Integrated Taguchi-GRA-PCA for optimising the heat transfer performance of nanofluid in an automotive cooling system

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Abstract

Purpose – In the present study, the thermal performance of engine radiator using conventional coolant and nanofluid is determined experimentally for the different flow rates. Further, the study implemented the Integrated Taguchi-GRA-PCA for optimising the heat transfer performance.

Design/methodology/approach – Nanofluids were prepared by taking ethylene glycol and water (25:75 by volume) with volume fraction of 0.01, 0.03 and 0.05% of TiO_2 nanopowder. Experimental Data were collected based on the design of experiments (DOE) L9 orthogonal array using Taguchi method. Statistical analysis via Grey relation analysis (GRA) and principal component analysis (PCA) were done to determine the role of experimental parameters on heat transfer coefficient and rate of heat transfer. Impact of three control factors, vol. % of TiO_2 concentration (ϕ), flow rate (LPH), and sonication time (min) on the performance characteristics on heat transfer coefficient and ratio of heat transfer rate is analysed to get the best combination of the parameters involved.

Findings – Analysis revealed the importance of parameters on heat transfer coefficient and can be sorted in terms of contributions from higher to lower degree. Finally, ANOVA test has been conducted to validate the effect of process parameters. The major controllable parameter is ϕ (concentration), contributing about 32.74%, then flow rate contributing 32.5% and finally sonication time showing small contribution of 18.57%.

Originality/value – A grey relational analysis integrated with principal component analyses (PCA) are implemented to get the optimum heat transfer coefficient and ratio of heat transfer rate. The novelty of the work is to adopt and implement the Integrated Taguchi-GRA-PCA first time for the purpose of thermal performance analysis of engine nano-coolant for radiator.

Keywords Nano-coolant, Taguchi, GRA, PCA, Optimisation

Paper type Research paper

1. Introduction

Nanofluid, a novel idea, has been in the news for several decades but it is going to change the face of technology in coming future. It has huge potential because of several reasons and some of them are better thermal properties, strength, compactness, etc. Due to its better thermo-physical properties as compared to the ethylene glycol and water solution, it is being

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researched and adopted by the automobile industry for cooling (Suganthi *et al.*, 2014). Also, nanofluids possess better thermal absorption properties, therefore it is being adopted as the working fluid for direct absorption solar collector (DASCs) (Mallah *et al.*, 2018). In the near future, nanofluids are going to replace all the conventional fluids such as water, ethylene glycol, propylene glycol, etc; because all the conventional fluids have sluggish response to the system and environment. Since most of the nanoparticles are composed of metallic part, they influence the thermal conductivity of the nanofluid.

(Leong *et al.*, 2010) prepared copper based nanofluid with ethylene glycol as the base fluid. This study was done on the automotive radiator system. Since, the nanofluid has better thermal performance as compared to conventional coolant, so it is used to enhance heat transfer in the radiator. Varying concentration (0–2%) of nanoparticles were used, and the rate of heat transfer increased with concentration. Maximum heat transfer of 45.2% was obtained corresponding to the volume fraction of 2%.

(Naraki *et al.*, 2013) suspended CuO nanoparticles in water to form nanofluid. In this experimental study, laminar regime ($100 \leq Re \leq 1000$) was maintained. Different samples corresponding to the volume fraction (0–8%) were prepared. The prepared nanofluids were stabilised by varying pH and using the suitable surfactant. The heat transfer coefficient increases with the volume fraction of particles. But, it decreases with increasing inlet temperature, that is 50–80°C. The statistical analysis of the obtained data is conducted by using Taguchi method through Qualitek-4 software.

(Hussein *et al.*, 2014a) dispersed SiO_2 in the water and prepared the nanofluid. Four different samples were prepared in the range of 1–2.5% volume fraction of nanoparticles. Varying flow rate was maintained, that is. 2–8 LPM (Litres per Minute). It was found that Nusselt number depended on several factors like volume concentration, flow rate and temperature. Maximum enhancement of 56% in Nusselt number was achieved here.

(Hussein *et al.*, 2014b) suspended two different nanoparticles namely TiO_2 and SiO_2 in pure water to prepare two nanofluid. In this experimental study, varying flow rates (2–8 LPM), temperature range (60–80°C) and varying concentrations (1–2%) were the input parameters. Significant increase in the rate of heat transfer as well as Nusselt number was observed. A value of 11 and 22.5% of enhancement in the Nusselt number were recorded for TiO_2 and SiO_2 respectively. Increase in Nusselt number depended on all the three input parameters but rate of heat transfer mainly depended on concentration of nanoparticles.

