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Experimental studies on heat transfer to Newtonian and non-Newtonian fluids in helical coils with laminar and turbulent flow

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ABSTRACT

Experimental studies on isothermal steady state and non-isothermal unsteady state conditions were carried out in helical coils for Newtonian and non-Newtonian fluids. Water, glycerol–water mixture as Newtonian fluids and dilute aqueous polymer solutions of sodium carboxymethyl cellulose (SCMC), sodium alginate (SA) as non-Newtonian fluids were used in this study. These experiments were performed for coils with curvature ratios δ = 0.0757, 0.064 and 0.055 in laminar and turbulent regimes. An innovative approach of correlating Nusselt number to dimensionless number '*M*' for Newtonian fluids based on experimental data is presented which is not available in the literature. Several correlations for the first time are proposed based on heat transfer data generated from the experiments performed for Newtonian fluids under isothermal and non-isothermal conditions (total 138 tests). These developed correlations were compared with the work of earlier investigators and were found in good agreement. Further, comparison of overall heat transfer coefficient U_o, and Nusselt numbers for Newtonian and non-Newtonian fluids under isothermal and non-isothermal conditions (total 276 tests) is presented in this paper. From the experimental results, it was found that overall heat transfer coefficient and Nusselt numbers for water are higher than glycerol–water mixture and non-Newtonian fluids. It was also observed from experimental results that as helix diameter increases, overall heat transfer coefficient and Nusselt numbers of both fluids decreases for the same flow rates.

1. Introduction

Passive heat transfer enhancement techniques in helical coiled tubes are used in several industrial applications. The use of additives is a technique applied to enhance the heat transfer performance of base fluids. Recently, as an innovative material, nanometer-sized particles have been used in suspension in conventional heat transfer fluids. The fluids with these solid-particle suspended in them are called 'nanofluids'. The suspended metallic or non-metallic nanoparticles change the transport properties and heat transfer characteristics of the base fluid. Based on the previous studies, nanofluids are proposed for various applications in heat energy transport fields such as cooling of electronic components, transportation, medical, heat exchanger, nuclear reactor and HAVC. This investigation is a kind of compound heat transfer enhancement techniques, because two passive techniques such as helical coil and nanofluids are taken together to enhance heat transfer. The secondary flow provides proper mixing to enhance heat transfer. The main reason is due to higher effective thermal conductivity of nanofluid, Brownian motion of particles and better fluid mixing [1,2].

Due to the compact size and high heat transfer coefficient as compared to straight tube, helical coil heat exchangers are frequently used in power generation, nuclear industries, refrigeration and air-conditioning systems, heat recovery systems, food and dairy processes and other thermal processing plants. A secondary flow induced by centrifugal force has significant ability to enhance heat transfer rate in helical coils. There are many industrial applications of helical coils for heat transfer such as: (1) in small non-industrial boiler regulation, the steam is generated by passing the water in helical coil and heat is transferred by burning the liquid fuel like light diesel oil, (2) polyethylene is manufactured by oxidation of ethylene in the helical coil in which heat of reaction is taken out from helical coil to outside cold fluid, (3) many industrial applications are condensing steam in helical coils for heating the vessel fluid under isothermal or non-isothermal process, and (4) the molasses is fermented in big vessel (reactor) and the heat of reaction (exothermic) is removed by passing cold water through helical coils to maintain the reactor temperature in isothermal conditions for continuous fermentation and non-isothermal conditions for batch reactor. There are many such applications seen for last 3–4 decades.

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Nomenclature

a	inner radius of tube (m)
a', b'	correlation constants
c_p	specific heat at constant pressure (J/kg K)
d	inner diameter of coil (m)
D	mean helix diameter of coil (m)
De	Dean number, De = Re $(a/R)^{1/2}$
h_i	inside convective heat transfer coefficient (W/m^{2}K)
h_o	outside convective heat transfer coefficient (W/m^{2}K)
k	thermal conductivity of water (W/mK)
L_c	length of coil (m)
$\dot{m}$	mass flow rate of cold water (kg/s)
M	dimensionless number, $M = \frac{Re^{0.64}}{0.26(a/R)^{0.18}}$
N	number of coil turns
Nu	Nusselt number, $h_i d_i/k$
Pr	Prandtl number, ν/α
Q	heat transferred to cold water (W)
R	mean helical radius of the coil (m)
Re	Reynolds number, vd_i/ν
Re_{cr}	critical Reynolds number
Gz	Graetz number, $(\dot{m}c_p)/(kb\ L)$
T	temperature (°C)
t	temperature (°C)
U_o	overall heat transfer coefficient (W/m^{2}K)
v	water velocity inside the coil (m/s)

