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Modeling of an Once Through Helical Coil Steam Generator of a Superheated Cycle for Sizing Analysis

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Abstract

A thermal sizing code, named as HSGSA (Helical coil Steam Generator Sizing Analyzer), for a sodium heated helical coil steam generator is developed for KALIMER (Korea Advanced LIquid MEtal Reactor) design. The theoretical modeling of the shell and tube sides is described and relevant correlations are presented. For assessment of HSGSA, a reference plant design case is compared to the calculational outputs from HSGSA simulation.

1. Introduction

Sodium heated steam generators have special design requirements for high reliability, availability, and safety because of the adverse effects of potential sodium-water reactions. For high temperature liquid metal reactor plants with fast thermal transients, helical coil steam generator (HCSG) designs offer the following inherent advantages over other designs:

- Relatively small number of tubes with longer length, larger diameter, and thicker wall
- Smaller number welds of tube-to-tubesheet and sodium to water pressure boundary
- Easier accommodation of tube-to-tube and tube-to-shell thermal expansion differentials
- Compact heat transfer surface arrangement
- More efficient heat transfer performance by extended nucleate boiling region

A HCSG of the above mentioned advantages was chosen as the reference steam generator design for the KALIMER which is being developed by KAERI. The KALIMER steam generator is a vertically oriented helical coil type heat exchanger with sodium-to-water counter-cross flow. For the tube side, water flows and is converted to steam. The tube side fluid goes through various heat transfer modes. The modes considered are a preheat mode, nucleate boiling mode, film boiling mode and superheat mode. The shell side flow remains in a liquid phase and the heat transfer mode is simple compared to the tube side mode although the shell side geometry is more complicated. For higher plant efficiency, an once through superheated steam cycle has been considered in the KALIMER steam generating system [1].

A computer code, named as HSGSA (Helical coil Steam Generator Sizing Analyzer), is developed for the thermal sizing/performance analysis of the KALIMER steam generator and its model is explained in the following sections.

2. Modeling of HSGSA

HSGSA is being developed to analyze the thermal sizing and performance of a steam generator and applicable to the following parameter ranges:

- Steam generator type: once through superheated heated helical coil steam generator
- Operating pressure: 5 MPa ~ 20 MPa

A mass conservation equation, one-dimensional energy balance equation, and pressure loss equation are used for the tube side and shell side. The governing equations are of a steady state and the energy balance equation consists of a convection term and a source term for the heat transfer between the tube and shell side flows. A typical tube bundle arrangement of the helical coil steam generator is shown in Fig. 1. Tube arrangement is determined by longitudinal pitch, transverse pitch, and tube pitch angle. A simplified one-dimensional model is chosen to analyze the steam generator sizing. Details of the HSGSA code are described in this section.

2.1 Mass Conservation

The continuity equation of each control volume for one-dimensional calculation is relatively simple as follows:

$$w_s = \text{const.} \tag{1}$$

$$w_w = \text{const.} \tag{2}$$

where, w_s: sodium flow rate; w_w: water flow rate

As mentioned above, the sodium flow rate per control volume is assumed as total sodium flow rate divided by total tube numbers.

2.2 Momentum Conservation

The total pressure drop for each control volume consists of accelerational, frictional, and gravitational pressure drops as shown in Eq. (3).

$$\Delta p = \Delta p_{acc,i} + \Delta p_{fric,i} + \Delta p_{grav,i} \tag{3}$$

where, $\Delta p_{acc,i}$: accelerational pressure drop

$$= \left(\frac{G_w^2}{\rho}\right)_i - \left(\frac{G_w^2}{\rho}\right)_{i-1}$$

$\Delta p_{fric,i}$: frictional pressure drop

$$= \frac{\Delta L_l}{d_i}\frac{G_w^2}{2\rho_l} + f\frac{\Delta L_{2\phi}}{d_i}\overline{\phi_{lo}^2}\frac{G_w^2}{2\rho_f} + f\frac{\Delta L_g}{d_i}\frac{G_w^2}{2\rho_g}$$

$\Delta p_{grav,i}$: gravitational pressure drop

$$= \rho_l g\Delta L_l + \langle\overline{\rho_H}\rangle g\Delta L_{2\phi} + \rho_g g\Delta L_g$$

