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ENTROPY GENERATION AND PERFORMANCE ANALYIS OF HELICALLY COILED TUBES

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ABSTRACT

Coiled tubes are characterized with secondary flow structures which are reflected in higher heat transfer coefficients compared to the flow through a straight pipe. However, the benefits of higher heat transfer are damped due to higher pressure drop associated with such tubes. Therefore, for evaluation of benefits of utilization of a coiled heat exchanger, one should consider heat transfer and pressure drop simultaneously. Thermal and pressure drop characteristics of coiled tubes in current paper are analyzed in terms of Nusselt number (Nu) and friction factor (f) as function of geometrical and fluid dynamic parameters of such tubes. Further, thermodynamic performance of coiled tubes is analyzed by comparison of generated entropy. Finally the practical performance of investigated tubes is analyzed based on comparison of heat transfer and pressure drop over coiled heat exchanger volume.

Keywords: coiled tube, heat transfer, pressure drop, entropy, performance

1. INTRODUCTION

Helically coiled tubes represent one of many solutions within passive heat transfer enhancement techniques. Changing of the flow direction due to the geometry of such tubes, results in static pressure and velocity distribution change within the cross section of the tube [1]. Due to such changes of the flow parameters, secondary flow structures are generated which on the other hand influences heat transfer and pressure drop of the fluid flowing inside the coiled tubes. Analysis has shown that heat transfer in coiled tubes is higher compared to the heat transfer within a straight tube but this is valid also for pressure drop. Hence, the designing of heat exchanger in form of helically coiled tube for practical applications such as in chemical reactors, air conditioning and refrigeration systems, food industry etc. is characterized with a tradeoff between benefits related to heat transfer and drawback related to pressure drop.

Basic thermodynamics tell us that both heat transfer and pressure drop are responsible for entropy generation within a heat exchanger. Therefore, in order to encompass the influence of both heat transfer and pressure drop in the designing phase, entropy generation for different flow regimes is analyzed and used to assess the coiled heat exchanger in terms of thermodynamic performance. Entropy generation analysis is followed by a comparison of the helically coiled tube performance in terms of heat transfer and pressure drop over the volume occupied by helically coiled tube.

2. GEOMETRY AND THERMOFLUIDDYNAMIC CHARACTERISTICS OF HELICALLY COILED TUBES

Basic parameter of the geometry of helically coiled tubes (Figure 1) consists of inner tube diameter *d*, the coil diameter D_c and the distance between two adjacent tubes known as pitch *h* [2].

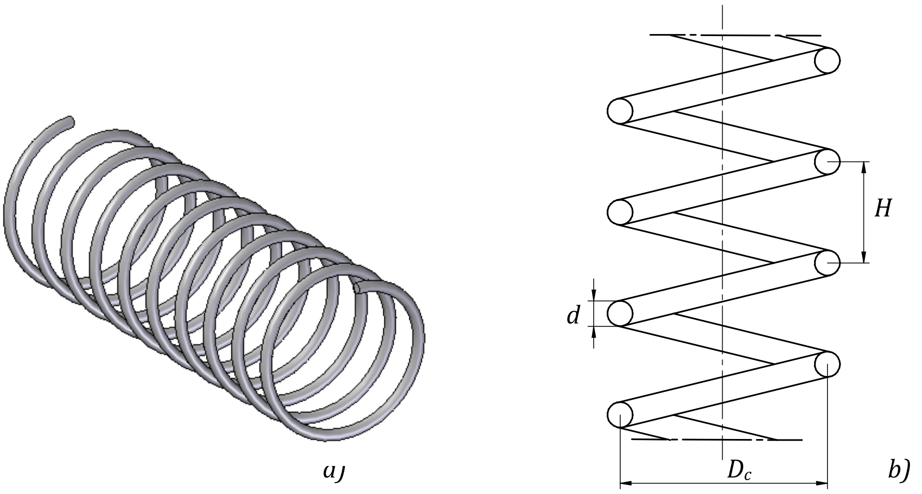

Figure 1. Helically coiled tube: a) 3D view, b) Plain view with geometrical parameters

Another important parameter is average diameter of curvature *D* defined as follows:

$$D = D_C\left[1+\left(\frac{H}{\pi D_C}\right)^2\right] \tag{1}$$

Heat transfer and pressure drop of the fluid flowing through helically coils are presented in terms of dimensionless variables such as Nusselt number (*Nu*) and friction factor (*f*). For the purpose of current paper it will be considered only heat transfer and pressure drop of fluid inside the coils. On the outside wall is considered to flow a fluid with constant temperature at 80 °C. Therefore, wall temperature of the coil may be set equal to 80 °C.

