Heat transfer studies on double tube heat exchanger with combined effect of propeller insert and water-based GO and Al₂O₃ nanofluids

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Abstract. The combined effect of water-based GO and Al₂O₃ nanofluids and Propeller Turbulator (PT) insert on enhancement in thermal performance of counter-flow double tube heat exchanger is investigated experimentally. Experiments were carried out with a hot water flowrate of Re = 2500 in the inner tube fitted with a propeller insert (Np: 6, 8, 10) and variable flow rates (500 ≤ Re ≤ 5000) of water-based GO and Al₂O₃ nanofluid (vol.%: 0.05, 0.1, 0.15) flowing in the annulus. Experimental results show that, Nusselt number increased by 29.43% and TPF by 1.32 times for tube fitted with 10 propellers and 0.15 vol.% of Al₂O₃ nanofluid. In the conducted combinations, the extreme increase was noted for the higher number of propellers and higher vol.% of Al₂O₃ nanofluid combination, with a slight increase in friction factor. Nusselt number and friction factor correlations were developed and predicted well within −14% to +10% and −10% to +5%, respectively.

Keywords. Augmentation; heat exchanger; nanofluid; passive technique; propeller turbulator; thermal performance.

1. Introduction

In the current scenario of industrial growth, the management of energy is a significant factor to preserve our energy resources. Most of the industries and power plants involved with the heat exchanging device known as a heat exchanger exist in different forms. Based on the application, heat exchangers are available as air-preheater, re heater, evaporator, condenser, boiler, conv ector, radiator, superheater, etc. A more efficient and compact thermal system is essential to exchange heat between two fluid streams efficiently to manage the growing demand and preserve energy resources for our future [1]. In this regard, a DTHE (Double Tube Heat Exchanger) is the most simple and capable heat exchanger ever and is well suited for applications operating at a higher pressure and a wide range of temperatures [2].

By keeping effective utilization of thermal energy and energy savings in mind, finding an efficient method to augment heat transfer is the motivation for comprehensive investigation and progress actions in the predictable future. Thus heat exchangers with effective augmentation techniques will upsurge the heat exchanger performance.

Active, passive and compound techniques [3] were recognized as heat transfer augmentation methods. Active techniques need some external power supply to create the preferred flow variation and enhancement in the heat transfer which involves more difficulties from the usage and design viewpoint. Hence, active techniques have limited application in comparison to the passive techniques. Passive methods commonly use geometrical or surface reforms to the flow path by including turbulators or supplementary devices that cause disturbance to the existing behavior of fluid outcomes greater heat transfer coefficients with a penalty in pressure drop. Similarly, extended surfaces intensify the heat transfer rate due to higher heat transfer area. The advantage of passive techniques over active techniques is that they do not require any external power input. A combination of more than one method in the above-said methods is used in combined techniques, with the intention of further intensification in heat exchanger performance.

Amongst, passive techniques were projected as the best method to enhance thermal performance by its ease of incorporation and are well suitable for DTHE’s without any design modification. Numerous investigations conducted by researchers on heat transfer intensification in a DTHE using several passive augmentation techniques, that using nanofluids and metal turbulators are revealed as the effective techniques [4].
A pioneering approach to improve the thermal conductivity of fluids is to add metallic, non-metallic and polymeric powder into the base fluids viz., water, oils and ethylene glycol to prepare slurries if the added particles are in a nanosize fluid is called nanofluid [5]. The use of nanofluid with very low concentrations retains the stability of particles in the base fluid, no blockage in systems, and a minor penalty in pressure drop. Nanoparticles in the base fluid significantly improve the thermal conductivity of nanofluids [6] resulting in a better heat transfer by convective mode.

The significance of using a metallic turbulator in a heat exchanger tube is to generate swirl and disrupt the fluid wall boundary in the flow path, resulting in intensification of heat transfer [7].

A systematic review of literature on the intensification of heat transfer in DTHE by passive augmentation methods is carried out. A few such studies which are related to this investigation are mentioned here.

