Development and analysis of a detailed parametric simulation model of condensers for nuclear power plants

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Abstract: Condensers are one of the most important items of equipment at nuclear power plants. This paper describes the development of a modular, parametric and detailed general condenser simulation model. Four different condenser structures are simulated separately based on the characteristics of the condenser so as to give users choices in building simulation models of differently structured condensers. Examples are given to show that the calculated errors of simulation models are verified as less than 1.5% both in steady and dynamic conditions. The simulation results show that the simulation models can accurately reflect the operating characteristics of nuclear power plant condensers under different operation conditions.

Keyword: condenser simulation model; parametric model

1 Introduction

The condenser is one of the most important items of equipment of the turbine-generator unit in nuclear power plants because the operational performance of the condenser directly influences the safety and economy of the plant [1]. Nowadays many studies on simulation models for condensers are based on specific equipment. In case the structure and parameters of the condenser change, the corresponding simulation models should be rebuilt from the scratch. Although these simulation technologies can obtain detailed parameters of the condenser, it results in large amounts of repetition of work and wasting of time. So if the variety of condensers and configurations are to be considered, the most important question is how to make the modeling and simulation work faster and more efficient and at the same time keep high accuracy and adaptability.

To solve these problems in general, this paper studies how to develop modular, parametric and detailed simulation models of condensers. The word “parameterization” in this context implies that users can change some parameters but need not change the whole model if they want to modify the design parameters of a specific condenser model. The word “detailed” means that improved multi-pressure node and distributed parameter modeling is used to build the condenser model. So different types of condenser models can be built and stored in the simulation model database, and as soon as the necessary input parameters are set in the initialized simulation model, the specific condenser simulation model is rapidly built.

2 Overview of condenser modeling technique

In this chapter some primary modeling techniques are introduced and compared.

Graphical modeling tools, such as JTopmeret[2] and Flowmaster[3]can perform the modeling of condensers. In such modelling tools, the pipelines and equipment are constructed using universal and graphical models, connecting with each other by mass flow lines and heat flow lines. Then by adjusting the conditions of the lines, the simulation model of the equipment or systems can be constructed. In this way pipelines and simple equipment can be simulated. However the structure of a condenser is typically too complex and this graphical modeling software cannot satisfy the precision requirements of the models.

The modeling of a condenser can also be undertaken using RELAP5[4]. RELAP5 is a general system program for transient behavior analysis of the primary loop system of nuclear power plants.

Received date: December 11, 2014
(Revised date: March 5, 2015)

Although RELAP5 meets the requirement of precision, it cannot reflect the flow and heat transfer characteristics inside the condenser, and the partition of nodes is too complex to debug.

According to the complexity of the condenser model, there are lumped-parameter models and distributed models. Lumped-parameter models consider the condenser as a node, and all parameters are evenly weighted. This method does not focus on the condenser internal flow and heat transfer, but mainly focuses on the input and output parameters during the dynamic operation period. The computational load is small, but it has lower calculation precision. Distributed models pay more attention to the internal flows and heat transfer characteristics. These models can better describe the nuclear power plant condenser's internal flows and heat transfer situation, so that it makes the simulation results more accurate. It divides the system evenly along the pipeline in the condenser, using lumped parameter methods? at every such node, and then dispersing the established partial differential equation, calculating the related parameters through numerical computation methods. This paper focuses on the distributed model, using both single-pressure and multi-pressure models separately to calculate the momentum equations and energy equations of each condenser node.

3 The modeling for modularization and parameterization of the condenser

At present, condensers of NPP are considered as a kind of tube-and-shell heat exchanger, where the in-flowing tube side is single-phase fluid, and the in-flowing shell side is phase-transition fluid. In the condenser, steam flows along the shell, and cooling water flows through the tube and receives heat from the steam continuously. According to the flow direction of the condenser along the tube side, the condenser is divided into several control-volumes, and each control-volume contains three parts: the vapor region, the metal tubes and the cooling-water region. Additionally the heat sink region control-volumes are set separately. This means, it can be modeled based on the different purposes and characteristics of the condenser. Four different structures of condenser models can be built separately: single-pressure two-process condenser, single-pressure one-process condenser , single-pressure double-tube-pass condenser and dual-pressure double-tube-pass condenser, as shown in Fig1 to Fig4. Here, single-pressure means the pressure of the vapor region on the shell side is constant across the unit, dual-pressure means the pressure of the vapor region on the shell side is divided into two parts. The number on the tube side means different nodes for the division of control volume. These four condenser models are established based on the fundamental principles of the condenser, so they are not confined to certain conditions or particular types of condensers. They can simulate the actual operation of general NPP condensers, and can meet the need of high precision simulation.

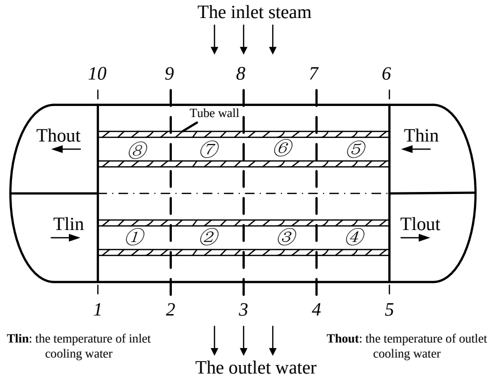

Fig.1 Simplified model of single-pressure two-process condenser.

