The water and heating wall temperature measurement data is sent from the DAQ system to the power control computer by Ethernet cable communication. The power control computer calculates the power change based on point reactor kinetic equations and then sent the power change order to the DC power supply by RS-485 communication. The DC power supply adjusts the power output according to the received control signal with a frequency of 10Hz.

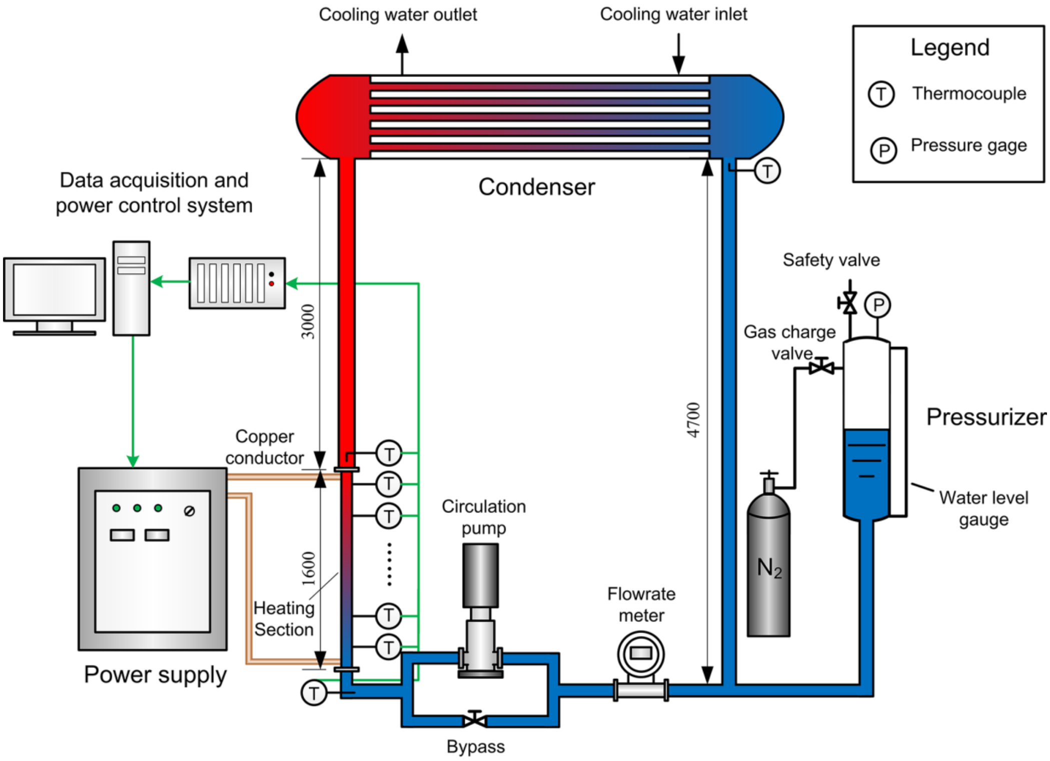

Fig.1 The schematic diagram of experimental apparatus.

3 Simulation model

3.1 Point kinetics model

The point kinetics model can give an estimate for the core-wide power change of nuclear reactor. It is applied in the present study to simulate the reactivity feedback process during the transitions between natural simulation and forced circulation. The point kinetics equations with six group delayed precursor groups are written as Equation 1 and Equation 2.

$$\frac{\mathrm{d}n(t)}{\mathrm{d}t}=\frac{\rho(t)-\beta}{\Lambda}n(t)+\sum_{i=1}^{6}\lambda_i C_i(t) \quad (1)$$

$$\frac{\mathrm{d}C_i(t)}{\mathrm{d}t}=\frac{\beta_i}{\Lambda}n(t)+\lambda_i C_i(t) \qquad i=1,2,\cdots,6 \ (2)$$

where $n(t)$ is the time-dependent neutron density and can also be regard as reactor power. C_i is the i-th group delayed precursor concentration, β_i is the i-th group delayed neutron fraction, and $\beta=\Sigma\beta_i$ is the total delayed neutron fraction, λ_i is the decay constant of i-th group delayed neutron precursor, $\rho(t)$ is the time-dependent reactivity, Λ is the neutron generation time and t is time.

