academicJournals

Vol. 9(7), pp. 181-188, 15 April, 2014
DOI: 10.5897/SRE2014.5843
Article Number: 06A188B43755
ISSN 1992-2248 © 2014

http://www.academicjournals.org/SRE

Scientific Research and Essays

Full Length Research Paper

Computational Fluid Dynamics (CFD) simulation to analyze the performance of tube-in-tube helically coiled of a heat exchanger

C. A. Chaves[1*], D. R. F. de Castro[1], W. Q. Lamas[1, 2,] J. R. Camargo[1], F. J. Grandinetti[1]

[1]Mechanical Engineering Department, University of Taubaté, Rua Daniel Danelli, s/nº - Jardim Morumbí, 12060-440 - Taubaté - SP - Brazil.
[2]Department of Basic and Environmental Sciences, School of Engineering at Lorena, University of Sao Paulo, Lorena, SP, Brazil.

Received 17 February, 2014; Accepted 25 March, 2014

This work deals with a comparative performance study of two different helically coiled heat exchangers with two and three helical coils through a Computational Fluid Dynamics (CFD) simulation for heat transfer characteristics. The helically coiled heat exchangers are typical industrial equipments found in process applications, such as: chemical, food, energy, electronics, environmental, spatial, and cryogenic. Numerical studies were performed with the assistance of a commercial computational fluid dynamics package (ANSYS-CFX v12). Simulations were performed using various temperatures (hot fluid inlet temperature of 25, 30, 35 and 40°C) and the inlet cold fluid temperature is 20°C. Results indicated that the performance of both heat exchangers for the temperature 25°C (hot fluid inlet) was quite similar, but for the temperature 40°C (hot fluid inlet), the heat exchanger with three turns was more efficient than another exchanger (two turns). It was shown that the performance could be increased by increasing the hot fluid inlet temperature with two and three helical coils.

Key words: Computational Fluid Dynamics (CFD) analysis, heat exchanger, helically coiled performance, number of helically coils.

INTRODUCTION

The helically coiled heat exchangers, also called TTHC (tube-in-tube helically coiled), are typical industrial equipments found in process applications, such as: chemical, food, energy, electronics, environmental, spatial and cryogenic (Kumar et al., 2006). Applications often involve heating or cooling of a fluid to evaporate or condense another fluid. The helically coiled heat exchangers are also used in not traditional processes as sterilization, pasteurization, concentration, crystallization, separation (distillation) etc.

Centrifugal forces acting on the fluid during the passage in the helical coil and due to the curvature of helical coils can generate a secondary fluid flow that has a circular motion; the consequence of this circular motion is that the fluid particle moves into the core tube, the temperature gradient in the pipe section is reduced and the heat exchange is increased. This mechanism for exchanging additional heat, perpendicular to the fluid

*Corresponding author. E-mail: chaves@unitau.br. Tel/Fax: +55 12 3621-8002

Figure 1. Industrial helically coiled heat exchanger (JMS Equipamentos, 2012).

motion is only found in heat exchangers curved tubes (Pimenta, 2010).

Figure 1 is shows an example of industrial helically coiled heat exchanger. Several authors have studied TTHC applications because of its flexibility and efficiency. Some CFD simulation of TTHC had been done for several boundaries conditions and had used actual models to make a comparison with a virtual analysis model (Sahoo et al., 2002; Sahoo et al., 2003; Jayakumar et al., 2008). Also, performance analysis of different TTHC were done and it highlighted that construction and geometry parameters influence significantly in the heat exchanger coefficients (Salimpour, 2009; Abdel-Aziz et al., 2010; Genic et al., 2012; Zhou and Chen, 2012).

Computational numerical simulation on a helically coiled heat exchanger performance has been done and compared to results measured in laboratory experiments (Rennie and Raghavan, 2006; Kumar et al., 2008; Munoz and Adanades, 2011; San et al., 2012; Li et al., 2012).

Computational numerical simulation can be used to study the fluid flow and heat transfer for a wide variety of engineering equipment. In this study, we use Flow Simulation to determine the efficiency of a counter-flow heat exchanger and to observe the temperature inside of it. With Flow Simulation the determination of heat exchanger efficiency is straightforward and by investigating the temperature patterns, the design engineer can gain insight into the physical processes involved, thus giving guidance for improvements to the design (Solidsworks Flow Simulation, 2009).

Purandare and Gupta (2012) carried out a comparative analysis of the different correlations given by different researchers for helical coil heat exchanger. They observed that the helical coils are efficient for low Re (laminar regime). Also the ratio of tube diameter to coil diameter should be large enough for large intensities of secondary flows inside the tubes.