(Suganthi *et al.*, 2014) used ZnO based two different nanofluid. Two base fluids were EG and mixture of water-EG. Nanoparticles with size ranging from 25 to 40 nm were employed to prepare the nanofluid. Probe ultra-sonication was done and no surfactant was used. Thermal properties such as thermal conductivity increased by 33.4 and 17.26% corresponding to the volume fraction of 4 and 2%. The increased property led to enhancement in heat transfer by better cooling when compared to base fluid alone.

(Ali *et al.*, 2015) prepared four different ZnO based nanofluids with varying concentration of 0.01, 0.08, 0.2 and 0.3%. They were used as a fluid medium to experimentally study the heat transfer in car radiator where flow rates ranging from 7 to 11 LPM (Litres per Minute) were maintained. It was noticed that heat transfer depended on the volume concentration of particles. Maximum heat transfer of 46% were achieved corresponding to 0.2% volume concentration. With increasing concentration, heat transfer increased but at 0.3% a lesser heat transfer is obtained. Also, it is to be noted that the nanofluid gave much better results when compared with only base fluid.

(Azmi *et al.*, 2016) utilised TiO_2 based nanofluid containing water-EG as the base fluid. Temperature for the fluid were maintained in the range of 30–80°C. Corresponding to 1.5% volume fraction, maximum thermal conductivity (15.4%) was obtained. Increasing Nusselt number was achieved with volume fraction as well as temperature. Nusselt number increased by 22.8 and 28.9% corresponding to 50 and 70°C respectively.

(Sandhya *et al.*, 2016) prepared TiO_2 based nanofluid with ethylene glycol and water as the base fluid in the ratio of 40:60 by volume. They conducted the experimental study of cooling performance in the automobile radiator. Three different samples of nanofluid was prepared with 0.1, 0.3 and 0.5% volume fraction of nanoparticles. The range of Reynolds number were maintained from 4,000 to 15,000. Heat transfer depended mainly on the fluid flow rate whereas inlet temperature to the radiator had little impact. Corresponding to the volume fraction of 0.5%, a maximum enhancement of 35% for the heat transfer was observed.

In almost all the reviewed literatures, it can be noticed that the thermal properties were influenced by different controllable parameters (e.g. flow rate, concentration, particle size etc.). This further helps in enhancing the heat transfer ability of the cooling systems where nanofluids are employed. Rate of heat transfer as well as Nusselt number has been increasing everywhere with increasing concentration as well as volume flow rates. But, inverse trend has been observed for the case of temperature. In order to obtain the maximum benefits of the system, it is required to have an optimum performance of them. Among the various methods available in the literature, optimization may be explored to gain the best solution, which may be obtained by either by the traditional methods or by Multi Criteria Decision Making (MCDM) techniques (Lootsman, 1999). The various MCDM methods have already been developed and implemented, like Grey Relational Analysis (GRA), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Multi-Objective Optimization by Ratio Analysis (MOORA) and others (Tiwari *et al.*, 2017; Asjad and Talib, 2018; Kumar *et al.*, 2016).

In the present study, grey relational analysis integrated with principal component analyses (PCA) are implemented to get the optimum heat transfer coefficient and ratio of heat transfer rate. The Taguchi method is applied for optimization under design of experiment (Doe) strategy. It is statistical approach which is economical, effective and efficient for obtaining the response of multiple variables involved in experiments to get their optimal level and individual contribution. Thus this method is adopted in the present study to determine the optimum parameters of a heat transfer performance using nanofluid in an automotive cooling system.

The context of paper is organized with section 2 demonstrates the experimentation and mathematical technique deployed to carry out the research and optimization while section 3 presents the results and analysis whereas section 4 concludes the research findings of the present study.

2. Methodology

2.1 Experimentation

In this work only one nanoparticle has been used, that is TiO_2 with average size of ~15 nm. Here, the two step method was employed to develop the nanofluid. TiO_2 nanoparticle has been purchased from Sigma–Aldrich and it was provided by the lab of Applied Physics Department of Aligarh Muslim University, India. The base fluid was developed by mixing ethylene glycol and pure water in the ratio of 25:75 by volume. Three different volume fractions (i.e. 0.01, 0.03 and 0.05%) were selected and corresponding nanofluids were prepared. With proper mixing through magnetic stirrer, ultra-sonication was also performed with the help of ultrasonic bath. The nanofluid used here is prepared by properly mixing TiO_2 nanoparticles with various concentration in the base solution comprises of 25% of ethylene glycol and 75% of water.

