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Influence of helical tube dimensions on open channel natural convection heat transfer

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ABSTRACT

Natural convection heat transfer of a helical tube was investigated experimentally for varying tube diameter, length, height, pitch, radius, and number of turns, in order to determine an appropriate characteristic length to describe the phenomenon. Mass-transfer rates of a $CuSO_4$–H_2SO_4 electroplating system were measured by replacing the heat transfer system according to the analogy concept. When the pitch-to-diameter ratio was larger than 5 and the pitch-to-radius ratio was smaller than 2.3, the heat transfer rates were very close to those of a horizontal cylinder, and decreased with the diameter of the tube while remaining unaffected by the total length and height. The natural convection heat transfer of the *N*th turn of a helical tube was measured for varying pitch-to-diameter ratio and number of turns, and the results were formulated as an empirical correlation.

1. Introduction

Helical-tube heat exchangers are widely employed because of their compactness and increased heat transfer area compared to straight-tube heat exchangers. They are used in solar-energy collectors, air conditioning, compact nuclear-power systems, refrigerators, and chemical-engineering applications [1].

Some helical-tube heat exchangers are driven by natural convection, but most are driven by forced convection. Nevertheless, when the driving forces of forced convection are weakened or lost, heat transfer in a helical tube is dependent on natural convection. Despite the wide range of applications, studies on natural convection heat transfer of helical tubes are limited. Most of the available studies are concerned with forced convection on the outside of the tube, or flow and heat transfer inside the tube [2].

There are a number of pioneering works on natural convection heat transfer on the outside of a helical tube. However, it should be noted that the characteristic length of the tube, used to describe the Rayleigh number, varies from one author to the next. Also, it is difficult to obtain a clear understanding on the heat transfer effects of factors such as the tube diameter, total length, height, pitch, and radius.

This study is aimed at exploring the effects of the aforementioned factors on natural convection heat transfer of a helical tube to determine an appropriate characteristic length to describe the phenomenon. Experiments were performed for varying physical dimensions using a $CuSO_4$–H_2SO_4 electroplating system as a mass-transfer system.

2. Background

2.1. Natural convection of a helical tube

Fig. 1 shows the geometry and dimensions of the helical tube considered in this study. *D*, *L*, *H*, *P*, and *R* are the diameter, total length, height, pitch of the tube and radius of the turn, respectively. *N* denotes the number of turns.

Natural convection of a helical tube in an open channel can be described in terms of a combination of two phenomena: natural convection on an inclined cylinder and the influence of the plume produced at the lower turns on the heat transfer of the upper turns.

Natural convection heat transfer on inclined cylinders is three-dimensional due to the circumferential and axial development of the boundary layers. The flow and heat transfer behavior is more complex than that of either horizontal or vertical cylinders [3,4]. According to Lia and Tarasuk [5] and Heo and Chung [4], the heat transfer rate of an inclined cylinder is highest when the cylinder is horizontal, and decreases as the inclination from the horizontal increases.

The angle of inclination of the cylinder of a helical tube is dependent upon the pitch (*P*) and radius (*R*) of the turns. The effect of inclination (including the pitch and radius) should be considered in any empirical correlation.

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Nomenclature

C_b	cupric ion concentration in the bulk (mol/m$^{3)}$
D	diameter of the helical tube (m)
D_m	diffusivity (m/s$^{2)}$
F	Faraday constant, 96,485 (C/mol)
g	gravitational acceleration, 9.8 (m/s^2)
H	height of the helical tube (m)
h	heat transfer coefficient (W/m^2 K)
h_m	mass transfer coefficient (m/s)
I_{lim}	limiting current (A)
k	thermal conductivity (W/m K)
L	total length of the helical tube (m)
N	number of turns of the helical tube
n	number of electrons in charge transfer reaction
Nu_D	Nusselt number based on the diameter (hD/k)
Nu_H	Nusselt number based on the height (hH/k)
Nu_L	Nusselt number based on the total length (hL/k)
P	pitch of the helical tube (m)
Pr	Prandtl number (ν/α)
R	radius of the helical turn (m)
Ra_D	Rayleigh number based on the diameter ($g\beta\Delta TD^3/\alpha\nu$)
Ra_H	Rayleigh number based on the height ($g\beta\Delta TH^3/\alpha\nu$)
Ra_L	Rayleigh number based on the total length ($g\beta\Delta TL^3/\alpha\nu$)
t_n	transference number
Greek symbols	
α	thermal diffusivity (m^2/s)
β	volume expansion coefficient (m^3/K)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Sedahmed et al. [6] performed natural convection mass-transfer experiments for a single horizontal ring, and found that variation of the radius (R) did not affect the mass-transfer rate. Thus, it may be inferred that variation of the radius does not affect the heat transfer rate of a helical tube, even though it is slightly inclined.

