Enabling Taguchi method with grey relational analysis to optimize the parameters of TiO$_2$/ZnO heat transfer nanofluid for heat pipe application

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Abstract

Our previous work demonstrated that the TiO$_2$/ZnO (1:1) nanocomposite suspended in ethylene glycol with CTAB (0.5 ml) as surfactant exhibits better heat transfer property than TiO$_2$ and ZnO nanofluid. As an extension, the influence of parameters such as wt.% of ZnO Nps in TiO$_2$/ZnO nanocomposite (0 wt.%, 25 wt.%, 50 wt.%, and 100 wt.%), the quantity of CTAB (250 $\mu$l, 500 $\mu$l, 750 $\mu$l, and 1000 $\mu$l) and vol.% of TiO$_2$/ZnO nanocomposite (1 vol.%, 2 vol.%, 4 vol.%, and 8 vol.%) are analyzed through Taguchi design constructed with L16 orthogonal array is emphasized in the present work. As per the Taguchi design, the responses such as viscosity, thermal conductivity, and normalized height % for the set of input parameters are evaluated. Besides, the multiple responses are graded employing Grey relational analysis and the optimum set of parameters to achieve the preparation of the best nanofluid is identified as 25 wt.% ZnO, 1 vol.% nanocomposite and 500 $\mu$l CTAB which display viscosity of 0.043 Pa.s, thermal conductivity of 0.35 Wm$^{-1}$K$^{-1}$, and normalized height % as 1%. Further, the optimal TiO$_2$/ZnO nanofluid is used as working fluid in heat pipe and compared its results with ethylene glycol. From the calculated thermal resistance and heat transfer coefficient values, the TiO$_2$/ZnO nanofluid outperforms the base fluid in a significant manner.

1. Introduction

In the past few decades, owing to the enormous industrial growth put forth numerous devices into the commercial market. In this context, the industries are trying to improve the durability and stability of the devices which majorly depends on the heat generated from the device [1]. As the devices are becoming more advanced with multitasking skills, the heat generation cannot be controlled. Therefore, to improve the heat dissipation generated from the devices, the heat transfer assembly is introduced [2]. The heat pipe is one of the heat transfer assemblies which possess applications in the areas such as spacecraft [3], nuclear power station [4], high performance computer systems [5], electric vehicles [6], etc. The heat pipes consist of working fluid that transports the heat energy from one end to the other through evaporation and condensation of the fluid [7]. Generally, the heat dissipation property of the heat pipe primarily dependent on the thermal conductivity of the fluid. In this context, researchers are trying to improve the thermal conductivity of the working fluid by suspending inorganic impurities and proved to possess better heat transfer ability than base fluid. As the present decade focuses on the technological advancements through nanotechnology, research related to nanofluids i.e. dispersing inorganic nanoparticles as supplement to improve the heat conducting behaviour of the working fluid is on a rise [8]. As the surface to volume ratio of the nanoparticles is at its peak, the heat transfer rate is drastically improved resulting in better cooling performance [9]. Apart from better heat transfer capability, nanofluids offer durability, necessary viscosity, homogeneity, etc [10, 11]. The heat transfer ability of the nanofluid primarily depends on the intrinsic nanomaterial properties such as density, specific heat capacity, and thermal conductivity [12]. So, the properties of the nanofluid can be tuned as per the requirement by selecting
the appropriate materials in a single phase or combinations. Ali et al. [13] developed nanofluid by dispersing ZnO nanoparticles in water and achieved improvement in heat transfer rate by 46% when compared to water. Nabil et al. [14] studied the hybrid nanofluid comprising TiO2 and SiO2 nanoparticles suspended in water and ethylene glycol mixture. Further, the hybrid nanofluid poses 45.9% higher heat transfer coefficient than the base fluid. Like the intrinsic property of the nanoparticles, the percentage of nanoparticles that are suspended in the working fluid also plays a major role in the heat transfer rate. Asadi et al. [15] studied the influence of concentration of ZnO nanoparticle and MgO nanoparticle suspended in engine oil for heat transfer performance. From the results, it is clear that the heat transfer performance is improved when the concentration of nanoparticles is increased. Likewise, Suganthi et al. [16] also obtained similar results where the ZnO nanoparticle concentration in the nanofluid tends to improve the heat transfer property making them a suitable approach to achieve better performance. However, the increase in nanoparticles content in the fluid facilitates sedimentation process due to high probability of particle collision [17]. Further, the sedimentation results in congestion that deteriorates the practicality of the nanofluid. The sedimentation of the nanoparticles is usually avoided by adding a suitable surfactant that improves the surface charge of the nanoparticles facilitating electrostatic repulsion [18]. The electrostatic repulsion is deliberately introduced resulting in restless nanoparticles. However, from the work of Li and Peterson [19], it is clear that the rate of improvement in thermal conductivity of the CuO and Al2O3 nanofluids are declined when volume concentration is higher than 6%. They have also stated that there is no occurrence of sedimentation in the nanofluid facilitated by the ultrasonication process. Therefore, the reduction in thermal conductivity may be due to the attainment of near saturation point where further increase in nanoparticle content does not improve the thermal conductivity. In our previous literature [20], the thermal conductivity of ZnO nanoparticles, TiO2 nanoparticles, and TiO2/ZnO (1:1) nanocomposite dispersed in ethylene glycol is estimated and concluded that TiO2/ZnO nanofluid exhibits better heat transfer characteristics than ZnO nanoparticles and TiO2 nanoparticles. However, from the above discussions, it is clear that three parameters such as nanomaterial composition, use of surfactant, and nanomaterial concentration play vital roles in the stability and thermal conductivity of nanofluids.

