The Local Scaling Analysis for Experiments of the Helically Coiled Tube Steam Generator

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1. Introduction

Recently, Korean institutions have made an effort to develop the innovative Small Modular Reactor (i-SMR). This reactor adopts the helically coiled tube Steam Generator (SG). Because of the helical shape of the tubes, centrifugal force is formed inside the SG heat exchanger tubes. Thus, the Thermo-Hydraulic (T/H) phenomena differ from straight or U-tube type SG, such as dry-out occurring at relatively low quality ($x = 0.7$) [1]. Therefore, analysis and experiments are needed to study these phenomena.

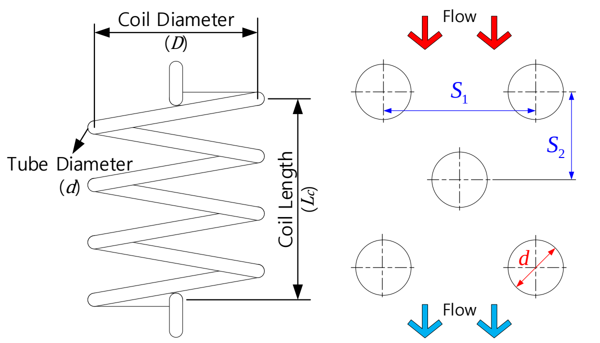
Ideally, the experimental facilities should be identical to the nuclear power plant (NPP) to confirm the same phenomena. However, the experimental facilities should be scaled down from the real because of space limitations and economic efficiency. Therefore, reducing the reality causes scale distortion, which needs to be analyzed.

This study conducted the scaling analysis for the helically coiled tube SG, derived the scaling ratios, and quantified the scale distortion.

2. Scaling Analysis

2.1. Helically coiled tube steam generator

In Fig. 1(a), the main design variables for the helically coiled tube SG are tube diameter (d), length (L), and helical coil diameter (D). Also, the SG heat exchanger consists of a bundle of tubes, so the transverse (S_1) and longitudinal (S_2) pitches are the other main design variables, as shown in Fig. 1(b). After the scaling analysis, each design variable for the scaled SG experiments can be specified.



(a) Helically coiled tube (b) Cross-section of SG

Fig. 1. Schematic of a helically coiled tube SG

2.2. Global scaling

The scaling laws of Carbiener and Cudnik, Nahavandi et al., and Ishii and Kataoka are typical global scaling laws [2]. The ATLAS designed by KAERI was developed using Ishii's third-level scaling law [3]. This study also uses the same scaling law as the ATLAS.

In global scaling, the governing equations for the system are dimensionless using dimensionless variables. Under the assumption that the material and fluid properties are conserved, the ratio of coefficients in each equation must be 1 ($\pi_{i,m}/\pi_{i,p} = 1$) for the T/H phenomena to be conserved between the prototype and the model. Table I organizes the coefficients derived from dimensionless governing equations and shows their main scale ratios.

Table I: Major coefficients and scale ratios

Coefficients	Governing Equations	Parameter	Scale ratio
$\pi_1 = \dfrac{g\beta\Delta T l}{u^2}$	Momentum	u_R	$l_R^{1/2}$
		t_R	$l_R^{1/2}$
		$\dot{m}_R$	$a_R l_R^{1/2}$
$\pi_2 = \dfrac{q_s''' l_s}{\rho_s c_{p,s} u \Delta T}$	Energy (solid)	${q_s'''}_R$	$l_R^{-1/2}$
		$\dot{Q}_R$	$a_R l_R^{1/2}$
$\pi_3 = \dfrac{4hl}{\rho c_p u d}$	Energy (fluid)	d_R	$a_R^{1/2}$
			$l_R^{1/2}$

2.3. Local scaling

Even if global scaling is performed, distortion may occur due to shape reduction in certain T/H phenomena. In addition, the diameter ratio (d_R) in Table I is different from $a_R^{1/2}$ and $l_R^{1/2}$. When $d_R = a_R^{1/2}$, the diameter of model decreases significantly, and distortion is expected to become severe, so in some cases, the diameter is preserved as $d_R = 1$. So, local scaling must be performed to preserve the specific T/H phenomena and specify the scale ratio.

