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A water level dynamics simulation model of AP1000's steam generator based on Åström-Bell model

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Abstract: The steam generator (SG) is a crucial component of the AP1000 pressurized water reactor (PWR) nuclear power plant systems. The operational stability of SG must be considered for entire nuclear power system's safety and availability. The presence of steam bubbles under the water level in the steam generator causes the shrink and swell phenomenon. It makes the water level control problem of SG complex. Therefore, a relatively simple lumped parameter model that agreed well with experimental data of SG was presented. First, a moderately complex fourth order nonlinear mathematical model of AP1000 U-type steam generator was established based on Åström-Bell model. Second, the simulation platform was built and then the simulation was conducted in MATLAB/Simulink environment. Finally, the model parameters were obtained from estimating from the standard AP1000 test data and the simulated results were compared with the standard test data. The results showed that the model could capture the dynamic fluctuation of water level in AP1000 SG over a wide operating range.

1. Introduction

The steam generator (SG) is the hinge of nuclear and conventional island in AP1000 pressurized water reactor(PWR) nuclear power plant systems[1], which transfers heat energy from the primary circuit to the secondary circuit. The water level control problem of SG has been a main cause of unexpected shutdowns of nuclear power plants, nearly 30% of emergency shutdowns of French PWR plants are caused by poor steam water level control [2]. The operational stability of SG must be considered for entire nuclear power system's safety and availability. The presence of steam bubbles under the water level in the steam generator causes the shrink and swell phenomenon [3], which turned the water level into a non-linear, high complexity, mutative and multi-variable control puzzle. Åström and Bell employed an empirical model derived from measured data to reduce the number of unknown parameters. Such an empirical model well captured the dynamics of the boiler water level [3]. Kim and Choi presented a model for water level dynamics in a natural circulation drum-type boiler. The model helps to investigate the water level dynamics for load changes from design values [4]. There are numerous researches on the water level of SG in AP1000. Wang et al. presented a thermal-hydraulic safety analysis code for AP1000. A distributed parameter model with two-phase drift flux model was used in the U-tube steam generator simulation. The code was equipped with three-region non-equilibrium model and multi-region non-equilibrium model respectively [5]. Ansarifar et al. developed an adaptive estimator-based dynamic sliding mode control method. The proposed method exhibits the desired dynamic properties over a wide range of he output [6].Wu et al. applied particle swarm optimization algorithm for the parameter optimization of the AP1000 U-tube steam generator (UTSG) feedwater control system. The simulation results demonstrate that optimized parameters of AP1000 UTSG feedwater control system can significantly improve the water level control performance with smaller overshoot and faster response [7]. Wang et al. developed a real-time nuclear steam supply system (NSSS) simulation platform and based on this presented the dynamic simulation and study of load rejection transients for the AP1000 NSSS. The simulation results showed that the NSSS control systems can successfully respond to load rejection transients without reactor trip or operation of the pressurizer or steam generator safety valves [8]. Jiang et al. modeled and simulated the vertical U-tube natural-circuit steam generator in RELAP5. The level change curves of steam generator were obtained under different parameter changes. The results show that the simulation results of RELAP5 are consistent with the actual situation [9]. Cong et.al ued Fluent's porous media model coupled to a two-phase flow mixture model to analyze the thermohydraulics of the steam generator secondary and the effects of the power level on thermal hydraulic characteristics in the steam generator [10].Therefore, it is necessary to derive a relatively simple lumped parameter model that agrees well with experimental data for the improvement of water level control analyzes of SG.

2. Material and Methods

Natural circulation steam generators are commonly used in present PWR nuclear power plant. The natural steam generator has a complicated geometry and there are many downcomer and U-tubes. It can be divided into a separator, feedwater inlet, downcomers, U-tubes, steam-water mixter, primary coolant nozzle and so on, as shown in Fig 1(a). In a natural circulation SG, feed water is continuously downwardly flown by gravity in the downcomer. In the ascending channel, the feed water absorbs heat released from the primary coolant flowing in the U-tubes. And it is heated to a saturated steam/water mixture. These mixtures are separated in the steam drum by steam, which enters the steam turbine to generate electricity, and the saturated water is mixed with the feed water for recycling. Gravity forces the fluid to rise causing a circulation in the riser-drum-downcomer loop. The process can be simplified as shown in *Fig 1*.

