Experimental Study of Heat Transfer Enhancement by Inserting Metal Chain in Heat Exchanger Tube

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ABSTRACT

Heat transfer augmentation in heat exchangers is important in many large industrial applications and many studies have been conducted on this subject. In this paper, an experimental study was used to verify the increased heat transfer of a circular heat exchanger tube with the insertion of metal chains, under turbulent flow conditions. A rig was designed and fabricated to investigate the effects of using the metal chain as turbulators inside the heat exchanger pipe, on heat transfer performance and on fluid flow behavior. The metal chains used were of different lengths of chain ring and different diameters of ring wire. Five ring length/tube diameter ratios (P/D) were used, (1, 2, 3, 4 and 5). Two wire diameter /tube diameter ratios (t/D) were used in this work (0.1 and 0.15). Heavy fuel oil (HFO) was used inside the tube, flowing at 30 °C with uniform tube wall temperature. The Reynolds numbers tested were between 5,000 and 15,000. The results showed the thermal enhancement factor (\(\eta\)) decreased with increasing Reynolds number for all cases, depending on lengths of chain ring (P) and thickness the weir chain (t) values. A maximum thermal enhancement factor (\(\eta\)) was found with a metal chain at P/D=3 and t/D= 0.15. The results also show that P/D=1 and t= 4mm, give the highest Nusselt number.

Key Words: Heat transfer enhancements, heat exchanger, insert turbulator
Nomenclature

| Symbol | Description                                      |
|--------|-------------------------------------------------|
| A      | Surface area of test tube (m²)                  |
| D      | Diameter of the test tube (m)                   |
| f      | Friction factor                                 |
| h      | Coefficient of heat transfer (W/m² K⁻¹)         |
| k      | Thermal conductivity to fluid (W/mK)            |
| L      | Length the test section (m)                     |
| m      | Mass flow rate (kg/s)                           |
| Nu     | Nusselt number                                  |
| P      | Length of metal chain rings (m)                 |
| ΔP     | Pressure drop (Pa).                             |
| Q      | Heat transfer rate (W)                          |
| Re     | Reynolds number                                 |
| HFO    | Heavy Fuel Oil                                  |
1. Introduction

Improvement of the thermal performance in heat exchange systems, which are used in much industrial work, is necessary to save energy and decrease operational costs. Heat exchangers are equipment that facilitate the trading of heat between two different liquids without mixing them, and are generally utilized as a part of chemical plants, cement plants, control plants, oil and gas industry and food manufacture. Heat transfer increase is often applied in heat exchanger systems to increase thermal performance in the heat exchanger. The use of a turbulator is one of the passive methods that is widely applied to augment heat transfer, and may take any of several forms such as the fin, tribe, propeller, winglet, baffle and roughened surfaces [1-4]. The turbulator inserted inside the tube of the heat exchanger provides interruption of a thermal boundary layer which increases the heat transfer by increased turbulence intensity or by quick fluid mixing [5]. It is thus possible to obtain more economical and practical heat exchanger systems.

Many efforts have been made to identify the most advantageous turbine to augment heat transfer to heat exchangers, including twisted tapes, wire coils, corrugated, dimpled, grooved tubes, and compound turbulators [6-10]. To date, much of the research has been explored the effect of turbulator inserts on heat transfer and friction factors. Wongcharee [11] studied the characteristics of heat transfer under swirl flow conditions together with twisted tape inserts inside the pipe that alternated between counter-clockwise and clockwise for Re = 830 to 1990. The study obtained a maximum heat transfer increase of 5.25% at a Re of 830. Ali Hussein and colleagues’ [12] simulation studied a circular tube with insert of metal chain, under turbulent flow and isothermal wall, their experiments were on heavy fuel oil, using different in the length of the rings, where P= (20,40,60,80 and 100) mm and diameter of the wire to chain 3mm. Du Plessis and others [13] used a conical ring with twisted tape inside the pipe for heat transfer augmentation, to study the combined effects of conical – ring with that of twisted tape in the circular
tube for heat transfer augmentation. They found that use of the twisted tape together with a conical ring provided a heat transfer rate 10% higher than the conical ring only.

