Modeling and Simulation of U-tube Steam Generator

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Abstract. The U-tube natural circulation steam generator was mainly researched with modeling and simulation in this article. The research is based on simuworks system simulation software platform. By analyzing the structural characteristics and the operating principle of U-tube steam generator, there are 14 control volumes in the model, including primary side, secondary side, down channel and steam plenum, etc. The model depends completely on conservation laws, and it is applied to make some simulation tests. The results show that the model is capable of simulating properly the dynamic response of U-tube steam generator.

1. Structure and characteristics of steam generator mathematical model
Vertical U-tube steam generator structure is shown in Figure 1 of this study. Mainly consists of water chamber, tube plate, U type tube bundle, steam water separator and cylinder body. The shell of the steam generator is composed of an upper and a lower two cylinders, which are different in diameter, and the middle part is over from a conical shape, and the upper end is a standard ellipsoidal head. The top center of the steam generator is the outlet of the main steam, and the lower end of the steam generator is a spherical head. The first circle water chamber is composed of tube plate, partition plate and spherical head with an inlet and outlet nozzle of the heat carrying agent, etc.

Each label in Figure 1 is shown as follow:
1. Secondary side shell
2. Inlet and outlet baffle
3. Heat carrier agent inlet pipe of first side
4. Heat carrier agent outlet pipe of first side
5. Spherical head
6. Tube sheet
7. U-tubes
8. Diffuser plate
9. Feed water of secondary side
10. Moisture separator
11. Steam outlet

Ⅰ. Downstream endothermic heating section
Ⅱ. Counterflow endothermic heating section
Ⅲ. Endothermic vaporization section

Figure.1 Schematic diagram of steam generator structure.
The high temperature and pressure heat carrier which comes out from the reactor enters into the mouth of the steam generator from the entrance of the hot section, and then enters the U-tubes. Heat is transferred to the secondary side fluid through the metal tube wall, and then carrier flows out of the U type tube, through the outlet nozzle, and then back to the reactor by the main circulating pump. Feed water of secondary side mixing with recirculation fluid from steam separator is given into the down channel of steam generator. The mixture enters heat transfer tubes from the bottom, then flows upward into the heat exchange area, and it is saturated with phase transition in the boiling section and boiling by absorbing the heat of the first side coolant, finally, a steam and water mixture is produced to flow upward through moisture separator. The saturated steam from the separator is brought into the steam plenum, which is extracted from the steam outlet plate and sent to the steam turbine for work.

The mathematical model structure of steam generator is illustrated in Figure 2. The secondary side is divided into six control volumes: preheat section; boiling section; rising section (including the separator); steam space; water supply chamber; down channel. The preheat section, the water supply chamber and the down channel are single-phase working fluid, and the boiling section and the rising section are two-phase working fluid. At the same time, the first side and the metal wall are correspondingly divided into four parts. According to the thermal hydraulic characteristics of the steam generator, the steam generator is divided into 14 control volumes.

In Figure 2, ‘P’ is first side, ‘M’ is metal, ‘S’ is secondary side, ‘Q’ is heat exchange, the arrows indicate the direction of flow of the working fluid, ‘SS’ is steam space, ‘SWS’ is steam water separator, ‘DC’ is down channel.

First side: Calculation of heat transfer in the metal wall. Metal area: Calculation of metal wall temperature. Secondary-side cooling section: Calculation of heat transfer between the working fluid and the metal area, pressure loss of working fluid. The inlet pressure and enthalpy of the boiling zone were calculated. Secondary side of the boiling section: Calculation of heat transfer, export pressure, temperature, enthalpy, etc. Separator: calculate the steam flow of the separator to the steam chamber and the recirculation flow of the down channel. Steam chamber: calculation of steam generator pressure, steam flow. Down channel: Calculation of the steam generator water level, the exit flow, the heavy pressure head and flow resistance, the working fluid outlet enthalpy.

2. Mathematical Model of PWR U-tube steam generator

2.1. Model simplification and assumptions
In order to establish a suitable simulation model of steam generator, the following assumptions are made in this paper:

(1) The thermal hydraulic characteristics of the working fluid in the steam generator only change along the axial direction, and ignore its radial variation, and the same cross section has the same state parameter;

(2) The separation efficiency of the steam water separator is 100%;

(3) The physical parameters of saturated water and saturated steam vary linearly with the working pressure of the steam generator;
(4) The secondary side of the steam generator is a single-phase fluid and does not have a phase transition. Boiling fluid is saturated, and the subcooled boiling is ignored.

(5) The first side and the secondary side working fluid pressure of the steam generator are the same with the change of time.

(6) Ignore the axial heat conduction of the first side, the secondary side and the U type pipe wall. Ignore the heat exchange between steam generator and external. Ignore the heat capacity of other components, except of the U-tube.

(7) The heat transfer between the working fluid and the fluid of secondary side is not considered.

(8) The saturated water separated from the steam water separator and feed water is rapidly and evenly mixed in the water supply chamber.

