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Experimental study of fluid flow properties in spiral tube heat exchanger with varying insert shape over spiral tube profile

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ABSTRACT

Experimental and computational analysis is carried out for analyzing the effect of different shapes of inserts. The inserts used are conical inserts, hemispherical shape insert, helical insert and these are mounted over cascaded spiral copper tube heat exchanger. The performance characteristics and fluid flow characteristics are studied for turbulent-counter flow and the fluid is water. Experimentation carried out for cold water at 304 K and hot water at 333 K and the rate of fluid flow for cold water inside spiral tube is 0.725 to 2.955 L/min. The hot water flows at 333 K with fluid rate of flow 4.025 L/min horizontally across outer shell. The comparative study of different shapes of insert with rate of fluid flow and Reynolds number is considered ranging from 4236 to18545. The study stated that the helical type insert gives promising and significant improvement by 18.5 % more than spiral tube without insert, 15.5 % more than conical insert and 11.5 % more than hemispherical shape insert for thermal performance under turbulent-counter flow. The minimum and maximum values obtained from the study for h_{htr}, Nu, f, effectiveness N.T.U and η_{tp} varies from 1298.5 to 3541.6, 88.28–160, 0.0438–0.0306, 0.89–0.59, 2.51–1.24 and 2.41–1.31 respectively. The maximum optimum value is obtained for performance factor (η_{tp}) is 1.51 for Reynolds number ranging 13,322 for helical insert of 2 mm diameter and 10 mm pitch distance.

1. Introduction

Recently researchers paid their attention in the field of thermal engineering specifically in nano technology and solar energy area. Now are days collaborative type research takes place, for enhancement of thermal and fluid flow behavior of hybrid heat transfer devices with diverse blends of fluids or nano fluids, including this different geometrical parameters like heat exchanger tubes, bundles of tubes, varying shape of tubes, shape and size of solar collector absorber plates with or without inserts, macro inserts, baffles, fins etc also responsible for enhancement of heat transfer and these are major research areas for researchers, analysis carried out for determining the effects of varying geometrical shapes of tube & inserts with diverse composition of fluids, such promising research plays an significant role for improvement of thermal, hydraulic and fluid flow behavior, which directly provide a good impact on the life of solar based devices, local appliances such as laptops, I phones, medical gadgets, other electronic macro machines etc. Many research performed experimentation on different shape of insert, in past literature some researchers used hollow circular ring with perforation [9,29,31], perforated hollow tapered rings [23], simple twisted tape [11,25] twisted tape with double counter [12], triple twisted-tape [13], twisted tapes installed inside circular-rings [14], twisted-tapes having helical shape with holes [15], baffles of Wedge and M-Shape[29], Z- Shape[31], spherical ball shape material has been used by researcher Kanojia N. et. al. [22,28,30,32,34] and these all insert and material has been installed inside a circular duct [5,11,12,13,14,15,21], in other literature insert like random parabolic insert/roughness [18], solo fins or LED along with fins surrounding [21,33] and annular duct having coiled shape [2] has been installed inside rectangular duct [2,18], few researchers focused on simple spiral tube with fins [1], helical coiled tubes [3], tubes having spiral grooving, and simple spiral tubes & bundles of plain tubes [6,16] installed in a concentric circular exchangers of heat [1,3,4,6,7,8,16] for determining the thermal behavior [2,3,7,8,9,11,13,16,26], performance behavior [1,4,9,12,24,27], cooling behavior [6,27], humidifi-

