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Experimental studies on heat transfer to Newtonian fluids through spiral coils

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ABSTRACT

Spiral coils are investigated for flow of petroleum base oils SN70, SN150 and SN300 under isothermal steady state and a combination of isothermal steady state & non-isothermal unsteady state conditions for "Graetz problem". The experiments were conducted with spiral coils with curvature ratios 0.01568, 0.01778, 0.019, 0.02466, 0.02525, 0.02666, 0.028055, 0.02952, 0.03011, under laminar flow condition. A new dimensionless number R' number is introduced which is proved by the method of dimensionless analysis. The Nusselt number is correlated with R' number for Newtonian fluids based on the experimental data. A number of correlations are developed for Newtonian fluids under isothermal steady state (total 130 tests) and a combination of isothermal steady state & non-isothermal unsteady state conditions (total 154 tests). It is found that R' number characterizes the heat transfer phenomenon very well and it also simplifies the correlations on curved coils. The developed correlations are compared with the correlations developed by earlier investigators and are found to be in good agreement. These correlations can be used for the design of spiral coil heat exchangers.

1. Introduction

Fluid flow through curvature pipe of path may increase the heat transfer effectiveness. This concept of heat transfer is experimented, investigated and correlated to Newtonians fluids under laminar flow at isothermal steady state and combination of isothermal steady state & non-isothermal unsteady state conditions. Spiral coils are generally used in heat exchangers, electronic cooling, chemical reactors, food industry, health industry etc. They are compact and their heat transfer rate is high against the straight tube or helical coiled tubes of same length. In a spiral tube the transfer of heat and pressure drop is dependent upon the following parameters and dimensionless numbers namely; the curvature ratio, the number of turns, the Reynold's number and Prandtl number. The influence of the above mentioned parameters and dimensionless numbers on heat transfer to Newtonian fluids flowing through the spiral coils has been described and investigated for the first time. In spiral coils as compared to other curved coils the variable centrifugal forces are present. These variable centrifugal forces give rise to variable secondary flow occurring through the whole length of the coil that ultimately increases the heat transfer. The early investigations on curved tubes in general were focused on experimental rather than the analytic or theoretical work. Dean [4,5] presented the first analytical proof of the existence of secondary flow in curved coils. The existence of critical velocity for a fluid flowing in the circular cross-section straight pipe was investigated by Reynolds in 1883. After Reynolds, who studied the straight coil flow characteristics Grindley and Gibson [1] were first to notice the difference in straight tube flow and curved coil flow. Eustice [2,3] studied the flow in a transparent 'U' tube by injecting a number of coloured dies which flowed along with the fluid through the 'U' tube. Eustice showed that a different type of flow existed along with the primary flow when the liquid flowed through the curved pipe. Noble et al. as cited in Kubair and Kuloor [8] studied the spiral coils without considering the representative parameters of the coil. Kubair and Kuloor [8] studied the flow of fluids flowing through the two spiral coils for 'Graetz problem'. Their study depicts the influence of the ratio of length to average diameter of the spiral coil on the heat transfer. The most important representative geometrical parameter of the spiral coil is its curvature ratio. Kubair and Kuloor [11] investigated the two spiral coils for 'Graetz problem' taking into consideration the curvature ratio of these two spiral coils. This is the only correlation involving curvature ratio term available for 'Graetz problem' on spiral coils. A comparison of helical coil, straight tube and spiral coil for heat transfer is experimented by Kubair and Kuloor [9]. The performance of spiral coils was found to be better than either straight tube or helical coil. The same authors [10] have developed

