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# Numerically investigating the influence of tube support plates on thermal-hydraulic characteristics in a steam generator

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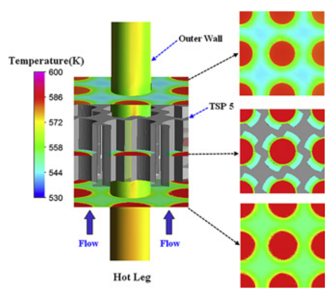
## HIGHLIGHTS

- ► A "unit pipe" model is utilized successfully in SG numerical simulation.
- ► Thermal phase change model for secondary vapor–liquid two-phase flow is used.
- ► Local vortex and recirculation distributions are reasonably obtained at the TSPs.
- ► Circumferential outer wall temperature shows periodic behaviors at the TSPs.
- ► Locations of most severe FIV damage are obtained.

## GRAPHICAL ABSTRACT

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## ABSTRACT

A three-dimensional "unit pipe" model coupled with broached tube support plates (TSPs) is developed to investigate the influence of TSPs on the thermal-hydraulic characteristics of the primary and secondary side of steam generator (SG). The model reasonably captures the unbalanced boiling phenomena in the SG secondary side, particularly in the regions surrounding the TSPs. At these points, there is an abrupt increase in secondary fluid velocity, generating recirculation distribution and local vortex. Nonuniform outer wall temperatures periodically fluctuate around the circumference of the tubes at the TSPs, with the corresponding temperature difference between the support location and flow hole gradually decaying in the primary flow direction. These thermal-hydraulic distributions are then used to determine the cross-flow energy, which is strongly related to flow-induced vibration (FIV) damage. According to the FIV distributions, FIV damage is predicted to be most severe at angles of $\theta = 65^{\circ}$ on the cold-leg side and $\theta = 120^{\circ}$ on the hot-leg side of the U-bend tube bundles. These simulated FIV damage results are in agreement with the measured plant data from a prototypical SG. Therefore, this developed "unit pipe" model can provide technical support to help alleviate FIV damage and minimize the probability of tube failure.



## 1. Introduction

Tube integrity represents a major concern for a steam generator (SG), as failure and degradation of the tubes can lead to undesirable leakage of contaminated primary coolant to the secondary system, seriously affecting the safety performance of the pressurized water reactor nuclear power plant. Foreign object wear is the cause of many of these failures, but flow-induced vibration (FIV) damage within SG is also a major concern since it can compromise structural integrity [1]. Broached tube support plates (TSPs) are typically added along the length of the tubes to restrain and support the vertical U-tubes in an SG. However, as operating time increases, concentration phenomena of aggressive solutes and impurities will continue in the restricted regions around the TSPs, which in turn may result in TSP flow hole (i.e. the flow path of secondary water) blockage [2]. The

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result is local stress corrosion cracking in the SG tubes, a failure mode enhanced due to the nonuniform circumferential wall temperatures and alternating wet and dry conditions associated with the thermal and hydraulic behavior of SG. Therefore, it is crucial to investigate the influence of TSPs on the thermal-hydraulic characteristics that include local distributions of boiling flow, coupled heat transfer, and FIV damage in the U-tube bundles of the primary and secondary side of SG by using a computational fluid dynamics (CFD) methodology.

Due to the specific and complicated geometry structure of tube bundle support plate systems installed in an SG, researchers typically choose experimental methods to investigate the impact of TSPs on thermal-hydraulic characteristics in the SG secondary region. Nevertheless, experiments generally model localized flow and heat transfer processes according to the similarity principle and dimensional analysis theory. However, the experimental conditions are typically quite different from practical SG operational processes, making it difficult to clearly illustrate actual thermal-hydraulic distributions within SG, especially in the regions of the TSPs. What's more, any empirical correlations drawn from such experiments have serious limitations as to their application, and some factors which impact SG performance need further investigation [3–7].

However, because of the dramatic progress in computer processing power, a substantial body of research is working toward developing CFD methodology for investigating the influence of TSPs on SG thermal-hydraulic characteristics. While much of this research work is dedicated to better understanding two-phase boiling flow heat transfer behavior in the secondary region through numerical simulation, it does so without considering TSPs. Ferng et al. [8,9] predicted the distribution of FIV damage in the U-bend region by considering the secondary vapor–liquid two-phase flow domain as a porous media domain, treating the primary-to-secondary heat as an internal heat source in the secondary side. Jo et al. [10,11] conducted a thermal-hydraulic analysis that provided a detailed three-dimensional two-phase flow field for the SG secondary region, and assessed the potential for fluidelastic instability of the SG U-tubes. Kuehlert et al. [12] performed a CFD prediction of FIV for an individual tube with a single-phase fluid in the SG secondary region.