Eiamsa-Ard et al [14] studied enhanced heat transfer via coiled wire with a twisted tape inserted together, the results showed the combination of twisted tape with coiled wire give better heat transfer than a twisted tape or coiled wire alone. Promvonge and colleagues [15] used inclined horseshoe baffles inside the circular tube to study any effect on heat transfer, the results were a maximum thermal enhancement factor of about 1.92 for horseshoe baffles at relative ring width ratios BR = 0.1 and relative ring pitch ratios PR= 0.5. Ozceyhan and colleagues [16] used the pipe with a circular ring to show the effect it on the Nusselt number, the results found the maximum enhancement to be nearly 18%, which was obtained at Re = 600.

Chang [17] experimentally studied axial heat transfer and pressure drop for a pipe with inserts of broken twisted tape, while Sivashanmugam twice [18,19] experimentally studied heat transfer and friction factor for a the pipe fitted with spaced helical screw-tape inserts both for turbulent and laminar flows. However, Herrmann et al [20] experimentally studied to the circular tube with insert of twisted tape under the turbulent flow and isothermal wall, experiments were on water and also ethylene glycol, using twisted tapes at ratios of 3, 4.5 and 6. The results showed that the relationships between the Nusselt number and friction factor improved.

Our review of the literature related to tubulators reveals that many studies have sought to identify novel and effective types of turbulator to enhance heat transfer in heat exchangers. These turbulators create swirls in the liquid, which increases the heat transfer, the flow of disturbance and distributes boundary layers. The aim of this study is to improve thermal performance in heat exchangers, by inserting metal chains as a new type of turbulator inside the heat exchanger tube. We have tested several types of metal chain for this purpose and calculated the thermal optimization of the exchanger for all cases. We then compared them, to find the best case.

2. Experimental rig

The experimental work was conducted in a closed-loop, as the schematic diagram for this experimental study shows in Figure 1. The experimental apparatus consisted of many devices, including the test section, thermocouples, data logger, pressure sensor, pressure logger, heater along the test tube, HFO pump 2kW, flow meter, HFO tank 200L, cooling tank 200L and valves.
2.1 The test section

The test section consists of a tube of carbon steel with a length of 2000 mm, the inner diameter 20 mm and the outer diameter 26 mm, surrounded by a 6,000-Watt heater with heat flux 48 kW/m². In addition, a set of 10 thermocouples, type K, is distributed along the tube to measure temperature distribution. The heavy fuel oil (HFO) flows inside the tube while differently-shaped metallic chains are inside the tube of the heat exchanger, having been inserted so that the insertion of the chains is confined with the inside pipe to ensure that the chain does not drift with fluid flow, and to facilitate study of their effect on heat transfer. In addition, the entrance length was designed for a large Reynolds number and it needed 42 cm to make a fully developed flow, as shown in Figure 2.
2.2 The turbulator used

Figure 3 shows a diagram of the metal chain. The metal chains were manufactured from a metal steel wire with different shapes and sizes.

Five lengths for the ring (P), where that a ring length/tube diameter ratio, P/D= 1, 2, 3, 4 & 5.

Two diameters for the wire of chain (t), where that a wire diameter/tube diameter ratio, t/D= 0.1 & 0.15.

The outer diameter of the metal chain, W= 20 mm and the total chain length, L= 2000 mm, were kept constant. Figure 4 shows the different types of metal chains used in this study.

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**Figure 3:** Diagram of the metal chain.

