Annals of Nuclear Energy 87 (2016) 400–410

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Modeling the thermal stress of heat transfer tubes with tube support plate gaps in a steam generator

Baozhi Sun *, Jianxin Shi, Liu Yang, Longbin Yang *, Yanjun Li, Shanghua Liu

College of Power and Energy Engineering, Harbin Engineering University, Nantong Street, Harbin 150001, PR China

ARTICLE INFO

Article history:
Received 4 April 2015
Received in revised form 11 September 2015
Accepted 15 September 2015

Keywords:
Steam generator
Tube support plates' gaps
Flow-heat-solid coupling
Thermal–hydraulic
Thermal stress

ABSTRACT

This work presents a three-dimensional "unit pipe" model with and without gaps between tubes and associated tube support plates in a steam generator. The model is used to simulate the thermal–hydraulic characteristics of the steam generator and obtain the distributions of key parameters of the heat transfer tubes, the primary and secondary sides. Using this model, we pass fluid calculation results to the structure through a flow-heat-solid coupling in workbench, conduct thermal stress calculations of the heat transfer tubes, and analyze the influence of gaps on the system's thermal–hydraulic characteristics and resulting thermal stress. The results indicate that there is a rapid change in the secondary side's velocity and heat transfer coefficient at the tube support plates, and that the steam quality and fluid velocity in the gaps is higher and lower, respectively, than in the flood holes. Moreover, the resulting thermal stress experienced by the heat transfer tubes shows a periodic fluctuation around their circumference at the tube support plates, while the thermal stress without gaps at the tube support plates is greater than the thermal stress seen with gaps, and its circumferential volatility is approximately twice the volatility with gaps present.

1. Introduction

Heat transfer tube failure in a steam generator (SG) is the most common accident in nuclear power plants that seriously affects their integrity and security. Failure is primarily due to Stress Corrosion Cracking (SCC) for deposition of corrosion products along with synergistic effect of stress stemming from a number of reasons and thermally induced stress is one of them and here it is critical to note that difference in temperature across the tube wall thickness leads to the thermal stress, and thus effect of tube support plate (TSP) gap is important for consideration of local effects (Chen et al., 2011). Therefore, investigation of the influence of gaps on the thermal stress of the heat transfer tubes in a SG is of critical significance for maintaining safe operation of a pressurized water reactor nuclear power plant.

Thermal stress within a SG is closely related to its thermal–hydraulic characteristics (Kao et al., 1982). The fluid flow and heat transfer between the primary and secondary sides is an especially complex two-phase flow, where the boiling heat transfer of the secondary side has a large impact on wall temperature. A porous media model was used by Ferng (2007) and Ferng and Chang (2008) to investigate the law of two-phase flow and heat transfer of the secondary side. Meanwhile, Li et al. (2013), Sun and Yang (2013) and Yang et al. (2013) used a coupled heat transfer model to study the influence of TSPs on the thermal–hydraulic characteristics in a SG without considering the existence of gaps at the TSPs, finding wall temperature at the contact points was significantly higher than at the flood holes because the TSPs were in direct contact with the tubes.

Strong thermal stress research has greatly enhanced the development of the theory underlying thermal stress in heat transfer tubes, and the thermal stress of an elastic tube has been theoretically studied by many researchers (see e.g., Sauer (1996), Guerreri and Cossa (1998), Orcan and Eraslan (2001), Cardella (2002), Eraslan and Orcan (2002)). Li et al. (1999) investigated the thermal stress of tube plates in a heat exchanger using a finite element method, and proposed methods to reduce and eliminate thermal stress and improve tube plate structure. Thermal stress caused by fully developed laminar flows and pulsatile flows inside heating tubes has also been investigated by Al-zaharnah et al. (2000, 2001a,b). Rahimi et al. (2003) conducted experimental research on the thermal stress distribution of a boiling bundle using a resistance wire heating method. Yapici and Albayrak (2004) conducted a numerical investigation of inner wall thermal

* Corresponding authors. Fax: +86 0451 82519305 (B. Sun). Fax: +86 0451 82569633 (L. Yang).

E-mail addresses: sunbaozhi@163.com (B. Sun), liyanjunhrb@163.com (L. Yang).

