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# EXPERIMENTAL STUDY OF THE THERMAL PERFORMANCE OF CORRUGATED HELICALLY COILED TUBE-IN-TUBE HEAT EXCHANGER

Hussein Al-Gburi*, Akeel Abbas Mohammed, Audai Hussein Al-Abbas

*Power Mechanics Techniques Engineering Department, Al-Musaib Technical College*

*Al-Furat Al-Awsat Technical University, Kufa, Iraq*

**ABSTRACT**

Transferring thermal energy efficiently necessitates utilizing a heat exchanger capable of producing the full thermal power of the energy supply at lowest possible cost and time. Therefore, in the present investigation, the impact of corrugated helical coil concentric tube-in-tube heat exchanger on the thermal performance is investigated experimentally. As a continuous in our issue of heat exchanger, the corrugated helical tube-in-tube is carried out and compared with smooth helical tube-in-tube for free convection heat transfer. The set-up of the experimental apparatus are designed and utilized to be appropriate for the cooling and heating systems of working fluid. The impacts of geometry and operating conditions on the thermal and hydraulic characteristics such as the thermal effectiveness, whole coefficient of heating-transfer, number of thermal unit, pressure drop, Number of Dean and Number of Nusselt are taken into consideration of this investigation. The steady state flow condition and the counter flow direction are assumed in this investigation. The experimental results demonstrated that the whole coefficient of heating-transfer, effectiveness, number of thermal units, and Number of Nusselt were improved significantly due to the adoption of the corrugated helical coil tube-in-tube heat exchanger. This is happened because of the impact of geometrical configuration of corrugated tube in comparison with that of smooth tube, which is affected on increasing of the coefficient of heating-transfer. The maximum enhancement magnitude of the whole coefficient of heating-transfer was 33% for water flow rate of 16 L/min. For the latter water flow rate, effectiveness found that the maximum enhancement was 35%. The high magnitudes of NTU and Number of Nusselt were 3.37 and 218.5, respectively at the corrugated coil tube-in-tube for 16 L/min of hot water flow rate. The pressure drop for the corrugated tube was higher than that of smooth tube due to the swirl flow of hot water inner tube.

***Keywords***: *heat transfer enhancement, Corrugated and smooth helical coil, flow rate, tube-in-tube, pressure drop.*

## 1. INTRODUCTION

The processes of conduction, convection, or radiation might transport heating, which is a kind of energy, from a hot item to a cool one. Issues with heating transmission have recently taken centre stage in thermophysical investigation. In fact, as advancements advance in the current period, there has been a constant rise in the standards for removing heating flux densities as well as advancements in the security and environmentally friendly functioning of heating/mass transfer machinery. There seems to be energy waste or a heating stream, which is expelled to the environment in a number of industrial activities. By heating a separate stream inside the process, the heating exchangers have a crucial function in recovering this heat (Jain, Huizhuyang et al.,2015,Ganesh and Palande,2015, Rahul, Bhardwaj et al.,2009 Jayakumar, Mahajani et al.,2008).The device that transfers heat between two fluids—possibly in direct contact or flowing independently in two tubes or channels—is known as a heating exchanger. Heat exchangers are mainly utilized in thermal power plants in boilers, condensers, air coolers, cooling tower (Karima,2014, Rahut,2015, Arun and Mahto,2018, Esam,2016, Patil and Dange, 2014). Corrugation and other surface modifications are often employed in heat exchangers because they are particularly effective in improving heat transfer processes. Corrugated tubes are a sort of increased heat transfer instrument that has a significant benefit in many engineering applications. They are also proving to be quite useful in practical applications because they encourage secondary recirculation flow by generating non-axial velocity components (Sirainieri and Pagliarini,2002, Rainieri, Bozzoli.et al., 2011).

