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Influence of ultrasound on the heat transfer of a helical coil

D. G. Lee, S. I. Baek, D. H. Shin and B. J. Chung*
Department of Nuclear Engineering, Kyung Hee University
#1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Korea
**Corresponding author: bjchung@khu.ac.kr*

1. Introduction

The helical coil has drawn research interest as it is adopted as the steam generator of many Small Modular Reactors (SMRs) due to large high heat transfer area and thermal stress flexibility [1,2]. Thus, many studies have been conducted addressing the heat transfer of helical coils [3–5]. However, most of the studies focused on the geometrical effect of the coil heat transfer [3–7]. Recently, to obtain a better performance, giving external input (active method) is considered such as the mechanical actuation [8]. As a method of enhancing heat transfer, the application of ultrasound has been widely used [8–11]. The ultrasound arises the cavitation by wave compression, which accelerates the flow mixing leading to better the heat transfer [9].

This study investigated the influence of ultrasound on the local heat transfer of helical coil simulated by the ring structure. Experiments were conducted with mass transfer experimental method based on the analogy between heat and mass transfers. The copper sulfate-sulfuric acid ($CuSO_4$- H_2SO_4) was adopted as the working fluid of experiments. The power of ultrasound was varied from 40 W to 60 W.

2. Background

2.1 Influence of ultrasound on the natural convection heat transfer

Legay et al. reviewed the enhancement of natural and forced convection heat transfer using the ultrasound [8]. They reported that the application of the ultrasound improved the heat transfer. When the ultrasound is generated, the cavitation occurs in the fluid near the heat source. Accordingly, the boundary layer become thinner by the creation of micro-turbulence in the fluid, thereby improving the heat transfer.

Mongkolkitngam et al. studied the natural convection heat transfer of the vertical cylinder according to the frequency of the ultrasound [9]. They visualized the cavitation of the fluid by the ultrasound and developed the heat transfer correlation for the vertical cylinder according to the frequency of ultrasound. The constant heat flux of the vertical cylinder was 14,150 W/m^2 and the frequency was varied from 40 kHz to 120 kHz. The distance between the cylinder and ultrasonic generator was varied from 5 cm to 15 cm. They reported that the heat transfer rate of the cylinder was maximum for 120 kHz with the distance of 10 cm, which showed 74.2 % increase compared to the heat transfer without the ultrasound. Their results were also similar to those reported by Legay et al. [8].

Cai et al. performed the experiments for the heat transfer of horizontal circular tube with varying the ultrasonic power [10]. The ultrasonic power was varied from 0 to 250 W and the length of circular tube was 50 mm. They found that heat transfer of the tube was enhanced with the increase of ultrasonic power. In their experimental results, the high-intensity cavitation due to the increase in ultrasonic power had strengthened the disturbing effect of cavitation in the fluid, thereby enhancing the heat transfer of the circular tube.

2.2 Natural convection of the helical coil by using rings

Sedamned et al. performed mass transfer experiment for the natural convection heat transfer of the helical coil and circular rings [12]. The diameter of coil and ring were 0.6 cm and 0.3 cm, respectively. According to their results, the heat transfer rate of the helical coil decreased as the coil diameter increased. In addition, the heat transfer phenomena of the helical coil and circular rings were similar. They reported that it is possible to simulate the helical coil using the circular rings and developed the heat transfer correlation for the helical coil.

Shin et al. conducted the natural convection heat transfer of a helical coil using the multiple horizontal rings [13]. The Ra_d and Sc were 3.64×10^7 and 2,094, respectively. They insisted that the increasing the pitch of helical coil improved heat transfer. This is due to the weakening of the preheating effect between the coils, which matched the existing correlation for the heat transfer of helical coil. They also confirmed the helical coil could be replaced by a bundle of horizontal rings, as reported by Sedamned et al. [12].

3. Experimental setup

3.1 Experimental methodology

Mass transfer experiments were conducted by replacing heat transfer experiments based upon the analogy between heat and mass transfer [14]. Copper electroplating system using Copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) was employed as the mass transfer system. More detailed about the methodology can be found in the study of Ko et al. [15]. 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 I presents the test matrix for the natural convection heat transfer of horizontal ring and Table II lists the test matrix for ultrasound application. To compare the heat transfer of ring with helical coil, the ring thickness (d) was varied as 0.003 m, 0.006 m, 0.009 m. For the experiments under ultrasonic condition, frequency was fixed as 40 kHz with varying the power of 40 W–60 W. The Sc corresponded to Pr was 2,094. Also, the ring diameter (D) was fixed as 0.05 m.

