Research and Development on Simulator of Fast Reactor in China

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Abstract. With the closed fuel cycle strategy, China develops the fast reactor and advanced reprocessing technology, which supports the sustainable development of China nuclear energy. Technical solutions for the simulator of China Experimental Fast Reactor (CEFR), modeling and simulation are mainly introduced. CEFR adopted a pool-type FR technology with three-loops, which has 216 subsystems. The full scope real-time simulator was finished by Nuclear Power Simulation Research Center (NPSRC) at Harbin Engineering University（HEU）in collaboration with China Institute of Atomic Energy (CIAE) and validated by CEFR. According to the principle, characteristics of system, structure and operation of CEFR, the relevant research to determine the scope and degree, establish models and design systems for the simulation of CEFR has been accomplished. The model and software have been developed for 71 CEFR subsystems. The reactor physics, primary coolant system, secondary coolant system, third coolant system, auxiliary system and passive decay heat removal system, etc. are included in the simulator, which has been applied to instruct the debugging and experimental operation of CEFR and improve the control methods.

Key Words: China Experimental Fast Reactor; Full Scope Real-time Simulator; Simulation System; Modeling

1. Introduction

With the closed fuel cycle strategy, China develops the fast reactor and advanced reprocessing technology, which supports the sustainable development of China nuclear energy. China began to develop the sodium-cooled fast reactor since March, 1992. With the international cooperation, CEFR has been constructed since May, 2000 and reached the first critical condition in July, 2010.

CEFR is the first fast reactor in China and designed, constructed and managed independently by Chinese. It is a pool-type fast reactor technology with three-loops including the sodium pool-sodium middle loop-water loop. The reactor core is cooled by the sodium pool and the heat transfer occurs in the intermediate heat exchanger (IHX) in which the heat is transferred from the sodium in the primary side to the sodium in middle loop. Once-through-steam-generator, which connects the middle loop and the third (water) loop, is divided into the evaporator and superheater.

The full scope real-time simulator was finished in 2013, which has been validated by CEFR. According to the overall technological scheme of simulation system for CEFR, this research has developed a full-scope real-time simulator for CEFR, by which the real-time operational environment of CEFR will be simulated continuously. The simulator can be used to study the operation characteristics and validate system design. It also can be applied to research the emergency operating procedure and train operators.

2. Technical Solutions for Simulator of CEFR

2.1 Technical Solutions

According to the principle, characteristics of system, structure and operation of CEFR, the following main researches have been accomplished: a) The scope of simulation has been determined; b) Based on the degree of system simulation, the simulation models have been established by using a modular modeling method; c) The CEFR simulation system which consists of 13 simulation systems is designed; d) 71 subsystems were simulated which are closely related with operating; e) To setup 86 initiating events, including leaking of pipes and equipment, loss of heat sink, etc. and 1,043 common failure points in 11 categories.

By the network interface, not only the results of the simulation models can be output to the virtual instruments and CRT in the main control room (MCR) for displaying and alarming, but also the operating data on the virtual control panel can be input to the simulating computer. The CEFR simulation models includes the reactor physics model, thermo-hydraulic models of the primary loop, the secondary loop and the third loop, control and protection system simulation model, etc. The data communication and interface between modules have been developed to ensure the convergence and stability during the calculating and the CEFR simulation systems have been finally designed.

71 sub-systems are simulated in the CEFR simulation system, such as the reactor physics, coolant system, nuclear auxiliary systems, steam-power conversion system (the third loop), and engineered safety features, etc. The simulated operation conditions cover from cold startup, power operation to faults and accident conditions. And 86 initiating events are simulated, including leaking of pipes and equipment, unexpected changes in the reactivity, heat deterioration of fuel assemblies, main coolant system loss of heat sink, increasing of heat removal, etc. [1]

2.2 Simulation System

During the development process, the simulation models of main systems and components are established. The simulation models could run on the simulation platform of SimExec software developed by the GSE Company [2]. The models and software have been developed for 71 CEFR subsystems. The main systems include reactor physics, primary coolant system, secondary coolant system, steam-power conversion system, control and logic system, auxiliary system, safety and protection system, radiation monitoring system and electrical system.