**Figure 4:** Five types of metal chain used in the present study.
2.3 Experimental Procedure

The following practical steps were taken for each experimental case after successful initial checking of the system. In the beginning, the flow rate was changed by the opening of the control valve to Reynolds numbers 5,000 to 15,000. The external surface of the tube was heated by the electrical heater to 150°C. All of the readings, data and results required, including the temperature distribution along the test tube, the volumetric flow rate and the pressure drop in heavy fuel oil, after approaching the system of steady status, were recorded. The Nusselt number and friction factor were calculated based on the average temperature of the liquid inlet and outlet. The experimental procedures were repeated twice for all cases, by changing the heavy fuel oil velocity, and replacing the metal chain in the test section.

3. Data deduction

In this research, enhancement of the heat transfer in a pipe with metal chains requires a parameter such as a Reynolds number (Re), the friction factor (f) and the thermal performance enhancement factor (η). These were obtained from several equations, as below:

The heat flux on the tube outer surface is given by the equation [21]:

\[ Q_{\text{heater}} = \text{Power of Heater} \]  

(1)

The amount of the heat transferred from the heating wire to the HFO is given by:

\[ Q_{\text{fluid}} = \dot{m}_{\text{HFO}} \times C_{\text{HFO}} \times (T_O - T_m) \]  

(2)

Where:
\[ \dot{m}_{\text{HFO}} : \text{mass flow rate of the HFO.} \]
\[ C_{\text{HFO}} : \text{specific heat of the HFO.} \]
\[ T_O, T_m \text{ inlet and outlet temperature of the HFO at the test section, respectively} \]

The experimental heat transfer coefficient is, calculated as follows [21]:

\[ h = \frac{Q}{A(T_w - T_b)} \]  

(3)

Where:
\[ A = \pi D_h L \]  

(4)

Where that Hydraulic Diameter \( D_h = D \)

\[ T_w = \frac{T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7 + T_8 + T_9 + T_{10}}{10} \]  

(5)

\[ T_b = \frac{T_i + T_o}{2} \]  

(6)
Nusselt number can be obtained by [20]:

\[ Nu = \frac{hD}{K} \]  

(7)

Friction factor can be computed by the equation as follows [21]:

\[ f = \frac{\Delta P}{2(\frac{L}{D})\rho v^2} \]  

(8)

Thermal performance factor (\( \eta \)) can be computed in a heat exchanger with new types of turbulator (metal chains), for all of the cases then the results compared with each other to show which is better. This can be obtained from the equation [22]:

\[ \eta = \left(\frac{Nu}{Nu_0}\right)^{\frac{1}{3}} \left(\frac{f}{f_0}\right)^{\frac{1}{3}} \]  

(9)

4. Results and Discussion

4.1 Validation the experiments using plain tube

First, results obtained from the experiment for the Nusselt number (Nu) & the friction factor (f) were validated using correlations made by Dittus Boelter for the Nusselt number and Petukhov for the friction factor, as shown below [23]:

\[ Nu = 0.023 \text{Re}^{0.8}\text{Pr}^{0.4} \]  

(10)

\[ f = (0.790\ln\text{Re} - 1.64)^{-2} \]  

(11)

Figures 5 and 6 show the comparisons of the Nusselt number (Nu) and the friction factor (f) of a plain tube obtained from this study with existing data from proposed correlations. The comparison showed agreement between the experimental result and the proposed correlation. The difference was ± 6% and ± 3% for Nusselt number (Nu) and friction factor (f) respectively.
4.2 Effect of metal chain insert on heat transfer enhancement

Figures 7 and 8 show the Nusselt number (Nu) variation with the Reynolds number (Re) for a tube fitted with five chains. The chain has ring length/tube diameter ratio, (P/D = 1, 2, 3, 4 & 5) with the wire diameter/tube diameter ratio ( t/D = 0.1 & 0.15). The results showed that the insert of metal chains in the heat exchanger tube increases the Nusselt number compared to the tube without the metal chains. This is because the metal chains create turbulence with a swirling motion from HFO when it’s flowing in the tube, and these swirling motions cut the boundary layers of liquid flow near the pipe wall. When the Reynolds number (Re) increases, the Nusselt number also increases. It is also shown that when the ring length/tube diameter ratio of the chain decreases, the Nusselt number increases. The results show that Nusselt number of the pipe with insertion of the metal chains increased by 2.2-2.7, 2.4-2.9, 2.6-3.2, 2.6-3.3 and 2.7-3.6 above the plain tube, depending on the Reynolds number (Re) for P/D = 1, 2, 3, 4 and 5, respectively, with t/D = 0.1.

