Development of heat transfer and pressure drop correlations in twisted tube heat exchangers

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Abstract. Heat transfer in concentric twisted tubes exchangers has several applications in the chemical and food industry mainly due to its compact structure and high transport coefficients, however, its use has been limited as a consequence of drop pressure. This study reports Nusselt number and friction factor correlations as a function of the dimensionless Dean number as well as Prandtl number, and a torsional step parameter. Simulations were carried out using ANSYS CFX® V16.0 software at workstations belonging to Grupo de Investigación en Materiales Avanzados y Energía of Instituto Tecnológico Metropolitano. Six geometries were developed with SolidEdge® ST9 academic license. Geometry modification, cleanup, and repair were made although DesignModeler® 2019 academic license. Finally Meshing® for discretization. The mesh size independence, and incidence of the turbulence model, and twisting step validated the computational tools use. Correlation numerically showed an increase of 60% average respect to smooth bending tube.

1. Introduction

Heat transfer rates in curved tube exchangers are higher compared to straight tubes [1], so they are widely used in the food industry [2]. Jayakumar in 2008 studied a heat exchanger with a passive improvement by bending and proposed a correlation for heat transfer estimation [3]. According to Zachár [4], curved tube exchangers study with heat transfer enhancement techniques, such as corrugations or insertions (which represent a second passive improvement), had not been performed at 2010. For this reason, he examined fully developed flow in tubes with double passive improvement and proposed correlations that allowed its dimensioning [4]. Nusselt number improvement in bending and twisting exchangers is due to secondary flows and vortex movement, facilitating turbulence development [5], and to increase of transfer area, because all that allows more particle contact with transfer surface; with the pressure drop increase associated with greater difficulty for fluid passage, and which carries greater energy consumption in drive systems, affecting the overall efficiency of the thermal systems that use them in industry [6-8].

The present research sought to develop Nusselt (Nu) number correlations for heat exchangers with double passive improvement different from Zachár's curved and twisted, allowing the sizing of these devices for their industrial application. Also, the research sought to develop correlations of friction factor (f) that will predict the pressure drop in these devices for their industrial application [9-11].

2. Methodology

The control volume of the external flow of a concentric curved tube heat exchanger was studied, with twisting characteristics varying its torsional pitch; the geometries developed in this study are presented in Figure 1, wherefrom Figure 1(a) to Figure 1(f) torsional pitch variation is showing an increase in turns number per exchanger length unit, torsional pitch parameter is defined as: p/D_h , relating torsional pitch (p - distance between edges measured on the axis) to hydraulic diameter D_h calculated for the inlet flow area. It was worked with a 225 mm radius of curvature, 63.5 mm helical step, and 4.314 mm of length in two turns. Volume occupied by fluid is discretized in cells (mesh), the mesh was optimized by applying an inflation of surfaces in which hydrodynamic boundary layer (inner and outer walls) and thermal boundary layer (inner wall) is developed, and mesh independence study was carried out that would guarantee almost invariable results with respect to those obtained by finer meshes that require longer computing time. Figure 2 shows images of meshes used in an independent study. Another study that was carried out was flow development, to verify the exchanger length incidence in simulation results [12].

The models incidence were studied too, k-ω turbulence model was used to represent turbulent flow [13], followed by processes involved materials and substances properties configuration, liquid water was configured with thermo-dependent properties at a standard temperature, but was modified to an estimated average temperature after some pilot tests in an iterative work. Afterward, boundary (or contour) conditions definition was worked, with a constant temperature in internal wall (Dirichlet condition) of 60 °C, and adiabatic (zero heat flux) condition in external wall; at outlet, free discharge was established, constant temperature input of 20 °C and variable speeds between 0.1 m/s and 1.0 m/s increasing 0.1 m/s at each step, for a total of 10 speeds per geometry; then semi implicit method gor pressure linked equations consistent (SIMPLEC) algorithm was used and simulations were run.