The CEFR simulation system is consisted of software and hardware. The hardware part consists of main computer, the integrated display console of main control room, I/O system, instructor station, monitor system simulation computer, local operating workstation, system control workstation, operation analysis workstation, the network hub system and developing and maintenance station, etc. The software part includes simulation support software, simulation model software, computer monitor system software and instructor station software. The simulation system configuration for CEFR is shown in FIG. 1.

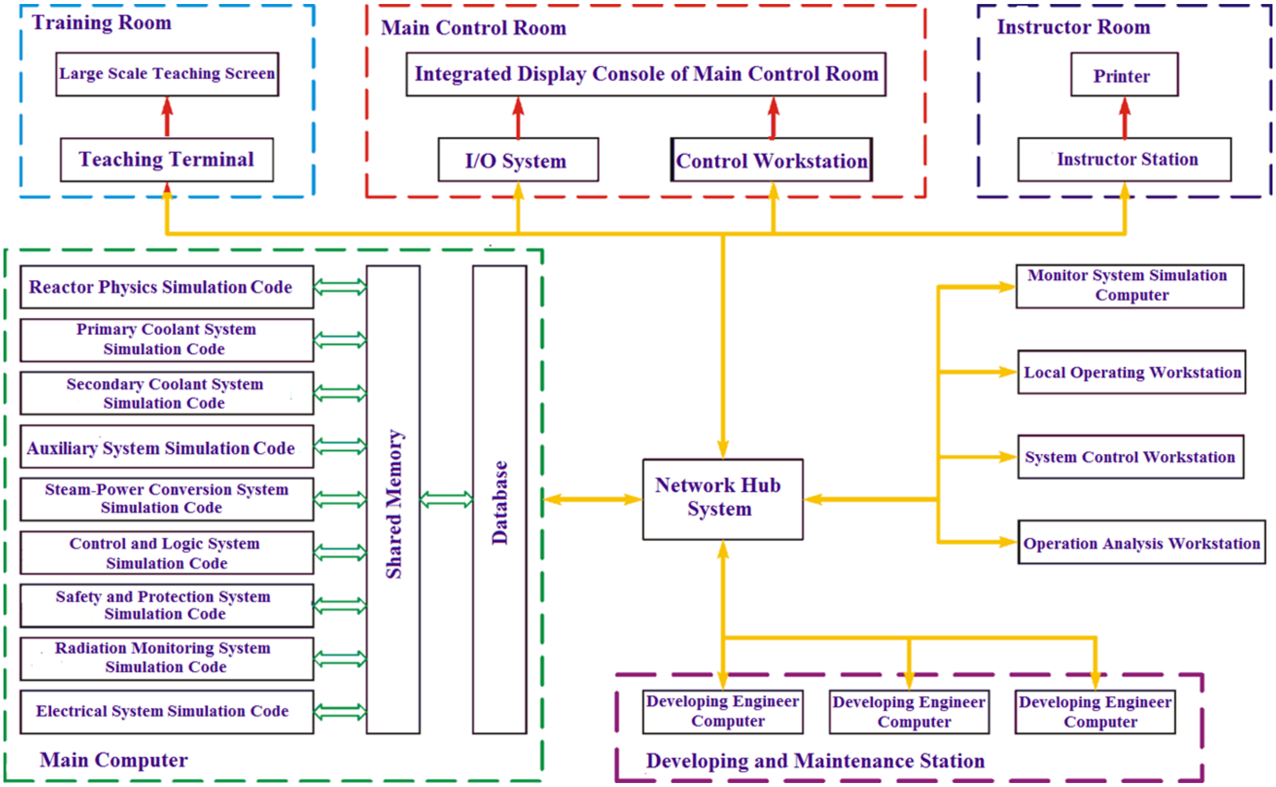


FIG. 1 CEFR simulation system configuration

3. Modeling and Simulation

The model and software for 71 CEFR subsystems have been developed. The complete interface of simulation system for CEFR is shown in FIG.2. Some main models will be introduced in details as follows.