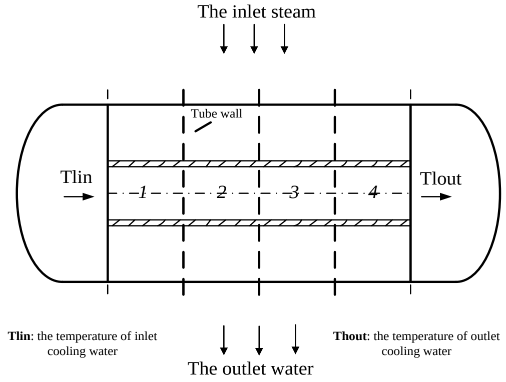

Fig. 2 Simplified model of single-pressure one- process condenser.

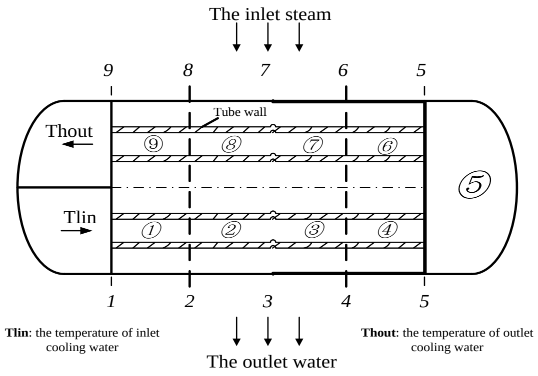

Fig. 3 Simplified model of single-pressure double-tube-pass condenser.

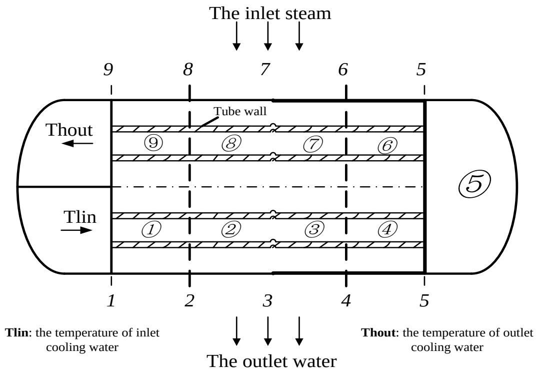

Fig. 4 Simplified model of dual-pressure double tube-pass condenser.

The parametric modeling approach (discussed earlier) is the most efficient and convenient method for modular modeling. It can avoid repeated work in simulation modeling and thereby improve the efficiency. In this paper a parametric method is used to establish the simulation models of condensers. Parametric modeling which is based on a complete modular model library means the user can perform the modeling work for any type of condenser by setting only the initial values of the thermal parameters and geometric parameters as prompted in the configuration interface. Table 1 shows the initial parameters of condenser model that need to be set according to the requirements.

Table1 Input parameters of the condenser model

No.	Physical meaning	Unit
1	Inner diameter of the heat transfer tube	m
2	External diameter of the heat transfer tube	m
3	Length of the tube	m
4	Material of the tube	——
5	Quantity of the tube	——
6	Heat exchange area	m^2
7	Volume of the shell	m^3
8	Pressure of the shell	MPa
9	Temperature of the metal wall	℃
10	Steam flow of the lateral shell	kg/s
11	Cooling water flow of the lateral shell	kg/s
12	Inlet temperature of cooling water	℃
13	Inlet enthalpy of steam	kJ/kg
14	Flow rate of cooling water	m/s
15	Number of passes	——

After entering these initial parameter values, the modular and parametric simulation program of the condenser calculates the output parameters, as given in Table2.

Table2 Output parameters of the condenser model

No.	physical meaning	unit
1	Outlet temperature of cooling water	℃
2	Temperature of heat sink water	℃
3	Flow in condensate outlet	kg/s
4	The enthalpy of the condensate outlet	kJ/kg
5	Operating pressure of condenser	MPa

4 Detailed modeling of condenser

Considering the internal flow and the characteristics of heat transfer in the condenser, this model can describe the flow and heat transfer conditions of condensers in large-scale nuclear power plants and make the simulation results of the internal condenser more accurate [5]. In this model, by using the void fraction to calculate the quality of the shell-side two-phase fluid, it can reflect the characteristics of heat transfer and flow in the condenser’s shell side accurately to obtain high simulation precision[6]. The model considers the flow loss (drop) caused by the steam flow rate, relative height and density changes in the steam in each control volume.

4.1 Model Hypothesis

Before modeling the condenser of nuclear power plant, there are some model simplifying assumptions firstly:

(1) The fluid on the tube side and shell side are considered as directional flows.

(2) The mixture of steam and water in the condenser is in a state of thermodynamic equilibrium.
(3) The energy loss due to slip between the vapor and the liquid can be ignored.
(4) Along the flow direction, the control volume can be considered as symmetrically distributed.
(5)On the shell side, vapor and non-condensable steam can be considered as ideal gases.

4.2 The division of control volume

Using distributed parameters to model the condenser, the condenser volume is divided into several control volumes. In this paper we divide the modular condenser into single-pressure two-process, single-pressure one-process, single-pressure double tube-pass and dual-pressure double tube-pass configurations. After dividing the condenser into several volumes, the above assumptions are used to simplify the model and establish a two-dimensional simulation model of the condenser. Along the direction of vapor flow, the pressure of each control volume will be gradually decreased, and the corresponding physical parameters will also change. By solving the simulation model, we can get the distribution of the pressure, temperature and vapor rate in the control volume of the condenser. Those calculated results are helpful to the optimized design of nuclear power station condensers.

