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Thermodynamic analysis of optimal mass flow rate for fully developed laminar forced convection in a helical coiled tube based on minimal entropy generation principle

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Abstract

The present paper analyzes the optimal mass flow rate for steady, laminar, fully developed, forced convection in a helical coiled tube with fixed size and constant wall heat flux by the thermodynamic second law based on the minimal entropy generation principle. Two working fluids, including air and water, are considered. The entropy generation analysis covers a coil curvature ratio (δ) range of 0.01–0.3, two dimensionless duty parameters related to fluid properties, wall heat flux and coiled tube size, α_1 range of 0.01–3.0 and α_2 range of 0.1×10^{-6}–1.2×10^{-6}. The optimal mass flow rate, denoted by a dimensionless parameter, β_{opt}, for cases with various combinations of the design parameters is given in the present paper. In addition, a correlation equation for β_{opt} as a function of α_1, α_2 and δ is proposed through a least square error analysis. For a thermal system composed of helical coiled tubes with fixed wall heat flux and tube size, the optimal mass flow rate β_{opt} should be selected so that the system can have the least irreversibility and the best exergy utilization.

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

1. Introduction

Helical coiled tubes are widely employed in heat exchanger devices because of their compact size and high heat transfer performance. Because of its practical importance, laminar forced convection in helical coiled tubes has received considerable attention during the past several decades. From the review works of Berger et al. [1] and Shah and Joshi [2], it can be seen that most of the previous studies concentrated on the effects of flow conditions and geometric parameters on the friction factor and Nusselt number in helical coiled tubes. The researches of Kalb and Seader [3] and Patankar et al. [4] tried to find correlations between the friction factor and Nusselt number by using theoretical and numerical methods in which the influences of

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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)
$\bar{h}$	average heat transfer coefficient in 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, $Nu = \bar{h}(2r_0)/k$
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)
$\dot{S}'_{\text{gen}}$	entropy generation rate per unit length (W/m K)
T	bulk temperature of stream (K)
V	average velocity in coil tube (m/s)
α_1	dimensionless parameter, $\alpha_1 = \pi kT/q'$
α_2	dimensionless parameter, $\alpha_2 = \frac{\mu^{3/2}}{\rho(q')^{1/2} r_0}$
β	dimensionless parameter, $\beta = \frac{\dot{m}}{\mu^{5/2}/\rho(q')^{1/2}}$
δ	coil to tube radius ratio, r_0/a
λ	dimensionless pitch, $b/2\pi a$
μ	molecular viscosity (kg/m s)
v	specific volume (m^3/kg)
ρ	density (kg/m^3)

the secondary flow motion on the pressure drop and heat transfer were investigated. A general correlation equation for the Nusselt number and friction factor in coiled pipes with finite pitch was developed by Manlapaz and Churchill [5]. In the numerical study of Lin et al. [6], both the Nusselt number and friction factor were found to increase as the curvature ratio of the helical coiled tube (ratio of tube radius to the curvature radius of coiled tube) increases.

A good design of heat exchangers should include considerations about how to increase the heat transfer performance and reduce the pressure drop simultaneously. However, an inevitable problem challenges all heat exchanger designers, i.e., the methods to enhance heat transfer performance usually cost an increase of pressure loss. For example, Narasimha et al. [7] has proposed a heat transfer enhancement method by using alternating axis coils to induce chaotic mixing. The method not only increases the heat transfer rate but also increases the pressure drop significantly at the same time. Accordingly, the conflict situation has made the optimal trade off between the heat transfer performance and pressure drop by selecting the most appropriate geometry and the best flow condition become a primary consideration in heat exchanger design work. Recently, the design related concept of efficient exergy use proposed by Bejan [8,9] has become the index for judging the optimal trade off. The entropy generation in a thermal system has been taken as a gauge. Based on the minimal entropy generation principle [8,9], the optimal design of a thermal system can be obtained