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Influence of Physicochemical Properties of Al_2O_3 Nanofluid as Coolant in Automotive Radiator Test rig and Multi Response Optimization of Heat Transfer Rate using Taguchi's Orthogonal Array

Kannan C* & Vijayakumar T

School of Mechanical and Building Sciences, VIT University, Vellore – 632 014, Tamilnadu, India

Abstract: In this research work, the heat transfer with water based nanofluids was experimentally compared to that of pure water as coolant in an automobile radiator. By varying the amount of Al_2O_3 nanoparticles blended with base fluid water, two different concentrations of nanofluids 0.25 % and 0.50 % (by vol.) were obtained. These nanofluids were allowed to flow through the vertical tubes present in the radiator. The flow rate ranges from 0.05 to 0.15 kg/s. The fluid inlet temperature was varying from 35°C to 59°C to find the optimum inlet condition. An attempt was also made to maximize the heat transfer rate of an automotive radiator without excessive compromise on radiator pumping loss and coolant cost. Three factors namely nanoparticle concentration, flow rate and inlet temperature of coolant were chosen as the influencing factors for the set objective. Experiments designed by employing design of experiments method and Taguchi's L_9 orthogonal array were adopted to run the automotive radiator test rig. An indigenous automotive radiator test rig was developed as part of this research work. MRSN ratio was calculated for the response variables and the optimum combination level of factors was obtained simultaneously using Taguchi's parametric design. Obtained combination was confirmed experimentally and significant improvement was observed in the response variables.
Keywords: Automotive Radiator, Heat Transfer, Nanofluid, Taguchi's Orthogonal Array, MRSN, DOE.

1. Introduction

Day by day, the need for improving the heat transfer rate from thermal equipments has been increasing for an effective cooling process. Even though, several methods are available at present to increase the heat transfer rate like introducing fins at the outer periphery of the thermal systems, increased flow rate of coolant through the thermal systems, these methods do have their own limitations. The increased flow rate of coolant also increases pump work thus results in low cycle efficiency. The introduction of fins leads to undesirable size increase in thermal management system. The conventional fluids like water, engine oil, refrigerants are not satisfying need of high compactness and effectiveness.

S Zeinali Heris et al [1] reported that heat transfer coefficient of a nanofluid increases with an increase in their nano particles concentration. However thermal conductivity is not the sole reason for heat transfer enhancement but other properties such as dispersion, chaotic movement of particles, brownian motion and particle migration are equally important.

Weerapun Duangthongsuk et al [2] conducted an experimental study on forced convective heat transfer of nanofluid, where the nano fluid is a blend of water and 0.2% TiO_2 (by Vol.) under turbulent flow conditions. The final results confirmed an increased heat transfer coefficient with an increase in the mass flow rate of hot water and decrease in nano particle temperature.

Kim et al [3] investigated the effect of nanofluid on the performance of convective heat transfer coefficient of a circular straight tube having laminar and turbulent flow with constant heat flux. Authors have found that the convective heat transfer coefficient of alumina nanofluids is improved in comparison to the base fluid by 15% and 20% in laminar and turbulent flow respectively.

Rea et al [4] studied the convective heat transfer coefficient of alumina/water and zirconia/water nanofluids in a flow loop with a vertical heated tube. The heat transfer coefficient in the entrance region and in the fully developed region was found to increase by 17% and 27% respectively for alumina/water nanofluid at 6% (by vol.) whereas it was 2% in the entrance region and 3% in the fully developed region for zirconia/water nanofluid at 1.32% (by vol.) with respect to pure water.

Farajollahi et al [5] measured the heat transfer characteristics of g-Al_2O_3/water and TiO_2/water nanofluids in a shell and tube heat exchanger under turbulent flow condition. According to their report, the maximum enhancement of the overall heat transfer co efficient of g-Al_2O_3/water nanofluids was approximately 20% which occurred at 0.5% volume concentration. At the Peclet number of 50,000, the enhancements of the overall heat transfer coefficient at 0.3%, 0.75%, 1%, and 2% nano particle volume concentrations were about 14%, 16%, 15% and 9% respectively. For TiO_2/water nanofluids the maximum enhancement was observed at 0.3% particle volume concentration.

S M Fotukian et al [6] experimentally studied convective heat transfer of diluted CuO/water nanofluid inside a circular tube. They used nanofluids with nano particles of volume fraction less than 0.3%. The heat transfer coefficient increased about 25% when compared to that of pure water.

