

Investigation on Helical Coiled Tube Heat Exchanger for Parallel and Counter Flow Using CFD Analysis



P. Saravana Bhavan and J. Selwin Rajadurai

Abstract Fluid flow design and heat transfer components utilising computational fluid dynamics (CFD) are relatively new because of cheaper and accurate method that becomes popular and reliable today. In this study, the helical coil tube heat exchanger is designed and modelled on solid modelling software. The modelled designs are analysed through ANSYS Fluent. The water is considered as working fluid, and copper as the solid material. The CFD analysis of parallel flow as well as counter flow is compared for the parameters like effective thermal conductivity, velocity and pressure. As an outcome, counter-flow heat exchanger provides effective outcome than the parallel-flow heat exchanger. The study explains about the numerical design and CFD analysis' procedures of the helical coiled tube heat exchanger.

Keywords Heat exchanger · CFD analysis · Helical coil · ANSYS Fluent

Nomenclature

| | |
|-------|--|
| Nu | Nusselt number |
| L | Tube length (m) |
| D_h | Hydraulic diameter (m) |
| u | Fluid velocity (m/s) |
| A | Area of heat transfer (m^2) |
| A_f | Cross sectional area of coil (m^2) |
| B | Outside diameter of inner cylinder (m) |
| C | Inside diameter of outer cylinder (m) |

P. Saravana Bhavan (✉)
Engineering Design, Department of Mechanical Engineering,
Government College of Engineering, Tirunelveli 627007, India
e-mail: bhavan270395@gmail.com

J. Selwin Rajadurai
Department of Mechanical Engineering, Government College of Engineering,
Tirunelveli 627007, India

| | |
|-----------------|--|
| c_p | Fluid heat capacity (J/kg K) |
| D | Inside diameter of coil (m) |
| D_e | Shell-side equivalent dia. of coil (m) |
| DH | Average dia. of helix (m) |
| DH1 | Inside dia. of helix (m) |
| DH2 | Outside dia. of helix (m) |
| d_o | Outside dia. of coil (m) |
| Gs | Mass velocity of fluid (kg/m ² s) |
| H | Height of cylinder (m) |
| h_i | Heat transfer coeff. based on inside dia. (W/m ² K) |
| h_{ic} | Heat transfer coeff. inside coiled tube (W/m ² K) |
| h_{io} | Heat transfer coeff. inside coiled tube (W/m ² K) |
| h_o | Heat transfer coeff. outside coil (W/m ² K) |
| j_H | Colburn factor for heat transfer |
| k | Thermal conductivity of fluid (W/m K) |
| k_c | Thermal conductivity of coil wall (W/m K) |
| N | Number of turns |
| M | Mass flow rate (kg/s) |
| N_{Pr} | Prandtl number |
| N_{Re} | Reynolds number |
| Q | Heat load (W) |
| q | Volumetric flowrate of fluid (m ³ /s) |
| r | Average radius of helical coil (m) |
| R_a | Shell-side fouling factor (m K/W) |
| R_t | Tube-side fouling factor (m K/W) |
| Δt_c | Corrected log mean temperature difference (K) |
| Δt_{lm} | Log mean temperature difference (K) |
| U | Overall heat transfer coefficient (W/m ² K) |
| V_a | Volume of shell (m ³) |
| V_c | Volume occupied by N turns of coil (m ³) |
| V_f | Volume available for fluid flow (m ³) |
| x | Thickness of coil wall (m) |
| μ | Fluid viscosity (kg/ms) |
| ρ | Fluid density (kg/m ³) |

1 Introduction

Interest to compact heat transfer devices such as heaters or heat exchangers has increased significantly nowadays. The compact heat exchangers are widely used in the process industries, such as chemical, oil and petrochemical, food, pharmaceutical, nuclear, automotive and others. The heat transfer in between the fluids is a significant process to be absorbed upon; thus, heat exchangers play an important role in our daily

life. The heat transfer mostly occurs by three principles. i.e., convection, conduction and radiation. The process conduction happens when there is a temperature gradient between the solid walls. The practice of helical tubes is detected in different applications such as processing of foods and the operation of nuclear reactor [1]. The helical coil deals with enormous area of heat transfer within a compact space, in addition to higher coefficient of heat transfer in co-operation with less distribution of residence time [2]. The pressure drops and friction factor have been explored in an inclined helical coil with two-phase flow [3]. A compact double-pipe helical coil provides more fluid interaction and reduces the dead zones [4]. Various correlations between flow rate and pressure drop for helical coil have been established [5]. The simulation of turbulent flow in helical coil was examined [6]. The features of transfer of heat in a double-pipe helical heat exchanger were investigated [7]. The Dean number diversifies directly with overall heat transfer coefficient; still the conditions of outer-pipe fluid flow that had a main influence in the overall heat transfer coefficient are carried out [8, 9].

A 3D COMSOL model is to pretend the heat transfer and exothermic chemical reactions in heat exchanger [10]. A study is presented using COMSOL–MATLAB interface to get the optimum helical pitch and radius [11]. The increasing of effectiveness is analysed for different parameters which affects the effectiveness [12]. The performance of heat transfer and the analysis of energy are analyzed in the shell as well as a tube of the heat exchanger through injection air bubbles at various points in the tube [13]. The effect of curved-pipe heat exchanger is compared with the straight-pipe heat exchanger [14]. The result of injection air bubbles at different locations in the entrance of heat exchanger is determined for different percentages of Al_2O_3 nano-particles [15]. The surface of interaction with fluid has to be simulated by applying the initial and boundary conditions, which are done using SolidWorks [16].