Since it was an experimental work, the setup consisted an engine, finned tube radiator, rotameter in the flow line, etc.; the photograph of the setup is shown in Plate 1.

From Figure 1, the complete phenomenon can be depicted. In the flow line there are two temperature gauges. One measures inlet temperature to the radiator whereas other one measures for the outlet temperature. Just at the entry to the engine, a rotameter with control

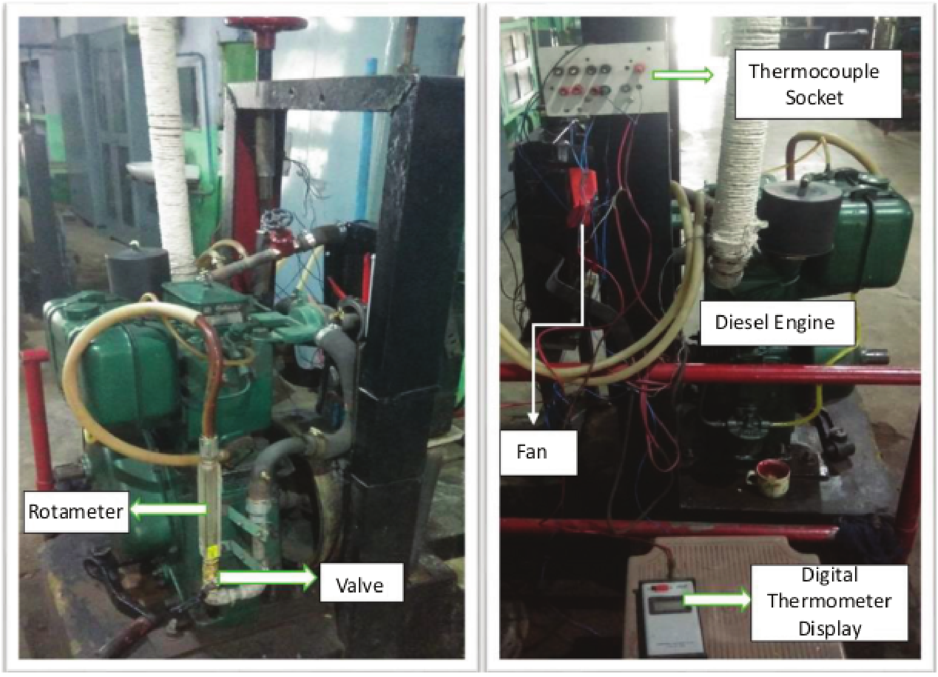

Plate 1.
Experimental setup

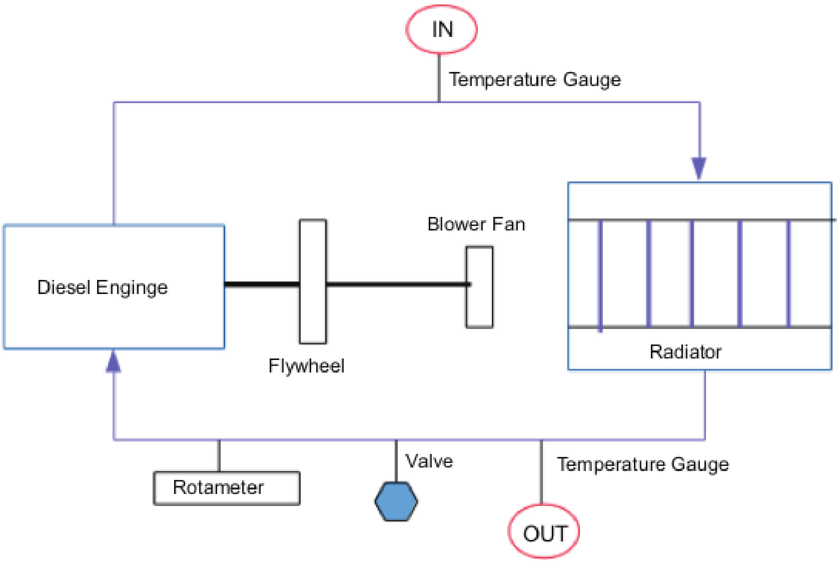

Figure 1.
Schematic line diagram

valve is installed which controls and measure the flow rate of working fluid within the system. Since, there were four staggered rows of tube in the radiator, in each row two wire thermocouple were installed so as to measure the wall temperature of radiator tubes. Average of all the eight tubes were taken to figure out the average wall temperature of the tubes. Also, a blower fan was installed to suck the atmospheric air from other side of the radiator which further picks up the heat from the wall of the tube and helps to cool the flowing fluid within the tube. In this way a large temperature drop was noticed at the outlet of radiator.

