Simulation Study on Secondary and Third Loop of CEFR

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Abstract. The present work discussed thermal-hydraulic characteristics of the secondary and third loop of China Experimental Fast Reactor (CEFR). The two-phase, multi-component models were taken into consideration to simulate the special working medium sodium in the secondary loop and the steam-water Ranking circle in the third loop. The matrix solving method was used in this paper to solve the mass, momentum, and energy balanced models accuracy, quickly and steady. This model is used to research the operating characteristics under different steady-state, dynamic-state and malfunction-state operations. The simulation results show that the errors of main parameters under different steady-state operations were less than 1%, the trend curves under dynamic-state operations were fit with the theory analysis, and the response of the secondary and third loop could show the operating and safety characteristics of CEFR.

Key Words: CEFR, modeling and simulation, two-phase flow, multi-component models

1. Introduction

The availability of fission fuel could be raised by the fast reactor which could get fissile material as breeder reactor [1], making development of nuclear energy without lacking of the fuel and taking some time to research the nuclear fusion [2]. The long-lives radioactive isotope also could be transmutation in fast reactor [3]. On the other hand, the safety of faster reactor is higher than the normal PWR. Based on these merits, it is significant for the nuclear energy to research the fast reactor and fast neutron technology. The current study of fast reactor are mainly based on experimental research and simulation analysis. Simulation is an important technology, it was attached by many research institute and university to research the fast reactors.

There are three loops in China Experimental Fast Reactor (CEFR). The structure of first loop is a sodium pool, which take the heat from the reactor core to the secondary loop, the secondary loop is a forced sodium circulation loop, and the third loop is in steam-water Ranking circle. The main purpose of this paper is to build a simulation model of the secondary loop and third loop, and the operating characteristics of CEFR under steady state and transient conditions are investigated.

2. Research subject

(1) 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, the working fluid is liquid sodium. At the top of sodium buffer tank is filled with argon gas to stabilize the pressure of secondary loop system. There are a large number of auxiliary systems to ensure the stable operation of the secondary loop coolant system, including secondary loop sodium charging and discharging system, secondary circuit sodium purification system, and secondary loop argon distribution system.

(2) Third loop system

The Ranking circle was used in third loop system of CEFR. The superheated steam came from steam generator was sent to the turbine system, then condensate by the condenser and pumped by the condensate water pump and booster pump. After heated by the regenerators, the condensate water was purified and heated in deaerator. The feed water was boosted by the feed water pump and sent to the steam generator, which finished the ranking circle. The main system in the third loop was contained main steam system, turbine system, condensate water system, low pressure heater system, feed water system, startup and shutdown cooling system, bypass drainage system, oil system, steam seal system, cooling water system and other steam-water system.

3. Mathematical models

The simulation model of CEFR secondary loop primary coolant and steam-water system is established using a two-fluids multi-component and non-equilibrium model. The basic conservation equations of mass, energy, and momentum according to the abovementioned basic assumptions can be given as follows.

3.1. Basic mathematical models

Two phase mixture continuity conservative equation:

Mass balance equation [5]：

$$A\frac{\partial(\alpha\rho)_n}{\partial t}+\frac{\partial F_n}{\partial z}=\sum\frac{\partial F_{bn}}{\partial Z}+\frac{\partial\Gamma_n}{\partial Z} \tag{4-1}$$

Where, α was the fraction of fluid; ρ was the density of fluid, kg/m^3; Z was the coordinate which the fluid flows; F_n was the flow rate of each component, kg/s; F_{bn} was the boundary flow of each component, kg/s; Γ_n was the changing rate of each component in nodes, kg/s.

