Assessment of pressure drop predictability of MARS-KS in helically coiled tubes

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1. Introduction

The helical geometry of helical-coil steam generator (HCSG) induces centrifugal-force-driven secondary flow, which enhances both heat transfer and pressure drop compared to straight tubes [1-3]. Both effects should therefore be represented in HCSG modeling. MARS-KS, a domestic regulatory confirmatory thermal-hydraulic system analysis code, incorporates Mori-Nakayama correlation to account for the heat transfer in helical tubes. However, it does not include hydraulic models for predicting pressure drops in such tubes [4]. The absence of adequate pressure drop model is expected to limit the code applicability and predictability for HCSG analyses. Accordingly, relevant assessment and model improvement are necessary.

In this study, the pressure-drop predictability of MARS-KS for helical tubes was assessed using representative experimental data from Santini et al. [5], Xiao et al. [6], and Su et al. [7]. To improve the code, helical-tube pressure-drop correlations for both the single-phase friction factor and two-phase friction multiplier were employed. The resulting performance improvement was evaluated through comparisons between the calculated results and the experimental data.

2. Method and Results

The secondary flow induced by tube curvature promotes radial mixing and changes the turbulence structure of the flow. Consequently, the tube-side wall heat-transfer rate is generally higher than that in a straight-tube arrangement. At the same time, the curved flow path introduces additional flow resistance, producing a larger pressure loss than that observed in straight tubes. These effects depend strongly on the coil geometry, particularly tube and coil diameters. For this reason, correlations developed for helically coiled heat exchangers commonly incorporate geometric influences through a curvature ratio, typically expressed as the ratio of tube diameter to coil diameter [8-9].

However, as summarized in Table I, MARS-KS applies the straight-tube correlations without accounting for the geometric effects of helical tubes. To represent theses pressure-drop characteristics, representative helical-tube correlations for the friction factor and two-phase friction multiplier listed in Table II were employed, and their performance was compared with that of the straight-tube correlations implemented in MARS-KS.

Table I. Pressure-drop correlations in MARS-KS

Parameters	Correlations
Friction factor	Zigrang-Sylvester [10]
Two-phase friction multiplier	HTFS modified Baroczy [11]

Table II. Pressure-drop correlations for helical tubes

Parameters	Correlations
Friction factor	Mori-Nakayama [12]
	Ito-Srinivasan [13-14]
	Zaidi et al. (PNU) [15]
Two-phase friction multiplier	Colombo et al. [16]
	Su et al. [7]
	Ferraris and Marcel (FEMA) [17]
	Zaidi et al. (PNU) [15]

2.1. Assessment models

Fig. 1 depicts the general nodal scheme developed for pressure-drop assessment. Specifications of the separate-effect tests selected for the assessment were summarized in Table III. Although all selected experiments have curvature ratios greater than that of the i-SMR design, no experimental data obtained under curvature-ratio conditions comparable to the relatively small value of i-SMR were identified. Therefore, the present assessment was conducted using the available experimental data to evaluate the general applicability of both the original straight-tube models in MARS-KS and the newly implemented helical-tube models.

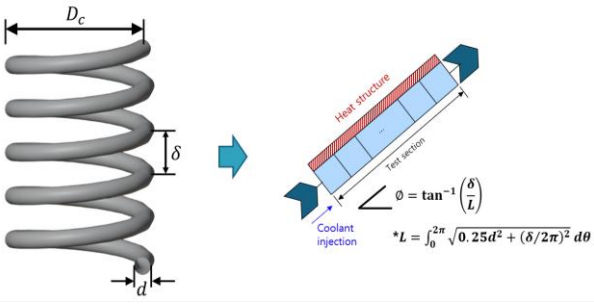


Fig. 1. General nodal scheme for pressure-drop assessment

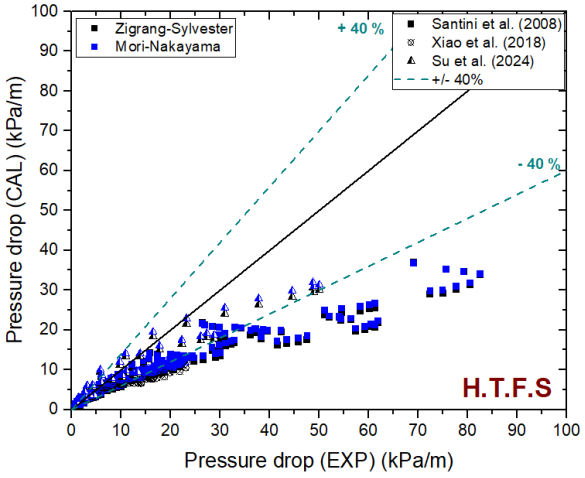
Table III. Specifications of helical tube experiments

EXP	Parameters (unit)	Values
Santini et al. [5]	Tube length (m)	32.42
	Tube diameter (mm)	12.53
	Coil diameter (mm)	1000
Xiao et al. [6]	Tube length (m)	8.00
	Tube diameter (mm)	12.5/14.5
	Coil diameter (mm)	180/280/380
Su et al. [7]	Tube length (m)	4.94
	Tube diameter (mm)	12.00
	Coil diameter (mm)	112

