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OPTIMIZATION OF TEMPERATURE AND VELOCITY ON HEAT TRANSFER ENHANCEMENT OF NON-AQUEOUS ALUMINA NANOFLUID

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Abstract

Nanofluids have been a subject of intensive study due to its distinctive thermal conductivity and convective heat transfer properties. Although numerous researches have evaluated the convective heat transfer properties of nanofluids, these evaluations were performed based on one-factor-at-a-time analysis, hence neglecting interaction effects between factors. Besides that, to the author's knowledge, optimization of factors affecting convective heat transfer was also never performed. Therefore in this investigation, a multifactorial design method, Design of Experiments (DOE) was used to evaluate the interaction between temperature and velocity on heat transfer of alumina nanofluids. Optimization of factors was also performed using both experimental and analytical analyses. The experimental study was executed using a straight circular tube with constant heat flux and laminar flow regime, whereas the analytical study was performed using Design Expert (version 7.0) on the basis of Central Composite Design (CCD) and Response Surface Methodology (RSM). Statistical analysis of variance (ANOVA) was performed to evaluate the significance of the results. Through both analyses, results have shown that the interaction effects between mentioned factors were found to be highly significant in influencing heat transfer enhancement. The maximum heat transfer enhancement was recorded at significant values of 115.5% and 108.8% for heat transfer coefficient and Nusselt number, respectively. Through optimization, the optimum operating conditions in this range of study were determined at temperature and velocity of 35 °C and 0.6 m/s, respectively. All experiments were performed with an uncertainty of below 5%.

Keywords: Nanofluids, Alumina, Heat transfer, Thermal conductivity, Optimization.

Nomenclatures

C_p	Specific heat capacity
CNT	Carbon nanotube
D	Inner diameter, m
EG	Ethylene glycol
h	Convective heat transfer coefficient, W/m²K
k	Thermal conductivity, W/mK
Nu	Nusselt number
P	Surface perimeter, m
Pr	Prandtl number
q"	Heat flux, W/m²
Re	Reynolds number
SDBS	Sodium dodecylbenzene sulfonate
T	Temperature, °C

Greek Symbols

$\dot{m}$	Mass flow rate, kg/s
μ	Viscosity, Ns/m²
ρ	Density, kg/m³

Abbreviations

ANOVA	Analysis of Variance
CCD	Central Composite Design
DOE	Design of Experiments
RSM	Response Surface Methodology
THW	Transient Hot Wire

1. Introduction

The unprecedented expansion of power consumption due to the exponential growth of technologies and industries in the recent years has made optimizing efficiency essential in many engineering design processes. Throughout the years, engineers and scientists have invested much effort in improving the productivity and efficiency of various engineering design processes such as the heat transfer process. Heat transfer process portrays a vital role in various fields of applications such as micro-electronics, refrigeration, cooling systems of nuclear power plants, biomedical applications and transportation [1]. However, the performance of heat transfer fluids such as water and ethylene glycol are often limited by their low thermal conductivities. Driven by the industrial needs of device miniaturization and process intensification, numerous methods have been attempted in the past few decades to improve the heat transfer characteristics of these fluids. One of the methods in augmentation of heat transfer is by instigating the development of nanofluids.