http://dx.doi.org/10.1016/j.anucene.2015.09.019
0306-4549/

Nomenclature

α	liquid phase	q	sensible heat transfer rate between the liquid phase and vapor phase (kJ/(m^3 s))
β	vapor phase	ε	thermal strain
φ	volume fraction	u	displacement of micro unit in the x direction (m)
ρ	density (kg/m^3)	v	displacement of micro unit in the y direction (m)
$m_{\beta\alpha}$	mass transfer rate from liquid phase to vapor phase (kg/(m^3 s))	w	displacement of micro unit in the z direction (m)
$\boldsymbol{u}$	velocity vector (kg/s)	E	Young's modulus (GPa)
t	time (s)	σ	thermal stress (GPa)
μ^e	effective dynamic viscosity (kg/(m s))	μ	Poisson's ratio
T	temperature (K)	ξ	thermal expansion coefficient
p	pressure (Pa)	ΔT	temperature variation (K)
g	gravitational acceleration (m/s^2)	γ	shear strain
$f_{\alpha\beta}$	the force exerted by liquid phase to vapor phase (N)	τ	shearing stress (GPa)
$f_{\beta\alpha}$	the force exerted by the phase change from vapor phase to liquid phase (N)	G	shear modulus (GPa)
H	enthalpy (kJ/kg)	∇^2	Laplacian
λ	thermal conductivity (W/(m K))	X, Y, Z	volume force component (N/m^3)
		e	volumetric strain

stress under non-uniform heat flux using commercial software, comparing the distribution of thermal stress under different heating methods and flow velocity. Özceyhan (2005) obtained the thermal stress distribution of the heat transfer tubes under non-uniform heat flux via different heating methods using a model based on the roughness of the heat transfer tubes and the velocity, and proposed methods to reduce thermal stress. Tashakor et al. (2011) predicted positions prone to stress corrosion by analyzing the positions of deposited impurities and corrosion products. Garrido et al. (2012) conducted a numerical simulation of the heat transfer and thermal stress of heat transfer tubes, pressure pipeline, and pump in a SG and predicted the range of fatigue load under given conditions.

As can be seen from the above analyses, SG investigations have mostly focused on thermal–hydraulic characteristics or on thermal stresses induced in the heat transfer tubes without considering the effect of TSP gaps on the thermal–hydraulic characteristics of the primary and secondary domains and U-tube bundles within SG, and the thermal stress have been typically analyzed by adding secondary or tertiary boundary conditions only considering the influence of secondary side. However there is a strong flow-thermal-solid coupling relationship among complex two-phase flow, the heat transfer and thermal stress in a SG, and the gaps at the TSPs directly affect the thermal–hydraulic characteristics of the SG, the thermal stress associated with the heat transfer tubes, and the coupling relationship. This paper conducts a numerical simulation of a SG's thermal–hydraulic characteristics that considers the gaps between the tubes and the TSPs in the actual structure of the SG on the basis of Li et al. (2013), Sun and Yang (2013) and Yang et al. (2013), then passes these fluid calculation results to the structure and calculates the thermal stress of the heat transfer tubes. This method reveals the influence of gaps on the thermal–hydraulic characteristics in a SG as well as the distribution of the thermal stress.

2. Physical model and mesh

This paper establishes a three-dimensional unit-pipe model, including primary and secondary sides, heat transfer tubes, and four-leaf plum-shaped support plates, using the structural and operational parameters of a SG at the Daya Bay Nuclear Power Plant (DBNPP). As shown in Fig. 1, the geometry of the model is identical to the actual steam generator for elements such as the diameter of the heat transfer tubes, tube pitch, etc. The inlet and outlet positions of the primary and secondary sides in the unit-pipe model are also consistent with the physical reference. The primary flow region is inside the tube, while the secondary flow region is in between the tubes, taking into consideration the tube wall thickness. In addition, we arrange nine pairs of four-leaf plum-shaped support plates along the axis in the secondary flow region, such that they have potential gaps between the TSPs and the heat transfer tubes. The tube diameter is 19.05 mm, wall thickness is 1.09 mm, tube pitch is 27.43 mm, the height of the straight tube section is 9 m, and the radius of the elbow section is 0.82 m. The thickness of the TSPs is 0.03 m, adjacent TSP pitch is 1 m and the gaps between the TSPs and the heat transfer tubes is 0.3 mm.

We first partition all the blocks for the model, adjust the positions of the mesh nodes around each gap, make the mesh size increase proportionally layer-by-layer, and meet the requirements of the expansion rate and number of grids using ICEM software. The mesh system is shown in Fig. 2. A careful mesh independence study was carried out in order to provide internally coherent numerical results. The eight mesh systems used in this study are summarized in Fig. 3. The final number of meshes is 5437326, based on the mesh distortion, aspect ratio, expansion rate and mesh independence.

3. Mathematical formulation

Since there are common equations governing U-tube heat conduction and single-phase convection heat transfer in the primary side, this paper does not provide any detail concerning these basic equations. Instead, the following section primarily illustrates the mathematical equations applied to the secondary domain and the thermal stress for the U-tube bundle.

3.1. Liquid–vapor two-phase flow model

For our flow model, the steam quality at the outlet of secondary side is about 0.25 and the flow pattern is only bubbly flow in the boiling process because of the low steam quality, thus we treat the secondary side of a SG experiencing a two-phase flow consisting of liquid and vapor phases as possessing continuous and discrete phases, respectively. The governing equations for the liquid and vapor phases are established using the fluid pair model (Sun and Yang, 2013).