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Nomenclature

Q_{ds}	Fluid Discharge (meter^3/sec)
Q_{hf}	Fluid rate of heat transfer (hot condition fluid) (kg/second)
Q_{cf}	Fluid rate of heat transfer (cold condition fluid) (kg/second)
m_{rf}	Fluid rate of flow (L/min)
m_{hf}	Fluid rate of flow (hot condition fluid) (L/min)
m_{cf}	Fluid rate of flow (cold condition fluid) (L/min)
C_{phf}	Fluid specific heat (hot condition fluid) (J. Kg^{-1}. °C^{-1})
C_{pcf}	Fluid specific heat of (cold condition fluid) (J. Kg^{-1}. °C^{-1})
h_{htc}	Fluid heat transfer of coefficient (W. m^{-2}. K)
K_{hf}	Fluid thermal conductivity (hot condition fluid) (W/m. K)
K_{cf}	Fluid thermal conductivity (cold condition fluid) (W/m. K)
Nu	Nusselt Number
μ_{hf}	Fluid viscosity (hot condition fluid) (Pa-second)
f	Friction Factor
Q_{htr}	Rate of heat elimination (J/Second)
v_{hf}	Fluid velocity (hot condition fluid) (m/second)
v_{cf}	Fluid velocity (cold condition fluid) (m/second)
ρ_{hf}	Fluid density (hot condition fluid) (kg/m^3)
ρ_{cf}	Fluid density (cold condition fluid) (kg/m^3)
η_{tp}	thermal performance
Q_{hfx}	Total heat flux (Watt./Meter ^{2})
μ_{cf}	Fluid viscosity (cold condition fluid) (Pa-second)

cation & dehumidification behavior [1,5,6], thermo-hydraulics behavior [14,16,26] and charging effect, discharging effect in terms of energy storage [5,22,28,30,32,34] with different types of fluids like air [2,6,7,8,9,14,21,22,23], water [1,3,4,5,6,7,8,11,12,19,21] ethylene glycol with or without paraffin [16] and nano fluids [16,17,19,20,25,26[nano refrigerant or lubricant, bio-oil [24,26,27,10,35,36] and coincidently these all insert shapes are showing good result in terms of managing temperature range of devices, so that they can perform well and effective heat removal enhance the life time of the machine or devices because these shape provide more turbulency in fluid during flow. Some of them focus on placement of insert profile or location for insert profile over the tube or inside the tube and it seems strange while analyzing the outcome that every location or placement of inserts profile plays crucial role for an enhancement of performance [1,9,12,13,14,18]. Few researchers paid attention on various operating parameters which governs and affect the process of enhancement for different geometries of insert. Recently researchers paid their attention on improvement of fluid domain by implementing the dispersion concept with nano particle into water and making new types of fluid with better properties, which is directly responsible for higher enhancement of performance of the devices, some researchers worked on nano fluid like Al_2O_3 with water as based fluid [16], Al_2O_3 with ethylene, Al_2O_3 with paraffin [16], CuO with water [17], Al_2O_3, ZnO, CuO with water [19,20], after comparing the performances of these fluids Al_2O_3, CuO with water performed well, when compared with others, due to its improved thermal properties like conductivity. As per the above research trend, selection of geometrical shape of inserts and shape of tube or duct, type of fluid, types of operating parameters have play a very important role in enhancing the output, after analyzing the above literature properly, best performing shapes with gaps has been identified, here in this present research prime focus is based on spiral tube and three different insert which will placed over spiral tubes for analyzing the effect of different selected shapes of insert and placement of insert with water as main fluid under turbulent counter flow condition for acknowledging the effects on performance of device when exchanging heat. The novelty in the research is that proposed work emphasis the use of diverse shape of insert mounted above the surface of spiral tube for enhancement of heat termination, with an increase level of turbulence, which directly affects the life span of diverse applications. Some researchers focused on nano refrigerant-lubricant [24,26,27], MWCNT/R134A [27], nano fluid (3D-Al_2O_3-water) [25], bio-lubricant or bio-oil [10,35,36] for evaluating the effect on diverse thermal [25] and performance parameters [24,27,35,36] and physio/chemical attributes [24,35,36] under diverse test rig like twisted tape [25], where concentration, sizing of particle etc. play an important role. Result predicted a crucial aspect about nano technology that lower particle sizing and higher concentration enhance pool/boiling phenomenon, thermal and physical performance of fluid and devices.