In this context, in the present work Taguchi design with Grey relational analysis is utilized to optimize the input parameters such as wt.% of ZnO, the quantity of cetyl trimethyl ammonium bromide (CTAB-surfactant) and vol.% of TiO2/ZnO in nanofluid and experimentally recorded the output responses such as viscosity, thermal conductivity, and normalized height %. Besides, the performance of optimal nanofluid is accessed by evaluating the thermal resistance and heat transfer coefficient by using it as working fluid in a heat pipe.

2. Material and methods

2.1. Preparation of ZnO nanoparticles

As per the procedure provided in the literature [20], the precipitation technique is used to prepare ZnO nanoparticles. Briefly, 100 ml distilled water containing 0.02 M of zinc acetate is added with 0.02 M of sodium ammonium oxalate with continuous stirring. The pH of the above solution is increased to 10 by adding ammonia which leads to the formation of white zinc oxalate. The precipitate is filtered, washed, dried, and calcinated at 700°C to obtain ZnO nanoparticles.

2.2. Preparation of TiO2 nanoparticles

TiO2 nanoparticles are prepared using the precipitation technique as mentioned in the literature [20]. 100 ml isopropyl alcohol containing 0.02 M titanium (IV) chloride is added with distilled water in a dropwise manner resulting in the formation of a white precipitate which is filtered, washed, dried, and calcinated at 700°C to obtain TiO2 nanoparticles.

2.3. Preparation of nanocomposite

The dry ball milling approach is used to prepare TiO2/ZnO nanocomposite where the suitable quantity of TiO2 nanoparticles and ZnO nanoparticles are taken and milled at 300 rpm. The ball milling is carried out for 1 h with 5 min interval at each 15 min. After the ball milling process, the nanocomposite is collected and stored in the vacuum.

2.4. Preparation of nanofluids

The nanofluids are prepared as per the experimental design constructed using Taguchi L16 orthogonal array. The input parameters that are considered here are wt.% of ZnO in TiO2/ZnO nanocomposite, the quantity of CTAB, and vol.% of TiO2/ZnO in the nanofluid. Here, wt.% of TiO2 and ZnO is involved for the preparation of TiO2/ZnO nanocomposite as vol.% may affect the repeatability of the experiment owing to the poly-disperse nature of the nanoparticles. In contrast, the nanofluids are prepared using vol.% since calculation using wt.%
may lead to incomparable results. This is due to the fact that the density of TiO₂ and ZnO are different. The quantity of CTAB that are used for the preparation of nanofluids are varied where the stock solution consists of 1 M conc. of CTAB. Table 1 shows the input variables with different levels that are utilized for the construction of the L16 orthogonal array for the preparation of nanofluids using Minitab software.

