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Experimental Investigation of Convection Heat Transfer in a Helical Coil and Shell Heat Exchanger and Drag Reduction by Guar Gum

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ABSTRACT

The prime motive of this experimental study is to design a helical coil and shell heat exchanger and analyzing thermal performance based on convection heat transfer. Then, a polysaccharide, guar gum is used to lessen the drag force of cold water in helical pipe inside the heat exchanger, which ultimately lowers the amount of pumping power needed. The shell is made by rolling a square sheet and tube is formed by bending of straight pipe. Then, they are joined by spot welding to fabricate the complete heat exchanger. The rate of flow of cold fluid (tube side) is varied keeping the hot fluid flow rate (shell side) constant. Outlet and inlet temperatures of hot and cold fluids are measured to derive the heat transfer rate and overall convection heat transfer coefficient of cold fluid. Reynolds number and Nusselt number are estimated as two effective parameters of convection heat transfer. Heat transfer rate, overall heat transfer coefficient, Nusselt number and Reynolds number all are noticed to increase gradually with the rise in flow rate of cold fluid. Then, three different concentrations (100 ppm, 250 ppm and 500 ppm) of guar gum solution are used as cold fluid in tube of heat exchanger. The amount of pressure drop in tube found lower than the pure water for same flow conditions. So, mixing of guar gum into water decreases drag force in pipeline and lowers the power required to pump fluids through heat exchanger's tubes that saves pumping cost. Maximum drop in pressure (50%) observed for maximum concentration.

Keywords: Helical tubes, Heat transfer, Guar gum, Drag reduction

1. Introduction

Helical coil heat exchangers are intensively used in industrial applications and power generation to avail the benefit of their compactness and high heat transfer rate. On account of having compact size and higher quantity of heat transfer co-efficient helical ones are superior to straight tubes [1]. When fluid moves forward inside a helical shaped tube the centrifugal force generated by the curvature of the pipe induces a secondary flow in the fluid [2]. The secondary flow has direction perpendicular to the primary fluid stream. Such phenomena intensifies the mixing of fluid which increases the heat transfer coefficient consequently [3].

D.G. Prabhanjan et al. [3] conducted a comparative study of straight and helical pipe heat exchangers where they found such outcome that indicates the superiority of thermal performance of helical pipe over straight ones as heat transfer coefficient with helical coil was estimated 1.16 and 1.43 times higher from the uncurbed pipes under similar state. An investigation to understand the consequence of different shapes of pipe over thermal performance was carried by Shirgire and Kumar [4]. Optimum flow rates for convective heat transfer coefficient were concluded. Taguchi method is implemented by Jamshidi et al. [5] to observe how different sizes of geometric parameters increase or decrease heat transfer performance. They concluded the perfect flow rates of fluid for desired output. Etghani and Baboli [6] carried out a numerical approach where they used different combinations of sizes of parameters and observed their effect. Optimum sizes were found out by the help of Taguchi analysis for better heat transfer. Flow rates, coil diameter and pitch are found the key factors for heat transfer in heat exchangers.

The authors conducted a research to develop an empirical relation between Reyleigh number and Nusselt number with different sets of characteristics length such as tube diameter, coil height and diameter and coil's overall length in [7]. Realizing the growing demand of helical heat exchanger in nuclear energy based power generation plants Sikandar [8] estimated design parameters for fabricating a helical coil heat exchanger. Diameter for tube was proposed large while vice versa for coil diameter for better performance. P.C. Kumar et al. [9] tested the heat transfer characteristics and friction of helical shaped coil passing flow of Al_2O_3 based water nanofluid. Outcomes of their study showed that frictional loss increases with the enhancement of concentration of nanofluid. Although power requirement upraises due to friction but such techniques make thermal energy transportation more efficient.