In the present study, boiling is not happened in the experimental loop and all the coolant is in liquid phase, thus only the reactivity induced by the change of coolant and fuel were considered in the simulation. The time-dependent reactivity $\rho(t)$ is calculated according to Equation 3

$$\rho(t)=\rho_0+c_f\Delta\overline{T}_f(t)+c_c\Delta T_c(t) \quad (3)$$

where ρ_0 is the initial reactivity of the reactor, c_f is fuel temperature coefficient of reactivity, c_c is coolant temperature coefficient of reactivity, $\Delta\overline{T}_f(t)$ is the fuel temperature variation from the initial fuel temperature and $\Delta T_c(t)$ is the coolant temperature variation from the initial coolant temperature.

During the transition experiments, the point kinetics equations are numerically solved using the real-time fuel and coolant temperature measurements. The numerical solution the point kinetics equations is calculated using fourth-order Runge–Kutta method and the step size is set to be quite short (0.001s) to avoid the stiffness problem. The heating power of the experimental loop is controlled in real time according to the calculation result of $n(t)$.

In the real case of reactor, the reactivity varies when the fuel and coolant temperature changes or the position of the control rod move. In our experimental simulation, the inducing of positive or negative reactivity is realized by changing the $\rho(t)$ in the neutron kinetic calculation. The $\rho(t)$ can be changed based on Equation 3 according to the change of water temperature and simulated fuel rod temperature. It can also be changed by the program's order to simulate the reactivity change caused by the movement of the control rod.

3.2 Fuel average temperature model

In the experiments, the temperature of the heating wall surface is measurable, but the temperature of the nuclear fuel is needed in the calculation of the reactivity. Therefore we estimated the average temperature of the fuel pellet by taking radial integral of the temperature on the fuel pellet. The result is shown as Equation 4

$$\overline{T}_f = T_{suf} + \frac{\Phi_{out}}{8\pi\lambda L} \tag{4}$$

where $\overline{T}_f$ is the average temperature of the fuel pellet, T_{suf} is the average heating wall surface temperature, Φ_{out} is the heating output of the fuel rod, λ is the thermal conductivity coefficient of the UO_2 fuel pellet and L is the length of the heating section. The estimated average fuel pellet temperature $\overline{T}_f$ is used to calculate the $\Delta\overline{T}_f(t)$ in Equation 3.

3.3 Fuel time constant

The heating section of the experimental loop is stainless steel tube, which has high thermal conductivity and small heat capacity. However, the real reactor UO_2 fuel pellets have larger heat capacity. Therefore, considering the transient heat transfer process in the UO_2 fuel pellets, the lumped parameter method is applied to calculate the time delay of the heating power output in the experiment. Because the stainless heating tube has similar thermal resistance with the zirconium alloy cladding, so only the thermal conduction in the fuel pellets was considered to simplify the thermal transfer model.

The heat transfer equation of the fuel rod based on lumped parameter method is written as

$$\begin{aligned} Mc\frac{\partial\overline{T}_f}{\partial t} &= \Phi_f - Ah(T_{suf} - T_\infty) \\ &= \Phi_f - Ah(\overline{T}_f - \frac{\Phi_{out}}{8\pi\lambda L} - T_\infty) \end{aligned} \tag{5}$$

where c is the specific heat capacity, M is the mass of the UO_2 fuel pellet, Φ_f is the heating power of fuel rod, A is the superficial area of the fuel rod, h is the convective heat transfer coefficient and T_∞ is the average temperature of the coolant.

The heating output of the fuel rod Φ_{out} is written as

$$\Phi_{out} = Ah(\overline{T}_f - \frac{\Phi_{out}}{8\pi\lambda L} - T_\infty) \tag{6}$$

Combining Equation 5 and Equation 6

$$Mc\frac{\partial\overline{T}_f}{\partial t} = \Phi_f - \Phi_{out} \tag{7}$$

The coolant temperature is considered as constant in short time span, so Equation 8 can be derived from Equation 6 by taking derivative.

$$\frac{\partial\Phi_{out}}{\partial t} = Ah\frac{\partial\overline{T}_f}{\partial t} - \frac{Ah\partial\Phi_{out}}{8\pi\lambda L\partial t} \tag{8}$$

Combining Equation 7 and Equation 8

$$\frac{Mc}{Ah}(1+\frac{rh}{4\lambda})\frac{\partial\Phi_{out}}{\partial t} = \Phi_f - \Phi_{out} \tag{9}$$

where $\frac{Mc}{Ah}(1+\frac{rh}{4\lambda})$ has a dimension of time and is named time constant of the fuel, noted t_c. The value of t_c is determined by the thermal capacity of the fuel rod and the boundary heat transfer condition. According to the fuel rod parameters and the coolant flowrate in real reactors, t_c is estimated to be 2-4 seconds.

