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Influence of Pitch on Natural Convection Heat Transfer of a Vertical Helical Coil

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1. Introduction

Small modular reactor (SMR) has increased attention as the main issue for the leading energy mix with high stability and economic feasibility [1,2]. Helical coil steam generator (HCSG) of compact design, enhanced heat transfer, and thermal stress flexibility is applied on the SMR or the next-generation reactors [2,3]. The SMR is based on a passive safety system, which uses a natural convection by the temperature difference between core and HCSG to enhance the safety [1]. For performance evaluation of the helical coil in passive system, the study of natural convective heat transfer of helical coil is needed [4]. Many studies for natural convection of helical coil have been conducted [4–6], but most of these were performed as inner coil flow.

This study offers the outer coil local heat transfer varying the pitch to diameter (P/d) for using piecewise electrodes. The mass transfer experiments were performed with a copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system, based on analogy concept. Ra_d was 4.55×10^6 and Sc corresponding the Pr was 2,094. Also, the pitch to diameter (P/d) was varied as 1.3, 1.7, and 2.6.

2. Theoretical background

2.1. Basic phenomena of helical coil

Figure 1 presents the geometry and parameters of the helical coil. The main parameter of the coil heat transfer is d, D, N, and P which are coil diameter, helical diameter, the number of coil turns, and the pitch of coil respectively.

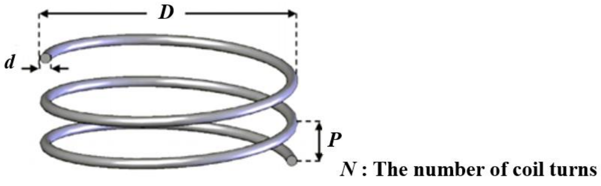

Fig. 1. Geometry and parameter of helical coil [7].

For the natural convective heat transfer of vertical helical coil in an open channel, the upper turn could be affected by a plume that generated from the bottom turn. Following three effects are caused by the plume from the under turn [8].

The heated plume from under turn decreases the heat transfer of the upper turn, which is the “preheating effect” [8,9]. The plume offers initial velocity to the upper turn, which enhances heat transfer for an upper turn. It is the “initial velocity effect” [8,9]. Also, the plume draws fluid between coils, and it enhances the heat transfer of under turn, which is the “chimney effect” [10].

2.2. Existing studies

Fernández-Seara et al. [11] investigated the parameter effects on the natural convection of a helical coil and suggested the heat transfer correlations for various characteristic lengths. Eq. (1) is one of the correlation for the coil diameter (d) as a characteristic length.

$$Nu_d = 0.4998 Ra_d^{\,0.2633}$$
$$4.67\times10^6 < Ra_d < 3.56\times10^7 \qquad (1)$$

Heo and Chung [8] studied the heat transfer of natural convection in the helical coil by using mass transfer experiments. They used the number of the coil turns and P/d as a multiplying factor of the correlation (Eq. (2)). On the P/d under 1.5, the preheating effect is dominant in the coil. However, after this point, The Nu_d increases up to P/d=2.6 which means the initial velocity effect is dominant at this range. These effects disappeared after $P/d\approx5$.

$$Nu_d = 0.54 Ra_d^{\,0.25}[1 - N(0.072 - 0.065(P/d) + 0.012(P/d)^2)]$$
$$5.5\times10^5 < Ra_d < 9.4\times10^8, P/d \le 4 \qquad (2)$$

Moawed [12] presents the local Nu_d of coil according to N for various Ra_d’s. The working fluid was air. Fig. 2 indicates the experimental result of Moawed [12]. Both top and bottom turns show higher local Nu_d. Also, mid turns show similar local Nu_d among themselves. It is due to two effects attributed by the plume. Since, every coil turns except the case of N=1 are affected by preheating effect which causes the decline of the Nu_d of upper turn. However, the initial velocity effect enhances the heat transfer of the top coil.

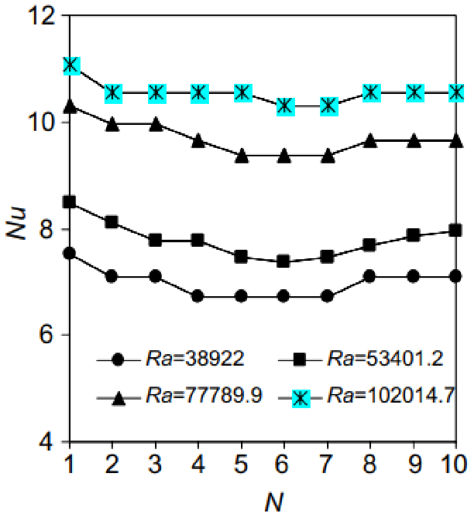

Fig. 2. Local Nu_d subject to variation of N and Ra_d [11].