Our research work focused on CFD analysis of parallel flow as well as counter flow which are compared for the parameters like effective thermal conductivity, velocity and pressure of the heat exchanger. As a result, the counter-flow heat exchanger provides effective outcome than the parallel-flow heat exchanger. The study explains about the numerical design and CFD analysis' procedures of the helical tube heat exchanger.

2 Helical Coil Heat Exchanger Design

2.1 Design Calculation

To design the heat exchanger, the following data are taken to start the actual design. Thus, following data is taken as input parameters to design the heat exchanger.

Table 1 Properties of fluid

| Input data | Units | Shell | Tube |
|---------------------------|-------------------|--------|--------|
| Material | | Copper | Copper |
| Inlet temperature | K | 403 | 313 |
| Outlet temperature | K | 383 | 333 |
| Heat capacity, C_p | J/kg K | 4185.5 | 4185.5 |
| Thermal conductivity, k | W/m K | 0.6048 | 0.6048 |
| Viscosity, μ | kg/m s | 0.001 | 0.001 |
| Density, ρ | kg/m ³ | 998 | 998 |
| Velocity, u | m/s | 0.1 | 0.1 |

Diameter of outer tube $d_o = 0.08$ m; diameter of inner coil $D = 0.07$ m; average diameter of the coil $D_h = 1$ m; average radius of the coil $r = 0.5$ m; pitch of the coil $p = 1.5 \times d_o = 0.12$ m (Table 1).

2.1.1 Length of the Coil

$$L = N\sqrt{(2\pi r)^2 + p^2}$$

$$L = 3.14 \text{ N}$$

2.1.2 Mass Flow Velocity of Fluid

$$G_s = \frac{M}{\left[\frac{\pi}{4} \{ (C^2 - B^2) - (DH_2^2 - DH_1^2) \} \right]}$$

$$C = 2r + d_o + (2 \times 0.5d_o), \quad B = 2r - d_o - (2 \times 0.5d_o),$$

$$DH_2 = 2r + d_o, \quad DH_1 = 2r - d_o$$

$$\text{AREA, } A = \frac{\pi}{4}(d_o)^2 = 0.0038 \text{ m}^2$$

$$M = \rho \times u \times A$$

$$G_s = \frac{0.379}{\left[\frac{\pi}{4} \{ (1.16^2 - 0.84^2) - (1.08^2 - 0.92^2) \} \right]}$$

$$G_s = 1.5169 \text{ Kg/m}^2 \text{ s}$$

2.1.3 Reynolds Number

Volume available in the shell side is

$$V_f = \frac{\pi}{4}(C^2 - B^2)pN - \left(\frac{\pi}{4}\right)d_o^2L = 0.584 \text{ N}$$

The shell side equivalent diameter is

$$D_e = \frac{4D_f}{\pi d_o L}$$

$$D_e = 0.296 \text{ m}$$

The Reynolds number is

$$N_{Re} = \frac{G_s \times D_e}{\mu} = 477.65$$

$$N_{Pr} = \frac{C_p \times \mu}{K} = 6.94$$

2.1.4 Heat Transfer Coefficient

$$\frac{h_o D_e}{K} = 0.6(N_{Re})^{0.5}(N_{Pr})^{0.31}$$

$$h_o = 26.493 \text{ W/m}^2\text{K}$$

The heat transfer coefficient inside the coil

The fluid velocity is

$$q = \frac{M}{\rho} = \frac{0.379}{998} = 0.00038 \text{ m}^3/\text{s}$$

$$A_t = \frac{\pi D^2}{4} = 3.85 \times 10^{-3} \text{ m}^2$$

$$u = \frac{q}{A_f} = 0.09 \text{ m/s}$$

The Reynolds number (tube-side)

$$N_{Re} = \frac{D u \rho}{\mu} = 6874.2$$

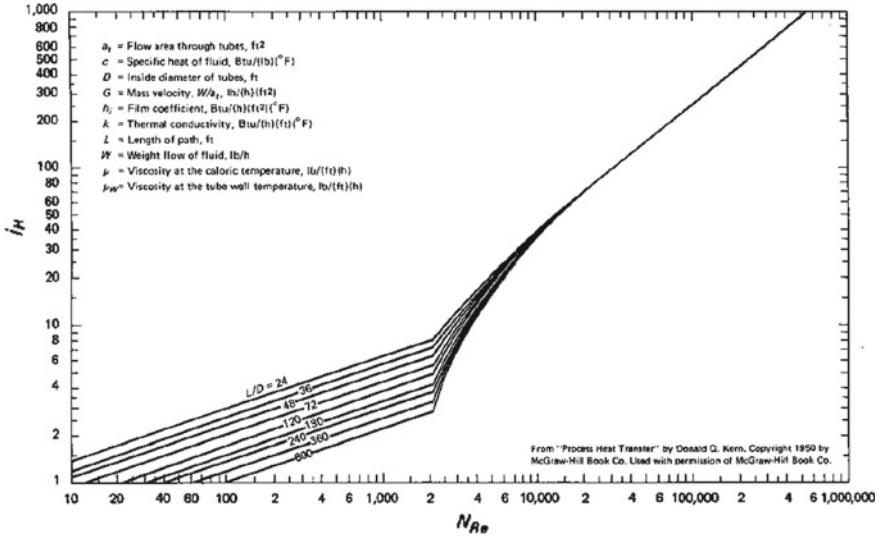


Fig. 1 Graph for determining Colburn factor for heat transfer

From Fig. 1, Graph for determining Colburn factor for heat transfer j_H is 30.