Sarafranz et al. [8] investigated experimentally on DPHE using biologically produced nanofluid (vol.%: 0.1, 0.5, 1) using ethylene glycol/water as base fluid under varied flow conditions. The outcomes show that, heat transfer enhanced by 22%, 36%, and 67% respectively for 0.1%, 0.5% and 1% volume fractions. Ravi Kumar et al. [9] investigated a DPHE with return bend in the flow range 15,000 ≤ Re ≤ 30,000 using Fe3O4 nanofluid resulting in improved convective heat transfer and TPF with a slight change in friction factor. Mohammad Hussein Bahmani et al. [10] carried out numerical simulations on heat transfer, thermal efficiency and temperature variations of Al2O3 nanofluid in a DPHE via parallel and counter flow settings, resulting in increased thermal efficiency and Nusselt number by 30% and 32.7%, respectively for counterflow condition. Cong Qia et al. [11] experimented on DTHE with water-based TiO2 nanofluids. The outcomes show that when compared to base fluid, nanofluids of mass fractions (%) 0.1, 0.3, and 0.5 can augment the rate of heat transfer respectively by 10.8%, 13.4%, and 14.8%.

Sheikholeslami et al. [12] experimentally investigated a DPHE on forced convection under turbulent flow with perforated turbulators fitted in the annulus. The results say that thermal performance increases with augmentation, up to 1.59 which is occurred for Re = 6000, Pitch Ratio = 1.06. Deepak Kumar et al. [13] conducted experiments on the intensification of heat transfer through a tube fitted with lanced ring (PR: 3.33-6.66) in the range of 10,000 ≤ Re ≤ 37,754. The outcomes show that Nusselt number and friction factors were varied respectively in the range of 1.69-4.1 and 16-72. Saurabh Yadav et al. [14] conducted investigations on DPHE using a helical surface disc turbulator with varied helix angle and pitch ratios. They found an increased thermal enhancement factor of 1.39 at lower pitch ratios and higher helix angles at Reynolds number 3,500. Adhikrao Patil et al. [15] investigated on tube fitted with a hexagonal ring turbulator (DR: 0.6, 0.7, 0.8 and PR: 1, 2, 3) with a varied Reynolds number range 6,000 ≤ Re ≤ 24,000. The results show that with minimum flow rate hexagonal ring turbulator (DR = 0.8 and PR = 1) agrees a maximum performance factor of 1.34. Rafał Andrzejczyk et al. [16] carried out experiments on U-bend exchanger fitted by wire in the range 800 ≤ Re ≤ 9,000. They compare their results with the literature and show that performance factor of a straight double tube was greater compared to U-bend heat exchanger. Sheikholeslami et al. [17] investigated DPHE with a perforated discontinuous helical turbulator (PR: 1.83-5.83) in the Reynolds number range 6,000 ≤ Re ≤ 12,000. By increasing PR results in a reduction of friction factor, Nusselt number and TPF. Muhammad Mostafa Kamal Bhuiya et al. [18] conducted investigations on tube fitted with helical tapes (TR: 1.88, 3.13, 4.69, 6.41, 7.81) with turbulent flow conditions (7200 ≤ Re ≤ 50,000). Reducing TR yields improved thermal performance with an increase in friction factor.