4.3 Basic control equation

(1) The mass conservation equation of the condenser on the steam-side is given by

$$\begin{aligned} \frac{dm_{s,j}}{dt} &= \sum D \\ \frac{dm_{a,j}}{dt} &= \sum D_a \end{aligned} \qquad (1)$$

Where:
$m_{s,j}$: the two-phase fluid mass of each control volume,(kg);
∑D: algebraic sum of in-and-out control volume,
s:mixture of steam and water in the condenser,(kg/s);
Da: the air in the condenser,(kg/s),
j:nodes of control volume.

(2)The energy conservation equation of the condenser on the steam-side is given by:

$$\begin{aligned} \frac{d(m_{s,j}u_j)}{dt} + (M_{s,j}C_{s,j})\frac{dT_{s,j}}{dt} &= \sum (D_j h_j) - Q_{s,j} \\ \frac{d(m_{a,j}u_{a,j})}{dt} + (M_{a,j}C_{a,j})\frac{dT_{a,j}}{dt} &= \sum (D_{a,j} h_{a,j}) - Q_{a,j} \end{aligned} \qquad (2)$$

Where:
$C_{s,j}$: the two-phase fluid specific heat of each control volume,(kJ/(kg・K));
$T_{s,j}$: the two-phase fluid temperature of each control volume,(K);
$\sum(D_j h_j)$: the two-phase fluid enthalpy in-and-out of each control volume,(kJ/s);
$Q_{s,j}$: the heat transfer rate between each control volume two-phase fluid and tube wall,(kJ/s);
s: mixture of steam and water ,
a:the air in the condenser, and
j: nodes of control volume.

(3)The energy conservation equation of the condenser on the water-side is given by

$$(m_{w,i}C_{p,i})\frac{dT_{w,i}}{dt} = Q_{w,i} - D_{w,i}C_{p,i}(T_{w,i} - T_{w,(i-1)}) \qquad (3)$$

Where:
$m_{w,i}$: cooling water mass of each control volume,(kg);
$T_{w,i}$: cooling water inlet temperature of each control volume,(K);
$Q_{w,i}$: the heat transfer rate between the control volume cooling water and tube wall,(kJ/s);
$D_{w,i}$: mass flux of cooling water,
w: the cooling water on the tube side of the condenser, and
i:nodes of control volume.
(4)Metal tube wall thermal storage equation is given by

$$M_{m,i}C_{m,i}\frac{dT_{m,i}}{dt} = Q_{s,j} - Q_{w,i} \qquad (4)$$

Where:
$M_{m,i}$: metal tube wall mass of each control volume,(kg);
$C_{m,i}$: metal tube wall specific heat of each control volume,(kJ/(kg・K));
m: metal of the tube,
i:nodes of control volume.

(5)The total thermal resistance K on the surface of the condenser is made up of water-side heat transfer thermal resistance, tube wall heat conduction thermal resistance, thermal resistance of fouling, vapor-side natural convection heat transfer thermal resistance and water film thermal resistance, as given by

$$\frac{1}{K}=\frac{1}{\alpha_{\mathrm{w}}}\times\frac{\mathrm{d}_1}{\mathrm{d}_2}+\frac{1}{\alpha_0 \mathrm{e}^{(-ce)}}+\frac{\mathrm{d}_1}{2\lambda}\ln\frac{\mathrm{d}_1}{\mathrm{d}_2}+\frac{1}{2\pi l\lambda_3}\ln\frac{\mathrm{d}_2}{\mathrm{d}_2-2\delta_3}+\frac{1}{2\pi l\lambda_2}\ln\frac{\mathrm{d}_1+2\delta_2}{\mathrm{d}_1} \quad (5)$$

Since forced convection heat transfer is assumed between the cooling water in the tube and tube wall, we can get the heat transfer coefficient in the tube using the Nusselt number in Dittus-Boelter equation：

$$\alpha_{\mathrm{w}} = 0.023\mathrm{Re}_f^{\ 0.8}\,\mathrm{Pr}^{0.4}\,\frac{\lambda_{\mathrm{w}}}{d_{\mathrm{i}}} \quad (6)$$

There is film condensation heat transfer between the vapor and the tube wall calculated from the Nusselt film condensation heat transfer equation. When the plane layout of the condenser bundle is assumed, we can get the convection heat transfer coefficient between pure vapor and the tube wall as follows:

$$\alpha_{\mathrm{o}} = 0.729\left[\frac{gr\rho_{\mathrm{c},j}^{\ 2}\lambda_{\mathrm{c},j}^{\ 3}}{v_{\mathrm{c},j}d_{\mathrm{o}}(t_{\mathrm{s},j}-t_{\mathrm{m},j})}\right]^{1/4} \quad (7)$$

Where:

α_{w}: cooling-water-side heat transfer coefficient of each control volume, (W/(m^2 • K));

α_{o}: heat transfer coefficient of pure static vapor, (W/(m^2 • K));

d_1: tube external diameter, (m);

d_2: tube internal diameter, (m);

λ: thermal conduction coefficient, (W/(m • K)) and

δ_2: liquid film thickness, (m).