$$h_i = j_H \left(\frac{K}{D} \right) (N_{pr})^{1/3} = 494.4 \text{ W/m}^2\text{K}$$

Corrected for coiled tube

$$h_{ic} = h_i \left(1 + 3.5 \left(\frac{D}{D_H} \right) \right) = 615.52 \text{ W/m}^2\text{K}$$

$$h_{io} = h_{ic} \left(\frac{D}{D_o} \right) = 538.59 \text{ W/m}^2\text{K}$$

2.1.5 Overall Heat Transfer Coefficient

Coil wall thickness

$$x = \left(\frac{d_o - D}{2} \right) = 0.005 \text{ m}$$

$$\frac{1}{U} = \frac{1}{h_o} + \frac{1}{h_{io}} + \frac{x}{K_c} + R_t + R_a$$

$$U = 18.57 \text{ W/m}^2\text{K}$$

2.1.6 Determine the Required Area

$$\Delta t_{lm} = \frac{[(T_{s,i} - T_{t,i}) - (T_{s,o} - T_{t,o})]}{\ln[(T_{s,i} - T_{t,i})/(T_{s,o} - T_{t,o})]}$$

$$\Delta t_{lm} = \frac{[(403 - 313) - (383 - 333)]}{\ln[(403 - 313)/(383 - 333)]} = 68.05 \text{ K}$$

$$\Delta t_c = C_f \times \Delta t_{lm} = 67.04 \text{ K}$$

The heat loads

$$Q = MC_p \Delta T = 31,722.3 \text{ W}$$

$$A = \frac{Q}{U \Delta T} = 25.36 \text{ m}^2$$

$$N = \frac{A}{\pi d_o L} = 32$$

$$H = (N \times p) + d_o = 3.92 \text{ m}$$

2.2 Design Model of Heat Exchanger

See Figs. 2, 3 and 4.

3 Results and Discussion

3.1 CFD Analysis of Parallel-Flow Heat Exchanger

3.1.1 Effective Thermal Conductivity Plot

The effective thermal conductivity of the parallel flow is high at the inlet of the helical tube and is gradually decreased till the end of the helical coil as shown in Fig. 5. The value of the helical tube varies from 23.47 to 5062 W/m k. The value obtained at the inlet of the helical tube by placing the probe tool is 4985 W/m k and at the middle of the helical coil is 980 W/m k and at the outlet of the helical coil is 25.135 W/m k.