An experimental investigation of the mixed convection heat transfer in a coil-in-shell heat exchanger is reported for various Reynolds number, various tube-to-coil diameter ratios and dimensionless coil pitch was carried out by Ghorbani et al. (2010) where the purpose was to assess the influence of the tube diameter, coil pitch, shell-side and tube-side mass flow rate over the performance coefficient of vertical helical coiled tube heat exchanger.

A numerical investigation of the heat transfer from vertical helically coiled tubes in a cylindrical shell was carried out by Mirgolbabaei et al. (2011). The particular difference in this study compared with other similar studies is the boundary conditions for the helical coil. Constant temperature (80°C) was considered for inlet flow to the coil and the inlet temperature of the shell-side fluid was 20°C. Cold water enters the shell-side at the bottom (inlet mass flowrate boundary condition) and leaves at the top (outlet boundary conditions). The shell-side mass flow rates of water were in the range 0.03 to 0.09 kg/s (the coil-side flow regime is laminar). The inner and outer walls of the pipe were defined as coupled for energy transfer from the hot fluid (inside the pipe) to the cold fluid (in the shell). For momentum equation, the walls were treated as no-slip ones. The inner and outer wall of the shell were taken as no-slip adiabatic ones. The influence of the tube diameter, coil pitch and shell-side mass flow rate on shell-side heat transfer coefficient of the heat exchanger was reasonably demonstrated.

This work deals with a comparative performance study of two different helically coiled heat exchangers with two and three helical coil through a computational simulation. CFD computations have been done for hot water which flows in helical copper coil, with cold water flowing

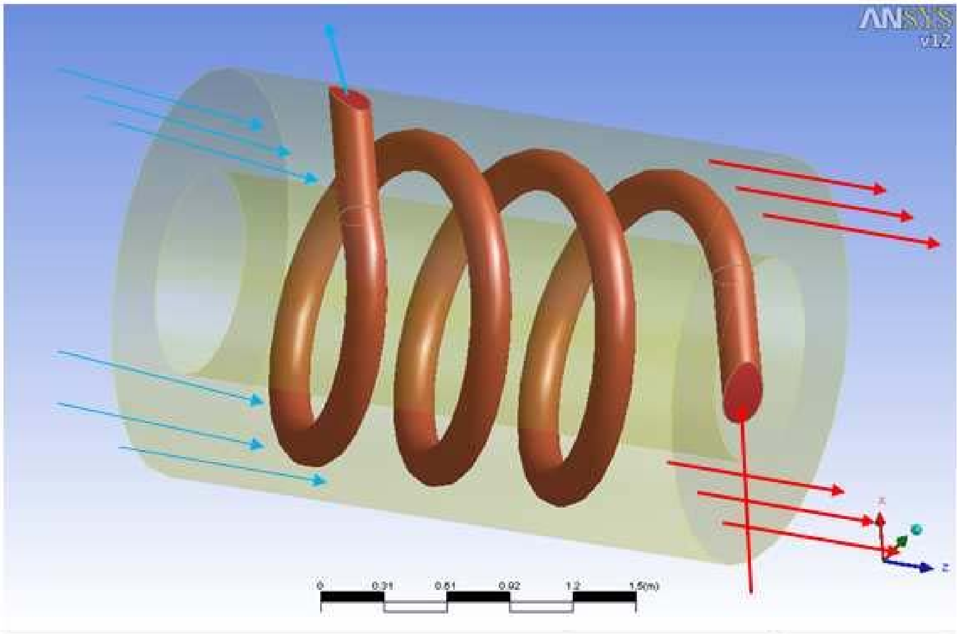

Figure 2. Schematic of the helically coiled heat exchanger.

Table 1. Fluids characteristics.

Properties	Values
Density [kg/m^3]	997
Specific heat capacity [J/kg.K]	4,187.7
Reference pressure [atm]	1
Reference temperature [°C]	20
Thermal conductivity [W/m.K]	0.6069
Dynamic viscosity [kg/m.s]	8.899×10^{-4}

Table 3. Heat exchanger with two helical coils – characteristics.

Characteristics	Values
Coil inner diameter [m]	0.196
Coil outer diameter [m]	0.2
Coils distances [m]	0.7
Coil angle [°]	79.6
Bigger cylinder diameter [m]	2
Smaller cylinder diameter [m]	1
Heat exchanger length [m]	3
Total coil length [m]	11

outside two concentric cylinders in the opposite direction.

METHODS

Simulations were performed using various temperatures (hot fluid inlet temperature of 25, 30, 35 and 40°C) and the inlet cold fluid temperature is 20°C. For momentum equation, the walls were treated as no-slip ones. The inner and outer wall of the shell were taken as no-slip adiabatic ones. Thermal energy transfer is modelled for a copper coil that carries hot water and has externally cold water passage, which has the fluid refrigeration function. Hot fluid inlet velocity was 0.01 m/s and Cold fluid inlet velocity was 0.1 m/s where the coil-side flow regime is laminar (Reynolds number corresponding to these velocities flow were 2,562 and 425 respectively). The inner and outer walls of the pipe were defined as coupled for energy transfer from the hot fluid (inside the pipe) to the cold fluid (in the shell).

