

Modification of the Heat Transfer Model of a Helically Coiled Tube in the SPACE Code

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1. Introduction

The helically coiled heat exchangers are widely used because of their compact structure and higher heat transfer capability [1]. Due to these advantages, they have been used in a variety of fields, especially in air conditioning, nuclear systems, etc. In the field of nuclear system, many small modular reactors (SMRs), such as NuScale, SMART, i-SMR, etc., have adopted a helical coiled steam generator (HSG) due to its excellent heat transfer capability. Therefore, the accurate prediction of heat transfer in HSG is essential for the optimum design and safety analysis of these SMRs.

For the previous study [2], the heat transfer model of HSG has been assessed in MARS-KS and SPACE codes. The results showed that the onset of transition boiling model, so called the point of first dryout (FDO) model, could have a significant impact on the predictability of heat transfer coefficient (HTC).

In this study, the FDO model proposed by Santini et al. [3] was implemented in the SPACE code and, the modified SPACE code has been assessed against collected experimental data. The results of the modified SPACE code was compared with the those of the original SPACE code [2]. The results are discussed in detail.

2. Heat transfer model of HSG

The heat transfer mechanism within a helical tube differ from that in a straight tube. In the thermal-hydraulic system code, such as the SPACE code, the heat transfer model inside the tube of HSG is divided into the regions of single-phase liquid, nucleate boiling, transition boiling, and single-phase vapor. In this section, the heat transfer models for the regions are described in detail.

2.1 Description of HSG model

For the single-phase liquid flow region, the Mori-Nakayama correlation [4] is used as follows.

$$\ddot{q} = \dot{h}_{M-N}(T_w - T_f), \quad (1)$$

where, $\dot{h}_{M-N} = 0.03846 \frac{k_f}{d} Re_f^{0.8}$

$$\times \frac{Pr_f}{(Pr_f^{2/3} - 0.074)} \left(\frac{d}{D}\right)^{0.1} \left[1 + \frac{0.098}{Re_f^{0.2} \left(\frac{d}{D}\right)^{0.4}}\right].$$

For the nucleate boiling region, the Chen nucleate boiling model [5] is represented as:

$$\ddot{q}_{NB} = \dot{h}_{M-N}(T_w - T_f)F + \dot{h}_{mic}(T_w - T_{sat})S, \quad (2)$$

$$\text{where } \dot{h}_{mic} = 0.00122 \frac{k_l^{0.79} C_{p,l}^{0.45} \rho_l^{0.49}}{\sigma_l^{0.5} \mu_l^{0.29} h_{fg}^{0.24} \rho_v^{0.24}} (\Delta T_w)^{0.24} \times (\Delta p)^{0.75} S.$$

For the transition boiling, the formation of chen correlation [6] is used as:

$$\ddot{q}_{TB} = \ddot{q}_{NB} a_f + \dot{h}_{M-N}(T_w - T_g)(1 - a_f), \quad (3)$$

$$\text{where } a_f = 1.0 - \frac{\min[\alpha, 0.999] - 0.99}{0.009} \text{ for } \alpha \geq 0.99.$$

In the SPACE code, the onset of transition boiling, so called the point of FDO, was considered to be when the void fraction is greater than 0.99. The end of the transition boiling region, so called the point of total dryout (TDO), is considered to be when the void fraction is greater than 0.999. From the point of TDO, Eq. (1) is also used for the single-phase vapor region.

For the previous study, we implemented the Pusan National University (PNU) nucleate boiling model [7], which has been developed for experimental data of saturated flow boiling in a helically coiled tube. The PNU model has been validated for thermal-hydraulic conditions with pressures ranging from 1.0 to 140 bar, heat fluxes of 46 to 620 kW/m², mass fluxes of 77 to 1000 kg/m²s, D/d of 12.4 to 81.0. The PNU nucleate boiling model can be used as a substitute for the Chen nucleate boiling model of Eq (2) and is as follows.

$$\ddot{q}_{NB} = \dot{h}_{lo} C_1 Co^{C_2} (1 + C_3 N_{CF,l})^{C_4} (T_w - T_f) + \dot{h}_{lo} (C_5 Bo^{C_6} + C_7) (T_w - T_{sat}), \quad (4)$$

where, $\dot{h}_{lo} = 0.023 Re_f^{0.8} Pr_f^{0.4} \frac{k}{D}$,

$$Co = \left[\left(\frac{1-x}{x} \right)^{0.8} \left(\frac{\rho_g}{\rho_f} \right)^{0.5} \right], x = \frac{m_g}{m_{tot}},$$

$$N_{CF,l} = \frac{G^2 (1-x)^2}{\alpha_l^2 \rho_l^2 g D_{HC} 1 + (P/\pi D_{HC})^2},$$