During the experiment, Φ_f is calculated from the solution of the point kinetics equations. The Equation 9 is solved in real-time coupled with the point kinetics equations using fourth-order Runge–Kutta method. The numerical solution of Φ_{out} is used as the power supply's output.

4 Results and discussion

4.1Transitions from forced circulation to natural circulation

The driving force of the circulation pump is usually much larger than the driving force caused by the density difference in the natural circulation. Therefore flowrate of natural circulation is much smaller than the one of forced circulation. During the transitions from forced circulation to natural circulation, the circulation flowrate will drop fast by losing the driving force from the circulation pump. The water temperature in the heating section and the riser tube increases because of this flowrate decrease, which make the density difference between the riser and the downcomer larger. Therefore the flowrate of the loop will reach a minimum and increased driving force will make the flowrate rise again. The system will finally reach a new steady state, which marks that the natural circulation is established.

The experiment of transition from forced circulation to natural circulation without reactivity feedback was conducted as a comparison. The results of flowrate and heating wall temperature are shown in Fig.2 and Fig.3. The heating power is 8kW and the pressure in the pressurizer is 0.44Mpa. There is no boiling happening in the heating section during the whole transition and the system pressure is steady. The circulation flowrate dropped from 0.63m^3/h to the minimum value of 0.09m^3/h and then rise to the steady natural circulation flowrate of 0.15m^3/h. The natural circulation flowrate is about 23% of the one in forced circulation condition.

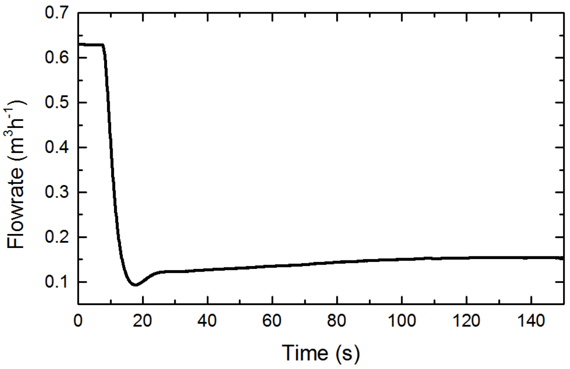

Fig.2 Flowrate in transition from forced circulation to natural circulation without reactivity feedback.

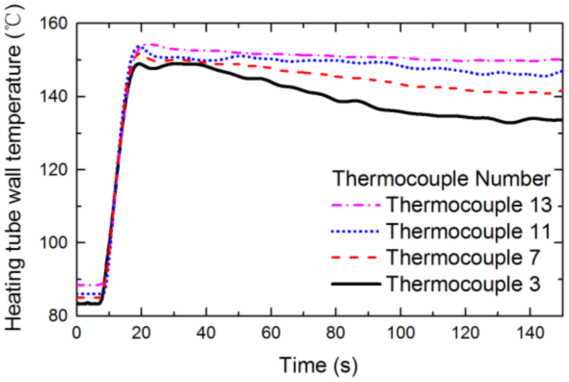

Fig.3 Wall temperature in transition from forced circulation to natural circulation without reactivity feedback.

During the transitions in real reactors, the fuel temperature will increase largely because of the fast decrease of the coolant flowrate. This increase of temperature will induce negative reactivity. To maintain the power of the reactor, a positive reactivity has to be inserted to the reactor during the transition. However, the fast insertion of positive reactivity is very dangerous to the real reactor and the power decrease in the initial stage of the transition can help to relieve the temperature increase of the fuel rod. Therefore, in the present experiment the negative reactivity caused by the temperature increase is only partially compensated in the initial stage of the transition, and the core power will be recovered after the natural circulation is established.

The experiments of transition from forced circulation to natural circulation with the initial heating power of 10kW, 11.5kW and 13 kW were conducted. The fuel temperature reactivity coefficient is set as -2×10^{-5} and the coolant temperature reactivity coefficient is set as -25×10^{-5}. The system was on steady state forced circulation condition at the start of the experiments, then the circulation pump was switched off and the reactivity feedback simulation took effect. A positive reactivity of 0.002 was inserted to the system to balance the negative reactivity induced by temperature change in the first 10 seconds. Another compensatory reactivity of 0.003 was induced in the following 20 seconds with a constant speed. The changes of heating power, overall reactivity, average fuel temperature and the flowrate during experiments are shown as Fig.4 to Fig.7.