(6) The mass calculation formula of two-phase fluid in the control volume

By considering the velocity of phase slip between the two-phase fluid, the steam mass of the two-phase region in each control volume is calculated. Approximate homogeneous flow model is used in this paper, with a void fraction model equation adopted, phase slip is reflected. Then the void fraction α is calculated as:

$$\alpha = \frac{1}{1+(\frac{1}{x_j}-1)S\frac{\rho_{\mathrm{s},j}}{\rho_{1,j}}} \quad (8)$$

Where x_j is the mass steam quality, the density of two-phase fluid ρ_i is calculated as:

$$\rho_j = \alpha\rho_{\mathrm{s},j} + (1-\alpha)\rho_{1,j} \quad (9)$$

According to the mean mass steam quality, the average density of the two-phase fluid and the following formula, the quality of the two-phase region in each control volume can be given by

$$m_{\mathrm{s},j} = V_{\mathrm{s},i}\times\rho_j \quad (10)$$

where $V_{s,i}$, P_j, $\rho_{s,j}$, $\rho_{l,j}$ and α are the volume of each control volume, two-phase fluid density of each control volume, vapor-phase fluid of each control volume, liquid-phase fluid of each control volume and void fraction respectively.

(7) The calculation of two-phase flow pressure loss.

Two-phase pressure loss is generally divided into three parts: the frictional pressure loss, gravitational pressure loss and acceleration pressure loss.

(i)Frictional pressure loss

To calculate two-phase flow frictional pressure loss in the homogeneous flow model, the two-phase mixture is considered as a kind of homogeneous mixed fluid and the physical parameters are the average of the two-phase parameters. The model assumes that two phases with the same velocity are in thermodynamic equilibrium, and can characterize two-phase flow by using the single-phase friction factor.

When the liquid-phase fluid quality is the same as the two-phase fluid flow through the channel, the gradient of pressure loss is given by:

$$(\frac{dp_{\mathrm{f}}}{dy})_{\mathrm{lo}} = \frac{\lambda_{\mathrm{lo}}}{D}\frac{G^2}{2}v' \quad (11)$$

The all-liquid friction coefficient is introduced and the gradient of frictional pressure loss of two-phase fluid is given by:

$$\Phi_{\mathrm{lo}}^2 = \frac{\lambda}{\lambda_{\mathrm{lo}}}\left[1+x_j\left(\frac{v''}{v'}-1\right)\right] \quad (12)$$

$$\frac{dp_{\mathrm{f}}}{dy} = (\frac{dp_f}{dy})_{\mathrm{lo}}\times\Phi_{\mathrm{lo}}^2 \quad (13)$$

Liquid-phase friction coefficient $\lambda_{1o}$is calculated by the Blasius Formula given by:

$$\lambda_{\mathrm{lo}} = 0.03164\mathrm{R_{ef}}^{-0.25} = 0.3164(\frac{GD}{\mu'})^{-0.25} \quad (14)$$

As the above formula shows, physical parameters associated with the friction coefficient are mainly given by the viscosity coefficient μ′, so the fluid Reynolds number is calculated by solving the average viscosity of the two-phase fluid in the node so as to solve the friction coefficient of the two-phase fluid.

Two-phase fluid average viscosity is solved by the Sigg Chitty Formula, as given by:

$$\mu = x_j \mu'' + (1 - x_j)\mu' \tag{15}$$

For two-phase fluid flow, the friction coefficient λ is given by:

$$\lambda = 0.3164\mathrm{R}^{-0.25} = 0.3164(\frac{GD}{\mu})^{-0.25} \tag{16}$$

For the steam-water mixture flowing on the shell side of the condenser, the friction coefficient is given by:

$$\Delta P_f = \lambda \frac{L}{\ } \frac{G^2}{\ } \nu' \left[1 + x_j \left(\frac{\rho'}{\ } - 1\right)\right] \tag{17}$$

(ii).Gravitational pressure loss:

Assuming that the two-phase fluid releases heat uniformly along the direction of flow, then gravitational pressure loss is given by:

$$\Delta P_{\mathrm{g}} = \frac{\mathrm{g}\sin\theta \mathrm{H}}{x_j} \ln\left[1 + x_j\left(\frac{\nu''}{\nu'} - 1\right)\right] \tag{18}$$

(iii).Acceleration pressure loss:

In the homogeneous flow model, since the void fraction at the exit is zero, and it is assumed that the channel has a constant cross section along the direction of flow, then acceleration pressure drop is given by:

$$\Delta P_{\mathrm{a}} = G^2\left[x_j\left(\nu'' - \nu'\right)\right] \tag{19}$$

4.4Calculation process of the simulation program

Existing calculation programs for condenser simulation calculate the pressure distribution iteratively through each outlet flow in of the control volume. This calculation method has high demands in selecting a proper initial value for the pressure distribution. If the initial parameter values of the condenser are not appropriate, the results of the calculations will be divergent. To develop a general modular and parametric condenser simulation model, it is required that the calculation program likewise has general applicability. In this paper, utilization of improved calculation methods are employed where the basic idea is calculating $P_{s,I}$ and $M_{s,j}$ separately. First, we use $M_{s,j}$ to calculate $P_{s,i}$ when the pressure $P_{s,i}$ is unknown. The equation for this is given by:

$$M_{s,total}^{(1)} = M_{s,total}^{(0)} + \left(W_{\mathrm{t}} + W_{\mathrm{ost}} + W_{\mathrm{fv}} + W_{\mathrm{dv}} - W_{\mathrm{dc}} - \mathrm{W_c} - \mathrm{W_{da}} - \mathrm{W_{airo}}\right)h \tag{20}$$