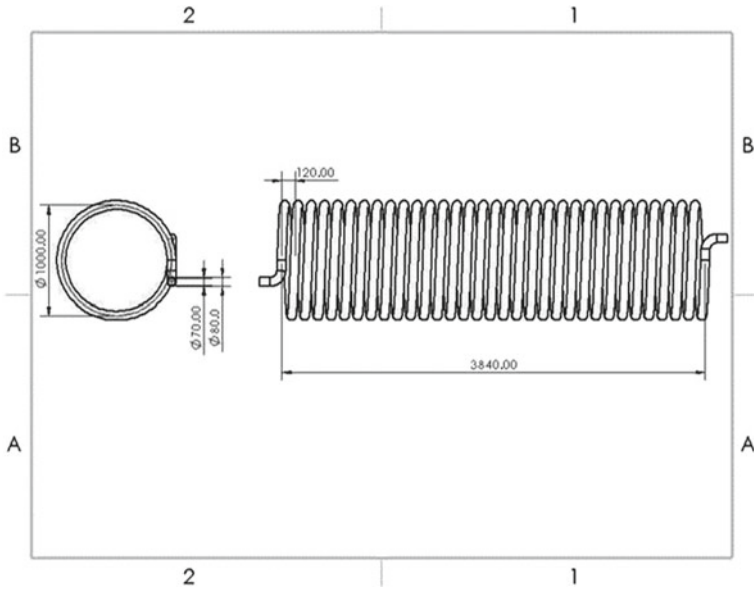


Fig. 2 Front and side view of tube

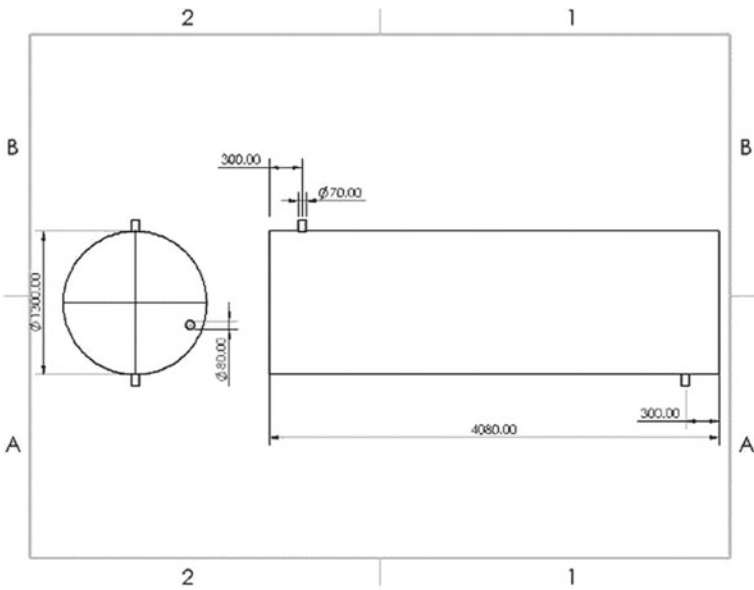


Fig. 3 Projection of heat exchanger

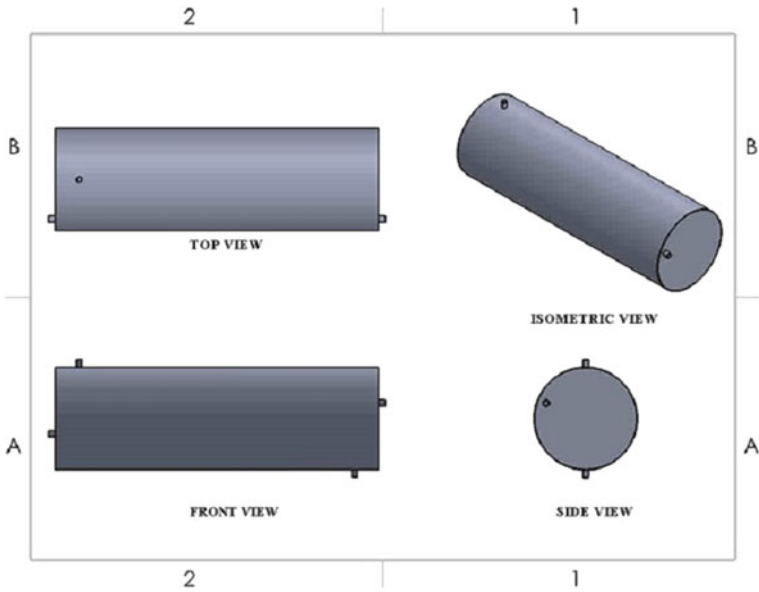


Fig. 4 Front and side view of shell

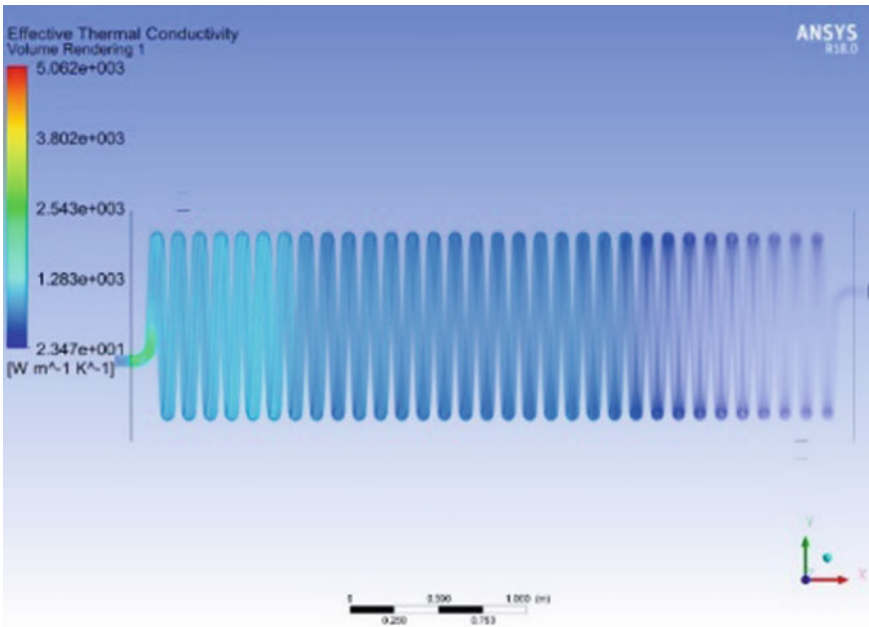


Fig. 5 Effective thermal conductivity plot for parallel-flow

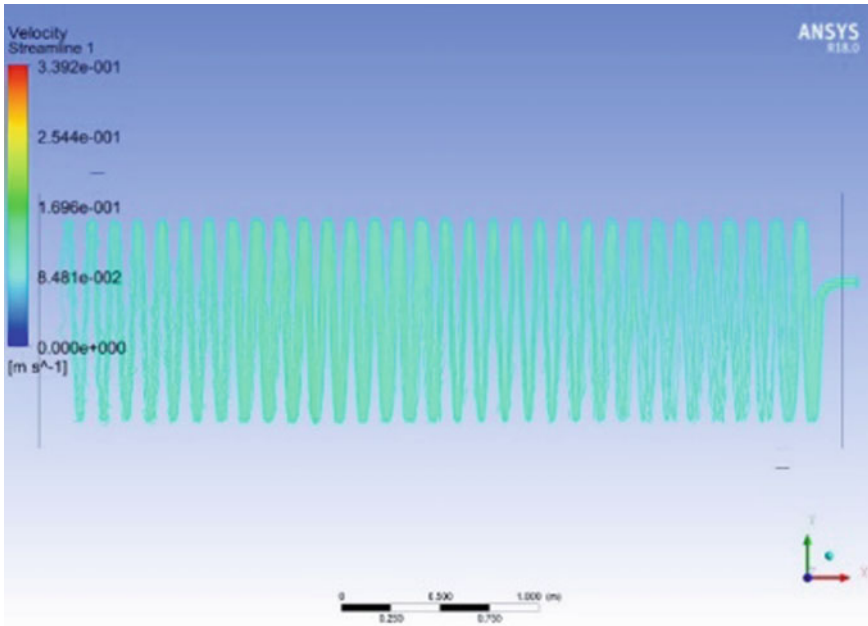


Fig. 6 Velocity plot for parallel-flow

3.1.2 Velocity Plot

It shows that the velocity at the inlet is very low, and it gradually increases towards the outlet of the helical coil as shown in Fig. 6. Initially, the velocity is at 0.08 m/s and increases to 0.23 m/s. By placing the probe, the values show that at inlet of helical tube it is 0.09 m/s and in middle of helical coil it is 1.56 m/s but in between the middle and outlet of coil the velocity gradually decreases and then it increases to 0.2 m/s (Fig. 7).

