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A Conceptual Design of a Double Wall Tube Steam Generator in a Prototype Fast Reactor

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1. Introduction

The reaction between sodium and water is one of the most serious problems encountered in the design of a steam generator in a fast reactor. To avoid such a sodium-water reaction, a double wall tube steam generator was developed. The objective of the present study is to develop a design code (DWTSG) for a double wall tube steam generator in a fast reactor and its application to the design of a 150MWe prototype fast reactor. A one dimensional approach is employed and the related pressure loss and heat transfer correlations are presented.

2. Pressure Drop and Heat Transfer Correlations

2.1 Pressure Drop Correlation for Sodium Side

The Blasius pressure drop correlation is used for the sodium side pressure drop;

$$\mathrm{Re} \le 2{,}100 \qquad f = \frac{64}{\mathrm{Re}} \tag{1}$$

$$2{,}100 \le \mathrm{Re} \le 30{,}000 \qquad f = 0.3164\,\mathrm{Re}^{-0.25} \tag{2}$$

$$\mathrm{Re} \ge 30{,}000 \qquad f = 0.184\,\mathrm{Re}^{-0.2} \tag{3}$$

2.2 Pressure Drop Correlation for Water Side

In a single phase region, the Blasius correlation is used, and in a two-phase region, a two-phase multiplier is multiplied by the Blasius correlation. The homogeneous equilibrium model, the modified Martinelli-Nelson or Jones model and the Thom void fraction - Thom friction factor are employed for a two-phase multiplier

2.3 Heat Transfer Correlation for Water Side

- Preheat region : Dittus-Boelter correlation

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{4}$$

- Nucleate boiling region : Chen correlation

$$h_B = S\,h_b + F\,h_c \tag{5}$$

where F is the Martinelli parameter and S is the : suppression factor

$$h_c = 0.023\left(\frac{k}{d_i}\right)(1-x)^{0.8}\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{6}$$

$$h_b = 0.00122\left[\frac{k_l^{0.79} Cp_l^{0.45} \rho_l^{0.49}}{\sigma^{0.5}\mu_l^{0.29} h_{fg}^{0.24} \rho_g^{0.24}}\right]\Delta t_{sat}^{0.24} P_{sat}^{0.75} \tag{7}$$

- Film boiling region : Bishop correlation

$$Nu_f = 0.0193\,\mathrm{Re}_f^{0.8}\,\mathrm{Pr}_f^{1.23}\left[x + (1-x)\frac{\rho_g}{\rho_f}\right]^{0.68}\left(\frac{\rho_g}{\rho_f}\right)^{0.068} \tag{8}$$

- Super heat region : Dittus-Boelter correlation

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{9}$$

-Fouling

$$h_{Fw} = 2.84 \times 10^4 W/m^2\,{}^\circ C \tag{10}$$

- Gap conductance

$$h_g = 3.5 \times 10^4 W/m^2\,{}^\circ C \tag{11}$$

-Critical quality : Duchatelle correlation

$$x = 1.69 \times 10^{-4} q^{0.719} G^{-0.212} e^{2.5\times10^{-8} P} \tag{12}$$

2.4 Heat Transfer Correlation for Sodium Side

- Graber-Rieger correlation :

$$Nu = a + b(Pe)^c \tag{13}$$

$$a = 0.25 + 6.20(P/D_h) \tag{14}$$

$$b = -0.007 + 0.032(P/D_h) \tag{15}$$

$$c = 0.8 - 0.024(P/D_h) \tag{16}$$

- Lubarsky-Kaufman correlation :

$$Nu = 0.625(Pe)^{0.4} \tag{17}$$

3. One Dimensional Model

3.1 Continuity equation

$$w_s = const \tag{18}$$

$$w_w = const \tag{19}$$

3.2 Momentum equation

$$\Delta p = \Delta p_{acc,i} + \Delta p_{fric,i} + \Delta p_{grav,i} \tag{20}$$

$$\Delta p_{acc,i} = \left(\frac{G_w^2}{\rho}\right)_i - \left(\frac{G_w^2}{\rho}\right)_{i+1} \quad (21)$$

$$\Delta p_{fric,i} = \frac{L_l}{d_i}\frac{G_w^2}{2\rho_l} + f\frac{L_{2\Phi}}{d_i}\overline{\Phi_{lo}^2}\frac{G_w^2}{2\rho_f} + f\frac{L_g}{d_i}\frac{G_w^2}{2\rho_g} \quad (22)$$

$$\Delta p_{grav,i} = \rho_l g L_l + \left\langle\overline{\rho_H}\right\rangle g L_{2\Phi} + \rho_g g L_g \quad (23)$$

$$\text{where } \left\langle\overline{\rho}\right\rangle_i = \frac{\langle\rho\rangle_i + \langle\rho\rangle_{i+1}}{2}, \ \langle\rho\rangle_i = \frac{1}{v_f + \langle x\rangle_i v_{fg}} \quad (24)$$