Yanaur et al. [10] investigated to observe the effect of guar gum in spiral pipe and it proved capable of lowering the drag force in case of spiral pipe and circular piping as well. Heterogeneous injection of guar gum was performed on flow and percentage of drag decrease in case of two phase flow was estimated by KS Sokhal et al. [11]. Drag reduction by guar gum was calculated for different concentrations. The authors investigated the decrease in drag reducing property of guar gum over time at [12]. They found due to high temperature and shear stress the drag reducing ability of these product start decreasing within 30 minutes of application. KS Sokhal et al. [13] used guar gum in flowing water of turbulent pattern and observed that turbulent was lowered after adding guar gum. Kim, C.A., et al. [14] studied the drag friction decreasing phenomena of guar gum on a rotating disk setup and found that it can tolerate more shear stress in comparison to drag reducing agents that are synthetic.

Therefore, we were inspired to design and fabricate a helical coil and shell type heat exchanger. We analyzed the thermal performance of the heat exchanger. To pass the fluids through tubes of heat exchanger pumps are used that consumes power. We used guar gum which is a compound used to decrease drag force of water flowing inside piping systems. Addition of this product lowers the drag force of water inside the tube of heat exchangers. Lowering drag force promotes decrease in power needed by the pumps to pass fluids through tubes that saves pumping cost.

2. Methodology

2.1 Model description

The model of the helical coil and shell heat exchanger drawn in SolidWorks is represented in Fig. 1. Shell of the heat exchanger is cylindrical in shape. It has a length of 330 mm and diameter 254 mm. There are two entrances and two exits for hot and cold fluids in the surface of shell. Shell will carry the hot fluid. The shell is made by rolling a 330 mm by 812 mm stainless steel (S.S.) sheet. The S.S. sheet is rolled around two rings of S.S. attached on both sides of two rods to form the shell. The inner tube is helical in shape. Tube inner diameter is 12.7 mm and thickness is 0.76 mm. Diameter of coil is 177.8 mm. The coil has 10 number of turns and pitch 25.4 mm. A straight pipe of 6.1 m length is bended in the bending machine. The tube is made of stainless steel. Stainless steel is chosen because it is corrosion resistant, easy to bend and economical. Copper has higher thermal conductivity but it has very low resistance to corrosion, more costly and difficult to bend uniformly. The coil and shell are assembled using spot welding. Leak proof joints are ensured during assembly. Fig. 2 depicts the fabricated heat exchanger.

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2.2 Experimental setup

The experimental setup of current study is illustrated in Fig. 3 and Fig. 4. It consists of two separate sealed storages for hot and cold water. At first, an electric heater is immersed in hot water storage to increase water temperature. After obtaining a certain temperature, hot water is supplied to the shell of the heat exchanger at a constant flow rate of 26 liters per minute (LPM) by a pump. Cold water from the other storage is pumped simultaneously into the helical tube at 20 LPM. The inlet and exit temperatures of cold and hot fluid are measured by four thermometers attached at each entrance and exit. Pressure drop of cold water inside the tube is measured by pressure gauges. Same process is repeated three times for cold fluid flow rate of 22 LPM, 24 LPM and 26 LPM keeping the hot fluid flow rate constant at 26 LPM. Then, three different concentrations of guar gum solution- 100 ppm, 250 ppm and 500 ppm are prepared using magnetic stirrer and electric hand mixture. Each solution of guar gum is used one by one as cold fluid to the heat exchanger maintaining same flow condition as for pure water and pressure drop is measured. The flow pattern in the heat exchanger remains parallel throughout the experiment.

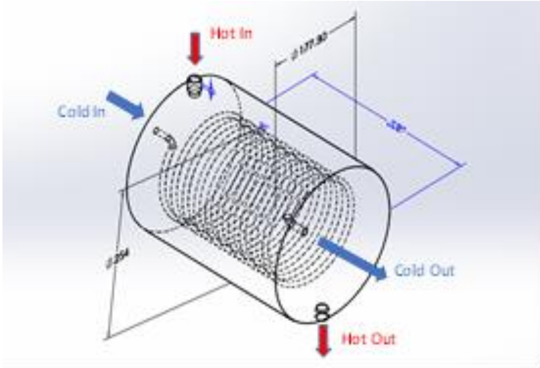

Fig. 1 Design of shell and helical coil heat exchanger.