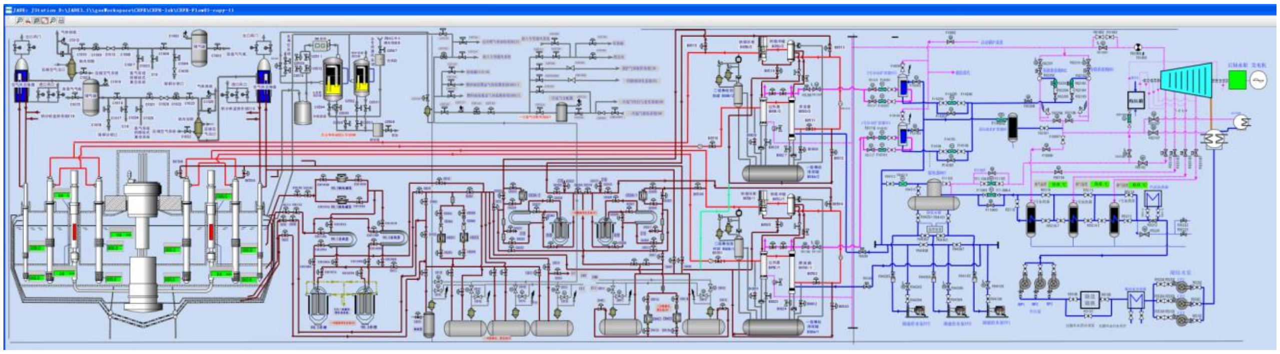
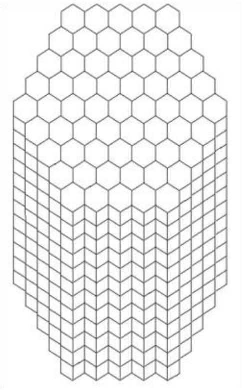


Fig.2 CEFR simulation system interface

3.1 Reactor Physics Model

The reactor physics real-time simulation model for core physics of CEFR has been established. There are some technical challenges to model the reactor physics due to the complex structure and physical characteristics. The breeding and fuel zones are consisted of multiple fuel assemblies. The fast neutrons have a wide spectrum and some are used for sustaining fission and some are used for breeding. Therefore the neutron dynamic process is quite complex in the fast reactor. Corresponding solutions are applied for neutron physics model in which 3D, four groups neutron diffusion equations are used to describe the neutron behavior in the reactor; the calculation zone is divided into 732 nodes including the breeding and fuel zone; the reactivity coupling equations have been modeled and the hexagon fuel assembly neutron program has been developed for the SFR, as shown in FIG.3.



$$\begin{aligned}\frac{1}{\upsilon_g}\frac{\partial\phi_g(r,t)}{\partial t} &= \nabla D_g(r,t)\nabla\phi_g(r,t)-\Sigma_{ag}(r,t)\phi_g(r,t)-\Sigma_{sg}(r,t)\phi_g(r,t)\\ &\quad+\sum_{g'=1}^{G}\Sigma_{sg'g}(r,t)\phi_{g'}(r,t)+(1-\beta)\chi_{pg}\sum_{g'=1}^{G}\nu_{g'}\Sigma_{fg'}(r,t)\phi_{g'}(r,t)\\ &\quad+\chi_{dg}\sum_{d=1}^{D}\lambda_d C_d(r,t)+S_g(r,t)\end{aligned}$$

$$\frac{\partial C_d(r,t)}{\partial t}=-\lambda_d C_d(r,t)+\beta_d\sum_{g=1}^{G}\nu_g\Sigma_{fg}(r,t)\phi_g(r,t)$$

Fig.3 Neutron Physics Model

Multi-group neutron diffusion space-time dynamics equations, amplitude function calculation equations, toxic calculation equations, reactivity calculation equations and power calculation equations are included in the real-time simulation models. The models are solved by the coarse mesh finite difference method. The neutron flux is decomposed into the shape and amplitude functions by the improved quasi-static approximation. The method simplifies the equation calculations. The shape function is solved by the improved the alternative direction implicit (ADI) method and the amplitude function is solved by using the point reactor kinetics equations. The difference method for the leakage of multi-group neutrons diffusion time-space dynamics equation with the hexagonal fuel assembly has also been derived and discussed. [3]

This research establishes the two-dimension model for the reactor physics of CEFR with HLIOES program. The cross sections with the multiple work conditions are provided by the models. The fuel temperature, coolant temperature and burnup are taken into consideration to calculate the cross-sections.