Figure 2 shows the helical copper coil arrangement described in which it is possible to see the outside of two concentric cylinders with coolant water passing between them.

The cold fluid passing between the cylinders is represented by the blue arrows, the orange arrows in the coaxial direction represent cold fluid upon heating and the red arrows in the radial direction (into the coil) represent the hot fluid that will be cooled.

A computer simulation to evaluate the thermal exchange and the fluids velocity during the process was done with ANSYS CFX v12 CFD software (ANSYS CFX, 2009). Several relevant characteristics about the heat exchangers dimensioning (physical dimensions of heat exchanger) and about working fluids are presented in Tables 1, 2, 3, and 4 (Pimenta, 2010).

The dimensions that were used in this simulation are compatible with the actual heat exchanger dimension normally found in industries. Some assumptions must be considered to perform the simulation and discuss results throughout the work.

The heat exchangers analyzed have counter-current flow because the performance is better compared to parallel-current heat exchangers. The water is used for both hot and cold fluids, and the metallic material of the heat exchanger is copper. The system is considered permanent and incompressible-fluid, as seen in Table 2. The criterion of convergence used for the variables velocity (u, v, w) and temperature was 10^{-4} RMS (residual mean

Table 2. Criterion of incompressibility.

Sound velocity in the fluid [v = 1,400 m/s]	v_{fluid} (m/s)	Mach number
Hot fluid inlet velocity	0.01	Ma = 0.0000071 < 0.3
Cold fluid inlet velocity	0.1	Ma = 0.000071 < 0.3

Table 4. Heat exchanger with three helical coils – characteristics.

Characteristics	Values
Coil inner diameter [m]	0.196
Coil outer diameter [m]	0.2
Coils distances [m]	0.6
Coil angle [degree]	82
Bigger cylinder diameter [m]	2
Smaller cylinder diameter [m]	1
Heat exchanger length [m]	3
Total coil length [m]	15

Table 5. Hot/cold fluid domain – mesh refining.

Domain	Nodes	Elements
Cold	250,931	932,592
Hot	147,665	467,159
Total	398,596	1,399,751

square) and the maximum number of iterations was 200.

The three-dimensional computational domain was modelled using Hexahedral meshes for both models are shown in Table 5. The complete domain consists of 932,592 elements (cold domain) and 42,602 elements (hot domain). A grid independence test was performed to check the validity of the quality of the mesh on the solution. Further refinement did not change the result by more than 2% which is taken as the appropriate mesh quality for computation.

The effectiveness concept is used for heat exchanger efficiency calculation. The effectiveness (ε) may be defined as the ratio of real heat transfer rate in the heat exchanger (q real) and the maximum possible one (q max), such as Equation (1) (Bergman et al., 2011).

$$\varepsilon = \frac{q_{real}}{q_{\max}} \tag{1}$$

$$q_{real} = C_h - \left(T_{h,i} - T_{h,o}\right) \tag{2}$$

$$q_{\max} = C_{\min} - \left(T_{h,i} - T_{c,i}\right) \tag{3}$$

Equations (2) and (3) present the magnitudes associated with this definition, Equation (1) (Bergman et al., 2011).
Where,
C_h – thermal capacity of hot fluid [kW/°C];
$T_{h,i}$ – temperature of hot fluid inlet [°C];
$T_{h,o}$ – temperature of hot fluid outlet [°C];
$T_{c,i}$ – temperature of cold fluid inlet [°C].

For Equation (3), C_{min} is the less value of C_h, Equation (4), and C_c, Equation (5)

$$C_h = \dot{m}_h - c_{p,h} \tag{4}$$

$$C_c = \dot{m}_c - c_{p,c} \tag{5}$$

Where:
C_c – thermal capacity of cold fluid [kW/°C];
$\dot{m}_h$ – mass flow of hot fluid [kg/s];
$c_{p,h}$ – specific heat of hot fluid [kJ/(kg.°C)];
$\dot{m}_c$ – mass flow of cold fluid [kg/s];
$c_{p,c}$ – specific heat of cold fluid [kJ/(kg.°C)].

For results of heat transfer through the helical coil, the following equations for Reynolds number have been used (Equation 6):

$$\mathrm{Re} = \frac{\rho\, u\, d}{\mu} \tag{6}$$

Where:

μ - coefficient of dynamic viscosity (kg/(m.s));
ρ - density of fluid (kg/m^3);
u - mean velocity of flow (m/s);
d - tube diameter (m).

