Modeling Heat Transfer in Helically Coiled Steam Generators Using Different Correlations

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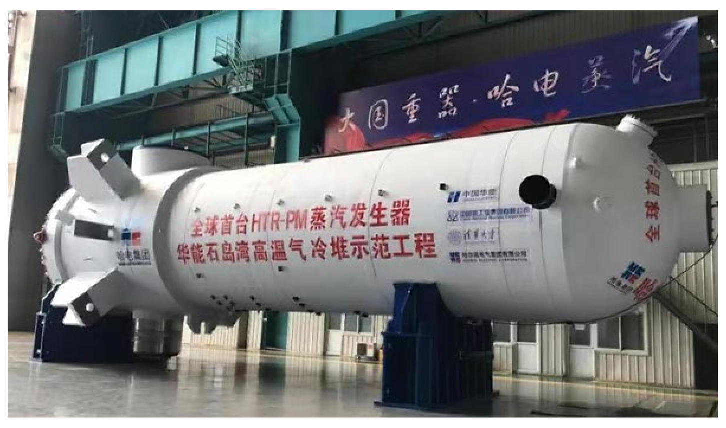
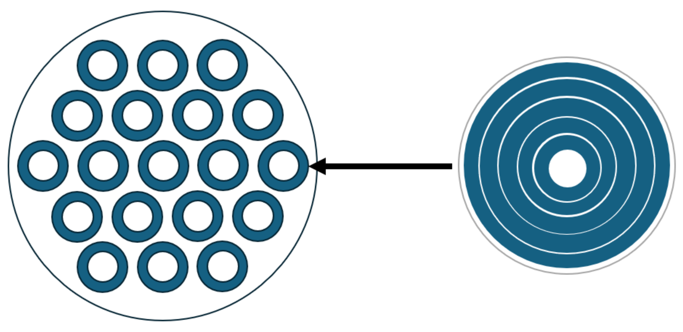
Introduction

- Small Modular Reactor (SMR) is spotlighted as next-generation clean energy source.
- Helical Steam Generator (HSG) design is widely adopted in SMR due to its compact sizing.
- Operating parameters of HTR-PM -High-Temperature Gas Reactor developed in China- were used to find optimal correlations to model heat transfer behavior in HSG in HTR-PM.



Outer view of HTR-PM HSG



Cross Section of HTR-PM HSG

Parameter	Primary	Secondary
Inlet Temperature [°C]	750	205
Outlet Temperature [°C]	250	566
Inlet Pressure [MPa]	7.0	13.24
Mass Flow Rate [kg/s]	96	95 *
Shell Height [m]	8.6	
Average Helical Diameter, D_c [m]	0.215 *	
Tube Inner / Outer Diameter, d_i / d_o [mm]	17 / 19	
Tube Vertical / Horizontal Pitch [mm]	30 / 25	
Tube Thermal Conductivity [W/m K]	T22: 32.1~37.2 (205~643°C)	Incoloy 800H: 22.2 (643°C~)

* Assumed values

Operating Parameters of HTR-PM

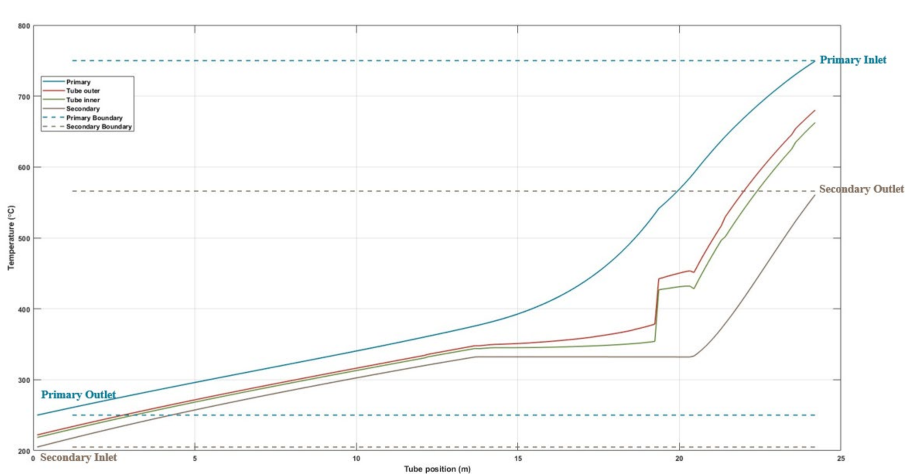
- The steam generator shell in HTR-PM contains 19 HSGs, and each HSG is composed of 35 helical tubes. Helium flows as primary coolant in the shell and steam flows in the tubes as secondary coolant.
- Heat transfer between secondary coolant in single tube and primary coolant in shell side was modeled using MATLAB. Each tube is modeled as an inclined straight tube as helical diameter is relatively large.

