Assessment of Flow Boiling Heat Transfer Prediction Capability of MARS-KS in Helical Coil Tube

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1. Introduction

In a nuclear reactor, steam generator is a key component that interfaces the primary and secondary sides. Helically coiled steam generator has high heat transfer performance and compact design [1]. Owing to these advantages, helically coiled steam generators have been adopted in many small modular reactor (SMR) designs. As numerous SMRs are currently under development, safety analysis must be conducted. For reliable SMR safety analysis, accurate prediction of heat transfer is necessary [3]. In this regard, an applicability assessment is required to employ MARS-KS for SMR safety analysis. Accordingly, this paper evaluated the flow boiling heat transfer (FBHT) prediction capability of MARS-KS for helical coil tube.

2. Modeling helical coil tube with MARS-KS code

2.1. Experiments on FBHT in helical coil tube

In this section, the experiments used for assessing the prediction capability of MARS-KS are summarized. Santini et al. [2], Chang et al. [1], and Xiao et al. [6] conducted heat transfer experiments in helical coil tubes under nucleate boiling conditions. Xiao et al. [4,5] studied post-dryout heat transfer in helical coil tubes. The experimental conditions of the cases used for evaluating the prediction capability of MARS-KS are summarized in Table I and Table II.

Table I: Experimental geometric information

Authors	d_i [mm]	D_C [m]	D_c/d_i
Santini [2]	12.49	1.0	80.06
Chang [1]	8.0	0.65	81.25
Xiao [4]	12.5 / 14.5	0.18 / 0.38	12.41 / 30.4
Xiao [5]	12.5	0.18	14.4
Xiao [6]	14.5	0.18	12.41

Table II: Experimental conditions

Authors	Pressure [MPa]	Mass flux [kg/m^2·s]	Heat flux [kW/m^2]
Santini [2]	2 - 6	200 - 820	46 - 200
Chang [1]	8 - 11	500 - 1000	100 - 200
Xiao [4]	2 - 4.8	400 - 800	200 - 400
Xiao [5]	2	600	300
Xiao [6]	2 - 7.6	400 - 1000	200 - 500

2.2. Modeling helical coil tube

Fig. 1 shows the nodalization of helical coil tube with MARS-KS. In each case, time-dependent volume (TMDPVOL 101) defines the inlet fluid boundary conditions and time-dependent junction (TMDPJUN 102) sets the mass flow rate. Helical coil tube is modeled using a pipe component (PIPE 103) and configured as an inclined pipe based on the geometry reported for each experiment. Heating of helical coil tube was implemented using a heat structure. To apply the helical coil heat transfer model in MARS-KS, the helical S/G tube-side boundary option was configured. MARS-KS modeling data for the helical coil tube in each experiment were summarized in Table III.

Table III: Nodalization data for MARS-KS modeling

	Heated length [m]	Number of nodes	Node length range [m]
Santini [2]	24.0	60	0.2 – 0.8
Chang [1]	2.45(1)	38 / 43	0.2 – 0.4
Xiao [4]	8.0	25 / 34	0.05 – 0.4
Xiao [5]	8.0	29	0.2 – 0.4
Xiao [6]	8.0	36	0.1 – 0.4

(1) For considering the figures of merit of the experiment, the heated lengths were modeled using 13.81 m and 15.86 m, respectively

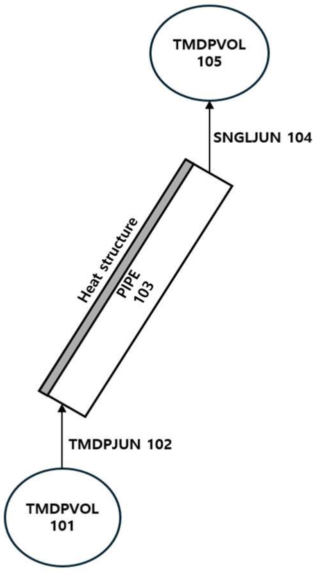


Fig. 1. Nodalization of helical coil tube.