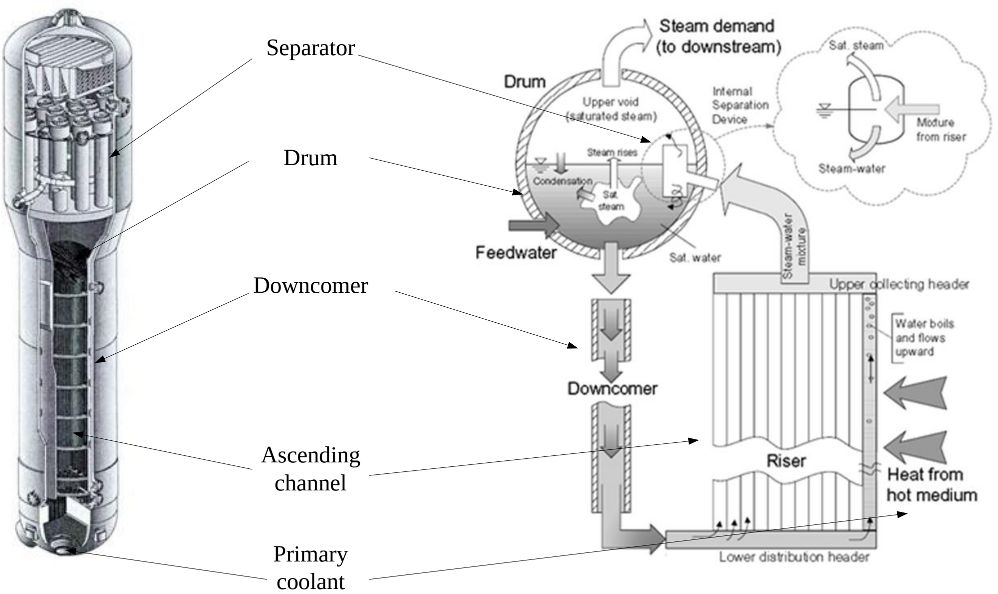

Fig. 1 The schematic and symplification diagram of a natural circulation steam generator

The working process of AP1000 SG is in accordance with conventional boil drum, which had been studied in depth by Åström and Bell [3]. In spite of the complexity of physical phenomena and geometry in SG, it turns out that global mass and energy balances can well captured its gross behavior. In order the construct a moderately complex nonlinear model, some simplifications as followed were made:

(1) The given state of the entire system is saturated;

(2) The resistance of the working fluid flow and the pressure head caused by the position difference are ignored;

(3) The changes of metal temperature and saturate water temperature are the same;

(4) The fluid characteristics on the cross section of the ascending channel are uniform.

The model of the AP1000 SG based on Åström-Bell model is constructed from the conversion of mass and energy, the distribution of the steam in the ascending channel and drum. The main structure of fourth-order model is shown as followed, for more details can refer to [3].

$$e_{11}\frac{dV_{wt}}{dt}+e_{12}\frac{dp}{dt}=q_f-q_s \tag{1}$$

$$e_{21}\frac{dV_{wt}}{dt}+e_{22}\frac{dp}{dt}=Q+q_f h_f-q_s h_s \tag{2}$$

$$e_{32}\frac{dp}{dt}+e_{33}\frac{d\alpha_r}{dt}=Q-\alpha_r h_c q_{dc} \tag{3}$$

$$e_{42}\frac{dp}{dt}+e_{43}\frac{d\alpha_r}{dt}+e_{44}\frac{dV_{sd}}{dt}=\frac{\rho_s}{T_d}(V_{sd}^0-V_{sd})+\frac{h_f-h_w}{h_c}q_f \tag{4}$$

$$e_{11}=\rho_w-\rho_s \tag{5}$$

$$e_{12}=V_{wt}\frac{\partial\rho_w}{\partial p}+V_{st}\frac{\partial\rho_s}{\partial p} \tag{6}$$

$$e_{21}=\rho_w h_w-\rho_s h_s \tag{7}$$

$$e_{22}=V_{wt}(h_w\frac{\partial\rho_w}{\partial p}+\rho_w\frac{\partial h_w}{\partial p})+V_{st}(h_s\frac{\partial\rho_s}{\partial p}+\rho_s\frac{\partial h_s}{\partial p})-V_t+m_t C_p\frac{\partial t_s}{\partial p} \tag{8}$$