3.1.3 Pressure Plot

The pressure at the inlet of the helical coil is high at 1505 Pa, and it is gradually decreased to 2 Pa at the outlet of the helical coil as shown in Fig. 9. By the probe value, it defines that at the inlet the pressure is 1500 Pa and in middle the pressure is about 1005 Pa and at the end of coil the pressure is about 50 Pa.

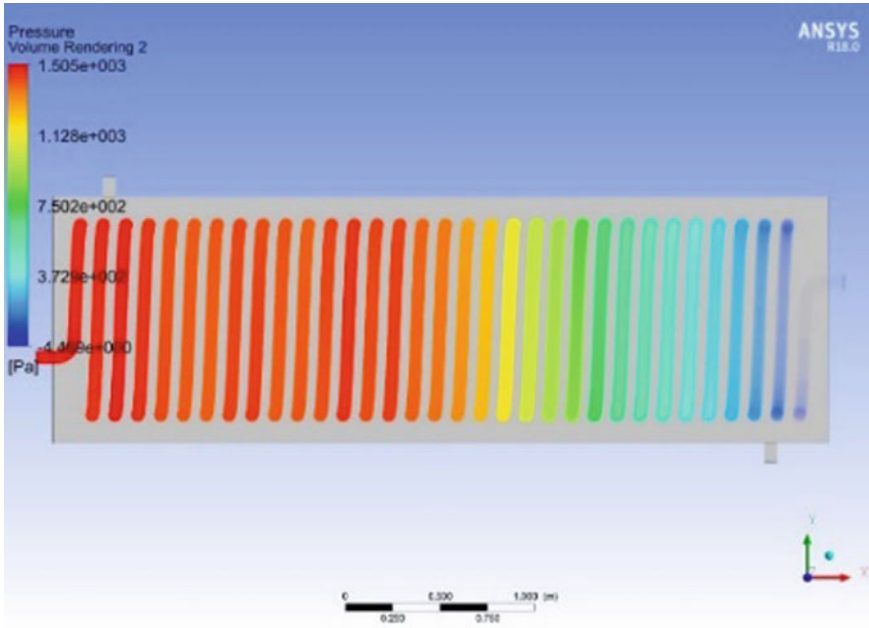


Fig. 7 Pressure plot for parallel-flow

3.1.4 Velocity Graph

At inlet, the velocity is at 0.2 m/s, and it varies alternatively between 0.1 and 0.117 m/s as shown in Fig. 8. At 1 m, the velocity attains 0.115 m/s, at 2 m, the velocity is 0.113 m/s, and at 3 m, the velocity is at 0.112 m/s. The lowest velocity of the heat exchanger is 0.1 m/s.