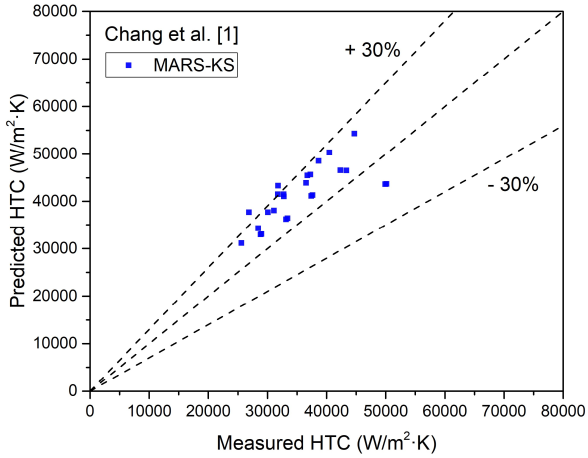
2.3. Results

Fig. 3 and Fig. 4 present MARS-KS calculation results under various experimental conditions. In Fig. 3, MARS-KS generally overpredicts the heat transfer coefficient (HTC) in the nucleate boiling regimes. Therefore, improvements to the nucleate boiling model are required to ensure prediction accuracy. Fig. 4 (a) shows that the results are dispersed. As shown in Fig. 4 (b) and (c), this is due to MARS-KS's inaccurate prediction of the dryout location. Because the HTC changes markedly after dryout, the MARS-KS predictions of post-dryout HTC showed large deviations from experimental values. Therefore, to achieve accurate predictions, the model for calculating the dryout location needs to be improved.

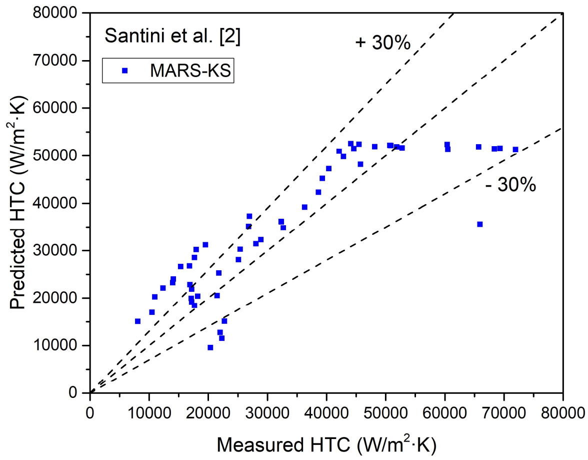
For the helical coil tube, MARS-KS employs Chen [8] correlation for the nucleate boiling regime and Mori and Nakayama [7] correlation for single phase forced convection term. For this, MARS-KS imposes an upper bound of 50,000 $W/m^2 \cdot K$ on the HTC for both convective and boiling terms, and therefore, the results exhibit a tendency to converge near 50,000 $W/m^2 \cdot K$, as shown in Fig. 3 and Fig. 4.

Table IV: Root mean square error against experimental data

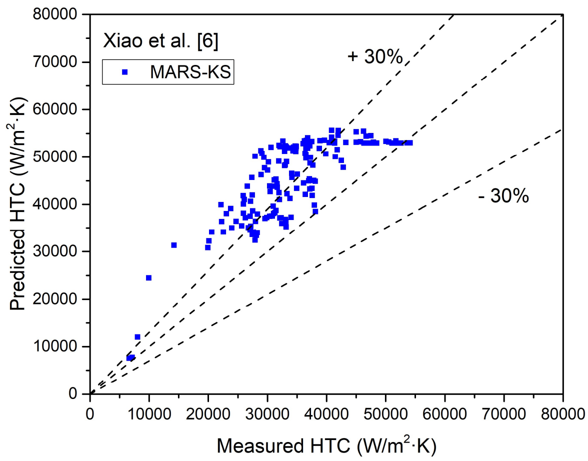
	Heat transfer coefficient
	RMSE[(CAL – EXP)/EXP]
Santini et al. [2]	0.3753
Chang et al. [1]	0.2175
Xiao et al. [4,5]	0.7261
Xiao et al. [6]	0.4146