The pathway of research and innovation in the field of nanofluids was initiated in 1995 at the Argon National Laboratory, where Choi [2] has conducted experiments in ultra-fine materials such as titanium dioxide, silicon dioxide and aluminium oxide and reported significant enhancement in thermal conductivity and heat transfer. Hence, Choi and his colleagues have then officially introduced and decided to coin the term "nanofluids" for these colloidal suspensions. As a consequence, the significant findings reported by Choi have sparkled interests of numerous researchers in investigating the thermal conductivity and heat transfer properties of various types of nanofluids. Wen and Ding [3] studied the heat transfer enhancement with the addition of alumina nanoparticles in deionized water in a copper tube under laminar flow regime. The results indicated that the Nusselt number was enhanced up to 47% with 1.6% volume fraction of nanoparticles. Wen and Ding concluded that the enhancement of convective heat transfer increases with Reynolds number, as well as particle concentration. Lai *et al*. [4] also performed research on the alumina nanofluids subjected to a constant wall heat flux at a Reynolds number of less than 270 and has reported agreeable results with Wen and Ding where the enhancement of Nusselt number was increased from 3% to 8% as the vol. conc. of nanoparticles were increased from 0.5% vol. conc. to 1% vol. conc. Besides that, Kim *et al.* [5] also investigated the effects of 3% vol. conc. of alumina nanofluids on convective heat transfer under constant heat flux of different Reynolds number in both laminar and turbulent flows and has reported an enhancement of 15% and 20% in laminar and turbulent flow, respectively. Apart from volume concentration and Reynolds number, temperature dependence of convective heat transfer with alumina nanofluids in turbulent flow region under constant heat flux were also studied by Kwon et al. [6] and results have shown an increase in convective heat transfer coefficient from 14% to 30% as the temperature increased from 22 °C to 75 °C. On the other hand, Heris *et al.* [7] have examined the laminar flow convective heat transfer under a constant wall temperature condition of alumina-water nanofluids through a circular tube and has reported an augmentation of heat transfer coefficient up to 40% with 2.5% vol. conc. of alumina nanoparticles. Heyhat *et al.* [8] also studied the laminar convective heat transfer of water-based alumina nanofluids with a constant wall temperature and reported an increase of 32% in the fully developed region at 2% vol. conc. of alumina nanoparticles. Besides that, Heyhat also highlighted that the augmentation in Reynolds number will significantly increase the convective heat transfer coefficient. On the other hand, Mojarrad *et al.* [9] conducted research in evaluating between the heat transfer enhancement of alumina/water and alumina/water-ethylene glycol 50-50 by volume (WEG50) nanofluids and have reported a maximum enhancement of 24% for 1% vol. conc. of alumina/water-ethylene glycol. Mojarrad also mentioned that the alumina/WEG50 nanofluids exhibit a higher heat transfer increment as compared to alumina/water nanofluids.

From these researches, it can be observed and concluded that volume concentration, velocity and temperature are all significant parameters in affecting the heat transfer of nanofluids. However, although numerous investigations were performed by varying the mentioned factors, these factors were performed on the basis of OFAT and are incapable of determining the true optimum as interaction between factors were neglected. Besides that, optimization of heat transfer enhancement was also never performed by any researcher at the moment, according to the author's knowledge. Therefore, the present investigation was performed using a multifactorial design consisting factors of temperature and velocity in order to study and evaluate their respective interaction effects. The optimization between the two mentioned factors was also performed under a constant heat flux boundary condition and in a laminar flow regime using Design of Experiments (DOE). DOE has been adapted by numerous researches in the recent years in their investigations to perform multi-levelled factorial designs and to determine their optimized desired factors in order to obtain either a minimized or maximized response. Recently, Gunaraj and Murugan [10] have performed CCD and RSM methods to optimize and determine the interaction effects between the open-circuit voltages, wire feed rate, welding speed and nozzle-to-plate distance in the submerged arc welding of pipes. Besides that, Ghafari *et al.* [11] also adapted the CCD and RSM techniques in optimizing operating variables versus pH value and coagulant dosage. Furthermore, Zabeti *et al.* [12] also performed optimization of the activity of CaO catalyst for biodiesel production using CCD and RSM, where the interaction effects and optimum values of variables: precursor dosage and calcination temperature were investigated to produce a maximum yield. Apart from that, Low *et al.* [13] also applied RSM in the optimization of thermophysical properties of composite materials. Ghadimi [14] also applied CCD, RSM and Box-Behnken Design (BBD) in the investigation of effects and interaction between nanoparticle volume concentration and power on the stability and thermal conductivity of nanofluids.