Both the internal and external surfaces of corrugated tubes are covered with several spiral projections. Because of the corrugation's turbulent flow impact on the internal and external surfaces of the tube, which is more than 1.3 to 2.6 times more than that for smooth tubes, the coefficient of total heat transfer was already dramatically enhanced. By enabling secondary flow swirls and surface curvatures to pass through fluid layers and cause pressure losses, spiral corrugation also enhances heat transmission (Dellil.2014, Zaid, Kareema et al.,2015). Kristina , Michael et al., 2021 studied the double corrugated tubes performance applied in a tube-in-shell heat exchanger. They compared and analyzed the investigated results to that of a heat exchanger utilizing straight tubes. Their research was based on a turbulent flow regime; and it is numerically calculated by the computational fluid dynamics (CFD) modelling at various mass flow rates. The findings indicated that although the double corrugated design has little to no impact on the

* Corresponding author. Email: hussein83@atu.edu.iq

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heating exchanger's internal pressure loss, it has the potential to increase its thermal performance by approximately to 25 percent. In tube-in-shell heating-exchanger, the effectiveness-numbers of transfer units (ε-NTU) relationship also demonstrated the superiority of the double corrugation tubes over straight tubes. Laohalertecha, Aroourat et al., 2014 presented the evaporation coefficient of heating transfer and pressure drop of R-134a flowing through corrugation tubes. The investigation was done in both experimental and simulation investigations. They utilized a horizontal counter-flow concentric tube-in-tube heat exchanger with a length of 2.0 meters serves as the test section. The internal tube is prepared of a corrugated tube and smooth tube with 8.7 mm internal diameters. A smooth copper tube with a 21.2 mm internal diameter is utilized for the external tube. 5.08, 6.35, and 8.46 mm were employed as corrugation pitches in their investigation. Corrugation depths are also 1, 1.25, and 1.5 mm. The result of this corrugated shape was that the max pressure drop and coefficient of heating-transfer were up to 19 and 22 percent, respectively higher than that of the smooth tube. The impact of nanofluid on turbulent heat transport and pressure decrease within concentric tubes was studied by (Rabientaaj, Mousa et al.,2012). The base fluid and nanoparticles utilized were water and $SiO2$ with average diameters of 30 nm, respectively. Plain tube and five roughened tubes with various corrugation pitches and heights were the subjects of experiments. The findings demonstrate that increasing the heat transfer while reducing pressure loss is possible by adding the required number of nanoparticles to pure fluid. Additionally, decreasing the corrugated pitch and raising the corrugated height induce the impact of nanoparticles on heat transmission to be more pronounced. The heat transmission and friction properties of spirally corrugated tubes for the external condensation of ammonia were empirically assessed by (Jose and Francisco,2021). Stainless steel tubes with nominal diameters of 18 to 20 mm were utilized in their experiment, which had wall subcooling temps ranging from 1 to 7.5 degree centigrade and a saturation temp of 40 degree centigrade. The results indicated that the parameters utilized to promote internal heat transmission varied from 2.11 to 2.53. In comparison to a smooth tube, friction coefficients were 4-5 times greater. Corrugated tubes generally performed better at transmitting heat than smooth tubes, by a factor of around 1.27. Based on the literature survey of this topic and our interesting issue of heat exchangers by (Audai H. Al-Abbas et al.,2020), it became clear that there is a small number of researches concerned with improving the performance of the heat exchanger utilizing corrugated tubes. In the present experiments, the major aim is to investigate the impact of flow rates for hot and cold water, and thermodynamics properties on the performance of corrugated and smooth helically coil tube-in-tube heat exchanger. Both the cooling and heating systems for working fluids are designed and considered in the investigation of the entire thermal system. For the corrugated coil tube-in-tube heat exchanger, the thermal effectiveness, whole coefficient of heating-transfer , number of thermal unit, Number of Dean and Number of Nusselt are investigated and compared with that one of smooth coil in this investigation.

## 2. METHODOLOG

The experiment tests in this investigation were essentially carried out for two various geometrical configurations of heat exchangers. The experiments were conducted to evaluate the impact of flow rates of the hot and cold water and thermodynamics properties on the performance of corrugated and smooth coil tube-in-tube heat exchangers. All experimental works were done at the thermodynamic Laboratory of Power Mechanics Engineering faculty in Technical College Al-Mussaib (TCM),Al-Furat Al-Awsat Technical University (ATU), Kufa, Iraq. The experimental set up of these tests were utilized two pumps, water heating and cooling systems, flow meters, thermometers, helical coil tube-in-tube heat exchanger, PC, water valves and data logger, as demonstrated in Figure 1.