Ahmet Selim Dalkılıç et al. [19] conducted experimental investigations on tube fitted with quad-channel twisted tape and Graphite-SiO2/Water hybrid nanofluid under turbulent flow range 3,400 ≤ Re ≤ 11,000. The results show the increase in Nusselt number with increased Re and vol.% of hybrid nanofluid. Further improved with an increase in twisted tape length. Durga Prasad et al. [20] investigated experimentally on U-tube fitted with twisted tape (TR: 5-20) using Al2O3 nanofluid (vol.%: 0.01, 0.03) in the range 3000 ≤ Re ≤ 30,000. The outcomes show that increase in Nusselt number by 31.28% and friction factor by 1.23 times with 0.03 vol.% and TR = 5. Eda Feyza Akyürek et al. [21] experimented on a concentric tube heat exchanger with Al2O3 nanofluids (vol.%: 0.4-0.8 and 1.2-1.6) and wire coil turbulators (Pitch: 25 mm, 39 mm) in the turbulent range of 4000 ≤ Re ≤ 20,000. They found that, improvement in Nusselt number with increasing in Re and vol.%. correspondingly tube fitted with a wire coil turbulator slightly increases the pressure drop. Khwanchit Wongcharee et al. [22] carried out investigations on a corrugated tube by using CuO-water (vol.%: 0.3, 0.5, 0.7) nanofluid and twisted tapes (TR: 2.7, 3.6, 5.3) in the Reynolds number range 6,200 ≤ Re ≤ 24,000. The results reveal an upsurge in TPF, heat transfer and friction factor by 1.57, 2.67 and 5.76 times respectively for vol.% = 0.7, TR = 2.7, Re = 6200.

The above research outcomes are evident that scope still exists to find the best passive method on the heat transfer enhancement and performance features of heat exchangers.

The main objective of the present work is to develop a compact double tube heat exchanger used as a heat recovery system with enhanced thermal performance. The specific objective of the research is to boost the thermal performance of heat exchangers by using combined augmentation techniques viz., propeller turbulator and nanofluids for a specified heat load and size of an exchanger. In the present work propeller turbulator is used in the inner pipe (hot fluid) to generate swirl and water-
based Graphene Oxide (GO) and Aluminum Oxide (Al$_2$O$_3$) nanofluids in the outer tube (Cold side) to enhance convective heat transfer. With this combined augmentation technique, the effects of some related parameters on thermal performance characters are investigated.

2. Experimental investigations

2.1 Experimental set up

A DTHE was fabricated to study Nusselt number, friction factor and TPF, using water-based GO/Al$_2$O$_3$ nanofluids and Propeller turbulator. As per ASHRAE standards, an experimental test rig was fabricated and conducted trial runs for the authenticity of reliability/repeatability.

The DTHE test rig (shown in figure 1) was used in the experiments. It comprises a test section (Double tube), two pumps, two stainless steel tanks with a capacity of 30 liters each, two digital flow meters, an electric heater, flow regulating valves, a high-speed stirrer, and a shell and tube heat exchanger for cooling nanofluid. The DTHE is made up of an inner copper tube (ID = 48 mm, OD = 51 mm) and an exterior stainless steel tube (ID = 108 mm, OD = 112 mm), with a total length of 2020 mm. Cotton wool is used to insulate the test area to prevent heat loss. The values at the intake and exit of DPHE were recorded using 4 K-type thermocouples and 4 pressure transducers, and the average surface temperature of the copper tube was read using 10 thermocouples.

Before conducting the experimental runs, the hot fluid flow rate is fixed at Re = 2500, while the cold fluid (water/nanofluid) flow rate is changed between Reynolds numbers 500 and 5000 to imitate the industrial heat exchanger conditions. After the system reached a steady-state, the final readings were taken. The experiment is repeated with and without metallic inserts, with different volume fractions of nanofluids and in combination. Within the test portion, the unaccounted heat loss from the experiments is 9.09%.

2.2 Propeller turbulator

The DTHE’s thermal performance is possible to enhance by effective passive augmentation techniques, generally by incorporating metal turbulator with geometrical external reforms. As a result, the passive method supports increasing convective heat transfer by changing the flow behavior. Thus, for the present study different configurations of Propeller turbulator were fabricated.

Figure 2 shows the stainless steel Propeller turbulator. It consists of propellers of dia 46 mm, blade thickness 1 mm, blade angle 30° and are located at equal distances on the central rod of dia 5 mm and 2020 mm length. The investigation was conducted with varied propeller numbers, viz., 6, 8 and 10 for effective swirl growth.