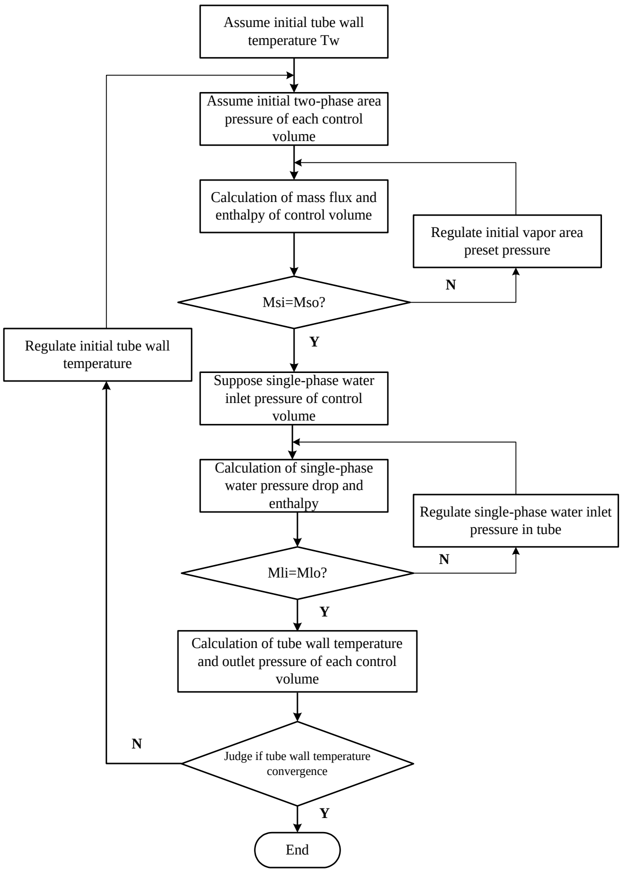

Fig 5 The flow chart of pre-processing calculations.

In Eq. (20), the time step his given, and all the parameters on the right side are assumed to be known, then $M_{s,total}$ on the left side of Eq.(20)can be obtained. Because of the correspondence between the pressure Ps,i and the total mass of the steam $M_{s,total}$, the total mass of the steam $M_{s,total}$ determines the pressure Ps,i uniquely. We use the mass flow at each node on the outlet steam to correct Ps,i, then we can calculate the other major parameter values of each node. Therefore, the dynamic and real-time simulated program of the condenser can be divided into two calculation parts, they are the pre-processing calculation and the main calculation of the formal programs is shown in Figs 5 and 6 in respective flow charts.

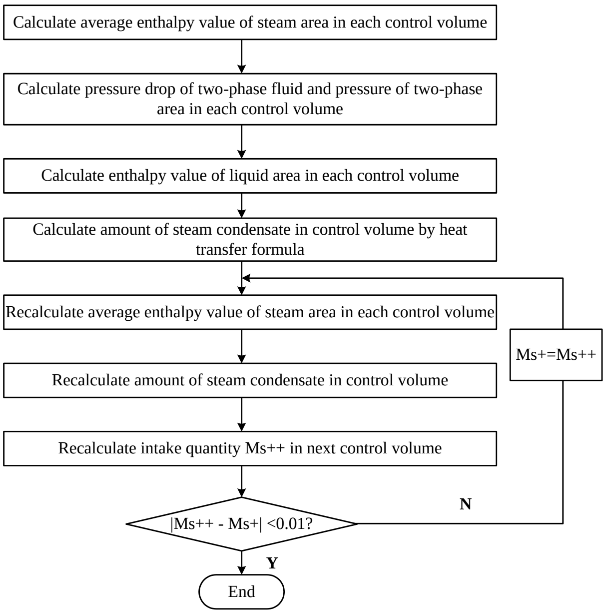

Fig. 6 Flow chart of main calculations.

5 Examples of verification

The established parametric modular condenser simulation model mentioned above is used to analyze the influence of related parameters on the condenser operation characteristics. Taking Qinshan-II nuclear power plant condenser, Yuanbaoshan power plant condenser and Pingyu power plant condenser as case studies, the authors of this paper conducted an analysis of their steady state characteristics. On this basis Qinshan-II nuclear power plant is selected as the example for studying the parametric settings on established single-pressure double tube-pass modular condensers, and then we replace it with the original condenser model of Qinshan-II nuclear power plant simulation platform developed by the cooperation of Harbin Engineering University and the Research Institute of Nuclear Power Operation to study the dynamic characteristics of the condenser. The secondary loop system of Qinshan-II nuclear power plant is shown in Fig 7.