$$\begin{aligned}e_{32}=&(\rho_w\frac{\partial h_w}{\partial p}-\alpha_r h_c\frac{\partial\rho_w}{\partial p})(1-\overline{\alpha}_v)V_r+((1-\alpha_r)h_c\frac{\partial\rho_s}{\partial p}+\rho_s\frac{\partial h_s}{\partial p})\overline{\alpha}_v V_r\\&+(\rho_s+(\rho_w-\rho_s)\alpha_r)h_c V_r\frac{\partial\overline{\alpha}_v}{\partial p}-V_r+m_r C_p\frac{\partial t_s}{\partial p}\end{aligned} \tag{9}$$

$$\begin{aligned}e_{42}=&V_{sd}\frac{\partial\rho_s}{\partial p}+\frac{1}{h_c}(\rho_s V_{sd}\frac{\partial h_s}{\partial p}+\rho_w V_{wd}\frac{\partial h_w}{\partial p}-V_{sd}-V_{wd}+m_d C_p\frac{\partial t_s}{\partial p})\\&+\alpha_r(1+\beta)V_r(\overline{\alpha}_v\frac{\partial\rho_s}{\partial p}+(1-\overline{\alpha}_v)\frac{\partial\rho_w}{\partial p}+(\rho_s-\rho_w)\frac{\partial\overline{\alpha}_v}{\partial p})\end{aligned} \tag{10}$$

$$e_{43}=\alpha_r(1+\beta)(\rho_s-\rho_w)V_r\frac{\partial\overline{\alpha}_v}{\partial\alpha_r} \tag{11}$$

$$e_{44}=\rho_s \tag{12}$$

The linearized behavior can be described by the wet surface at the operating level. The water level deviation measured from its rated operating level is:

$$l=\frac{V_{wd}+V_{sd}}{A_d} \tag{13}$$

Form the model it can be seen that the inputs of this model are heat flow rate to the risers (Q), feedwater mass flow rate (q_f),steam mass flow rate (q_s) and feed water temperature. The outputs variables are the pressure (p) and water level (l) in SG. Four state variables (V_{wt}, p, α_r, V_{sd}) are chosen, the balance between energy dynamic changes of steam and water can be completely described, and the reverse characteristics of the water level in SG can be well described. The model is based on physical principles and has a small number of parameters, most of which are determined from structural parameters of design area, volume and mass. The parameters needed in the model are listed in *Table.1*. The model is built and solved in Simulink. The property of the steam and water are based on IAPWS-IF97.

Table.1 The model parameters

Parameter		Parameter	
V_t	total volume	β	parameter in empirical equation
V_d	drum volume	A_d	drum area at normal operating level
V_r	riser volume	A_{dc}	the area of the downcomer
V_{dc}	downcomer volume	k	friction coefficient in downcomer-riser loop
m_t	total metal mass	T_d	residence time of steam in drum
m_d	total drum mass	V_{sd}^0	the volume of steam in the ascending channel with no steam condensation
m_r	total riser mass		

3. Results

In order to validate the model built in Simulink. The parameters in reference [3] are chosen to test the model.

$V_t = 40m^3$, $V_r = 37m^3$, $V_{dc} = 11m^3$, $m_t = 300000kg$, $m_r = 160000kg$, $\beta = 0.3$, $A_d = 20m^2$, $A_{dc} = 0.4m^2$, $k = 25$, $T_d = 12s$, were chosen. The results were shown in *Fig. 2*. The *Fig.2*showed the responses of drum water level, drum pressure, steam quality at the riser outlet(a_r) and vapor volum under the drum (V_{sd}) to a step in fuel flow rate of 10MW at 100s. And the results of the model built in this paper has good accordance with that in reference [3] under the same parameters. So the model can be used for analyzes of the AP1000 SG.