Devices used in the experimental analysis are often subjected to error because some amount of uncertainty is always associated with them. Hence, uncertainty analysis for the temperature measuring device, that is thermocouple has been done. Error in the reading of temperature by the thermocouple is within 3%. Hence, the temperature measurement system is accepted. Each experiment consisted several steps in order to note down the reading. Before taking the readings, it was necessary to achieve steady state so that the variation in reading is eliminated. Initially, change the coolant in the radiator. Then, start the diesel engine and afterwards maintain and control the volume flow rate of coolant. Then, wait for some moment so that steady state is achieved. (i.e. when the temperature reading shows no fluctuation, it indicates that the steady state has been achieved). Now, note down the Temperature readings at inlet, outlet and tube-wall of Radiator. After the reading is complete, then change the volume flow rate for next reading. This procedure has to be followed for different concentration of nanofluids.

2.2 Stability analysis of nanofluid

Stability is one of the key features for any nanofluid in system application. There is a strong tendency of nanoparticles to form aggregates/agglomeration in the liquid media, resulting in not only the clogging of microchannels but also degradation of its thermal properties. Therefore, the stability study plays a key role that adversely affect the thermo-physical properties of nanofluids in practical application, thus it is suggested to measure the dispersion stability of nanofluids. For measuring the stability of nanofluids, the zeta potential test was done for all the samples of 10 mL (see Plate 2). Zeta Sizer product of Malvern Company was employed for this purpose in Applied Physics Department, AMU. Zeta potential is more about finding the stability of colloidal formulation.

It gives an idea about how stable are the particles in the solution. When the particles are very charged, they repel each other. They stay apart and they have stable solution. When they have zero charge, they tend to coagulate with each other and stick together permanently,

Plate 2.
10 mL sample of Nano coolant

leading to unstable solution. Zeta potential is measured in absolute value in mV, the value below 25 referred to as unstable while 30–40 moderately stable, above this demonstrates very good stability. In Figure 2, zeta potential is plotted against pH for different concentrations as well as sonication times. For acidic as well as basic regions, higher zeta potential is noted.

2.3 Effect of volume fraction on the convective heat transfer coefficient

In Figure 3, convective heat transfer coefficients for different cases have been compared. It is observed that water-EG gives superior result when compared with water only. All the three nanofluids (ϕ = 0.01, 0.03, 0.05% volume fraction) give better result in comparison to water-EG coolant. Among the three nanocoolant, nanofluid with ϕ = 0.03% gives the best result.

2.4 Optimization

2.4.1 Doe using Taguchi method. Various Researchers have implemented the potential capabilities of MCDM tools and techniques for optimization of process parameters in numerous energy systems (Pandey *et al.*, 2017; Naqiudin *et al.*, 2018; Hong *et al.*, 2018; Wu

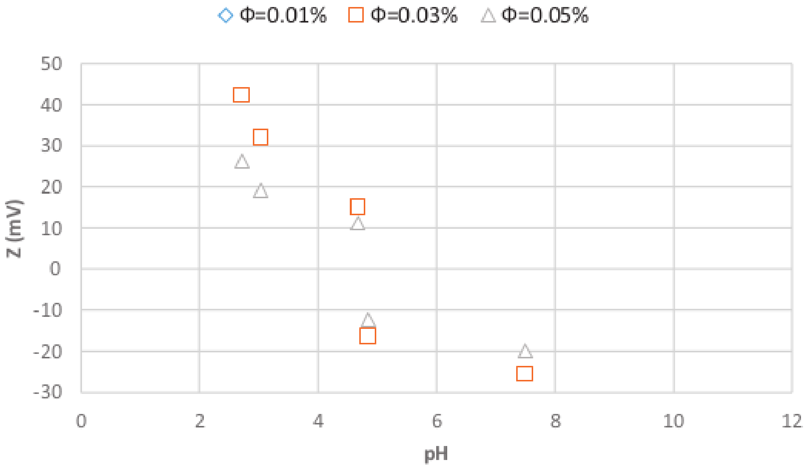

Figure 2.
Zeta potential variation with the pH value of TiO_2/water-EG nanofluid of different particle concentrations and sonication time of 90 min