3. Experimental setup

3.1. Experimental methodology

This study performed mass transfer experiments using the electroplating system based on analogy between heat and mass transfer.

A mass transfer experiment using the electroplating system was performed first by Levich [13]. After that, Selman [14] organized mass transfer correlations in different conditions.

Eq. 3 represents the equation for calculate the mass transfer coefficient (h_m).

$$h_m = \frac{(1-t_n)I_{ilm}}{nFC_b} \tag{3}$$

The transfer of cupric ions from anode to cathode corresponds to heat transfer, which is measured by the electric current. Chung et al [15] performed mass transfer experiments to explain the methodology in detail.

3.2. Test matrix and apparatus

Table I shows the test matrix for the natural convection heat transfer on the helical coil. The coil diameter (d) was 3 mm which corresponds to a Ra_d of 9.11×10^6. The pitch to diameter ratio (P/d) was varied as 1.3, 1.7, and 2.6, respectively. The number of coil turns (N) was fixed to 8 turns. The helical diameter of the ring (D) was 0.05 m. The experiments were performed at copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) of 0.1 M and 1.5 M, respectively. The solution Sc, which corresponded to Pr, was 2094.

Figure 3 presents the schematic of the experimental apparatus. To confirm only the pitch effect in the helical coil heat transfer, we realized the cathode coil to the horizontal rings. Experiments were conducted by piecewise electrodes to measure the local heat transfer of coil. Every cathodes structure except coil parts were insulated. Coils had a 25 mm distance from the floor structure. The anode of the circuit was a copper cylinder which has sufficient surface compare to the cathode. Coils were submerged in the top-opened (W 300 mm × L 300 mm × H 400 mm) acryl tank. The electrical potential was applied using a power supply (K1810, Vüpower). The electric current was measured by a Data acquisition system (DAQ).

Table I: Test matrix for the helical coil heat transfer of natural convection

d (m)	Ra_d	P/d	N	D (m)	Sc (Pr)
0.003	4.55×10^6	1.3, 1.7, 2.6	8	0.025	2,094

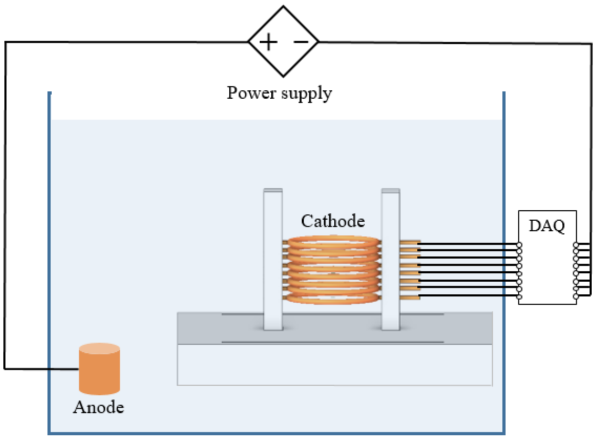

Fig. 3. Schematic of the experimental apparatus.

4. Results and discussion

4.1. Average Nusselt number of horizontal rings

Figure 4 shows the comparison of experimental results with the existing correlation. The dashed line represents the correlation of Heo and Chung [8], and the symbols indicate experimental results of P/d=1.3, 1.7, 2.6.

The increasing tendency up to P/d=2.6 in this study was similar to the existing correlation. However, the measured Nu_d's are higher than the correlation with average relative error of 8%. It is caused by the difference in geometrical characteristics between the horizontal rings and the helical coil.

The Nu_d's increased with the increase of P/d as the main effect at the coil differs according to the P/d. For P/d=1.3, the main effect was the preheating, which impairs the heat transfer of upper ring due to the heated plume from lower ring. In case of P/d=1.7 and 2.6, the initial velocity was dominant. It offered the initial velocity causing from the flow of lower ring to upper rings, which caused higher average coil Nu_d than the case of P/d=1.3.