RESULTS AND DISCUSSION

The simulation results with two and three coils were developed in the study cases appointed in 1 and 2, with 25 and 40°C respectively for hot fluid inlet temperature. The results are presented in the diagram of temperatures for several heat exchange sections obtained by computation software for each device.

Heat exchanger with two coils

The heat exchanger with two coils is preliminarily analyzed following exactly the characteristics presented in Table 3. The working fluid is water and its characteristics are verified in Tables 1 and 2.

Study case 1: Inlet temperature of hot fluid at 25°C

Figure 3 shows the temperatures along the heat exchanger with two coils. Temperature homogeneity can

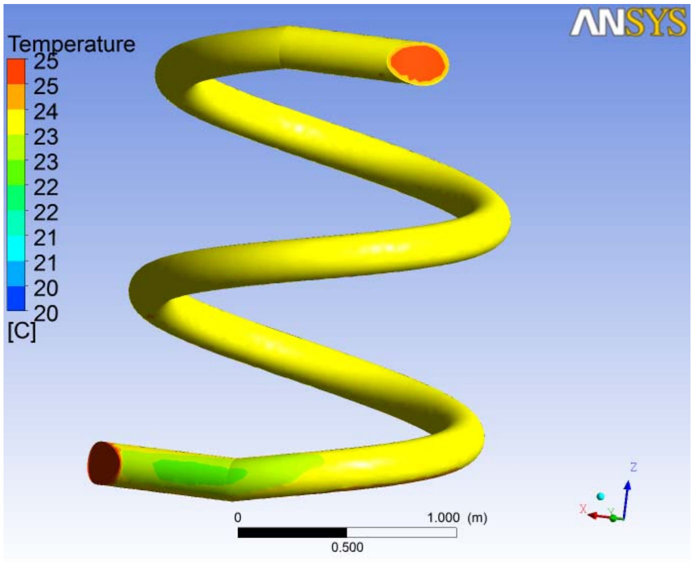

Figure 3. Two coils and hot fluid inlet temperature at 25°C - temperature map.

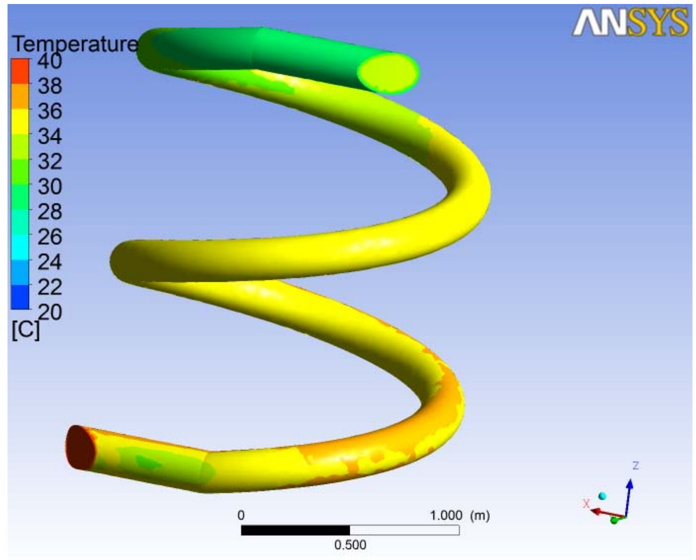

Figure 5. Two coils and hot fluid inlet temperature at 40°C – temperature map.

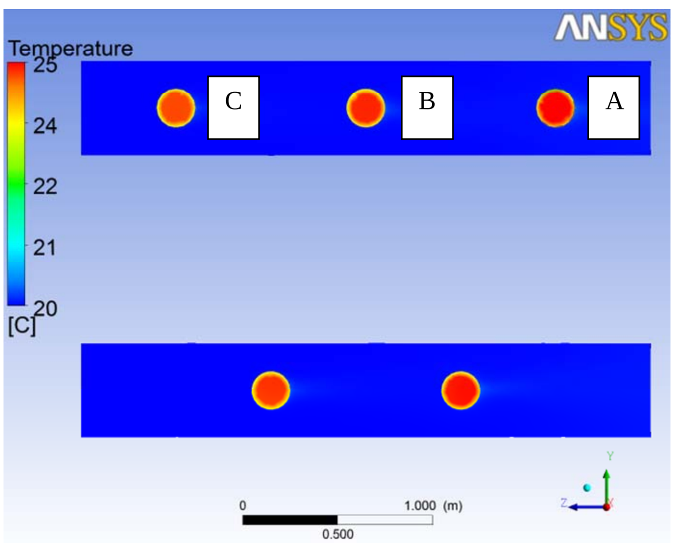

Figure 4. Two coils and hot fluid inlet temperature at 25°C – temperature.