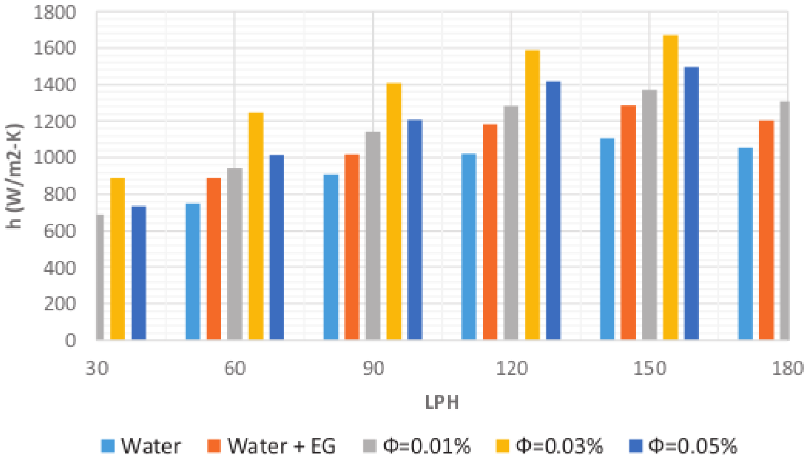

Figure 3.
Convective heat transfer coefficient for different cases

et al., 2011; Wang *et al.*, 2015). Taguchi method is one of the effective tools that may be implemented for various designing issues in getting the optimal performance measures under the experimentation constraint. This technique is based on calculating the signal to noise ratio (S/N ratio) statistically for estimating the output responses based on input parameters. The S/N ratio is a measure useful in engineering applications that provide interplay between desired signal and background noise in a controlled manner. In the present research work, heat transfer coefficient and the ratio of heat transfer rate are considered to be larger the better. Hence, S/N ratio is calculated using an appropriate Equation given in Table 1.

2.4.2 Grey relational Analysis(GRA). GRA was designed and developed by Ju-Long (1982). It is based on the normalization of desired output values (e.g. *h and Qr* in this study) to estimate the grey relational coefficient (GRC) and grey relational grade (GRG). It calculates the optimal level of input parameters and through integration with ANOVA it is used to predict the best level of grey relational grades.

Heat transfer rate ratio and coefficient of heat transfer are important quality components of automotive cooling system. In this work, the aim is to maximize the output parameter, that is the larger the better. The first step is to generate the range of grey relational coefficient in between 0 and 1 using Equation (1).

$$X_i(k) = \frac{X_i^0(k) - \min X_i^0(k)}{\max X_i^0(k) - \min X_i^0(k)} \tag{1}$$

In Equations (1) $i = 1$ to m and $k = 1$ to n; where, m is the number of experimental trials and n is the number of parameters involved in the problem. The term $X_i^0(k)$ represents the basic or inherent sequence; $\max X_i^0(k)$ and $\min X_i^0(k)$ represents the maximum and minimum values in the basic or inherent sequence; $X_i(k)$ represents the sequence generated after the initial processing of data, as given in Equations (2) and (3) [20, 21].

$$\Delta_{o,i}(k) = X_o(k) - X_i^0(k) \tag{2}$$

$$\xi_i(k) = \frac{\Delta_{\min} + \psi.\Delta_{\max}}{\Delta_{o,i}(k) + \psi.\Delta_{\max}} \tag{3}$$

where $\Delta_{o,i}(k)$ is deviation sequence of basic sequence $X_o(k)$ and compatibility sequence $X_i^0(k)$; while ψ is grey coefficient and is generally taken 0.5 when equal weight is given to the each output parameters. In the last stage of analysis, the GRG is computed based on Equation (4) given in (Ju-Long, 1982; Çaydaş and Hasçalık, 2008; Yang *et al.*, 2006). The principal component analysis is implemented to assign the weight value of each output characteristics based on which the GRG is obtained using Equation (5). The GRG values are gauge in the range of 0 and 1. Higher the value of GRG better the relation among the combinations of process parameters at that level and it is predicted to be an optimal level. However, the response of each variable did not depicts the same effect on the output in real applications.

$$\gamma_i(GRG) = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{4}$$

Table 1. Signal to noise (S/N) ratio formulas

S/N ratio	S/N ratio formula
Smaller is better	$\frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{j=1}^{n} Y_j^2\right)$
Larger is better	$\frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{j=1}^{n} \frac{1}{Y_j^2}\right)$

$$\gamma_i(GRG) = \frac{1}{n}\sum_{k=1}^{n}\omega_k.\xi_i(k) \tag{5}$$

In Equation (4) γ_i represents the grey relational grade of the ith experiment and n denotes the number of process parameters. In Equation (5) ω_k represents the weighted value of factor k. In this investigation, the corresponding weightage values ω_k have been acquired from principal component analysis (PCA), which is illustrated in the subsequent section.

