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Analysis of wall temperature jump of China Generation IV SFR Steam Generator

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ABSTRACT

This paper presents a thermal-hydraulic model of the sodium-heated once-through steam generator and its application to analyze the wall temperature jump of China Generation IV SFR Steam Generator (CSSG). Firstly, this model is verified with experimental data and another design code, which proves the reliability of this model. Secondly, the heat transfer characteristics of CSSG is obtained by using this model. Thirdly, the location and magnitude of maximum water wall temperature jump are chosen as figures of merit for the sensitivity analysis for CSSG. Based on numerical calculations and conservative consideration, it is concluded that the sodium inlet temperature and the water inlet mass flow rate must be strictly controlled in the operation of CSSG, and that the maximum water wall temperature jump is set to around 30 °C in the following stress design.

1. Introduction

Sodium-Cooled Fast Reactor (SFR) features a fast-spectrum reactor and closed fuel system (Aoto et al., 2014), which has been chosen as one of the six potential reactors for Generation IV nuclear systems (Kelly, 2014). Most SFRs adopt three-coolant systems: a primary sodium coolant system, an intermediate sodium coolant system, and a steam-water, turbine-condenser coolant system. The sodium-to-sodium heat exchange is an intermediate heat exchanger (IHX), and the sodium-to-water/steam heat exchange is a steam generator. After successful development of China Experiment Fast Reactor (Wang and Cao, 2007), China is developing its Generation IV SFR. China Generation IV SFR Steam Generator (CSSG) is a once-through steam generator (OTSG), consisting of an evaporator and a superheater as shown in Fig. 1.

Feed water is pumped into the tube side (water/steam side) of this evaporator inlet and flows from bottom to top in the evaporator. It absorbs heat from the shell (sodium) side, and finally turns into micro-superheated steam. Then the micro-superheated steam is delivered to the superheater inlet, and flows from up to down in the superheater. The liquid sodium from the IHX enters the shell side of the superheater inlet, then flows from bottom to up in the superheater and from up to down in the evaporator. The feed water in the evaporator undergoes the subcooled water, nucleate boiling, film boiling, and superheated steam state. The water wall temperature rises rapidly at the specific position of the evaporator due to heat transfer deterioration. The location of the maximum temperature jump proves to be the location of dryout, which shifts in space at a frequency of about 0.3–1 Hz (Jun et al., 1992). It may induce thermal stresses in the tube wall and thus cause fatigue failure of the tube wall.

In recent years, thermal-hydraulic analysis of the OTSG has been the subject of concern. Shi et al. (2016) focused on the prediction of the dryout and post-dryout wall temperature of the straight-pipe OTSG designed by B&W. A three-dimensional two-fluid model was introduced and the influence of heated water mass flux, inlet subcooling, system pressure and heat flux was analyzed. Coupling between the tube side and the shell side was not taken into consideration and thus the heat flux was given directly. Ma et al. (2014) developed a code to analyze the thermal hydraulic characteristics and two-phase instability behavior of the helical tube steam generator of China High Temperature Gas-cooled Reactor. Vaidyanathan et al. (2009) developed a one-dimensional code named DESOPT for thermal-hydraulic design of sodium-heated OTSG of India Prototype Fast Breeder Reactor. The code has been validated against some SG design data and some predictions were given. Yoon et al. (2000) developed a code named ONCESG for coiled-tube OTSG and the code has been verified with several OTSG design data. Sun et al. (2016) developed a thermal-hydraulic code using the Homogeneous-fluid model for the design of the OTSG of China Fast Reactor 600. The sensitivity analysis of the thermal

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Nomenclature

A	flow area (m^2)
C_0	concentration parameter (–)
C_K	kinematic wave velocity (m/s)
C_p	constant-pressure specific heat (J/(kg °C))
D_2	tube outer diameter (m)
D_h	hydraulic diameter (m)
g	gravitational acceleration (m/s^2)
G	water mass flux ($kg/(m^2 \cdot s)$)
h	enthalpy (J/kg)
h_{fg}	latent heat of vaporization of water (J/kg)
H	heat transfer coefficient ($W/(m^2 \cdot °C)$)
j	volumetric velocity (m/s)
j_g	vapor superficial velocity (m/s)
L	tube length (m)
Nu	Nusselt number (–)
p	pressure (Pa or MPa)
P	perimeter (m)
Pe	Peclet number (–)
Pr	Prandtl number (–)
P_t	tube pitch (m)
q	heat flux (W/m^2)
r	channel radius (m)
R	heat resistance (°C/W)
Re	Reynolds number (–)
T	temperature (°C)
t	time (s)
V	velocity (m/s)
V_{gj}	local drift velocity of the vapor (m/s)
x_e	equilibrium steam quality (–)
x_c	critical steam quality (–)
z	axial coordinate (m)