Although extensive amounts of researches in terms of optimization in various fields were carried out, there are very limited studies that were conducted on the optimization of heat transfer enhancement of nanofluids. Therefore, in the present investigation, optimization of two independent variables; namely temperature and velocity was performed in order to determine a maximum enhancement of heat transfer in alumina nanofluids. CCD and RSM were both chosen as methods of optimization in this investigation and were both performed to analyze and evaluate the obtained results. By performing optimization, a maximum performance of heat transfer can be obtained. This is especially important when nanofluids are adapted in various fields of applications in the future such as heating, ventilation and air-conditioning (HVAC) systems and pressurized water reactor in nuclear reactors which are all operating in enormous scales. Therefore, a maximized performance of heat transfer will be achieved in these systems to attain the highest effectiveness and ultimately resulting in a significant improvement in both cost efficiency and productivity.

2. Experimental Procedure

The initial step of this investigation was to prepare a stable and homogenized nanofluid suspension from alumina nanoparticles and base fluid. Once a stable nanofluid suspension was prepared, the thermal conductivity and viscosity of nanofluids were determined. Next, the experimental setup used to measure heat transfer coefficient was calibrated to ensure validity and accuracy of results. Upon calibration, the experiment was then performed at different temperatures and velocities in accordance to the runs generated by DOE. Once sufficient data was obtained, the significance of the factors and their interactive effects on the heat transfer enhancement were analysed and evaluated using CCD and RSM methods. Optimization of temperature and velocity were also performed to determine the optimum operating conditions of this specific study. Lastly, error analysis was performed using ANOVA to determine the significance and adequacy of the investigation. These series of procedures mentioned will chronologically be further elaborated in each sub-section.

2.1. Preparation of nanofluids

The nanoparticle selected for this investigation was the commercially available γ-aluminium oxide (Al_2O_3) with an average size of 13 nm and a purity of 99.8% purchased from Sigma Aldrich. On the other hand, the base fluid comprises of a mixture of high purity ethylene glycol (EG) purchased from Fluka Company and deionized water with a mass ratio of 60:40. This mixture is commonly used as heat transfer fluids for heat exchangers, automobiles and building heating systems in cold regions as ethylene glycol serves as an anti-freeze agent that will significantly lower the freezing point of a mixture to prevent solidification [15]. An anionic surfactant, sodium dodecylbenzene sulfonate (SDBS) in technical grade was also purchased from Sigma Aldrich in order to enhance dispersion.

The conventional two-step method was adapted to prepare the alumina nanofluid suspensions as it is known as one of the most common and reliable nanofluid preparation technique [15, 16]. To begin, ethylene glycol and water was firstly added and stirred via a magnetic stirrer for approximately 10 minutes. Next, SDBS was added into the mixture with an equal amount of mass used for nanoparticles. Again, the suspension was stirred with a magnetic stirrer for about 15 minutes to ensure homogeneity. According to Dehkordi *et al.* [16], SDBS has shown fair results in dispersing alumina nanoparticles without influencing the thermal conductivity and viscosity of the suspension. Upon achieving a homogenous mixture, alumina nanoparticles of 1% vol. concentration were weighed via a four decimals balance by A&D Weighing (Model GR-200) and were added to the suspension. The colloidal suspension was then ultrasonicated for exactly 90 minutes with an ultrasonic bath by Branson (Model 3210 R-MT) with a 40 kHz ultrasonic frequency and power of 350 W. In accordance to Dehkordi [15], 90 minutes of ultrasonication period is determined as the optimum ultrasonication time. It is crucial to ensure that the ultrasonication period does not exceed the optimum ultrasonication time as this will trigger the agglomeration of nanoparticles and promote settling of particles, ultimately causing a reverse effect. The stability of alumina nanofluids were evaluated via sediment photograph capturing and were observed to be stable over a period of more than one week without any visible sedimentation.