2.4.3 Principal component analysis. The PCA was proposed and developed by Pearson and Hotelling, (Pearson, 1901; Hotelling, 1933) which determine the variance and covariance of all performance characteristics integrating them linearly. Equation (6), m denotes the number of experimental trials and n represents the number of performance parameters. In this study, X denotes the grey relational coefficient of each performance parameters. Thus, $n = 2$ and $m = 9$, after this the correlation coefficient array is computed using Equation (7).

$X_i(j)$, $i = 1$ to m, and $j = 1$ to n.

$$X_i = \left.\begin{array}{c} X_1(1)\ X_1(2)\ldots\ldots\ldots\ldots\ldots\ldots\ldots X_1(n) \\ X_2(1)\ X_2(2)\ldots\ldots\ldots\ldots\ldots\ldots\ldots X_2(n) \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ X_m(1)\ X_m(2)\ldots\ldots\ldots\ldots\ldots\ldots X_m(n) \end{array}\right\} \tag{6}$$

$$R_{jl} = \left(\frac{cov(X_i(j), X_i(l))}{\sigma_{Xi}(j)\times\sigma_{Xi}(l)}\right), \quad j = 1 \text{ to } n \quad \text{and} \quad l = 1 \text{ to } n \tag{7}$$

In Equation (7) $cov(X_i(j), X_i(l))$ are the covariance of sequences $X_i(j) \wedge X_i(l)$ respectively; $\sigma_{Xi}(j)$ and $\sigma_{Xi}(l)$ represents the standard deviation of sequence of $X_i(j) \wedge X_i(l)$ respectively. The determination of eigenvalues and has been done using the correlation coefficient array:

$$(R - \lambda_k I_m).V_{ik} = 0 \tag{8}$$

In Equation (8) λ_k represents eigenvalues and V_{ik} represent eigenvector corresponding to λ_k. Finally the principal components are computed using the following equation:

$$y_{mk} = \sum_{i}^{n} X_m(i)^* V_{ik} \tag{9}$$

Equation (9) produces y_{m1} as the first principal component, y_{m2} as the second principal component, and so on.

3. Results and analysis

3.1 Grey coupled PCA

In this section the optimal value of performance parameters is estimated using hybrid Taguchi-Grey-PCA based method. The identification of controllable factors plays a crucial role in obtaining the fruitful results in term of performance (Ansari *et al.*, 2018; Yahya *et al.*, 2014). Thus for this research work, the process parameters are given in Table 2.

The next stage of this method is to select an appropriate orthogonal array (OA) which is dependent upon the number of input variables along with their levels. The number of experimental trials needed for the analysis based on the Taguchi method can be obtained from the relation (L-1)*$P + 1$, where L is the number of levels and P is the number of input variables. In the current analysis, $L = 3$ and $P = 3$, thus, the minimum number of experiment required is seven. The parametric estimation has been carried out based on the Doe, L9 orthogonal array and the results are presented in Table 3. The Signal to Noise ratios values for the output variables are tabulated in Table 1. In this study, S/N ratio higher the better is used for estimation of the values of h and Q_r respectively, and is given in Table 3. A liner normalization of the S/N ratio is also performed in the range of 0 and 1 and it is depicted in Table 3. The grey relational coefficient of each performance measure is listed in Table 3. These data were used to evaluate the correlation coefficient matrix and to determine the corresponding eigenvalues (refer section 2.4.3). The weighing values corresponding to the particular performance characteristics are evaluated using PCA. The relative significance of the weighing values are reflected in the GRA.

The Eigen values and deviation for principal component along with Eigen vector corresponding to the Eigen value and their contribution is given in Table 4. From Table 4, it can be seen that for the first principal component characterizing the three performance characteristic is 99%. Therefore, the squares of its corresponding eigenvectors are taken as the weight of the corresponding performance measure.