3.2 System Model for Primary Coolant System

The structure of primary coolant system consists of the core, core structure, shield layer, sodium pump, rod driven system, intermediate heat exchanger, individual heat exchanger and core vessel. The practical thermal-hydraulic processes for sodium pool are complex including heat conduction, convection, natural and forced circulation, three-dimensional (3D), dynamic and physical process. The single-phase flow model is used based on the assumption that the coolant would not boil and the program will give an alarm and stop running when the coolant temperature reaches the boiling point. For the shortage of relevant experiments and datum to describe the core disruptive accident of CEFR, it is considered that the system could maintain geometrical shape in the calculation. As shown in FIG.4, the heat is removed by wall cooling for hot pool, wall cooling for cold pool, natural circulation, forced circulation, wall conduction, heat convection and thermal process of argon gas.

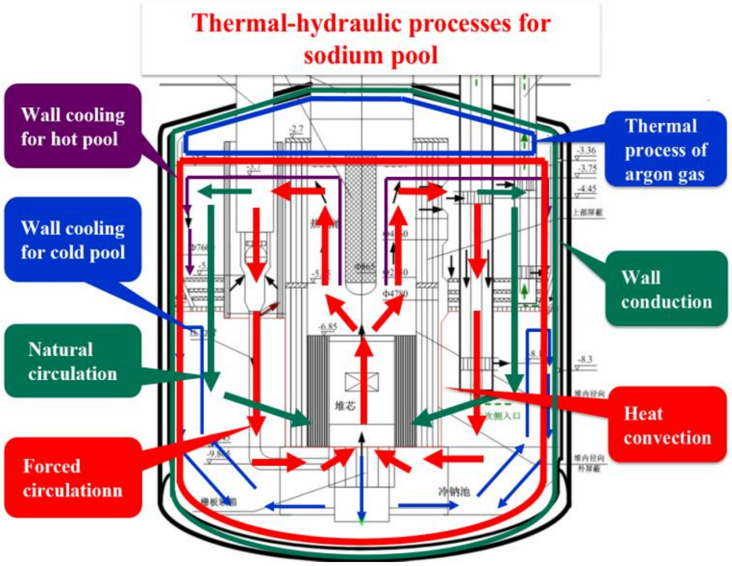


FIG.4 Thermal-hydraulic processes for sodium pool

Based on the thermal-hydraulics processes for sodium pool, a series of reasonable mathematical and physical models are set up. The models include the basic thermal-hydraulic model of coolant, the heat transfer model of fuel pellet, the thermal model of IHX, the hydraulic model of primary pump, the distribution model of loop coolant flux, the flow friction and heat transfer correlations, the thermo-physical properties, etc. The fine control volume method is used in the setup of models. The high-fidelity thermal-hydraulic analysis code is developed including 513 control volumes for primary coolant system. Gear method is applied to solve the thermal-hydraulic model of coolant and heat transfer model of fuel pellet. Quasi-newton iteration method is used to solve the flux distribution equations. The model and numerical method contribute to the accuracy and efficiency of calculation to meet the requirement of real-time simulation. [4-7]

The design parameters of CEFR are used to validate six different steady-state conditions from 26.5%FP to 100%FP and the steady-state calculation of the reactor main vessel cooling system is also finished. Then normal operation conditions including the planned shutdown, etc. and the reactivity insertion accident, the loss of coolant accident and the loss of heat sink accident are simulated [4, 8]. The critical parameters such as the reactor power, the coolant and fuel temperature were obtained and the results were analyzed compared with the DINROS calculation results in the final safety analysis report of CEFR. The simulation system model for the primary loop of CEFR is shown in FIG.5.