$\overline{\phi_{lo}^2}$: two-phase multiplier

$\langle\bar{\rho}\rangle_i = \dfrac{\langle\rho\rangle_i + \langle\rho\rangle_{i-1}}{2}$: average density for i-th control volume

$\langle\rho\rangle_i = \dfrac{1}{v_f + \langle x\rangle_i v_{fg}}$: local density for i-th node

The definition of the node and control volume numbers is shown in Fig. 2. The pressure drop model described above is mainly for the tube side flow. In shell side the sodium flow is always single liquid phase and the effects due to two-phase and gas phase are not considered

The correlations used for the sodium- and water-side pressure drops are listed in Table 1.

2.3 Energy Conservation

2.3.1 Heat Transfer Coefficient

The tube side flow patterns for a helical coil tube are similar to that of a vertical straight tube in single-phase flow. In the case of two-phase flow, the centrifugal force and the body force due to the gravity influence the flow pattern. For the steam generator operating conditions the gravity effect becomes negligible except for at a low load operation. In the coiled tube the centrifugal force produces a radial velocity component which results in a secondary flow pattern superimposed on the main flow along the tube axis. The secondary flow pattern makes the helical coil tube very efficient in distributing the liquid on the tube surface even at high quality. The heat transfer and pressure drop correlations that account for the effects of the coiled tube geometry are presented in Table 1. Single-phase forced convection heat transfer is encountered in the inlet and outlet of the tube where the fluid enthalpies are below and above that of saturated water, respectively. That is usually described as a preheat region and a superheat region, respectively. In the two-phase region, the heat transfer is modeled into three different regions, i.e., saturated nucleate boiling, forced convective heat transfer through liquid film, and liquid deficient regions. Chen proposed using combination of a nucleate boiling component and a forced convection counterpart for the nucleate boiling region analysis, where h_b is originally developed by Forster and Zuber for pool boiling and modified by Chen to account for convective boiling effects as shown in Table 1. For the liquid deficient region, film boiling mode where the heated surface is dry and the liquid phase is carried by the vapor is assumed. This region is encountered when the local quality is greater than the average steam quality at the point of departure-from-nucleate-boiling (DNB), which is calculated by Duchatelle et al.'s experimental correlation.

For the energy conservation we assume the sodium flow rate per control volume is equivalent to total sodium flow rate divided by total tube numbers. This flow rate, also, apply to the evaluation of the shell side heat transfer correlation in the in-line flow model, which simplifies the shell side flow as a counter-current parallel flow. The equivalent hydraulic diameter required for heat transfer correlation application in in-line flow model is determined by Eq. (4).

$$D_h = \frac{4 \cdot A_{flow}}{p} \tag{4}$$

where, p is wetted perimeter and is applied to the shell side models.

In the cross flow model, the shell side flow through helical coil rod bundles is considered as $(90^\circ - \theta)$-oblique flow, where θ is tube pitch angle and the sodium flow rate per control volume for calculating the heat transfer coefficient is total sodium flow rate divided by total tube row numbers. The derivation of the geometric factor in the heat transfer correlation is corresponded to an interpretation of the effective pitch of the tube bundle taken as the mean of the transverse and the longitudinal pitches. Although the correlation strictly apply to equilateral parallel tube bundles, it is adopted as the obliqued cross flow heat transfer correlation whereas the actual steam generator tubes are cross-inclined with an equal transverse and longitudinal pitches.

In the shell side models, Lubarsky-Kaufmann and Kalish-Dwyer correlations are applied to the in-line flow and cross flow models, respectively.

2.3.2 Heat Transfer Balance

For the energy conservation we assume the sodium flow rate per control volume is equivalent to total sodium flow rate divided by total tube numbers. For the energy balance for an i-th control volume is expressed by the properties of i-1-th and i-th nodes. The theoretical model of a control volume for heat transfer is shown in Fig. 2.