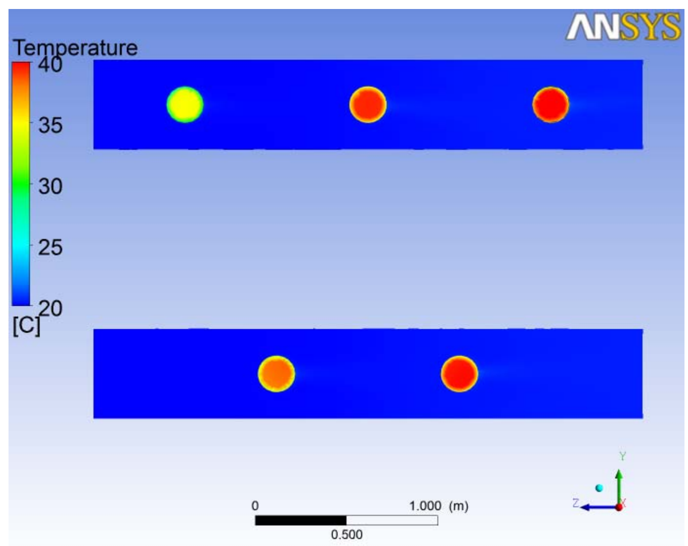

Figure 6. Two coils and hot fluid inlet temperature at 40°C – temperature.

be verified throughout the heat exchanger. It can be explained by the hot fluid temperature very near to cold fluid temperature (ΔT = 5°C).

Figure 4 shows the coil front cuts temperatures in heat exchanger. Obviously the inlet temperature in the point (A) has the largest value and it can be verified to have a gradual reduction of temperature in each section of pipe (B and C) until the lower temperature (point C). The homogeneity of temperature can also be seen in Figure 4 being consistent with Figure 3.

Study case 2: Inlet temperature of hot fluid at 40°C

Figure 5 shows the diagram for temperatures along the coils length. It is verified to exhibit a temperature drop more pronounced in Figure 5 compared to Figure 3. Due to the fact that the hot fluid temperature inlet is higher than study case 1, so, there is a temperature drop more sharply on the first turn. In this case, it has a ΔT_{max} = 30°C.

The results observed shown in Figure 6 are quite similar to the first one in study case 1 (25°C). The system

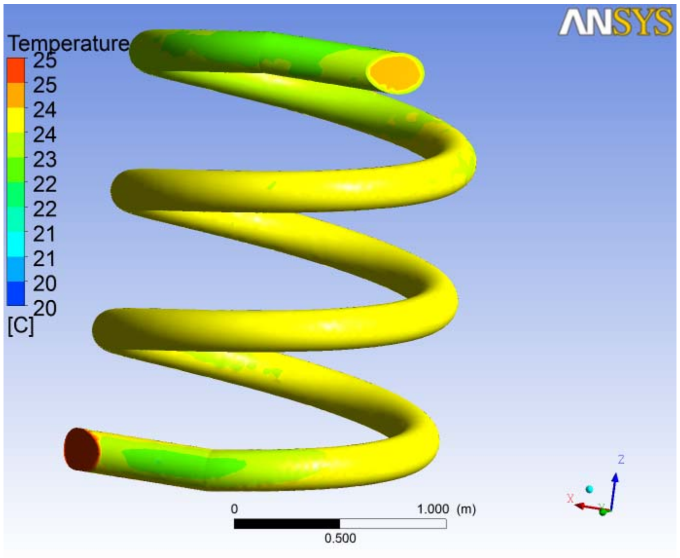

Figure 7. Three coils and hot fluid inlet temperature at 25°C – temperature map.

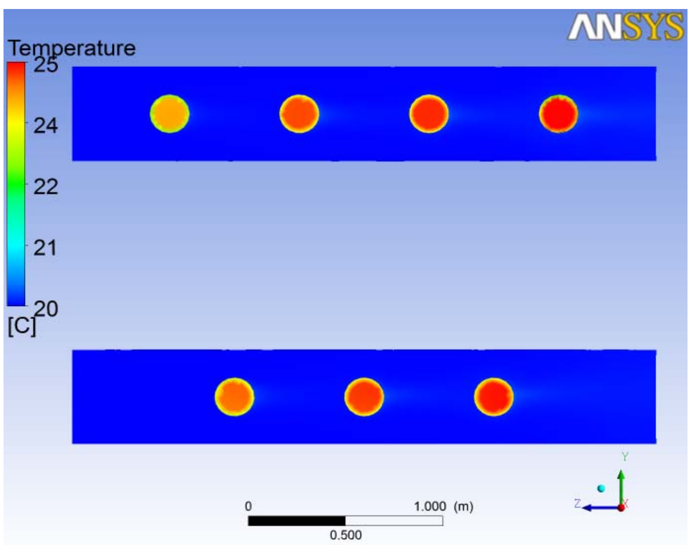

Figure 8. Three coils and hot fluid inlet temperature at 25°C – temperature.

efficiency in study case 1 was lower than the study case 2 and this fact can be explained by the small number of turns which means a smaller area of heat exchange and the temperature of upper hot fluid inlet (40°C). There is not sufficient proper area to achieve the heat exchange.