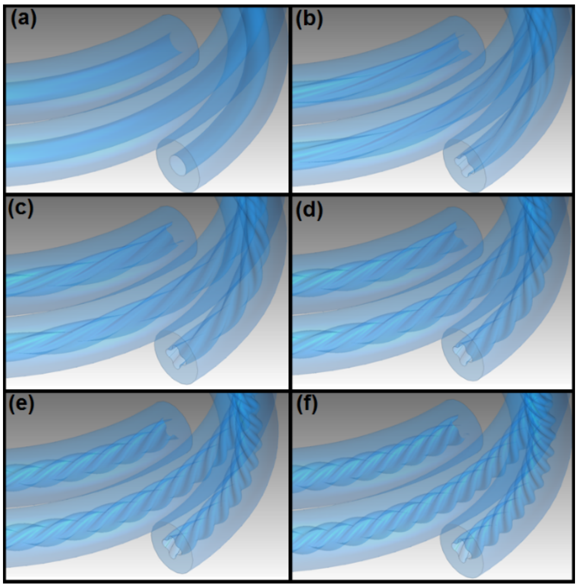

Figure 1. Geometries of length independence study: (a) smooth: $\frac{p}{D_h} = \infty$, (b) $\frac{p}{D_h} = 14.65$, (c) $\frac{p}{D_h} = 7.32$, (d) $\frac{p}{D_h} = 4.88$, (e) $\frac{p}{D_h} = 3.36$, y (f) $\frac{p}{D_h} = 2.93$.

After obtaining simulation results, the development of heat transfer correlation was followed by statistical regression using a nonlinear regression model of the potential type given the form that has been traditional to Nusselt number correlations, as Equation (1): empirical correlation proposed by Jayakumar in [3], and Equation (2): numerical correlation proposed by Záchar in [4].

$$\mathrm{Nu} = 0.025\mathrm{De}^{0.9112}\mathrm{Pr}^{0.4};\ 2000 < \mathrm{De} < 12000;\ 1 < \mathrm{Pr} < 3.5 \tag{1}$$

$$\mathrm{Nu} = 0.5855\mathrm{De}^{0.6688}\mathrm{Pr}^{0.408}\left(\frac{h}{D_h}\right)^{0.166}\left(\frac{p}{D_h}\right)^{-0.192};\ 30 < \mathrm{De} < 1400;\ 3 < \mathrm{Pr} < 30, \tag{2}$$

where h the corrugation depth was studied by Zachár in [4] as the second improvement in its exchanger. Following the same methodology, pressure drop correlation was developed to predict friction factor (f) as a function of Dean number (De) and torsional pitch parameter p/D_h.

Nonlinear regression involves the function linearization by logarithm and coefficients determination by multivariate linear regression that allows estimating each parameter in a 95% confidence interval.

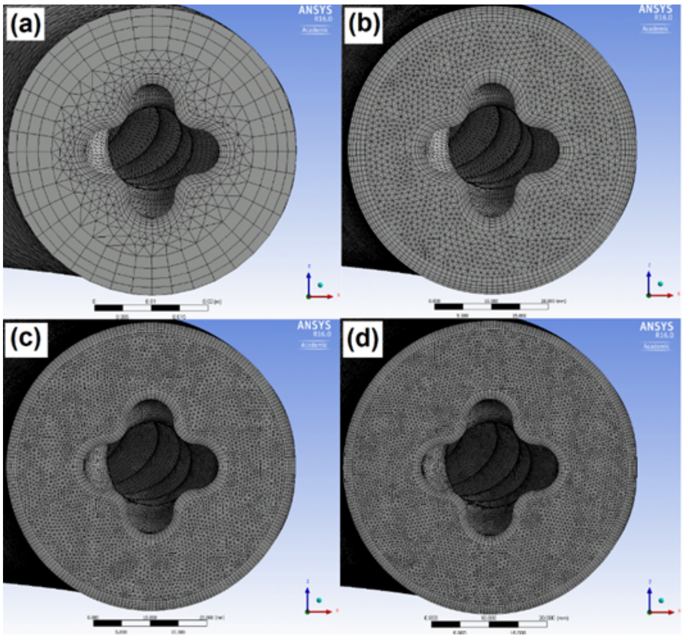

Figure 2. Meshes used in independence study: Minimum size (a) by default, (b) 0.01000 mm, (c) 0.00625 mm, and (d) 0.00550 mm.