Heat transfer rate through tube wall is:

$$\Delta Q = U \Delta A_o \, \Delta T_o \tag{5}$$

Heat transfer rate from sodium flow is:

$$\Delta Q = w_s(h_{s,in} - h_{s,out}) \tag{6}$$

Heat transfer rate to water flow is:

$$\Delta Q = w_w(h_{w,out} - h_{w,in}) \tag{7}$$

where, ΔT_o: average temperature difference

$$= \frac{(T_{s,in} + T_{s,out})}{2} - \frac{(T_{t,in} + T_{t,out})}{2}$$

ΔA_o: heat transfer area

$$= \pi d_o \Delta L$$

2.4 Overall Heat Transfer Coefficient for each Control Volume

The lateral heat transfer rate should be all the same in the connected regions of sodium side, tube wall, water side, and fouling regions, as described below.

$$\Delta Q = h_s \Delta A_o(T_s - T_{Fs}) = h_{Fs} \Delta A_o(T_{Fs} - T_o) = \Delta A_o \frac{2k}{d_o} \frac{T_o - T_i}{\ln(\frac{d_o}{d_i})}$$

$$= h_{Fw} \Delta A_i(T_i - T_{Fw}) = h_w \Delta A_i(T_{Fw} - T_w) \tag{8}$$

From above relations, overall heat transfer coefficients is obtained as following:

$$U = \frac{1}{\frac{1}{h_s} + \frac{1}{h_{Fs}} + \frac{d_o}{2k} \ln(\frac{d_o}{d_i}) + \frac{d_o}{d_i} \frac{1}{h_{Fw}} + \frac{d_o}{d_i} \frac{1}{h_w}} \tag{9}$$

Outer and inner tube wall temperatures are obtained by following relations:

$$T_o = T_s - \frac{\Delta Q}{\Delta A_o}(\frac{1}{h_s} + \frac{1}{h_{Fs}}) \tag{10}$$

$$T_i = T_w + \frac{\Delta Q}{\Delta A_i}(\frac{1}{h_{Fw}} + \frac{1}{h_w}) \tag{11}$$

and the average wall temperature for tube properties calculation is:

$$T_m = \frac{T_o + T_i}{2} \tag{12}$$

Models for sodium- and water-sides heat transfer coefficients are listed in Table 1.

2.5 Code Structure

Major assumptions used in calculation are as follows.

- Constant heat load for each control volume
- Properties at the i-th control volume are corresponding to the average values of the i-1-th and i-th nodes

- Convergence criteria, 10^{-5}, is applied to relative variations of temperature and pressure for each control volume with respect to the previous iteration values, respectively

The input parameters are the SG heat transfer rate, flow rate, exit and inlet temperatures of the shell and tube sides, and steam exit pressure. As shown in the flow chart of Fig. 3, the solution goes through an iterative process.

3. Assessment of HSGSA

Performance of HSGSA was assessed making a sample calculation and comparing the results against design data prepared by the ALMR helical coil steam generator design [2].

3.1 Condition for sample calculation

The condition of the sample calculation is the same as the condition of the data to be compared for the HSGSA performance assessment and is listed in the Table 2.

The correlations used in the sample calculation are as follows.

	Heat Transfer			Pressure Drop	
	subcooled	saturated	superheated	single phase	two-phase
sodium side	Kalish-Dwyer	NA	NA	Gunter-Shaw	NA
water side	Seban-McLaughlin	Modified Chen	Modified Bishop	Mori-Nakayama	Jones

In the heat transfer calculation, a fouling factor was considered only to the water side. This case is assumed as only nucleate boiling heat transfer coefficient is applied to the whole two-phase flow region.

3.2 Comparison of the Results

The results of the sample calculation is shown in Table 3. The calculated values are compared to the data of the ALMR steam generator as shown below.

Parameters	Reference Plant	Case 1[1]	Case 2[2]	Remark
Overall Tube Length	85.30 m	89.51 m	102.00 m	
Tube Side Pressure Drop	0.975 MPa	0.842 MPa[3]	0.990 MPa[3]	

Note 1. Only modified Chen model for the saturated two-phase region (Fig. 4)
2. Modified Chen model with the film boiling correlation for the saturated two-phase region (Fig. 5)
3. Pressure drop calculation only for the tube bundle (The pressure drop in the inlet and outlet regions are not included in this work.)