Based on the numerical values of the contribution in Table 4, the grey relational grades were calculated using (Equation 5), which is clearly presented in Table 5. Thus, the optimization design was performed with respect to a single grey relational grade rather than complicated performance characteristics.

Parameters	Units	Symbols	Levels Level 1	Level 2	Level 3
Φ (Concentration)	% Volume	A	0.01	0.03	0.05
Flow rate	LPH(litres/h)	B	60	90	120
Sonication time	Minutes	C	60	90	120

Table 2. Process parameters and their levels

S. No	Input levels A	B	C	Experimental outputs H	Qr	S/N ratio of outputs h	Qr	Normalized S/N ratio h	Qr	Grey relation coefficient h	Qr
1	1	1	1	939.84	1.046	59.46108	0.390634	0	0	0.333333	0.333333
2	1	2	2	1146.01	1.108	61.18377	0.890795	0.379127	0.284126	0.446081	0.411227
3	1	3	3	1283.68	1.129	62.16914	1.053879	0.595986	0.376769	0.553089	0.445144
4	2	1	3	1248.81	1.148	61.92993	1.198838	0.543341	0.459116	0.522652	0.480361
5	2	2	1	1130.21	1.131	61.06318	1.069252	0.352588	0.385502	0.435763	0.448632
6	2	3	2	1585.79	1.281	64.00491	2.150983	1	1	1	1
7	3	1	2	1016.3	1.074	60.14044	0.620086	0.149513	0.130345	0.370237	0.365055
8	3	2	3	1207.4	1.138	61.63702	1.122845	0.478878	0.415946	0.489657	0.461232
9	3	3	1	1180.11	1.101	61.43845	0.835746	0.435177	0.252854	0.469562	0.400916

Table 3. Experimental layout and result

Principal component	Eigenvalue	Explained variation	Eigenvector h	Q_r
First	1.9810	0.99	0.707	0.707
Second	0.0190	0.010	0.707	0.707
Contribution			0.4999	0.4999

Table 4. Eigen values and explained variation for principal components

The response table of Taguchi method was employed to calculate the average grey relational grade for each process parameters for heat transfer enhancement level. The grey relational grades shown in Table 6, gives the best combination of process parameters as A2(ϕ (%)), B3(Flow Rate (LPH)), C2(Sonication Time (min)). It is also confirmed with the ANOVA test and presented in Figure 4. This result is also in line with latest fuzzy PIV optimisation study of engine radiator cooling using nanofluid by Seraj *et al.* (2020), which

Table 5.
Grey relation grade and its order

No	Grey relation grade	Order
1	0.333266	9
2	0.428568	7
3	0.499017	3
4	0.501406	2
5	0.442109	5
6	0.9998	1
7	0.367572	8
8	0.475349	4
9	0.435152	6

Table 6.
Response table for grey relation grade

Symbol	Parameters	Level 1	Level 2	Level 3	Difference
A	Φ	0.4203	0.6478	0.4260	0.2275
B	Flow rate	0.4007	0.4487	0.5986	0.2439
C	Sonication time	0.4035	0.6447	0.4919	0.1951

