Influence of coil thickness on natural convection heat transfer of helical coil

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1. Introduction

A helical coil steam generator (HCSG) allows compact design with high thermal efficiency [1,2]. Many studies have been devoted to the investigation of the heat transfer characteristics of HCSG, with special focus on the HCSG tube side phenomena [3–5]. Several studies measured the heat transfers of the outer coil varying the geometrical parameters. However, their studies investigated the coupled influence of various helical coil parameters as in Eq. 1 [6] with limitation to access the individual influence. Thus, an investigation on the local heat transfer of the helical coil is needed.

This study experimentally investigated the local heat transfer of outer coil by replacing the coil to the ring bundle with varying the coil thickness(d) and the coil pitch(P). The mass transfer experimental method was used to achieve the high buoyancy of the system with the compact test rig based on analogy concept between heat and mass transfers.

$$D = \sqrt{\left(\frac{L}{N\pi}\right)^2 - \left(\frac{P}{2}\right)^2} \quad (1)$$

2. Theoretical background

2.1 Natural convective heat transfer of helical coil

Fig. 1 shows the geometrical parameters of the helical coil as the coil thickness(d), the pitch of coil(P), the helical diameter(D) and the number of turns(N). The main phenomena of the heat transfer for the helical coil depends on the plume development [4,6,7]. As the specific configurations, the plume makes two effects on upper turn of coil [7]. For the small pitch of coil, the heat transfer of the upper turn is impaired by the heated plume from lower turn (Preheating effect). Otherwise, as the pitch increased, the plume from lower turn offers the initial velocity to the upper turn, which enhances the heat transfer of upper coil (Initial velocity effect) [8].

Heo and Chung [8] mentioned that the heat transfer get impaired at narrow pitch of coil because of the preheating effect. the effect was prominent for the range of $P/d < 1.5$. As the increase of the P/d, the heat transfer of coil was gradually enhanced by initial velocity effect as $P/d < 2.6$. Furthermore, for the P/d after 2.6, The heat transfer of coil was converged since the pitch was wide enough to make any interaction between each turn.

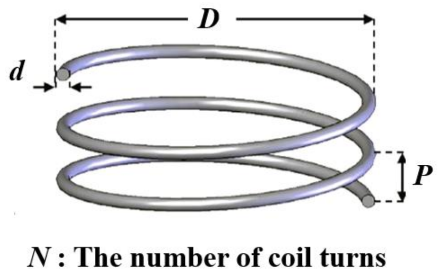

Fig. 1. Parameter of helical coil [10].

As the influence of N, Moawed [7] revealed that the transition point was made where the flow becomes turbulence by experiments. In case of $N = 10$, the lowest heat transfer of coil was measured at the point of $N = 5$. Then, the heat transfer was recovered by the flow development. Similarly, Xin and Ebadian [4] also confirmed the lowest heat transfer point at $N = 5$ with using coil of $N = 10$.

2.2 Existing correlations

Many researchers developed the natural convection heat transfer correlations for helical coil as the function of d [4,8,9,11]. They commonly mentioned that the heat transfer of a single turn of coil is close to that of the horizontal cylinder with same d which is used as characteristic length. Their correlations showed the similar trends within the $Ra_d = 10^6–10^8$. The correlations are represented on Fig. 2.

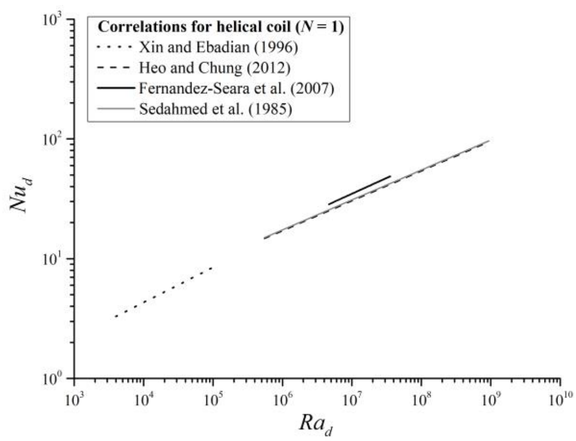

Fig. 2. Existing correlations for helical coil.

