Modelling and Dynamic Operation Characteristics Analysis of UTSG Under Disturbance Conditions

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Abstract. In order to quantitatively analyze the maneuverability of ship nuclear power system, based on the working principle of UTSG, a modularized lumped parameter model was established based on the one-dimensional simplification of the working fluid by the homogeneous flow model. The modularized lumped parametric model is used as a tool to study the operating characteristics of UTSG. Through the analysis of the coolant flow rate disturbance and the feed water flow rate disturbance, we show the change rules of the operation parameters of UTSG. The research results can provide a basis for the maneuverability analysis of the ship nuclear power system.

Introduction
Steam generator is an important device in nuclear power ship. Its main function is to transfer the thermal generated by the reactor to the working fluid in the secondary side. U-tube steam generator (UTSG) is commonly used in nuclear power plants.

The steam generator modelling methods include distributed parameter modelling [1] and lumped parameter modelling [2,3]. Because this paper mainly researches the change rules of the operating parameters of UTSG under disturbance, the lumped parameter modelling method is selected. For the two-phase flow in the riser, there are two commonly used processing methods: the drift flow model [4] and the homogeneous flow model [5,6]. Because the research object in this paper has the characteristics of large flow velocity and small quality, the homogeneous flow model is selected.

According to the working principle of UTSG and research needs of this paper, referring to the division of the steam generator by Kerlin [7], the UTSG model is divided into four modules: primary side (P), riser (R), down-comer (DC), and steam dome (SD). In addition, two modules are added to calculate the heat transfer rate between the primary side and the riser and the mass flow rate in riser. The module division of UTSG is shown in Fig. 1.

Figure 1. The module division of UTSG.
Modular Model
The assumptions in the modelling of this paper are as follows:
(1) The two-phase fluid in the riser is a homogeneous fluid without relative velocity. The enthalpy and density of the working fluid are expressed by the average value;
(2) The heat transfer between the reactor coolant and the tube bundle on the primary side is completed in an instant. The reactor coolant and the tube bundle are regarded as a thermal source together;
(3) The sleeve is insulated, and there is no heat transfer between the riser and the down-comer;
(4) The efficiency of the steam-water separator is 100%;
(5) Regard the pressure in UTSG as a constant.

Nomenclature

| Symbol | Description |
|--------|-------------|
| F      | Flow area ($m^2$) |
| C      | Specific heat capacity ($KJ/(KG \cdot K)$) |
| i      | Specific enthalpy ($KJ/KG$) |
| K      | Heat transfer coefficient ($KW/(m^2 \cdot K)$) |
| M      | Mass ($KG$) |
| P      | Pressure ($MPa$) |
| Q      | Heat transfer ($KJ/s$) |
| G      | Mass flow rate ($KG/s$) |
| T      | Temperature ($K$) |
| E      | Opening |
| d      | Inner diameter ($m$) |
| S      | Perimeter ($m$) |
| L      | Length ($m$) |
| V      | Volume ($m^3$) |
| x      | Quality |
| ρ      | Density ($KG/m^3$) |
| λ      | Heat conductivity ($KW/(m^2 \cdot K)$) |
| α      | Heat transfer coefficient ($KW/(m^2 \cdot K)$) |
| δ      | Thickness ($m$) |
| ζ      | Local resistance coefficient |
| f      | Frictional resistance coefficient |

Subscripts

- d: Down-comer
- p: Primary side
- r: Riser
- sd: Steam dome
- f: Liquid
- g: Steam
- fw: Feed water
- se: Mass flow rate in riser
- v: Valve
- s: Saturated
- ro: Outlet of riser
- pi: Inlet of primary side
- po: Outlet of primary side
- m: Tube

Primary Side Module

The focus of this model is not the temperature distribution in the U-shaped tube. Consider it as a uniform heat source, and take the average temperature of the heat carrier as the temperature of the heat source. The thermal conservation equation on the primary side is shown in Eq. 1 [10].

\[
(M_p C_p + M_m C_m) \frac{dT_{pa}}{dt} = G_p C_p (T_{po} - T_{pi}) - Q_T
\]

Discretize Eq. 1 by Euler's method, the average temperature and the outlet temperature of the primary heat transfer agent can be expressed as Eq. 2 and Eq. 3.

\[
T_{pa}^{(n)} = T_{pa}^{(n-1)} + \frac{2G_p C_p (T_{pa}^{(n-1)} - T_{pi}) - Q_T}{M_p C_p + M_m C_m} DT
\]

\[
T_{po}^{(n)} = 2T_{pa}^{(n)} - T_{pi}
\]

Down-Comer Module

The feed water and recirculate water on the secondary side are mixed in the down-comer and then enter the barrel for heat transfer. The mass conservation equation and thermal conservation equation on the down-comer is shown in Eq. 4 and Eq. 5.
\[
F_d \rho_d \frac{dL}{dt} = G_{fw} - xG_{se}
\]  \hspace{1cm} (4)

\[
F_d \rho_d L \frac{di_d}{dt} = G_{fw}i_{fw} + (1-x)G_{se}i_{fs} - G_{se}i_d
\]  \hspace{1cm} (5)

Discretize Eq. 4 and Eq. 5 by Euler’s method, the water level and the enthalpy value of working fluid in the down-comer can be expressed as Eq. 6 and Eq. 7.

\[
L^{(n)} = L^{(n-1)} + \frac{G_{fw} - xG_{se}D_T}{F_d \rho_d} DT
\]  \hspace{1cm} (6)

\[
i_d^{(n)} = i_d^{(n-1)} + \frac{G_{fw}i_{fw} + (1-x)G_{se}i_{fs} - G_{se}i_d^{(n-1)}}{F_d \rho_d L} DT
\]  \hspace{1cm} (7)

**Riser Module**

The thermal conservation equation of the riser is shown in Eq. 8.

\[
G_{se}(i_{ro} - i_d) = Q_T
\]  \hspace{1cm} (8)

The quality of the working fluid at the outlet of the riser is calculated according to the definition of quality as shown in Eq. 9.

\[
x = \frac{i_{fs} - i_{ro}}{i_{fs} - i_{gs}}
\]  \hspace{1cm} (9)

According to the assumption of the homogeneous flow model, the average density of the working fluid in the riser is calculated as shown in Eq. 10.

\[
\rho_r = x\rho_{gs} + (1-x)\rho_{fs}
\]  \hspace{1cm} (10)

**Steam Dome Module**

The steam space is the storage space for steam, and its volume varies with the water level. The process of steam entering the steam space from the inlet is regarded as an isothermal expansion process.

