Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

Experimental investigation on natural convective heat transfer of a helical coil

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1. Introduction

A Helical Coil Steam Generator (HCSG) is widely employed in various Small Modular Reactors (SMR's) [1]. It allows relatively large heat transfer area and contributes to the compact design [2,3]. The studies for the optimal design of the helical coil are needed to confirm and improve the thermal efficiency of the SMR as the heat exchanger design is technology lead engineering rather than science. Many studies have been performed to investigate heat transfer of HCSG, however, most of the studies are focused on the inside of the HCSG rather than the outside [4–6]. Several studies [4,5] measured the heat transfers of the outer coil varying the geometrical parameters. Meanwhile, it seems that an investigation on the fundamental phenomena in the local heat transfer of the helical coil is still needed.

This study measured the local heat transfer of outer coils varying P/d and N. The mass transfer experimental method was employed to achieve high buoyancy of the system with compact test rig based on analogy between heat and mass transfers. Copper electroplating system was adopted and copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) was used as working fluid.

2. Theoretical background

2.1 Influence of coil thickness

Figure 1 represents the geometrical parameters of the helical coil, which affect natural convection heat transfer of the outer coil [7]. The heat transfer increases as the thickness of the coil (d) increases. Xin and Ebadian [5], Heo and Chung [8] and Fernández-Seara et al. [9] developed heat transfer correlations and they insisted that the heat transfer of the single turn of helical coil showed similar heat transfer to that of the horizontal cylinder with same coil thickness (d).

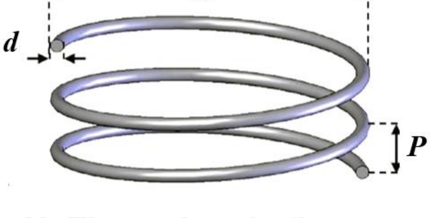

Fig. 1. Parameter of helical coil [7].

2.2 Influence of pitch to coil diameter ratio

Heo and Chung [8] reported that the heat transfer is impaired due to the preheating effect, when the pitch to coil diameter ratio (P/d) < 1.5. The thermal plume arose from the lower coil impairs the heat transfer of the upper coil. A further increase in the P/d, recovers the heat transfer as the plume from the lower cylinder provide the initial velocity to the upper one, which results in the enhanced heat transfer. Hence, the interaction between the two effects either impairs or enhances the heat transfer of the helical coil [5,8].

2.3 Influence of coil turns

Moawed [10] measured the local heat transfer of the helical coil. The result revealed that there is a transition point where the flow becomes turbulence. In case of ten coil turns (N), the lowest heat transfer was measured at the fifth turn. Xin and Ebadian [5] also measured lowest heat transfer at the fifth turn using helical coil of $N = 10$. Meanwhile, the transition phenomenon did not appear at the small N, in case of $N = 5$.

3. Experimental setup

3.1 Experimental methodology

Mass transfer experiments were performed replacing heat transfer experiments based upon analogy concept between heat and mass transfer [11]. 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 Ko et al. [12]. The mass transfer coefficient (h_m) can be calculated by Eq. (1) by measuring current value from the experiment.

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

3.2 Test matrix and apparatus

Table 1 lists the test matrix for the experiments. The coil diameter (d) was fixed as 0.006 m, which corresponds to $Ra_d = 3.63\times10^7$. The number of coil turns (N) was varied as 2, 4, 8 and 12. Also, the pitch to diameter ratio (P/d) was varied as 1.08 and 1.50. 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*
0.006	3.638×10^7	2 4 8 12	1.08 1.50	0.05	2,094

Figure 2 shows the circuit diagram of experimental apparatus. The helical coil is replaced by bundle of horizontal rings to measure the local average heat transfers. The rings are submerged in top-opened acryl tank. Power supply (K1810, Vüpower) applied the current and cell potential, which are collected and recorded by data acquisition system (DAQ, NI 9227).