For the preparation of nanofluids, the suitable composition of the TiO₂/ZnO nanocomposite in required vol.% is added to ethylene glycol. Subsequently, the required quantity of CTAB is added along with the above suspension and subjected to the stirring process. After the stirring process, the fluid is ultra-sonicated to obtain an evenly distributed nanoparticle suspension ready for the heat transfer performance evaluation. The constructed L16 orthogonal array is tabulated in table 2 using which the responses such as thermal conductivity, normalized height, and viscosity of the nanofluid are determined experimentally. The other parameters such as operating temperature (90°C) and nanocomposite preparation conditions are fixed as constant. In the present work, the accurate thermal conductivity of the nanofluids is measured using the transient hotwire method. Higher thermal conductivity is required for better heat transfer performance of the nanofluid. The viscometer is used to estimate the viscosity of the nanofluid. The viscosity of the nanofluid consistently rely on the vol.% of suspended nanoparticles. However, the increase in viscosity hinders the heat transfer rate since the flow rate of high viscous fluid is low. It is also reported that the increase in viscosity is attributed to the sedimentation of the nanoparticles and if the improvement in viscosity is four times larger than the relative improvement in thermal conductivity then the nanofluid perform worse than the base fluid [21]. Therefore, keeping the viscosity at a reasonable value is essential for the better performance of nanofluids. The normalized height elucidates the sedimentation process which is evaluated using the expression [22],

\[
\text{Normalized height\%} = \frac{\text{height of the sediment}}{\text{total height of the fluid}} \times 100
\]  

The normalized height is evaluated after keeping the nanofluid for 15 days without any disturbances. Evaluating the normalized height is important since sedimentation leads to cake formation at the bottom which is very difficult to re-suspend under operating conditions [22]. For accurate results, the experiments are performed in triplicate. For better heat transfer performance of the nanofluid, thermal conductivity should be larger, the viscosity should be minimum, and normalized height % should be minimum. Therefore, the set of

### Table 1. Input factors and their levels for nanofluid preparation.

| Factor       | Symbol | Units | Level 1 | Level 2 | Level 3 | Level 4 |
|--------------|--------|-------|---------|---------|---------|---------|
| ZnO %        | Z      | Wt.%  | 0       | 25      | 50      | 75      |
| Volume % of TiO₂/ZnO | V      | Vol.% | 1       | 2       | 4       | 8       |
| CTAB         | C      | μl    | 250     | 500     | 750     | 1000    |

### Table 2. Experimental design for L16 orthogonal array and the experimental output.

| Sl. No | Z (wt.%) | V (vol.%) | C (μl) | Viscosity (P.s) | Thermal Conductivity (Wm⁻¹K⁻¹) | Normalized Height(%) |
|--------|----------|-----------|--------|-----------------|-------------------------------|---------------------|
| 1      | 0        | 1         | 250    | 0.042 ± 0.002   | 0.29 ± 0.01                  | 1                   |
| 2      | 0        | 2         | 500    | 0.047 ± 0.001   | 0.33 ± 0.01                  | 1                   |
| 3      | 0        | 4         | 750    | 0.057 ± 0.002   | 0.38 ± 0.01                  | 1.5                 |
| 4      | 0        | 8         | 1000   | 0.073 ± 0.002   | 0.45 ± 0.015                 | 1.5                 |
| 5      | 25       | 1         | 500    | 0.043 ± 0.001   | 0.35 ± 0.01                  | 1                   |
| 6      | 25       | 2         | 250    | 0.047 ± 0.002   | 0.36 ± 0.01                  | 1.5                 |
| 7      | 25       | 4         | 1000   | 0.06 ± 0.002    | 0.46 ± 0.01                  | 1                   |
| 8      | 25       | 8         | 750    | 0.073 ± 0.001   | 0.5 ± 0.015                  | 1.5                 |
| 9      | 50       | 1         | 750    | 0.045 ± 0.002   | 0.36 ± 0.005                 | 1                   |
| 10     | 50       | 2         | 1000   | 0.05 ± 0.001    | 0.38 ± 0.01                  | 1                   |
| 11     | 50       | 4         | 250    | 0.058 ± 0.002   | 0.43 ± 0.01                  | 2                   |
| 12     | 50       | 8         | 500    | 0.074 ± 0.002   | 0.48 ± 0.005                 | 1.5                 |
| 13     | 75       | 1         | 1000   | 0.047 ± 0.001   | 0.33 ± 0.005                 | 1                   |
| 14     | 75       | 2         | 750    | 0.051 ± 0.002   | 0.35 ± 0.01                  | 1                   |
| 15     | 75       | 4         | 500    | 0.061 ± 0.002   | 0.42 ± 0.01                  | 1.5                 |
| 16     | 75       | 8         | 250    | 0.074 ± 0.002   | 0.46 ± 0.01                  | 2.5                 |
parameters which constitute better results is analyzed through Grey relational analysis. The Grey relational analysis develops a single grade from multiple responses and from these grades, the set of input parameters that provides better responses is identified. The Grey relational analysis starts with the normalization of all the responses using expressions