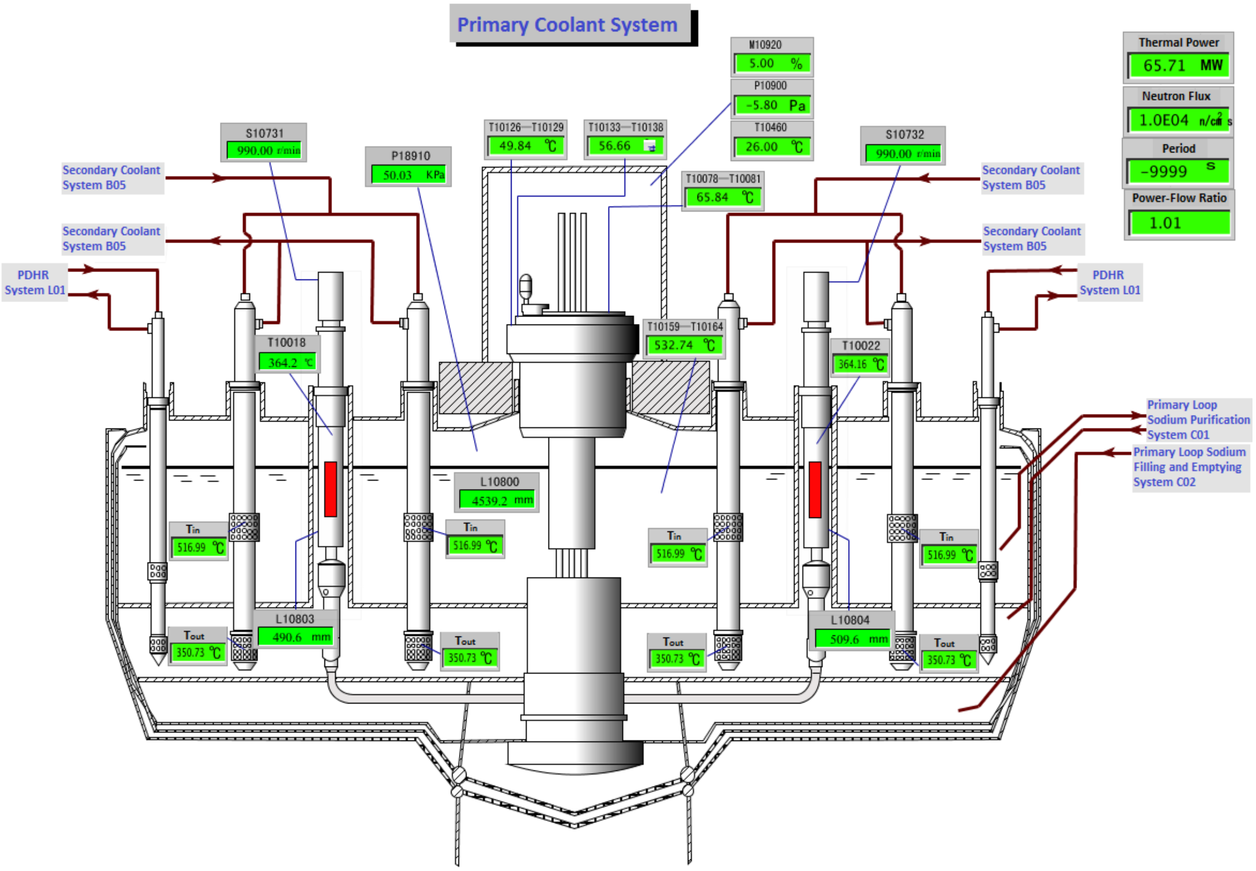


FIG.5 System model for primary loop

3.3 System Model for Secondary Loop Coolant System

The secondary loop coolant system is the main intermediate system to transfer heat from primary loop to the steam-water loop. It is composed of two identical loops in which the working fluid is the liquid sodium. The top of sodium buffer tank is filled with the argon gas to stabilize the pressure of the secondary loop system. The secondary loop system is divided into nodes based on the system features. The mass, momentum and energy conservation equations are established for the gas-liquid two-phase flow. The equipment models consist of the heat exchanger model, once through steam generator (OTSG) model, secondary loop circulation pump model, sodium buffer tank model and electric heating system model. The interface program is prepared for the connection between the secondary coolant system and other systems. Eventually the real-time simulation model of the secondary coolant system is formed.