3. Experimental setup

3.1 Experimental methodology

Mass transfer experiments were adopted replacing heat transfer experiments based upon analogy concept between heat and mass transfer [12]. Copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system was employed as the mass transfer system. More detailed explanation of the methodology can be found in Park et al. [13]. The mass transfer coefficient (h_m) can be calculated by Eq. (2) by measuring current value from the experiment.

$$h_m = \frac{(1-t_n)I_{lim}}{nFC_b}. \qquad (2)$$

3.2 Test matrix and apparatus

Table 1 lists the test matrix for the experiments. The coil diameter (d) was varying as 0.003 m, 0.006 m and 0.009 m, which corresponds to the Ra_d range of 4.54×10^6–1.23×10^8. The N was fixed as 2. Also, The P/d was varied as the range of 1.1–4.0, which is the area that the plume effects appear [7,8]. The helical diameter (D) was fixed as 0.05 m. The Schmidt number, Sc of the working fluid was 2,094, which corresponds to the Prandtl number, Pr in the heat transfer system.

Table 1. Test matrix.

d (m)	Ra_d	N	P/d	D (m)	Sc
0.003 0.006 0.009	4.54×10^6 3.64×10^7 1.23×10^8	2	1.1, 1.3, 1.5, 1.7, 2.0, 3.0, 4.0	0.05	2,094

Fig. 2 reveals the circuit diagram of experimental apparatus. The helical coil can be replaced by bundle of horizontal rings to measure the heat transfers interaction between each position. The rings were submerged in top-opened acryl tank. Power supply (K1810, Vüpower) applied the current and cell potential, which are collected and recorded by the data acquisition (DAQ, NI 9227) system. Fig. 3 shows the various cathode rings with different d.

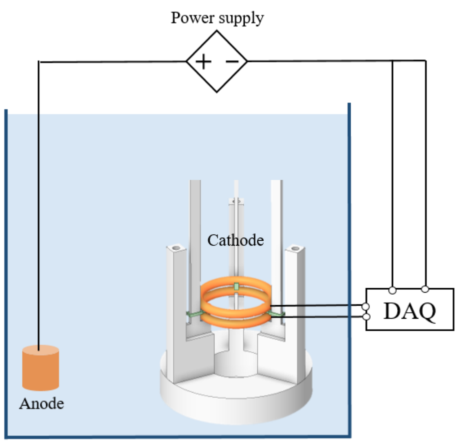

Fig. 2. Electric circuit and experimental apparatus.

(a) d = 3 mm (a) d = 6 mm (a) d = 9 mm

Fig. 3. Cathode rings for experiments.

4. Results and discussion

4.1 Validity of ring bundle heat transfer

Fig. 4 shows Nusselt number (Nu_d) of single ring compared to the correlations of horizontal cylinder. Each symbols represents the difference d of ring and all the results were well agreed with the correlations. Also, the results implied that the curvature effect of the ring used in this work was negligible due to the high Sc (Pr) condition of the experiments.

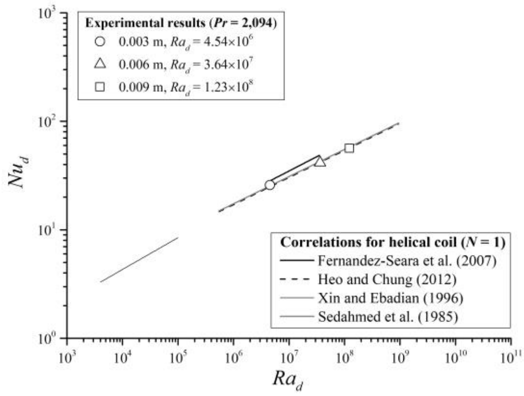

Fig. 4. Nu_d of ring bundle and helical coils.