2. Equations used

Equations were used for determining, fluid flow properties including performance properties and the experimentation was obtained by following data reduction method, for obtaining the fluid rate of flow (hot condition fluid) and fluid rate of flow (cold condition fluid). Here, m_{rf} is the fluid rate of flow which is used to calculate the rate of heat elimination of hot condition fluid and cold condition fluid, the data governed by following equation as,

$$Q_{ds} = \frac{\text{Volume}}{t} \tag{1}$$

where,

$$Q_{ds} = \text{Area.Volume} \tag{2}$$

$$m_{rf} = \rho_f.A.V_f \tag{3}$$

$$Q_{hf} = m_{hf}.C_{phf}(T_{in} - t_{out}) \tag{4}$$

$$Q_{cf} = m_{cf}.C_{pcf}(T_{out} - t_{in}) \tag{5}$$

where, T_{in} = Outer GI Shell tube inlet temperature, T_{out} = Outer GI Shell tube outlet temperature, t_{in} = Spiral inner tube inlet temperature and t_{out} = Spiral inner tube outlet temperature. Further steps using L.M.T.D, method for obtaining heat transfer of coefficient and overall coefficient of transfer of heat as per governing equation:

$$Q_{htr} = h_{htc}.A.\Delta T \tag{6}$$

where,

$$\Delta T = \frac{(\Delta T1 - \Delta T2)}{ln(\frac{\Delta T1}{\Delta T2})} \tag{7}$$

$$\Delta T_1 = (T_{out} - t_{in}) \tag{8}$$

$$\Delta T_2 = (T_{in} - t_{out}) \tag{9}$$

$$U = \frac{1}{(\frac{1}{hi} + \frac{1}{ho})} \tag{10}$$

After evaluating above parameters, further steps are used to determine fluid flow properties (cold condition fluid) as per governing equation:

$$Nu = \frac{h.D}{k} \quad (11)$$

$$Nu_s = \frac{h.D}{k} = 0.023Re^{0.8}Pr^{0.4} \quad (12)$$

where,

$$Re = \frac{\rho.A.D}{\mu} \quad (13)$$

$$f = \frac{\Delta P}{\left(\frac{L}{D}\right)\left(\frac{\rho.v^2}{2}\right)} \quad (14)$$

After evaluating above parameters, further steps are used to determine the performance parameters (cold condition fluid) as per governing equation:

$$\varepsilon = \frac{Q_{actual}}{Q_{max}} \quad (15)$$

where,

$$Q_{acual} = m_{cf}.C_{pcf}(t_{out} - t_{in}) = m_{hf}.C_{phf}(T_{in} - T_{out}) \quad (16)$$

$$Q_{max} = C_{min}(T_{in} - t_{in}) \quad (17)$$

$$T_{out} = T_{in} - \frac{Q_{max}}{C_{max}} \quad (18)$$

$$t_{out} = t_{in} + \frac{Q_{max}}{C_{min}} \quad (19)$$

$$NTU = \frac{U.A_s}{C_{min}} \quad (20)$$

where,

$$C_{min} = m.C_{cp} \quad (21)$$

$$NTU_{counter} = \frac{1}{c-1} ln\left(\frac{\varepsilon - 1}{\varepsilon c - 1}\right) \quad (22)$$

$$\eta_{tpf} = \frac{\left(\frac{Nu}{Nu_s}\right)}{\left(\frac{f^{0.33}}{f_s^{0.33}}\right)} \quad (23)$$

$$f_s = 0.316Re^{-0.25}(\text{Blasius Eq.}) \quad (24)$$

$$f_s = [0.79\ Ln(Re) - 1.64]^{-2}(\text{Petukhov Eq.}) \quad (25)$$

3. Experimentation details of test setup

Figure Number 3.1 shows the plane geometrical models of spiral tube having different insert shapes like conical insert, helical inserts hemispherical insert located at outer surface of inner spiral copper tube, where as Figure Number 3.2 shows schematic structure of experimental setup.