As the reference case does not consider the film boiling region in the tube side, it can be compared with Case 1. This overpredicts that about 5% in the overall tube length and underpredicts about 13.6% in the tube side pressure drop. The deviations between them are caused mainly by the different pressure drop models in the tube side flow including helical coil geometric aspect.

In Figs. 4 and 5, the temperature distributions for the shell and tube sides including the tube wall sides is shown for the two cases. As shown in Fig. 4, the tube inner wall temperature for the Case 1 varies smoothly according to the tube side temperature variation. When the film boiling region is considered using Duchatelle et al.'s model (refer to Fig. 5), the temperature of the tube inner wall jumps up a little at the point of DNB occurrence.

For the Case 1 model, the water-side heat transfer coefficient, heat flux, and quality with respect to the tube axial position is shown in Fig. 6. In the view point of sizing calculation, this approach is more conservative.

4. Conclusion

A thermal sizing code, HSGSA, for a sodium heated helical coil steam generator is developed for KALIMER steam generator design. The theoretical modeling of the shell and tube sides are described and relevant correlations are presented. For an assessment of HSGSA code, a reference plant case is compared to the calculational outputs from HSGSA simulation. The result shows a reasonable agreement between them. Further works will be done to refine the HSGSA model and incorporate the steam generator performance analyses, e.g. two-phase pressure drop and heat transfer models, geometric aspect, and operational effects such as formation of rippled magnetite, etc.

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Table 1. Heat Transfer and Pressure Drop Correlations

Regions	**Correlations**
(Water Side)	**(Heat Transfer)**
Preheat	Seban-McLaughlin: $Nu = .023Re^{.85}\mathrm{Pr}^{.4}(\frac{d_i}{D_c})^{.1}$ Mori-Nakayama: $Nu = \frac{\mathrm{Pr}^{.4}Re^{5/6}}{41.0}(\frac{d_i}{D_c})^{1/12}\{1+\frac{.061}{[Re(\frac{d_i}{D_c})^{2.5}]^{1/6}}\}$ for $\mathrm{Pr}>1$
Nucleate Boiling	Chen (Modified for h_c): $h_B = Sh_b + Fh_c$ where, F: Martinelli parameter; S: suppression factor $h_c = .023(\frac{k}{d_i})(1-x)^{.8}Re^{.8}\mathrm{Pr}^{.4}(\frac{d_i}{D_c})^{.1}$ $h_b = 0.00122\left[\frac{k_l^{.79}c_{p_l}^{.45}\rho_l^{.49}}{\sigma^{.5}\mu_l^{.29}h_{fg}^{.24}\rho_g^{.24}}\right]\Delta t_{sat}^{.24}\Delta p_{sat}^{.75}$: modified Forster-Zuber equation Owhadi: $h_{TPF} = h_c A e^{1.436-29.722X_n+141.237X_n^2-325.34X_n^3+272.58X_n}$ where, $h_c = .023(\frac{k}{d_i})Re^{.85}\mathrm{Pr}^{.4}(\frac{d_i}{D_c})^{.1}$ $A=1$ when $X_n>.05$; $A=(\frac{D_c}{20d_i})^{.25}$ when $X_n\le .05$
Film Boiling	Bishop et al.: $Nu_f = 0.0193Re_f^{0.8}\mathrm{Pr}_f^{1.23}[x+(1-x)\frac{\rho_g}{\rho_f}]^{0.68}(\frac{\rho_g}{\rho_f})^{0.068}$
Superheat	Modified Bishop: $Nu = .0073Re^{.906}\mathrm{Pr}^{.61}(\frac{d_i}{D_c})^{.1}$ Mori-Nakayama: $Nu = \frac{\mathrm{Pr}^{.4}Re^{5/6}}{41.0}(\frac{d_i}{D_c})^{1/12}\{1+\frac{.061}{[Re(\frac{d_i}{D_c})^{2.5}]^{1/6}}\}$ for $\mathrm{Pr}>1$
Fouling	25,000 W/m^2-℃
(Water Side)	**(Critical Quality)**
	Duchatelle et al.: $x = 1.69\times10^{-4}q^{.719}G^{-.212}e^{2.5\times10^{-7}p}$
(Water Side)	**(Pressure Drop)**
Preheat/Superheat	Mori-Nakayama: $f = (\frac{d_i}{D_c})^{.5}\{\frac{.192}{[Re(\frac{d_i}{D_c})^{2.5}]^{1/6}}\}\{1+\frac{.068}{[Re(\frac{d_i}{D_c})^{2.5}]^{1/6}}\}$ Duchatelle: $f = (\frac{d_i}{D_c})^{.5}\{\frac{.1614}{[Re(\frac{d_i}{D_c})^{2.815}]^{1/6.63}}\}\{1+\frac{.002}{[Re(\frac{d_i}{D_c})^{2.815}]^{1/6.63}}\}$
Two-Phase	Homogeneous Equilibrium Model Modified Martinelli-Nelson or Jones Model Chisholm Model
(Sodium Side)	**(Heat Transfer)**
	Kalish-Dwyer: $Nu = \varphi(d/p)(5.44+.228Pe^{.614})(\frac{\sin\theta+\sin^2\theta}{1+\sin^2\theta})^{1/2}$ where, $\varphi(d/p)$: Geometric Factor using Hsu[1964] (cross flow model) Lubarsky-Kaufman: $Nu = .625Re^{.4}\mathrm{Pr}^{.4}$ (in-line flow model)
(Fouling	25,000 W/m^2-℃)
(Sodium Side)	**(Pressure Drop)**
	Gunter-Shaw: $\Delta p = \frac{f_c}{2}\frac{G^2L}{\rho_b D}(\frac{\mu_b}{\mu_w})^{.14}(\frac{D_v}{s_T})^{.4}(\frac{s_L}{s_T})^{.6}$ where, $\frac{f_c}{2} = .96(\frac{D_vG}{\mu_b})^{.145}$