Fig. 2 Fabricated helical coil and shell heat exchanger.

2.3 Mathematical formulations

The heat transfer rate of cold fluid is determined from Newton's cooling law stated in Eq. (1) putting the values of temperature and mass flow rate. Then, the overall heat transfer coefficient is estimated from Eq. (2).

$$q_c = m_c \times c_{pc} \times (T_{co} - T_{ci}) \quad (1)$$

$$U = \frac{q_c}{A \times \Delta T_m} \quad (2)$$

Where, A denotes area of outside surface of tube, q_c is the heat transfer rate of cold water and ΔT_m indicates the log mean temperature difference. Log mean temperature difference is necessary to consider as temperature profile is curve line and to trace the exponential profile.

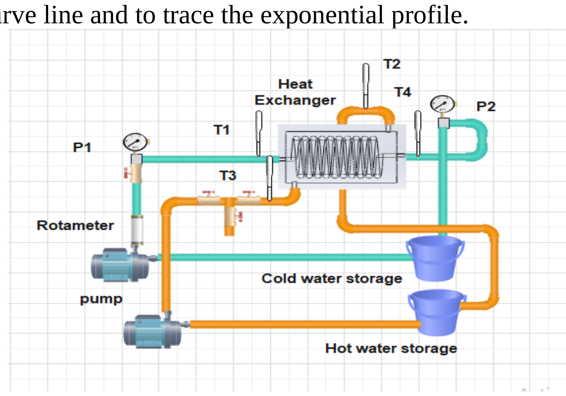

Fig. 3 Schematic diagram of the experimental setup of shell and helical coil heat exchanger.

Fig. 4 Photographic view of the experimental setup of shell and helical coil heat exchanger.

The Reynolds number of cold water (tube side) is calculated using Eq. (3).

$$Re = \frac{(\rho \times v \times d)}{\mu} \quad (3)$$

The Nusselt number of cold water is found from Eq. (4).

$$Nu = \frac{h \times d}{k} \quad (4)$$

Here, ρ is the water density, v is the velocity of water, μ denotes the kinematic viscosity of water and d indicates tube inner diameter in Eq. (3). Again in Eq. (4), h is the convective heat transfer coefficient and k indicates the thermal conductivity of water. The relationship between Nusselt number and Reynolds number is observed also.

2.4 Experimental uncertainty

In this study, error in measurement of temperature, flow rate and pressure arises uncertainty of experimental data. Standard uncertainty of the thermometers is estimated ±0.14 °C. A rotameter (PRM FMZ400410GPM 1-10 GPM) having ±4% accuracy is used. Standard uncertainty of the pressure gauges is calculated ±0.11 psi.

2.5 Drag reduction by guar gum

Guar gum, a chemical compound that mainly contains two types of carbohydrates- galactose and mannose. It is a long chain polysaccharide having a structure consisting of single-membered, linear chain of –D-mannopyranosyl units connected in 1-4 fashion. 2:1 is the typical ratio of mannose to galactose [15]. The chemical formula of guar gum is given in Fig. 5. Guar gum stretches out when it is mixed in fluid flowing at turbulent pattern performing as a shock absorber. As a result, eddies responsible for turbulence are damped out by shock absorbing capacity of long chain of polymers. So, the fluid tend to flow in more laminar pattern and low turbulent pattern. That's save the waste of energy.

