INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH & DEVELOPMENT

ISSN 2278 – 0211 (Online)

Heat Transfer Analysis of a Helically Coiled Heat Exchanger

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Abstract:
Enhancing the heat transfer by the use of helical coils has been studied and researched by many researchers because the fluid dynamics inside the pipes of a heat exchangers offer certain advantages over a straight tubes, shell and tube heat exchanger, in terms of better heat transfer and mass transfer coefficients.
After validating the methodology of CFD analysis of a heat exchanger against the numerical results available in literature, the effect of considering the actual fluid properties instead of a constant value is established. The characteristics of heat transfer inside a helical coil for different boundary conditions are compared. The flow field through the helically coiled tube is simulated by solving the appropriate governing equations: conservation of mass, momentum and energy. The turbulence is taken by Shear Stress Transport (SST) k-ε of closure.SST k-ε has a blending function which acts as a standard k-ε in main stream flow and as standard k-ε near the boundary layer where the gradient is much steeper.
It is observed that the specification of a constant temperature or constant heat flux boundary condition for an actual heat exchanger does not yield proper modelling. Hence, conjugate heat transfer and temperature dependent properties of heat transport media are considered for the analysis of the heat exchanger. The CFD calculation results are obtained using the CFD package FLUENT 14.0.Since the above work necessitates the knowledge in CFD package FLUENT, a sample model of the helical coil heat exchanger is made using FLUENT before taking up the above mentioned project. The present report summarizes few of the studies thus made. The report also mentions the work performed with regard to the project problem.

Keywords: *Helical coil Heat exchanger, CFD or computational fluid dynamics, Conjugate heat transfer, Heat transfer correlation.*

1. Introduction

It has been widely reported in literature that heat transfer rates in helical coils are higher as compared to those in straight tubes. Due to the compact structure and high heat transfer coefficient, helical coil heat exchanger find extensive use in industrial applications such as power generation, nuclear industry, process plant, heat recovery system, refrigeration system, food industry etc.

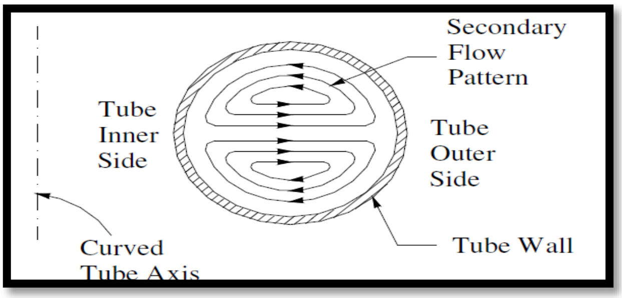

Figure 1: Fluid flow in curved pipes

1.1. Terminology of Helical Coiled Pipes

Fig. 2 gives the schematic of the helical coil. The pipe has an inner diameter *2r*. The coil diameter is represented by *2RC* (measured between the centers of the pipes). The distance between two adjacent turns, called pitch is *H*. The coil diameter is also called as pitch circle diameter (*PCD*). The ratio of pipe diameter to coil diameter (*r/Rc*) is called curvature ratio, □.The ratio of pitch to developed length of one turn (*H/2□ Rc*) is termed non-dimensional pitch, □. Consider the projection of the coil on a plane passing through the axis of the coil. The angle, which projection of one turn of the coil makes with a plane perpendicular to the axis, is called the helix angle, □. Consider any cross section of the pipe created by a plane passing through the coil axis. The side of pipe wall nearest to the coil axis is termed inner side of the coil and the farthest side is termed as outer side of the coil. Similar to Reynolds number for flow in pipes, Dean Number is used to characterize the flow in a helical pipe.

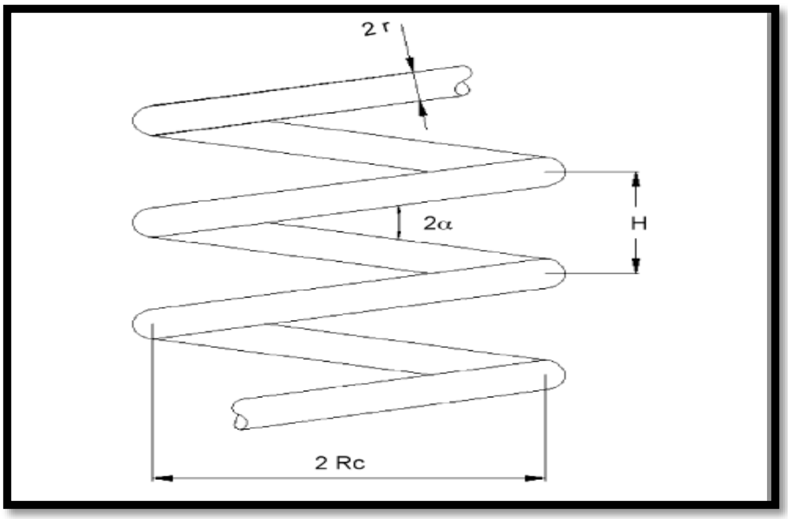

Figure 2: Basic geometry of a helical pipe.