Heat exchanger with three coils

Figure 7 shows the diagram of temperatures throughout the heat exchanger with three coils.

Table 6. Results comparison for two coils – study cases 1 and 2.

Case	Case 1	Case 2
Hot fluid inlet temperature [°C]	25	40
Efficiency [%]	6.5	33.97

Table 7. Results comparison for three coils – Study cases 1 and 2.

Case	Case 1	Case 2
Hot fluid inlet temperature [°C]	25	40
Efficiency [%]	17.58	77.7

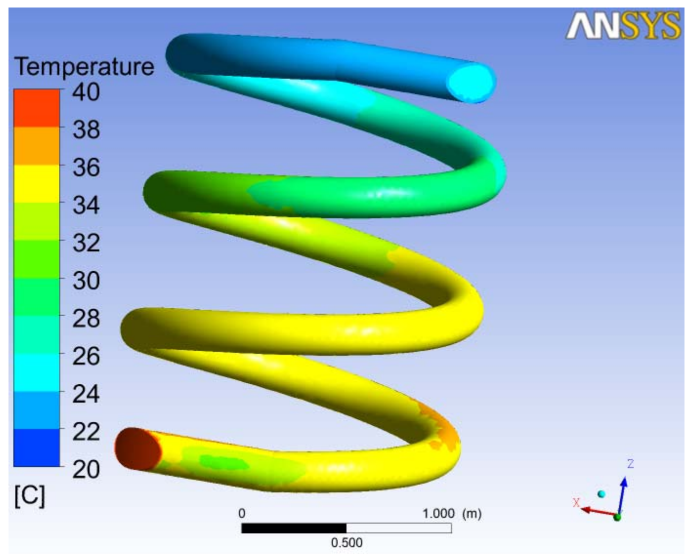

Figure 9. Three coils and hot fluid inlet temperature at 40°C – temperature map.

Study case 1: Inlet temperature of hot fluid at 25°C

Figure 8 show results for study case 1 with three coils, where the hot fluid inlet temperature is 25°C, for temperatures map. Figure 8 present homogeneity, a characteristic that was also observed for the heat exchanger with two coils. It was verified that a ΔTmax = 5°C is relatively significant, if the heat exchanger has two or three coils (Tables 6 and 7). The efficiency for the heat exchanger with three coils in the study case 1 was superior to the heat exchanger with two coils, so, in the case of small ΔT, the addition of a coil was significant.

Study case 2: Inlet temperature of hot fluid at 40°C

Figures 9 and 10 show results for study case 2 with three coils, where the hot fluid inlet temperature is 40°C, for

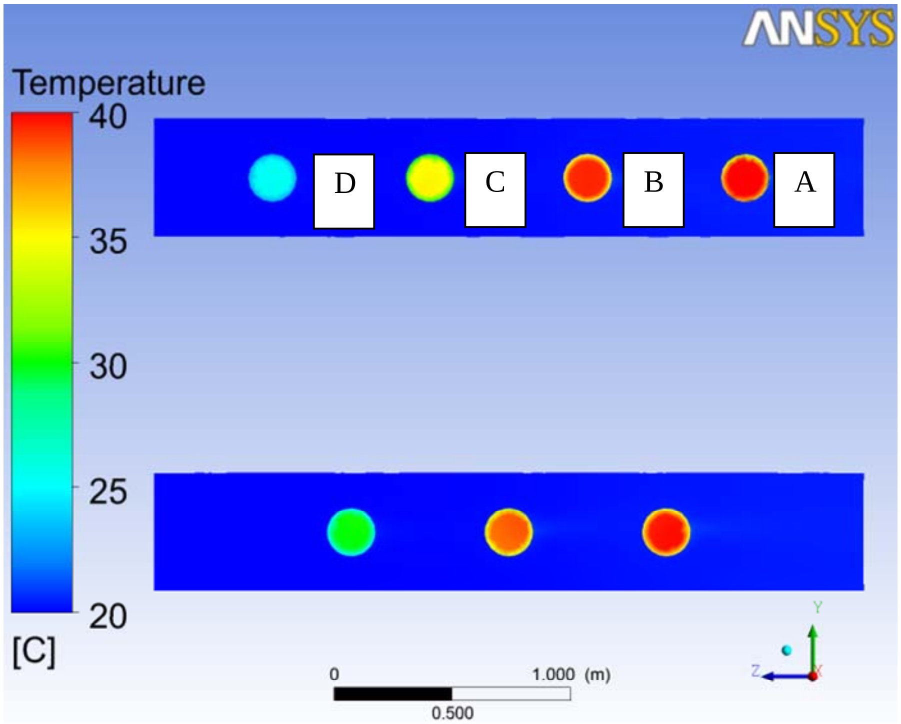

Figure 10. Three coils and hot fluid inlet temperature at 40°C – temperature.