Table 2. Plant Conditions for the ALMR Steam Generator

Operating Parameters		Design Value
Heat Load	:	479 MWth
Sodium Inlet Temperature	:	438.3 ℃
Sodium Outlet Temperature	:	288.3 ℃
Sodium Flow Rate	:	2477.78 kg/sec
Steam Outlet Pressure	:	9.96 MPa
Water/Steam Flow Rate	:	215.622 kg/sec
Number of Tubes/Rows	:	429/22
Tube OD/ID	:	.0254/.01953 m
Tube Bundle Transverse Tube Pitch	:	.05715 m
Tube Bundle Longitudinal Tube Pitch	:	.03810 m
Tube Pitch Angle	:	6.05 degrees

Table 3. Sample Calculation Output for Reference Plant Steam Generator (Case 1)

Shell Side Information			
Inlet Pressure	[MPa]	:	0.185
Inlet Temperature	[℃]	:	438.074
Outlet Pressure	[MPa]	:	0.220
Outlet Temperature	[℃]	:	288.300
Outlet Flowrate	[kg/sec]	:	2477.780
Input Thermal Power	[MWth]	:	479.000
(Total Pressure Drop	[kPa]	:	34.603)
Tube Side Information			
Inlet Pressure	[MPa]	:	10.802
Inlet Temperature	[℃]	:	215.600
Outlet Pressure	[MPa]	:	9.960
Outlet Temperature [℃]		:	415.632
Inlet Flowrate	[kg/sec]	:	215.622
Output Thermal Power	[MWth]	:	479.000
Tube Flow Region			
Total Tube Length	[m]	:	89.514
Subcooled Region Length	[m]	:	33.717
Saturated Region Length	[m]	:	41.410
Superheated Region Length	[m]	:	14.387
Total Pressure Drop	[MPa]	:	0.842