Table I: Test matrix for the horizontal ring.

d (m)	Gr_d	Ra_d	D (m)	Sc (Pr)
0.003	2.17×10^3	4.54×10^6	0.05	2,094
0.006	1.74×10^4	3.64×10^7		
0.009	5.87×10^4	1.23×10^8		

Table II: Test matrix for ultrasound application.

d (m)	Ra_d	Frequency (kHz)	Power (W)
0.006	3.64×10^7	40	40, 52, 60

Figure 1 shows the electric circuit of the experiments. To confirm the local effect of helical coil, the ring structure was adopted. The cathode ring maintained enough distance from the floor of tank to simulate open pool. The copper sulfate-sulfuric acid ($CuSO_4$- H_2SO_4) of 0.1 M, 1.5 M solution was used. Experiments were conducted with top-opened ultrasonic generator tank (W 290 mm× L 240 mm× H 150 mm, LK-U150D). The electrical potential was supplied by using a power supply (K1810, Vüpower). The electric current was obtained by a data acquisition system (DAQ, NI 9227).

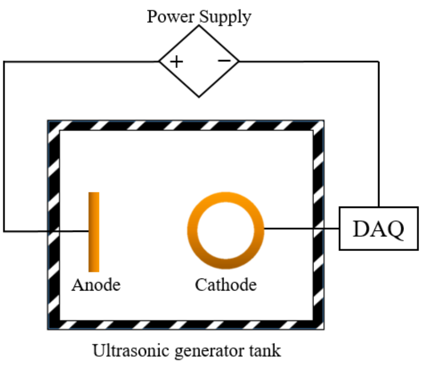

Fig. 1. Electric circuit of the experiment.

4. Results and discussion

4.1 Natural convection of the horizontal ring

Figure 2 shows the experimental results compared to the existing correlations for heat transfer of helical coil [3,4,6,12]. The experimental results for each cases matched well with existing correlations and the average relative error was 2.7 %. Therefore, it was confirmed that the helical coil could be analyzed by replacing it with the horizontal ring.

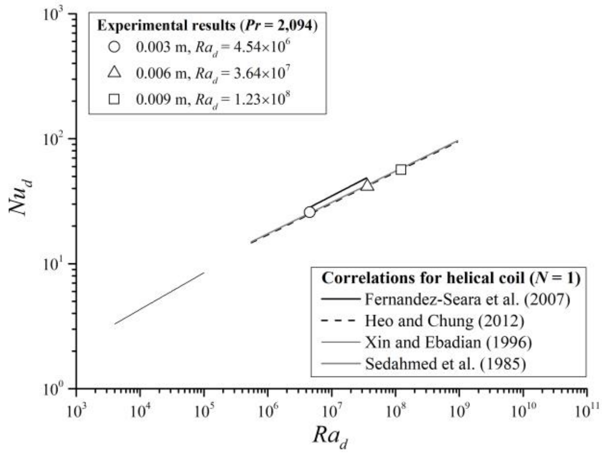

Fig. 2. Comparison of experimental results with existing correlations for helical coil.

4.2 Heat transfer of the horizontal ring under ultrasonic condition

Figure 3 shows the measured Nu_d's for the horizontal ring according to the ultrasonic power. The heat transfer of horizontal ring was enhanced by ultrasonic in all cases. This is because the turbulence caused by the cavitation thinned the boundary layer of the horizontal ring. In addition, the heat transfer rate of ring was improved proportionally with ultrasonic power. For the ultrasonic power of 60 W, the Nu_d of the horizontal ring was increased about 50 % compared to the ring without ultrasound. This is due to the acceleration of cavitation by the ultrasonic power. As the ultrasonic power increases, the amplitude of ultrasound intensifies with the same frequency. Thus, it allows the enhancement of amplitude, which makes the flow mixing stronger, thereby the boundary layer of horizontal ring became thinner.

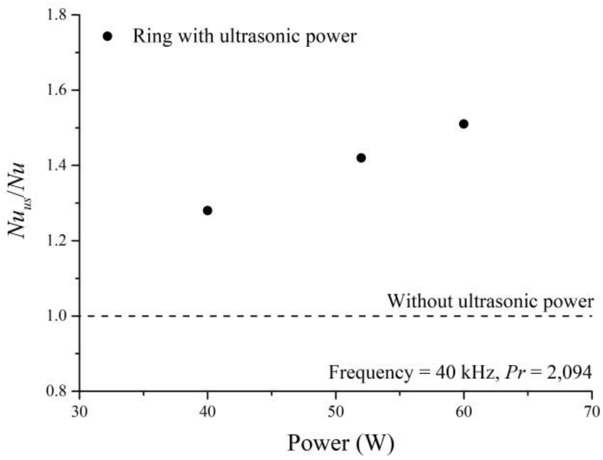

Fig. 3. Nu_d ratios for the horizontal ring according to ultrasonic power.

5. Conclusions

We investigated the heat transfer enhancement of the helical coil by application of ultrasound. Based on the analogy concept, we performed the mass transfer experiment using the copper sulfate-sulfuric acid electroplating system. The natural convection heat transfer of horizontal ring agreed well with the existing correlations for the helical coil and the simulation of helical coil with multiple ring was verified by the experiments. The natural convection heat transfer of horizontal ring was enhanced with the increasing ultrasonic power, which results from the strengthened the flow mixing near the horizontal ring.

Based on this work, a further study is planned for the applications of different frequency and ultrasonic power to observe the various enhancement effects.

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