2.3 Nanofluids preparation and its properties

The idea of nanofluid is derived from the knowledge of dispersion of nanoparticles in a base fluid to improve their thermal performance [23]. Many researchers tried and
shown that nanofluids express enhanced thermal conductivity compared to conventional fluids. Thus, for current investigations, water-based GO and Al₂O₃ nanofluids (30–50 nm) were procured and tested in Particle Size Analyser to access typical particle size in nanofluids, and it results in 50 and 55 nm respectively.

It is significant to prepare Nanofluids by proper mixing, and stabilization of the particles by addition of Polyvinylpyrrolidone (PVP) surfactant to nanofluids and agitated by Ultrasonic sonicator constantly for 30 min subsequently stirred by mechanical stirrer (3000 rpm) for 2 h earlier to the conduction of experiment for all flow conditions. The water-based GO and Al₂O₃ nanofluids were prepared for vol.%: 0.05, 0.1 and 0.15. Figures 3 and 4 show GO and Al₂O₃ nanofluids used for the experimentation.

The following correlations available in the literature were used for the calculation of nanofluid properties at different vol.%: 0.05, 0.1, 0.15 of nanofluids and temperatures, and were used for heat transfer calculations.

Density (kg/m³):
\[
\rho_{\text{nf}} = \phi \rho_p + (1 - \phi) \rho_{bf}
\]

Dynamic Viscosity (N-s/m²):
\[
\mu_{\text{nf}} = \mu_{bf}(1 + 2.5\phi)
\]

Specific Heat (J/kg-K):
\[
C_{\text{nf}} = \phi C_p + (1 + \phi) C_{\text{bf}}
\]

Thermal Conductivity (W/m-K):
\[
K_{\text{nf}} = K_{\text{bf}} \left[ \frac{K_{\text{np}} + (n - 1)K_{\text{bf}} - \phi(n - 1)(K_{\text{bf}} - K_{\text{np}})}{K_{\text{np}} + (n - 1)K_{\text{bf}} + \phi(K_{\text{bf}} - K_{\text{np}})} \right]
\]

Where \( n = 3/w \), in which \( n \) is the empirical shape factor and \( w \) is the sphericity, defined as the ratio of the surface area of a sphere (of the same volume as the given particle) to the surface area of the particle. The sphericity is 1 and 0.5 for the spherical and cylindrical shapes.

The prepared GO and Al₂O₃ nanofluid samples were tested to check the stability (Zeta Potential) of the particles before conduction of the experiments. The Zeta potential values of GO nanofluids were \(-29.2 \text{ mV}, -33.7 \text{ mV}, -38.1 \text{ mV}\) and Al₂O₃ nanofluids were \(-32.2 \text{ mV}, -38.7 \text{ mV}, -43.2 \text{ mV}\) respectively for 0.05, 0.1, 0.15 volume concentrations (%). The prepared GO and Al₂O₃ nanofluid volume concentrations were left 48 hours before measuring zeta potential values. The zeta potential values for all the volume concentrations of both GO and Al₂O₃ nanofluids were between ±20 and ±60 mV. Hence, all the prepared volume concentrations had adequate repulsive force between the particles, leading to reduced particle aggregation and good physical stability of colloidal substances [24].

2.4 Experimental procedure

Experiments are carried out with a constant flow rate (Re = 2500) of water (hot side) and by changing nanofluid (cold side) flow rates (500 ≤ Re ≤ 5000) in the annulus. The stages of experimentation are as follows:

- Preparation and characterization of the water-based GO/Al₂O₃ nanofluids.
- Experimentation using distilled water in the absence of nanofluid and propeller turbulators.
- Experimentation using water-based GO/Al₂O₃ nanofluids (vol.%: 0.05, 0.10, 0.15) alone.
- Experimentation using Propeller turbulator (NP: 6, 8, 10) alone.
• Experimentation based on the combined effect of nanofluid and Propeller turbulator.

2.5 Uncertainty analysis

Uncertainty is important in experimentation because it certifies the validity of measured and investigated values. Table 1 shows the uncertainty associated with measurement devices.