3. Results and discussion

The heat transfer correlation developed is presented in Equation (3). A comparison between simulation results and predicted values by Equation (3) are reported in Figure 3 as numerical results for twisted tube corresponding to the geometry with relation p/D_h = 2.93, and as a result of Equation (3) evaluated for a Prandtl number (Pr) of 5.5, and good fit can be seen due to rigor applied in correlations development through statistical regression.

$$\mathrm{Nu} = 0.9574\mathrm{De}^{0.7546}\mathrm{Pr}^{-0.7242}\left(\frac{\mathrm{p}}{\mathrm{D_h}}\right)^{-0.0378}$$
$$920 < \mathrm{De} < 8500;\ 3 < \mathrm{Pr} < 30;\ 2.93 < \frac{\mathrm{p}}{\mathrm{D_h}} < 14.65 \quad (3)$$

Also, numerical results obtained are presented for simulation with a smooth tube, and results obtained in [3] with Jayakumar’s correlation, Equaion (1), for its application were used De and Pr values that characterized the corresponding simulated situation, with a good fit and same trend. This shows that heat transfer in curved exchangers increases with the flow rate increase, which leads to average fluid velocity increase through cross-section, and this, in turn, is expressed as a value growth of Dean parameter that characterizes flow, being verified that when increasing De is increased Nu; meaning of individual exponents reflects inversely proportional effects, for torsional pitch parameter, whose decrease means a higher twist density and greater flow complexity, evidences heat transfer increase. Effects of second passive improvement induced on exchanger with its torque can also be compared in Figure 3, but in Figure 4 is presented a comparison between results of prediction proposed by Equation (3) and Jayakumar's Equation (1) in [3], there were variable increases between 33% and 84%, but when compared with the Equation (2) proposed by Zachár in [4], there were increases between 80% and 197% with respect to smooth tube, showing insertion second improvement better than twisting, for simulated cases in the present study.

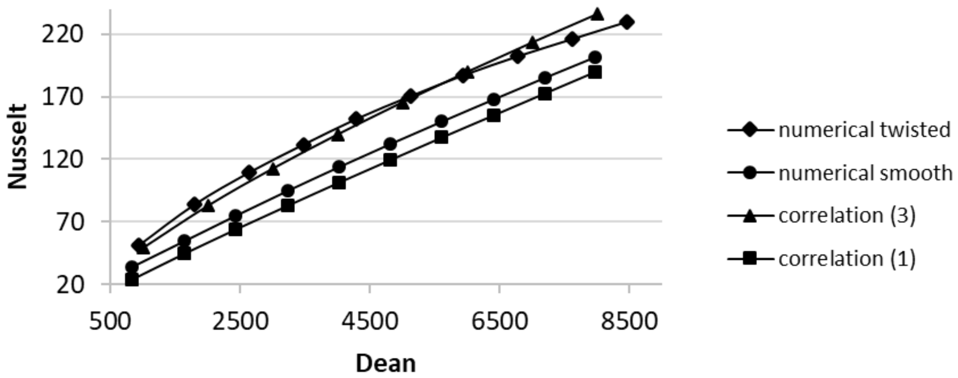

Figure 3. Comparison of numerical results and results by heat transfer correlation.

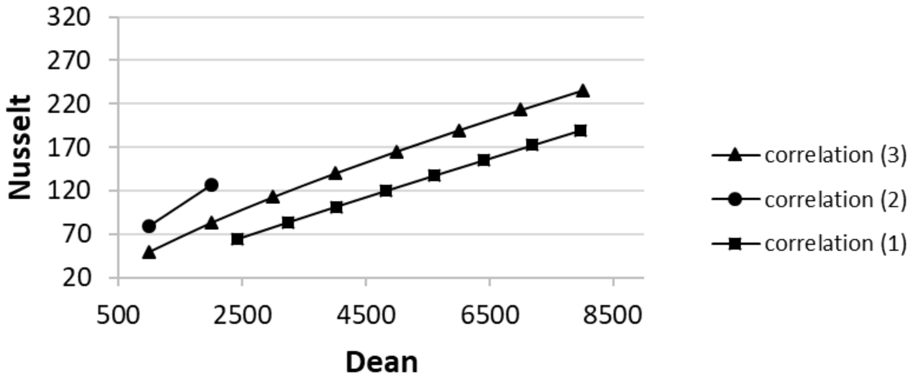

Figure 4. Comparison of second passive improvement effects on heat transfer.