System Modeling Using MATLAB

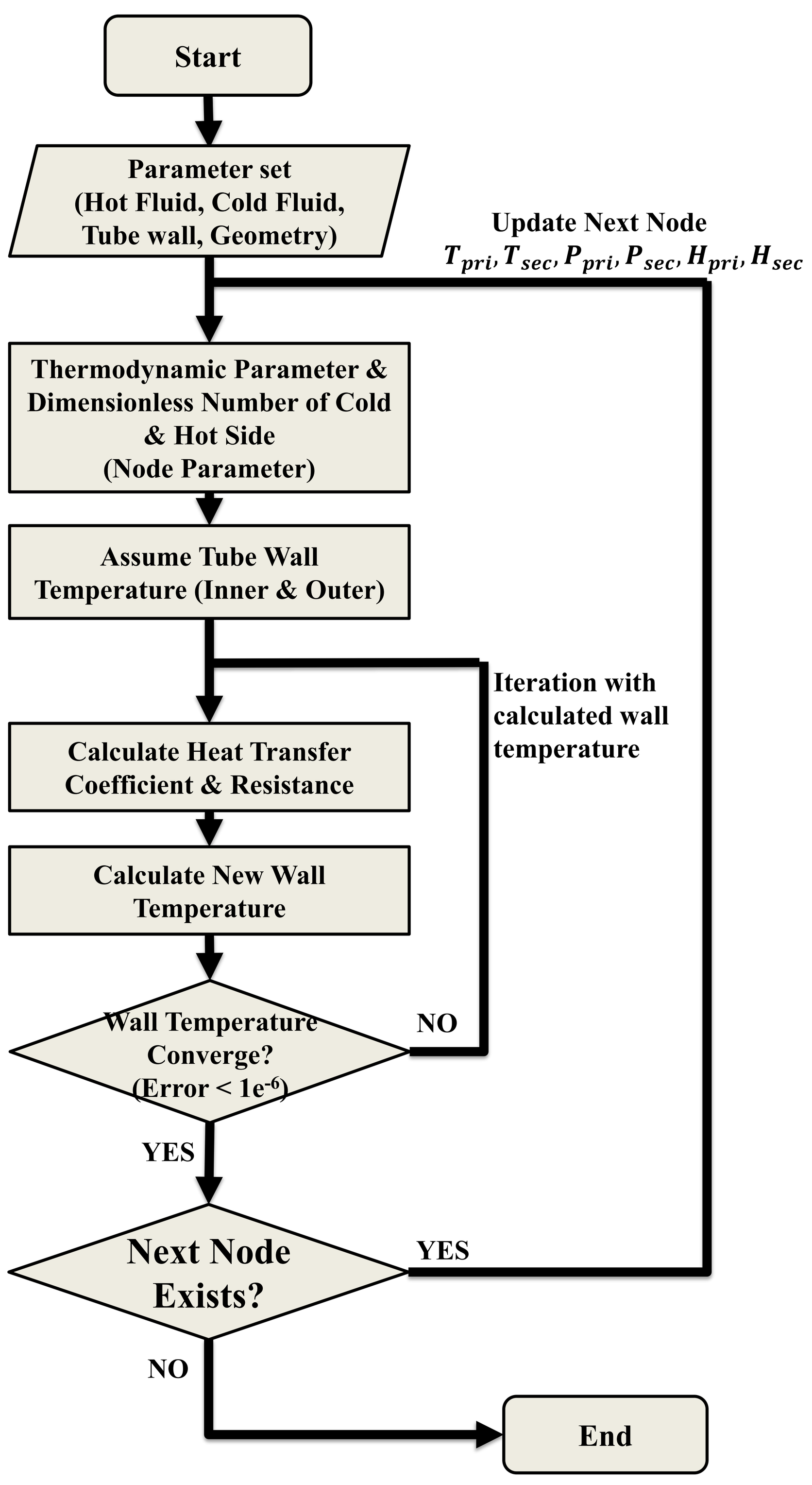
- The following correlations, which were utilized in the work of Sun et al. on optimization of parameters of HTR-PM, were input into MATLAB.
- The resulting temperature profile behaves similarly as Sun's model, but with different values. Sun's model approximates the optimal tube length as 60m, whereas this model predicts 24.2m. The difference between the two models implies that input parameters are different.