In the initial stage of the transition, the negative reactivity induced by fast fuel temperature increase is larger than the compensatory reactivity. The heating power dropped because of the total negative reactivity of the simulation system. The decreased heating power restrained the increase of the fuel temperature. Then the insertion of more positive compensatory reactivity make the heating power rises again. The power finally reaches a steady state after all the positive compensatory reactivity is inserted. In this control strategy, the insertion speed of positive reactivity is controlled to avoid the risk of local power transients in real reactors. The fuel temperature didn't largely exceed the temperature in steady natural circulation condition during the whole process of the transition transient. The flowrate change is not much different from the one without reactivity feedback, because the flowrate's response to heating power is relatively slow in natural circulation condition.

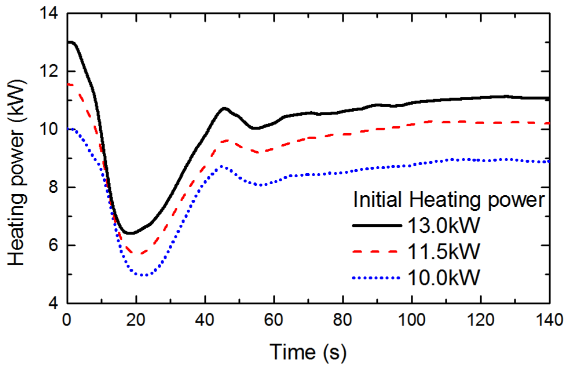

Fig.4 Core power in transition from forced circulation to natural circulation.

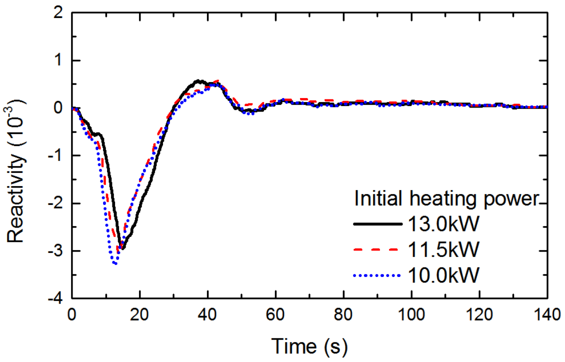

Fig.5 Reactivity in transition from forced circulation to natural circulation.

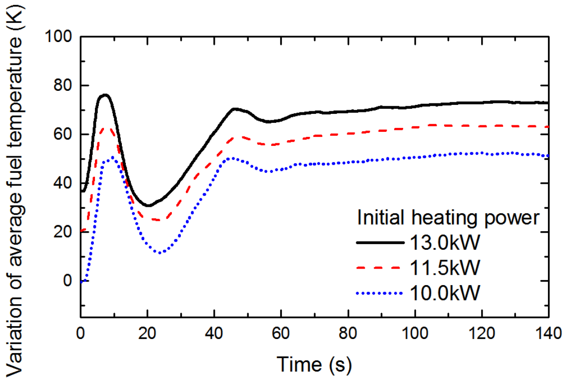

Fig.6 Variation of average fuel temperature in transition from forced circulation to natural circulation.

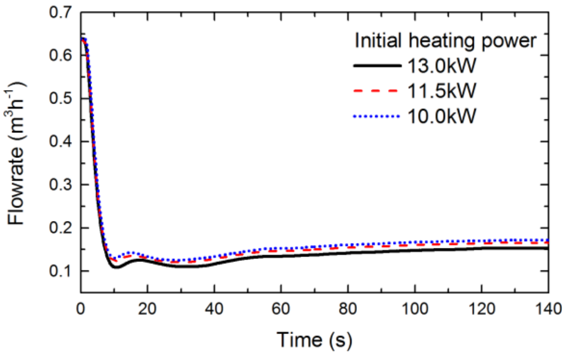

Fig.7 Flowrate in transition from forced circulation to natural circulation.

