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Optimal Reynolds number for the fully developed laminar forced convection in a helical coiled tube

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Abstract

This paper analyzes the optimal *Re* for the steady, laminar, fully developed forced convection in a helical coiled tube with constant wall heat flux based on minimal entropy generation principle. Two working fluids, water and air, are considered. It is found that the entropy generation distributions are relatively insensitive to coil pitch, λ. Through the entropy generation analysis for cases of coil curvature ratio, δ ranging from 0.01 to 0.3, and two dimensionless duty parameters, η_1 from 0.1 to 3.0, and $\eta_2/10^{20}$ from 0.01 to 1.0, the optimal *Re* for cases with various combinations of the design parameters is reported. In addition, a correlation equation for the optimal *Re*, δ, η_1, and η_2 is proposed after a least-square-error analysis. The optimal *Re* should be adopted as the operating condition according to the relevant design parameters of the helical coils so that the thermal system can have the best exergy utilization with the least irreversibility.

Keywords: Helical coiled tube; Minimal entropy generation principle; Exergy; Irreversibility

1. Introduction

The fluid dynamics and heat transfer in a helical coiled tube receive considerable attention because of the tube's practical importance in many industrial applications, such as piping systems, heat exchangers, storage tanks, and chemical reactors. During the past several decades, a number of theoretical and numerical studies have been presented for investigating the effects of the secondary flow motion, which is generated by the curvature effect and centrifugal force in the helical coils, on the pressure drop and heat transfer. These studies aimed to clarify the correlations between the friction factor and the Nusselt number [1–3]. The general correlation equations for the Nusselt number and friction factor in the coiled pipes with finite pitch were developed by Manlapaz and Churchill [4]. Their expression was constructed to include application to the limiting case of a straight pipe. The review work of Berger et al. [5] and Shah and Joshi [6] gave a good survey on the abundant researches relevant to the fluid flow and heat transfer in helical coils, from which it is found that all of the previous studies are restricted to the analysis based on the first law of thermodynamics.

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Nomenclature

a	radius of coil curvature (m)
b	coil pitch (m)
Be	Bejan number
Dn	Dean number, $Dn = Re(r_0/a)^{1/2}$
f	friction factor
He	Helical number, $He = Dn/[1 + (b/2\pi a)^2]^{1/2}$
h	specific enthalpy (J/kg)
$\overline{h}$	average heat transfer coefficient in the coil tube (W/m^2 K)
k	thermal conductivity (W/m K)
$\dot{m}$	mass flow rate (kg/s)
N_S	entropy generation number
$(N_S)_P$	entropy generation number due to frictional irreversibility
$(N_S)_T$	entropy generation number due to heat transfer irreversibility
Nu	Nusselt number, $Nu = \overline{h}(2r_0)/k$
P	pressure (Pa)
q'	heat transfer rate per unit coil length (W/m)
Re	Reynolds number, $Re = \rho V(2r_0)/\mu$
r_0	radius of coil tube (m)
s	specific entropy generation (J/kg K)
$\dot{S}'_{gen}$	entropy generation rate per unit length (W/m K)
T	bulk temperature of the stream (K)
V	average velocity in the coil tube (m/s)
v	specific volume (m^3/kg)
η_1	dimensionless parameter, $\eta_1 = \pi kT/q'$
η_2	dimensionless parameter, $\eta_2 = 32\dot{m}^2\rho^2 q'/\mu^5\pi^3$
δ	coil-to-tube radius ratio, r_0/a
λ	nondimensionless pitch, $b/2\pi a$
ρ	density (kg/m^3)

An inevitable problem met by heat exchanger designers is that the heat transfer enhancement in a thermal system is always achieved at the expense of an increase in friction loss. For example, Narasimha et al. [7] proposed a heat transfer enhancement method by using alternating axis coils to induce chaotic mixing, but the method increases the device complexity and pressure drop. The optimal trade-off by selecting the most appropriate configuration and the best flow condition has become the critical design challenge. Because of the impact on the environment and limited resources, the design-related concept of efficient exergy use and entropy generation minimization [8] is usually addressed as one of the primary objectives for a thermal system design recently. Based on the systematic methodology of computing entropy generation through heat and fluid flow in heat exchangers described by Bejan [9], considerable optimal designs of thermal systems have been proposed [10–13]. As for helical coils, there are several important design parameters which have effective influence on the heat and momentum transport phenomena in the devices. These parameters contribute to irreversibilities that inherently compete with one another. However, very rare exergy analysis has been addressed on the helical coils in previous publications. In the recent research of Ko and Ting [14], the optimizing work of the helical coils by using the minimal entropy generation concept has been carried out, in which the optimal Reynolds number and curvature ratio of the helical coils have been investigated. However, only some specific cases were considered in the research. As a further extensive investigation, the present paper intends to include the more general flow configurations and surroundings of the laminar forced convection in a helical coiled tube with constant wall heat flux, and attempts to propose a correlation equation for providing