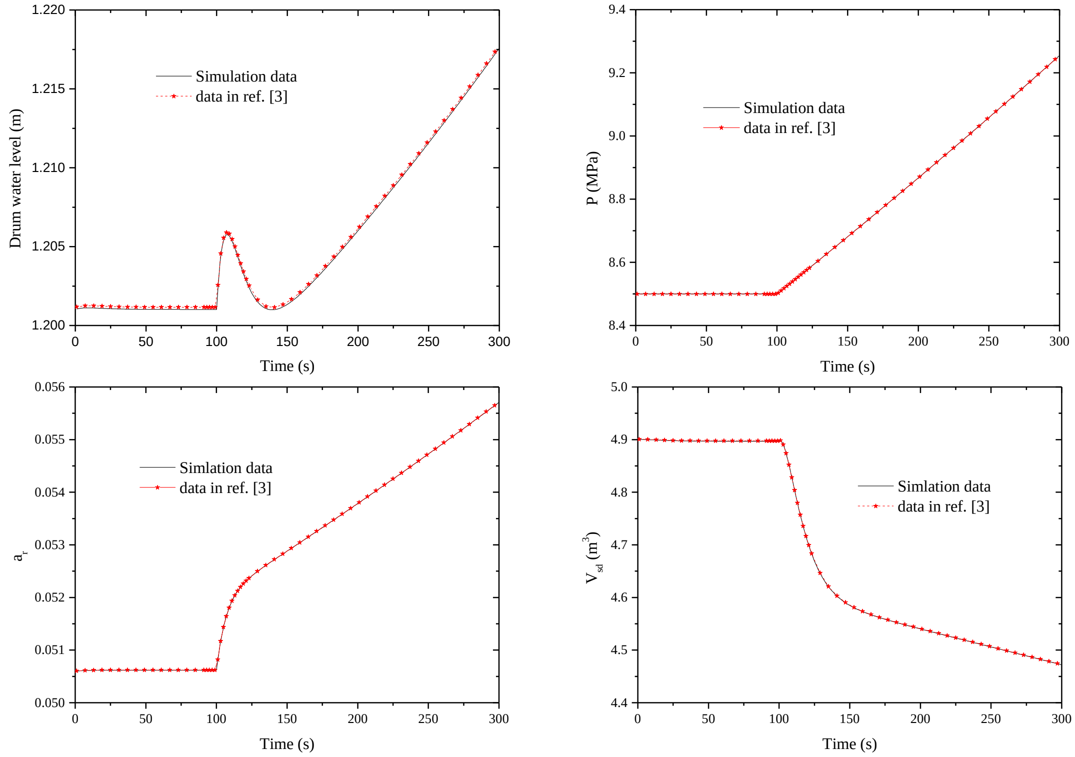

Fig.2. Simulation data compared with reference[3]

Apply the model to AP1000 SG. Nine of the model parameters are determined from structural parameters of design area, volume and mass. The values can be determined by the design drawings. The remaining four immeasurable parameters (k, β, T_d, V_{sd}^0) can only be estimated with test data.

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$V_t = 250m^3$, $V_r = 119.5m^3$, $V_{dc} = 25m^3$, $m_t = 6 \times 10^5 kg$, $m_d = 1 \times 10^5 kg$, $m_r = 3.2 \times 10^5 kg$, $\beta = 0.3$, $A_d = 118.1m^2$, $A_{dc} = 0.4m^2$, $k = 9.275$, $T_d = 2.672$, $V_{sd}^0 = 16.81m^3$, were chosen.

4. Discussion

Bring the new parameters into the model and compare the model simulation results with the AP1000 standard test operating data. The results are shown in *Fig. 3.-Fig. 5*. In the operating state, when the steam generator load suddenly decreased at time 50s, the steam flow rate decreased from 254 kg/s to 167kg/s as shown in *Fig.3* and from 944 kg/s to 838 kg/s as shown in *Fig. 5*.The average bubble coefficient of the steam/water two-phase mixture would suddenly decrease in accordance with the increase of steam pressure, causing a sharp decrease of the water level. As the feed water flow rate stated unchanged at this moment, the water level would then rise back, as shown in *Fig.3* and *Fig.5*.