4.2 Local Nusselt number of horizontal rings

Fig. 5 shows the experimental data of lower ring's Nu_d. For confirming the influence of downstream, the Nu_d of lower ring was measured. Regardless of P/d, results showed constant Nu_d value as that of single rings. The exprimental results implied that the influence of downstream was sightly exist on the heat transfer of helical coil.

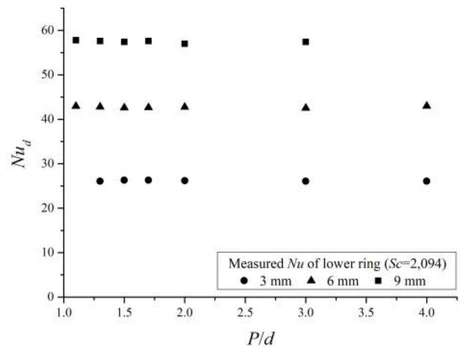

Fig. 5. the Nu_d of lower ring with difference d.

Fig. 6 represents the measured Nu_d for upper ring (Nu_{up}) to that of the lower ring (Nu_{low}). For the cases of small *P*/*d*, the impaired heat transfer of coil was observed due to preheating effect. Because of narrow pitch, the heated plume was disturbing the heat transfer of upper ring. As the increase of *P*/*d*, the Nu_d of upper ring was enhanced by initial velocity effect, which also relatively depressed the preheating effect. The plume from bottom offered the initial flow to upper ring so that the temperature difference was maintained. Also, the peak point was observed at the *P*/*d* range from 1.5 to 1.7, which was shown commonly regardless of *d*.

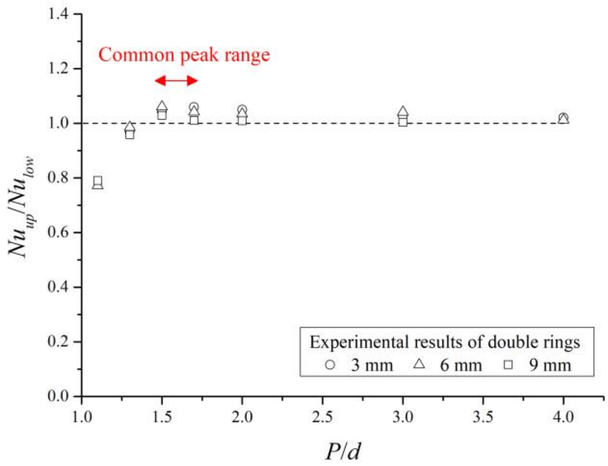

Fig. 6. the Nu_d ratio of ring bundle with difference *d*.

5. Conclusions

Natural convection heat transfers at the outside of the helical coil were measured, which is a promising steam generator configuration for the SMR. Local heat transfers were measured to investigate influence of *P*/*d* and *d*. The ring bundles are adopted to distinguish the clear heat transfer influence by geometrical parameters.

Lower turns of the coil showed constant local heat transfers regardless of *P*/*d*, which implied the influence of the upstream or downstream of the helical coil is negligible. However, the Nu_d of the upper turns were affected by the *P*/*d*. For the small *P*/*d*, the heat transfer was impaired due to the preheating effect predominated at the system. With the increase of *P*/*d*, the initial velocity effect appeared. The Nu_d of coil showed a peak due to the competition between the preheating and the initial velocity effects. The peak was shown at the range of *P*/*d* = 1.5–1.7, commonly. The results can offer the optimal heat transfer performance for the helical coil of the SMR.

Based on these results, further studies would be conducted by expanding the range of *N*. Also, the correlation for the heat transfer of coil will be developed with reflecting geometrical effect.

ACKNOWLEDGEMENT

This study was sponsored by the Ministry of Science and ICT (MIST) and was supported by nuclear Research & Development program grant funded by the National Research Foundation (NRF) (Grant codes 2020M2D2A1A02065563)

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