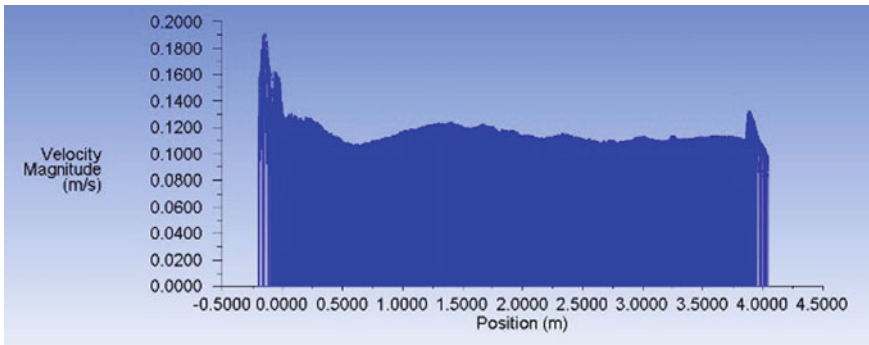


Fig. 8 Velocity graph for parallel-flow

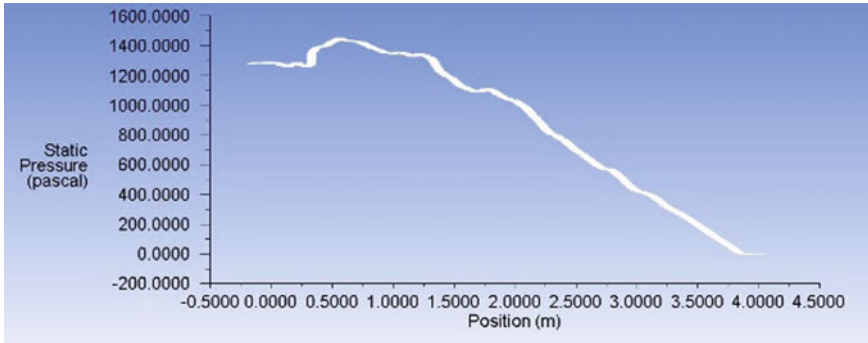


Fig. 9 Pressure graph for parallel-flow

3.1.5 Pressure Graph

The pressure inside the heat exchanger gradually decreases from 1500 to 0 Pa as shown in Fig. 9. At the cold inlet of the coil, the pressure is at 1300 Pa, and when it enters into the shell, the pressure increases to 1400 Pa. At 1 m of heat exchanger, the pressure is 1100 Pa, at 2 m position, the pressure is 900 Pa, and at 3 m, the pressure is about 200 Pa.

3.2 CFD Analysis of Counter-Flow Heat Exchanger

3.2.1 Effective Thermal Conductivity Plot

The effective thermal conductivity of the counter flow is high at the inlet of the helical tube and is gradually decreased till the end of the helical coil as shown in Fig. 10. Values of the helical tube vary from 10.29 to 9976 W/m k. The value obtained at the inlet of the helical tube by placing the probe tool is 9785 W/m k, at the middle of the helical coil, it is 4565 W/m k, and at the outlet of the helical coil, it is 15.85 W/m k.

3.2.2 Velocity Plot

It shows that the velocity at the inlet is high, and it gradually decreases towards the outlet of the helical coil as shown in Fig. 11. Initially, the velocity is at 0.23 m/s and decreases to 0.07 m/s. By placing the probe, the values show that at inlet of helical tube it is 0.195 m/s and in middle of helical coil it is 0.15 m/s but in between the middle and outlet of coil the velocity gradually decreases to 0.079 m/s.