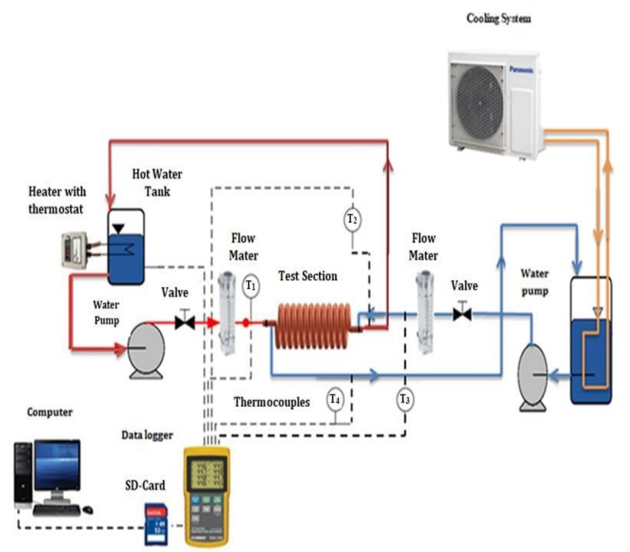


**Fig.1** Schematic diagram of the rig

### 2.1 Experimental set up

For these experimental tests, the cold water and hot water are basically prepared by utilizing cooling and heating systems, respectively, as demonstrated in Figure (1). The hot water is firstly pumped from the hot water tank to pass through the internal tube of the helical coil heat exchanger (HCHE) at point 1 and leave at point 2. Simultaneously, the cold water is pumped at the same time from the cold water tank to pass through the external tube of the HCHE at point 3 and leave at point 4under the counter flow direction. Two flow control valves and two flow meters (model: LZM-Z) are adjusted and set up in flow lines in order to control the volume flow rates. In the heating system, the water tank was provided with electric water heater (800 W), and the magnitudes of hot water are adjusted by thermostat. Data logger (model: BTM-4208SD) with four thermocouples (type-K) are utilized to measure the water temperatures at points 1, 2, 3, and 4. In the cooling system, the power consumption of both the compressor and condenser was 3710 W in order to attain the perfect operating conditions. Full geometry details for the corrugated and smooth tube-in-tube HCHEs are presented in Table 1.

**Table 1** specifications of corrugated and smooth helical coil tube-in-tube

| Specifications | Helical coil corrugated tube | | Helical coil smooth tube | |
|---|---|---|---|---|
| | Internal | External | Internal | External |
| Length tube | 4 m | 4 m | 4 m | 4 m |
| External Diameter | 6 mm | 17 mm | 6 mm | 17 mm |
| Internal Dimeter | 4.5 mm | 15.5 mm | 4.5 mm | 15.5 mm |
| Roughness height | 0.8-1 mm | | 0.8-1 mm | |
| Envelope Diameter | 18.6 mm | | - | |
| Corrugated Pitch | 10 mm | | - | |

The magnitudes of water temperatures at inlet and outlet of tube-in-tube HCHE are accurately recorded by the data logger at measuring points under the steady state condition. Once the first test is done, the hot and cold water are returned to the hot and cold tanks, respectively to be ready for the next measurements, as demonstrated in figure 1. In addition to the impact of geometry (corrugated and smooth tubes), the fluid flow and thermodynamics properties are also taken into consideration of this investigation, as listed in Table 2. Digital stopwatch and measuring container are utilized to calibrate the flow meters, while four utilized

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thermocouples are calibrated by cure fitting method, as presented in Figure (2). The detailed information of uncertainty analysis of this experimental study are listed in Table 3. This is used to estimate the measurement uncertainties of the experimental data results. For more details about how to calculate the uncertainty errors, it can be found in Ref. of Audai H. Al-Abbas et. al. 2020.