$$Bo = \frac{\ddot{q}}{G h_{fg}}, C_1 = 0.983,$$

$$C_2 = -0.874, C_3 = 0.024, C_4 = 0.377,$$

$$C_5 = 3858.4, C_6 = 0.920, C_7 = 0.517.$$

2.2 Modification of dryout model

From the previous study, it was shown that FDO model could have a significant impact on the predictability of heat transfer coefficient. Among FDO models, the model proposed by Santini et al. [3] et al. has been validated for thermal-hydraulic conditions with pressures ranging from 10.7 to 60.7 bar, heat fluxes of 43.6 to 209.3 kW/m², mass fluxes of 199 to 810 kg/m²s. In some literature [8, 9], the model is used to predict the point of FDO and is reported to have a low average error. The model of Santini et al. [3] is as follows.

$$X_{eq} = (0.44 - 0.006p)G^{0.114} \quad (5)$$

where, X_{eq} is thermal equilibrium quality, p is in bar and, G is in kg/m²s. Instead of $\alpha = 0.99$, Eq. (5) is used as FDO model in the SPACE code. In Ref. [9], $X_{eq} = 1.0$ as the TDO model was recommended in the RELAP5 code. Therefore, instead of $\alpha = 0.999$, X_{eq} is used as 1.0.

3. Assessment of HSG heat transfer model

3.1 Experimental data

Some studies related to the HSG heat transfer have been conducted over several years. Among them, we have collected some experimental database to evaluate the HSG heat transfer model in both codes. As shown in Table 1, the experimental data covers a wide range of thermal-hydraulic conditions. The experimental data of Hardik and Prabhu [10] include the single-phase and nucleate boiling region (low quality region). The experimental data of Chang et al. [11] and Santini et al. [12] cover the nucleate boiling region (low- and high-quality region). The experimental data of Xiao et al. [13] include the transition boiling region (post-dryout region). The experimental data of Wu et al. [14] include all flow regions.

Table 1. Experimental conditions

Experiment	Press. (bar)	Heat flux (kW/m ²)	Mass flux (kg/m ² s)	D/d (-)
Hardik and Prabhu [10]	1.0 ~2.0	100~620	129 ~400	14.4 17.1
Chang et al. [11]	80.0~ 110.0	100~290	500 ~1000	81.3
Santini et al. [12]	20.0 ~60.0	51~200	200 ~820	80.1
Xiao et al. [13]	20.0 ~48.0	200~400	400 ~800	12.4 30.4
Wu et al. [14]	24.0	250	250	247
Total	1.1 ~110	51~620	129 ~1000	12.4~ 247

3.2 Assessment results

The nodalization for the validation of heat transfer model of HSG is shown in Fig. 1. It consists of two boundary condition (TFBC), two pipes at the inlet and outlet of the heated section, and a pipe and a heat structure for the heated section of a helical tube. The heated section is divided into 20 nodes for each experiment.

Using the nodalization, we simulated the collected experiments using three heat transfer model package in the SPACE code. The first is the default model of HSG without using any special model in Section 2.1. The second is a model in which the Chen nucleate boiling model is replaced with the PNU nucleate boiling model in the default HTC model package. The third is a model in which the Chen nucleate boiling model and the original dryout model is replaced with the PNU nucleate boiling and the modified dryout model mentioned in Section 2.2.

As shown in Fig. 2(a), (b), (c), for single-phase liquid, nucleate boiling regions, the original SPACE showed a tendency to overpredict experimental data. On the other hand, the SPACE codes using the PNU nucleate boiling (SPACE_PNU) showed a tendency to primarily underpredict experimental data. Meanwhile, the results of SPACE_PNU and SPACE_PNU with the modified dryout model are almost identical. This is because the heat transfer model is the same before dryout occurs.

As shown in Figs. 2(d), (e), in the case of experiments including post-dryout regions, the original SPACE code showed that the point of FDO was predicted late and, thus, the HTC was overpredicted for the transition region. The SPACE_PNU also predicts FDO late, but it predicts HTC better than original SPACE for transition boiling region. It seems that because the PNU nucleate boiling model under-predicted HTC, and the original FDO model caused HTC to over-predict. Thus, the error was reduced due to the combination of the two models. In the SPACE_PNU with the modification of dryout model, the predictability of FDO has been significantly improved. As a results, the results of SPACE_PNU with the modification of dryout model showed the best agreement with experimental data among the three codes. As presented in Table 2, the RMSE assessment results also showed the best agreement of the SPACE_PNU with the modification of dryout model.