Two phase mixture momentum conservative equation:

$$\frac{dF_f}{dt}=-\frac{\alpha_f A}{K_u}\left(\frac{dP}{dZ}+f_{f-w}+f_{f-f}+K_u\rho_f\vec{g}-\delta P_{pump}\right)+\sum\delta F_{bn}\vec{v}_s \tag{4-2}$$

Where, K_u was the unit conversion factor; $f_{f\text{-}w}$ was the friction factor of fluid and wall; $f_{f\text{-}f}$ was the friction factor between fluids; P_{pump} was the pump power; $\Sigma F_{bn}\, v_s$ was the momentum exchanger by the boundary.

Two phase mixture energy conservative equation:

$$A\frac{\partial(\alpha\rho h)_f}{\partial t}=-\frac{\partial(hf)_f}{\partial Z}+A(\Gamma h_{sat}+Q-W)_f+\sum\delta h_s F_{bn} \tag{4-3}$$

Where, Γh_{sat} was the energy of phase exchanger (for steam-water system was latent heat), kW; Q was the energy exchanged to the environment, kW; W was the energy doing the work, kW; f was the flow rate, kg/s; h was the enthalpy of fluid, kJ/kg; A was the flow area, m^2.

3.2. Equipment models

(1) Heat exchangers model

Taking the slab as a controlled node, based on the energy balanced equation:

$$M_s C_{ps} \frac{\partial \bar{T}_s}{\partial t} = Q_{g1} + Q_{l1} - Q_{g2} - Q_{l2} + \quad (4\text{-}4)$$

Where, C_{ps} was the specific heat volume of slab, kJ/kg.K; M_s was the mass of slab, kg; $\bar{T}$ was the average temperature of slab, K; Q_{g1} was the heat transferred from the higher temperature fluid in gas phase to the slab, kJ/s; Q_{L1} was the heat transferred from the higher temperature fluid in liquid phase to the slab, kJ/s; Q_{g2} was the heat transferred from the slab to the lower temperature fluid in gas phase, kJ/s; Q_{L2} was the heat transferred from the slab to the lower temperature fluid in liquid phase, kJ/s; Q_{ext} was the heat transferred from the slab to the environment, kJ/s; ρ_s was the density of slab, kg/m^3.

The heat transfer coefficient under different conditions was calculated by the empirical equation. The equations was listed in Table 1.

TABLE 1: EMPIRICAL EQUATIONS USED IN HEAT TRANSFER MODEL.

Regime	**Equations**
Convection (Liquid and gas)	Dittus-Boelter
Natural convection	
Nucleate boiling	Chen
Film boiling	Bailey
Condensation	Boyko Kruzhilin

(2) Centrifugal pump

The relationship between flow and head under different speed was shown as below:

$$H = K_1 (C_v N)^2 + K_2 C_v N \frac{F}{\sqrt{\rho}} + K_3 \frac{F^2}{\rho} \quad (4\text{-}5)$$

Where, H was the pump head, m; K_1, K_2, K_3 was the constant to describe the characteristics of centrifugal pump; C_v was the cavitation factor; N was the normalization speed; F was the liquid flow rate, kg/s; ρ was the density of fluid, kg/m^3.

(3) Turbine

The simplified model was used to simulate the turbine, the nodes in turbine couldn't stand for a real stage. There were two parts of power in turbine, at first was the working done by the steam in stages:

$$W_V = K_{t1} \sqrt{\frac{F}{\rho_{in}}} (P_{in} - P_{out})^{K_{t2}} \quad (4\text{-}6)$$

Where, W_V was the working done in stages, kW; K_{t1}, K_{t2} was the constant of turbine power; F was the flow rate of steam, kg/s; ρ_{in} was the steam density inlet, kg/m^3; ρ_{out} was the steam density outlet, kg/m^3; P_{in} was the steam pressure inlet, MPa; P_{out} was the steam pressure outlet, MPa.

When the vane was in light load or zero load, the working was:

$$W_B = K_{t3}\rho_{out} N_t \tag{4-7}$$

Where, W_B was working under the vane in light load or zero load, kW; K_{t3} was the constant of working loss; N_t was the speed of turbine, r/min.