3.3 Energy equation

-Heat transfer from the tube wall :

$$\Delta Q = U\ \Delta A_o\ \Delta T_o \quad (25)$$

-Heat transfer from sodium flow :

$$\Delta Q = w_s\left(h_{s,in} - h_{s,out}\right) \quad (26)$$

-Heat transfer from water/vapor

$$\Delta Q = w_w\left(h_{w,out} - h_{w,in}\right) \quad (27)$$

$$\text{where } \Delta T_o = \frac{\left(T_{s,in} + T_{s,out}\right)}{2} - \frac{\left(T_{t,in} + T_{t,out}\right)}{2} \quad (28)$$

$$\Delta A_o = \pi\ d_o\ L \quad (29)$$

- Overall heat transfer

$$\begin{aligned}\Delta Q &= h_s\Delta A_o(T_s - T_{Fs}) = h_{Fs}\Delta A_o(T_{Fs} - T_o) \\ &= \frac{2k}{d_o\ln(\frac{d_o}{d_g})}\Delta A_o(T_o - T_{g+}) = h_g\Delta A_g(T_{g+} - T_{g-}) \\ &= \frac{2k}{d_g\ln(\frac{d_g}{d_i})}\Delta A_g(T_{g-} - T_i) = h_{Fw}\Delta A_i(T_i - T_{Fw}) \\ &= h_w\Delta A_i(T_{Fw} - T_w)\end{aligned} \quad (30)$$

$$U = \frac{1}{\frac{1}{h_s} + \frac{1}{h_{Fs}} + \frac{d_o}{2k}\ln(\frac{d_o}{d_i}) + \frac{d_o}{d_g}\frac{1}{h_g} + \frac{d_o}{d_i}(\frac{1}{h_{Fw}} + \frac{1}{h_w})} \quad (31)$$

$$T_o = T_s - \frac{\Delta Q}{\Delta A_o}\left(\frac{1}{h_s} + \frac{1}{h_{Fs}}\right) \quad (32)$$

$$T_i = T_w + \frac{\Delta Q}{\Delta A_i}\left(\frac{1}{h_{Fw}} + \frac{1}{h_w}\right) \quad (33)$$

4. Results and Discussion

The computer code DWTSG is developed for the design of a double wall tube steam generator in a 150MWe prototype fast reactor [1]. From the test design, it is shown that the present code can be used in a practical design [2]. Table-1 shows the operating conditions and design results for the prototype fast reactor being developed at KAERI.

Table-2 Design Results

SG type	Straight double wall tube
Thermal capacity (MWt)	196.8
Number of tubes (without plugged tubes)	704 (640)
Sodium inlet/outlet temperature (℃)	527/324
Feed water inlet/steam outlet temperature (℃)	230/503
Sodium/Feed water flow rate (kg/s)	757.95/85.35
Feed water inlet/steam outlet pressure (MPa)	19.5/16.5
Tube heat transfer length (m)	28.
Tube inner/gap/outer diameter (mm)	13.8/16/19
Tube Inner/outer thickness (mm)	1.1/1.5
Heat transfer area (m²)	1068
SG tube bundle diameter (m)	0.885
Tube longitudinal and transverse P/D	1.67
Tube material	Mod 9Cr-1Mo
SG height (m)	~ 36
Tube side pressure loss (KPa)	192
Shell side pressure loss (KPa)	234
Distance between bundle and shell (m)	~ 0.0157
SG shell inner diameter (m)	0.954

5. Conclusions

A design code for a double wall tube steam generator (DWTSG) in a fast reactor was developed. The theoretical basis is briefly presented and the correlations for pressure loss and heat transfer are presented. Theoretically, a one dimensional model is used and is briefly summarized. The code is applied to the design of the double wall tube steam generator in a 150MWe prototype reactor and the design results are presented.

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REFERENCES

[1] S. K. Choi, User Manual for DWTSG Computer Code, LMR/FS200-CM-01-Rev.0/07, 2007.

[2] S. K. Choi, Thermal Sizing of a Double Wall Tube Steam Generator for a Prototype Fast Reactor, SFR-FS400-CA-02-2012Rev.01, 2012.