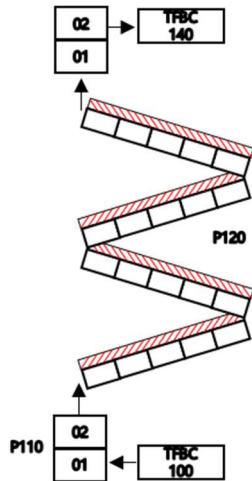
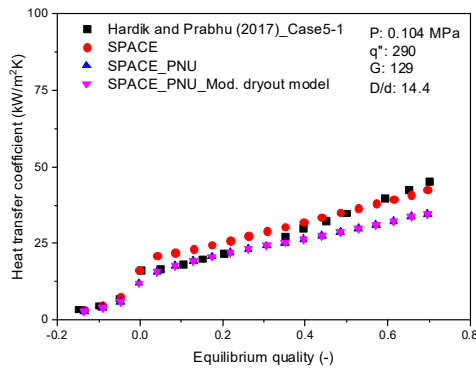
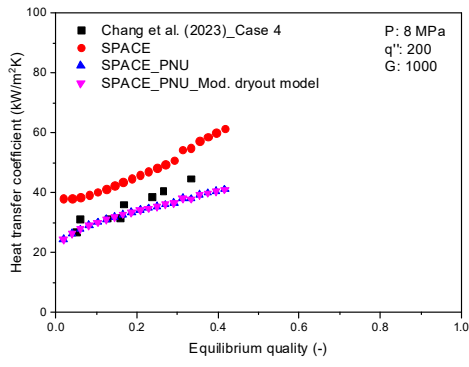


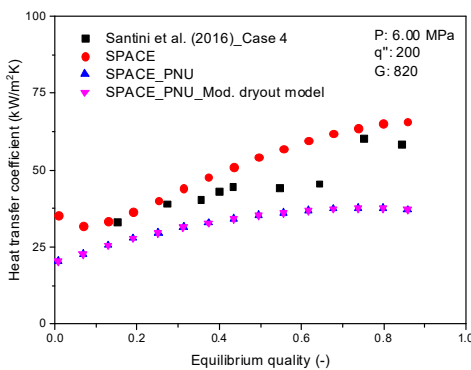
Fig. 1. The nodalization for the validation of heat transfer model of HSG.



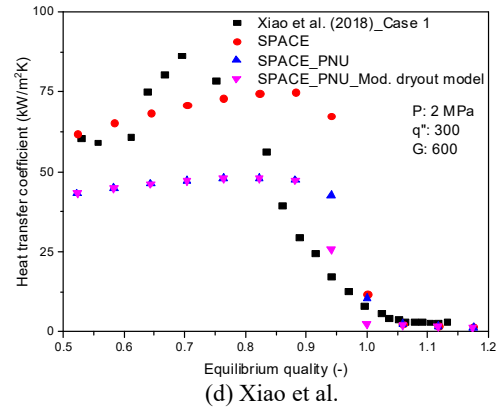
(a) Hardik and Prabhu



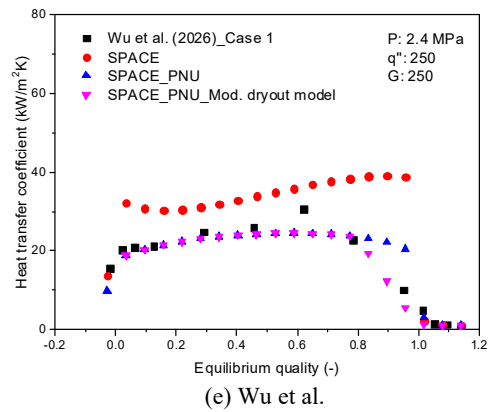
(b) Chang et al.



(c) Santini et al.



(d) Xiao et al.



(e) Wu et al.

Fig. 2. The simulation results.

Table 2. MAPE assessment results

Experiment	$MAPE = \frac{1}{N} \sum_{i=1}^N \left[\frac{ h_{exp,i} - h_{cal,i} }{h_{exp,i}} \right] \times 100$		
	SPACE	SPACE_PNU	SPACE_PNU_Dryout model
Hardik and Prabhu [10]	14.5	18.59	18.59
Chang et al. [11]	21.0	25.67	28.28
Santini et al. [12]	25.68	26.21	30.3
Xiao et al. [13]	129.69	65.64	31.30
Wu et al. [14]	73.90	29.61	17.40
Total	52.95	33.14	25.17

4. Conclusions

In the SPACE code, the heat transfer coefficient model of a helically coiled tube related to dryout model has been modified and assessed against experimental data. The results showed that the predictability of FDO has been significantly improved in the SPACE_PNU with the modification of dryout model. As a results, the

modified SPACE_PNU showed the best agreement with experimental data among the three HTC model package. The RMSE assessment results also showed the best agreement of the modified SPACE_PNU.

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