The experimental test setup consisting following units namely shell tube, plane spiral tube, spiral tube profile with different insert shapes and the outer side of shell was insulated properly by glass wool in which different profiles were installed and fix with flanges and bolts with thermocouple attachment at inner side and outer side of the tube with data acquisition system.

Test setup made of different elements and these elements of test setup were constructed in such a manner/way that its each element can be assembled and disassembled easily. Now, the test setup were assembled with different other sub units like flow controlling and measuring unit, temperature controlling unit properly. Test setup consists of 6 RTD thermocouples Tc_1, Tc_2, Tc_3, Tc_4, Tc_5 and Tc_6 which is attached at inner side and outer side of the shell and spiral tube profile with computer based acquisition system. Some dimensional parameter of experimental set up has been selected like Inside diameter & Outside diameter of spiral coil, Coil turns & Coils in number, Space between coils, Outer Shell outside &

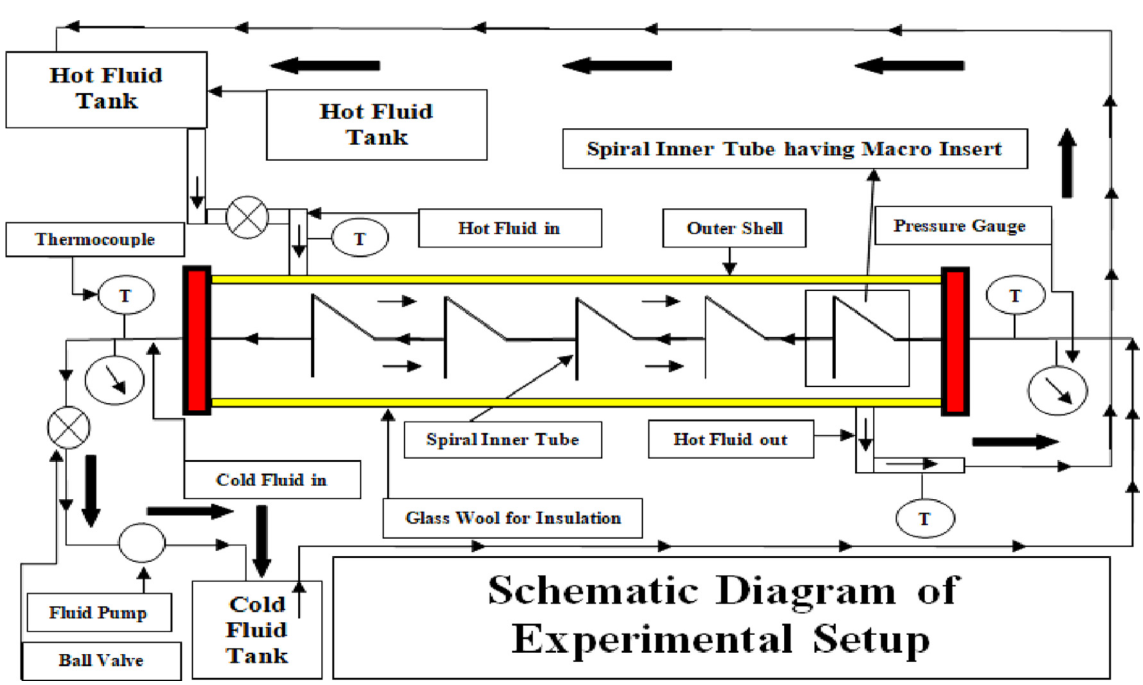

Fig. 1 (*continued*)