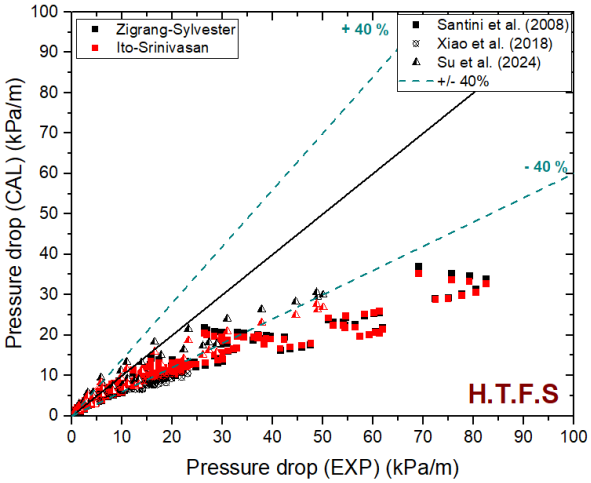
2.2. Assessment results

Fig. 2 compares the MARS-KS predictions obtained using the straight-tube correlations with those calculated using helical-tube friction factor correlations. As shown in the figure, the straight-tube correlations failed to adequately reproduce the pressure-drop behavior of the experiment, substantially underpredicting the pressure drop. Moreover, applying the helical-tube friction factor correlations produced no significant change relative to the predictions obtained with the straight-tube correlations.

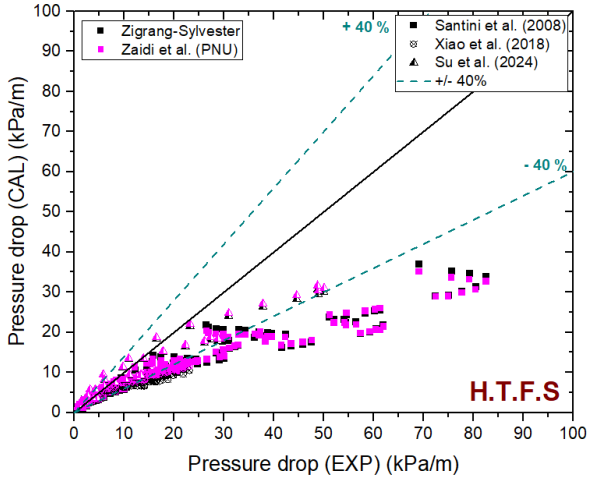
Fig. 3 compares the MARS-KS predictions with results obtained by applying helical-tube correlations for both the friction factor and the two-phase multiplier. With the helical-tube two-phase multiplier, the predicted pressure drops increased overall, and the predictions generally agreed with the experimental results within an error range of 40%. The Colombo correlation tended to overpredict the pressure drop relative to the other correlations, whereas FEMA, Su, and PNU correlations showed similar predictions. As summarized in Table IV, applying the two-phase friction multiplier produced a clear overall improvement in pressure-drop predictions for helical tubes. Overall, the Su correlation yielded the lowest root-mean-square error (RMSE). Although the results showed limited sensitivity to the selected single-phase friction factor correlation, the Mori-Nakayama correlation coupled with the Su two-phase multiplier provided the best predictions among the evaluated combinations.



(a) Mori-Nakayama

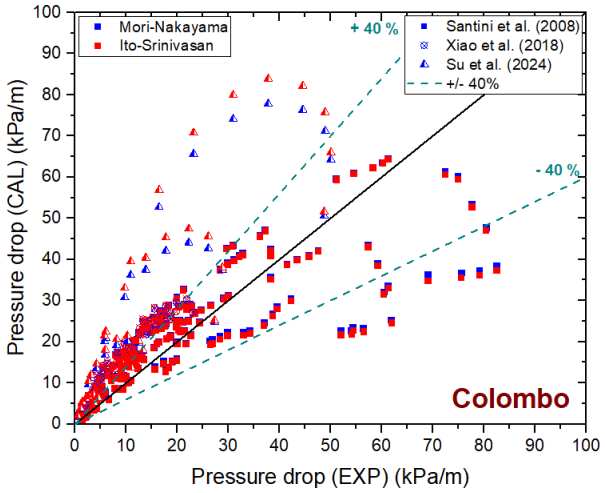


(b) Ito-Srinivasan

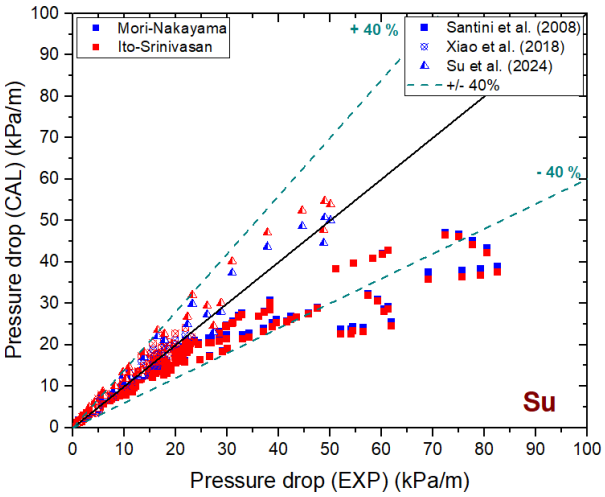


(c) Zaidi et al. (PNU)