The mass conservation equation for establishing the steam space is shown in Eq. 11.

\[
V_{sd} \frac{d\rho_g}{dt} = (V_{to} - LF_d \rho_d) \frac{d\rho_g}{dt} = xG_{se} - G_g
\]  \hspace{1cm} (11)

Discretize Eq. 11 by Euler’s method, and the density of the steam in the steam dome is calculated as shown in Eq. 12.

\[
\rho_g^{(n)} = \rho_g^{(n-1)} + \frac{xG_{se} - G_g}{V_{to} - LF_d \rho_d} DT
\]  \hspace{1cm} (12)

The steam flow changes with the change of steam pressure, which depends on the pressure difference between the steam dome and the secondary side. There is an approximate square relationship between the two, as shown in Eq. 13 [8].

\[
G_g = c \cdot E_v \cdot \sqrt{\Delta P}
\]  \hspace{1cm} (13)

**Heat Transfer Rate Calculation Module**

The arithmetic mean of the maximum temperature difference and the minimum temperature difference in the heat transfer area is taken as the heat transfer temperature difference, as shown in Eq. 14.
\[ \Delta T = \frac{1}{2} (\Delta T_{\text{max}} + \Delta T_{\text{min}}) = T_{p_a} - \frac{1}{2} (T_d + T_s) \]  

(14)

The heat transfer process from the primary side to the working fluid in the secondary side is a composite process. The expression of the heat transfer coefficient and the heat transfer rate is shown in Eq. 15 [9] and Eq. 16.

\[ K_r = \frac{1}{\alpha_p + \frac{\delta}{\lambda_m} + \frac{1}{\alpha_r}} \]  

(15)

\[ Q_r = K_r \cdot S \cdot L_r \cdot \Delta T \]  

(16)

The heat transfer coefficient of primary side and secondary side are calculated according to Dittus-Boelter equation and Rohsenow equation [9].

**Mass Flow Rate Calculation Module**

The working fluid of UTSG forms a natural hydrodynamic cycle. When the working fluid flows stably, the driving pressure formed by the density difference of the working fluid in the down-comer and the riser is balanced with the flow resistance.

The hydrodynamic equilibrium equation is shown in Eq. 17. The mass flow rate in the riser can be expressed as Eq. 18.

\[ \rho_d L - \rho_r L_r = \left( \zeta + f \frac{L_r}{d} \right) \frac{G_{se}^2}{2g \rho_r F_r^2} \]  

(17)

\[ G_{se} = \sqrt{\frac{2g \rho_r F_r^2 (\rho_d L - \rho_r L_r)}{\zeta + f \frac{L_r}{d}}} \]  

(18)

**Connection of Modules**

According to the established mathematical model, the running code of each module is written on the SimuWorks platform, and all the modules are connected according to the input-output relationship between the model variables. The valve elements are added to realize the control of the coolant flow rate and the feed water flow rate. The module connection is shown in Fig. 2. This paper uses the structural dimensions and thermodynamic parameters provided by Kerlin [7].
Simulation and Conclusion
The steam generator will be subject to various disturbances during operation. In this paper, the simulation of dynamic characteristics of the steam generator is carried out by taking the changes of the flow rate of the coolant and feed water.

Coolant Flow Rate Disturbance
When the flow rate of the coolant suddenly decreases, the simulation results are shown in Fig. 3- Fig. 6.

Decreasing the amount of flow rate of the coolant reduces the amount of thermal carried by the coolant. The heat transfer efficiency reduces. As a result, the water level increases. The rising water level makes the quality of steam decreases. Since the temperature difference between the working fluid and the reactor coolant has not changed, when the same thermal is transferred, the reactor coolant needs a larger temperature drop to meet the thermal demand. The outlet temperature of the coolant further decreases, the temperature difference between the working fluid and the reactor coolant increases, and the heat transfer amount starts to rise, which will cause the outlet temperature of the coolant to then decrease. At this time, the feed water flow rate should be reduced to promote the rebalancing of the system and also improve the steam quality.

Feed Water Flow Rate Disturbance
When the feed water flow rate suddenly decreases, the simulation results are shown in Fig. 7- Fig. 10.
The direct effect of a sudden decrease in feed water flow rate will lead to a decrease in the water level in the down-comer. It will lead to a decrease in the flow rate in the riser. The steam content will decrease and the quality will continue to increase, resulting in an increase in steam quality. The decrease in the flow rate in the riser causes the heat transfer efficiency decrease, the heat transfer amount starts to decrease. As a result, the outlet temperature of the coolant increases. At this time, the emission of the steam should be reduced to ensure the efficiency of heat transfer.

Summary
In this paper, the mathematical model of UTSG is established and its dynamic characteristics are simulated. The results show that the disturbance of the reactor coolant and feed water flow has a relatively impact on the operation of the steam generator. The research results have certain reference value for the research on the maneuverability and operational stability of nuclear power systems.

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