The uncertainty of derived quantities was estimated, according to Kline and McClintock [25] (Refer “Appendix A”). The overall experimental uncertainty is 2.89 ± 0.1%, including 1.91 ± 0.1% uncertainty in Re, 1.01 ± 0.1% uncertainty in h, 1.88 ± 0.1% uncertainty in Nu, 1.01 ± 0.1% uncertainty in f.

2.6 Data reduction

Based on the data obtained from the experimentation, the calculations were done with the following equations to find the Nusselt number, friction factor and TPF for each operating condition.

Reynolds number (Re):

\[
Re = \frac{\rho V d}{\mu}
\]  

Average rate of heat transfer (Q):

\[
Q = \frac{Q_h + Q_c}{2}
\]  

Where Heat loss by the hot fluid

\[
Q_h = m_h c_p (T_{hi} - T_{ho})
\]

Heat gain by the cold fluid

\[
Q_c = m_c c_p (T_{co} - T_{ci})
\]

Logarithmic Mean Temperature Difference (LMTD):

\[
LMTD = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln[(T_{hi} - T_{co})(T_{ho} - T_{ci})]}
\]

Convective heat transfer coefficient (h):

\[
h = \frac{Q_{surf}}{A_{surf} \times (T_s - T_c)}
\]

Nusselt Number (Nu):

\[
Nu = \frac{h d}{k}
\]

Experimental friction factor (\(f_{exp}\)):

\[
f_{exp} = \frac{\Delta P_{exp}}{(L/d) \left(\frac{v^2}{2}\right)}
\]

Thermal Performance Factor (TPF):

\[
TPF = \frac{[Nu/Nu_p]^{1/3}}{[f/f_p]^{1/3}}
\]

3. Results and discussions

Present work intended to find Nusselt number, friction factor and TPF in a DTHE influenced by different vol.% of water-based GO and Al₂O₃ nanofluids with Propeller turbulator. Three trial runs were conducted to establish the repeatability of the tests by changing flow rate of cold fluid. The experimental results are reproducible and trustworthy, as shown in Figure 5.

3.1 Effect on Nusselt number and friction factor using Nanofluid alone

Figures 6(a) and (b) show the effect of water-based GO and Al₂O₃ nanofluids with varied flow rates on Nusselt number and friction factor. Figure 6(a) is evidence that,

Table 1. Uncertainty of measuring instruments.

<table>
<thead>
<tr>
<th>Instrument name</th>
<th>Variable measured</th>
<th>Range</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple</td>
<td>Temperature, °C</td>
<td>0 to 100°C</td>
<td>±0.1</td>
</tr>
<tr>
<td>Flowmeter</td>
<td>Mass flowrate, lpm</td>
<td>0 to 20 lpm</td>
<td>±0.2</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>Pressure drop, mbar</td>
<td>0 to 10 mbar</td>
<td>±0.01</td>
</tr>
<tr>
<td>Power meters</td>
<td>Heat input, Watts</td>
<td>0 to 3000 W</td>
<td>±1</td>
</tr>
</tbody>
</table>

Figure 5. Experimental repeatability.
Nusselt number increased with an increase in vol.%. The maximum increase was 16.53% for 0.15 vol.% of Al$_2$O$_3$-water nanofluid and a lower increase was 6.75% for 0.05 vol.% of GO-water nanofluid, owing to the improved thermal conductivity at higher vol.% of nanofluids, significances in the superior capability of fluid to heat transport [26]. The friction factor gradually decreased by increasing in flow rate and increased with the high viscous nanofluids at higher volume concentrations [27] shown in figure 6(b). This is consistent with the existing literature and hence nanofluids can be used as potential candidates to further augment the heat transfer if used in conjunction with metallic inserts.