2.2. Measurement of thermal conductivity and viscosity

The thermal conductivity and viscosity of alumina nanofluids were measured prior to performing the experiment as both of these parameters were preliminary parameters required to measure the convective heat transfer and Nusselt number. As the temperature range in this study falls between 15 °C to 35 °C, both parameters were measured at a range of 15 °C to 35 °C at 5 °C intervals (15, 20, 25, 30 and 35 °C). The thermal conductivity of alumina nanofluids were measured using a KD2 Pro Thermal Properties Analyzer manufactured by Decagon Devices. No calibration was required as the equipment is factory calibrated. A total of 5 readings of thermal conductivities at an average of 15-minute interval was recorded for each temperature measurement and was averaged out to minimize error and to ensure data reproducibility. In order to regulate temperature, the suspension was immersed in a refrigerated bath circulator manufactured by WiseCircu with an accuracy of ±0.1 °C. On the other hand, the viscosities of alumina nanofluids were determined via a Vibro Viscometer manufactured by A&D Company (Model SV-10) with an uncertainty of ±3%. Prior to measuring the viscosity, the viscometer was calibrated using distilled water to ensure accuracy and reliability.

2.3. Experimental system

After obtaining the required preliminary data, the following step would be to measure the convective heat transfer coefficient of alumina nanofluids. The experimental system constructed to measure convective heat transfer coefficient was represented in a schematic diagram as shown in Fig. 1. The experimental loop consists of a nanofluid reservoir, a peristaltic pump, a heat transfer section, a data acquisition system, a cooling system and lastly a DC power supply. The peristaltic pump used for this investigation was manufactured by Longerpump (Model BT600-2J) with an attachable pump head (Model YZ1515x) and a rotating diameter of 0.056 m with an adjustable rotating speed. The heat transfer section on the other hand consists of a copper tube of 1.54 m in length and 3.53 mm in inner diameter. Four K-type thermocouples with a precision of 0.1 °C were mounted on the heating section along the copper tube at axial positions from T_1 to T_4 of 78 mm, 443 mm, 689 mm and 1191 mm, respectively from the inlet as seen in Fig. 1 in order to measure wall temperature distribution. Two K-type thermocouples (T_{in} and T_{out}) were also installed at the inlet and outlet of the test section to measure bulk temperature. The heating section was heated with a silicon rubber flexible heater linked to a DC power supply with a maximum power of 90 W manufactured by Watlow Electrics. In order to obtain a constant heat flux condition, the copper tube was insulated with a thick thermal isolating layer to minimize heat loss. Lastly, the inlet temperature of the heating section was manipulated by using a cooling system consisting of a thermal water bath and a heat exchanger. The ranges of temperature and velocity performed in this experiment falls between 15 °C to 35 °C and from 0.35 m/s to 0.75 m/s, respectively due to experimental limitations. The experiment was performed in accordance to a set of runs determined by the design matrix generated by Design of Experiments software. All data collected for the experiment were logged using a Graphtec data logger.

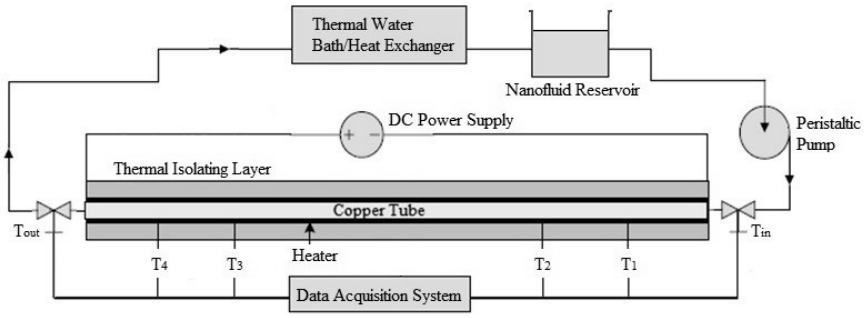


Fig. 1. Schematic diagram of experimental system.

2.3.1 Calibration of experimental system

Prior to the experiment, calibration was performed in order to evaluate the accuracy and reliability of the experimental system. The experimental setup was tested using deionized water as the working fluid and the obtained results were evaluated with the predictions of the well-known Shah equation under the state of constant heat flux and laminar flow regime [17]:

$$Nu \begin{cases} 1.953(\mathrm{Re}\,\mathrm{Pr}\dfrac{D}{x})^{1/3} & (\mathrm{Re}\,\mathrm{Pr}\dfrac{D}{x}) \geq 33.3 \\ 4.364 + 0.0722\,\mathrm{Re}\,\mathrm{Pr}\dfrac{D}{x} & (\mathrm{Re}\,\mathrm{Pr}\dfrac{D}{x}) < 33.3 \end{cases} \tag{1}$$

The comparison of the heat transfer coefficient between measured data and Shah equation was presented in Fig. 2, at Re = 1157.

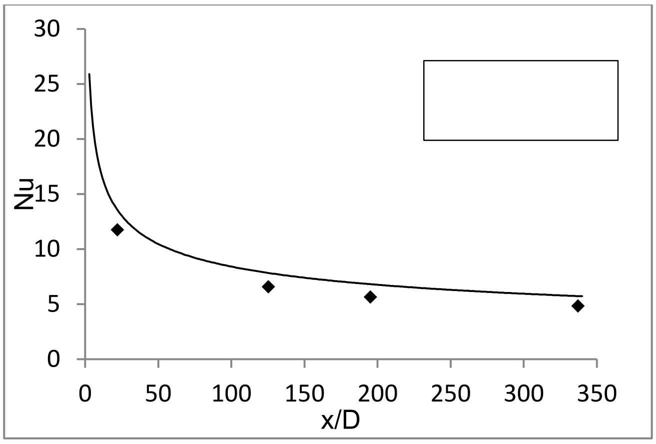


Fig. 2. Comparison of heat transfer coefficient between measured data and Shah equation at Re = 1157 using deionized water.

From Fig. 2, a reasonably good agreement was observed between measured data and Shah equation, with a maximum deviation of 16% observed. The reason for this deviation may be due to the difference in tube sizing, as Shah equation was formulated on the basis of large channel tubes, but the copper tube used in this experiment is much smaller in comparison [5, 18, 19].

3. Theory

Upon executing the experiment and obtaining sufficient data, the calculation of average heat transfer coefficient, Nusselt number and Reynolds number were performed for both alumina nanofluids and base fluids, respectively. The average convective heat transfer coefficient was calculated by following the Newton's law of cooling equation as of Eq. (2):

$$h_{avg} = \frac{q''}{T_{out} - T_{in}} \tag{2}$$

Parameters involved in calculation of Eq. (2) include q", T_{out} and T_{in} which represent heat flux, outlet temperature and inlet temperature, respectively. Heat flux used throughout the experiment remains constant at a constant power supply of 67.5W. With the convective heat transfer coefficient obtained, the representative dimensionless group of heat transfer, the average Nusselt number was determined by:

$$Nu_{avg} = \frac{h_{avg} D}{k} \tag{3}$$

where parameters D and k denote the inner diameter of copper tube and thermal conductivity, respectively. Lastly, Reynolds number was also calculated using Eq. (4) as of below:

$$\mathrm{Re} = \frac{\rho V D}{\mu} \tag{4}$$

Parameters ρ, V, and μ in this equation constitutes to the density of working fluids, velocity of fluid flow and viscosity of working fluids, respectively. Upon obtaining the average heat transfer coefficient, Nusselt number and Reynolds number of both alumina nanofluids and base fluids at different temperatures and velocities, the enhancement ratio was calculated and the heat transfer enhancement of alumina nanofluids were analysed and evaluated using CCD and RSM methods of DOE.

3.1. Optimization using Design of Experiments (DOE)

The Design Expert (version 7.0) software was used to perform the optimization of the heat transfer enhancement of alumina nanofluids. In this investigation, a five level two factor Central Composite Design (CCD) and Response Surface Methodology (RSM) were utilized to optimize the experiment.