2.2. Heat transfer model of first side single-phase medium

The primary side working fluid of the steam generator does not change during the flowing process, and belongs to a single phase fluid. P1, P2, P3, P4, the mechanism of these four control volumes is the same, mainly consider the heat transfer characteristics. Taking P1 as an example, the equilibrium equations are expressed in terms of differential equations.

Mass balance equation of first side working fluid is:

$$W_1 - W_2 = V \frac{d \rho_{s2}}{dt}$$

where, $W$, is mass flow. $V$, is the first side volume. $\rho_{s2}$, is first side outlet working fluid density.

Energy balance equation of first side working fluid is:

$$W_1 h_{p1} - W_2 h_{p2} - Q_1 = V \frac{d \left( \rho_{p2} h_{p2} \right)}{dt}$$

where, $Q$, is heat exchange capacity. $h$, is enthalpy.

Differential equation of heat storage equation of metal wall is:

$$T_{m} = T_m' + DT \frac{Q_1 - Q_2}{M C_w}$$

where, $M$, is metal wall quality. $C_w$, is The metal wall heat capacity. $T$, is metal wall temperature.

Heat transfer equation of first side to metal wall is:

$$Q_1 = HK \left( T_{m} + T_{p2} - T_{m} \right)$$

where, $H$, is first side heat transfer area. $K_1$, is first side heat transfer coefficient.

Calculation of pressure node method for first side loop pressure drop is:

$$P_1 - P_2 = \frac{1}{C} W_2^2$$

where, $P$, is pressure. $C$, is admittance. $W$, is mass flow.

2.3. Down channel model

The following equation is the global energy balance for the down channel:

$$V_{s1} \rho_{s2} \frac{dh_{s2}}{dt} = W_{s1} h + W_{s1} h_{s1} - W_{s2} h_{s2}$$

Then, we can get the outlet enthalpy of working fluid:

$$h_{s2} = \frac{V_{s1} \rho_{s2} h_{s2} + W_{s1} h + W_{s1} h_{s1}}{V_{s1} \rho_{s2} + W_{s1}}$$

Where, $V$, is volume. $\rho$, is working fluid density at exit. $W_{s1}$, is feed water flow. $W_{s2}$, is working fluid flow at exit. $h$, is enthalpy. $W_{s1}$, is working fluid flow from separator. $x_j$ represents down channel.

Mass balance equation is:
\[ M = M_0 + \left( W_R + W_{sjj} - W_{sj2} \right) DT \tag{8} \]

Water level of steam generator can be obtained as following:

\[ L = \frac{M}{F_{sj} \rho_{sj}} \tag{9} \]

Where, \( M_0 \) is feed water quality, \( L \) is water level, \( F_{sj} \) is circulation area of down channel. \( \rho_{sj} \) is working medium average density of down channel.

### 2.4 Down channel model

Take S1 as an example, the derivation of energy balance equation and the enthalpy is similar to the equation (6) and (7).

Heat transfer equation of the metal wall to the secondary side is:

\[ Q_{ss1} = H K_2 \left( T_w - \frac{T_{ss1} + T_{ss2}}{2} \right) \tag{10} \]

Where, \( H \) is heat transfer area. \( K_2 \) is heat transfer coefficient. \( T_{ss1} \) is inlet temperature of secondary side cooling section working fluid. \( T_{ss2} \) is outlet temperature.

Determination of phase change position is:

\[ L_1 = C_1 L_{ssg} \left( h_{ss} - h_{sj2} \right) \tag{11} \]

Where, \( L_1 \) is height of saturation section. \( C_1 \) is correction factor of heating load. \( L_{ssg} \) is the height of U-tube. \( h_{ss} \) is enthalpy of saturation water.

Subcooled section pressure drop of secondary side is:

\[ \Delta P_{g1} = \rho_{g1} g L_1 + \xi_{g1} \frac{u_{g1}^2}{2} \rho_{g1} \tag{12} \]

Where, \( \Delta P_{g1} \) is differential pressure. \( \rho_{g1} \) is average working fluid density. \( \xi_{g1} \) is resistance coefficient. \( u_{g1} \) is working fluid mean velocity. \( gl \) represents subcooled section.

### 2.5 Boiling section model of secondary side

Take S2 as an example, its absorption heat equation is same as subcooled section. The derivation of energy balance equation, the enthalpy and heat transfer equation is similar to the equation (6), (7) and (10).

Pressure loss is:

\[ \Delta P_{bh} = \xi_{bh} \frac{u^2}{2} + \rho_{m} g \left( L_{ssg} - L_1 \right) \tag{13} \]

Where, \( \rho_{m} \) is average density. \( u \) is average velocity.

The void fraction (\( \alpha \)) of Vapor liquid two phase flow is calculated using the method for calculating void fraction of steam water mixture. This method involves the calculation of the boiler water cycle.

\[ \alpha = \frac{1}{1 + \frac{1}{S} \left( \frac{1 - \beta}{\beta} \right)} \tag{14} \]

Where, \( S \) is slip ratio, it is the ratio of the real velocity of the gas phase to the liquid phase. \( \beta \) is volumetric quality.