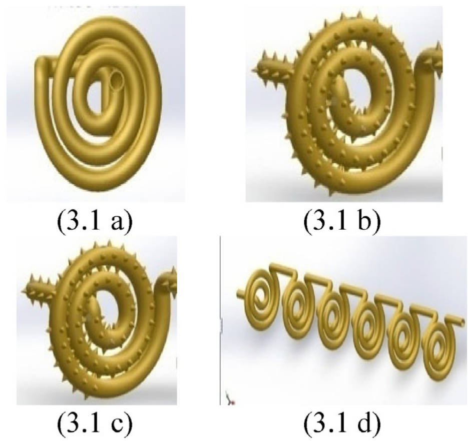

Fig. 3.1. (a) Diagram of plane spiral profile (b) Diagram of plane spiral profile with conical insert (c) Diagram of plane spiral profile with hemispherical insert (d) Side view of plane spiral profile. [21] Figure Number 3.2: Diagram of experimentation working unit. [21].

Table 3.1
Geometrical profile used in experimentation.

Profiles	Abbreviation
Plane spiral profile	Without Insert
Plane spiral profile having hemispherical macro insert	Insert 1
Plane spiral profile having conical macro insert	Insert 2
Plane spiral profile having helical macro insert	Insert 3

Outer Shell inside diameter and Shell length & Helical pitch whose values are 10.6 & 12.6(mm), 3 & 6, 11.4(mm), 162 & 154(mm) and 850 & 30(mm) respectively. Hot condition fluid supplied from hot condition fluid storage tank and cold condition fluid supplied from cold condition fluid storage tank to test section. For obtaining pressure drop and rate of flow, different measuring equipments are installed near inlet and outlet side of shell tube and spiral tube profile properly. During experimentation of flow meters were used to calculate rate of flow of hot and cold condition fluid where as pressure indicators and digital temperature data loggers were used to calculate the differential pressure and temperature of cold and hot condition fluid. During experimentation operating and fluid flow condition like Inlet Fluid Temperature, Rate of Flowing Fluid, Fluid Specific Heat (cp), Density ρ, Prandtl (Pr) number, Viscosity (μ), and Thermal Conductivity (K), for hot fluid are 333(K), 4.02 (L/min), 4185(J/kg. °C), 0.983(g/m^3), 2.99, 0.000474(Ns/m^2) and 653(W/m^2-K), where as for cold fluid 304(K), 0.72-0.2.95(L/min), 4178(J/kg. °C), 0.995(g/m^3), 5.3, 0.000780(Ns/m^2) and 619(W/m^2-K) respectively. Table Number 3.1 shows abbreviation of different geometrical profile used in experimentation.

4. Results and discussions

In this proposed research, observation carried out for fluid flow properties. The effects of different insert shape mounted over the spiral tube profile on thermal behavior of fluid has been acknowledged, as shown in figure number 4.1, 4.2, 4.3, 4.4, 4.5 with varying Re number range from 4236 to 18,545 under turbulent-counter flow condition for water. f factor varies from 0.0408 to 0.0279 for without insert tube, 0.0420 to 0.0301 for insert 1, 0.0435 to 0.03025 for insert 2, 0.0438 to 0.0306 for insert 3. Here, all profiles showing decrement as Re number and rate of flow is increasing as shown in figure number 4.1 because pressure drop is increasing. On the other hand, it has been noted that the f factor simulation result for suggested profile with different shape of inserts, also showing decrement as Re number and rate of flow is increasing and the f factor result varying from 0.0391 to 0.0270 for without insert tube, 0.0412 to 0.0287 for insert 1, 0.0426 to 0.0289 for insert 2, 0.0428 to 0.0297 for insert 3 as shown in Fig. 4.1. Whereas, an increment in Nu number has been noticed because of high fluctuation of temperature drop and pressure drop which directly impact the thermal transfer rate and Nu number is dependent on thermal transfer rate and conductivity with different increasing range of Re number as shows in Fig. 4.1 for different insert shapes and their range varies from 36.25 to 111 for without insert tube, 47.15 to 128 for insert 1, 76.18 to 145.25 for insert 2, 88.28 to 160 for insert 3. Comparative results based on experimentation for all these insert shapes reveals that, insert 3 showing optimum and best results as compared with other insert shapes, because helical insert shape (insert 3) produce more turbulency during flow of fluid. Turbulency occurs because of following reason that is insert shape & insert design, insert pitch value, artificial roughness and exposed surface area etc. Optimum results achieved for insert 3 where optimum values for Nu number, f factor is 144.05 and 0.00305 for the effective fluid rate of flow i.e. 2.95 L/min with range of Re number 4236 to 18,545 under counter flow condition.