Zone	Correlations
Heat Transfer Correlations	
Single-phase liquid zone (shell side)	Žukauskas
Single-phase liquid zone (tube side)	Schmidt
Subcooled boiling zone	Hardik
Saturated boiling and forced convection Evaporation Zone	Yang's Revision of Chen
Liquid deficiency zone	Xu and Jia's rei vision of Mirop ol'skiy
Single-phase vapor zone (tube side)	Mori and Nakayama
Pressure Drop Correlations	
Single-phase liquid zone (shell side)	Gilli
Single-phase liquid zone	Ito
Two-phase liquid zone	Colombo

Correlations Used in Computational Model



Temperature Variation of Primary Coolant, Inner & Outer Tube wall, and Secondary Coolant along the tube length



Logic Flow Chart of Computational Model

- Two-phase correlations are modified version of Chen and Miropol'skiy since the original correlations are made for straight tubes and do not account for the centrifugal force arising from the helical structure

Different Two Phase Correlations

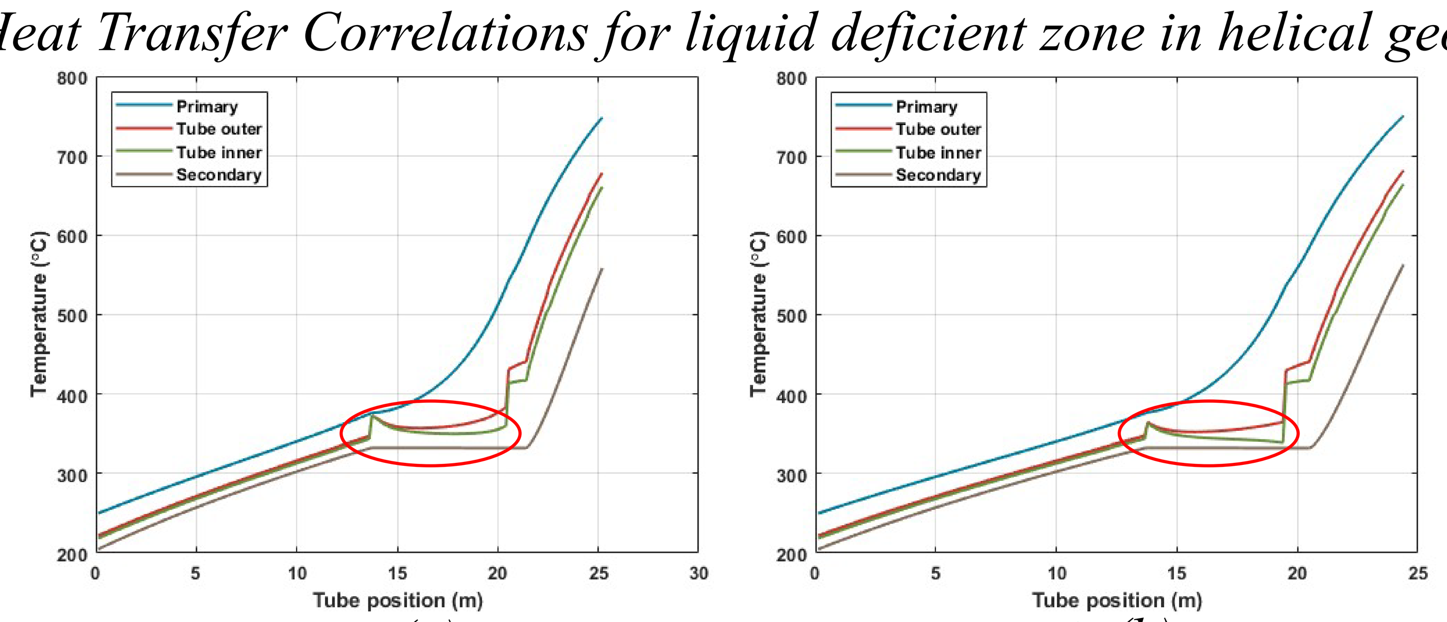
- Below are other correlations for two phase flow regime in helical geometry that were developed in previous researches. Two were chosen (based on their operating condition) for each zone and were tested.

Researchers	Correlations
Guo	$\frac{h_{tpc}}{h_{lc}} = 7.51\left(\frac{1}{X_{tt}}\right)^{0.727}\left(\frac{p}{p_c}\right)^{0.577}$ $\frac{h_{lc}d}{\lambda_l} = 0.021 Re_l^{0.8} Pr_l^{0.4}\left(\frac{d}{D}\right)^{0.1},$ $Re_l = \frac{Gd}{\mu_l}$
Zhao	$h_{TP} = Fh_l,$ $F = 1.6(X_{tt})^{-0.74} + 183{,}000 Bo^{1.46}$ $h_l = \frac{1}{41} Re_l^{0.8} Pr_l^{0.4}\left(Re_l\left(\frac{d}{D}\right)^2\right)^{1/20}\frac{k_l}{d}$