Some works have studied the impact of TSP geometry on thermal-hydraulic behavior in a single-phase flow domain. Dai et al. [13] numerically analyzed the single-phase flow and heat transfer in the shell side of a cinquefoil orifice-baffle support heat exchanger, using a simplified model to obtain the corresponding fitting formulas. Liu et al. [14] studied the effective elastic constants of support plates, focusing on various perforation shapes, such as hetero-diameter holes, trefoil, and quatrefoil holes, popularly used in SG. Currently, researchers are increasingly attempting to develop empirical formulas and theoretical models to better understand localized FIV information for TSP systems within an SG. Hassan et al. [15–17] performed a numerical study of the response of a single flexible loosely supported tube within a rigid array subjected to cross-flow in an SG. Based on a similar method, Park and Lee [18] numerically investigated the effect of gap clearances between the tubes and their support plates. In addition, a plurality of research work [19–23] has concentrated on simulating the complex flow and heat transfer processes of phase changes using one-dimensional and coarse multi-dimensional computational models or semi-empirical formula. However, few CFD simulations have been undertaken which can reveal the influence of broached TSPs on the thermal-hydraulic characteristics of the primary and secondary domains and U-tube bundles within SG.

This present work is an extension of the numerical study of Yang et al. [24], who performed a simulation of vapor–liquid two-phase flow and boiling heat transfer characteristics in the SG secondary side by using variable heat flux as boundary conditions. In this paper, a primary and secondary side coupled flow and heat transfer model is used to calculate the thermal-hydraulic characteristics of an SG. Meanwhile nine pairs of quatrefoil TSPs are added into the computational domain to numerically investigate the influence of TSPs on the thermal-hydraulic behavior of the primary and secondary side of SG using the "unit pipe" model. This physical model is the reasonably well modeled flow region of a section of the vertical natural circulation SG at the Daya Bay Nuclear Power Plant (DBNPP), a pressurized water reactor located in Southern China. The thermal-hydraulic characteristics available in the model include the secondary flow structure, boiling heat transfer behavior, local circumferential wall temperature characteristics near the TSPs, and the distribution of localized FIV damage on the U-bend tube bundles of the SG. In addition, the experimental results of Ding [25] and data measured by the plant [26] for flow and temperature distributions are also utilized to assess the present CFD model.

## 2. Mathematical formulation

The two-fluid model proposed herein includes continuity, momentum and energy equations, turbulence modeling, and a thermal phase change model for a two-phase mixture. Since common equations govern U-tube heat conduction and single-phase convection heat transfer in the primary side, this paper does not provide any detail on these basic equations. The present section mainly illustrates the mathematical equations applied to the secondary region.

### 2.1. Conservation equations

The present study focuses on saturated boiling and bubbly flow in the two-phase region of the SG secondary side, where steam quality is relatively low. The SG at DBNPP has a maximum steam quality of just 0.25. The liquid is treated as a continuous phase (phase $\alpha$) while the vapor is treated as a dispersed phase (phase $\beta$). The ensemble-averaged conservation equations in the two-fluid model for each phase are expressed by

Continuity equation

$$\frac{\partial}{\partial \tau}(r_\alpha \rho_\alpha) + \nabla \cdot \left( r_\alpha \rho_\alpha \vec{U}_\alpha \right) = -\dot{m}_{\beta\alpha} \tag{1}$$

$$\frac{\partial}{\partial \tau}\left(r_\beta \rho_\beta\right) + \nabla \cdot \left( r_\beta \rho_\beta \vec{U}_\beta \right) = \dot{m}_{\beta\alpha} \tag{2}$$

Momentum equation

$$\frac{\partial}{\partial \tau}\left(r_\alpha \rho_\alpha \vec{U}_\alpha\right) + \nabla \cdot \left( r_\alpha \left( \rho_\alpha \vec{U}_\alpha \vec{U}_\alpha - \mu_\alpha^{\text{eff}} \left( \nabla \vec{U}_\alpha + \left( \nabla \vec{U}_\alpha \right)^T \right) \right) \right) = r_\alpha (\rho_\alpha g - \nabla p_\alpha) + \vec{F}_{\alpha\beta} - \dot{m}_{\beta\alpha} \vec{U}_\alpha \tag{3}$$

$$\frac{\partial}{\partial \tau}\left(r_\beta \rho_\beta \vec{U}_\beta\right) + \nabla \cdot \left( r_\beta \left( \rho_\beta \vec{U}_\beta \vec{U}_\beta - \mu_\beta^{\text{eff}} \left( \nabla \vec{U}_\beta + \left( \nabla \vec{U}_\beta \right)^T \right) \right) \right) = r_\beta \left(\rho_\beta g - \nabla p_\beta\right) + \vec{F}_{\beta\alpha} + \dot{m}_{\beta\alpha} \vec{U}_\beta \tag{4}$$

Energy equation

$$\frac{\partial}{\partial \tau}(r_\alpha \rho_\alpha H_\alpha) + \nabla \cdot \left( r_\alpha \left( \rho_\alpha \vec{U}_\alpha H_\alpha - \lambda_\alpha^{\text{eff}} \nabla T_\alpha \right) \right) = q_{\alpha\beta} - \dot{m}_{\beta\alpha} H_\alpha \tag{5}$$

$$\frac{\partial}{\partial \tau}\left(r_\beta \rho_\beta H_\beta\right) + \nabla \cdot \left( r_\beta \left( \rho_\beta \vec{U}_\beta H_\beta - \lambda_\beta^{\text{eff}} \nabla T_\beta \right) \right) = q_{\beta\alpha} + \dot{m}_{\beta\alpha} H_\beta \tag{6}$$