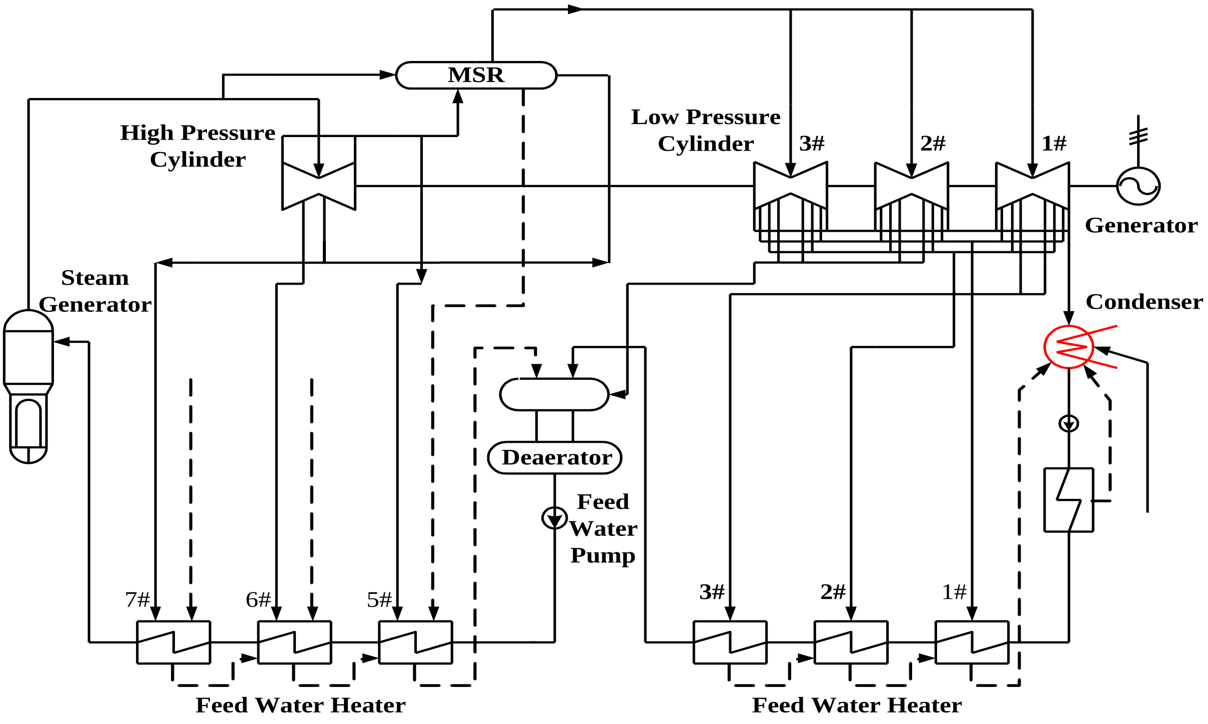

Fig. 7 Secondary loop system of Qinshan-II nuclear power plant.

The condenser which is drawn in red was replaced with the newly developed model. The simulation results were then compared with the original condenser model. The value of some basic parameters of the Qinshan-II nuclear power plant condenser is shown in Table 3.

Table3 Value of some basic parameters of Qinshan-II nuclear power plant condenser

No.	Physical meaning	Value	Unit
1	Inner diameter of the heat transfer tube	0.0236	m
2	External diameter of the heat transfer tube	0.025	m
3	Length of the tube	12.988	m
4	Material of the tube	Titanium-steel	——
5	Quantity of the tube	34656	——
6	Heat exchange area	35400	m^2
7	Volume of the shell	890.2	m^3
10	Steam flow of the lateral shell	179.11	kg/s
11	Cooling water flow of the lateral shell	12708.1	kg/s
12	Inlet temperature of cooling water	23.94	℃
13	Inlet enthalpy of steam	2362.4	kJ/kg
14	Flow rate of cooling water	2.3	m/s
15	Number of passes	2	——

5.1 Steady state analysis

In this paper the specific variables of Qinshan-II nuclear power plant condenser, typical condensers of thermal power stations Yuanbaoshan power plant condenser and Pingyu power plant condenser were used to test and verify the established simulation model steady state parameters. The calculated results are shown in Table 4.

Table 4 Comparison of calculated parameters with the design parameters

	Pressure(kPa)			Cooling-water outlet temperature (℃)		
	Design	Calculated	Error(%)	Design	Calculated	Error(%)
Qinshan-II NPP	5.43	5.49	+1.10%	30.2	30.5	+0.99%
Pingyu power plant	4.903	4.96	+1.16%	24.10	24.15	+0.2%
Yuanbaoshan power plant	5.3	5.38	+0.15%	29.5	29.8	+1.0%

From Table 4, it can be seen that the simulation model established in this paper is of high precision, he error between the design value and calculated value of each parameter is less than 1.5%. The precision of established parametric modular simulation models can meet the requirements of training and engineering analysis well. The prominent feature of this simulation program is the low time requirement for modeling and the ease of debugging.

5.2 Dynamic characteristic analysis

With increasingly larger power steam turbines, the condenser should operate effectively across a broader range of conditions. In the course of actual operation of the condenser, it is necessary to calculate the performance parameters when the condition changes. In this paper a full-scale Qinshan-II nuclear power plant simulation platform developed by Harbin Engineering University and the Research Institute of Nuclear Power Operation was chosen as the research object, for the parametric settings of a single-pressure two-process multi-node condenser from the four condenser models. The original condenser was then replaced in the platform by connecting the output parameters from the turbine with the input parameters from the established condenser, attaching the output parameters from the established condenser with the condensate pipeline, and also linking the input and output interface of the cooling water with the related parameters of the condenser. In this way, the dynamic characteristics are studied.