Figures 7(a) and (b) show the deviation in relative Nusselt number and friction factor with varied vol.% of water-based GO and Al$_2$O$_3$ nanofluids. The relative Nusselt number (Nu$_{rel}$/Nu$_0$) substantially improved with a rise in flow rate and is more than unity throughout as
shown in figure 7(a), this results in a useful addition to heat transfer augmentation using nanofluids [28]. A jump may be seen in figures 7(a) at Re 3500 and 5000. This is due to the effective swirl, an increasing number of disturbances appear within the flow at the optimum fluid flow velocity, resulting in improved Brownian motion of nanofluid (zig-zag movement of colloidal particles in colloidal solution), which results in better heat transfer and TPF than in the laminar region. Figure 7(b) shows a decreasing trend of relative friction factor ($f_{nf}/f_{d}$) for all vol.% of nanofluids.

3.2 Effect on Nusselt number and friction factor with Propeller Turbulator alone

Figures 8(a) and (b) present the effect on Nusselt number and friction factor by using a Propeller turbulator with distilled water (hot side) in a heat exchanger. The higher
number of propellers (Number of propellers = 10) in the turbulator increases the Nusselt number by 25.78% as shown in figure 8(a). This is due to the growth in swirl divulged to the hot fluid stream results in progressed turbulent intensity, consequently reducing the boundary layer thickness throughout the tube inner surface, resulting in better convective heat transfer throughout the conducted Reynolds number range [29].

Figure 8(b) presents the effect of differently configured Propeller turbulators on friction factors. The friction factor is increased with Propeller turbulator as compared to without turbulator and it is maximum for 10 propellers. This is due to a more fluid interface with turbulator and an inner surface of the tube, restriction to fluid flow and reduced viscosity near the tube surface, swirl growth in the flow path. Correspondingly, the rise in
in pressure drop owing to the interaction of the inertial and pressure forces near the tube boundary [30].

3.3 Effect on Nusselt number and TPF by combined augmentation techniques

The foremost concern of this work is to investigate the combined impact of water-based GO/Al₂O₃ nanofluid and Propeller turbulators on the improvement of DPHE’s thermal performance. Hence, the experiments were carried out with varied vol.% (vol.%: 0.05, 0.1, 0.15) of water-based GO and Al₂O₃ nanofluid used as cold fluid in annulus and Propeller turbulator (N_p: 6, 8, 10) fitted on hot side of heat exchanger.

Figures 9, 10 and 11 present the deviation of Nusselt number and TPF for a conducted range of Re with the combined effect of water-based GO and Al₂O₃ nanofluid (vol.%: 0.05, 0.1, 0.15) and Propeller turbulator (N_p: 6, 8, 10). All the combinations of Propeller turbulator and GO-water/Al₂O₃-water nanofluid fitted to a heat exchanger, increase the Nusselt number and TPF with an increase in Re.

Experiments were conducted for the 6, 8 and 10 number of Propellers in combination with different vol.% of water-based GO and Al₂O₃ nanofluids. Figures 9, 10 and 11 show
that the lowest increase in Nusselt number and TPF was 20.44% and 1.199 for 0.05 vol.% of GO nanofluid with 6 propellers and the highest increase in Nusselt number and TPF was 41.43% and 1.476 for 0.15 vol.% of Al₂O₃ nanofluid with 10 propellers compared to plain tube values. The intensification is maximum with higher number of Propellers when combined with higher vol.% of Al₂O₃ nanofluid.

The above outcomes show that the TPF is increasing with an increase in vol.% of nanofluid, and it is more than unity for Propeller turbulator in combination with both the GO-water and Al₂O₃-water nanofluids. Further, the performance factor improved with an increase in Re, this could be accepted that the Propeller turbulator absorbed heat in the fluid to some extent at the hot side and surplus heat transfer was promising with nanofluid carrying heat by convection from a hot surface.
4. Discussion

Propeller turbulator at hot side cause swirl or secondary flow combined with better mixing of fluid in the flow path, due to this effect, throughout the tube wall boundary layer would be thinner. Consequently tube wall allows more heat to transfer from hot to cold fluid, resulting in better heat exchange [31]. Further, the powerful swirl leading to the flow separation of fluid into multi streams and mixing of fluid, which was caused by the induced centrifugal force and tangential velocity in the flow field could augment heat transfer rate significantly forming an adverse effect to pressure gradient in the radial direction from flow path [32].