The friction factor correlation developed in this study is presented in Equation (4). Pressure drop in curved exchangers increases with the flow rate increase, proving that Dean increasing cause the friction factor increases. Since the torsional pitch parameter decrease means a higher twist density and greater flow complexity, the pressure drop increase is evidenced. Referring to Figure 5, numerical results for a twisted tube, corresponding to geometry with relation $\mathrm{p/D_h}$ = 2.93, and as result of the correlation of Equation (4) evaluated for a Pr = 5.5 and the same relation $\mathrm{p/D_h}$, and a more conservative result can be seen in prediction made by correlation of Equation (4).

$$\mathrm{f} = (2.5306\mathrm{x}10^{-16})\mathrm{De}^{3.8980}\left(\frac{\mathrm{p}}{\mathrm{D_h}}\right)^{-0.2051}$$
$$920 < \mathrm{De} < 8500;\ 3 < \mathrm{Pr} < 30;\ 2.93 < \frac{\mathrm{p}}{\mathrm{D_h}} < 14.65 \qquad (4)$$

Once the direct proportional effect of Dean on friction factor has been verified, the significance of the other exponent is evaluated, for example, the one corresponding to $\mathrm{p/D_h}$ parameter, finding that in the established domain it has an inverse proportional effect (negative exponent) whose maximum intensity reaches 32.2%. The effects of second passive improvement on pressure drop experienced by fluid upon passing through the twisted exchanger can also be compared in Figure 5, when comparing numerical results between twisted and smooth tubes there is a variation between 100% and 112%.

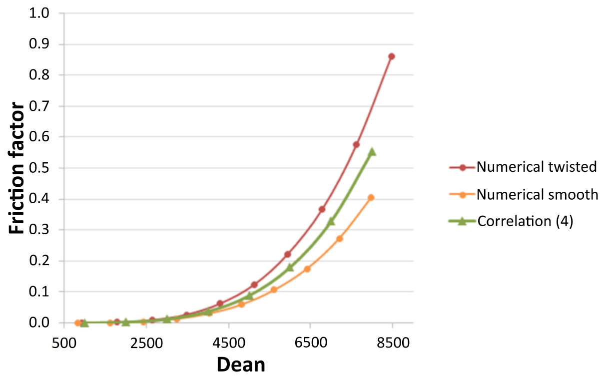

Figure 5. Comparison of second passive improvement effects on friction factor.

4. Conclusions

It is possible the numerical develop of heat transfer and pressure drop correlations, which allow us to passively improved heat exchangers design, using different computational fluid dynamics tools provided by ANSYS® CAE package. Such development requires independent verification of its simulation results and can be achieved by appropriate statistical regression of numerical data.

Both, heat transfer and pressure drop characteristics, of double passive improvement heat exchangers, increase with the flow rate increase, so, for each particular design, both parameters must be evaluated join to increase of pumping power.

Heat transfer correlation numerically developed in present study shows a 60% average increase respect to smooth bending tube, that is, as an effect of the second improvement, this contrasts with a 100% average increase obtained with Záchar prediction that simulates a helical insert, when manufacturer of curved and twisted option proposes 300% increases, this leads to the conclusion that the studied geometry still differs from the Turbotec® commercial geometry and leads to project proposal of correlations experimental development.

It must be noted, in Figure 4 correlation of Equation (1) was proposed for fully developed turbulent flow, and correlation of Equation (2) was proposed for laminar flow, while the correlation proposed in this study applies to laminar, transitional and turbulent regimes; in the future, we also aspire to study them separately with more realistic geometry.

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