5.2.1 Analysis of 100% full power operation reduced to 50% power operating conditions

In the 100% full power steady operating condition, the power reduction commands are sent to the system, target power is 325MW, power reduction rate is 15MW/min as shown in Fig 8, the system which contains the model established in this paper operates synchronously with original system which contains the original model. From the calculated results it can be seen that the simulation model has the same changing tendency with that of original model. Because of the functioning of the condenser water level control system, the heat sink liquid level remains unchanged as Fig 9 shows. Since the inlet cooling water temperature is constant, the turbine exhaust steam decreases will lead to the decrease of heat exchange rate. Accordingly the outlet cooling water temperature will decrease as shown in Fig 10. The heat exchange rate decreases also lead to the pressure of vapor region decrease as shown in Fig 11. And the decrease of pressure causes the decrease of saturated temperature which means the condensate temperature decreases as shown in Fig 12. The horizontal sections 350 seconds from the beginning and 1600 seconds after are the steady running state before and after decreasing the power.

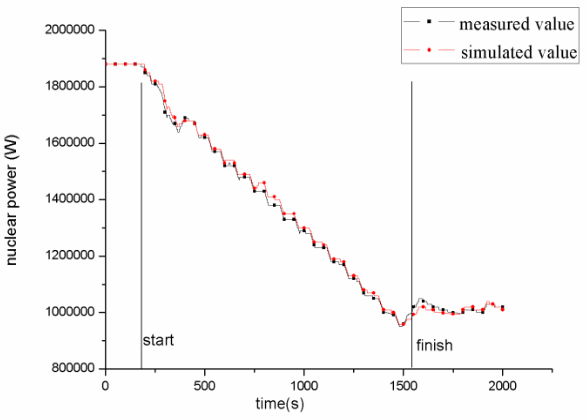

Fig. 8 Nuclear power reduction.

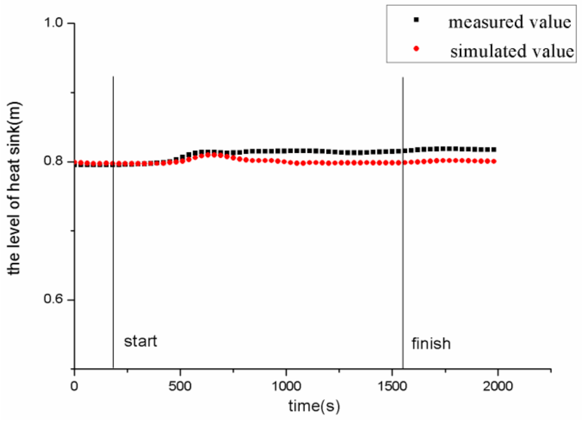

Fig. 9 Liquid level of heat sink.

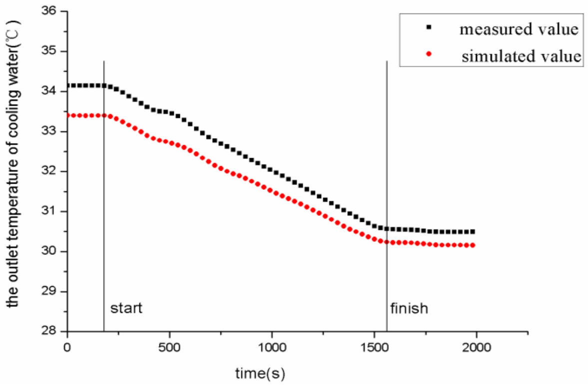

Fig. 10 Outlet temperature of cooling water.

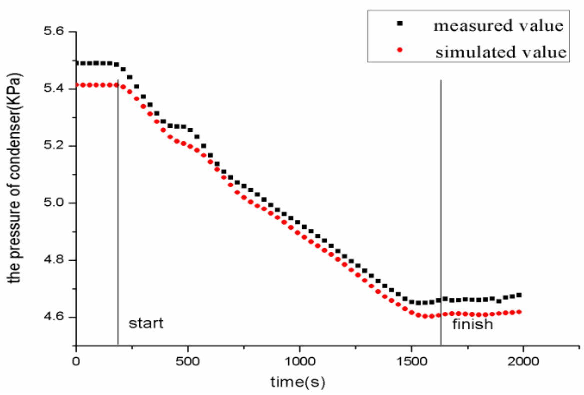

Fig. 11 Pressure of condenser.

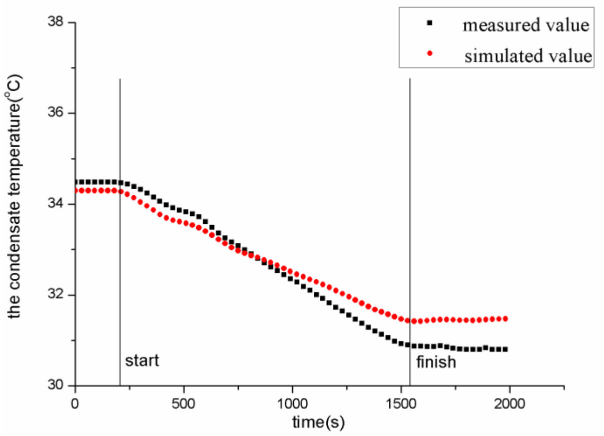

Fig. 12 Condensate temperature.

Since the detailed simulation model is used in this study, it can calculate the pressure of the condenser, outlet and inlet temperature of condenser and so on at each node, in order to make the simulation results more precise and the simulated types of fault and accident richer. Then the curves of characteristic parameters in each area are shown in the following figures.