Greek letters

α	void fraction (–)
β	volumetric flow fraction (–)
λ	thermal conductivity ($W/(m \cdot °C)$)
σ	surface tension (N/m)
ρ	density (kg/m^3)
Γ_g	thermal-equilibrium vapor generation rate ($kg/(m^3 \cdot s)$)

Subscripts

1	inner side wall of the tube
2	outer side wall of the tube
f	liquid component
g	vapor component
mix	two-phase mixture
N	sodium side
sf	liquid component at saturated state
sg	vapor component at saturated state
t	tube
w	water/steam side

Acronyms

CSSG	China Generation IV SFR Steam Generator
IHX	Intermediate Heat Exchanger
LWTJ	Location of Maximum Water Wall Temperature Jump
MWTJ	Magnitude of Maximum Water Wall Temperature Jump
OTSG	Once-Through Steam Generator
SFR	Sodium-cooled Fast Reactor

power relative to the design parameters was performed. Although the above-mentioned work has obtained deep insights into the thermal-hydraulic characteristics of the OTSG, the analysis of temperature jump of sodium-heated OTSG is rarely open-published. The analysis of temperature jump of sodium-heated OTSG is indispensable for the design of the OTSG and for its real operation safety. Moreover, the configurations and the working condition of CSSG are different from the above OTSGs in Shi et al. (2016), Ma et al. (2014), Vaidyanathan et al. (2009), Yoon et al. (2000), Sun et al. (2016).

Therefore, this paper presents a model for analysis of OTSG temperature jump and its application to CSSG.

2. Model development

Seven key assumptions for thermal-hydraulic analysis are listed below.

(1) Control equations of both the shell side and tube side are in axial direction form.
(2) Heat transfer through the tube is not considered in the axial direction.
(3) Radiation heat transfer is not under consideration.
(4) Fouling resistance is not under consideration.
(5) Four regions are divided in the tube side following these criteria and are depicted in Fig. 2.
   - Subcooled region: when $h_w \leqslant h_{sf}$.
   - Nucleate boiling region: when $h_w > h_{sf}$ and $x_e \leqslant x_c$.
   - Film boiling region: when $x_e > x_c$ and $h_w \leqslant h_{sg}$.
   - Superheated region: when $h_w > h_{sg}$.
(6) The feed water, superheated steam and sodium are incompressible in the single-phase region.
(7) Thermal equilibrium is considered and Zuber-Findlay drift-flux model (Zuber and Findlay, 1965) is adopted in the boiling region.

2.1. Mass conservation equations

$$\frac{\partial V_f}{\partial z} = 0 \tag{1}$$

$$\frac{\partial[(1-\alpha)\rho_{sf}]}{\partial t} + \frac{\partial[(1-\alpha)\rho_{sf}V_f]}{\partial z} = -\Gamma_g \tag{2}$$

$$\frac{\partial(\alpha\rho_{sg})}{\partial t} + \frac{\partial(\alpha\rho_{sg}V_g)}{\partial z} = \Gamma_g \tag{3}$$

$$\frac{\partial\rho_g}{\partial t} + \frac{\partial(\rho_g V_g)}{\partial z} = 0 \tag{4}$$

$$\frac{\partial V_N}{\partial z} = 0 \tag{5}$$

Eqs. (2) and (3) can be written in terms of a mass conservation equation for volumetric flux density and a density propagation equation (Chan, 1979). They are given as below.

$$\frac{\partial j}{\partial z} = \frac{\Gamma_g(\rho_{sf}-\rho_{sg})}{\rho_{sf}\rho_{sg}} \tag{6}$$

$$\frac{\partial\rho_{mix}}{\partial t} + C_K\frac{\partial\rho_{mix}}{\partial z} = -[(1-C_0)\rho_{sf} + C_0\rho_{mix}]\frac{\Gamma_g(\rho_{sf}-\rho_{sg})}{\rho_{sf}\rho_{sg}} \tag{7}$$

where

$$C_K \equiv V_{gj} + C_0 j + \alpha\frac{\partial V_{gj}}{\partial\alpha} \tag{8}$$