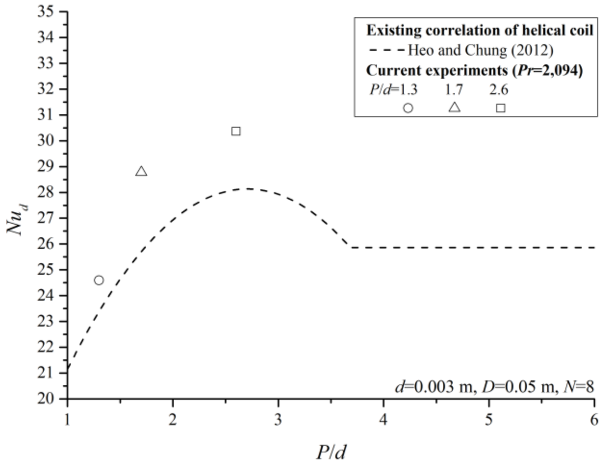

Fig. 4. Average Nu_d subject to P/d.

4.2. Local Nusselt number of horizontal rings

Figure 5 indicates the local Nu_d according to N for each P/d. In the case of P/d=1.3, the Nu_d decreased with increasing N, and then the Nu_d of the top ring increased. This tendency was similar to the experiments of Moawed [12]. For this case, the preheating plume impaired the heat transfer of upper rings, and the final flow developed along with coil helped to increasing the Nu_d of the top ring.

Otherwise, for P/d=1.7 and 2.6, the Nu_d increased with increasing N, and then the Nu_d of the top ring decreased. In the velocity dominant region, the plume caused the chimney effect with the initial velocity effect. The upper plume drew the under plume, which enhanced the heat transfer of the under ring. Therefore, these two effects were reinforced up during in mid turns, and the heat transfer of the top ring was impaired because it had no chimney effect.

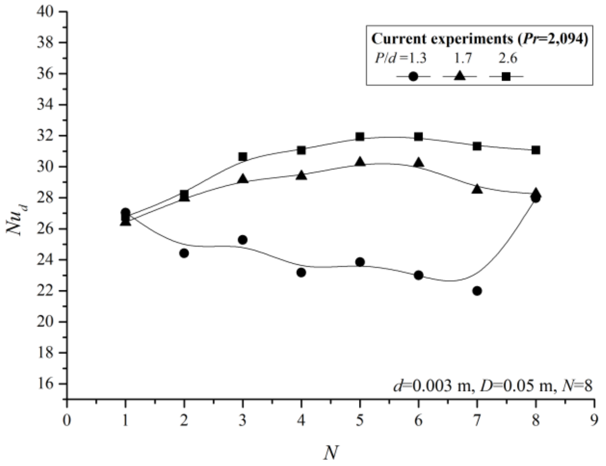

Fig. 5. Local Nu_d of rings for varying turns (N).

5. Conclusions

This study investigated the influence of a pitch of helical coil on the natural heat transfer using the copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system of mass transfer.

Through, the comparison of results between current experiments and the correlation of Heo and Chung [8], we identified that the dominant effect differs depending on the pitch to coil diameter ratio (P/d) and it caused the difference of the average Nu_d.

By measuring the local Nu_d, we also confirmed that the local heat transfer tendency is affected by the dominant effect in the helical coil. When the coil was affected by preheating effect, the middle of coil performed less heat transfer relative to both ends of the coil. While the coil was affected by the initial velocity effect, the middle of the coil performed better heat transfer relative to both ends of the coil.

Based on this study, we will expand the test matrix to investigate the influence of pitch with difference coil diameter at natural convective heat transfer in the helical coil.

NOMENCLATURE

C_b	Cupric ion concentration in the bulk [kmole/m^3]
D	Helical diameter [m]
d	Coil diameter [m]
F	Faraday constant [94,485 × 10^3 C/kmole]
h_m	Mass transfer coefficient [m/s]
I_{lim}	Limiting current density [A/m^2]
N	Number of coil diameter [#]
Nu_d	Nusselt number ($h_h d/k$)
n	Number of electrons in charge transfer reaction
P	Pitch of coil [m]
Pr	Prandtl number (ν/α)
Ra_d	Rayleigh number ($g\beta\Delta Td^3/\alpha\nu$)
Sc	Schmidt number (ν/D_m)
t_n	Transference number of Cu^{2+}

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