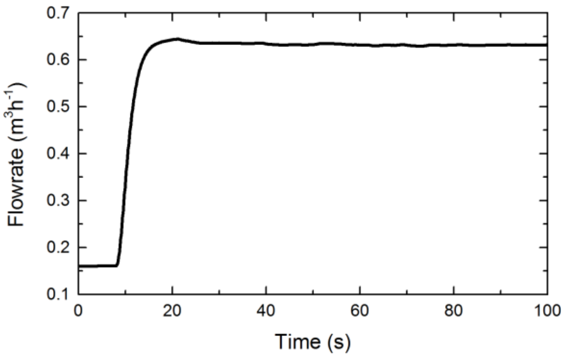

Fig.8 Flowrate in transition from natural circulation to forced circulation without reactivity feedback.

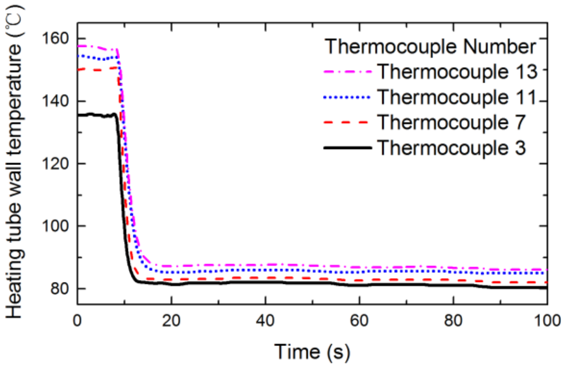

Fig.9 Flowrate in transition from natural circulation to forced circulation without reactivity feedback.

4.2 Transitions from natural circulation to forced circulation

During the transitions from forced circulation to natural circulation, the circulation flowrate increase rapidly after the circulation pump is started. The fuel and coolant temperature will decrease because more heat is absorbed by water and the cooling is enhanced. The fuel and coolant temperature decrease will cause a positive reactivity change. This positive reactivity has to be compensated in time to keep the operation condition stable.

The experiment results of transition without reactivity feedback are given as a comparison. The flowrate and heating wall temperature change in the transition from natural circulation to forced circulation without reactivity feedback simulation is shown as Fig.8 and Fig.9. The heating power is 9kW and the pressure in the pressurizer is 0.46Mpa. Boiling did not happen during the whole transition and the system pressure kept steady. The circulation flowrate increased from 0.16m^3/h to the steady forced circulation flowrate of 0.63m^3/h. The forced circulation can achieve the steady condition faster because the circulation flowrate is much larger than the natural circulation.

In the present study, the transition experiments with reactivity compensation inserted with different speed were conducted to investigate the appropriate control strategy. In the start of the experiments, the system was in the same natural circulation condition. The initial heating power is 9kW, fuel temperature reactivity coefficient is set as -2×10^{-5} and the coolant temperature reactivity coefficient is set as -25×10^{-5}. In each experimental condition, a reactivity of -0.005 was induced to the system to balance the positive reactivity caused by temperature change. The reactivity is induced with a constant speed within 5 seconds, 10 seconds and 15 seconds to simulate the insertion of the control rod in different speed. The change of heating power, total reactivity, average fuel temperature and circulation flowrate in experiments are shown as Fig.10 to Fig.13.

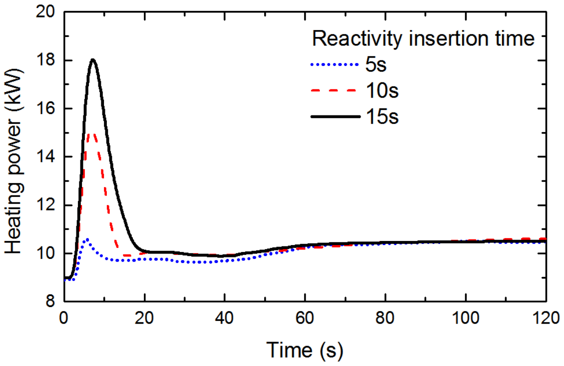

Fig.10 Heating power in transition from natural circulation to forced circulation.

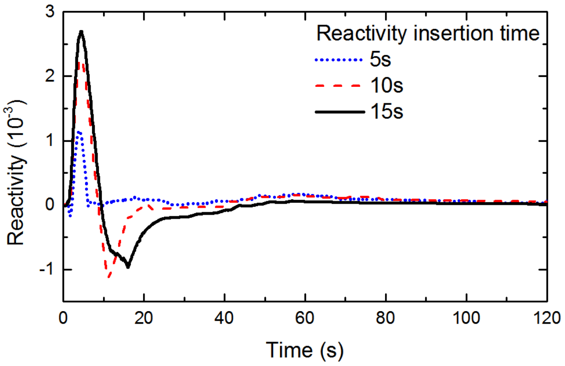

Fig.11 Reactivity in transition from natural circulation to forced circulation.

