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Prediction of heat transfer coefficients of shell and coiled tube heat exchangers using numerical method and experimental validation

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ABSTRACT

In this work, the heat transfer of shell and helically coiled tube heat exchangers was investigated. Numerical and experimental methods were used to investigate the effect of physical properties of fluid (i.e. viscosity, thermal conductivity, specific heat capacity and density), operational parameters (i.e. the velocity and temperature of fluid) and geometrical parameters (i.e. pitch, diameter of the tube, diameter of shell's inlet, diameters of coil and shell, heights of coil and shell, and the distance between the inlet and outlet of the shell) on Nusselt numbers of both sides. Totally 42 cases and 15 tests were investigated in the numerical analysis and experimental work, respectively. Measurements and analysis were performed, when the steady state was attained. The working fluid of both sides is water, which its viscosity and thermal conductivity were assumed to be dependent on temperature, in the numerical analysis. Results indicate that if the pitch size is doubled, the shell side Nusselt number increases by 10%, while the coil side Nusselt numbers increases by only 0.8%. Also it was found that an increase of 50% in the height and diameter of the shell causes a decrease of 34.1% and 28.3% in the Nusselt number of the shell side, respectively. Based on the results, two correlations were developed to predict Nusselt numbers of coil side and shell side for wide ranges of Reynolds and Prandtl numbers ($1000 < Re_c < 27{,}000$, $2000 < Re_{sh} < 49{,}000$ and $1.9 < Pr_c$ and $Pr_{sh} < 7.1$). These correlations were compared with the experimental data of the present study and previous works. It was found that these correlations are in good agreement with the experimental data for wide ranges of operational and geometrical parameters.

1. Introduction

Helically coiled tube heat exchangers are widely used in various industries such as piping systems, air conditioning, storage tanks, and chemical reactors. In petroleum units, the heat exchanger, which is used to cool the lubricating oil of the mechanical seal of pumps, is a shell and coiled tube heat exchanger. These types of exchangers are one of the compact heat exchangers types used to increase heat transfer rate, require less volume and weight compared with other types of heat exchangers. Modeling of the heat transfer characteristics of this type of heat exchanger, was considered in different literatures. Most studies are about the coil side heat transfer characteristics, while the shell side heat transfer was not investigated in more details.

Salimpour [1] investigated heat transfer coefficients of shell and helically coiled tube heat exchangers experimentally. He found that the shell side heat transfer coefficient increases, with increase of the pitch size. Two correlations were developed to predict the inner and outer heat transfer coefficients as follows:

$$Nu_c = 0.152De^{0.431}\mathrm{Pr}^{1.06}\gamma^{-0.277} \quad (1)$$

$$Nu_{sh} = 19.64\mathrm{Re}_{sh}^{0.513}\mathrm{Pr}^{0.129}\gamma^{0.938} \quad (2)$$

M. Moawed [2] experimentally studied the forced convection from outside surfaces of helical coiled tubes with constant wall heat flux. Experiments were performed in an open circuit airflow wind tunnel system, operated in suction mode. A general correlation for the average Nusselt number was obtained as follows:

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Nomenclature

A	area m^2
C	specific heat capacity J/kg c°
d	diameter m
De	dean number = $Re(d_t/d_c)^{0.5}$
f	distance between inlet and outlet of the shell m
H	height m
h	heat transfer coefficient W/m^2 K°
j	Fanning friction factor
K	turbulence kinetic energy J/kg
k	thermal conductivity W/m K
l	coil's length m
$\dot{m}$	flow rate kg/s
Nu	Nusselt number
p	pitch m
Pr	Prandtl number = μ C/k
Q	heat transfer rate W
q	heat flux W/m^2
Ra	Rayleigh number
Re	Reynolds number
S	uncertainty
T	temperature K° or C°
u	average velocity m/s

Greek symbols

γ	dimensionless pitch $p/\pi d_c$
δ	curvature ratio $d_{t,i}/d_c$
ε	turbulent dissipation J/kg
μ	viscosity Pa.s
ρ	density kg/m^3

Subscripts

b	bulk
c	coil
cr	critical
Deq	equivalent diameter
h	hydraulic
i	inner
k	stage
Ln	normalized length
o	outer
sh	shell
t	tube
v	shell's inlet
w	wall

$$Nu_o = 0.0345\mathrm{Re}^{0.48}(d_c/d_{t,o})^{0.914}(p/d_{t,o})^{0.281} \quad (3)$$

Which is applicable for:

$6.6\times10^2 \le \mathrm{Re} \le 2.3\times10^3$
$7.086 \le dc/d_{t,o} \le 16.142$
$1.81 \le p/d_{t,o} \le 3.205$

Beigzadeh et al. [3] developed Artificial Neural Network (or ANN) models to predict the heat transfer and friction factor of the coil side, in helically coiled tubes. The predicted Nusselt numbers of the coil side, were compared with the proposed equation by Xin and Ebadian [4] and a reasonable agreement was observed. Xin and Ebadian [4] Studied effects of the Prandtl number and geometric parameters on the local and average convective heat transfer characteristics in helical pipes and suggested the following equation for the coil side Nusselt number:

$$Nu_c = \left(2.153 + 0.318De^{0.643}\right)\mathrm{Pr}^{0.177} \quad (4)$$

Which is applicable for:

$20 \le \mathrm{De} \le 2000$
$0.7 \le \mathrm{Pr} \le 175$
$0.0267 \le d_{t,i}/dc \le 0.0884$

And:

$$Nu_c = 0.00619\mathrm{Re}^{0.92}pr^{0.4}\left(1 + 3.455\frac{d_{t,i}}{d_c}\right) \quad (5)$$

Which is applicable for:

$5000 \le \mathrm{Re} \le 10000$
$0.7 \le \mathrm{Pr} \le 5$
$0.0267 \le d_{t,i}/dc \le 0.0884$

Jayakumar et al. [5,6] numerically and experimentally studied the coil side of shell and helically coiled tube heat exchangers and found that the use of temperature dependent properties of working fluids results in prediction of more accurate heat transfer coefficients. They also found that arbitrary boundary conditions, such as constant wall temperature and constant heat flux are not applicable for prediction of heat transfer, when fluid-to-fluid heat transfer occurs in a heat exchanger. Correlations were developed to calculate the coil side heat transfer coefficient of the heat exchanger as follows:

$$Nu_c = 0.025De^{0.9112}\mathrm{Pr}^{0.4} \quad (6)$$

Which is applicable for [5]:

$2000 < \mathrm{De} < 12000$

And:

$$Nu_c = 0.085De^{0.74}\mathrm{Pr}^{0.4}\delta^{0.1} \quad (7)$$

$$Nu_c = 0.116\mathrm{Re}^{0.71}\mathrm{Pr}^{0.4}\delta^{0.11} \quad (8)$$

Which are applicable for [6]:

$14000 < \mathrm{Re} < 70000$
$3000 < \mathrm{De} < 22000$
$3 < \mathrm{Pr} < 5$
$0.05 < \delta < 0.2$

Genic' et al. [7] experimentally studied the shell side heat transfer of helically coiled tube heat exchangers. They investigated three heat exchangers (with different geometrical parameters) and proposed the following correlation for the shell side Nusselt number (the Reynolds number is based on the hydraulic diameter):