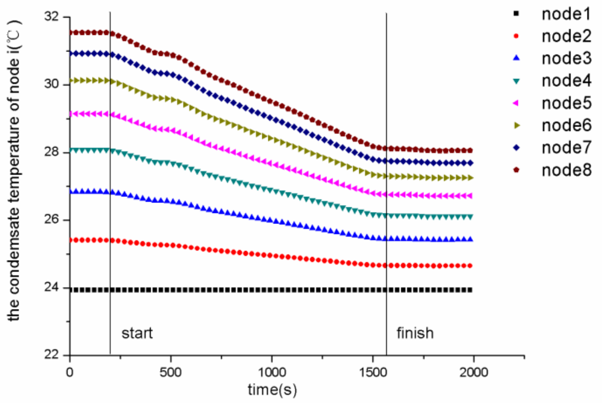

Fig. 13 Inlet temperature of cooling water in each node.

In Fig 13, by comparison with the Fig 10, the inlet temperature in each node of the tube side is increasing continually to show the changing of the temperature on the tube side.

5.2.2 Process analysis of pipeline leakage

In the 100% full power steady conditions, the leakage were inserted to the node one of the pipelines of the condenser at 100 seconds through the Distributed Control System interface of the platform, and the flow rate of the leakage is 217 kg/s. By operating the platforms separately including the simulation model and the original model at the same time, the cooling water in the tube side goes into the shell side. Since the leakage into the shell side was condensed to liquid water, the pressure of the condenser is almost constant as shown in Fig 14. But the condensate temperature must be lower than before as shown in Fig15. The change of the outlet temperature of cooling water is shown in Fig 16.

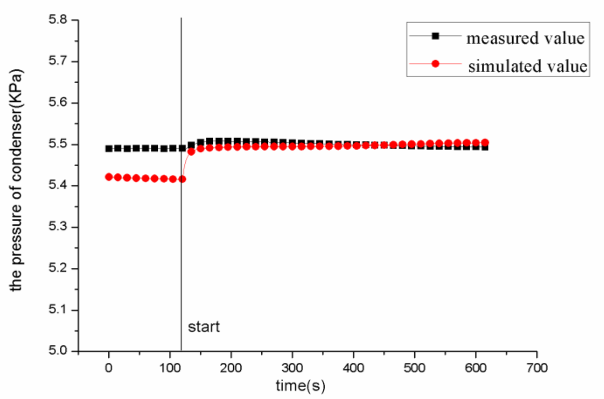

Fig. 14 Pressure of condenser.

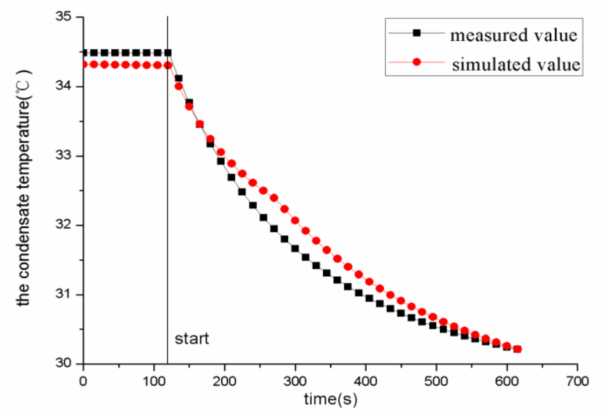

Fig. 15 Condensate temperature.

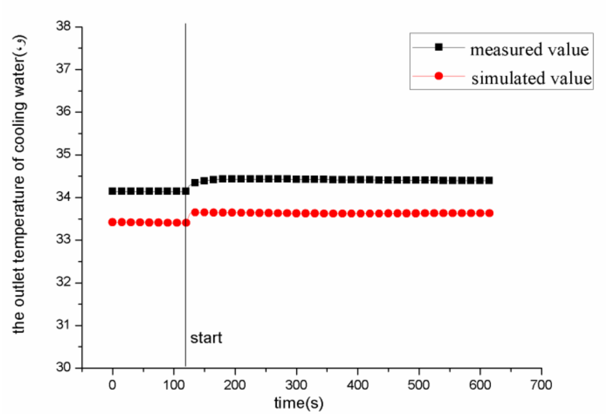

Fig. 16 temperature of cooling water.

6 Conclusions

A modular, parametric and detailed condenser model has been developed and applied to the characteristics of condensers in Chinese nuclear power stations. According to the specific structure of the condenser, different types of simulation model are established, such as lumped-parameters models and improved multi-pressure-node model.

The steady-state analysis verification shows that the calculation values of the parametric and modularized condenser models are consistent with the actual values, and the errors are less than 1%.In the dynamic analysis based on a NPP simulator, the single-pressure two-process multi-node condenser simulation code is transplanted and added to the simulation program of Qinshan-II nuclear power plant which was developed by Harbin Engineering University and the Research Institute of Nuclear Power Operation. Therefore the simulator can analyze the characteristic parameters in the process of power transients and leakage faults on the tube side of the condenser, and the results of experiment show that the developed condenser program has higher level of precision.

The condenser model developed in this paper has excellent static and dynamic characteristics, and it can reflect the different operating conditions of nuclear power plant condensers. Moreover, due to its specific features of being parametric and modular the condenser model can be used for various condensers with different structures.

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