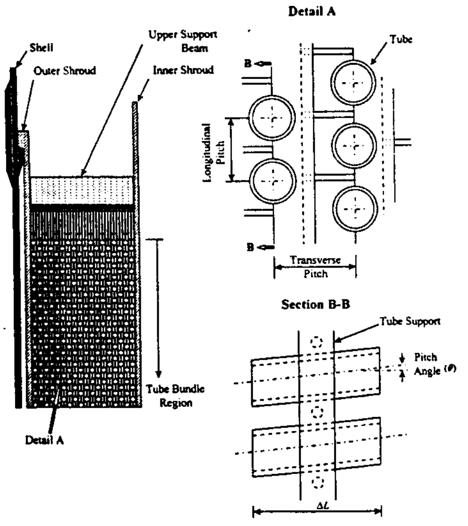

Fig. 1 Typical Tube Bundle Arragement for a Helical Coil SG

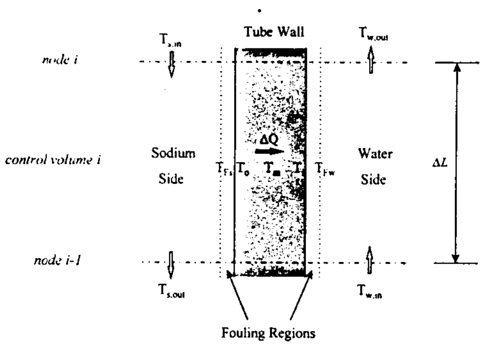

Fig. 2 Theoretical Model of a Control Volume for Heat Transfer

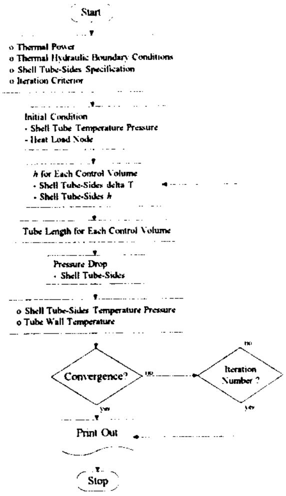

Fig. 3 HSGSA Sizing Calculation Flow Chart

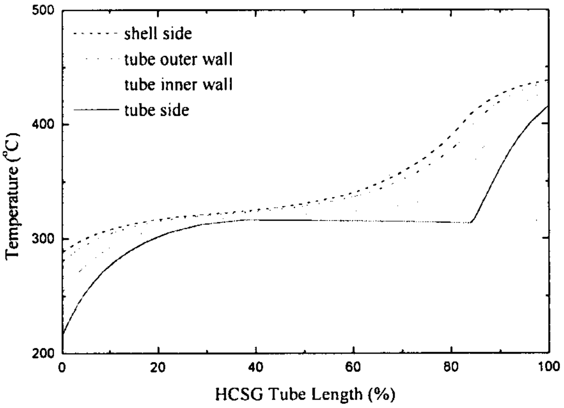

Fig. 4 Sample Calculation for Reference Plant Steam Generator (Case 1)

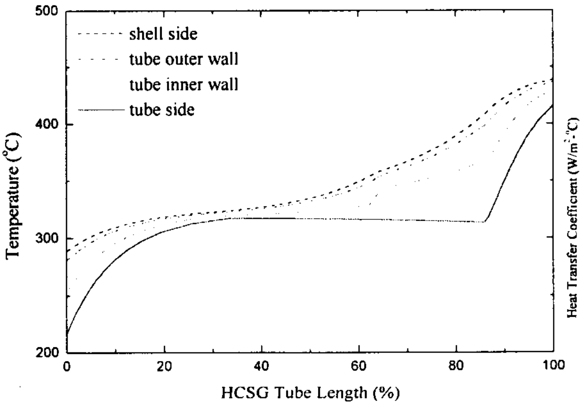

Fig. 5 Sample Calculation for Reference Plant Steam Generator (Case 2)

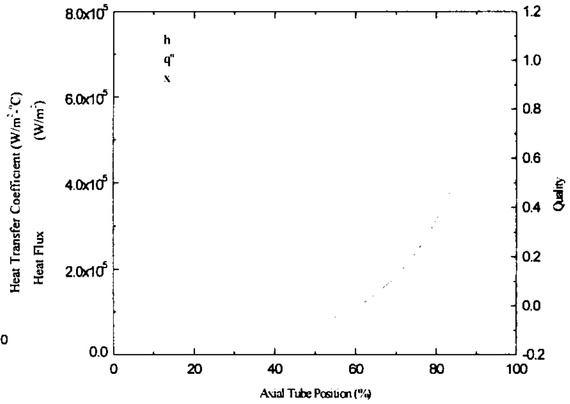

Fig. 6 Heat Transfer Coefficient, Heat Flux, and Quality wrt Axial Position (Case 1)