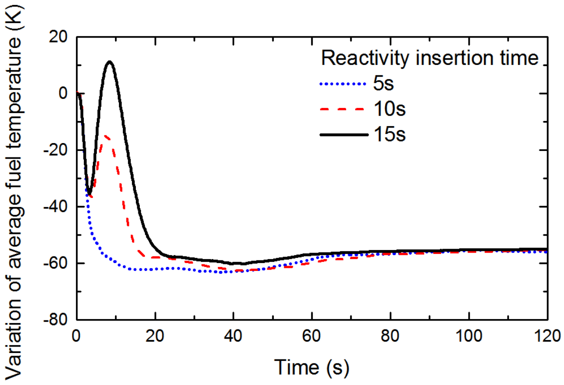

Fig.12 Variation of average fuel temperature in transition from natural circulation to forced circulation.

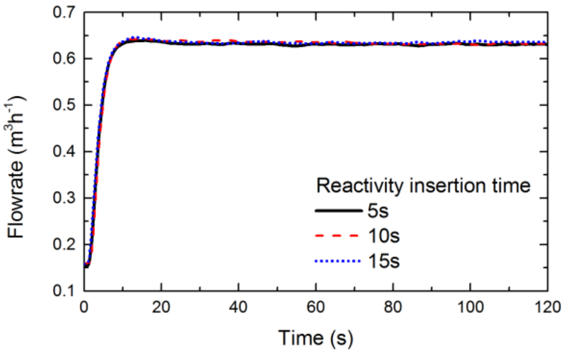

Fig.13 Flowrate in transition from natural circulation to forced circulation.

According to the experimental results, the simulation system in all the three experimental conditions finally reached similar heating power level. This result is reasonable because the inserted negative reactivity in each condition is the same. However, the experimental condition with shorter reactivity compensation insertion time (5 seconds) can avoid significant heating power change during the transition transient. While in the other experimental conditions (the negative reactivity is inserted in 10 seconds or 15 seconds), the heating power and reactivity experienced an obvious increase peak.

The reason is that after circulation pump start, the fuel and coolant will decrease rapidly and induce a large positive reactivity. If this positive reactivity is compensated in time, the overall reactor reactivity will not increase too much and the core power can be almost steady. Otherwise the positive reactivity of the reactor will cause a quick increase of the core power and fuel temperature. In the condition with reactivity compensation insertion time of 15 second, the heating power doubled in 10 second and the overall reactivity became as large as 2.7×10^{-3}, which will definitely not be allowed in the real nuclear reactors. Besides, the average fuel temperature also exceeded the operation temperature in natural circulation condition. Therefore, during the transition from natural circulation to forced circulation in real reactors, enough negative reactivity compensation should be inserted as soon as the transition starts to avoid the unwanted fluctuation of the operation condition. Besides, the flowrate curve in each condition do not have much difference with each other. The reason is that the flowrate is determined by the driving force of circulation pump and do not be much influenced by the change of heating power in the forced circulation condition.

5 Conclusions

Experimental simulation and investigation of the transition transients between forced circulation and natural circulation was carried out. A neutronics-thermal-hydraulics coupling experimental system was designed to simulate the reactivity feedback process based on point kinetics model. A real-time power control system was installed to the thermal-hydraulic loop. The real-time power control system can calculate the artificial reactivity according to the real-time temperature measurement. Experiments of transition transients from forced circulation to natural circulation and from natural circulation to forced circulation with artificial temperature reactivity were conducted. The following conclusions are drawn according to the experiment results.

In the transition transients from forced circulation condition to natural circulation condition, the fuel temperature increase drastically because of the reduction of circulation flowrate. This increase will cause a negative reactivity and bring down the core power. The reduction of the core power in the initial stage of the transition can help to restrain the fast increase of the fuel temperature. The operators should induce positive reactivity to the reactor to recover the core power to former level after the flowrate rise again.

In the transition transients from natural circulation condition to forced circulation condition, the decrease of fuel and coolant temperature will cause a large positive reactivity change and result in fast core power increase. The operators should induce enough negative reactivity to the system as soon as the circulation pump is restarted to avoid the sudden increase of the core power and the fuel temperature.

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