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Investigation of natural convection induced outer side heat transfer rate of coiled-tube heat exchangers

A. Zachár *

Institute of Informatics, College of Dunaújváros, Táncsics M. u. 1, Dunaújváros H-2103, Hungary

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ABSTRACT

Natural convection induced heat transfer has been studied over the outer surface of helically coiled-tube heat exchangers. Several different geometrical configurations (curvature ratio $\delta \in [0.035, 0.082]$) and a wide range of flow parameters ($60 <= T_{tank} <= 90$, $T_{in} = 19$ and $60 <= T_{in} <= 90$, $T_{tank} = 20$, $4000 <= Re <= 45000$) have been examined to broaden the validity of the results gained from this research. A fluid-to-fluid boundary condition has been applied in the numerical calculations to create the most realistic flow configurations. Validity of the numerical calculations has been tested by experiments available in the open literature. Calculated results of the inner side heat transfer rate have also been compared to existing empirical formulas and experimental results to test the validity of the numerical computation in an independent way from the outer side validation of common helical tube heat exchangers. Water has been chosen to the working fluid inside and outside of the coiled tube ($3 < Pr < 7$). Outer side heat transfer rate along the helical tube axis has been investigated to get information about the performance of the heat transport process at different location of the helical tube. It was found that the outer side heat transfer rate is slightly dependent on the inner flow rate of any helical tube in case of increasing temperature differences between the tank working fluid temperature and the coil inlet temperature. A stable thermal boundary layer has been found along the axial direction of the tube.

In addition to this the qualitative behavior of the peripherally averaged Nusselt number versus the axial location along the helical tube function is strongly dependent on the direction of the heat flow (from the tube to the storage tank and the reversed direction). Inner side heat transfer rate of helical coils have also been investigated in case of fluid-to-fluid boundary conditions and the calculation results have been compared with different prediction formulas published in the last couples of decades.

1. Introduction

Helically coiled-tube heat exchangers are used in many industrial applications ranging from solar energy applications to nuclear power production, and several other fields of engineering. Heat transfer rate of helically coiled heat exchangers is significantly larger because of the secondary flow pattern induced by the unbalanced centrifugal forces. Several different research works conducted to analyze the heat transfer rate of coiled tube heat exchangers which are focused on the examination of the inside heat transfer process. In the last couples of years an increasing attention turns toward the investigation of the outside heat and mass flow process of helical tubes.

According to the author's knowledge a few experimental study are published the investigation of natural convection induced outer side heat transfer rate from helically coiled tubes and no data is available in the open literature concerning the numerical examination of the developing natural convection induced flow and temperature field around a helical coil. One of the first noticeable experimental investigations of the outer side heat transfer rate characteristic of helically coiled tubes can be dedicated to Ali [1]. Four coil diameter to tube diameter ratios and five different helical pitch-to-outer diameter ratios of helical tubes submersed in water have been studied. Average outside heat transfer coefficients obtained for turbulent natural convection from the outer surface of the coiled tubes and a fluid-to-fluid heat exchanger has been investigated in his study. Xin and Ebadian [2] examined three different helical coils to gain useful information about the outside heat and mass flow process. The studied coils have been oriented vertically and horizontally. A constant heat flux boundary condition is specified on the surface of the helical tubes. Ali [3] conducted experimental investigations of laminar natural convection from uniformly heated helically coiled tubes oriented horizontally in air. Average heat transfer coefficients are obtained for laminar natural convection, the experimental data are correlated with Rayleigh number using the coil tube diameter as the characteristic length. A comparison between the heat transfer rate of helically

* Tel.: +36 25 551 643.
E-mail address: zachar.andras@mail.duf.hu

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Nomenclature

d_c	diameter of the coil (m)
d_{in}	inside diameter of the helical pipe (m)
d_{out}	outside diameter of the helical pipe (m)
De	Dean number (=Re$(d_{in}/d_c)^{0.5}$)
He	Helical number (=Re$(\delta/(1+(p_c/(\pi d_c))^2))^{0.5}$)
k_{avg}	area averaged thermal conductivity at a specific cross section (W m^{-1} K^{-1})
Nu	peripherally averaged Nusselt number (=$q_w\ d_{out}/k_{avg}(T_w - T_m)$)
$\mathrm{Nu_{ax}}$	axially averaged Nusselt number
p_c	helical pitch of the coil (m)
Pr	Prandtl number (= $c_p\eta/\lambda$)
q_w	area averaged wall heat flux at a specific cross section of coiled tube (W m^{-2})
Q_{in}	tube side inlet flow rate (kg s^{-1})
Re	Reynolds number (=$\rho V_{avg}\ d_{in}/\eta$)
s	distance between the wall of the tank and the outer surface of the helical pipe (m)
T_{tank}	initial temperature of the water inside the storage tank (°C)
T_w	area averaged wall temperature at a specific cross section of coiled tube (°C)
T_m	mass-flow averaged mean temperature of the fluid at a specific cross section (°C)
T_{in}, T_{out}	area averaged inlet/outlet temperature of the helically coiled heat exchanger (°C)
V_{avg}	area averaged velocity at a specific cross section of coiled tube (m s^{-1})