1.2. Heat Transfer Coefficient:

As in literature [12, 18] in case of convective heat transfer taking place from surface to fluid, circulating current dies out in the immediate vicinity of the surface and film of fluid, free of turbulence, covers the surface. Through this film heat transfer takes place by thermal conduction and as thermal conductivity of most fluids is low, the main resistance lies there. Therefore increase in velocity of fluid over the surface results in improved heat transfer mainly because of reduction in thickness of film. The equation for rate of heat transfer by convection under steady state is given by,

$$\mathbf{Q = h.A.\Delta T}$$

Where 'h' is the film coefficient or surface coefficient. The value of 'h' depends upon the properties of fluid within the film region, hence it is called 'Heat Transfer Coefficient'. It depends on various properties of fluid, linear dimensions of surface and fluid velocity (i.e. nature of flow).

Numerically, Heat Transfer Coefficient (h) is the quantity of heat transferred in unit time through unit area at a temperature difference of one degree between the surface and the surrounding. Its SI unit is (W/m^2K). The term 1/h is the thermal resistance.

The 'overall Heat Transfer Coefficient' can be in terms of thermal resistances. The summation of individual resistances is the total thermal resistance and its inverse is the overall Heat Transfer Coefficient, U. That is,

$$\frac{1}{U} = \frac{1}{h_o} + \frac{A_o}{A_i}\frac{1}{h_i} + R_{fo} + \frac{A_o}{A_i}R_{fi} + R_w$$

Where,

U = overall heat transfer coefficient based on outside area of tube wall

A = area of tube wall

h = convective heat transfer coefficient

R_f = thermal resistance due to fouling

R_w = thermal resistance due to wall conduction

and suffixes 'i' and 'o' refer to the inner and outer tubes respectively. Due to existence of superimposed secondary flow, the heat transfer rates (& the fluid pressure drop) are higher in curved tube than in an equivalent straight tube at the same flow rate and the transfer mechanisms are also more complicated.

1.3. Broad Objective:

The objective of the topic is to obtain a better and more quantitative insight into the heat transfer process that occurs when a fluid flows in a helically coiled tube. For this, the heat transfer analysis in a helically coiled tube is performed using CFD package FLUENT 14.0 considering:

Constant wall temperature boundary condition.

(a) Constant heat flux boundary condition.

(b) Constant heat transfer coefficient boundary condition.
(c) Fluid–fluid heat exchange by taking actual fluid properties rather than constant values.
(d) To compare the CFD simulation results of heat transfer analyses obtained by using various boundary conditions.

1.4. Applications

Use of helical coils for heat transfer applications:

1. Helical coils are used for transferring heat in chemical reactors and agitated vessels because heat transfer coefficients are higher in helical coils. This is especially important when chemical reactions have high heats of reaction are carried out and the heat generated (or consumed) has to be transferred rapidly to maintain the temperature of the reaction. Also, because helical coils have a compact configuration, more heat transfer surface can be provided per unit of space than by the use of straight tubes.
2. Because of the compact configuration of helical coils, they can be readily used in heat transfer application with space limitations, for example, in steam generations in marine and industrial applications.
3. The helically coiled tube is eminently suited for studying the characteristics of a plug flow reactor in reaction kinetic studies because the secondary motion present in the helical coil destroys the radial concentration gradient.
4. The existence of self induce radial acceleration field in helical coils makes helical coils most desirable for heat transfer and fluid flow applications in the absence of gravity field, such as for space ships in outer space. Helical coiled tubes have been and are used extensively in cryogenic industry for the liquefaction of gases.