Xie et al [7] demonstrated that using Al_2O_3, ZnO, TiO_2 and MgO nanofluid with a mixture of 55% (by vol.) distilled water and 45% (by vol.) ethylene glycol as the base fluid in laminar flow inside a circular copper tube with constant wall temperature could enhance the convective heat transfer. MgO, Al_2O_3 and ZnO nanofluids exhibited superior enhancements of heat transfer coefficient, with the highest enhancement up to 252% at a Reynolds number of 1000 for MgO nanofluid.

Leong et al [8] investigated the performance of Cu/Ethylene Glycol nanofluids in an automotive car radiator. They revealed that overall heat transfer coefficient of 164 W/m^2K can be achieved for 2% (by vol.) Cu/Ethylene Glycol nanofluid compared to that 142 W/m^2K with the base fluid.

In this work, the multi response optimization of heat transfer rate of automotive radiator was performed using Al_2O_3 nanofluid as coolant and optimum combination of nanoparticle concentration, flow rate and inlet temperature of the coolant was determined using MRSN ratio and reported in this paper.

2. Nanofluid Preparation and Stabilization

The preparation of a stabilized nanofluid is of great importance in heat transfer applications which utilizes that nanofluid. Inappropriate preparation of nanofluid will render biphasic heat transfer and also poses the danger of nano particle aggregation. Furthermore, particle instability results in particle fouling in reservoir, pipes, pumps and other equipment of thermal cycle, all of which are considered undesirable factors in our experiment. Al_2O_3 nano particles used in this study are approximately spherical with an average diameter of about 45 nm. The other physicochemical properties of the nano particle are shown in Table 1. The nanofluid under investigation was purchased in the form of colloidal dispersion from Alfa Aesar, US and the same was dispersed in the base fluid water using ultrasonicator for 2 hours prior to the experimentation. It has been found that the nanofluid had the lowest nano particle sedimentation and highest stability even after 60 h in a stationary state.

Table 1 Physico-chemical Properties of Nanofluid

Parameter	Aluminum Oxide
Chemical formula	Al_2O_3
Product Number & Brand	A1522 & Sigma-Aldrich
Thermal conductivity(W/mK)	36
Particle Size (nm)	42
Relative density (kg/m^3)	3600
Melting point (°C)	2980
Experimental Refraction Index	1.7625
Experimental Solubility	Soluble in hexane, toluene

3. Experimental Programme

3.1. Experimental Setup

The schematic layout and photographic view of the experimental system used in this research is shown in Fig 1. It includes a reservoir tank, a feed pump, an electrical heater, a flow meter, a forced draft fan, a temperature controller, two thermocouples and an automobile radiator. The test section of the radiator was placed in front of the forced draft fan and its configuration is the louvered fin-and-tube type. Nanofluid was allowed to pass through the 57 vertical tubes with stadium-shaped cross section. The fins and the tubes are made with aluminium.

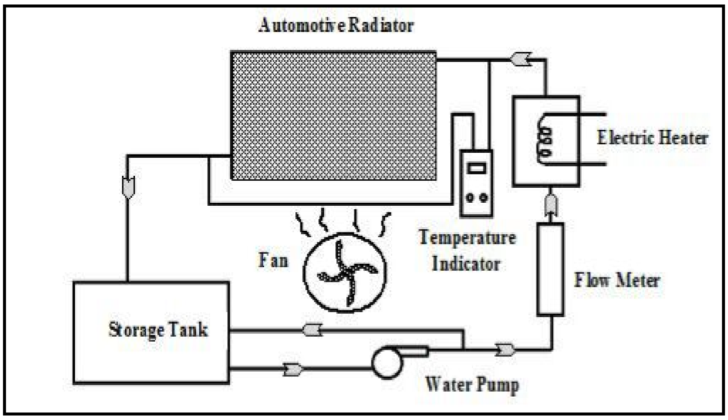

Fig 1.Schematic layout and photographic view of experimental setup

The size and dimensions of the radiator is shown in Table 2. For cooling the liquid, a forced draft fan (Almonard 1440 rpm) which is capable of producing air delivery of 270 m^3/hr was installed facing the radiator core. The inlet air temperature was about 27°C in the whole experiments. The pump was driven at constant speed to deliver a constant flow rate of 0.24 m^3/h, and the flow rate to the test section was being regulated by using an appropriate flow meter. The reservoir tank is having the storage capacity of approximately 32L in which, the working fluid always fills 62.5% of storage capacity. The connecting lines were covered with insulating materials to reduce heat loss to the surrounding. A flow meter (RMS Controls India) was used to control and manipulate the liquid flow rate with high precision. For heating the working fluid, an electrical heater (3000 W) and a temperature controller were used to vary the temperature between 35 and 59°C. Two K type thermocouples were implemented on the flow line to record the radiator fluid inlet and outlet temperatures. The temperatures from the thermocouples were measured by using a digital multimeter (RMS Controls India) with accuracy of 0.1 °C.

Table 2 Geometrical Properties of radiator

Description	Value
Fin Type	Ruffled
Fin Thickness (m)	0.04 x 10^{-3}
Hydraulic diameter (m)	0.6 x 10^{-3}
Frontal area of radiator (m^2)	129.8
Number of tubes	57

The experimental runs were made by the usage of nanofluids in the radiator but with different concentrations of nanofluids. The concentration of nanofluids used in this experiments were 0.25 % and 0.5 % Al_2O_3 in Water (Vol %), while the flow rate was varied from 0.05 kg/s to 0.15 kg/s, the inlet temperature was varied from 35°C to 59°C in these runs. The results were shown in Fig 2 and 3.

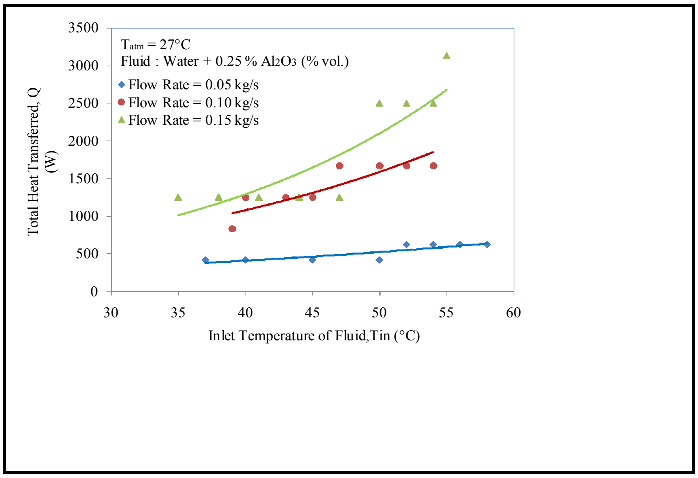

Fig 2. The influence of inlet temperature and flow rate of Al_2O_3 nanofluid (0.25 % Vol) on the total heat transferred from radiator

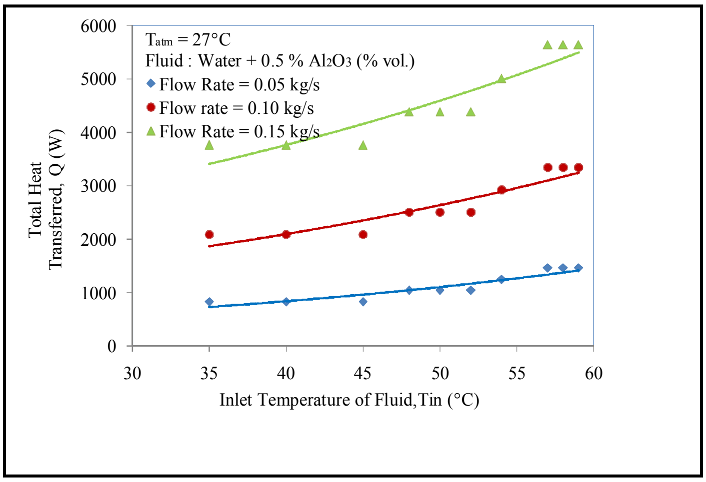

Fig 3. The influence of inlet temperature and flow rate of Al_2O_3 nanofluid (0.50 % Vol) on the total heat transferred from radiator

The effect of flow rate and nano fluid concentration on the amount of heat transferred from the automotive radiator for a constant inlet coolant temperature of 50°C was shown in Fig 4. From the figure, it was evident that an increase in the coolant flow rate optimistically influenced the amount of heat transferred. The same trend was observed in all the three cases, when the nano fluid concentration was increased from 0 % to 0.25 % and then next to 0.50 % (vol.). This may be due to the fact that increased thermal conductivity due to the addition of nano particles in the base fluid water. The thermal conductivity was increased 0.7 % and 1.4 % for 0.25 % and 0.50 % nanofluid concentrations respectively.

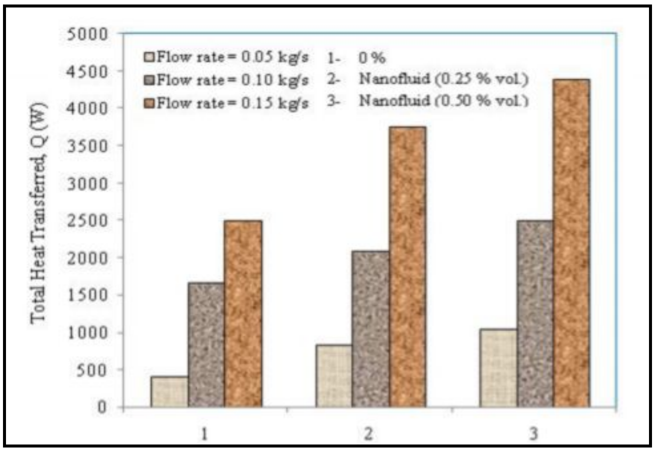

Fig 4. Effect of flow rate and concentration of nanofluid on the total heat transferred

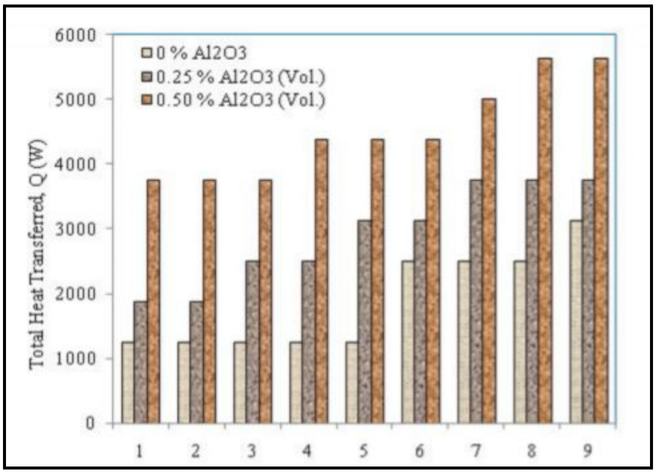

Fig 5. Effect of nanofluid concentration of nanofluid on the total heat transferred for varying inlet temperature

The effect nano fluid concentration on the amount of heat transferred from the automotive radiator for varying inlet temperature of coolant from 35°C to 57°C was shown in Fig 5. The outlet temperature was measured for every 3°C increase in the inlet temperature. From that, the amount of heat transferred from the radiator was calculated. An increase in heat transfer was observed for the increase in coolant temperature. As the concentration of nanofluid increases, the amount of heat transferred was also found to be slightly increased.

3.2. Taguchi Design and Selection of Factor Levels

Before proceeding with optimization, the experiment was designed by following the design of experiments (DOE) method. For the formulated problem, nanoparticle concentration, flow rate and inlet temperature of coolant are considered as the factors influencing the objective.

The levels of the factors to be included for testing were chosen based on the conclusion of the earlier researchers during their research work with those factors individually. For concentration of nanoparticles in the coolant, three levels were chosen such as 0% (without nanoparticle addition), 0.25 % (by vol.) in the base fluid and 0.50 % (by vol.) in the base fluid. Further increase in the concentration of nanoparticles will lead to sedimentation problems [5]. To avoid the increase in pumping loss, the maximum flow rate of coolant was fixed as 0.15kg/s and within that 0.05 kg/s and 0.10 kg/s were chosen as the other two levels. For the inlet temperature of coolant, 55°C was fixed as the maximum temperature considering the smooth operation of the radiator and two more levels were chosen including this level. Table 3 shows the three levels of the chosen factors.

Table 3 Factors influencing the objective with chosen values

Factor No	Factors influencing the objective	Level of Factors		
		1	2	3
1	Nanoparticle concentration (%)	0	0.25	0.50
2	Flow rate of coolant (kg/s)	0.5	0.1	0.15
3	Inlet temperature of coolant (°C)	45	50	55

Taguchi Orthogonal Array (OA)

In full factorial experiment for three factors with three levels, the number of experiments will be $3^3 = 27$. To reduce the number of experiments to be conducted, experiments were designed by using Taguchi orthogonal array (OA) technique. For more than two numbers of three level factors, the recommended OA is L_9 [31] which were given in Table 3. In Table 4, column 1 indicates the levels of factor 1 (nanoparticle concentration), column 2 the levels of factor 2 (flow rate of coolant) and column 3 the levels of factor 3 (inlet temperature of coolant).

Table 4 L_9 Orthogonal array OA)

Trial No	Column 1	Column 2	Column 3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

3.3. Uncertainty analysis

Errors and uncertainties in the experiments can arise from instrument selection, condition, calibration, environment, observation, reading and test planning. The percentage uncertainties of various parameters like coolant flow rate, air flow rate, coolant inlet temperature and outlet temperature were calculated using the percentage uncertainties of various instruments. Total percentage uncertainty of this experiment is = Square root of {(uncertainty of coolant flow rate)^2 + (uncertainty of air flow rate)^2 + (uncertainty of inlet temperature)^2 + (uncertainty of outlet temperature)^2} =square root of $\{(1)^2 + (1)^2 + (0.5)^2 + (0.5)^2\} = 1.58\%$. Furthermore, to check the reproducibility of the experiments, some runs were repeated later which proved to have excellent repeatability.

3.4. Estimation of Nanofluid Properties

In this research, the nano particles had been dispersed within the base fluid using ultrasonicator and further it was assumed uniform particle concentration throughout the system. The effective physical properties of nanofluid like density, specific heat, viscosity and thermal conductivity at different temperatures and concentrations were calculated using the following relations.

$$\rho_{nf} = \varphi\rho_p + (1-\varphi)\,\rho_w \qquad (1)$$
$$(\rho C_p)_{nf} = \varphi(\rho C_p)_{nf} + (1-\varphi)\,(\rho C_p)_w \qquad (2)$$
$$\mu_{nf} = \mu_w\,(123\varphi^2 + 7.3\varphi + 1) \qquad (3)$$
$$k_{nf} = [k_p + (n-1)k_w - \varphi(n-1)(k_w-k_p)] \,/\, [k_p + (n-1)k_w + \varphi(k_w-k_p)]*k_w \qquad (4)$$

In the above equations, the subscripts p, w and nf refer to the particles, water, and nanofluid respectively. n is empirical shape factor given by $n = 3/\psi$ where ψ is the particle sphericity and is defined as the ratio of the surface area of a sphere with volume equal to that of the particle, to the surface area of the particle, and in this paper n considered to be 3 and φ is volume fraction of the nano particle added to the water.

4. Analysis of Data

The obtained responses from each trial for different operating conditions of automotive radiator were analyzed to get a result for the formulated problem.

4.1. Optimization

For the formulated problem, three variables have been chosen as the responses and multi response signal to noise ratio (MRSN) was used to get the optimum level of combination. The procedure employed in the optimization process is explained.

4.1.1. Loss Function

As per the Taguchi categorization of response variables, smaller the better principle is considered to minimize the nanoparticle concentration and coolant cost. For the heat transfer rate, larger the better principle is considered to maximize it. For each of that case, the corresponding loss function can be expressed using Equations (5) and (6).

For larger the better (heat transfer rate)

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{y^2_{ijk}} \tag{5}$$

For smaller the better (nanoparticle concentration and coolant cost)

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n} y^2_{ijk} \tag{6}$$

Where n is the number of repeated experiments, L_{ij} is the loss function of the i^{th} response variable in the j^{th} experiment and y_{ijk} is the experimental value of the i^{th} response variable in the j^{th} experiment at the k^{th} test.

4.1.2. Normalizing the Loss Function

Because of the different measured unit, the loss function was normalized in the range between zero and one. Normalization of loss function was done using Equations (7) and (8).

For larger the better (heat transfer rate)

$$S_{ij} = \frac{\min L_{ij}}{L_{ij}} \tag{7}$$

For smaller the better (pumping loss and cost)

$$S_{ij} = \frac{L_{ij}}{\max L_{ij}} \tag{8}$$

For larger the better (heat transfer rate) where S_{ij} is the normalized loss function for the response variable in j^{th} experiment, L_{ij} is the loss function for the ith response variable in the j^{th} experiment and L_{ij} is the average loss function for the i^{th} response variable.

4.1.3. Assigning Weighting

To determine the importance of each normalized loss function, weighting method was employed. The total loss function can be expressed using Equation (9)

$$TL_i = \sum_{i=1}^{m} w_i s_{ij} \tag{9}$$

Where w_i is the weighting factor for the i^{th} response variable and m is the number of response variables.