2.3.1. Tube side pressure drop

Unlike the straight pipes, the pressure drop inside the helical tube must consider the centrifugal force. Xiao et al. pressure drop correlation [4] (Eq. (1) to (3)) was developed with their experimental data, and it considers the curvature effect of the helical coil as shown in Eq. (2).

$$\Delta P_{2\phi} = \phi_{lo}^2 f \frac{L}{d}\frac{G^2}{2\rho'} \quad (1)$$

$$f = \frac{0.3164}{Re_{lo}^{0.25}}\left(1 + Re_{lo}^{0.053}\left(\frac{d}{D_c}\right)^{0.404}\right) \quad (2)$$

$$\phi_{lo}^2 = (0.377 + 6.79x - 5.66x^2)\left[1 + x\left(\frac{\mu''}{\mu'} - 1\right)\right]^{0.25} \quad (3)$$

By the global scaling, the pressure drop ratio should be $\Delta P_{2\phi,R} = \Delta P_{2\phi,m}/\Delta P_{2\phi,p} = l_R$. Then, the local scaling is performed as follows procedures. 1) By the assumption that fluid properties are conserved, the scaling ratio of the 2-phase multiplier ϕ_{lo}^2 is 1. 2) Only the geometry of the tube and Re are the scaling parameters. It mentioned that before, d_R is different from 1 and $l_R^{1/2}$. By substituting each d_R to Eq. (4), the distortion of the pressure drop scale can be quantified (Fig. 2(a)).

$$\Delta P_{2\phi,R} = \frac{f_m}{f_p}\frac{L_m}{L_p}\left(\frac{d_m}{d_p}\right)^{-1}\left(\frac{v_m}{v_p}\right)^2 = f_R l_R d_R^{-1} l_R = l_R \quad (4)$$

$$f_R = \frac{f_m}{f_p} = \left(\frac{Re_m}{Re_p}\right)^{-0.25}\frac{\left(1+Re_m^{0.053}\left(\frac{d}{D}\right)_m^{0.404}\right)}{\left(1+Re_p^{0.053}\left(\frac{d}{D}\right)_p^{0.404}\right)} \quad (5)$$

2.3.2. Tube side heat transfer

Similar to pressure drop scaling, heat transfer scaling should consider centrifugal force, as in Guo et al.'s correlation (Eq. (6)) [5]. Assuming that the heat transfer coefficient is conserved between the prototype and model, then the scaling ratio can be derived as Eq. (7).

$$h = \frac{0.021kRe^{0.8}Pr^{0.4}\left(\frac{r}{R_c}\right)^{0.1}}{2r} \quad (6)$$

$$h_R = \frac{h_m}{h_p} = \left(\frac{Re_m}{Re_p}\right)^{0.8}\left(\frac{(r/R_c)_m}{(r/R_c)_p}\right)^{0.1}\left(\frac{r_m}{r_p}\right)^{-1} = 1 \quad (7)$$

In Fig. 2(b), the distortion of the heat transfer is quantified, and the tube diameter ratio is decided as $l_R^{1/2}$.

Also, tube thickness can be defined by scaling the conduction heat transfer equation, as in Eq. (8). As a result, tube thickness should be the same as the prototype tube.

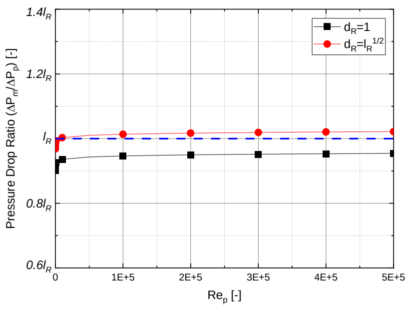
$$q''_{cond} = \frac{k\Delta T}{r\ln(r_2/r_1)} \quad (8)$$

2.3.3. Shell side heat transfer

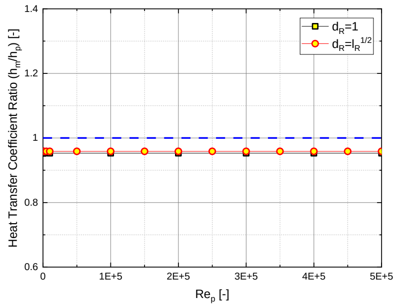
Fig. 1(b) shows the cross-sectional view of the SG. Scaling Zukauskas (1987) models can define the transverse and longitudinal pitches ratio. Eq. (9) to (12) show heat transfer models [6]. These models were developed from low to high Re conditions.

$$h = \frac{k}{d}1.04Re^{0.4}Pr^{0.36}\left(\frac{Pr}{Pr_w}\right)^{0.25} \quad (1.6 \le \mathrm{Re} \le 40) \quad (9)$$

$$h = \frac{k}{d}0.71Re^{0.5}Pr^{0.36}\left(\frac{Pr}{Pr_w}\right)^{0.25} \quad (40 \le \mathrm{Re} \le 10^3) \quad (10)$$