\[ Y\(_{i}(k) = \frac{\text{max } y\(_{j}(k) - y\(_{i}(k))}{\text{max } y\(_{j}(k) - \text{min } y\(_{i}(k)} \]  

For ‘lower the better’ category of response

\[ Y\(_{i}(k) = \frac{\text{min } y\(_{i}(k) - y\(_{j}(k))}{\text{max } y\(_{j}(k) - \text{min } y\(_{i}(k}} \]  

where the normalized value is represented as \( Y\(_{i}(k) \), the maximum and minimum of the experimental value is represented as \( \text{max } y\(_{j}(k) \) and \( \text{min } y\(_{i}(k) \) and the experimental value is given as \( y\(_{j}(k) \) at \( k \)th position.

From the normalized data, the Grey relation co-efficient is estimated through the expression,

\[ \xi\(_{i}(k) = \frac{\Delta \text{min} + \Psi \Delta \text{max}}{\Delta \text{0}(k) + \Psi \Delta \text{max}} \]  

where \( \Delta \text{0}(k) = \| y\(_{j}(k) - y\(_{i}(k) \| \), the minimum and maximum of \( \Delta \text{0} \), which are represented as \( \Delta \text{min} \) and \( \Delta \text{max} \), and the distinguishing coefficient is denoted as \( \Psi (0.5) \). The \( \Psi \) value distinguishes the normalized reference series and normalized comparative series. However, experimentally it has been proved that the value of \( \Psi \) does not affect the ranking of Grey relational grade in the final analysis [24]. Using \( \xi\(_{i}(k) \), the Grey relational grades for the multiple responses are evaluated using the equation [23],

\[ \gamma\(_{i} = \frac{1}{n} \sum_{k=1}^{n} \xi\(_{i}(k) \]  

The highest Grey relational grade value is ranked at the top and the corresponding input parameters are chosen as the optimum.

### 2.5. Heat pipe application

The nanofluid developed using the optimum set of input parameters is used as a working fluid to evaluate the heat transfer performance for heat pipe. The heat pipe consists of an evaporator section (100 mm), adiabatic section (80 mm), and condenser section (150 mm) where the thermocouples are placed at positions as shown in figure 1. At the evaporator section, the nanofluid collects the heat generated from the device and at the condenser region, the heat is liberated. The heating is performed using three different heating power such as 40 W, 80 W, and 120 W and their corresponding temperature at each position of the thermocouple is recorded. Further, from the obtained data, the thermal resistance (\( R \)) and overall heat transfer coefficient (\( h \)) are evaluated using the expressions [25, 26],

\[ R = \frac{\Delta T}{Q} \text{°C W}^{-1} \]  

\[ h = \frac{Q}{A(T_{e} - T_{c})} \text{W m}^{-2} \text{°C}^{-1} \]  

where \( \Delta T \) is the difference in temperature between evaporator section and adiabatic section, \( A \) is the surface area at the heat transfer region in evaporator section, \( T_{e} \) and \( T_{c} \) are the temperatures at evaporator and condenser section respectively and \( Q \) is the input heat.
3. Results and discussion