(a) Chang et al. [1]

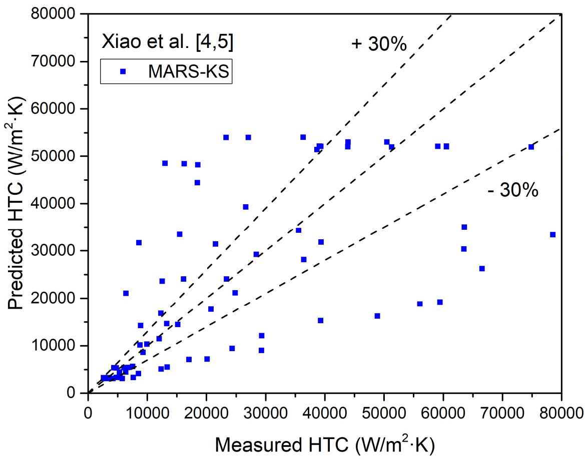


(b) Santini et al. [2]

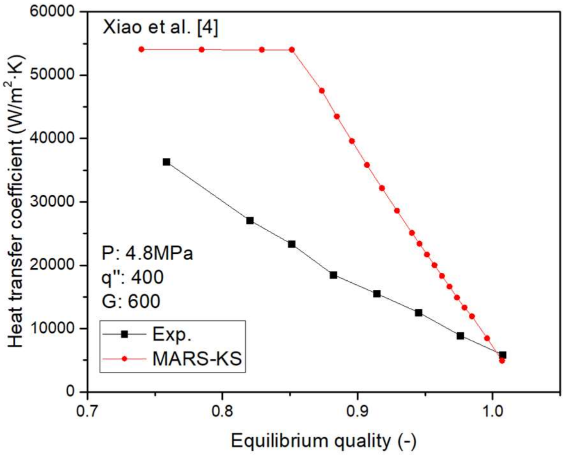


(c) Xiao et al. [6]

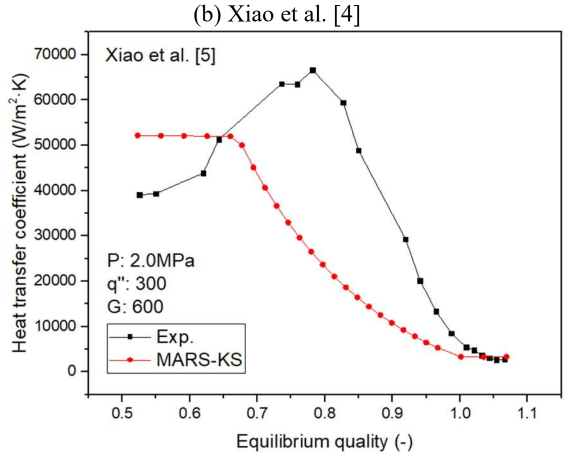
Fig. 3. Calculated results for nucleate boiling test case



(a) Xiao et al. [4,5]



(b) Xiao et al. [4]



(c) Xiao et al. [5]

Fig. 4. Calculated results for dryout test cases

3. Conclusion

In this study, the prediction capability of MARS-KS for FBHT in helical coils was evaluated using experimental data across various operating conditions. In helical coil tubes, MARS-KS exhibited a general tendency to overpredict the HTC in nucleate boiling regime. Moreover, it was inaccurate in predicting the dryout location resulted in substantial differences after dryout. Therefore, model improvements are needed to enhance prediction capability of MARS-KS. As future work, various helical coil heat transfer correlations will be applied to MARS-KS to evaluate prediction capability.

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