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Numerical investigation of thermal–hydraulic characteristics in a steam generator using a coupled primary and secondary side heat transfer model

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ABSTRACT

A coupled primary and secondary side heat transfer and thermal phase change model is used to investigate the thermal–hydraulic characteristics of a steam generator (SG) at Daya Bay Nuclear Power Plant (DBNPP). The simulation results reasonably reveal the ununiform boiling behavior in the secondary hot and cold legs. Vapor velocity is slightly higher than that of water and the corresponding slip-ratio first increases rapidly before gradually decreasing in the secondary hot leg and cold leg regions, a result which agrees with predictions using the drift-flux model. Cross-flow energy, which accounts for flow-induced vibration (FIV) at the U-bend tubes, is determined with the aid of localized thermal–hydraulic distributions, and the resulting FIV damage is predicted to be most severe at 0.35 m on the cold leg side and −0.2 m on the hot leg side of the U-bend region, respectively. These FIV damage predictions agree with measured plant data for the prototypical SG, showing that this model can provide the use information to improve thermal–hydraulic characteristics and help alleviate FIV damage in a SG.

1. Introduction

The fluid–solid coupled heat transfer process within a steam generator (SG) is a function of the high-temperature and high-pressure primary fluid within the heat exchange U-tubes. The process includes primary single-phase convection heat transfer, U-tube heat conduction, and secondary flow boiling heat transfer with a phase change. Temperature and heat flux vary dynamically at the fluid–solid interface between the primary and secondary side fluids during the coupled process due to interactions between the fluid flows and the tube wall. These variations indicate that thermal boundary conditions cannot be utilized to model the coupled heat transfer process. Therefore, a primary and secondary side coupled flow and heat transfer model must be used instead of thermal boundary conditions when calculating the thermal–hydraulic characteristics of a SG, particularly for determining the characteristics of a system involving the thermodynamic behavior of the primary coolant fluid. The thermal phase change process of liquid evaporation and vapor condensation—coupled with other factors such as the influence of flow-induced vibration (FIV), alternating dry and wet conditions, and so on in the two-phase region of the secondary side—enhances the complexity of the SG's thermal–hydraulic distribution characteristics. These factors, along with concern over the coupled heat transfer characteristics within the SG, can also significantly affect plant performance. Therefore, it is very important for pressurized water reactor nuclear power plants to investigate the thermal–hydraulic characteristics of its SG using a coupled primary and secondary side heat transfer model in order to ensure safe operation.

There is a large number of available experimental and theoretical works analyzing the thermal–hydraulic characteristics of the SG secondary regions because of the specific and complicated geometry structure of the tube bundle. Experiments typically model the coupled heat transfer process using the similarity principle and dimensional analysis theory, as it is quite difficult to achieve accurate experimental measurements of vapor–liquid two-phase flows. Thus, experimental requirements tend to be far different from actual SG operating processes, resulting in serious limitations to applying the empirical correlations. Moreover, some factors which impact SG performance still require further investigation (Ding, 1983; Umminger et al., 1993; Schoen and Weber, 1997). Because of continued dramatic progress in computer processing power, more researchers are turning to computational fluid dynamics (CFD) to model coupled heat transfer phenomena, providing detailed knowledge of the thermal–hydraulic distribution characteristics of the primary and secondary sides within a SG. However, the majority of the research work previously conducted has been limited to investigations of vapor–liquid two-phase flow and boiling heat transfer behaviors in the SG secondary side. Yang et al. (2012) carried out a numerical simulation of the vapor–liquid two-phase flow and boiling heat transfer characteristics in the SG

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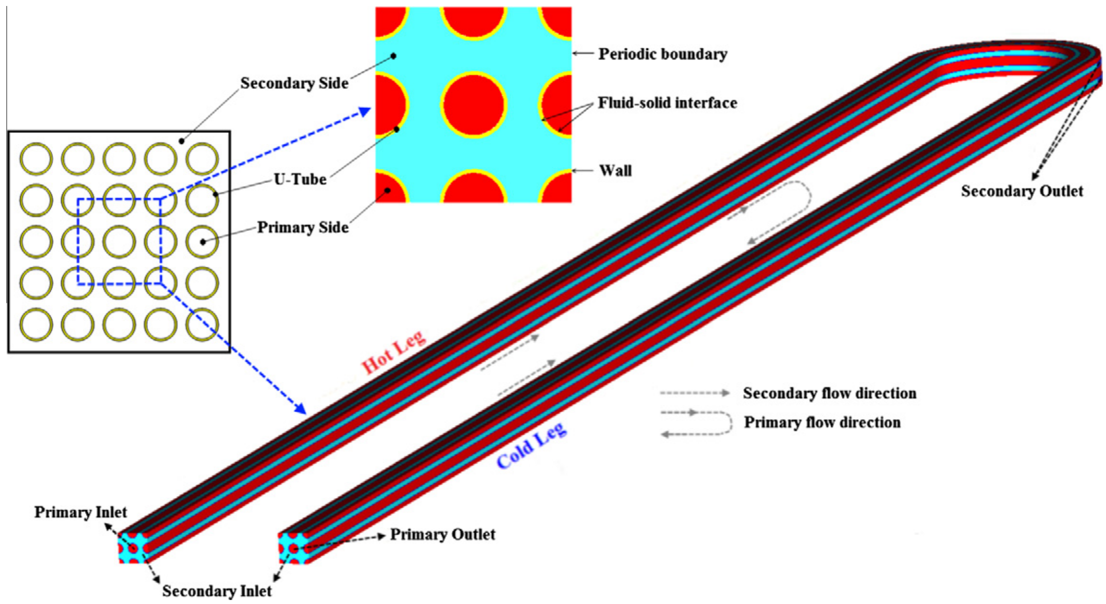