Whereas, it has been seen from the results that the Nu number simulation values for suggested profile with different insert shapes, also showing enhancement as Re number and fluid rate of flow is increasing and Nu number values varying from 39.25 to 118 for without insert tube, 53.08 to 138 for insert 1, 82.95 to

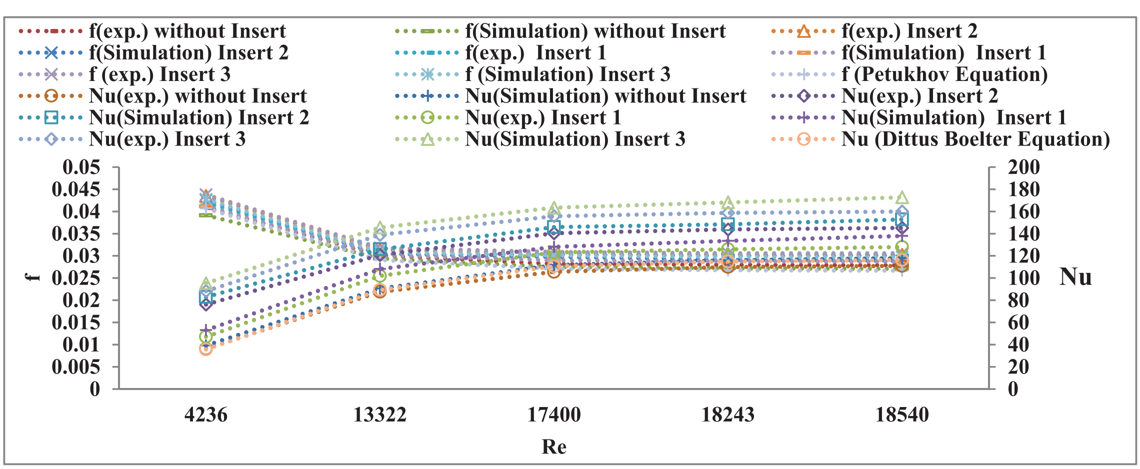

Fig. 4.1. Graphical representation of f Factor, Nu Number regarding different profiles.