Percentage of drag reduction by guar gum is determined from Eq. (5).

$$DR\% = \frac{\Delta P \text{ with guar gum} - \Delta P \text{ without guar gum}}{\Delta P \text{ without guar gum}} \quad (5)$$

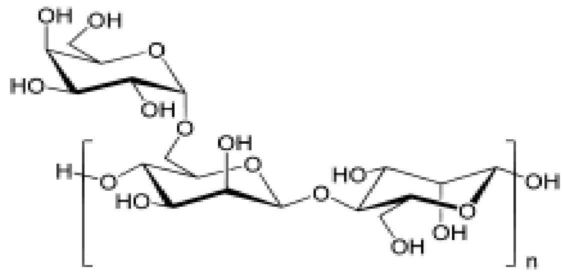

Fig. 5 Structure of guar gum [15]

3. Results and discussion

3.1 Heat transfer rate of cold water

The effect of flow rate of cold water over heat transfer rate is investigated. The flow rate varied from 20 LPM with two steps increment up to 26 LPM. It is observed that heat transfer rate increases with the gradual increment in flow rate. This relation is illustrated in Fig. 6.

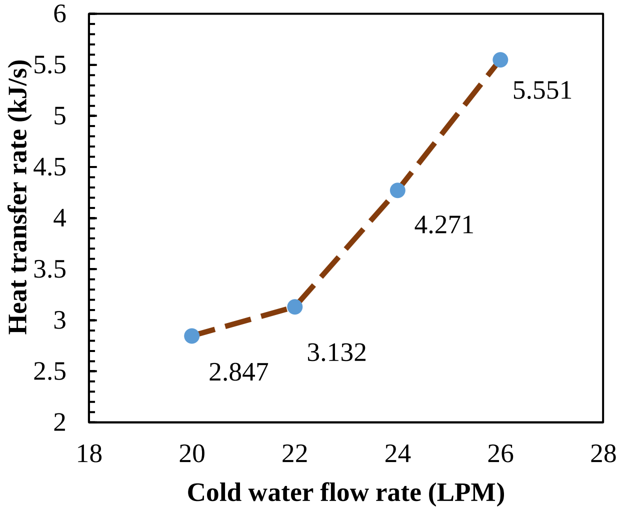

Fig. 6 Variation of cold water heat transfer rate with respect to flow rate.

The reason behind this trend is the turbulence of water increases with the rise of flow rate. Higher turbulence enhances rapid mixing of fluid inside tube. As a result, heat transfer rate rises up. Maximum heat transfer rate found for highest flow rate.

3.2 Overall heat transfer coefficient

The overall heat transfer coefficient is estimated for four different flow rates. Tendency to rise in overall heat transfer coefficient has been noticed with the rise of water flow rate. It is obvious due to increase in turbulence in flow of water as the velocity rises. This happens because of directly proportional relationship of Reynolds number to fluid velocity. When the value of Reynolds number rises up, the flow tends to be more turbulent. Increase in turbulence means more intense mixing of fluid that causes the enhancement of heat transfer rate. Fig. 7 shows the proportional relation between overall heat transfer coefficient and flow rate.

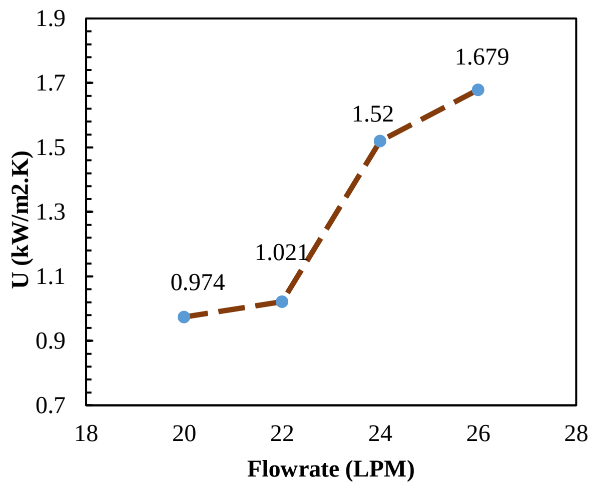

Fig. 7 Variation of overall heat transfer coefficient with flow rate.

