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Dynamic heat transfer performance study of steam generator based on distributed parameter method

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ABSTRACT

Using the steam generator of Daya Bay nuclear power plant as prototype, a one-dimensional dynamic mathematical model of nuclear-powered steam generator is built addressing the primary side fluid, the secondary side fluid and the inner and outer walls of the u-tubes based on distributed parameter method and reasonable assumptions. A dynamic simulation program is developed based on MATLAB using Runge–Kutta method and dynamic heat transfer performance simulation of steam generator is conducted under varying power. The calculation results show that the outlet temperature of primary side, the vapor saturation temperature and the mass fraction of secondary side agree with actual operating data of Daya Bay Nuclear Power Plant. Outer wall temperature at interface between parallel flow preheating-section and boiling-section is the highest. It provides a theoretical basis for the analysis of steam generator actual operating condition to build a one-dimensional mathematical model of steam generator based on the distributed parameter method and apply in simulation successfully.

1. Introduction

Steam generator is the heat exchanger that produces steam that is needed for steam turbine in nuclear power plant. It is one of the main pieces of equipment for double loop nuclear power plant and a barrier to separate the primary and the secondary coolant sides. Meanwhile, it is also the high accident probability equipment in nuclear power plants. Since 1970s, the world PWR operation experience survey indicates that the number of steam generator heat transfer tube rupture accounts for 40% of total devices surveyed every year (Liu et al., 2004). It affects normal operation, reduces power operation or forces to shutdown. The steam generator, because does not have the same lifetime as the nuclear power plant, is even replaced (Dong and Gao, 2004; Ding, 2005). Therefore it is particularly important to conduct modeling and simulating of steam generator and analyze its thermal performance in order to avoid accidents (Guo, 2007).

Currently, most of dynamic simulations of steam generator use the lumped parameter method of distributed system and research inlet and outlet thermal parameters of fluid in the primary side and the secondary side only. In addition, the system is divided into several control volumes and the inlet and outlet thermal parameters of each control volume are studied using quasi lumped parameter method. Xiong and Fu (1989) divided the secondary side into six sections and divided the primary side and u-tube wall into four sections correspondingly according to difference of flow and heat transfer characteristics in each part of u-tube steam generator. Model built by Yang et al. contained 15 control volumes, including 12 control volumes that changed with power in operational model and could disappear or reappear with mobile boundary. Song et al. (2007) did control volume division of natural circulation steam generator based on lumped parametric dynamics model of distributed parameter thermal object. Steam generator was divided into 14 control volumes, there were 6 control volumes in secondary side and 4 control volumes in primary side and heat transfer u-tube in hot side and cold side respectively corresponding to control volumes of the secondary side. Zhang et al. (2010) regarded steam generator as a cylinder and built a simplified two-phase lumped parameter dynamic mathematical model of u-tube steam generator according to dynamics principles, basic mass and energy conservation equation of thermal system. Then modular modeling theory was used to package the mathematical model. Lumped parameter dynamic model of steam generator was put forward successively according to mass, momentum and energy conservation equation by Khaleeq et al. (1998), Dong et al. (2008) and Guimaraes et al. (2008). It was a group of ordinary differential equations whose variables were functions of time only.

Most of previous research focused on the inlet and outlet parameters changing rule of the primary and secondary side fluid in published literatures. Research of internally arbitrary position flow in each passes and the u-tube wall temperature distribution

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were not reported (Liu and Xu, 1994; Zhang and Zhang, 2006; Cui et al., 1992). However, overheating that leads to tube explosion is just one of main cause of steam generator tube rupture transient (He et al., 2006). Therefore, it is of great significance to prevent accidents of tube explosion because of overheating to build one-dimensional dynamic mathematical model of the primary side, the secondary side and the u-tube wall of nuclear-powered steam generator using distributed parameter method, to explore changing rule with time and space of thermal parameter in internally arbitrary position of steam generator by simulation, and it is helpful to realize working process of steam generator in detail in order to judge accident-prone point.

Distributed parameter system has at least one variable related to the spatial location. Its mathematical model is ordinary differential equation of space independent variables for the steady state model. The mathematical model is partial differential equation of space and time independent variables for the dynamic model. A one-dimensional dynamic mathematical model for the primary side fluid, the secondary side fluid and the u-tube wall of steam generator is built in this paper, using distributed parameter method. The power of steam generator decreases from full power to 70% and simulation of the model is conducted. Changing rules of parameters that vary with power and space are discussed. Distributed rules and influencing factors of the inner and outer wall temperature are summarized. Positions with worst working condition are obtained and causes are analyzed.