Fig. 1. "Unit pipe" three-dimensional physical model of SG.

secondary region using a thermal phase change model. Ferng and Chang (2008) and Ferng and Ma (2000) considered 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 region—and determined the distributions of boiling characteristics in the U-bend region. Similar to the above porous media approach, Jiang et al. (2008) also applied a CFD methodology to single-phase flow heat transfer in the secondary region located between the tube sheet and the first support plate, and analyzed the distributions of the single-phase fluid velocity field. Jo and Shin (1999) and Jo et al. (2005) conducted a thermal–hydraulic analysis which provided a detailed three-dimensional two-phase flow field in the SG secondary side, and assessed the potential for fluidelastic instability in the SG's U-tubes. Kuehlert et al. (2008) performed a CFD prediction of FIV for an individual tube with a single-phase fluid in the secondary region.

Previous SG thermal–hydraulic analyses have also addressed slip-ratio variations in the two-phase region. Hoeld (2002, 2007) derived a two-phase drift flux model coupled with the slip-ratio theory to calculate a SG's thermal and hydraulic characteristics. In addition, a number of research works (Kim et al., 2007; Liao and Guentay, 2009; Chu et al., 2011; Tashakor et al., 2011; Hu et al., 2011; Zhang and Hu, 2012) have investigated the coupled heat transfer process using one-dimensional and coarse multi-dimensional computational models or semi-empirical formulas. However, few researchers have considered such a coupled heat transfer response that looks at a combination of the primary domain, secondary domain, and U-tube bundle within a SG.

This paper investigates the thermal–hydraulic characteristics of both the primary and secondary sides of a SG using the developed "unit pipe" model, which is an extension of the numerical model proposed in a previous work of Yang et al. (2012). This approach models the flow region coming from a section of the vertical natural circulation SG at Daya Bay Nuclear Power Plant (DBNPP), a Westinghouse-type pressurized water reactor located in Southern China. Key thermal–hydraulic parameters such as tube wall temperature, secondary fluid velocity, steam quality, slip-ratio, and cross-flow energy are determined using localized distributions of flow and temperature fields and then used to predict FIV distributions around the U-bend region. These calculated results can provide information useful for plant staff to take appropriate actions to improve the thermal–hydraulic characteristics of a SG and alleviate FIV damage.

2. Numerical treatment and model approach

2.1. Mathematical models

The mathematical models used to simulate the thermal–hydraulic behaviors of the SG include the two-fluid model, the turbulent model and the thermal phase change model for the two-phase mixture, which are used to determine the mass, momentum, energy transfer processes on each side of the phase interface. In addition, these CFD models can be referred to the previous work of Sun and Yang (2013) and the present paper does not provide any detail on these governing equations.

2.2. Computational domain and grid system

Since there are greater than four thousands tubes in a SG at the DBNPP, it is so difficult for us to model the entire SG. Therefore, we selected a reasonable sectional flow region of a prototypical SG to simulate the aforementioned "unit pipe" model. As shown in Fig. 1, this model comprises a primary fluid region (red[1]) consisting of a center U-tube and its adjacent eight U-tubes, and a secondary fluid region (blue) which is surrounded by U-tubes (yellow). The tube diameter is 19.05 × 1.09 mm, tube pitch is 25 mm, the height of the straight section is 9 m, and the radius of the bend section is 0.63 m.

Several appropriate assumptions are needed in deriving the aforementioned "unit pipe" model to numerically predict FIV damage distribution in U-bend tube bundles of SG. These assumptions are presented as follows:

- Due to the high and complicated geometry of a SG, the vertical or horizontal inlet has almost no influence on flow and heat transfer characteristics within SG, which is confirmed through previous simulations (Yang et al., 2012). Thus, the radial hori-

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.