Nanofluid in annulus significantly enhanced the heat transfer ability due to the enhanced thermal conductivity of a nanofluid at a higher volume concentration, with a slight pressure drop penalty. The friction factor gradually decreased by increasing in flow rate and increased with nanofluid viscosity at higher volume concentrations [33].

The relative graphs 9, 10 and 11 showed that the thermal performance of DTHE increased with an increase in Reynolds number. The TPF was greater than unity in all the configurations of propeller inserts used, and it improved with increased vol.% of nanofluids. This could be due to the novel combined augmentation technique where the coolant is a nanofluid used in a closed system. Further, the DTHE fitted with combined augmentation techniques yields higher thermal performance than the passive method used alone in the DTHE. Thus, the combined augmentation techniques viz, Propeller turbulator (hot side) and Nanofluid (cold...
side) significantly affected the heat transfer and TPF of DTHE.

5. Development of correlations

The Nusselt number and friction factor correlations were developed using experimental data obtained from DTHE with water-based GO/Al₂O₃ nanofluids (0.05% < φ < 0.15%) and Propeller turbulator (6 < N_p < 10) in the range 500 ≤ Re ≤ 5000. The terms Nusselt number and friction factor were influenced by flow rate, geometry of turbulator and vol.% of nanofluid. Nusselt number, hot side and cold side friction factors can be related to the variables functionally as follows:

\[ \text{Nu} = f_1(\text{Re}, N_p, \phi) \]  \hspace{1cm} (15)

\[ f_{\text{hot}} = f_2(\text{Re}, N_p) \]  \hspace{1cm} (16)

\[ f_{\text{cold}} = f_3(\text{Re}, \phi) \]  \hspace{1cm} (17)

Considering the above functional relationships using regression analysis [34] Nusselt number and friction factor correlations were developed. Figures 12, 13 and 14 show the steps involved in the development of Nusselt number, \( f_{\text{hot}} \) and \( f_{\text{cold}} \) correlations.

Equations (18), (19) and (20) show the developed correlations from the experimental data.

Nusselt number (R\(^2\) = 0.95729):

\[ \text{Nu} = 0.09769(\text{Re})^{0.84386}(N_p)^{0.05280}(\phi)^{0.04812} \]  \hspace{1cm} (18)

Hot side friction factor (R\(^2\) = 0.98958):

\[ f_{\text{hot}} = 8062.00998(\text{Re})^{-1.51982}(N_p)^{0.46472} \]  \hspace{1cm} (19)

Cold side friction factor (R\(^2\) = 0.99885):

\[ f_{\text{cold}} = 25.51192(\text{Re})^{-1.81274}(\phi)^{0.02122} \]  \hspace{1cm} (20)

Developed correlations were tested for their accuracies. Figures 15 and 16 show the % deviation of results obtained by the developed correlations (Predicted) when compared with the experimental results.

From figure 15, it is confirmed that predicted values of Nusselt number with accuracies of −14% to +10% deviation, similarly from figure 16 the predicted values of hot side and cold side friction factors with accuracies of −10% to +5% compared to experimental results. Hence, developed correlation results are fairly converging with the experimental results.

Further, the validation of the developed correlations was made with existing correlations. Assessment of Nusselt number and hot side friction factor values with Khwanchit Wongcharee et al [35] and cold side friction factor values with Ravi Kumar et al [9] and Weerapun Duangthongsuk et al [36] along with the values from the developed correlations (Predicted) and experimentation are presented in figures 17 and 18. Figures show a similar trend and the small deviation could be due to different configurations of propeller turbulators and varied flow conditions.

6. Conclusions

The investigation of experiments on heat transfer, friction factor and TPF in a DTHE fitted with combined passive techniques, like inner tube fitted with Propeller Turbulator (N_p: 6, 8, 10) and water-based GO and Al₂O₃ nanofluid (vol.%: 0.05, 0.1, 0.15) on the annulus. From
the investigation outcomes, the following inferences are summarized.