On the other hand, the following values were obtained as 2.4-3.0, 2.7-3.3, 2.9-3.6, 3.0-3.8 and 3.1-4.1, respectively, at t/D = 0.15.
4.3 Effect of metal chain insert on friction factor

An important factor to be taken into account in improving heat transfer is loss of pressure. The relationship between pressure drop or friction factor and Reynolds number, for a pipe with metal chain inserted that have given ring length/tube diameter ratio and wire diameter/tube diameter ratio, and also for a plain tube, is given in Figures 9 and 10. The results reveal that the use of a metal chain in the tube gives a higher friction factor ($f$) than a tube without a chain, as expected. Also, we note decreased friction factor ($f$) with an increased ring length/tube diameter ratio P/D and Reynolds number, a decrease of friction factor by a decrease of wire diameter/tube diameter ratio, with increased Reynolds number. The greatest friction factor (pressure drop) was obtained for the case P/D = 1 & t/D= 0.15 included given ring length/tube diameter ratio P/D and wire diameter/tube diameter ratio, t/D. It was found that friction factors for a tube with the metal chain inserts are about 2.3-3.8, 2.7-4.6, 3.1-5.3, 3.8-6.9 and 4.1-7.1 times that from a tube without the chain for P/D = 1, 2, 3, 4 and 5, respectively, at t/D = 0.1. Also, we achieved 2.9-4.6, 3.5-5.6, 4.0-6.5, 5.1-8.1 and 5.9-8.6 times that from a tube without the chain at the same ring length/tube diameter ratio, respectively, at t/D = 0.15.

Figure 7: (Nu) with (Re), for a different ratio of P/D at (t/D = 0.1).

Figure 8: (Nu) with (Re), for a different ratio of P/D at (t/D = 0.15).
4.4. Effect of metal chain insert on heat transfer ratio

Results showed clear heat transfer enhancement for a tube with use of the metal chain. The improvement ratios varied according to the type of the chain, including the ring length/tube diameter ratio and the wire diameter/tube diameter ratio. Figures 11 and 12 show variation in heat transfer enhancement with the Reynolds number for five different ring length/tube diameter ratios. P/D = 1, 2, 3, 4 & 5 of a metal chain with t/D = 0.1 and t/D = 0.15, respectively. Generally, we noted a decrease in the heat transfer enhancement with an increase in Reynolds number. It is also clear from these figures that heat transfer enhancement is higher than 1.0 for all cases. The t/D = 0.15 gave a higher enhance than t/D = 0.1.

**Figure 11:** Heat transfer enhancement with (Re) for different P/D at (t/D= 0.1).

**Figure 12:** Heat transfer enhancement with (Re) for different P/D at (t/D= 0.15).
5. Conclusions

The Nusselt number (Nu) increases with the Reynolds number (Re) increase for all case, whereby the Nusselt number achieved the highest result at P/D=1 and t/D=0.15, compared with other forms. The same form achieved the highest friction factor compared with other forms, friction factor (f) decreased with the Reynolds number’s (Re) increase in all case. The results also indicate that the metal chain type of P/D=3 and t/D=0.15 gave the best enhancement of heat transfer compared with other forms, and the thermal enhancement factor (η) decreased at increased Reynolds number in all cases. Therefore, the results obtained from this study indicate that the metal chains included in the heat exchanger tube may substantially enhance heat transfer with low pressure, and thus could be used in manufacturing heat exchangers to increase efficiency.

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