Greek symbols

δ	coil curvature ratio, a/R
α	thermal diffusivity (m^{-2} s^{-1})
ν	kinematic viscosity (m^{-2} s^{-1})

Subscripts

c	coil
cr	critical
i	inner
o	outer
s	straight

In spite of their abundant use in industrial applications, there is limited experimental information and correlations available in literature on fluid-to-fluid heat transfer under non-isothermal conditions in case of Newtonian and non-Newtonian fluids [35]. Table 1 gives the correlations developed for helical coils by earlier investigators for different experimental parameters.

A first comprehensive review on heat transfer and flow through a curved tube is presented by Berger et al. [11]. The latest review of flow and heat transfer characteristics is provided by Naphon and Wongwises [12] and recently, a critical review of heat transfer through helical coils of circular cross section is presented by Pawar et al. [13].

Aqueous glycerol solutions are widely used in experimental studies of flow phenomena. Experimentation with glycerol solutions facilitates investigation of flows in a wide range of Reynolds numbers. Though glycerine has over 1500 known end uses, very limited published experimental data on heat transfer is available in the literature. Cheng [14] proposed an empirical formula for the calculation of the viscosity of glycerol–water mixture for mass concentrations in the range of 0–100% and temperatures varying from 0 to 100 °C. It is simple to use as compared with similar relations developed by earlier investigators [15–17]. Various analytical and experimental treatments for the flow of non-Newtonian fluids in helical coils have been reported [18–22] in the literature. Rao [21] reported the friction factors and heat transfer for turbulent flow with power-law fluids having a flow behavior index from 0.78 to 1.0. Rajasekharan et al. [23] performed experimental studies for laminar flow in coiled pipes with pseudo-plastic and dilatants fluids. They correlated Nusselt number to the curvature ratio, the flow behavior index and a modified Graetz number, and also measured the diametrical pressure drop at different locations along the coil.

Critical literature review reveals that there is no evidence of Nusselt number correlation with M number in the present research work available. Also, limited experimental information is available in the literature on heat transfer coefficients for non-Newtonian fluids in helical coil heat exchangers of fluid-to-fluid type heat transfer. The determination of these heat transfer coefficients for isothermal steady state and non-isothermal unsteady state conditions is important step in the design of helical coil heat exchangers.

2. Objective

The main objectives of this experimental study were:

(1) To develop for the first time, new correlations correlating Nusselt number to dimensionless 'M' number and validation of these heat transfer correlations with the works of earlier investigators. Also to develop correlations such as: Nu/Pr$^{0.4}$ vs. De, Nu/Pr$^{0.4}$ vs. Gz for Newtonian fluids under isothermal steady state and non-isothermal unsteady state conditions.
(2) To compare experimental Nusselt numbers of various non-Newtonian fluids and comparison of Nusselt numbers in helical coil for water with straight pipe using Pigford's correlation.
(3) To compare experimental overall heat transfer coefficient under isothermal steady state and non-isothermal unsteady state conditions for Newtonian and non-Newtonian fluids.

2.1. Dimensionless number 'M'

In helical coil, a complex flow pattern exists in laminar as well as turbulent flow regimes which are responsible for the enhancement of heat transfer coefficient. Due to mixing of primary and secondary flow pattern simultaneously in helical coil, it becomes difficult to characterize the hydrodynamics of fluid flow. Neither the Reynolds number nor the Dean number could characterize the hydrodynamics of flow through helical coils. Therefore, Mujawar and Rao [7] established for the first time, the criteria for laminar flow in coiled tubes on the basis of a new dimensionless number, M, deduced from a knowledge of the effect of coil curvature ratio on the flow curves. Based on their experimental results, the criteria for laminar flow in coiled tubes for any type of fluid, either Newtonian or non-Newtonian and for any curvature ratio is given in generalized form as:

$$M = \frac{Re_{,}gen_c}{(a/R)^{m'_c}} \leqslant 2100 \tag{1}$$

For Newtonian fluids, Eq. (1) is simplified to set the criteria for laminar flow based on their experimental data as: