Optimization on heat-transfer coefficient of plate heat exchanger using MWCNT-TiO₂ nanofluid by response surface methodology

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Abstract
In this present study, MWCNT-TiO₂ hybrid nanocomposite synthesized by solvothermal synthesis method with TiCl₄ as a precursor. Then the hybrid nanocomposite based nanofluid produced using base fluid water/Ethylene-glycol (50:50). The microscopic techniques like SEM, TEM and XRD were used to characterize the morphological studies of synthesized MWCNT-TiO₂. The heat-transfer coefficient of synthesized nanofluid inside the Plate Heat Exchanger (PHE) has experimented at selected levels of particle concentrations, inlet temperature and volume flow rate by RSM based Box-Behnken method. The findings revealed a more substantial linear effect at the heat-transfer coefficient of MWCNT-TiO₂ hybrid nanofluid by chosen process parameters. ANOVA results showed that the heat-transfer coefficient of hybrid nanofluid considerably enhanced at a selected higher level of particle concentration and volume flow rate of the MWNCT-TiO₂ hybrid nanofluid. At the same time, the heat-transfer coefficient decreased at a higher level of inlet temperature of MWNCT-TiO₂ hybrid nanofluid. The optimization result compared with the confirmatory experiments, and it yielded less than 1% error which ensures a better agreement with the predicted results.

Introduction
The liberation of enormous heat from the electronic applications in the range of macro to microsystems has become a critical issue and also affecting gadgets performance severely. In particular, semiconductor chip systems like laptops, cell phones, due to their increased power density, have faced this typical challenge. Consequently, the management of thermal energy discharge has become essential to protect the equipment against damages that are not reparable. Plate heat exchangers (PHE) and tubular heat exchangers (THE) devices deployed in numerous microelectronic and electronic cooling applications [1]. PHE is well established for the cooling of electronic equipment where space, coolant and external pumping are restricted since there is no external pumping required for the circulation of coolants and further cooling takes place through evaporation of the working fluid [2]. In the past decade, heat-transfer base fluids such as water, ethylene glycol (EG) and metallic fluids were generally used as a working fluid [3] in many industrial applications. However, they lack thermal properties due to their suspension properties due to clogging of micro-sized particles [4]. Due to instability and surface properties, sedimentation of these micro-range particles induces channel blockage [5]. The PHE’s thermal strength depends upon the working fluid’s thermal properties. Moreover, the thermal and rheological properties of operational fluids were more critical to improving the heat transfer performance of heat exchangers [6]. The thermal stability and non-settling of nanofluids from nanoparticles over week or months thus preferred over traditional thermal transfer fluids under fixed conditions [7]. Compared to normal liquids, the nanofluids provide an increased heat-transfer rate. Working nanofluid’s heat-transfer rate depends on significant factors of rheological properties [8]. These nanofluids dispersed inside the different base fluids like water, EG for proper nano-sized particle suspensions [9]. Nanoparticle size, formed shape, added volume fraction and particle concentration have performed a significant part in enhancing nanofluid heat-transfer properties by stabilizing the rheological character [10, 11]. Nanofluid solid nanoparticles have the efficiency of
quick settlement from suspension and clogging within the small transport channels. It is, therefore referred to as heat-transfer nanofluids with better thermal conductivity and physical stability from a device perspective [12]. The nanofluids were used to fabricate by two step method, which considered being highly successful in metallic nanoparticles [13]. The various kinds of surfactants and sonication time were also critical in predicting the thermal stability of the nanofluids.

Hussein et al [14] synthesized two metallic nanofluids of heat transfer such as SiO$_2$/water as well as TiO$_2$/water, and then tested inside the radiator of a car. The findings indicated an enhancement of heat-transfer by increasing flow rate, inlet temperature and nanoparticles concentration. Farajollahi et al [15] analyzed the influence of Pecllet number, the particle fraction of suspended TiO$_2$ nanoparticle, and its fluid characteristics on tubular heat exchangers. Sundar et al [16] examined the hybrid nanofluids of MWCNT–Fe$_3$O$_4$ for application of heat exchanger, and the results revealed that heat transfer was directly proportional to particle concentration whereas Reynolds number at 2200 of nanofluids. Overall, the outcome showed that the maximum thermal conductivity attained at higher volume percentage and temperature. Madhesh et al [17] investigated copper and titanium–dioxide based hybrid nanofluid for the improved performance of the heat-transfer coefficient in tubular based heat exchanger system. The results revealed that the heat-transfer coefficient drastically enriched with a higher volume percentage of synthesized bimetallic nanofluid concentration.

Thierry Maré et al [18] studied thermal convective transfers of CNT nanofluids inside the PHE. The results revealed the occurrence of convective coefficient under the lower temperature of 2 °C–10 °C. Sarafraz and Hormozi [19] developed smaller fouling resistance on MWCNT based nanofluids to carry out pressure drop analysis, and it enhanced the coefficient of heat transfer drastically than any other nanofluids.

Esfe et al [20] studied heat-transfer efficiency of Al$_2$O$_3$–MWCNT nanoparticles based oil lubricant by varying different temperatures and volume concentrations as well as found that increasing both temperature and concentration increased the heat-transfer ratio. The findings of this study show that temperature and particle concentration improve thermal characteristics. Nafchi et al [21] conducted studies on thermal conductivity of Titanium Dioxide and Zinc Oxide based bimetallic nanofluid dispersed inside ethylene glycol as a base liquid and the results inferred that, thermal conductivity was directly proportional to volume concentration and given solution pH. Hemmat Esfe et al [22] analyzed the thermal conductivity of single-walled CNT–MgO/water–EG nanofluids at various inclined temperatures and solid concentration. The outcome proved that the relative thermal conductivity was maximized with higher particle concentration and higher temperature. Dong et al [23] analyzed the effects of uniform cluster orientation and phonon on thermal conductivity of the ferrofluids under the influence of the magnetic field. The results show that the anisotropic thermal conductivity in ferrofluids was induced by anisotropic thermal conductivity in clusters.

In this present study, MWCNT–TiO$_2$ nanocomposite was synthesized using the solvothermal method, and the heat-transfer coefficient inside a plate heat exchangers (PHE) was investigated. Experiments were performed using the RSM model to find the significant process parameters dominantly influencing the heat-transfer coefficient of prepared novel MWCNT–TiO$_2$ nanocomposite based nanofluids inside the PHE for better thermal transfer performance.

**Synthesis of MWCNT–TiO$_2$ nanocomposite**

MWCNT was purchased from Sigma Aldrich followed by the purity testing by characterization. Titanium chloride (TiCl$_4$), Nitric acid (HNO$_3$), Sulfuric acid (H$_2$SO$_4$) and Ethanol are the other materials utilized in this synthesis process. The MWCNT–TiO$_2$ hybrid nanoparticles were synthesized using TiCl$_4$ as a precursor by solvothermal method. Based on the molarity calculation, TiCl$_4$ was mixed into the ethanol/water (50:50) mixed base fluid and stirred continually up to get the completely transparent yellow solution. Then, selected amounts of MWCNT were dissolved inside the prepared solution followed by an ultrasonic bath for 60 min. Finally, the solution was transferred into the autoclave and kept at 160 °C for 12 h. Then, dark ash precipitate was obtained. The precipitous particles were centrifuged thoroughly using deionised water to remove impurities. Then the obtained material is calcinated at different temperatures for 3 h in order to produce the MWCNT–TiO$_2$ hybrid nanoparticles. Figure 1 shows the microstructural analysis of the MWCNT–TiO$_2$ hybrid nanoparticles using TEM and SEM. From SEM analysis, MWCNT nanoparticles and TiO$_2$ particles are clearly visible without any separate heaping which results in proper dispersive interaction. Figure 2 shows the XRD pattern of the MWCNT–TiO$_2$ hybrid nanoparticles. XRD pattern confirmed that there is no distorted peak which insures fewer impurities.

**Synthesis of MWCNT–TiO$_2$ nanofluids**

A two-step synthesis process was used to produce a nanocomposite based nanofluid. MWCNT–TiO$_2$ with three different particle concentrations was used inside the base fluid water/EG (50:50), then it is placed inside
the ultrasonic device for more than 6 h at optimal frequency and power. The nanofluid samples were kept for proper stability and deposition under a specific duration before investigating the heat-transfer coefficient experiments.
Analysis of heat-transfer coefficients

Heat-transfer coefficient of nanofluid examined using the following experimental setup [24], and it was shown in figure 3.

The operating temperature of PHE is around 196 °C–204 °C and maximum operating pressure of 33 bar. The Plate thickness of PHE is 0.6 mm, and the total area of heat-transfer 0.16 m². The stainless steel made storage tank was used to prevent corrosion. The tank was made of twin sheets of glass wool with some space between them to prevent loss of heat. To heat the nanofluid, 2 kW heater was installed into the storing tank. Due to the solvent movement within the exchanger, precipitation of nanoparticles is bleak because of the mixture. Four RTD PT-100 probes find the inlet channel and outlet passage temperatures of all streams. Two rotameters controlled the nanofluid and the cold water flow rate. The flow rate for nanofluid varied between 2 and 4 LPM, whereas in all tests, the flow rate for the cold stream was 1 LPM. The minimum nanofluid needed for setup is 800 ml. Typically, a performed test lasted around 60 min. The steady-state conditions were achieved by using the nominal time interval in this system. The temperatures were tracked continuously to define if the system attained its steady-state limits. The real-time data utilized to calculate the heat transfer coefficient of given nanofluids [24]. The Reynolds number of cold water was estimated using the passage channel’s mass velocity and hydraulic diameter as follows

\[ Re_w = \frac{G_w D_h}{\mu_w} \]  \hspace{1cm} (1)

Where \( D_h = 2b_c \) is the diameter of channel. The channel velocity (\( G_w \)) mass was obtained from the following relation:

\[ G_w = \frac{m_w}{n_{ch} b_c W} \]  \hspace{1cm} (2)

Where \( n_{ch} = 3 \)—cold and, \( n_{ch} = 2 \)—hot stream, correspondingly.

The heat was removed by nanofluids, and the cold water, \( Q_c \), calculated by the recorded temperature and overall mass flow rate using equation (3).
Estimation of fluidic properties at bulk temperatures are denoted as:

\[ T_{b,c} = \frac{T_{c,i} + T_{c,o}}{2} \]  

Nusselt number of cold fluid was obtained by,

\[ Nu_c = 0.455 \; Re_c^{0.66} Pr_c^{0.33} \]  

The constructor obtains such values from standardizing the exchanger’s water. The number of Prandtl set as follows:

\[ Pr_c = \frac{\mu C_p}{k} \]  

The cold stream (water) heat-transfer coefficient was analysed by,

\[ h_c = \frac{Nu_c \; D_h}{k} \]  

The performed real-time experimental values found the heat-transfer coefficient as:

\[ U = \frac{Q_c}{A.F. \Delta T_{LMTD}} \]  

Where \( A \) = Over-all heat-transfer area of the PHE and \( F = \) correction factor of temperature while the counter current flow at 1.

\[ \Delta T_{LMTD} = \frac{(T_{nf,i} - T_{w,o}) - (T_{nf,o} - T_{w,i})}{\ln \left( \frac{(T_{nf,i} - T_{w,o})}{(T_{nf,o} - T_{w,i})} \right)} \]  

The heat-transfer coefficient of synthesized nano fluids was measured by overall heat transfer coefficient inclusive of heat-coefficient of a water stream. Finally, heat transfer coefficient nano fluid was obtained from the following relationship; where \( k \) is the plate’s thermal conductivity, \( k '\) where \( \Delta x \) is its thickness,

\[ h_{nf} = \left( \frac{\Delta T_{LMTD}}{U} \right) - \left( \frac{\Delta T_{LMTD}'}{h_w} \right) - \frac{\Delta x}{k} \]  

The typical photograph of the nanofluid before and after the experiments is shown in figure 4.

**Experimental design by using response surface methodology**

Response surface methodology (RSM) is one of the best-suited techniques for empirical optimization, which evaluates the relationship between input factors and experimental outputs (responses). Box-Behnken Design
factorial method is one of a combination of RSM techniques, and it can be used as an alternative method of convectional factorial design because BBD could reduce the higher number of experimental runs as well as determine the consistency of the input parameters on the experiments.

Table 1 represents the coded and un-coded variables with lower and higher levels of three factors. Following equations described the relationship between coded and un-coded variables:

\[
m_1 = \frac{(A_1 - 50)}{10} \quad (11)
\]

\[
m_2 = \frac{(A_2 - 0.06)}{0.03} \quad (12)
\]

\[
m_3 = \frac{(A_3 - 3)}{1} \quad (13)
\]

Where, \(A_1, A_2, A_3\) were un-coded and \(m_1, m_2, m_3\) were coded variables, respectively [25]. It is clearly stated that the coded variables factors were dimensionless, whereas un-coded factors have their units. The quadratic model (equation (14)) were used to study the effects of those variables of on heat transfer coefficients.

\[
\beta = v_0 + \sum_{i=1}^{n} v_i \chi_i + \sum_{i=1}^{n} v_i^2 \chi_i^2 + \sum_{i<j}^{n} v_{ij} \chi_i \chi_j \quad (14)
\]

Let \(\beta = \) responses (Heat-transfer coefficient) and \(v_{00}, v_i, v_{ij}\) = offset term, linear, quadratic and interactive effects. While, \(\chi_i\) and \(\chi_j\) were independent as well as coded variables [26, 27].

RSM suggested second-order quadratic fit model to the obtained response and the predicted results with actual experimentation results were shown in table 2. Design-Expert software version 10 was used to find the statistical summary for each fitted model, which is shown in table 3. Statistical summary suggested quadratic model as a best-fitted model. ANOVA analysis was carried out to analyse the linear, quadratic and interactive effects of each process parameters towards output response which is shown in table 4.
The model $F$—value was obtained at 154.34, implies that this model was significant. Further, it was just 0.01% chances for large $F$ value and due to noise it could have happened. Also, the obtained $P$-values (<0.05) shown that model terms such as $A$, $B$, $C$, $B^2$, $C^2$ were significant.

The predicted $R^2$ value was obtained at 0.9198, which was in reasonable agreement with the value of adjusted $R^2$ (0.9885), which means the difference was less than 0.1, as shown in table 5. The signal to noise ratio was measured by Adeq precision, whereas the ratio greater than four was desirable. In this model, we obtained the ratio of 42.6530 specifies an adequate signal.

The estimated coefficient represents the expected change in response per unit change in each factor value, while all remaining factors were kept constant. The coefficients differ around this average which depends on the process parameter settings of the component. The factors were orthogonal, which means that VIFs were obtained at 1. In such case, VIFs were greater than 1, which suggest that multi-collinearity factors, while higher value VIFs cause factor correlation in the model as shown in table 6. The model can be conceived after determining the importance of each parameters by removing the least performing significant terms. Finally, the regression equation (equation (15)) of this model was to define the relationship between time, speed and concentration of the given feed.

\[
\text{Heat transfer Coefficient} = 1.33176 + -0.002995 \times A + -1.33875 \times B \\
+ -0.0066125 \times C + 0.00641667 \times AB + -2.25e - 05 \times AC \\
+ -0.0466667 \times BC + 1.05e - 05 \times A^2 + 13.3611 \times B^2 + 0.003325 \times C^2
\]  

(15)

Despite the fact, the value of $R^2$ was found at 91.98 which was decreased marginally, while the $R_{adj}^2$ was calculated at 98.85, which inferred that determining the fit of the regression model was considered being one of the most crucial factor in the analysis. In this case, $R^2$ was changed from 91.98 to 92.44. In addition, $P$-value was <0.001 which represents the more significant effect on this model.

### Table 3. Statistical summary.

| Sources        | P-value | $R^2$      |
|----------------|---------|------------|
|                | Sequential | Adjusted | Predicted |
| Linear         | <0.0001 | 0.8181 | 0.7481 |
| 2FI            | 0.9544  | 0.7708 | 0.5032 |
| Quadratic      | <0.0001 | 0.9885 | 0.9198 | Suggested |
| Cubic          | <0.0001 | 0.9999 |

### Table 4. Heat-transfer coefficient results by using ANOVA.

| Sources       | Sum of squares | Mean square | Degree of freedom | F-value | $P$-value |
|---------------|----------------|-------------|-------------------|---------|-----------|
| Model         | 0.0050         | 0.0006      | 9                 | 154.34  | <0.0001  | Significant |
| $A$—Inlet temperature | 0.0021   | 0.0021      | 1                 | 592.31  | <0.0001  |
| $B$—Particle concentration | 0.0014   | 0.0014      | 1                 | 399.29  | <0.0001  |
| $C$—Volume flow rate | 0.0007   | 0.0007      | 1                 | 198.12  | <0.0001  |
| $AB$         | 0.0000         | 0.0000      | 1                 | 4.14    | 0.0813    |
| $AC$         | $2.025 \times 10^{-7}$ | $2.025 \times 10^{-7}$ | 1             | 0.0566  | 0.8188    |
| $BC$         | $7.840 \times 10^{-6}$ | $7.840 \times 10^{-6}$ | 1             | 2.19    | 0.1823    |
| $A^2$        | $4.642 \times 10^{-6}$ | $4.642 \times 10^{-6}$ | 1             | 1.30    | 0.2921    |
| $B^2$        | 0.0006         | 0.0006      | 1                 | 170.19  | <0.0001  |
| $C^2$        | 0.0000         | 0.0000      | 1                 | 13.01   | 0.0087    |
| Residual     | 0.0000         | $3.577 \times 10^{-6}$ | 7             |         |           |

### Table 5. Fit statistics.

|                     |           | $R^2$ | Adeq Precision |
|---------------------|-----------|-------|----------------|
| Standard deviation  | 0.0019    | 0.9950|                |
| Mean value          | 1.20      | 0.9885|                |
| Coefficient of variation (C.V)% | 0.1574    | 0.9198|                |
|                     |           |       | 42.6530        |

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Accuracy check of prescribed model

An accuracy check was inevitable for obtaining an ample model; the accuracy was obtained by comparing the experimental and predicted results of heat transfer coefficients. Figure 5(b) depicts that the linear relationship between predicted and real time measured heat-transfer coefficient. Furthermore, normal plot of residuals was
also plotted (figure 5(a)) between the externally studentized residuals versus normal probability (percent). These data of residuals could be used to extend the assumptions of ANOVA’s model. In addition, the standard deviations of predicted and experimental values were calculated by using externally studentized residuals. The prediction and run number of the externally studentized residuals were shown in figures 5(c) and (d).

**Influence of process parameters on the heat-transfer coefficient**

Figure 6 shows the deviations on heat transfer coefficients of MWCNT-TiO₂ nano-fluid at various levels of inlet temperature and various levels of particle concentration. As shown in figure 6(a), the 3D graph depicts that the heat-transfer coefficient was directly proportional to the weight fraction of nanoparticles and inversely proportion to the inlet temperature. The accumulation of nanoparticles increases the particle collisions and interactions at persistent volume flow rate. The penetration of nanoparticles and the relative motions near the wall plates can also increase the transfer of heat. Figure 7 shows the heat transfer coefficient variations of MWCNT-TiO₂ nano-fluid at various levels of temperatures and volume flow rates at constant particle concentration. The heat-transfer coefficient of MWCNT-TiO₂ nano-fluid increased with decrease in the inlet temperature. The reason behind the decrease in the heat-transfer coefficient of the nano-fluid with increasing
the nano-fluid inlet temperature is due to the quick alignment of nanoparticles in lower viscosity fluids, which does not provide enough contact between nanoparticles. Figure 8 shows the variations of the heat-transfer coefficient of MWCNT-TiO$_2$ nanofluid at different volume flow rates with different particle concentrations at constant inlet temperature. At a constant inlet temperature, higher particle weight concentration of nanoparticles and a higher flow rate of nanofluids cause a more exceptional heat-transfer coefficient ratio. Although the flow rate of nanofluids increases the effect of collision with nanoparticles on the surface of the wall, which elevates the temperature. The result of this investigation nanofluid coefficient ratio showed that the coefficient heat-transfer ratios of nanofluids are significantly increasing.

After finding out the interaction among the process parameters, the numerical optimisation was performed to maximise the heat-transfer coefficient of the nanofluids from the selected level of inputs. The desirability of 1.00 obtained for the process parameter inlet temperature, nanoparticle concentration and volume flow rate with the response of maximised heat-transfer coefficient, as shown in figure 9.

The optimized results with the process parameters and its levels from the solution for heat-transfer coefficient were shown in table 7.

From the optimized results, the selected input parameters were taken into consideration for the confirmatory experiments, and it performed parclose to the predicted results. The error percentage between the
predicted and experimental results just under 1%, and it is enough evidence to prove that the predicted model holds a good agreement with the performed real-time results which validates the significance of RSM model.

**Conclusion**

MWCNT-TiO$_2$ nanocomposite based nanofluids has revealed its better heat transfer characteristics for their application inside the PHE. The heat-transfer coefficient of a nano-fluid inside the plate heat exchanger was analyzed using the design of experiments developed from RSM based Box-Behnken design which are essential to improve the influence of process parameters. The experiments were done with the selected levels of volume flow rate, nanoparticle concentration, and inlet temperature of the nanofluid to find the optimal process parameters towards the better heat-transfer coefficient. From the results, it is evident that the heat-transfer coefficient increased with an increase in particle concentration and volume flow rate of the MWCNT-TiO$_2$ nano-fluid. At the same time, a decrease in inlet temperature increases the heat-transfer coefficient of the hybrid nanofluid. Even though there are very less interactive effects among the parameters, but individually all the parameters significantly contributed towards the heat-transfer coefficient of MWCNT-TiO$_2$ nanofluid inside the PHE.

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