The effective power of turbine was equal to the difference of these two parts:

$$W_T = W_V - W_B \tag{4-8}$$

3.3. Numerical solving methods

The flow nets contain many nodes and flows were built to simulate the real systems, the pressure of each nodes and the flow rates of each flows could be calculated by the matrix of pressure. For each pressure node, basing on the mass balance equation, the pressure nodes quantity m and flows quantity n, thus the matrix ordered in [(m+n)*(m+n)] could be gotten:

$$[A]*[X]=[C] \tag{4-9}$$

Where the matrix [X] contained the unknown values, including pressure and flow rates, solved by LU decomposition method.

4. Research model

The research model was set up when the system are simplified according to the composition and function to meet the requirements of real-time simulation. The thermal-hydraulic analysis code of primary coolant system, secondary loop coolant system, the third loop steam - water systems and other auxiliary systems run simultaneously, and interactive the data with the support of real-time simulation platform SimExec.

4.1. Secondary loop coolant system

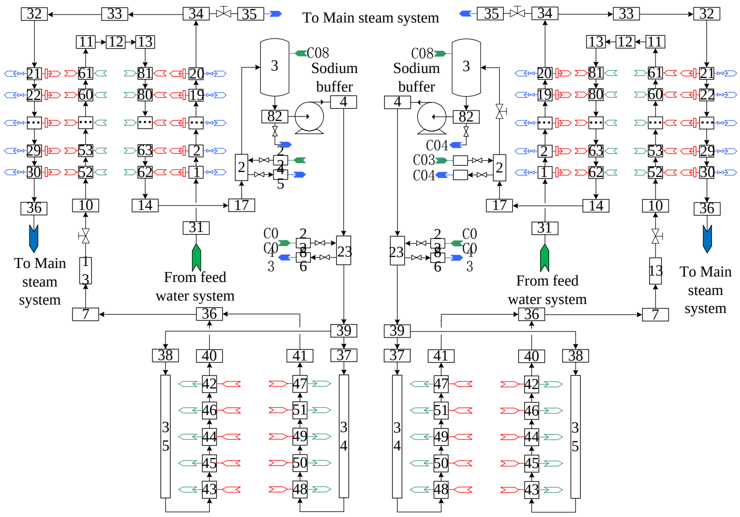
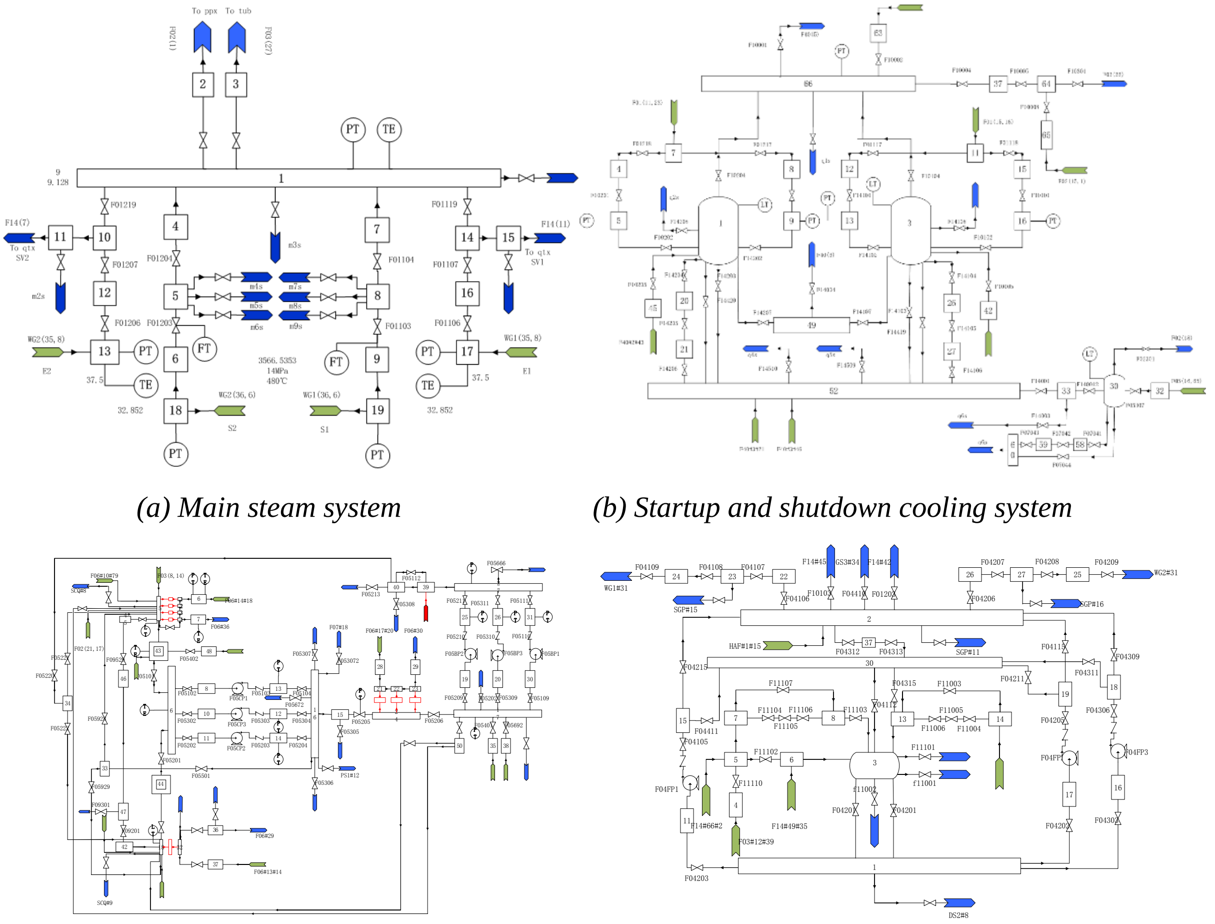


