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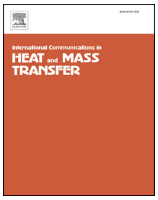

Natural convection of an inclined helical coil in a duct☆

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ABSTRACT

The natural convection heat transfer of a helical coil in a duct was measured experimentally. The Ra_D was fixed at 4.55×10^6 and the pitch to diameter ratio varied from 1 to 5, the number of turns from 1 to 10, and the inclination of the helical coil from horizontal to vertical. To achieve a high Rayleigh number, mass transfer experiments were performed based on the analogy between heat and mass transfer. The measured Nu_D for a single turn of the helical coil was close to the prediction derived from the McAdams heat-transfer correlation developed for a horizontal cylinder. The heat transfer of the helical coil varied with respect to the pitch, number of turns, and duct height, demonstrating the complexities associated with velocity, preheating, and chimney effects. It is expected that the results from this study will contribute to a phenomenological understanding of natural convection heat transfer in compact heat exchangers.

1. Introduction

Helical tube heat exchangers are commonly adopted to compact systems with spatial limitations such as vessels and transport systems. They provide for large heat transfer areas, compared with straight-tube-type heat exchangers. Although heat-transfer in helical coil heat exchangers has been studied extensively, phenomenological study of these systems has been limited [1–3]. Most of the available studies are concerned with forced convection or the internal heat transfer of helical-coil tubes [4–6].

The helical coils can be conceived as a series of inclined cylinders. The heat transfer of the upper turns is affected by the plumes generated at the lower turns. The vertically oriented helical coil can be conceived as a series of in-line inclined cylinders and the inclined helical coil as a staggered arrangement. The duct containing the helical coil acts as a chimney, preventing plume dispersion.

In this study, the natural convection heat transfer from the helical coil in a duct was measured. The geometry and dimensions of the helical coil considered in this study are shown in Fig. 1, where H, D, P, L, R, θ, and N represent the height, diameter, pitch, total length, winding radius of the coil, the inclination angle from the horizontal, and the number of turns, respectively. Based upon the analogy between heat and mass transfer, mass transfer experiments were performed instead of heat transfer experiments. A cupric acid–copper sulfate electroplating system was used as the mass transfer system.

2. Previous studies

2.1. Open-channel natural convection heat transfer of a helical coil

The natural convection heat transfer of a vertical helical coil is affected significantly by the coil diameter D, as shown by Heo and Chung [7]. The pitch-to-diameter ratio (P/D) is another important factor affecting the dynamics of the plumes. For a small P/D, the plumes generated at the lower turns affect the heat transfer of the upper turns. When P/D is greater than a certain distance, the heat transfer of each turn becomes independent of the plumes generated from the lower turns.

The plumes from the lower turns have two major effects on the upper turns of the helical coil: the preheating effect and the velocity effect. In the preheating effect, the hot plume generated at the lower turn reaches the upper cylinder, reducing heat transfer. With the velocity effect, the plume from the lower turn provides an initial velocity to the heat generated by the upper turns, improving heat transfer [8]. For small P/D, the preheating effect is dominant. However, as P/D increases, the velocity effect becomes more prominent. With further increase of P/D, the plume influence disappears. An increasing number of turns in the helical coil amplifies these two effects.

The vertical helical coil can be conceived as a series of in-line inclined cylinders; the inclined helical coil can be viewed as a series of staggered arrangements. Natural convection heat transfer of a single-turn vertical coil is similar to that of a slightly inclined cylinder. Heo and Chung [7] reported that natural convection heat transfer from the horizontal cylinder and that from a cylinder of inclination less than 30° show less than 5% difference.

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Nomenclature

C_b	Cupric ion concentration in the bulk $[mol/m^3]$
D	Diameter of the helical coil $[m]$
D_m	Mass diffusivity $[m/s^2]$
g	Gravitational acceleration, 9.8 $[m/s^2]$
H	Height of the helical coil $[m]$
h_h	Heat transfer coefficient $[W/m^2K]$
h_m	Mass transfer coefficient $[m/s]$
k	Thermal conductivity $[W/mK]$
L	Total length of the helical coil $[m]$
N	Number of turns of the helical coil
Nu_D	Nusselt number based on the diameter $[h_hD/k]$
P	Pitch of the helical coil $[m]$
Pr	Prandtl number $[\nu/\alpha]$
R	Winding radius of the helical coil $[m]$
Ra_D	Rayleigh number based on the diameter $[g\beta\Delta TD^3/\alpha\nu]$
Sh_D	Sherwood number $[h_mD/D_m]$
T	Temperature $[K]$
t_n	Transference number
U_x	Uncertainty of x

Greek symbols

α	Thermal diffusivity $[m^2/s]$
β	Volume expansion coefficient $[1/K]$
θ	Inclination of the helical coil [°]
μ	Viscosity $[kg/m\ s]$
ν	Kinematic viscosity $[m^2/s]$
ρ	Density $[kg/m^3]$

2.2. Chimney effect

The chimney height determines the acceleration of the hot plume. Heat transfer is enhanced with an increase in the chimney height, because this increases the flow rate [9]. The heating section at the bottom of the chimney generates a plume. The plume is accelerated by buoyancy as it rises within the chimney, because the chimney acts as a shroud, preventing dispersion of the plume [10].