3.3 Reynolds number's effect on Nusselt number

Reynolds number is calculated for each flow rate. Reynolds is proportional to the velocity of fluid flowing. As the flow velocity rises with the increment in flow rate, the value of Reynolds number increases that is showed in Fig. 8. Nusselt number is noticed to increase as the flow rate rises gradually. This is because convection heat transfer is occurred by movement of fluid particles. As movement of particles enhances with flow rate, heat transfer by convection increases. Fig. 9 represents the impact of flow rate on Nusselt number. Analysis of the relationship between Nusselt and Reynolds number is impactful in the study of convection heat transfer investigation taking place inside heat exchangers. It is clear from above discussion, the increasing flow rate as well as Reynolds number allows the enhancement of heat transfer by convection. Consequently, the Nusselt number increases as being the ratio of heat transfer through convection to conduction. The relation between these two parameters is illustrated in Fig. 10. Maximum value of Nusselt number is found 34.4 for the highest Reynolds number. Therefore, more turbulent the flow pattern becomes more heat transfer will take place from hot to cold fluid.

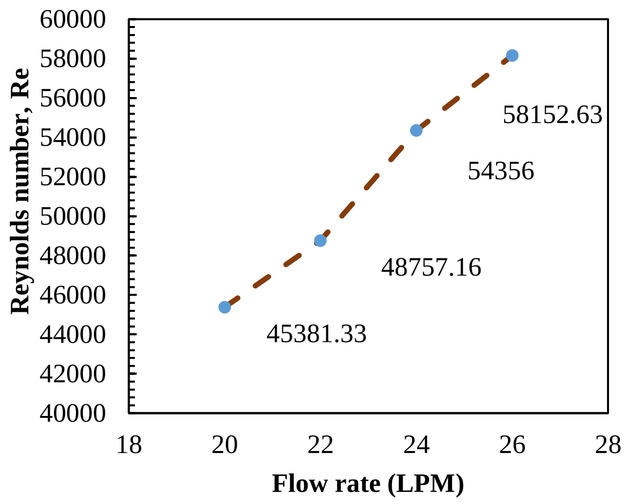

Fig. 8 Changes in Reynolds number with flow rate.

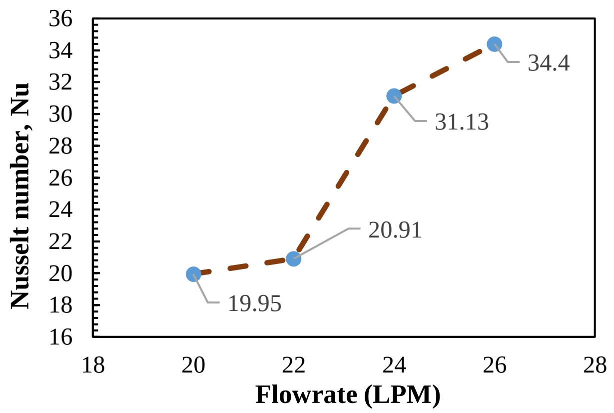

Fig. 9 Changes in Nusselt number with flow rate.