FIG. 1. THE NODALIZATION OF SECONDARY LOOP COOLANT SYSTEM.

The secondary loop system was divided into nodes based on system features, mass, momentum and energy conservation equations were established for gas-liquid two-phase flow. The equipment models including the heat exchanger model, once through steam generator model, secondary loop circulation pump model, sodium buffer tank model and electric heating system model. The nodalization of secondary loop coolant system is shown in Fig. 1.

4.2. The third loop steam - water system

The third-loop was divided into 14 partial systems, including main steam system, turbine system, condensate water system, low pressure heater system, feed water system, cooling water system and other steam-water system. Based on the structure and function of each equipment in CEFR, the nodes and flows were established in this paper. The simulation diagram of main systems in third-loop was shown in Fig. 2.



(a) Main steam system *(b) Startup and shutdown cooling system*

(c) Condensate water system *(d) Main feed water system*

FIG. 2. THE NODALIZATION OF THIRD LOOP STEAM-WATER SYSTEM.

5. Results and discussion

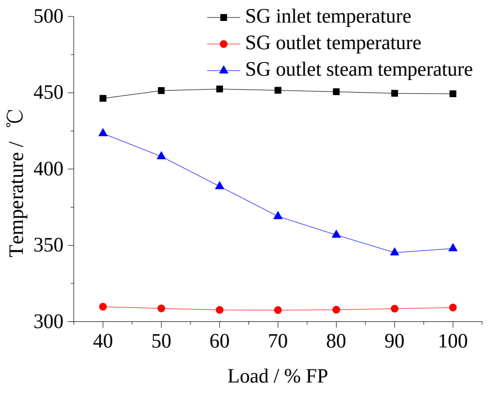
5.1. Steady state characteristics

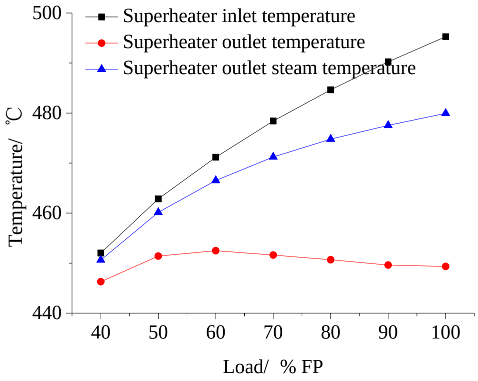
The steady-state operation calculation obtained by the simulation program at 100% FP conditions were compared with the design parameters, as shown in Tab.2. The results are in good agreement. The maximal deviation of the calculated value is -1.81% (Feed water pressure), and the minimum deviation is only 0.02% (SG inlet temperature).

TABLE 2: THE COMPARISON OF CALCULATION AND DESIGN PARAMETERS.

System parameters	**Design value**	**Calculation value**	**Error/ %**
Secondary coolant flow/ (kg/s)	137.5	137.4	-0.1
Buffer tank pressure/ MPa	0.2	0.2007	0.35
Buffer tank level/ m	<3.5	2.78	
SG inlet temperature/ ℃	495.0	495.3	0.02
SG outlet temperature / ℃	310.0	309.26	0.12
Steam temperature/ ℃	480.0	480.03	0.05
Steam flow/ (kg/s)	13.33	13.28	0.36
Steam pressure/ MPa	14	13.85	1.07
Electrical power/ MW	20.00	20.02	0.10
Condensator pressure/ MPa	0.0202	0.02	1.00
Dearator pressure/ MPa	1.3	1.285	1.15
Dearator temperature/ ℃	190	187.89	1.11
Feedwater flow/ (kg/s)	13.33	13.28	0.36
Feedwater pressure/ MPa	16	16.29	1.81

Under different load conditions, the feedwater control system adjust the flow of water to ensure constant steam generator outlet sodium temperature, but the superheater inlet sodium temperature decreases with the decreasing reactor power, as shown in Fig.3. As the secondary loop sodium flow decreases with the load decreasing, the steam generator inlet (superheater outlet) sodium temperature changes are small. At low load conditions, the steam temperature at steam generator outlet is increased obviously, while the outlet steam temperature of superheater is reduced by the limit of the inlet sodium temperature.





(a) Steam generator temperature *(b) Superheater temperature*

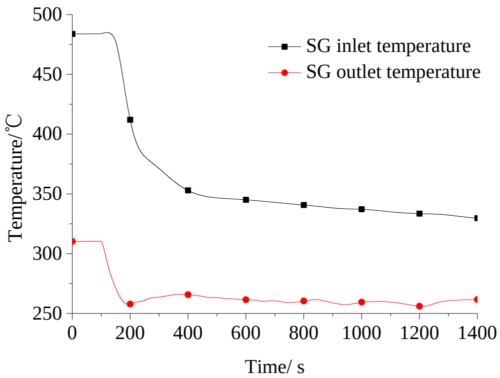
FIG. 3. THE CHANGE OF TEMPERATURE AT DIFFERENT LOAD CONDITIONS.