Greek symbols

φ	angular coordinate normal to the tube cross section (radian)
δ	curvature ratio (=d_{in}/d_c)

coiled tubes and straight tubes has been presented by Prabhanjan et al. [4].

Prabhanjan et al. [5] presents results of an experimental investigation of natural convection heat transfer from helically coiled tubes submersed in water. Different characteristic lengths have been studied to correlate the outside Nusselt number to the Rayleigh number.

Numerical study of laminar flow and mixed convective heat transfer around a helical tube placed in a cylindrical shell has been carried out by Mirgolbabaei et al. [6]. Various coil-to-tube diameter ratios and non-dimensional coil pitches have been tested with realistic fluid-to-fluid boundary conditions for the studied heat exchangers. A comparative study has been conducted by Conté et al. [7] to examine the forced laminar fluid flow induced convective heat transfer over conical and helical coils with circular cross-section. It was concluded that the conical geometry gives higher outer side heat transfer rate compared to the common helical coils. Experimental study of mixed convection heat transfer in vertical helically coiled tubes for various Reynolds numbers, tube-to-coil diameter ratios and non-dimensional coil pitches have been investigated by Ghorbani et al. [8]. Forced convection heat transfer coefficients of shell and helically coiled tube heat exchangers were examined experimentally by Salimpour [9].

Basic aim of this study is to investigate the impact of different flow rates, inlet position of the tube side flow, temperature differences between the coil inlet temperature and the storage tank initial working fluid temperature and the most important geometrical properties (curvature, relative coil pitch) for the outside heat transfer rate of helical tube heat exchangers.

In this study the following objectives have been investigated:

Developed flow field over the outer surface of helical coils with different geometrical parameters.

Axial distribution of the heat transfer intensity on the outer surface of helical coils.

Axial distribution of the inner side Nusselt number in case of fluid-to-fluid boundary conditions.

Dependency of the outer side heat transfer rate from the inlet fluid flow rate.

Impact of the location (upper or lower) of the inlet flow for the axial distribution of the heat transfer intensity.

Table 1 contains the different test configurations studied in this article.

2. Mathematical formulation

2.1. Conservation equations

This section provides a short summary to the applied mathematical models to describe the velocity field and the temperature distribution inside and around the heat exchanger coils. The physical problem is a steady, three dimensional flow configuration. The momentum equation of the fluid is based on the three dimensional Navier–Stokes equations. The applied turbulence model is the SST $k-\omega$ model which can be used to model correctly the low Reynolds number turbulent flow state. A SIMPLE like method is applied to solve the momentum, continuity, heat and turbulent transport equations.

The conservation equations are formulated in the Cartesian coordinate system because the applied flow solver (Ansys CFX 11.0) uses the Cartesian system to formulate the conservation equations for all (vector U_i and scalar T, P, k, ω) quantities. Description of the entire geometry of the studied flow problems is incorporated into the generated unstructured numerical grid which was created by the ICEM CFD grid generator.

Table 1
Studied geometrical parameters of the coils.

	d_c [mm]	d_{in} [mm]	d_{out} [mm]	p_c [mm]	Num. of turns	δ [–]	p_c/d_c [–]
Coil I Prabhanjan et al. [4]	203	15.7	18.1	18.1	10	0.07733	0.08916
Coil II Prabhanjan et al. [5]	203	11.5	13.5	40.5	9.5	0.05665	0.1995
Coil III, d_{tank} = 400 mm	340	25.4	30	60	4	0.07471	0.1764
Coil IV, d_{tank} = 400 mm	340	12	14	60	4	0.03529	0.11911
Coil V, d_{tank} = 400 mm	260	28	30	30.5	4	0.10769	0.11730
Coil VI, d_{tank} = 460 mm	340	28	30	30.5	4	0.08235	0.08970
Coil VII, d_{tank} = 450 mm	203	15.7	18.1	28	10	0.07733	0.1379