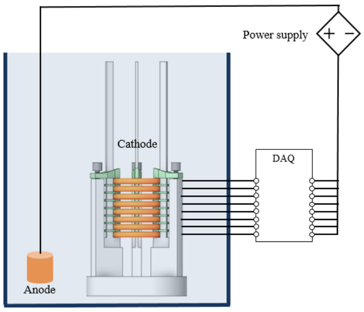

Fig. 2. Electric circuit and experimental apparatus.

4. Results and discussion

4.1 Validity of ring bundle heat transfer

Figure 3 compares the Nusselt number (Nu_d) of single ring with the heat transfer correlations developed for horizontal cylinders. The result agreed well with the correlations. It implies that the curvature of the ring showed negligible effect to the heat transfer.

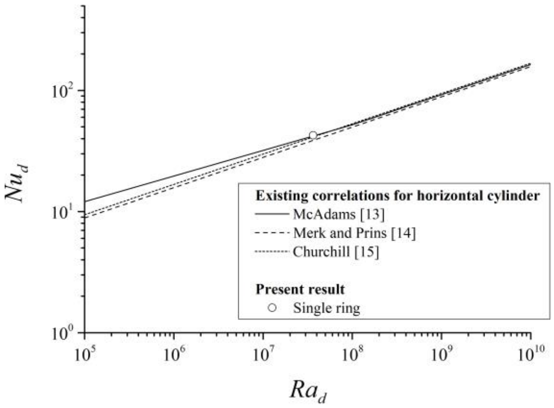

Fig. 3. Nu_d of single ring and horizontal cylinders.

Figure 4 compares the mean Nu_d of the ring bundle with the correlations developed for helical coils [5,8,9,16]. The mean Nu_d of ring bundle again agreed well with the heat transfer correlations. Hence, the authors concluded that the ring bundle can replace the heat transfer of the helical coils.

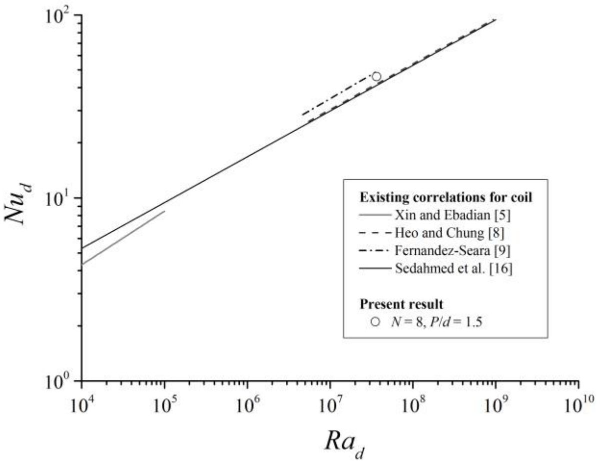

Fig. 4. Nu_d of ring bundle and helical coils.

4.2 Mean Nusselt number of ring bundle

Figure 5 shows mean Nu_d of ring bundles according to the *P*/*d* and *N*. In case of *P*/*d* of 1.08, the Nu_d decreased as *N* increased. It is due to the intensified preheating effect with increased *N*. The thermal plume arose from lower rings impaired the heat transfer of upper rings. The thermal plumes got more heated and heat transfers of the upper rings were always lower than those of the lower rings. Hence, the developed thermal boundary layer consistently impaired the heat transfer along the ring bundle.

Meanwhile, in the case of P/d = 1.50, the Nu_d according to the *N* showed different tendency. The Nu_d was enhanced as the *N* increased. It is due to the initial velocity effect, which becomes dominated as flow distance increased. Despite the still existing preheating effect, it seems that the initial velocity effect overcame the preheating effect.