temperatures diagram. Figures 9 and 10 show temperatures in sections A, B, C, and D. At the points B and C, the centre pipe has a slightly higher temperature if compared to the end. This fact can be justified, because the helically coil heat exchangers generated a secondary flow in the pipe core direction, benefiting the heat exchange in the ends. At point D, it is possible to check a considerable drop of temperature compared to point A. In the heat exchanger with two coils, it was not possible to see this significant difference between points A and D.

Table 7 presents the results for this simulation with an average efficiency. The efficiency for the heat exchanger with three coils in the study case 2 was superior to the heat exchanger with two coils. This fact is quite reasonable to be expected due to the greater area of heat exchanger than is achieved with one additional coil. It was also verified that for small ΔT, the difference about the efficiency is not significant.

Heat exchanger with simulations in other operating conditions

Figure 11 shows results for study case 1 with two coils and case 2 with three coils, where the hot fluid inlet temperature is 25 and 40°C, respectively for hot fluid inlet temperature, with simulations in other operating conditions (30°C and 35°C). When the hot fluid inlet temperature increases there seems to be an increase of the efficiency played by a secondary flow in the pipe core direction, for both cases. Figure 11 indicates a stronger effect of secondary flow as the temperature increases.

Conclusions

It can be concluded from this work that the difference in performance of the heat exchanger with two and three coils for a heat exchange relatively low, ΔT_{max} = 5°C between the refrigerant and fluid to be cooled, is very small, with no evident advantages for the heat exchanger with a larger number of coils. However, there was greater ΔT in study case 2, for example, ΔT_{max} = 30°C between refrigerant and fluid to be chilled. The performance efficiency of the heat exchanger with three coils compared to two coils showed considerably better efficiency. For the study case 2, with two coils, it was verified that the heat exchange efficiency was below that for the study case 1. It can be explained by the hot fluid inlet temperature to be higher in the study case 2 and the lower number of coils (two in this case).

It was not possible to perform suitable heat exchange, due to the smaller area of heat exchange and the inlet with higher temperature. This situation was not noticed in the heat exchanger with three coils. This research also revealed that it is necessary for future works to study the number of coils vs. project cost vs. heat exchanger performance for best optimization of the process of heat

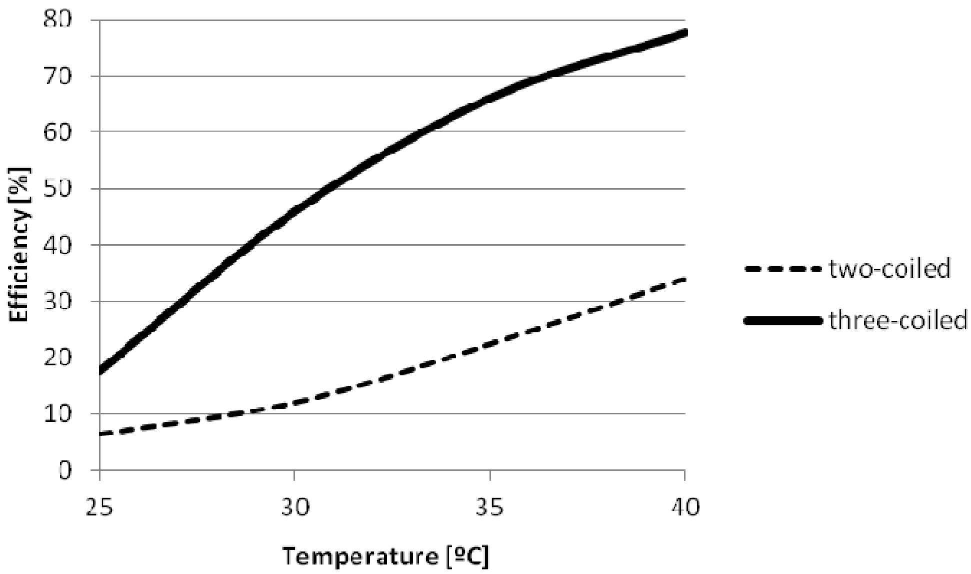

Figure 11. Efficiency-Temperature relationship of the heat exchanger with two and three coils.

exchange, due to the constant industrial need to reduction costs and work with best performances.

Conflict of Interests

The author(s) have not declared any conflict of interests.