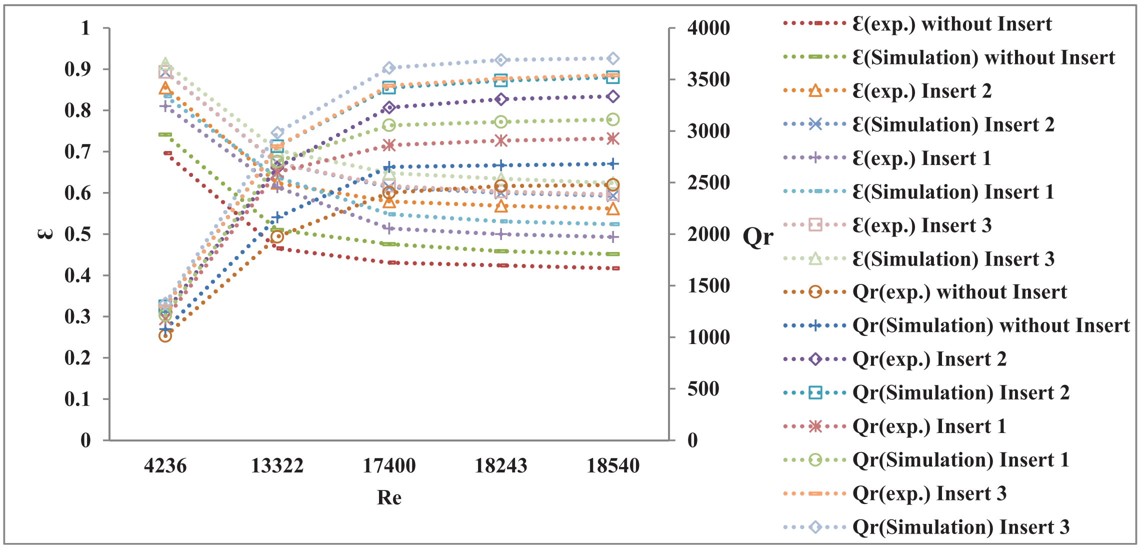

Fig. 4.2. Graphical representation of Effectiveness and Rate of Heat Transfer for different profiles.

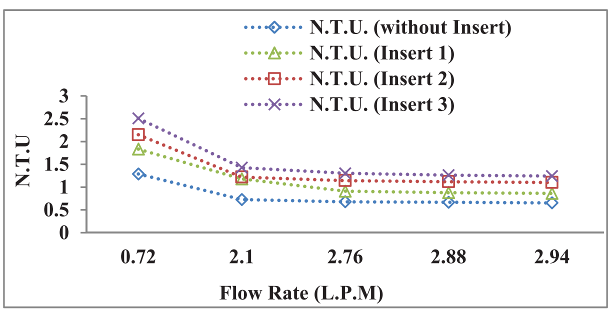

Fig. 4.3. Graphical representation of N.T.U and Mass Flow Rate for different profiles.

152.85 for insert 2, 95.45 to 172.85 for insert 3 as shown in Fig. 4.1. Thus, close conformance has been observed after comparing all the experimental results with simulation results. It also validates experimental values generated from experimentation for Nu number & f factor in which maximum deviation is limited to 4 % to 5 %.

Again validation takes places for Nu number and f factor experimental readings by numerical technique for without insert through Petukhov Equation and numerical technique for without insert through Dittus–Boelter Equation as mention in equation (25) and (12). While comparing both the data's came from simulation and experimentally in the form of values form different insert shapes and profiles such as without insert tube, insert 2, insert 1 and insert 3 etc, it was noted that simulation readings were coming higher than experimental readings because heat loss occur through the fabricated setup, but simultaneously it has been observed that the obtained error percentage is minimum between simulated readings and experimental readings, which was varying from 3 % – 5 % for suggested profiles. Thus, such condition of % error validates present research work.

It is also observed from the figure number 4.3 that as fluid rate of flow is enhancing from 0.72 to 2.95 L/min, N.T.U readings is showing a decrement from 1.29 to 0.65 for without insert tube, 1.83 to 0.86 for insert 1, 2.15 to 1.10 for insert 1, 2.51 to 1.24 for insert 3. While comparing the readings, it was noted that insert 3 achieved best result as compared with other insert shapes because