**Table 2** information for tested situations

| Flow Factors | Thermodynamics Factors | | | |
|---|---|---|---|---|
| $Q_{in}$ (L/min) | $T_{c,in}$ $^0$C | $T_{c,out}$ $^0$C | $T_{h,in}$ $^0$C | $T_{h,out}$ $^0$C |
| 5 | 23.5 | 36.2 | 45.8 | 38.3 |
| 9 | 22 | 38.8 | 51.9 | 40.7 |
| 13 | 19.4 | 39.2 | 54.8 | 41.5 |
| 16 | 15.7 | 39.8 | 56.9 | 41.9 |

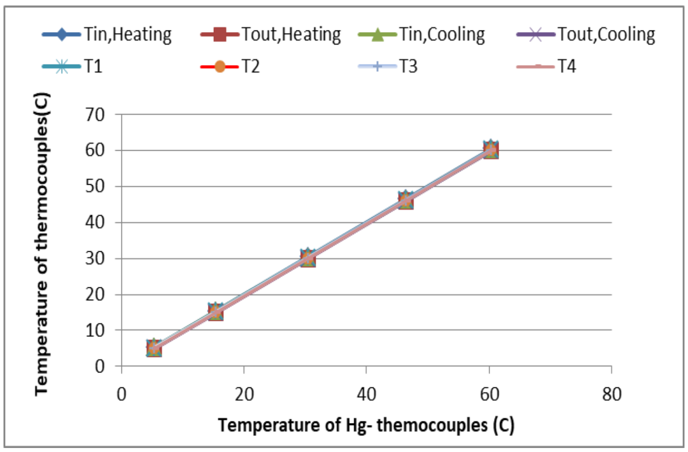


**Fig. 2** Calibration cure of thermocouples

**Table 3:** The uncertainty analysis of the experimental work

| VARIABLES | VARIABLE ERRORS |
|---|---|
| DATA LOGGER (TEMPERATURE READERS) | ∓0.8 |
| HOT SIDE TEMPERATURE (°C) | ∓0.6 |
| COLD SIDE TEMPERATURE (°C) | ∓0.6 |
| HOT SIDE MASS FLOW RATE | ∓0.03 |
| COLD SIDE MASS FLOW RATE | ∓0.03 |

## 2.2 Experimental Procedure

In this investigation, thermal performances of corrugated helically coiled tube-in-tube heat exchanger were assessed under steady state operating conditions and counter flow direction. Many parameters such as fluid flow, thermodynamics, and geometrical shapes are taken into account in these experimental investigations. These key parameters are utilized to investigate the heat transfer processes between the internal and external tubes for the corrugated and smooth HCHEs. For all examined tests, the volume flow rates were limited to 16 (L/min.) and the Number of Reynolds is less than 5000. And this is because of the high pressure drop occurred in the HCHE. Nevertheless, for each variable that is measured, the rest of the variables are constant in each experimental test.

The experimental procedure consists of the following steps: -

Step 1: Ensuring that the cooling tank and heating tank are filled with water, and then switch on the power to the electric panel.

Step 2: Operating the heating system for 5-15 minutes, and then operate the cooling system until the required temp; and this needs 10-15 minutes and also ensure that there is no defect in the system.

Step 3: Operating both pumps for cooling and heating systems and ensure there is no leakage in the pipes, including pipes entering and out of the corrugated helical coil heat exchanger.

Step 4: Ensuring that all the thermocouple sensors in the right location, and then turn on the digital data logger which is attached to the corrugated helical heat exchanger to test the cooling and heating systems.

Step 5: Controlling the flow meter in which we work on valve by changing the amounts of flow from5 L/min to 16 L/min.

Step 6: Appling all the above mentioned steps to the smooth helical coil heat exchanger to make a clear comparison between these two various configuration heat exchangers.

## 2.3 Specifications of smooth and corrugated helical coil tubes

Copper tube is a type of tube that is frequently utilized in refrigeration and air conditioning equipment's, as it is utilized for internal connection to the main parts of the thermal systems. Copper tubes allow fluid to flow directly and evaporate from one part of the unit to the other. Two tubes (tube in tube) were utilized of this investigation for being a good conductor of heat. Figure (3A and 3B) demonstrates the corrugated and smooth helical coil tubes. Table (1) the specifications of corrugated helical coil, and smooth tube utilized in the test.