The steady-state and transient operation characteristics of secondary loop coolant system are analyzed using the real-time simulation model. There is a good agreement that the steady-state operation calculation results obtained by the simulation program at 100% FP conditions are compared with the design parameters. The operating characteristics of OTSG at different load conditions indicate that the steam generator model established in this research has a good performance to simulate the water heated to the superheated steam. The analysis of the different transient accident conditions indicates that the model could simulate the leak of main intermediate heat transfer tube, the reaction of sodium and water caused by the steam generator tube leak and the sodium pumps failure accident conditions, and the model could also meet the specific accident needs of real-time simulation.

3.4 System Model for Third Loop Coolant System

The third loop system is an important system of CEFR, by which the thermodynamic cycle process of steam is realized and the electric power is provided. The modeling and simulation for the third loop system is an important work for building the CEFR simulator. The simulation systems include the main steam system, the auxiliary steam system, the steam turbine by-pass system, OTSG start and stop system, the condensate system, the circulating water system and feed water system. The main working fluids of the third loop system are steam and water. Because the complicated phase transition would happen during the flow and heat transfer process, it is difficult to build the simulation models. The function and composition of systems in the third loop system are analyzed and divided into many simulation nodes. The equations for the conservation of mass, momentum and energy are calculated and different simulation models of heat transfer equipment including the phase transition, heat transfer and single phase heat transfer are established.

3.5 System Model for Auxiliary System

The auxiliary system plays an important role to provide the support and protection for the reactor operation and to achieve its function for the safe operation. The main auxiliary systems include the sodium pump oil cooling system for the primary loop, the distilled water cooling system for the primary loop sodium pump, the sodium pump oil cooling system for the secondary loop, the distilled water cooling system for the sodium pump of the secondary loop, the steam generator accident protection system, the sodium loop purification system of the primary loop, the sodium filling and emptying system of primary loop, the sodium purification system of the second loop, the sodium receiving and filling system of secondary loop, the analysis and monitoring system of sodium for the primary and secondary loop, the overpressure protection system of reactor vessel, the primary argon distribution system, secondary argon distribution system, the primary argon purging and decay system, the nitrogen flooding system, the covering gas monitoring system for fuel rod failure. The auxiliary system simulation model is established using the two-fluid multi-component and nonequilibrium state model. The system is reasonably simplified according to the composition and function to meet the requirements of real-time simulation.

With the support of SimExec real-time simulation platform, the system models are established for testing and analyzing the steady-state and transient characteristics of auxiliary systems. The calculation results in the steady-state operation of the simulation program are in good agreement with the design parameters. The results show that the running state of the auxiliary system models established could well reach its features to meet the needs of real-time simulation.

3.6 System Model for Passive Decay Heat Removal System

A series of reasonable mathematical and physical models were set up to simulate the passive decay heat removal system. The models include the basic thermal-hydraulic model of coolant, thermal model of independent heat exchangers and air heat exchangers, hydraulic model of sodium expansion drum, coolant flow rate distribution model, thermo-physical properties of liquid sodium, the flow friction and heat transfer correlation, etc.

The design parameters of CEFR are used to validate the steady-state conditions, and the results are compared with the data obtained in some references [9-15]. The validity and applicability of this model is proved. The operations of passive decay heat removal system caused by the emergency shutdown are simulated. The variations of some main parameters such as the reactor power, coolant and fuel temperature were obtained and the analysis about the results are given compared with the calculation results by DINROS program in the final safety analysis report of CEFR. Some accident conditions of PRHRs are analyzed and the results show that the trend of simulation curves for transient condition is reasonable, which is in accordance with the actual physical process. In addition, the real-time character of the program is analyzed.

4. Comparison and Effect

The CEFR simulator has been applied to instruct the debugging and experimental operation of CEFR and improve the control methods. There is an example of the reactor scram analysis by the CEFR simulator as shown in FIG.6 and FIG.7.