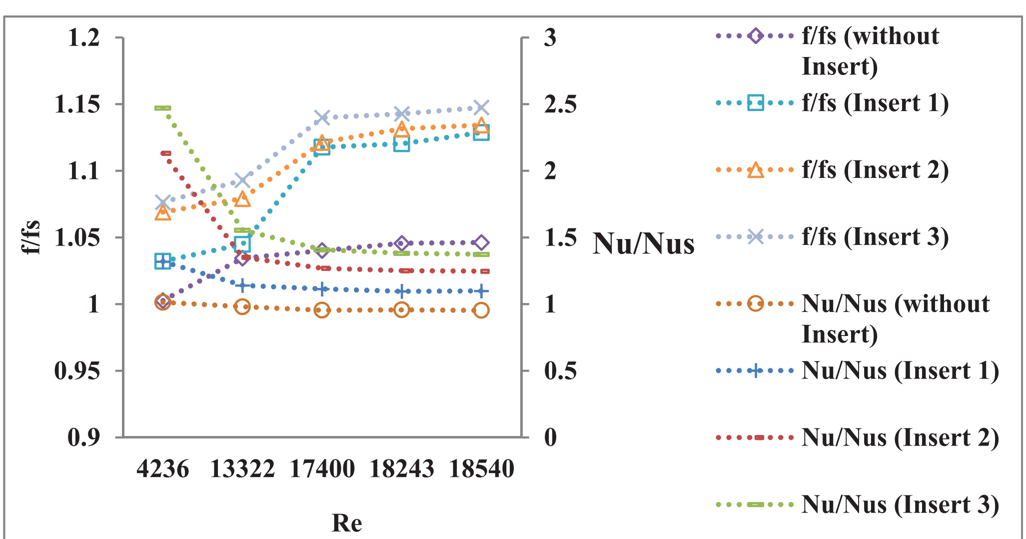

Fig. 4.4. Graphical representation of Thermal Performance Factor and Reynolds Number for different profiles.

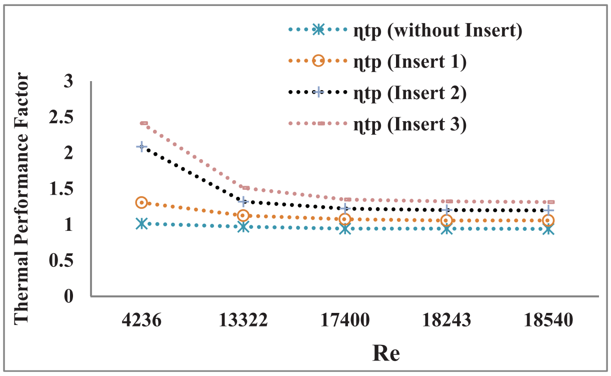

Fig. 4.5. Graphical representation of Nu/Nu_s and f/f_s for different profiles.

insert 3 have larger exposed & contact area, more turbulency occur during fluid flow due to selected pitch i.e. 1 cm than other shapes of macro insert profile and this phenomenon influences the number of transfer unit (NTU). From Fig. 4.2 it was clearly seen that the effectiveness showing decrement because of decrement in temperature drop with an increment range of Re number and on the other hand fluid rate of heat transfer is enhancing because of higher flow rate with range of Re number 4236 to 18545. It has been clearly noticed through figure number 4.5 and 4.4 that as f/fs is enhancing because of high pressure drop and Re number, but Nu/Nus and thermal performance is showing decrement because of temperature drop and flow rate with range of Re number 4236 to18545 but comparing with other insert shape profiles, only insert 3 (helical insert profile) show best and promising results.

5. Conclusions

The experimental and computational study for spiral copper tube exchanger is investigated. The result shows very close agreement between experimental and computational study. The experimental and computational study is performed in different shapes of insert mounted over spiral copper tube heat exchanger. Helical insert gives significant enhancement by 18.5 %, 15.5 %, 11.5 % compared with spiral tube without insert, conical insert and hemispherical shape insert for thermal performance under turbulent-counter flow. The maximum and optimum values obtained from the experimental and computational study for h_{htr}, Nu, f, effectiveness, η_{tp} and N.T.U is 2851.485–2983.092, 138.98–145.58, 0.0328–0.0329 0.672–0.703 and 1.51, 1.42 respectively for Reynolds number ranging 13,322 For helical insert of 2 mm diameter and 10 mm pitch distance. Here, Nu, h_{htr}, is increasing and f, effectiveness, N.T.U. and η_{tp} is decreasing with respect to Reynolds number. The involvement of different insert shapes over spiral tube profile increases the surface area of heat-transfer surface for water. This is because the water particles became more turbulent near the surface area of insert and hence, enhance the transfer of heat.

Data availability

The data that has been used is confidential.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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