2. Literature Review:

It has been widely reported in literature that heat transfer rates in helical coils are higher as compared to a straight tube. Due to the compact structure and high heat transfer coefficient, helical coil heat exchangers are widely used in industrial applications such as power generation, nuclear industry, process plants, heat recovery systems, refrigeration, food industry, etc. (Xin et al., 1996 [35]; Abdulla, 1994 [1]; Bai et al. [3], 1999; Jensen and Bergles, 1981 [11]; Futagami and Aoyama, 1988 [7]; Patankar et al., 1974) [23].. Heat exchangers with helical coils are used for residual heat removal systems in islanded or barge mounted nuclear reactor system, wherein nuclear energy is utilized for desalination of seawater (Manna et al., 1996) [17]. The performance of the residual heat removal system, which uses a helically coiled heat exchanger, for various process parameters was investigated by Jayakumar and Grover (1997) [10]. In all these studies, empirical correlations were used to estimate the amount of heat transfer and pressure drop in the helical coils. Heat transfer and flow through a curved tube is comprehensively reviewed first by Berger et al. (1983) [4] and subsequently by Shah and Joshi (1987) [33]. The latest review of flow and heat transfer characteristics is provided by Naphon and Wongwises (2006) [22]. The characteristics of flow, pressure drop and heat transfer have been reported by many investigators. The heat transfer enhancement in helical coil systems is reported by Prabhanjan et al. (2004) [24], Berger et al. (1983) [4], Janssen and Hoogendoorn (1978) [9] and Ruthven (1971) [30]. Condensing heat transfer and pressure drop of refrigerant R 134A in helicoidal (helical double pipe heat exchanger) is experimentally investigated by Kang et al. (2000) [14]. The effect of torsion on the flow in a helical tube of circular cross-section is experimentally investigated by Yamamoto et al. (1995) [36] for a range of Reynolds numbers from about 500 to 20,000.

Several investigations on heat transfer coefficients are for simplified boundary conditions such as constant wall temperature or constant heat flux (Prabhanjan et al., 2004; Shah and Joshi, 1987; Nandakumar and Masliyah, 1982) [24, 33, and 21]. The constant wall temperature situation is idealized in heat exchangers with phase change such as condensers. The constant heat flux boundary condition finds application in electrically heated tubes and nuclear fuel elements. However, the case of fluid–fluid heat exchange has not been studied well. Experimental studies of a double pipe helical heat exchanger were conducted by Rennie and Raghavan (2005) [25].

The double pipe helical coil heat exchanger was further numerically investigated by Rennie and Raghavan (2006a, b) [26, 27]. Pressure drop and heat transfer in tube-in-tube helical heat exchanger was studied by Kumar et al. (2006) [16]. For a double pipe heat exchanger, the co-current or counter-current flow situation can be applied. However, in the helically coiled heat exchanger, which is taken up in the present study, practically cross flow exists in the shell side.

In this project work, it is proposed to perform the heat transfer analysis in a helically coiled heat exchanger considering constant wall heat transfer modes and to be more realistic; the analysis is further done considering fluid–fluid heat exchange in a helically coiled heat exchanger. The heat transfer phenomena in the heat exchanger are analysed numerically using a commercial CFD code FLUENT Version 14.0. Instead of specifying an arbitrary boundary condition, heat transfer from hot fluid to cold fluid is modelled by considering both inside and outside convective heat transfer and wall conduction. Temperature dependent values of thermal and transport properties of the heat transfer medium are used in these analyses.

3. Conclusion:

1. Heat transfer analysis of a helically coiled heat exchanger using CFD code FLUENT 14.0 has been presented in the thesis.
2. Analysis has been carried out for the helically coiled tube considering constant wall temperature, constant wall heat flux and constant heat transfer coefficient boundary conditions.
3. A number of numerical experiments have been carried out to study the influence of different boundary conditions on the heat transfer in a helically coiled tube.

4. It is observed that the use of constant values for the thermal and transport properties of the heat transport medium results in prediction of inaccurate heat transfer coefficients. Also for prediction of heat transfer in a situation of fluid-to-fluid heat transfer, as it occurs in the case in a heat exchanger, arbitrary boundary conditions such as constant wall temperature, constant heat flux, etc., are not applicable. In this situation, it is essential to model the heat exchanger considering conjugate heat transfer. Heat transfer characteristics of the heat exchanger with helical coil were also studied using the CFD code FLUENT 14.0.

4. Acknowledgement:
We would like to thank our guide Prof. Shylesha Channapattana Sir for his valuable guidance also we are thankful to our Principal Dr. A.M. Nagraj Sir for his support and motivation, we also would like to thank to all those who directly or indirectly contributed to our work.

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