For obtaining the optimal parameters for the preparation of heat transfer nanofluid, L16 orthogonal array is constructed using Taguchi design with three factors and four levels where the experimental responses for each set of parameters are conducted and provided in table 2. From table 2, it is clear that the viscosity, thermal conductivity, and normalized weight % directly proportional to the vol.% of nanoparticles in the nanofluid. However, only the thermal conductivity displays a constructive response as it stands with the category ‘larger the better’ whereas the viscosity and normalized height % should be minimum for better heat transfer performance. The normalized height % provides information about the sedimentation of TiO\textsubscript{2}/ZnO nanocomposite. However, the thermal conductivity is inversely proportional to the sedimentation and thereby, the increase in normalized height % has a negative impact on thermal conductivity. Likewise, the improvement in viscosity hinders the thermal conductivity of the fluid as the fluid flow rate will be reduced upon increment in viscosity. The wt.% of ZnO in the nanocomposite doesn’t have significant influence over the normalized height %. This may be due to the fact that there is no considerable difference in the density of TiO\textsubscript{2} (4.23 g cm\textsuperscript{-3}) and ZnO (5.61 g cm\textsuperscript{-3}). In contrast, wt.% of ZnO in TiO\textsubscript{2}/ZnO nanocomposite has an effect on the thermal conductivity of the nanofluid. The change in thermal conductivity is due to the synergic material properties of ZnO and TiO\textsubscript{2} nanoparticles. The quantity of the surfactant (CTAB) added to the nanofluid influences the viscosity and normalized height %. The viscosity is improved with an increase in the quantity of CTAB attributed to the decline in the sedimentation process. Subsequently, the normalized height is declined as there is no sedimentation. From all these discussions, it is clear that all the responses are interdependent to all the input parameters which are further elucidated from the signal to noise (S/N) ratios predicted for all the responses.

Figures 2(a)–(c) show the dependency of input parameters on S/N ratios of viscosity, thermal conductivity, and normalized height %. The change in the rate of S/N ratio determines the effect of input parameter towards the response. Here, the ‘larger is better’ criteria are applied for thermal conductivity and the ‘smaller is better’ criteria are applied for viscosity and normalized height %. The effect of input parameters is in the order V > Z > C for viscosity, V > Z > C for thermal conductivity, and V > C > Z for normalized height %. For all the three responses, vol.% of nanoparticles in the nanofluid is the most significant parameter. From figure 2(a), it is inferred that as the input parameters increases, the viscosity also increases. Therefore, the S/N ratio shows a decreasing trend with respect to increase in input parameter suggesting undesired results. The increase in thermal conductivity primarily depends on the wt.% of ZnO and vol.% of nanocomposite in the fluid (figure 2(b)). However, the thermal conductivity reduces when wt.% of ZnO nanoparticles in the nanocomposite exceeds 25% and declined drastically after 50% owing to the intrinsic material property. In the case of parameter C, the graph shows an increasing trend in S/N ratio substantiating the fact that the improvement in concentration of CTAB improves thermal conductivity to a certain limit. For the response normalized height %, the Z and V have a negative impact whereas the C displays a positive influence (figure 2(c)). The positive influence from the surfactant is due to the reduced sedimentation process owing to the introduction of electrostatic repulsion between the nanoparticles.

The analysis of variance (ANOVA) for the output such as viscosity, thermal conductivity, and normalized height % are shown in table 3. Vol.% of nanocomposite contributed 98%, 85%, and 50% towards the response’s viscosity, thermal conductivity, and normalized height % respectively. The quantity of surfactant displays a 32% contribution towards normalized height. All the other contributions are found to be very low. The regression equations obtained for responses from the input parameters are obtained and given as

\[
\text{Viscosity} = 0.056375 - 0.001625 \, Z_0 - 0.000625 \, Z_{25} + 0.000375 \, Z_{50} \\
+ 0.001875 \, Z_{75} - 0.012125 \, V_1 - 0.007625 \, V_2 \\
+ 0.002625 \, V_4 + 0.017125 \, V_8 - 0.001125 \, C_{250} \\
- 0.000125 \, C_{500} + 0.000125 \, C_{750} + 0.001125 \, C_{1000} \tag{8}
\]

\[
\text{Thermal Conductivity} = 0.39562 - 0.03313 \, Z_0 + 0.02187 \, Z_{25} + 0.01687 \, Z_{50} \\
- 0.00562 \, Z_{75} - 0.06313 \, V_1 - 0.04062 \, V_2 + 0.02688 \, V_4 \\
+ 0.07688 \, V_8 - 0.01063 \, C_{250} - 0.00062 \, C_{500} \\
+ 0.00187 \, C_{750} + 0.00038 \, C_{1000} \tag{9}
\]

\[
\text{Normalized Height} = 1.3438 - 0.094 \, Z_0 - 0.094 \, Z_{25} + 0.031 \, Z_{50} + 0.156 \, Z_{75} \\
- 0.344 \, V_1 - 0.219 \, V_2 + 0.156 \, V_4 + 0.406 \, V_8 + 0.406 \, C_{250} \\
- 0.094 \, C_{500} - 0.094 \, C_{750} - 0.219 \, C_{1000} \tag{10}
\]

From all the above discussions, it is clear that for enhanced thermal conductivity, the vol.% of nanocomposite should be high which compromises the requirement of viscosity and normalized height %.
Therefore, choosing the set of input parameters for nano fluid preparation without compromising with viscosity, thermal conductivity, and normalized height % is required and hence, Grey relational analysis is employed.

The Grey relational analysis is a technique that constructs a single grade from multiple responses which are then used to rank the input parameters. As per the instructions given in section 2.4, the Grey relational grades are estimated by evaluating the normalized value and Grey relational co-efficient. For calculating the normalized value of thermal conductivity, the expression for 'larger the better' is employed while for viscosity and normalized height, the expression 'smaller the better' is employed. From the normalized values, the Grey relational coefficient is developed and consequently, Grey relational grades are constructed where ranks are allotted as higher the value better the ranking (table 4). From table 4, the input parameters with wt.% of ZnO = 25 wt.%, vol.% of nanocomposite = 1 vol.% and 500 μl of CTAB used for the preparation of nano fluid display highest Grey relational grade where the responses are viscosity = 0.043 Pa.s, thermal conductivity = 0.35 Wm \(^{-1}\)K \(^{-1}\), and normalized height % = 1%. From the obtained results, it is inferred that

Figure 2. Influence of factors on S/N ratio of (a) viscosity, (b) thermal conductivity, and (c) normalized height %.
while adding 25 wt.% ZnO to the nanocomposite, the nanofluid displays optimum responses owing to inherent properties of TiO$_2$/ZnO at the same composition. Also, the vol.% of the nanocomposite for the preparation of nano fluid is found as minimum. Even though higher percentage of nanocomposite displays higher thermal conductivity, it also improves the viscosity and sedimentation rate leading to deprived practical application. Likewise, 500 μl of CTAB is obtained as optimum quantity of surfactant because higher value results in improved viscosity leading to slower fluid flow. Therefore, it is clear that the optimal input parameters are good for practical applications.

Further, the nano fluid prepared through the obtained optimum set of parameters is used as a working fluid in a heat pipe. The temperature distribution along the heat pipe with different heat input are recorded using the thermocouple between the evaporator section and condenser section and are shown in figure 4. The temperatures are recorded after 30 s of heat input heat. From figure 4, it is clear that the temperature increases with an increase in input power. Also, the temperature deteriorates from the evaporator section to the condenser section recorded using the thermocouple. While comparing the temperature of heat pipe added with ethylene

| Viscosity | Source | DF | Adj SS | F-Value | P-Value |
|-----------|--------|----|--------|---------|---------|
| Z         | 3      | 0.000027 | 35.67 | 0.000 |
| V         | 3      | 0.002021 | 2695.00 | 0.000 |
| C         | 3      | 0.000010 | 13.67 | 0.004 |
| Error     | 6      | 0.000002 | 35.67 | 0.000 |
| Total     | 15     | 0.000060 | 35.67 | 0.000 |

Thermal Conductivity

| Viscosity | Source | DF | Adj SS | F-Value | P-Value |
|-----------|--------|----|--------|---------|---------|
| Z         | 3      | 0.007569 | 28.16 | 0.001 |
| V         | 3      | 0.049069 | 182.58 | 0.000 |
| C         | 3      | 0.000819 | 3.05 | 0.114 |
| Error     | 6      | 0.000538 | 3.05 | 0.114 |
| Total     | 15     | 0.057994 | 3.05 | 0.114 |