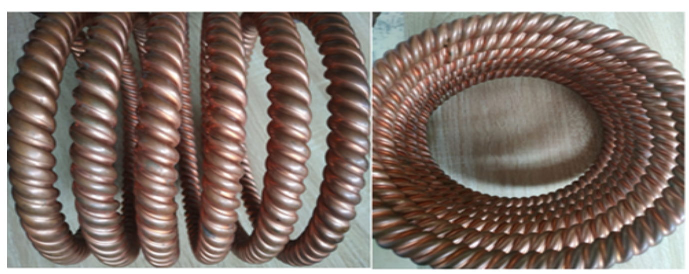

**Fig.3A** Corrugated tube

**Fig.3B** Smooth tube

## 2.4 Calculations of thermal Characteristics:

Whole coefficient of heating-transfer , effectiveness, number of thermal units (NTU), Number of Nusselts, Reynolds and Dean Number are taken into calculations in this experimental investigation, as presented below:

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The heat transfer rate through an insulated heat exchanger can be assessed from Formula (1). ( Moosavi, Abbasalizadeh et al.2016)

$$q = \dot{m}_h C_{p,h}(T_{in,h} - T_{out,h}) = \dot{m}_c C_{p,c}(T_{out,c} - T_{in,c}) \quad (1)$$

Where:

Q= heat transfer (watt)

where $\dot{m}_h$ , $\dot{m}_c$ , $C_{p,h}$ , $C_{p,c}$, $T_{in,h}$, $T_{out,h}$, $T_{out,c}$ and $T_{in,c}$ signify the hot fluid's mass flow rate, cold fluid's mass flow rate, the hot fluid's heating capacity, the cold fluid's heating capacity, the hot fluid's inlet temp, the hot fluid's outlet temp, the cold fluid's inlet temp and the cold fluid's outlet temp, respectively.

The whole coefficient of heating-transfer could be determined from Formula (2 ). ( Moosavi, Abbasalizadeh et al. 2016).

$$U = \frac{q}{As.\ Tm} \quad (2)$$

$A_s$= surface area $A_s = \pi\, d\, L$ ($m^2$)

The mean temp difference (Tm) for counter flow is determined from Formula (3). ( Moosavi, Abbasalizadeh et al. 2016).

$$T_m = \frac{(T_{h,i} - T_{c,o}) - (T_{h,i} - T_{c,i})}{In\left(\frac{T_{h,o} - T_{c,o}}{T_{h,i} - T_{c,i}}\right)} \quad (3)$$

The effectiveness of a heat exchanger is the proportion of the actual to max possible heat transfer, and it can be assessed from Formula (4) (Ali, Hameed et.al. 2019).

$$\mathcal{E} = \frac{q}{Cmin(Tin,h - Tout,C)} \quad (4)$$

The number of thermal unit (NTU) is determined from Formula (5). (Ali, Hameed et.al. 2019).

$$NTU = \frac{As.U}{C_{min}} \quad (5)$$

where represents the minimum magnitude of heat transfer capacity in the heat $Cmin$ ($mCp$) exchanger, is the whole coefficient of heating-transfer and is the heat transfer area. (Ali, Hameed et.al. 2019).

Nusselts Number can be calculated by utilizing the formulas (6-8) (Asnkan, and Farzadveysi. 2016)

$$Nu = \frac{h\,D}{K} = 0.023(Re)^{0.8}(Pr)^{0.4} \text{ for hot water} \quad (6)$$

$$Nu = \frac{h\,Dh}{K} = 0.023(Re)^{0.8}(Pr)^{0.3} \text{ for cold water} \quad (7)$$

$$Re = \text{Number of Reynolds} = \frac{V_m}{\vartheta} D \quad (8)$$

Pr= Prandtl Number

Dh= HydraulicDiameter (m)

h= Coefficient of heating-transfer ($w/m^2.C^0$)

k= Thermal Conductivity ($Kw/m.C^0$)

Number of Dean could be assessed from Formula (9). (Ruchal, Suraj. 2014)

$$De = Re\sqrt{\frac{d_t}{D_c}} \quad (9)$$

Where

De= Number of Dean

$D_c$= Coil diameter (m)

$d_t$= Out diameter (m)

## 3. RESULTS AND DISCUSSIONS

Experimental investigations are carried out to investigation the impact of thermal effectiveness ($\mathcal{E}$), Whole coefficient of heating-transfer (U), NTU, Number of Dean ($D_e$) and Number of Nusselt on the heat transfer in corrugated and smooth helical coil tube-in- tube heat exchangers.