Since the main objective of the present work was to increase heat transfer rate from radiator with minimum pumping loss and cost. Hence higher weightage was assigned to heat transfer rate when compared to the other two. Initially 0.6 (w_1), 0.4 (w_2) and 0.1 (w_3) were assigned as weighting factors for the response variables heat transfer rate, pumping loss and cost respectively.

4.1.4. MRSN

Multi response signal to noise ratio (MRSN) was calculated from the total loss function by using the Equation (10).

$$MRSN = -10\log(TL_i) \tag{10}$$

Taguchi technique was employed to determine the optimal level of combinations for the obtained MRSN ratio corresponding to the assigned weighting factor. Finally the obtained combination was confirmed through an experiment.

4.1.5. Verification

After conducting the confirmation experiment with the optimum combination, the improvement in the response variable was verified by comparing it with the normal operating conditions.

5. Results and Discussion

5.1. MRSN Ratio

MRSN ratio for the experiments conducted was given in Table 5 for the weighting factor of $w_1 = 0.6$, $w_2 = 0.4$ and $w_3 = 0.1$. From the table the combination which has the maximum MRSN ratio will be taken as the best combination among the nine in achieving the objective. It can be observed that the experiment number 4 (2-1-2) is the best combination among the nine.

Table 5 MRSN ratio for $w_1 = 0.5$, $w_2 = 0.4$ and $w_3 = 0.1$

Exp. No	Loss Function (L_{ij})			Normalization (S_{ij})			Weighting ($w_{ij}S_{ij}$)			TL_i	MRSN ratio
	Larger the Better	Smaller the Better									
	Heat Transferred	Viscosity	Cost								
1	0.000005726	0.59598400	0	0.0	0.8	0.0	0.00	0.34	0.00	0.34	4.6
2	0.000000357	0.47472100	0	0.1	0.6	0.0	0.07	0.27	0.00	0.34	4.6
3	0.000000101	0.42380100	0	0.5	0.6	0.0	0.25	0.24	0.00	0.49	3.0
4	0.000001431	0.50979600	4000000	0.0	0.7	0.2	0.01	0.29	0.02	0.33	4.8
5	0.000000159	0.46376100	4000000	0.3	0.6	0.2	0.16	0.26	0.02	0.45	3.4
6	0.000000159	0.59598400	4000000	0.3	0.8	0.2	0.16	0.34	0.02	0.52	2.8
7	0.000000636	0.55651600	1600000	0.0	0.8	1.0	0.04	0.31	0.10	0.45	3.4
8	0.000000229	0.69889600	1600000	0.2	1.0	1.0	0.11	0.40	0.10	0.61	2.1
9	0.000000051	0.60684100	1600000	1.0	0.8	1.0	0.50	0.34	0.10	0.94	0.2

5.2. Confirmation Experiment

Optimum combination level obtained by Taguchi's parametric design was confirmed experimentally and the response variables of optimum combination have been compared with the response variables of the experiments conducted with the normal operating condition. Table 5 shows the response variables at the optimized condition and the same is compared with the variables at normal operating condition. It can be seen that heat transferred was increased as a result of this combined effect. This increase in heat transfer rate was due to enhanced heat transfer mechanism due to the addition of nanoparticles. Since the main objective of the work was to increase the heat transfer rate without much pumping losses, second level of nanoparticle concentration (0.25%), first level of flow rate (0.05 kg/s) and second level of inlet temperature (50°C) was the optimum combination. This combination increases the heat transfer rate by a factor of 2 with a reduction of 7.5 % in pumping losses.

From the optimization results, it was concluded that out of the three operating parameters considered, the flow rate was found to be the most influencing parameter which was followed by nanofluid concentration and inlet temperature of nano fluid respectively. Hence if one wants to increase the amount of total heat transferred from the radiator, the emphasis should be given to flow rate of nanofluid instead of concentration and their inlet temperature.

6. Conclusions

In the present work the optimum combination of nanoparticle concentration, flow rate and inlet temperature of the coolant in increasing the heat transfer rate without much compromise on pumping losses was arrived by calculating MRSN ratio. MRSN ratio was calculated by assigning different weighting factor to each response variable. From the results of the optimization techniques, the following conclusions are drawn.

1. Flow rate of nanofluid coolant plays a crucial role in increasing the heat transfer rate and reduced pumping losses.
2. Inlet temperature of nanofluid coolant was less effective on the set objective when compared with other two.
3. Nanoparticle concentration of 0.25 % with flow rate of 0.05 kg/s and inlet temperature of 50°C will be the optimum combination for increasing the heat transfer rate with much less pumping losses.

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