(a) Pressure drop



(b) Heat transfer coefficient

Fig. 2. Local scaling results (tube side)

$$h = 0.35\left(\frac{S_1}{S_2}\right)^{0.2}\frac{k}{d}Re_d^{0.6}Pr_d^{0.36}\left(\frac{Pr}{Pr_w}\right)^{0.25} \quad (10^3 \le \mathrm{Re} \le 2\times10^5) \quad (11)$$

$$h = 0.031\left(\frac{S_1}{S_2}\right)^{0.2}\frac{k}{d}Re_d^{0.8}Pr_d^{0.4}\left(\frac{Pr}{Pr_w}\right)^{0.25} \quad (2\times10^5 \le \mathrm{Re}) \quad (12)$$

After the scaling analysis, the pitch ratio for the scaled experiment can obtained with Eq. (11), which has the largest range of Re. And the quantified distortion is -17 % to +30%, as shown in Fig. 3.

$$(S_1/S_2)_R = \frac{(S_1/S_2)_m}{(S_1/S_2)_p} = l_R^{-1/2} \quad (13)$$

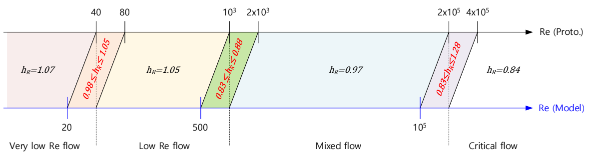


Fig. 3. Shell side heat transfer local scaling result

2.3.4. Shell side pressure drop

The IDELCHIK book [7] was referred to for the scaling analysis of the pressure drop on the shell side. The correlation includes information on the transverse and longitudinal pitches, the number of helical tube layers (z_r), and the inclination angle (θ). After scaling analysis with $\Delta P_R = 1$, the derived results can be obtained (Eq. (15)).

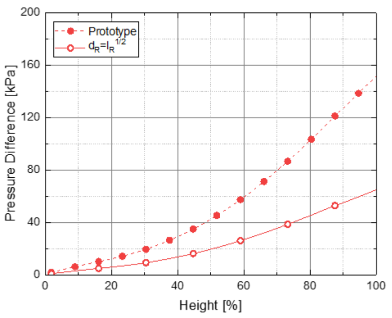
$$\frac{\Delta P}{\rho_{av}u_{av}^2/2} = \psi A Re_{av}^{-0.27}(z_r + 1) + \Delta\zeta_t \quad (14)$$

where ψ is constant, including θ, and A contains tube outer diameter and pitch information.

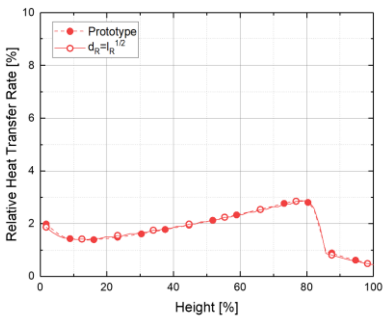
$$(\bar{S} + 1)^2{}_m = (\bar{S} + 1)^2{}_p (l_R)^{0.27}\frac{(z_r+1)_p}{(z_r+1)_m} \quad (15)$$

3. Evaluation of the scaling analysis

Using MARS-KS, a system analysis code, we evaluated whether the T/H phenomena of the reduced-scale SG above are similar to that of the prototype SG. As shown in Fig. 4, the pressure drop and heat transfer rate in the helically coiled tube SG were found to simulate the prototype well.



(a) Pressure drop



(b) Heat transfer coefficient

Fig. 3. MARS-KS calculation results

4. Conclusion

This study performed global and local scaling analysis on the helically coiled tube SG and derived the scale ratios for the main design variables inside and outside of the tube. Also, the scale distortion was quantified.

When the scale ratios of the tube diameter and thickness were $d_R = l_R^{1/2}$ and $t_R = 1$, the quantified distortions and results are as follows:

1) Pressure drop (tube): -7 % to 1.6 %
2) Heat transfer coefficient (tube): -4 %
3) Heat flux (tube): ±5 %
4) Heat transfer coefficient (shell): -17 % to 30 %

The pressure drop and internal heat transfer of the prototype and model were compared through MARS-KS, and it was found that the T/H behaviors were similar.

NOMENCLATURE

A Coefficient for pitch and tube diameter
d Tube diameter
D Helical diameter
f Friction factor
h Heat transfer coefficient
L Tube length
$\dot{m}$ Mass flow rate
ΔP Pressure drop
Pr Prandtl number
q''' Volumetric heat transfer rate
q'' Heat flux
$\dot{Q}$ Heat transfer rate
r Tube radius
Re Reynolds number
S_1 Transverse pitch
S_2 Longitudinal pitch
$\bar{S}$ Coefficient of pitch
t Tube thickness
ΔT Temperature difference

Greek symbols

β Thermal expansion coefficient
$\Delta\zeta_t$ Temperature difference
ρ Density

Subscripts

c Coil
m Model
p Prototype
R Ratio between model and prototype
w Wall

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