In the chimney, the mass flow rates should be the same at all elevations. The flow velocity near the inlet with lower buoyancy and that near the outlet with higher buoyancy should be the same, which affects the development of the boundary layer, and hence, the heat-transfer behavior [11].

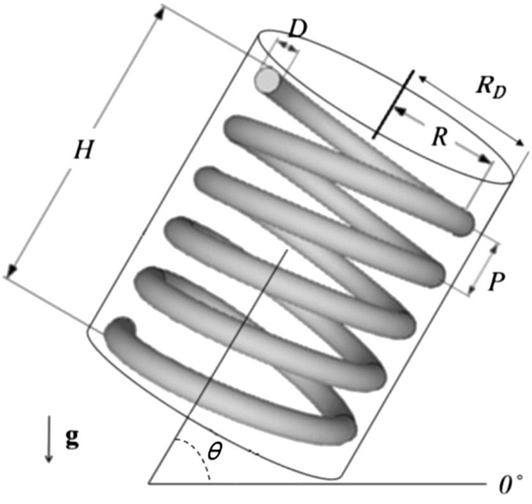

Fig. 1. Inclined helical coil.

2.3. Mass transfer experimental method based on the analogy concept

The analogy between heat and mass transfer systems is based on the similarities between the governing equations and parameters of these systems; thus, heat transfer systems can be transformed into mass transfer systems, and vice versa. Table 1 compares the governing parameters of heat and mass transfer.

In this study, a cupric acid–copper sulfate (H_2SO_4–$CuSO_4$) electroplating system was adopted as the mass transfer system. The idea of using an electrochemical system to represent heat-transfer problems was suggested by Levich [12]. Selman and Tobias [13] further developed this idea and applied it to convective diffusion. In this study, the physical properties of the heat transfer/mass transfer system were calculated based on correlations (1)–(8) developed by Fenech and Tobias [14]. These properties are known to be well within a 5% error at 22 °C.

$$\rho\left(kg/m^3\right) = (0.9978 + 0.06406C_{H_2SO_4} - 0.00167C^2_{H_2SO_4} + 0.12755C_{CuSO_4} + 0.01820C^2_{CuSO_4}) \times 10^{-3} \tag{1}$$

$$\mu(cp) = 0.974 + 0.1235C_{H_2SO_4} + 0.0556C^2_{H_2SO_4} + 0.5344C_{CuSO_4} + 0.5356C^2_{CuSO_4} \tag{2}$$

$$\mu D_m\left(m^2/s\right) = \left(0.7633 + 0.00511C_{H_2SO_4} + 0.02044C_{CuSO_4}\right) \times 10 \tag{3}$$

$$t_{Cu^{2+}} = \left(0.2633 - 0.1020C_{H_2SO_4}\right) \times C_{CuSO_4} \tag{4}$$

$$\Delta\rho/\rho = C_{CuSO_4}\left(\beta_{CuSO_4} - \beta_{H_2SO_4}\left(\Delta C_{H_2SO_4}/\Delta C_{CuSO_4}\right)\right) \tag{5}$$

$$\Delta C_{H_2SO_4}/\Delta C_{CuSO_4} = -0.000215 + 0.113075\gamma^{1/3} + 0.85576\gamma^{2/3} - 0.50496\gamma \tag{6}$$

$$\text{where,}\quad \gamma = C_{CuSO_4}/\left(C_{CuSO_4} + C_{H_2SO_4}\right) \quad \text{and} \tag{7}$$

$$\beta_j = 1/\rho\left[\partial\rho/\partial C_j\right]_{T,C_{k\neq j}} \tag{8}$$

Ko et al. [15], Kang and Chung [16], Chae and Chung [8], Heo and Chung [7], and Heo and Chung [17] performed a series of experiments involving the application of an electroplating system to various convective heat-transfer systems. A detailed description of the methodology can be found in Ko et al. [15]. When determining the mass transfer coefficient with the electroplating system, the limiting current method is used because the cupric ion concentration at the cathode surface is

Table 1
Dimensionless numbers for the analogous systems.

Heat transfer		Mass transfer	
Nusselt number	$\frac{h_hD}{k}$	Sherwood number	$\frac{h_mD}{k}$
Prandtl number	$\frac{\nu}{\alpha}$	Schmidt number	$\frac{\nu}{D_m}$
Rayleigh number	$\frac{g\beta\Delta TD^3}{\alpha\nu}$	Rayleigh number	$\frac{gD^3}{D_m\nu}\frac{\Delta\rho}{\rho}$