Heat Transfer Correlations for two-phase flow in helical geometry

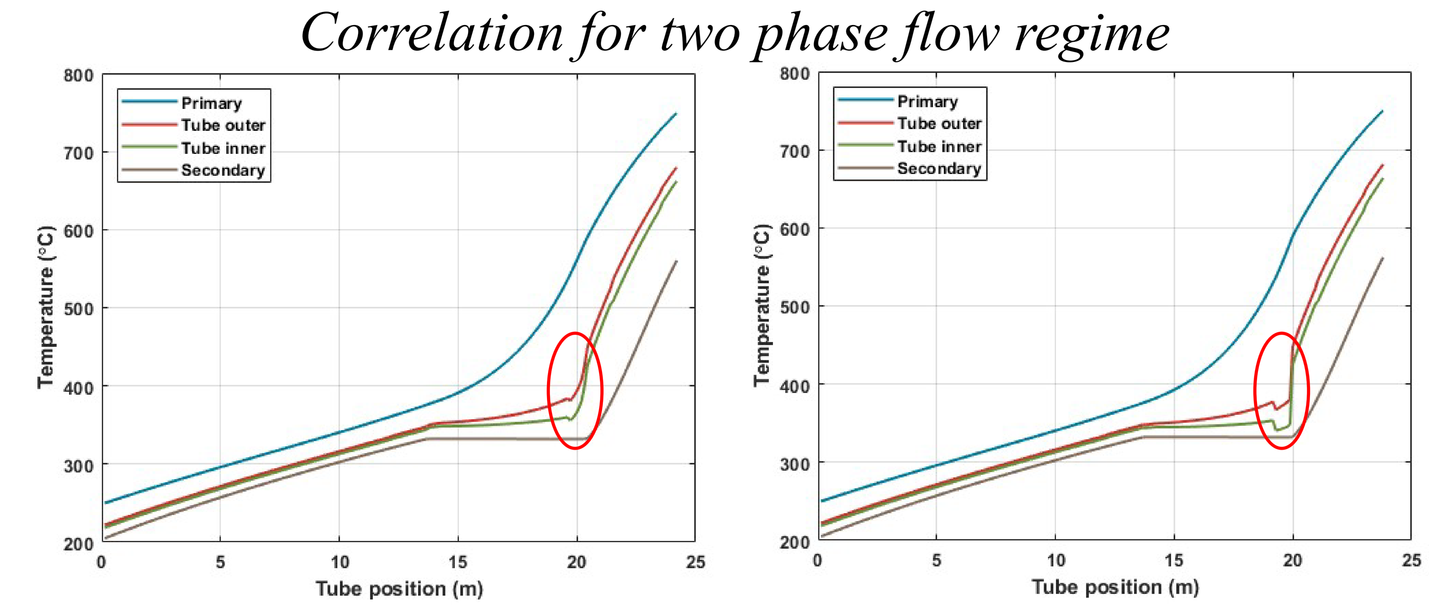
Researchers	Correlations
Guo	$\frac{h_{tpc}}{h_{lc}} = 26.5\left(\frac{1}{X_{tt}}\right)^{-0.248}$
Xiao	$Nu_g = 0.00567\left[\frac{GD}{\mu_g}\left(x + \frac{\rho_g}{\rho_l}(1-x)\right)\right]^{0.565} Pr_g^{-0.245} Y,$ $Y = \left[1 - 0.1\left(\frac{\rho_l - \rho_g}{\rho_g}\right)^{0.4}(1-x)^{0.4}\right]^{-4.5}\left(\frac{4q}{h_{fg}G}\right)^{-1.1}\left(\frac{1}{X_{tt}}\right)^{-0.447}$

Heat Transfer Correlations for liquid deficient zone in helical geometry



(a) (b)

Temperature Variation using (a) Zhao and (b) Guo Correlation for two phase flow regime



(c) (d)

Temperature Variation using (c) Xiao and (d) Guo Correlation in liquid deficient zone

- Switching from Yang to Zhao and Guo displays an abrupt jump in wall temperature when the phase of flow changes to two phase flow, meaning the two correlations overestimate the heat transfer coefficient. Zhao correlation estimates optimal length to be 25.2m, and Guo 24.4m.
- Change from Xu to Xiao and Guo changes the temperature jump of tube wall. Xiao correlation predicts a smooth but steep rise in wall temperature, and Guo shows that jump happens at the end of the zone. Xiao correlation estimates optimal length to be 24.2m, and Guo 23.8m.

Results and Discussion

- Yang seems to be the best approximation for two phase zone. The overestimation of Zhao and Guo correlations imply that these correlations are not suitable for operating parameters of HTR-PM.
- The Xiao correlation provides the best approximation for liquid deficient zone. Both correlations predict a wall temperature jump of approximately 80°C, which is significantly higher than the expected 30-50°C range.
- Future works should focus on obtaining experimental data to validate the numerical model. Additionally, validating the assumed operating parameters will further enhance model accuracy.