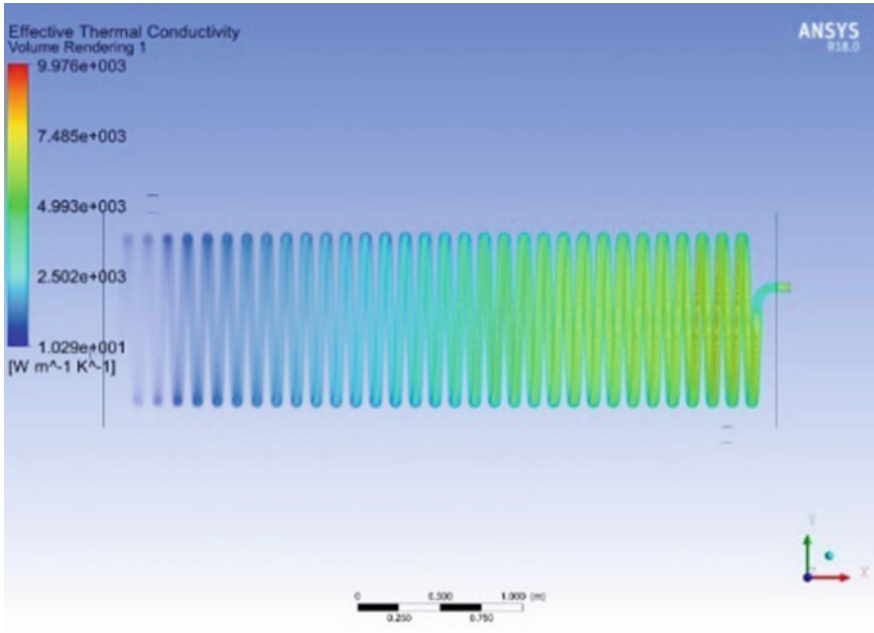


Fig. 10 Effective thermal conductivity plot for counter-flow

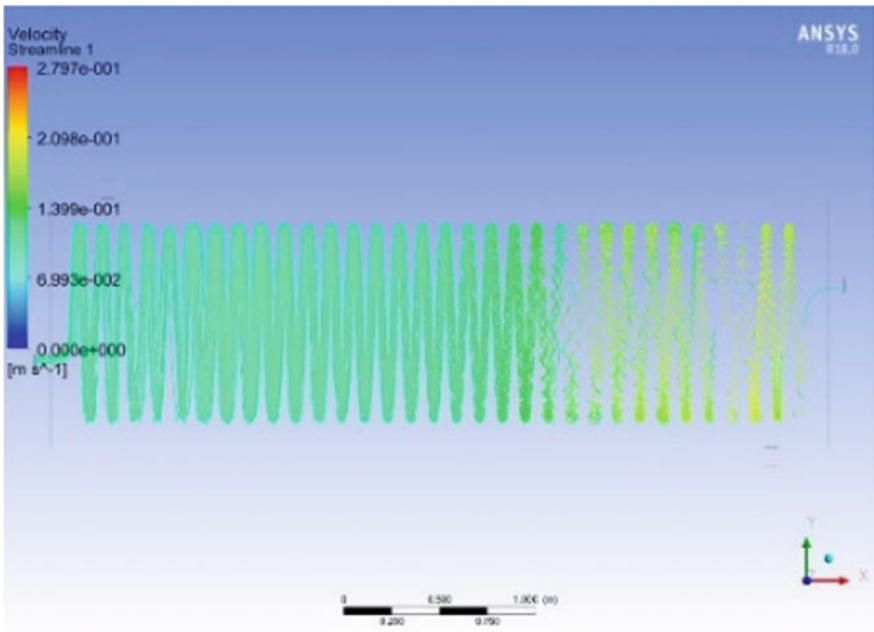


Fig. 11 Velocity plot for counter-flow

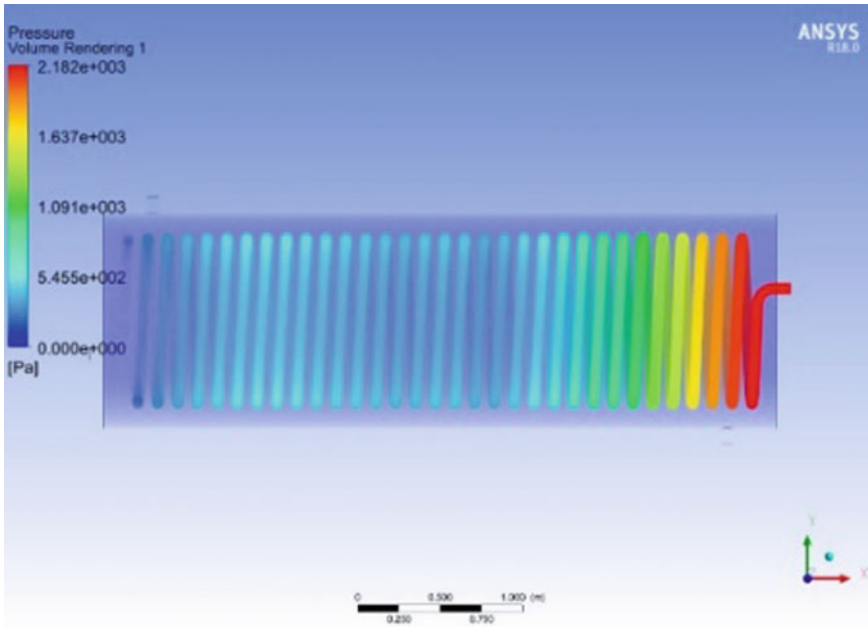


Fig. 12 Pressure plot for counter-flow

3.2.3 Pressure Plot

The pressure at the inlet of the counter-flow helical coil is high at 2182 Pa, and it is gradually decreased to zero pascal at the outlet of the helical coil as shown in Fig. 12. By the probe value, it defines that at the inlet the pressure is 2170 Pa and in middle the pressure it is about 957 Pa and at the end of coil the pressure it is about 20 Pa.

3.2.4 Velocity Graph

The graph is plotted for velocity with the position of the total heat exchanger. X-axis defines the position of the coil in metre, and Y-axis defines the velocity of the fluid flow in metre per second as shown in Fig. 13.

At inlet, the velocity is at 0.25 m/s, and it gradually decreases to 0.2 m/s at outlet. At 1 m, the velocity attains 0.105 m/s, at 2 m, the velocity is 0.15 m/s, and at 3 m, the velocity is at 0.23 m/s. The lowest velocity of the heat exchanger is 0.1 m/s. The velocity is vigorously decreased between 1.5 and 3 m.

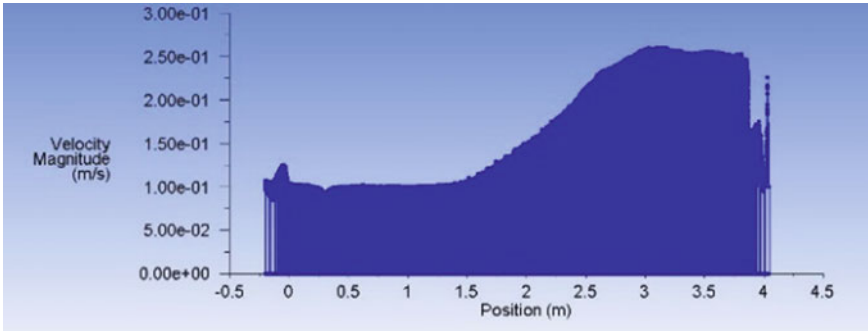


Fig. 13 Velocity graph for counter-flow

3.2.5 Pressure Graph

The pressure inside the heat exchanger gradually decreases from 4000 to 150 Pa as shown in Fig. 14. At the cold inlet of the coil, the pressure is at 3950 Pa, and when it enters into the shell, the pressure decreases to 250 Pa. At 1 m of heat exchanger, the pressure is 750 Pa, at 2 m, position the pressure is 1500 Pa, and at 3 m, the pressure is about 3250 Pa.

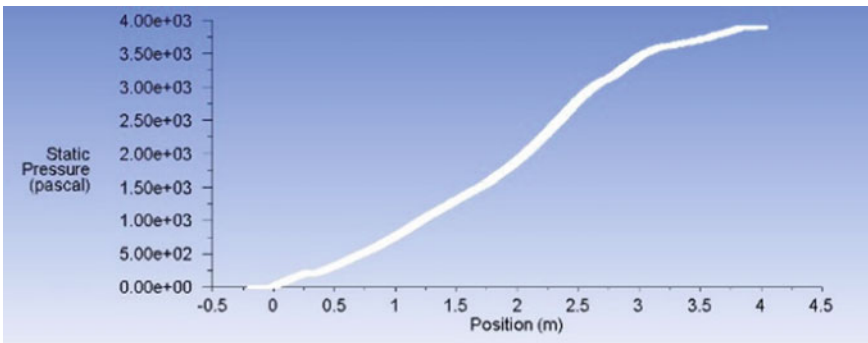


Fig. 14 Pressure graph for counter-flow

3.3 Result Comparison

3.3.1 Effective Thermal Conductivity Comparison

See Table 2.