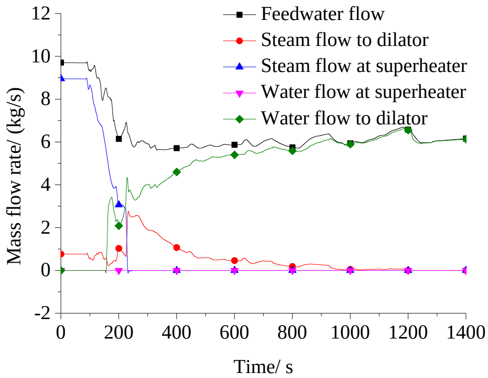
5.2. Transient characteristics

5.2.1 Steam turbine load shedding

The turbine load shedding accident occurred when the reactor is running at 75% FP, the high steam pressure trigger reactor shutdown, leading to a rapid decline in reactor power. The core outlet temperature decreases rapidly with the decreasing nuclear power. Due to the large thermal inertia of the sodium pool, the inlet temperature of intermediate heat exchanger is higher than the core outlet coolant temperature, so the inlet sodium temperature of the steam generator drops slowly. After the accident, steam generator outlet temperature decreases rapidly, manually adjust the water flow to ensure that the sodium temperature is greater than 250 degrees. The change of sodium temperature of the secondary loop is shown in Fig.4a.

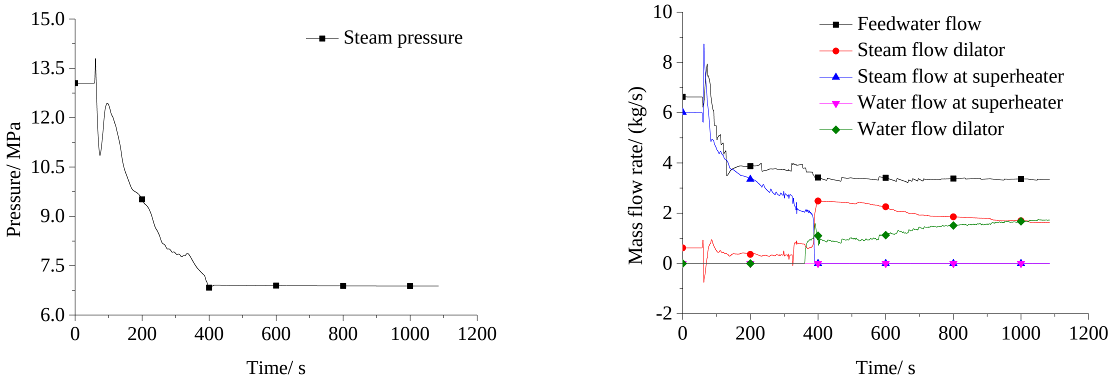
As the feed water flow decreases, the steam flow at the superheater outlet is decreasing. At 230s, open the steam generator bypass valve, and isolate the superheater. Two phase fluid enters the start-up dilator from the steam generator. The mass flow rate of steam decreases and the mass flow rate of water increases as the steam generator heat transfer is reduced. Eventually, only cold water enters the start-up dilator, as shown in Fig.4b.





(a) Secondary loop sodium temperature change *(b) Third loop flow change*

FIG. 4. MAIN PARAMETERS CHANGE AT TURBINE LOAD SHEDDING.



(a) Steam pressure change. *(b) Steam flow change.*

FIG. 5. MAIN PARAMETERS CHANGE AT SUPER POWER SHUTDOWN ACCIDENG.

5.2.2 Super power shutdown accident

When reactor power reaches 110% of the current power, the power anomaly alarm be triggered, the reactor shutdown as reactor core shut down rod drops to the bottom quickly. After the accident, control the main steam pressure decreases by adjusting the bypass valve and water flow. When the steam pressure is dropped to 7MPa, maintain the vapor pressure remains constant, as shown in Fig.6. The variation of steam flow is shown in Fig.7. Reduce the steam pressure, high-pressure two-phase shock can be avoided to ensure the stability of the three-loop operation.

6. Conclusions

In this work, the mathematical model of CEFR is established and the operating characteristics at steady and transit state is researched. According to the analysis results, the major conclusions are summarized as follows:

(1) The error of the important parameters is less than 1% under the steady state condition compared with the design value, which can meet the precision requirement of the simulator.

(2) The simulation model can achieve stable operation under different load conditions, and the steady-state operation characteristics of the steam generator can provide the correct running trend.

(3) By analyzing the different transient accident conditions, he simulation model can be used to load variable and transient process analysis.

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