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Development of a Design Code for a Double Wall Tube Steam Generator in a Liquid Metal 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 liquid metal reactor. In order 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 liquid metal reactor. One dimensional approach is employed and the related correlations are presented. The overall features of the DWTSG is nearly the same as reported in Kim[1] for a helically coiled steam generator.

2. Pressure Drop and Heat Transfer Correlations

Pressure Drop Correlation for Sodium Side

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

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

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

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

Pressure Drop Correlation for Water Side

In the single phase region the Blasius correlation is used, and in the 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 the two-phase multiplier

Heat Transfer Correlation for Water Side

(1) Preheat region : Dittus-Boelter correlation

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

(2) 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

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

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

(3) Film boiling region : Bishop correlation

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

(4) Super heat region : Dittus-Boelter correlation

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

(5) Fouling

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

(6) Gap conductance

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

(7) Critical quality : Duchatelle correlation

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

Heat Transfer Correlation for Sodium Side

(1) Graber-Rieger correlation :

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

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

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

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

(2) Lubarsky-Kaufman correlation :

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

3. One Dimensional Model

Continuity equation

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

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

Momentum equation

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

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

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

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

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

Energy equation

(1) Heat transfer from tube wall :

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

(2) Heat transfer from sodium flow :

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

(3) Heat transfer from water/vapor

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

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

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

(4) Overall heat transfer

$$\Delta Q = h_s \Delta A_o (T_s - T_{Fs}) = h_{Fs} \Delta A_o (T_{Fs} - T_o)$$

$$= \frac{2k}{d_o \ln(\frac{d_o}{d_g})} \Delta A_o (T_o - T_{g+}) = h_g \Delta A_g (T_{g+} - T_{g-})$$

$$= \frac{2k}{d_g \ln(\frac{d_g}{d_i})} \Delta A_g (T_{g-} - T_i) = h_{Fw} \Delta A_i (T_i - T_{Fw})$$

$$= h_w \Delta A_i (T_{Fw} - T_w) \quad (30)$$

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

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

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

The details are given in Choi [2] and are not presented here.

4. Results and Discussions

The test operating conditions are given in Table-1 and these data come from the JAEA experiment. Table-2 shows the design results and one can see that the difference between the two designs is minimal and that the computer code developed in the present study is reliable for practical design.

5. Conclusions

A design code for a double wall tube steam generator in a fast breeder reactor was developed. The theoretical basis is briefly presented and a test design was performed. From the test design it is shown that the present code can be used in a practical design.

Table -1 Test Operating Conditions

Operating Parameters	Design Value
Heat Load	1785 MWth
Sodium Inlet Temperature	520 ℃
Sodium Outlet Temperature	335 ℃
Sodium Flow Rate	7583.33 kg/se
Steam Outlet Pressure	16.7 Mpa
Feed Water Inlet Temperature	233 ℃
Water/Steam Flow Rate	787.78 kg/sec
Number of Tubes	5551
Tube ID/IG/OD	0.0138/0.016/0.019 m
Tube Bundle Transverse Pitch	0.0318 m

Table-2 Design Results

Item	JAEA Design	KAERI Design
S/G type	Straight tube	Straight tube
Thermal capacity (MWt)	1785	1785
Heat transfer area (m2)	9228	9286
Tube inner/medium/outer diameters (mm)	13.8/16/19	13.8/16/19
Heat transfer length (m)	28.00	28.03
Tube number	5551	5562
Tube pitch (mm)	31.8	31.8
Tube material	12Cr steel	12Cr steel
Sodium flow rate (kg/sec)	7583.33	7583.33
Water/steam flow rate (kg/sec)	787.78	787.78
S/G Diameter (m)	2.515	2.490

REFERENCES

[1] Y. S. Kim, User Manual for HSGSA Computer Code, KALIMER/FS-4CM-98-001, 1998.
[2] S. K. Choi, User Manual for DWTSG Computer Code, LMR/FS200-CM-01-Rev.0/07,2007.