Fig. 4 demonstrates the relation between thermal effectiveness and various hot and cold water flow rates. The impact of the corrugated coil tube-in-tube in both heat and cold water on the effectiveness was obvious as compared to the smooth coil tube-in-tube for various water flow rates. Effectiveness found the max enhancement for the corrugated coil tube-in-tube hot water flow rate was 35% for 16L/min, while in the case of cold water was 24.6% for 16L/min. On the other hand, the effectiveness was minimum for corrugated coil tube-in-tube hot water, and it was 24.2% for 5 L/min and it is minimum for corrugated coil tube-in-tube cold water, and it was 14% for 5L/min. This is happened due to the influence the surface area of the corrugated coil tube-in-tube heat exchanger.

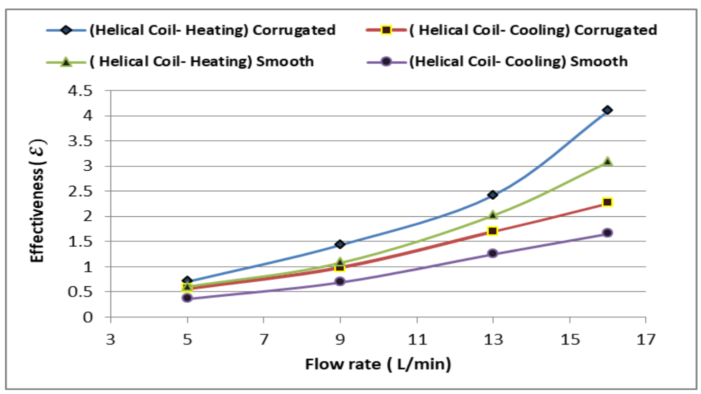


**Fig. 4** relationship between effectiveness with various hot and cold water flow rates.

The relationship between whole coefficient of heating-transfer and various hot and cold water flow rate is presented in Fig 5. The impact utilized for the coil tube-in- tube corrugated in both cases heat and cool water were clear compared with smooth coil tube –in- tube. It can be view that, the amounts of whole coefficient of heating-transfer increases with cooling case, and they were 15.2 %, 17.1 %, 20.5 % and 22.2 % for 5, 9, 13 and 16 L/min, respectively. As for heating processes, the whole coefficient of heating-transfer increases were 21.2 %, 22.6 %, 25.5 % and 33 % for 5, 9, 13 and 16 L/min, respectively. The influence of varying water flow rates can be attributed to increases in whole coefficient of heating-transfer. This is can be contributed due to the density water bubbles inside the helical coil tube –in- tube.

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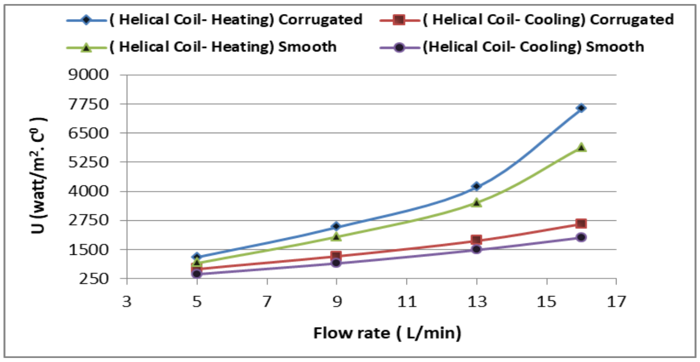


**Fig. 5** relationship between whole coefficient of heating-transfer with various hot and cold water flow rates.

Fig.6 demonstrates the NTU with various hot and cold water flow rate. For the impact of helical coil corrugated tube-in-tube, it is extremely evident compared with helical coil smooth tube-in-tube heat exchanger. The minimum magnitude obtained from NTU was 0.41 hot and 0.12 cold water for 5L/min with smooth coil tube-in-tube. As for coil corrugated, it was 0.63 hot and 0.32 cold water for 5 L/min. The high magnitude of NTU was 3.37 hot and 1.40 cold water for 16 L/min coil corrugated tube-in-tube. In terms of coil smooth, the results were 2.13 hot and 0.73 cold water for 16 L/min.