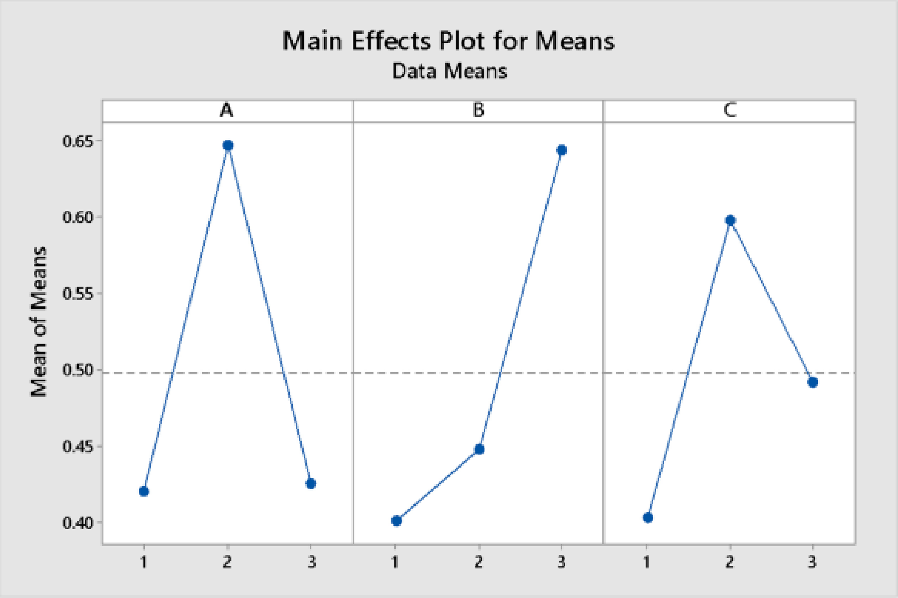

Figure 4.
Graph showing main effects of grey relational grade

follows the same trend as present work. In their work Fuzzy PIV was used to rank the eighteen experimental runs based on the overall proximity index values. The optimal performance of the nanofluid based engine cooling system was obtained for 60°C nanofluid inlet temperature (level 2), 5 kW engine load (level 1), 1.25 l/min nanofluid flow rate (level 1), and 1.0% vol concentration of the nanofluid (level 3). Further from ANOVA results, it was observed that concentration of the nanofluid, nanofluid inlet temperature and nanofluid flow rate significantly affected the multi-responses of the engine cooling having contribution of 41.72, 37.98 and 10.91% respectively.

3.2 Application of ANOVA

ANOVA is a statistical tool that may use to check the any difference in the average performance of group of variables (Yahya *et al.*, 2019; Seraj *et al.*, 2020; Danish *et al.*, 2019). It also helps in finding the interactions among the response variables by comparing the mean square. From Table 7, it is evident that at a significance level of 5% that is $\alpha = 5\%$. The main aim of ANOVA is to identify the importance of input parameters and from the analysis, it is found that ϕ is the most significant process parameter of the said investigation and it's affect the multiple performance characteristics due its highest percentage contribution amongst the process parameter.

3.3 Conformation test

The confirmation test is carried out to validate the optimal results. It is the last stage of any design of experiment. The main aim is to check the robustness of the suggested optimum values or any improvement needed, which can be predicted using (Equation 10) [12].

$$\eta_o = \eta_m + \sum_{i=1}^{j} (\eta_i - \eta_m) \tag{10}$$

Where, j is the number of factors that may affect the performance measure and η_m is the mean value of S/N ratios in all experimental trials, η_i are the S/N ratios corresponding to optimum factor levels. In order to validate the results obtained, confirmation experiments were conducted for each of the performance characteristics (h and Q_r) at optimal levels of the process variables. The average values of confirmation results have been compared with the predicted values. The results are listed in Table 8.

Symbol	Parameters	DOF	Sum of square	Mean square	*F* value	Contributions (%)
A	ϕ	2	0.10096	0.05048	2.02	32.74
B	Flow rate	2	0.10020	0.05010	2.01	32.5
C	Sonication time	2	0.05729	0.02864	1.15	18.57
Error		2	0.04993	0.02497		16.19
Total		8	0.30837			

Table 7.
Results of the analysis of variance

Performance characteristics	Estimated optimal value	Actual value (value obtained through confirmation experiment)
H	64.00491	64.25
Qr	2.150983	2.2062

Table 8.
Results of confirmation experiment

4. Conclusion

In almost all the reviewed literatures, it can be noticed that the thermal properties were influenced and mainly increased. This further helps in enhancing the rate of heat transfer as well as Nusselt number has been increasing everywhere with increasing concentration as well as volume flow rates. But, inverse trend has been observed for the case of temperature.

This paper explored the effect of three parameters of a heat transfer ability of the cooling systems where nanofluids are employed, i.e. ϕ, Flow Rate and Sonication Time. Further, grey relational analysis along with principal component analysis was used to perform multi-response optimization of an automotive cooling system in order to obtain best combination of the process parameters. In addition, ANOVA was employed to determine the significance of the controllable parameters. Based on the results of the present study, following conclusions are drawn:

(1) The optimal combination of process parameters is the set with A2 (Concentration), B3(Flow Rate (LPH)), C2(Sonication Time (min)).

(2) The major controllable parameter that significantly affects the multi-performance characteristics of the automotive cooling system is the ϕ (%).

(3) Confirmation experiments were conducted for each of the performance characteristics (h and Q_r) at optimal levels of the process variables that validate the obtained results.

(4) This piece of research work will be helpful to designers, academician, researchers and other concerned persons, in understanding the importance, severity and benefits obtained by the application, implementation and enhance the heat transfer performance using nanofluid in an automotive cooling system.

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Integrated Taguchi-GRA-PCA for optimising the heat transfer performance of nanofluid in an automotive cooling system

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