3.3.2 Comparison of Velocity

See Table 3.

3.3.3 Comparison of Pressure

See Table 4.

Table 2 Comparison of effective thermal conductivity

| Position (m) | Parallel flow (W/m K) | Counter flow (W/m K) |
|--------------|-----------------------|----------------------|
| 0 | 4080 | 23 |
| 1 | 2013 | 2308 |
| 2 | 1080 | 4873 |
| 3 | 320 | 7209 |
| 4 | 57 | 9780 |

Table 3 Comparison of velocity

| Position (m) | Parallel flow (m/S) | Counter flow (m/S) |
|--------------|---------------------|--------------------|
| 0 | 0.09 | 0.05 |
| 1 | 0.07 | 0.061 |
| 2 | 0.085 | 0.079 |
| 3 | 0.072 | 0.12 |
| 4 | 0.063 | 0.19 |

Table 4 Comparison of pressure

| Position (m) | Parallel flow (Pa) | Counter flow (Pa) |
|--------------|--------------------|-------------------|
| 0 | 1493 | 25 |
| 1 | 1235 | 560 |
| 2 | 1080 | 1028 |
| 3 | 728 | 1765 |
| 4 | 230 | 1980 |

4 Conclusion

In this study, the CFD investigation is conducted on the parallel-flow and counter-flow helical coil tube heat exchanger. The water is taken as the working fluid, and the helical coil has 32 turns. The copper is taken as the shell and tube material. On that, investigation result of the parameters like effective thermal conductivity, velocity and pressure is taken as output. The thermal conductivity of the counter flow has higher rate than the parallel flow. The pressure reduces faster on the parallel flow.

By considering the result parameters, the counter-flow helical coil tube heat exchanger provides the best results for the given input. The more knowledge on the heat exchanger is gathered from various literatures, books and articles. The geometry was created using SolidWorks 18 and CFD analyses in ANSYS Fluent 18.

5 Future Work

On the future research, the cross section of the circular tube is to be changed as elliptical, and fins and turbulator are added so that the performance of the heat exchanger is analysed and improvements are determined.

References

1. Genssle A, Stephan K (2000) Analysis of the process characteristics of an absorption heat transformer with compact heat exchangers and the mixture. *Int J Therm Sci* 39:30–38
2. Ruthven DM (1971) The residence time distribution for ideal laminar flow in a helical tube. *Chem Eng Sci* 26(7):1113–1121
3. Guo L, Feng Z, Chen X (2001) An experimental investigation of the frictional pressure drops of steam-water two-phase flow in helical coils. *Int J Heat Mass Transf* 44:2601–2610
4. Kshirsagar MP, Kansara TJ, Aher SM (2014) Fabrication and analysis of tube-in-tube helical coil heat exchanger. *Int J Eng Res Gen Sci* 2(3)
5. Ali S (2001) Pressure drop correlations for flow through regular helical coil tubes. *Fluid Dyn Res* 28:295–310
6. Hüttl TJ, Friedrich R (2000) Influence of curvature and torsion on turbulent flow in helically coiled pipes. *Int J Heat Fluid Flow* 21(3):345–353
7. Rennie TJ (2004) Numerical and experimental studies of a double pipe heat exchanger, A thesis submitted to McGill University in partial fulfilment of the requirements of the degree of Doctor of Philosophy
8. Rennie TJ, Raghavan VGS (2005) Experimental studies of a double-pipe helical heat exchanger. *Exp Thermal Fluid Sci* 29:919–924
9. Jakkula S, Sharma GS (2007) Analysis of a cross flow heat exchanger using optimization techniques
10. Rennie TJ, Raghavan VGS (2006) Effect of fluid thermal properties on heat transfer characteristics in a double pipe helical heat exchanger. *Int J Thermal Sciences* 45:1158–1165
11. Raju M, Kumar S (2010) Modeling of a helical coil heat exchanger for sodium alanate based on-board hydrogen storage system. In: Excerpt from the proceedings of the COMSOL conference Boston

12. Purandarea PS, Leleb MM, Gupta R (2012) Parametric analysis of helical coil heat exchanger. *Int J Eng Res Technol* 1(8)
13. Ankanna C, Reddy S (2014) Performance analysis of fabricated helical coil heat exchanger. *Int J Eng Res* 3
14. Nandan A, Singh G (2016) Experimental study of heat transfer rate in a shell and tube heat exchanger with air bubble injection. *IJE Trans B: Appl* 29(8):1160–1166
15. Al-Dawody MF, Hamzah DA (2018) Comparative study between curved and straight pipe heat exchanger using solid works. *J Univ Babylon, Eng Sci* 26(2)
16. Thakur G, Singh G, Thakur M, Kajla S (2018) An experimental study of nano fluids operated shell and tube heat exchanger with air bubble injection. *IJE Trans A: Basics* 31(1):136–143