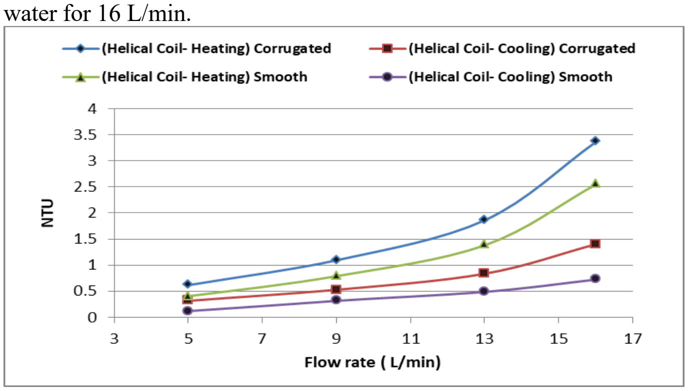


**Fig. 6** variation of NTU with various hot and cold water flow rates.

Fig.7 demonstrates the results of Numbers of Nusselt versus Number of Reynolds for various water flow rates. It can be observed that, the influence of the increase Number of Reynolds is obvious on Number of Nusselt. The high magnitude of Nu was 218.5 at the corrugated coil tube-in-tube for 16L/min of hot water, and the minimum Nu was 79.77 at smooth coil tube (5L/min) cold water.

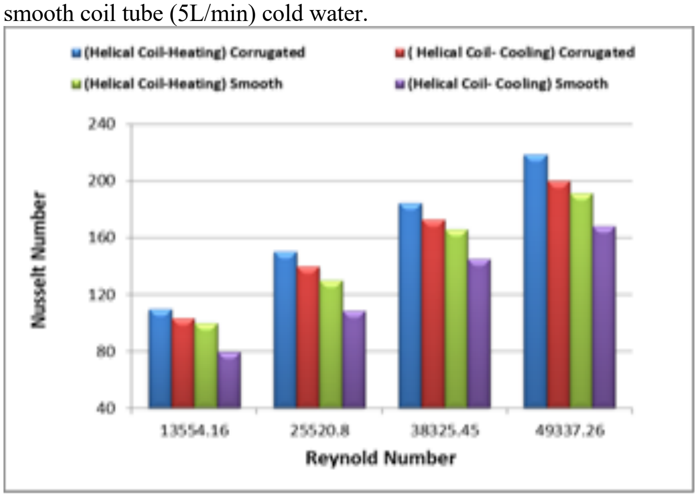


**Fig.7** variation of between Numbers of Nusselt with Reynolds at various hot and cold water flow rates.

Fig.8 Demonstrates the variation in calculated Nussult Number of corrugated and smooth helical coil tube-in-tube with Number of Dean. The impact of increases with corrugated helical coil tube-in-tube was clear compared with smooth helical coil tube-in-tube, where it led to an increase in the Nussult Number. It is obvious that, the enhancement of the Nussult Number for corrugated coil tube-in-tube was 16.7% at 16L/min. Nevertheless, these improvements on the fluid flow characteristics are occurred due to the envelope diameter and corrugated pitch adopted in the corrugated helically tube-in-tube heat exchanger. These results are highly agreed with similar recent research works (Ahmed Ramadhan Al-Obaidi et. al, 2022, Qingxiang, Xinhe et al. 2022, Wei, Yaning et al. 2019).