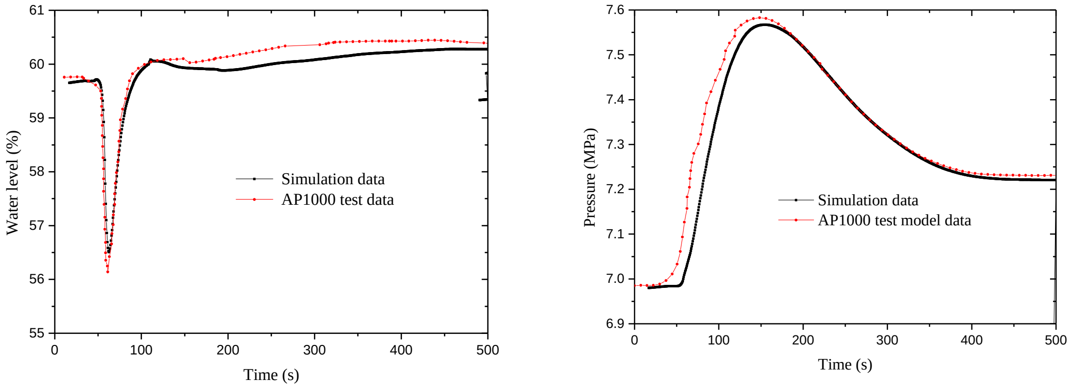

Fig.3 SG load changed from 30% to 20%

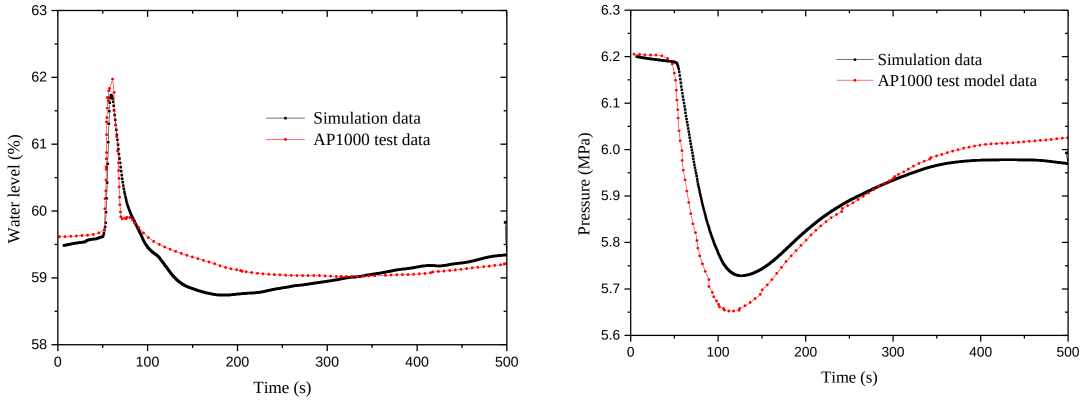

Fig.4 SG load changed from 75% to 85%

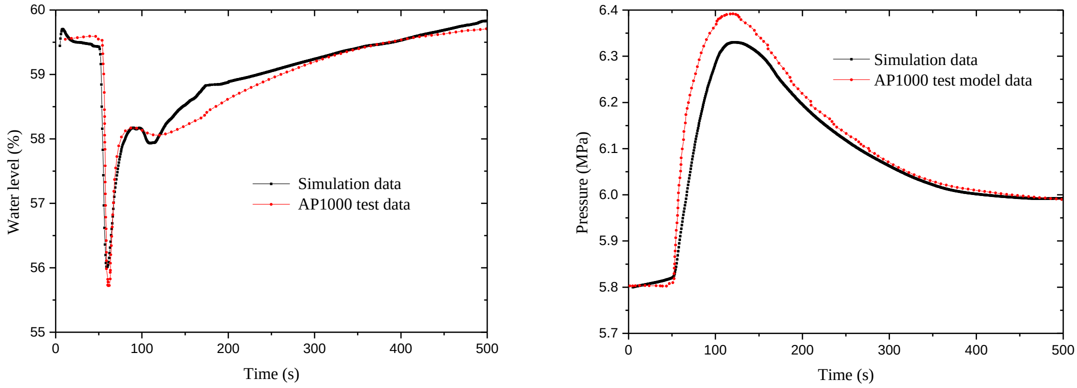

Fig.5 SG load changed from 100% to 90%

When the steam generator load suddenly increased at time 50s, the steam flow rate increased from 682 kg/s to 782kg/s as shown in *Fig.4*, the average bubble coefficient of the steam/water two-phase mixture would suddenly increase due to the decrease of the steam pressure, causing a sharp rise in the water level. In fact, since the feed water flow rate has not changed at this time, the increase of the steam flow rate destroys the material balance of the steam generator, and the water level of the steam generator would then quickly lowered, as shown in *Fig. 4*.

It can be seen that the modified model has a good fitting effect with the AP1000 standard test data under low, medium and high load working conditions. The model can capture the water level fluctuation of the AP1000 SG under load change, which can be used for water level control studies based on models.

5. Conclusions

A moderately complex fourth order nonlinear model of AP1000 steam generator was established based on Åström-Bell model. The model was validated with AP1000 standard test data. The results showed that the model could reflect the dynamic fluctuation of water level in AP1000 SG under low, medium and high load changes. A simplified AP1000 SG model was provided to the dynamic water level control analyze of the AP1000's nuclear power plant.

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