Fig. 2. Effect of single-phase friction factor for helical tubes

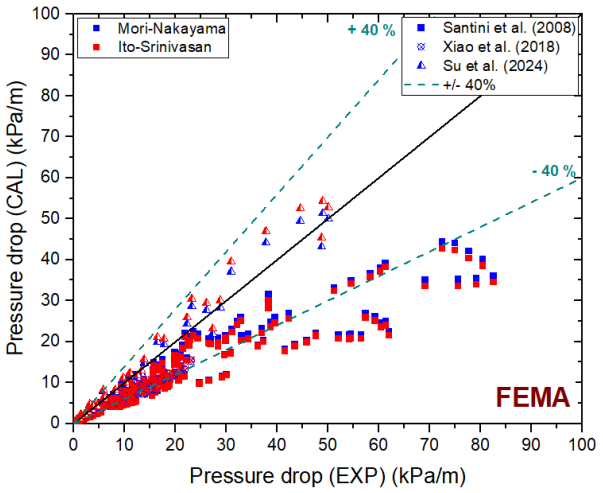


(a) Colombo

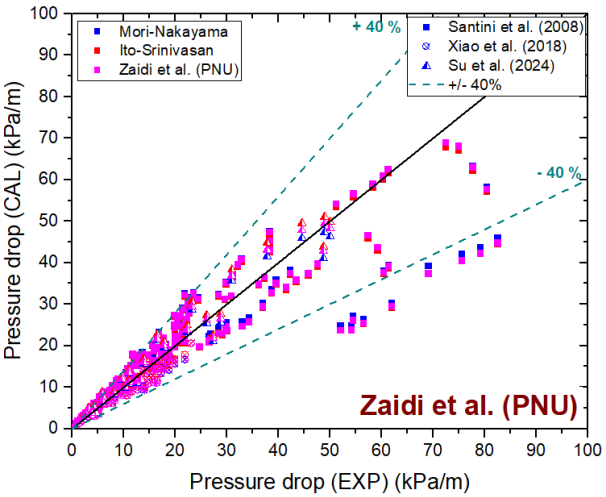


(b) Su

Fig. 3. Effect of two-phase friction multiplier for helical tubes (1/2)



(c) FEMA



(d) Zaidi et al. (PNU)

Fig. 3. Effect of two-phase friction multiplier for helical tubes (2/2)

Table IV. Comparison of RMSE results

Model	EXP			
	Santini	Xiao	Su	Total
Z-S (Straight)	0.3805	0.3874	0.4731	0.3933
M-N (Straight)	0.3840	0.3197	0.5069	0.4014
I-S (Straight)	0.3934	0.3106	0.4037	0.3947
PNU (Straight)	0.3946	0.3199	0.4669	0.4044
M-N (Colombo)	0.7132	0.8985	1.6437	0.8848
I-S (Colombo)	0.7036	0.9515	1.8162	0.9195
M-N (Su)	0.2784	0.1379	0.2867	0.2794
I-S (Su)	0.2787	0.1692	0.3480	0.2883
M-N (FEMA)	0.3178	0.3737	0.2251	0.3078
I-S (FEMA)	0.3312	0.3555	0.2600	0.3232
M-N (PNU)	0.3266	0.1770	0.2646	0.3195
I-S (PNU)	0.3180	0.1556	0.3076	0.3167
PNU (PNU)	0.322	0.1769	0.2678	0.3213
Z-S (Straight) : friction factor (Zigrang-Sylvester) / two-phase multiplier (HTFS) M-N (Straight): friction factor (Mori-Nakayama) / two-phase multiplier (HTFS) I-S (Straight) : friction factor (Ito-Srinivasan) / two-phase multiplier (HTFS) PNU (Straight): friction factor (Zaidi et al.) / two-phase multiplier (HTFS)				

3. Conclusions

In this study, the pressure-drop predictability of system code, MARS-KS, was assessed against helical-tube experiments conducted by Santini, Xiao, and Su. The assessment revealed substantial deficiencies in the pressure-drop predictions, as the code could not adequately reproduce the experimental pressure-drop behavior without an appropriate two-phase friction multiplier correlation for flow in helical tubes. The use of straight-tube correlations resulted in significant underprediction, while applying only helical-tube friction factor correlations did not produce a noticeable improvement. However, when both helical-tube friction factor and two-phase multiplier correlations were applied, the predicted pressure drops increased overall and agreement with the experimental results improved substantially. The Colombo correlation generally overpredicted the experimental pressure drops. Although the FEMA, Su, and PNU correlations showed comparable predictions, the Su correlation provided the best overall predictions. The results showed limited sensitivity to the selection of friction factor correlation. However, among the evaluated combinations, the Mori-Nakayama correlation coupled with the Su two-phase multiplier produced the most accurate predictions.

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