Normalized Height

| Viscosity | Source | DF | Adj SS | F-Value | P-Value |
|-----------|--------|----|--------|---------|---------|
| Z         | 3      | 0.1719 | 1.00 | 0.455 |
| V         | 3      | 1.4219 | 8.27 | 0.015 |
| C         | 3      | 0.9219 | 5.36 | 0.039 |
| Error     | 6      | 0.3438 | 5.36 | 0.039 |
| Total     | 15     | 2.8594 | 5.36 | 0.039 |

DF = Degrees of Freedom, SS = sums of squares, F = F-ratio, P = Probability.

Table 4. Grey relational analysis.

| Experimental data | Normalized data | Grey relational coefficients | Grey relational grades (GRG-I) | Rank |
|-------------------|-----------------|-----------------------------|--------------------------------|------|
| Viscosity PkPa    | Thermal Conductivity Wm$^{-1}$K$^{-1}$ | Normalized Height % | Viscosity PkPa    | Thermal Conductivity Wm$^{-1}$K$^{-1}$ | Normalized Height % | Viscosity PkPa    | Thermal Conductivity Wm$^{-1}$K$^{-1}$ | Normalized Height % | GRG-I |
| 0.042             | 0.29            | 1                           | 1.000                        | 0    | 1                           | 1.000                        | 0.333            | 1.000                        | 0.778            | 2    |
| 0.047             | 0.33            | 1                           | 0.844                        | 0.190476 | 1                           | 0.762                        | 0.382            | 1.000                        | 0.715            | 5    |
| 0.057             | 0.38            | 1.5                         | 0.531                        | 0.428571 | 0.666667                    | 0.516                        | 0.467            | 0.600                        | 0.528            | 14   |
| 0.073             | 0.45            | 1.5                         | 0.031                        | 0.761905 | 0.666667                    | 0.340                        | 0.677            | 0.600                        | 0.539            | 13   |
| 0.049             | 0.35            | 1                           | 0.969                        | 0.285714 | 1                           | 0.841                        | 0.412            | 1.000                        | 0.784            | 1    |
| 0.047             | 0.36            | 1.5                         | 0.844                        | 0.333333 | 0.666667                    | 0.762                        | 0.429            | 0.600                        | 0.597            | 10   |
| 0.06              | 0.46            | 1                           | 0.438                        | 0.809524 | 1                           | 0.471                        | 0.724            | 1.000                        | 0.732            | 4    |
| 0.073             | 0.5             | 1.5                         | 0.031                        | 0.666667 | 0.340                        | 1.000                        | 0.647            | 0.600                        | 0.647            | 9    |
| 0.045             | 0.36            | 1                           | 0.906                        | 0.333333 | 1                           | 0.842                        | 0.429            | 1.000                        | 0.757            | 3    |
| 0.05              | 0.38            | 1                           | 0.756                        | 0.285714 | 1                           | 0.667                        | 0.467            | 1.000                        | 0.711            | 7    |
| 0.058             | 0.43            | 2                           | 0.500                        | 0.666667 | 0.333333                    | 0.500                        | 0.600            | 0.429                        | 0.510            | 15   |
| 0.074             | 0.48            | 1.5                         | 0.000                        | 0.904762 | 0.666667                    | 0.333                        | 0.840            | 0.600                        | 0.591            | 11   |
| 0.047             | 0.33            | 1                           | 0.844                        | 0.190476 | 1                           | 0.762                        | 0.382            | 1.000                        | 0.715            | 6    |
| 0.051             | 0.35            | 1                           | 0.719                        | 0.285714 | 1                           | 0.640                        | 0.412            | 1.000                        | 0.684            | 8    |
| 0.061             | 0.42            | 1.5                         | 0.406                        | 0.619048 | 0.666667                    | 0.457                        | 0.568            | 0.600                        | 0.542            | 12   |
| 0.074             | 0.46            | 2.5                         | 0.000                        | 0.809524 | 0                           | 0.333                        | 0.724            | 0.333                        | 0.464            | 16   |

while adding 25 wt.% ZnO to the nanocomposite, the nano fluid displays optimum responses owing to inherent properties of TiO$_2$/ZnO at the same composition. Also, the vol.% of the nanocomposite for the preparation of nano fluid is found as minimum. Even though higher percentage of nanocomposite displays higher thermal conductivity, it also improves the viscosity and sedimentation rate leading to deprived practical application. Likewise, 500 μl of CTAB is obtained as optimum quantity of surfactant because higher value results in improved viscosity leading to slower fluid flow. Therefore, it is clear that the optimal input parameters are good for practical applications.