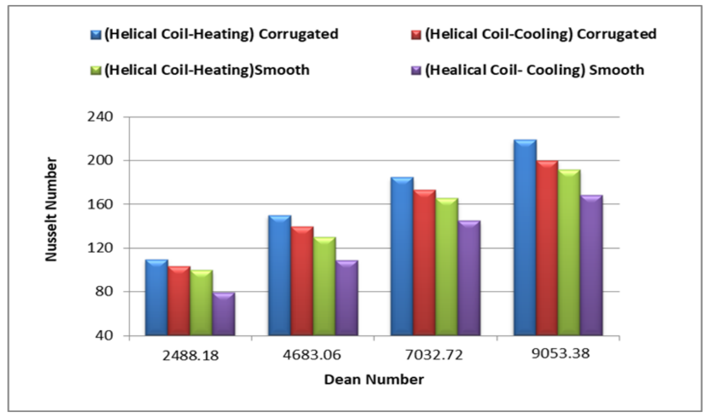


**Fig. 8** relationship between Numbers of Nusselt with Dean at various hot and cold water flow rates

Fig. 9 shows the effect of coil type (corrugated and smooth tube-in-tube) and volume flow rate on pressure drop in the HCHE for the hot water inner tube. As seen, the pressure drop is gradually increased with the volume flow rates of the hot water inner tube. But, that drop in pressure was higher in case of corrugated tube in respect to that of smooth tube. This is happened due to the enhancement in the turbulent flow impact on the internal and external surfaces of the corrugated inner tube; and this makes secondary flow swirls which helps to pass through the fluid layers and resulted an increase in the pressure drop with increasing the flow water rates. The results indicate that the corrugated configurations result in a significant pressure drop with corrugated tube, and it was about 21.1% in comparison with that of smooth tube.

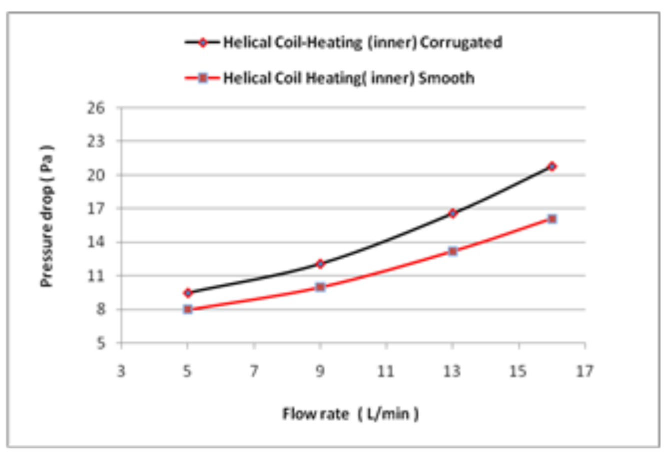


**Fig. 9** Effect of coil type (corrugated and smooth tube-in tube ) and volume flow rate on pressure drop in HCHE for the hot water inner tube

## 4. CONCLUSIONS

In this investigation, an experimental investigation of the thermal performance for corrugated helically coiled tube-in-tube heat exchanger is carried out. For the heating and cooling systems, the experimental set-up is perfectly designed in order to take the impact of thermal and hydraulic characteristics into considerations during these tests. Under the steady state conditions, the thermal effectiveness, whole coefficient of heating-transfer , number of thermal unit, Number of Dean and Nusselts number are calculated for each test case of the corrugated tube-in-tube HCHE and the smooth tube-in-tube HCHE. It is noted that the thermal performance for the corrugated tube-in-tube HCHE is better than that for the smooth tube-in-tube HCHE due to the impacts of curvatures and corrugations. Furthermore, the max enhancement magnitudes of the whole coefficient of heating-transfer , effectiveness and Number of Dean were 33%, 35%, 16.7% respectively in case of the corrugated tube-in-tube HCHE for 16 L/min of hot water flow rate. In addition, the max magnitudes of NTU and Nusselts number for the corrugated tube-in-tube HCHE were 3.37 and 218.5, respectively for water flow rate of 16 L/min. Finally, this experimental work is considerably affected the thermal and hydraulic characteristics on the corrugated tube-in-tube HCHE in comparison to the smooth tube-in-tube HCHE under counter flow condition. The pressure drop was about 21.1% higher for the corrugated tube in related to smooth tube in the hot water inner tube.

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