### 2.6 Boiling section model of secondary side

The working fluid respectively out of S2 and S3, their team quality (x) is constant. At the same time, the mixture enters the separation section, and it is separated into pure saturated vapor and saturated
water. Saturated water and feed water flow into the down channel, and saturated steam enters the steam chamber.

Mass balance equation is:

\[ W_s = \eta \left( x_{s1} W_{s1} + x_{s2} W_{s2} \right) \]  
(15)

\[ W_R = (1 - x_{s1}) W_{s1} + (1 - x_{s2}) W_{s2} + (1 - \eta) \left( x_{s1} W_{s1} + x_{s2} W_{s2} \right) \]  
(16)

Energy conservation equation is:

\[ W_s h_s = \eta \left( x_{s1} W_{s1} h_{s1,bq} + x_{s2} W_{s2} h_{s2,bq} \right) \]  
(17)

\[ W_R h_R = (1 - x_{s1}) W_{s1} h_{s1,bs} + (1 - x_{s2}) W_{s2} h_{s2,bs} \]  
+ \( (1 - \eta) \left( x_{s1} W_{s1} h_{s1,bs} + x_{s2} W_{s2} h_{s2,bs} \right) \]  
(18)

Where, \( W_S \), is steam flow of separator. \( W_R \), is recirculation flow of separator. \( x \), is team quality. \( W \), is outlet flow. \( h \), is enthalpy. \( \eta \), is separator efficiency. \( bq \) represents saturated steam. \( bs \) represents saturated water.

2.7. Steam chamber model

In the whole simulation process can be considered that there is only one pressure on secondary side. The pressure is provided by the steam chamber. The derivation of mass balance equation is similar to the equation (1).

Because the steam chamber is connected to the water supply passage. The space occupied by the saturated steam \( V_{sat} \) is the sum of the steam chamber and the space above the water level of down channel.

\[ V_{sat} = V_{SD} + (L_D - L) F_{xj} \]  
(19)

Where, \( V_{SD} \), is volume of steam chamber. \( L_D \), is height of down channel. \( F_{xj} \), is circulation area of down channel.

The relationship between saturated vapor density and pressure is

\[ \frac{d \rho_b}{dt} = \frac{\partial \rho_b}{\partial P} \frac{\partial P}{\partial t} \]  
(20)

Steam flow enters into the turbine. The flow is calculated by pressure node method. Steam can be expressed as follow equation:

\[ W = CE_v \sqrt{|P - P_0|} \]  
(21)

Where, \( C \), is coefficient. \( E_v \), is valve opening of steam regulating valve. \( P_b \), is Inlet pressure of steam turbine.

3. Simulation and Discussion

Based on the simuworks simulation system platform, according to the established simulation model, using C++ language to write the corresponding module of the general simulation algorithm. Based on the operating characteristics of the steam generator, the real-time simulation model of the steam generator of PWR nuclear power station was built by the method of module lap. In this paper, the steam generator of Dayawan nuclear power station is studied, and the model is verified.

Because of the operation characteristics of nuclear power steam generator, it is difficult to control at low load, and the phenomenon of "false water level" is easy to occur, so the test procedure is carried out on the basis of the 20% load. Under current conditions, when the steam regulating valve opening and the feedwater flow are disturbed, the simulation experiment is done to the steam generator, and the dynamic response curve of the steam generator is obtained.

In this paper, the following disturbance conditions are given: increase or decrease of feed water flow rate 12% ; increase or decrease of steam regulating valve opening 20%. Under the above conditions, the system simulation is completed. And the corresponding dynamic curves are obtained. We can draw a conclusion that the simulation results are in agreement with the theoretical analysis. The model of U-tube steam generator is reasonable.
In Fig.3-Fig.7:
SG_MOD0_L1 is level of steam generator (m).
SG_MOD0_P is outlet steam pressure of Steam chamber (MPa).
SG_MOD19_WWE is feed water flow (Kg/s).
SG_MOD19_W is outlet steam flow of steam chamber (Kg/s).

Fig.3 is the operating data of 20% operating conditions. Fig.4 is the response process of feed water flow rate from 85kg/s to 95kg/s. Fig.5 is the response process of feed water flow rate from 85kg/s to 75kg/s. Fig.6 is The response process of steam valves opening from 0.107 to 0.127. Fig.7 is The response process of steam valves opening from 0.107 to 0.085.

4. Conclusion
In this paper, the steam generator of Dayawan nuclear power station is studied. According to the first side or secondary side flow and heat transfer characteristics, the control volume is divided. The whole dynamic mathematical model of steam generator is established based on the theory of drift flow. This model comprehensively reflects the structural characteristics and working process of the U-tube steam generator. The simulation results show that the model is reasonable, and it can accurately reflect the dynamic characteristics of the steam generator in real time. The model have good adaptability in a wide range of industrial control. And this research is significance to practical engineering.

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