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Nomenclature

a', b'	correlation constants
$a2, b2$	correlation constants
$c2, d2$	correlation constants
$a3, b3$	correlation constants
$c3, d3$	correlation constants
φ, e	correlation constants
C_p	specific heat at constant pressure (J/kg K)
D	average diameter of curvature for a spiral (m)
D_{co}	maximum diameter of coil (m)
D_{ci}	minimum diameter of coil (m)
D_i	inside diameter of spiral coil tube (m)
D_o	outside diameter of spiral coil tube (m)
De	Dean number $= Re\sqrt{(D_i/D)}$
$\left(\frac{D_i}{D}\right)$	variable curvature ratio
Gz	Graetz number $= \dot{m}C_p/kL$
h_i	inside film heat transfer coefficient (W/m^2 K)
k	fluid thermal conductivity (W/m K)
L	tube length (m)
m	mass of the fluid (kg)
$\dot{m}$	mass flow rate (kg/s)
n	number of spiral coil turns
Nu	Nusselt number $= hD_i/k$
P	pitch of coil (m)
Pr	Prandtl number $= \frac{\mu C_p}{k}$
Q	heat transfer rate (W)
q	heat flux (W/m)
Re	Reynold's number $= \rho v D_i/\mu$
$Re_{crit.min.}$	minimum critical Reynold's number
$Re_{crit.max.}$	maximum critical Reynold's number
R'	a new dimensionless number $= 4\dot{m}C_p/\pi kD$
t_1	inlet temperature of fluid (°C)
t_2	outlet temperature of fluid (°C)
Δt_{lm}	logarithmic mean temperature (°C)
t_p	temperature of the inside surface of the spiral coil tube (°C)
t_{w1} to t_{w3}	outer wall temperatures of the spiral coil tube (°C)
v	mean axial velocity (m/s)
V	volumetric flow rate (m^3/s)

Greek symbols

Δ	prefix denoting a difference or change
θ	angle of spiral coiled tube as it advances from centre (rad)
μ	dynamic viscosity (Pa s)
ρ	fluid density (kg/m^3)

correlations for friction factors under laminar, transition and turbulent flow in spiral coiled tubes for different fluids. Many papers on spiral coils are generally focused on numerical CFD study, simulation on various software and then experimentally verifying the results obtained. Laminar flow and heat transfer in wholly developed flow in curved tubes was studied by Zapryanov et al. [12]. They have considered the forced convection problems in tubes that are curved in nature, which are generally utilized in various heat exchange equipments, cooling, heating systems, chemical reactors, heat engines and such and other apparatus, devices and equipments. Curvature ratio effect on the heat transfer and development of flow in the spirally coiled horizontal tubes was investigated by Naphon et al. [19]. The results that they predicted for the convective heat transfer and characteristics of flow were in nice agreement with their experiment. Their investigations reveal that the centrifugal force has an important effect on the enhancement of transfer of heat and drop in pressure. Due to the centrifugal force the Nusselt number and drop in pressure obtained from tubes coiled spirally are 1.49–1.50 times higher than the straight tube. A review of fluid flow and heat transfer for curved coils is done by Naphon et al. [18]. An extensive review has been done on spiral coil in literature by Shah [13] and Kakaç [21]. A number of papers and books on curved coils are referred [6,16,17,20,23,27,29,33] in the present study. Fluid flow and heat transfer characteristics of spiral coiled tube in constant wall heat flux was investigated by Geun-jong et al. [24]. A numerical analysis for investigation of flow and heat transfer characteristics in tubes with spiral heat exchanger was undertaken by them. Developing laminar flow in spiral coil tubes is investigated by Altac and Altun [25]. They have numerically investigated steady state combined developing flow and heat transfer in spiral tube coils. The study on spiral coils is limited in open literature and there is a need to study the different aspects of fluid flow and heat transfer in spiral coils (see Table 1).

Table 1
Developed correlations by earlier researchers on spiral and helical coils.

Investigator	Curvature ratio	Type of flow	Regime	Correlations developed and notes.
Noble et al. as cited in [8]	0.045	Laminar	Graetz Problem	$Nu = 0.215(Gz^{0.741})$ $1200 < Gz < 5000$. Geometrical parameters of spiral coils are not considered
Kubair et al. [8]	0.022–0.031	Laminar	Graetz Problem	$Nu = [0.27(L/D) - 2.3]Gz^{0.6}$ $11 \leqslant Gz < 180$ $170 < Re < 6000$ Nusselt Numbers are calculated at arithmetic mean temperature. Length, as a geometrical parameter is taken into consideration
Kubair et al. [11]	0.022–0.031	Laminar	Graetz Problem	$Nu = [(1.98 + 1.8(D_i/D)]Gz^{0.7}$ $9 \leqslant Gz < 1000$ $80 < Re < 6000$ $20 < Pr < 100$ Nusselt numbers are calculated at arithmetic mean temperature. Effect of curvature ratio on heat transfer is studied
Rainieri et al. [35]	0.06	Laminar	Graetz Problem	$Nu = 1.168(De^{0.47})Pr^{0.16}$ $12 < De < 280$ $125 < Pr < 300$ Corrugated helical coils were investigated, highly viscous fluids were used