On the inside part of the coil is considered to flow water under turbulent regime. For this flow regime, following expression for calculation of Nusselt number is applied [2]:

$$Nu = \frac{h\cdot d}{k} = \frac{(\xi/8)\mathrm{Re}\,\mathrm{Pr}}{1.0+12.7(\xi/8)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)}\left(\frac{\mathrm{Pr}}{\mathrm{Pr}_w}\right)^{0.14}, \quad 2<\mathrm{Pr}<5 \text{ and } 2\cdot 10^4<\mathrm{Re} \tag{2}$$

where h= heat transfer coefficient, *d*= inside coil diameter, k= thermal conductivity of the fluid inside the coil, Pr= Prandtl number, Pr_w= Prandtl number at the wall temperature $\mathrm{Re} = wd/\nu$ = Reynolds number, w= fluid flow velocity inside, ν = kinematic viscosity of the fluid inside coil and ξ = friction factor defined as follows:

$$\xi = \left[\frac{0.3164}{\mathrm{Re}^{0.25}} + 0.03\left(\frac{d}{D}\right)^{0.5}\right]\left(\frac{\mu_w}{\mu}\right)^{0.27} \tag{3}$$

where μ and μ_w stays for dynamic viscosity at bulk and wall temperature of the fluid.

For calculation of pressure drop of the turbulent flow through a helically coil following equation is recommended [2]:

$$f=\frac{0.3164}{\mathrm{Re}^{0.25}}\left[1+0.095\left(\frac{d}{D}\right)^{0.5}\mathrm{Re}^{1.4}\right],\ \mathrm{Re}_{crit}<\mathrm{Re}<10^{5} \tag{4}$$

where critical Reynolds number is defined as:

$$\mathrm{Re}_{crit}=2300\left[1+8.6\left(\frac{d}{D}\right)\right]^{0.45} \tag{5}$$

Influence of the ratio (d/D) of a coil with total length of l_c=1.65 m, inside diameter of d=10 mm and number of turns n=11, in Nu and f is presented in Figure 2.

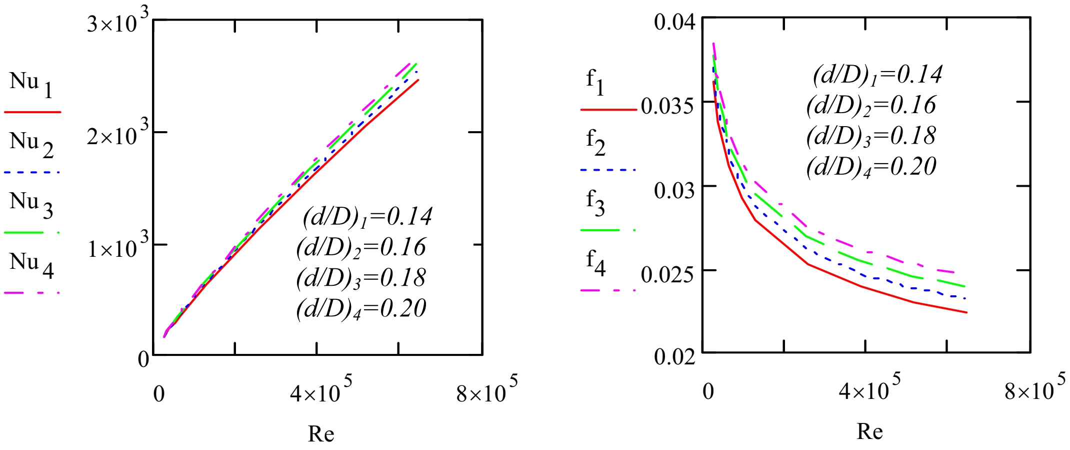

Figure 2. Variation of Ns and f over Re for different ratio d/D

3. IRREVERSIBILITIES AND OVERALL PERFORMANCE OF COIL TUBES

Thermodynamic irreversibility's of the flow associated with heat transfer through a helically coiled tube are reflected in entropy generation within the coil. The rate of entropy generation for fluid flow inside tubes may be estimated based on Bejan theory [3], which is based on analysis of a small section of the tube of length dx and then integration along the tube length. Same theory may be applied also for the flow inside coiled tubes. Hence, following equation derived for incompressible fluids inside straight tubes with constant wall temperature [4] may be applied also for entropy generation rate within coiled tube:

$$\dot{S}_{gen}=mc_{p}\left[\ln\left(\frac{1-\tau e^{-4St\,l_{d}}}{1-\tau}\right)-\tau\left(1-e^{-4St\,l_{c}}\right)+\frac{1}{8}f\frac{E_{c}}{S_{t}}\ln\left(\frac{e^{4St\,l_{d}}-\tau}{1-\tau}\right)\right] \tag{6}$$

Where $St=h/(\rho w c_p)$ is Stanton number, $Et=u^2/(c_pT_w)$ Eckert number, $\tau=(T_w-T)/T_w$ dimensionless temperature and $l_d=l_c/d$ dimensionless length.