In regard to the plume effect, Yuncu and Batta [7] carried out a numerical study on a vertical array of two horizontal cylinders for P/D ranging from 2 to 9, and Ra_D ranging between 2×10^4 and 2×10^5. Degradation in the heat transfer of the upper cylinder was observed for $P/D < 3$–4 due to the preheating effect. However for $P/D > 3$–4, the heat transfer of the upper cylinder was enhanced, since the preheating effect vanished and forced convection dominated the fields. When P/D reached 9, the heat transfer effect of the lower cylinder disappeared.

Table 1 summarizes natural convection heat transfer correlations for helical tubes proposed by several authors. Ali [8] conducted natural convection heat transfer experiments with air on the outside of a helical tube, and suggested a heat transfer correlation. Four diameter-to-radius ratios and five pitch-to-diameter ratios were investigated for two tubes with different diameters (D): 0.0008 and 0.012 m. Prabhanjan et al. [9] performed similar tests with water. Four tubes with diameters (D) ranging from 0.013 to 0.015 m, radii (R) ranging from 0.406 to 0.610 m, and pitches (P) ranging from 0.0135 to 0.0474 m were used. They also suggested an experimental heat transfer correlation. Eqs. (1), (2), (6), and (7) of Table 1 are the correlations suggested by Ali [8] and Prabhanjan et al. [9]. In both studies, the total length (L) was used as the characteristic length. Eqs. (8)–(10) show the dependency of the heat transfer coefficient (h) on the total length (L) in Eqs. (1), (2), (6). There is no consistency amongst these equations.

$$h \propto L^{-0.115} \tag{8}$$

$$h \propto L^{0.548} \tag{9}$$

$$h \propto L^{0.1916} \tag{10}$$

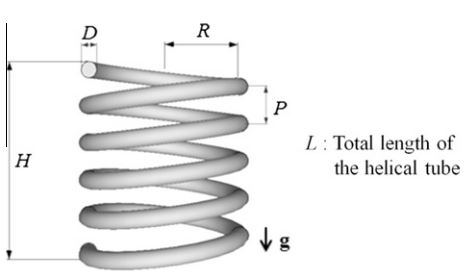

Fig. 1. Physical dimensions of the helical tube.

Ali [8] and Prabhanjan et al. [9] also proposed correlations (3) and (7) using the height as the characteristic length. The exponents of Ra_H in correlations (3) and (7) are close to 1/3, which means that the height dependencies on both sides of the equations cancel each other out, and variation of the height (H) does not affect the heat transfer coefficient (h).

The correlations of Ali [8] and Prabhanjan et al. [9] do not consider the influence of the diameter, even though both authors used tubes of different diameters. Therefore, if a phenomenon is governed by the diameter, these correlations are of limited use.

The effect of pitch is also not considered in Ali's correlation, although his experimental pitches (P) varied from 0.012 m to 0.042 m. Thus, Xin and Ebadian [1] declared that the large behavioral differences between the various tube diameters in Ali's experiments were inexplicable.

Xin and Ebadian [1] studied the natural convection heat transfer of air on the outside of a helical tube using tubes of diameter (D) 0.0127 and 0.0254 m. They constructed heat transfer correlation (4) using the diameter (D) as the characteristic length. Sedahmed et al. [6] performed natural convection mass-transfer experiments on the outside of a helical tube using a $CuSO_4$–H_2SO_4 solution. For a fixed diameter (D) of 0.0006 m and radius (R) of 0.0885 m, they varied the pitch (P) from 0.005 to 0.02 m and the number of turns (N) from 1 to 10. They suggested mass-transfer correlation (5) using the diameter (D) as the characteristic length. Using the mass-transfer analogy, mass-transfer correlations can be transformed into heat transfer correlations.

Moawed [2] carried out similar experiments with two different tubes of diameter (D) 0.0095 and 0.0127 m, corresponding to Ra_D of 1.5×10^3–1.1×10^5. He used the diameter (D) as the characteristic length, and analyzed the effects of varying the diameter (D), total length (L), and number of turns (N) on the heat transfer. The heat transfer coefficient of the first turn was almost the same as that of a single horizontal cylinder, but the heat transfer coefficient of the next turn was reduced by the effect of the plume that developed below. This result is similar to the case of a vertical array of horizontal cylinders proposed by Smith and Wragg [10].

According to Moawed [2], the plume from the lower turns produces two effects on the heat transfer of the upper turns. The first of these is the preheating effect: the hot plume that develops at the lower turns degrades the heat transfer of the upper turns. The second is the forced convection effect: the plume provides an initial velocity and increases the intensity of the flow turbulence for the next turn, which could improve the heat transfer of the upper turns. The preheating effect is dominant at the bottom of a helical tube, and the forced convection effect is dominant at the top.