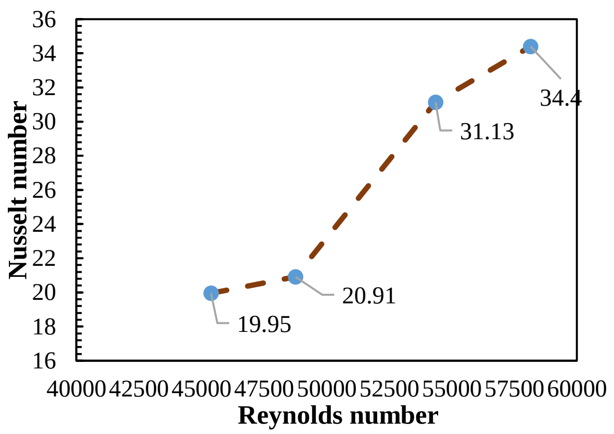

Fig. 10 Impact of Reynolds number on Nusselt number

3.4 Pressure drop effect of guar gum

Effect of three different concentrations of guar gum is investigated- 100 ppm, 250 ppm and 500 ppm. For each concentration, pressure drop is measured by two pressure gauges at both ends of the tube for the four flow rates- 20 LPM, 22 LPM, 24 LPM and 26 LPM. Pressure drops for the same flow rates were measured earlier when pure water was used in the tube. Comparison of pressure drop without guar gum and with guar gum is illustrated in Fig. 11 and percentage of drag reduction are shown in Table 1.

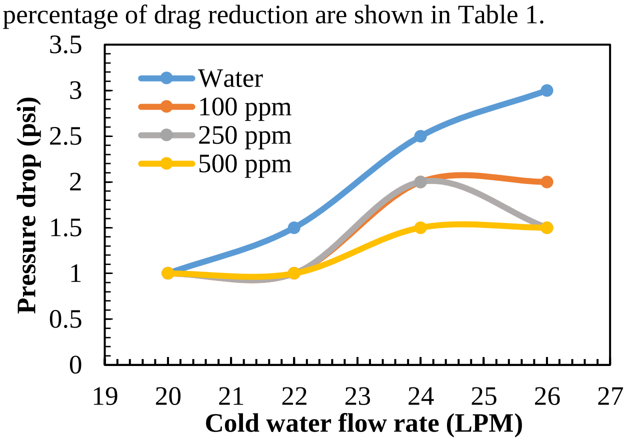

Fig. 11 Comparison of pressure drop without and with the addition of guar gum.

For lowest flow rate (20 LPM), pure water and all the concentrations of guar gum provided same pressure drop. With increasing flow rate amount of pressure drop using guar gum is clearly lower than the pressure drop for pure water. The amount of pressure drop decreases

Table 1 percentage of pressure drop of guar gum.

Tube side flow rate (LPM)	% of drag reduction		
	100 ppm	250 ppm	500 ppm
20	0	0	0
22	33.33	33.33	33.33
24	20	20	40
26	33.33	50	50

with the increase in concentration. Highest pressure drop (50%) has been observed for highest concentration (500 ppm). For 250 ppm, pressure drops more rapidly from 24 to 26 LPM than 100 ppm as pressure drop effect increases with concentration.

4. CONCLUSION

The current study experimentally investigated the effect of cold fluid flow rate on thermal performance of a helical coil and shell heat exchanger. Then, the effect of a drag reducing polymer (guar gum) is investigated to reduce the power demand of pump for passing fluids through heat exchangers.

- With increasing fluid flow rate the heat transfer rate increases as turbulence increases. Turbulence promotes intense mixing of fluid. Overall heat transfer coefficient also increases as a consequence.
- Nusselt number increases with the increment in rate of flow as fluid velocity rises. Increase in Nusselt number indicates increase in heat transfer by convection as movement of fluid particles increases.
- Pressure drop effect by guar gum polymer increases with concentration. Maxim pressure drop (50%) found for maximum concentration (500 ppm). Reduction in pressure drop means lowering the pumping power required.

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Nomenclature

c_{pc}	: specific heat at constant pressure, kJ･kg^{-1}･K^{-1}
T	: temperature, K
q_c	: heat transfer rate, kJ･s^{-1}
m_c	: mass flow rate, m^3･s^{-1}
U	: overall heat transfer coefficient, kW･m^{-2}･K^{-1}
ΔT_m	: log mean temperature difference, K
Nu	: Nusselt number
K	: thermal conductivity, W･m^{-1}･K^{-1}
μ	: water viscosity, Pa･s
d	: tube inner diameter, m
ρ	: water density, kg･m^{-3}