REFERENCES

Abdel-Aziz MH, Mansour IAS, Sedahmed GH (2010). Study of the rate of liquid-solid mass transfer controlled processes in helical tubes under turbulent flow conditions. Chem. Eng. Proc: Proc. Int. 49(7):643-648.
http://dx.doi.org/10.1016/j.cep.2009.06.004

ANSYS CFX 12.0 (2009). Tutorials Manual.

Bergman TL, Lavine AS, Incropera FP, DeWitt DP (2011). Fundamentals of Heat and Mass Transfer. 7 ed. John Wiley & Sons, New York.

Equipamentos JMS (2012). Heat exchanger coil. JMS Equipamentos. http://www.jmsequipamentos.com.br/trocador-de-calor/ Accessed 10 November 2012.

Genic SB, Jacimovic BM, Jaric MS, Budimir NJ (2012). Research on the shell-side thermal performances of heat exchangers with helical tube coils. Int. J. Heat Mass Trans. 55(15-16):4295-4300. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.03.074

Ghorbani N, Taherian H, Gorji M, Hessam Mirgolbabaei H (2010). An experimental study of thermal performance of shell-and-coil heat exchangers. Int. Com. Heat Mass Trans. 37:775-781. http://dx.doi.org/10.1016/j.icheatmasstransfer.2010.02.001

Jayakumar JS, Mahajane SM, Mandal JC, Vijayan PK, Bhoi R (2008). Experimental and CFD estimation of heat transfer in helically coiled heat exchangers. Chem. Eng. Res. Des. 86(3):221-232. http://dx.doi.org/10.1016/j.cherd.2007.10.021

Kumar V, Saini S, Sharma M, Nigam K (2006). Pressure drop and heat transfer study in tube- in-tube helical heat exchanger. Chem. Eng. Sci. 61(13):4403-4416. http://dx.doi.org/10.1016/j.ces.2006.01.039

Kumar V, Faizee B, Mridha M, Nigam KDP (2008). Numerical studies of a Tube in tube helically coiled heat exchanger. Chem Eng Proc: Proc. Int. 47(12):2287-2295.

Li Y-x, Wu J-h, Wang H, Kou L-p, Tian X-h (2012). Fluid flow and heat transfer characteristics in helical tubes cooperating with spiral corrugation. Energ. Proc. 17-A:791-800. http://dx.doi.org/10.1016/j.egypro.2012.02.172

Mirgolbabaei H, Taherian H, Domairry G, Ghorbani N (2011). Numerical estimation of mixed convection heat transfer in vertical helically coiled tube heat exchangers. Int. J. Num. Meth. Fluids. 66:805-819. http://dx.doi.org/10.1002/fld.2284

Munoz J, Adanades A (2011). Analysis of internal helically finned tubes for parabolic trough design by CFD tools. Appl. Energ. 88(11):4139-4149. http://dx.doi.org/10.1016/j.apenergy.2011.04.026

Pimenta TA (2010). Studies transfer and fluid flow in Newtonian and non newtoanianos in a helical pipe. Thesis, University of Porto.

Purandare PM, Gupta MMLR (2012). Parametric Analysis of Helical Coil Heat Exchanger. Int. J. Eng. Res. Tech. 1(8):1-5.

Rennie TJ, Raghavan VGS (2006). Effect of fluid thermal properties on the heat transfer characteristics in a double-pipe helical heat exchanger. Int. J. Therm. Sci. 45(12):1158-1165. http://dx.doi.org/10.1016/j.ijthermalsci.2006.02.004

Sahoo PK, Ansari MIA, Datta AK (2002). Computer-aided design and performace evaluation of an indirect type helical tube ultra-high temperature (UHT) milk sterilizer. J. Food Eng. 51(1):13-19. http://dx.doi.org/10.1016/S0260-8774(01)00030-9

Sahoo PK, Ansari MIA, Datta AK (2003). A computer based iterative solution for accurate estimation of heat transfer coefficients in a helical tube heat exchanger. J. Food Eng. 58(3):211-214. http://dx.doi.org/10.1016/S0260-8774(02)00370-9

Salimpour MR (2009) Heat transfer coefficients of shell and coiled tube heat exchangers. Exp. Therm. Fluid Sci. 33(2):203-207. http://dx.doi.org/10.1016/j.expthermflusci.2008.07.015

San J-Y, Hsu C-H, Chen S-H (2012). Heat transfer characteristics of a helical heat exchanger. Appl. Therm. Eng. 39:114-120. http://dx.doi.org/10.1016/j.applthermaleng.2012.01.048

Solidsworks flow simulation (2009). Tutorials Manual.

Zhou Y, Yu J, Chen X (2012). Thermodynamic optimization analysis of a tube-in-tube helically coiled heat exchanger for Joule-Thomson refrigerators. Int. J. Therm. Sci. 58:151-156. http://dx.doi.org/10.1016/j.ijthermalsci.2012.02.028