The X-ray Diffraction (XRD) pattern of TiO$_2$/ZnO nanocomposite prepared in the ratio 75:25 (wt.%) is shown in figure 3. The pattern displays peaks corresponding to both the tetragonal phase of TiO$_2$ and hexagonal wurtzite phase of ZnO. The peaks obtained at 27.46°, 36.12°, 39.27°, 41.32°, 44.15° and 54.45° confirms the presence of TiO$_2$ and 31.80°, 34.39°, 36.12°, 47.61°, 56.59°, 62.88°, 68.08° and 69.02° confirms the availability of ZnO phase. Further, there is no evidence for the formation of intermetallic compounds while preparing the nanocomposite.

Further, the nano fluid prepared through the obtained optimum set of parameters is used as a working fluid in a heat pipe. The temperature distribution along the heat pipe with different heat input are recorded using the thermocouple between the evaporator section and condenser section and are shown in figure 4. The temperatures are recorded after 30 s of heat input heat. From figure 4, it is clear that the temperature increases with an increase in input power. Also, the temperature deteriorates from the evaporator section to the condenser section recorded using the thermocouple. While comparing the temperature of heat pipe added with ethylene
glycol and TiO$_2$/ZnO nanofluid as the working fluid, TiO$_2$/ZnO nanofluid displays lesser temperature ascribed to the better heat dissipation efficiency. This phenomenon is applicable for all three heat loads substantiating the workability of TiO$_2$/ZnO nanofluid under various heating conditions.

To further validate the heat transfer ability of the TiO$_2$/ZnO nanofluid, the thermal resistance between the evaporator and adiabatic section is evaluated for all heat input and is shown in figure 5. From the figure, it is inferred that the thermal resistance of heat pipe while using TiO$_2$/ZnO nanofluid is significantly lower than compared to that of using base fluid which is found true irrespective of the input power. Lower thermal resistance validates the fact that the presence of TiO$_2$/ZnO nanofluid improved the heat dissipation process of the heat pipe. Further, the heat transfer coefficient is evaluated as 369.48 W/m$^2$°C, 383.56 W/m$^2$°C, and 567.46 W/m$^2$°C for 40 W, 80 W, and 120 W, respectively.

From all these findings, it is inferred that the TiO$_2$/ZnO nanofluid prepared using optimized condition display better efficacy while used as working fluid in heat pipe than base fluid.
4. Conclusion

In the present work, the effect of parameters for the preparation of nanofluid such as wt.% of ZnO in TiO$_2$/ZnO nanocomposite, vol.% of TiO$_2$/ZnO nanocomposite, and quantity of CTAB are studied. Using Taguchi L16 orthogonal array, the experiments are designed, performed and the responses such as viscosity, thermal conductivity, and normalized height % are recorded. Besides, the responses are graded using Grey relational analysis and the parameters are ranked as per the grades obtained. The optimal parameters are found as 25 wt.% ZnO, 1 vol.% nanocomposite and 500 $\mu$l CTAB providing viscosity of 0.043 Pa.s, the thermal conductivity of 0.35 Wm$^{-1}$K$^{-1}$, and normalized height % as 1%. Further, the same nanofluid is utilized as working fluid in the heat pipe where the thermal resistance and heat transfer coefficient values of TiO$_2$/ZnO nanofluid display improved efficiency than ethylene glycol. Therefore, the present study provides information about the optimal set of parameters to achieve better heat transfer performance of the nanofluid as well as the practical usability of such nanofluids as working fluids for heat pipes.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Figure 5. Thermal resistance of heat pipe while using nanofluid and ethylene glycol as working fluid.
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