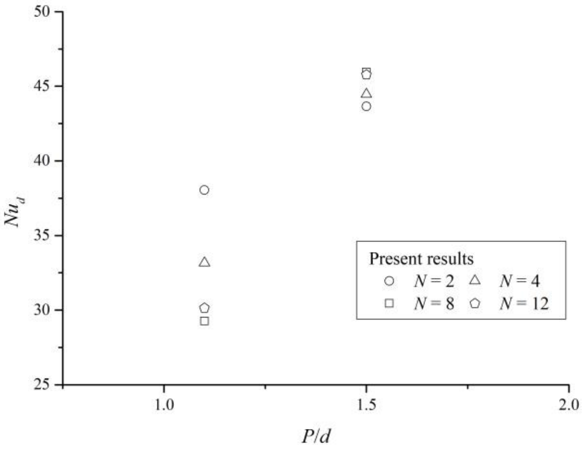

Fig. 5. Average Nusselt number of horizontal rings

4.3 Local Nusselt number of horizontal rings

Figure 6 shows the ratios of Nu_d to that of the bottom ring (Nu_0) in the case of P/d = 1.08. The Nu_d/Nu_0 gradually decreased from the bottom ring in all cases. It is due to the preheating effect as explained in previous section. All the case of N showed similar decreasing slope. However, dip points are measured at the case of N = 8, 12. It seems that the added plumes from bottom to the 6th ring worked as the initial velocity to the upper rings [5,10].

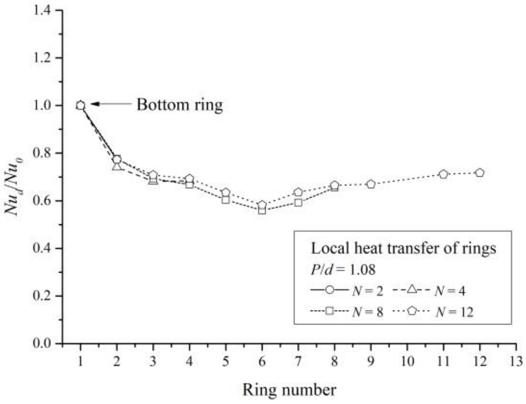

Fig. 6. Local average heat transfer of P/d = 1.08.

Figure 7 shows the ratios of Nu_d to that of the bottom ring (Nu_0) in the case of P/d = 1.50. The Nu_d gradually increased from the bottom ring in all cases. The initial velocity effect predominated at the system due to the increased P/d, which relatively depressed the preheating effect.

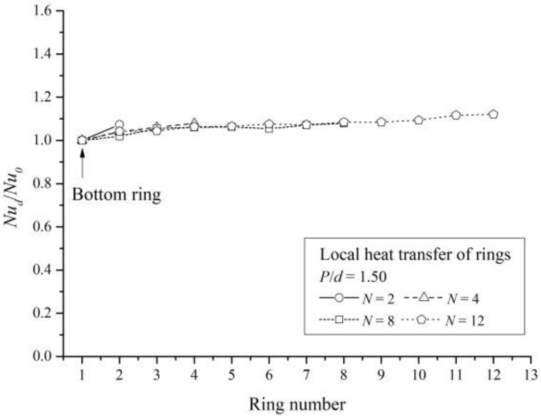

Fig. 7. Local average heat transfer of P/d = 1.50.

5. Conclusions

Natural convection heat transfers occurred at the outer side of the helical coils were measured to investigate the fundamental phenomena for the Helical Coil Heat Exchangers frequently adopted in the designs of the SMR's. Local heat transfers were measured to investigate influence of P/d and N. The ring bundles are adopted to simulate helical coil configuration using mass transfer experiment.

The preheating effect, which impairs the heat transfer predominated at the system when the P/d is sufficiently small, 1.08. Thus, mean Nu_d decreased as N increased. However, the local heat transfer showed dip point due to the enhanced flow due to the accumulation of the flows from each ring for N = 8, 12 cases. Despite the recovered heat transfer, the preheating effect still governed the phenomenon at small P/d.

Meanwhile, the initial velocity effect, which enhances the heat transfer overcame the preheating effect in case of P/d = 1.50, resulting in increased mean Nu_d as N increased. The local heat transfer of this case gradually increased from the bottom in all the N cases.

Based on these results, further works will be performed by expanding range of P/d and N to optimize heat transfer performance of helical coil of the SMR.

ACKNOWLEDEGEMENT

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

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