- Enhancement in Nusselt number and TPF with more propellers and increase in the GO/Al₂O₃ nanoparticles volume concentration.
- The combined augmentation technique results in an increased Nusselt number by 29.43% and enhanced thermal performance of the heat exchanger up to 1.316 times.
- A slight rise in friction factor was noted with a higher number of propellers and higher nanofluid concentration, which is lesser as compared to the heat transfer gain.

Appendix A: Uncertainty calculations

Reynolds number

\[
\frac{U_{Re}}{Re} = \left[ \left( \frac{U}{\rho} \right)^2 + \left( \frac{U_m}{m} \right)^2 + \left( \frac{U_{di}}{d_i} \right)^2 + \left( \frac{U_{\mu}}{\mu} \right)^2 \right]^{1/2}
\]

\[
= \left[ (1 \times 10^{-5})^2 + (2.635 \times 10^{-3})^2 + (0.01388)^2 \right]^{1/2}
= 0.0173 = 1.73%
\]  

Heat transfer coefficient

\[
\frac{U_{ho}}{h_o} = \left[ \left( \frac{U_{Qavg}}{Q_{avg}} \right)^2 + \left( \frac{U_A}{A} \right)^2 + \left( \frac{U_{AT}}{AT} \right)^2 \right]^{1/2}
\]

\[
= \left[ (2.058 \times 10^{-6})^2 + (0.01)^2 + (1.449 \times 10^{-3})^2 \right]^{1/2}
= 0.0101 = 1.01%
\]  

Nusselt number

\[
\frac{U_{Nu}}{Nu} = \left[ \left( \frac{U_h}{h} \right)^2 + \left( \frac{U_{di}}{d_i} \right)^2 + \left( \frac{U_K}{K} \right)^2 \right]^{1/2}
\]

\[
= \left[ (7.281 \times 10^{-5})^2 + (0.01)^2 + (0.0159)^2 \right]^{1/2}
= 0.0188 = 1.88%
\]  

Friction factor

\[
\frac{U_{fc}}{f_c} = \left[ \left( \frac{U_{Re}}{Re} \right)^2 + \left( \frac{U_{di}}{d_i} \right)^2 + \left( \frac{U_{DP}}{DP} \right)^2 \right]^{1/2}
\]

\[
= \left[ (3.46 \times 10^{-5})^2 + (0.01)^2 + (1.904 \times 10^{-2})^2 \right]^{1/2}
= 0.0101 = 1.01%
\]  

Overall uncertainty

\[
U_{Overall} = \left[ \left( \frac{U_{AT}}{AT} \right)^2 + \left( \frac{U_m}{m} \right)^2 + \left( \frac{U_{AP}}{AP} \right)^2 + \left( \frac{U_W}{W} \right)^2 \right]^{1/2}
\]

\[
= \left[ (1.449 \times 10^{-3})^2 + (2.635 \times 10^{-3})^2 + (1.904 \times 10^{-2})^2 \right]^{1/2}
= 0.0289 = 2.89%
\]  

List of symbols

- \( V \) Velocity, m s\(^{-1}\)
- \( d \) Diameter, m
- \( L \) Length, m
- \( T \) Temperature, °C
- \( C_p \) Specific heat, J kg\(^{-1}\)K\(^{-1}\)
- \( Q \) Heat transfer
- \( K \) Thermal conductivity, W m\(^{-1}\)K\(^{-1}\)
- \( h \) Heat transfer coefficient, W m\(^{-2}\) K\(^{-1}\)
- \( Re \) Reynolds number
- \( Nu \) Nusselt number
- \( Pr \) Prandtl number
- \( f \) Friction factor
- \( \Delta P \) Pressure drop, bar
- \( N_p \) Number of propellers
- \( U \) Uncertainty
- \( n \) Sample size

Greek/Roman/Latin Letters

- \( \rho \) Density, kg m\(^{-3}\)
- \( \mu \) Dynamic viscosity, kg m s\(^{-1}\)
- \( \phi \) Volume concentration
- \( \sigma \) Standard deviation
References