Thermodynamic assessment of helically coil acting as heat exchanger may be addressed by analyzing the behavior of entropy generation number defined as:

$$Ns=\frac{\dot{S}_{gen}}{(mc_p)} \tag{7}$$

Behavior of Ns as function of Re is presented graphically in Figure 3. Obviously helically coiled tubes with law (d/D) ratio are characterized with a low entropy generation number. Further for each (d/D) ratio analyzed, a minimum entropy generation number could be identified. This minimum shifts toward lower Re with increasing of the ratio (d/D).

Overall practical assessment of the performance of a heat exchanger is based on comparison of heat transfer and pressure drop taking place during the operation of the heat exchanger but also by comparison of the space occupied by heat exchanger. Hence, for such kind of comparisons, a quite practical tool may be graphical comparison of heat transfer rate per unit volume q_v versus the required pumping power per unit volume e_v occupied by helically coiled tube calculated as[5]:

$$q_v = \frac{Q}{V_c} \qquad \text{and} \qquad e_v = \frac{\dot{V}\,\Delta p}{\eta\, V_c} \tag{8}$$

where Q= is heat transferred by coiled tube, Vc= volume occupied by coiled tube, $\dot{V}$ volume flow rate through the coiled tube, Δp pressure drop of the flow inside coiled tube and η efficiency of pump (=0.8).

By analyzing of q_v over e_v (Figure 4) it may be concluded that the influence of (d/D) values actually used is insignificant. However the enlarged part of the diagram shows that the lower (d/D) values the higher are laying corresponding curves in the diagram which is an indication of better performance of coils with lower (d/D) ratios.

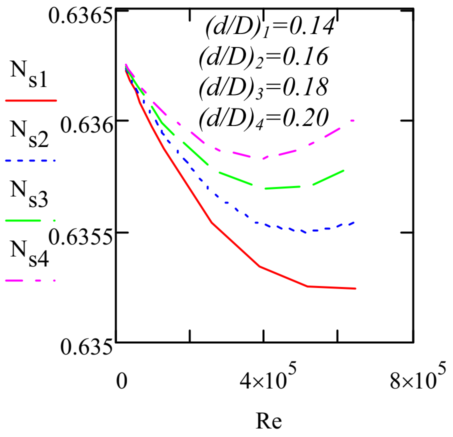

Figure 3. Comparison of helically coiled tube performance based on variation of heat transfer rate over pumping power

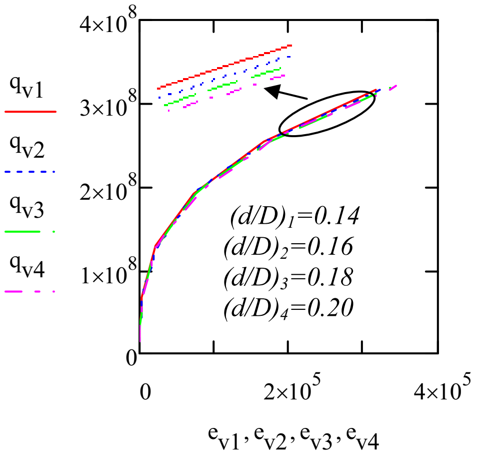

Figure 4. Comparison of helically coiled tube performance based on variation of heat transfer rate over pumping power

4. CONCLUSIONS

Current work provides an analysis of the performance of a helically coiled tube heat exchanger depending on coils geometry, in particular depending on (d/D) ratio. Analysis has shown that with increasing of the ratio (d/D) the Nu and hence heat transfer increases but at the cost of even more increase of friction factor f, respectively pressure drop. Further analysis demonstrates that the behavior of entropy generation number Ns may indicate the best performance of helically coiled tube by considering both heat transfer and pressure drop. Finally practical comparison of heat transfer rate over pumping power per volume of coiled tube shows that coiled tube designs with lowest entropy generation numbers are characterized with higher lying curves means with better overall performance.

5. REFERENCES

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