2. Working situation and physical model of steam generator

Vertical steam generator diagram is shown in Fig. 1 and its effective length is L. The primary coolant (water) which comes from reactor of the primary side is high temperature fluid inside u-tube and flows up first and then flows down. The feed water of the secondary side that flows up is low temperature fluid in u-tube shell side and it goes through u-tube shell side longitudinally. Fluid of the secondary side is heated from subcooling to boiling and flows out of heat exchange u-tube at last when its mass fraction reaches a certain value. Heat exchange between the primary and secondary side is parallel flow first and then counter flow. Phase of the secondary side fluid changes when it flows up, so its heat transfer laws are different from single-phase convective heat transfer. Therefore heat transfer process of steam generator is divided into four sections along flow direction of the primary coolant, i.e. parallel flow preheating-section, parallel flow boiling-section, counter flow boiling-section, counter flow preheating-section.

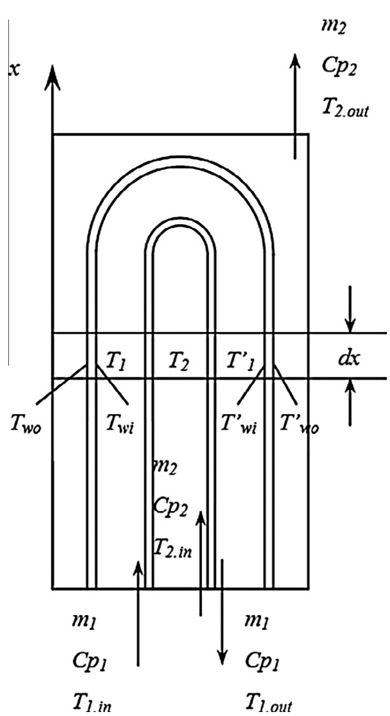

Fig. 1. Steam generator diagram.

For the infinitesimal dx in Fig. 1, temperature of secondary side fluid is T_2 which corresponds with T_1, temperature of parallel flow primary side fluid; T_{wi}, temperature of parallel flow inner wall; T_{wo}, temperature of parallel flow outer wall; T'_1, temperature of counter flow primary side fluid; T'_{wi}, temperature of counter flow inner wall and T'_{wo}, temperature of counter flow outer wall.

3. Dynamic mathematical model of steam generator

Work condition and actual work process of steam generator is considered to put forward the following assumptions in order to build heat-transfer mathematical model of steam generator.

(1) Flow is close to plug-flow and the fluid in both primary and secondary side does not mix axially. It belongs to distributed parameter system.
(2) Parameters of the primary side, the secondary side and the u-tube wall change only along axial direction, i.e. they are simplified to one-dimensional model. Parameters of the same fluid in same direction and cross section are equal.
(3) The secondary side fluid is homogeneous flow and its speed and temperature of steam–water two-phase are equal.
(4) Axial direction heat conduction of u-tube is ignored and its temperature along axial direction depends on temperature change of the primary and secondary side fluids.
(5) u-Tube bundle is simplified to an equivalent u-tube and its flow area is sum of all tubes.
(6) u-Tube band section is simplified to straight tube and parameters of parallel flow endpoint are equal for the primary side to that of counter flow starting point correspondingly.

Taken the primary side fluid, the secondary side fluid, the inner and outer wall of u-tube as research object, steam generator fixed tube plate as starting point and height direction of heat exchange u-tube as x axis, one-dimensional heat-transfer mathematical model of steam generator is built on the basis of thermodynamics first law to infinitesimal dx under simplified assumptions mentioned above (Luo, 2005; Zhang et al., 2012).

Firstly, give heat dynamic balance equation of parallel flow of primary side as follow:

$$M_1 c_{p1} dx \frac{\partial T_1(x,t)}{\partial t} = m_1 c_{p1} T_1(x,t) - m_1 c_{p1}\left[T_1(x,t) + \frac{\partial T_1(x,t)}{\partial x}dx\right] + nK_1 \pi d_i dx [T_{wi}(x,t) - T_1(x,t)] \quad (1)$$

simplify Eq. (1):

$$\frac{\partial T_1(x,t)}{\partial t} = -\frac{m_1}{M_1}\frac{\partial T_1(x,t)}{\partial x} + \frac{nK_1 \pi d_i}{M_1 c_{p1}}[T_{wi}(x,t) - T_1(x,t)] \quad (2)$$

where x is position coordinate along axial direction of the heat transfer tube; t (s) is time; n is number of heat transfer tubes; T_1 (°C) is temperature of the primary side; T_{wi} (°C) is temperature of the u-tube inner wall; K_1 (W/(m^2 K)) is average heat transfer