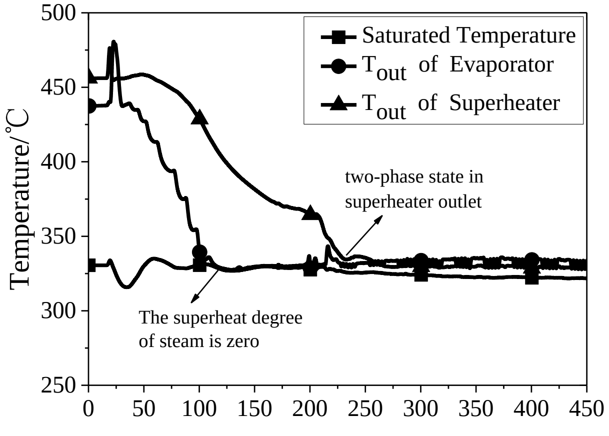


FIG.6 Outlet temperature distributions of the evaporator and superheater

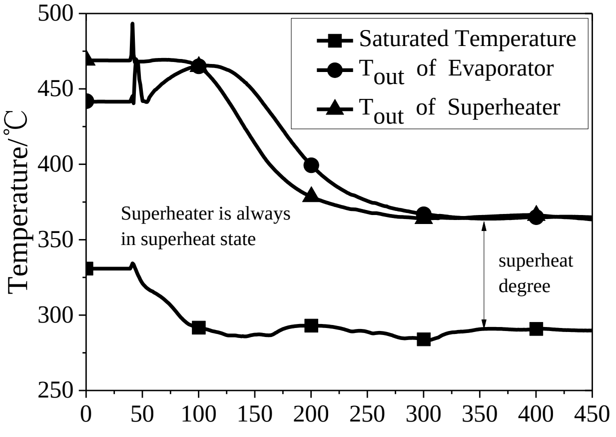


FIG.7 Outlet temperature distributions of the evaporator and superheater after improvement

When the control rod drops down, the reactor would scram; then the primary sodium pump in the sodium pool would speed down, and the flow rate of sodium would become low; the secondary loop pump also would speed down, so that the flow rate of sodium becomes low. However, the flow rate of feed water keeps constant, the superfluous cold water would flow into the superheater, which would cause the large thermal stress on the heat transfer tubes and severely with the tubes crack the sodium-water reaction may occur.

As shown in FIG.6, When the transient condition of power decreasing is simulated on the simulator, the phenomena that the steam temperature at the outlet of superheater has been reduced to the saturated temperature and the coolant is in two-phase state are discovered. The reason is that the flow rate of feed water remains constant but the heat power decreases and it is not enough to heat the feed water to the superheated steam. To avoid the sodium-water reaction accident, the flow rate of feed water should be regulated as the total heat transfer of OTSG. As shown in FIG.7, there is enough superheat degree in the superheater after the improvement.

5. Conclusions

According to the principle, characteristics of system, structure and operation of CEFR, The models and software have been developed for 71 CEFR subsystems. The reactor physics, primary coolant system, secondary coolant system, third coolant system, auxiliary system and passive decay heat removal system, etc. are included in the simulator. The conclusions are summarized as follows:

(1) CEFR simulation system has been established based on the actual physical processes to simulate the operation states for CEFR. Compared with the design parameters, the simulation results indicate that the simulation models and numerical solutions can satisfy the requirement of engineering accuracy and simulation speed.

(2) For the steady-state operation, the errors of some main parameters such as the average coolant temperature, the temperature of hot and cold pool, the reactor power, the coolant pressure, the steam generator pressure, etc. , are all less than 3% and the errors of other parameters are less than 10%. The accuracy and efficiency of calculation could meet the requirement of real-time simulation.

(3) For the transient operations and accident conditions, the trend of simulation curves are reasonable, which are in accordance with the actual physical process. Some failures of actual operations are set up to meet the demand of training the operators to analyze and study the operation conditions.

(4) The CEFR simulator has been applied to instruct the debugging and experimental operation of CEFR and improve the control methods, which would continuously play an important role in the relevant research field of sodium-cooled fast reactor.

Acknowledgments

This study was supported by Projects of Nuclear Energy Development and the International Exchange Program of Harbin Engineering University for Innovation-oriented Talents Cultivation. The authors thank them for the financial support.

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