The initial step in performing optimization was to identify suitable independent factors and desired responses. As mentioned, the factors in this investigation were identified as temperature and velocity, and the corresponding ranges of these factors are from 15 °C to 35 °C and from 0.35 m/s to 0.75 m/s, respectively. On the other hand, the responses were determined as Nusselt number and Reynolds number. Upon identifying the factors, ranges and responses, a design matrix was then developed where a randomized set of runs were generated by DOE. The experimental runs were then conducted and the responses attained were keyed into the software. Two quadratic polynomial equations for each response were then generated by the software based on the results obtained.

Consecutively, analysis of variance (ANOVA) was performed to evaluate the adequacy of the models. ANOVA determines which factors have a significant effect on the responses by using Fisher's statistical test (F-test). Effects calculated using ANOVA that falls below a confidence level of 95% were discarded to improve regression model. Once the models were validated, the relationships between the factors and the corresponding responses will be graphically illustrated as a 3D response surface plot using RSM in order to obtain the optimum values of parameters that gives the highest response. The acquired optimal parameters were then repeated in order to evaluate the accuracy and consistency of results.

4. Results and Discussion

4.1. Average convective heat transfer

The results obtained from the calculation of the average convective heat transfer and Nusselt number of alumina nanofluids using Eqs. (2) and (3) were tabulated in a design matrix generated using CCD. The design matrix consists of 13 randomized runs in order to minimize the error of uncontrollable factors. Factors A and B represent temperature and velocity in both coded and actual values, and Responses 1 and 2 represent responses of Nusselt and Reynolds number. The design matrix comprises of 4 factorial points, 4 axial points and 5 replications of center point as illustrated in Table 1. The objective of the replications of center points (Runs 13, 11, 12, 9 and 10) was to obtain a good estimation of experimental errors.

Table 1. Design matrix generated using CCD of variables temperature and velocity and responses of Nusselt and Reynolds number.

Runs	*Factor A Temperature (°C) (Coded Value)*	*Factor B Velocity (m/s) (Coded Value)*	*Response 1 Nusselt Number*	*Response 2 Reynolds Number*
8	25 (0)	0.65 (+0.5)	4.72	136.0
3	15 (-1)	0.75 (+1)	4.89	107.5
13	25 (0)	0.55 (0)	4.39	115.0
11	25 (0)	0.55 (0)	4.29	115.0
1	15 (-1)	0.35 (-1)	3.33	50.1
6	30 (+0.5)	0.55 (0)	4.50	124.3
5	20 (-0.5)	0.55 (0)	4.06	92.3
12	25 (0)	0.55 (0)	4.34	115.0
4	35 (+1)	0.75 (+1)	5.67	184.5
7	25 (0)	0.45 (-0.5)	4.10	94.1
9	25 (0)	0.55 (0)	4.34	207.3
2	35 (+1)	0.35 (-1)	3.80	86.1
10	25 (0)	0.55 (0)	4.34	207.3

From the design matrix illustrated in Table 1, two initial quadratic polynomial equations for Nusselt and Reynolds number were formulated. These initial mathematical models were developed to predict the results of Nusselt and Reynolds number as a function of temperature and velocity. The mathematical models were respectively shown below in terms of coded factors:

$$Nusselt\ No. = 4.33 + 0.44A + 0.62B + 0.077AB - 0.22A^2 + 0.3B^2 + 0.24A^2B - 0.13AB^2 \quad (5)$$

$$Reynolds\ No. = 114 + 32A + 41.9B + 10.25AB - 17.06A^2 + 9.94B^2 - 2.95A^2B - 3.75AB^2 \quad (6)$$

With the equations generated, analysis of variance (ANOVA) was then performed to determine the significance and to assess the “goodness of fit” for both the equations. The first ANOVA analysis was performed and the initial mathematical models were modified by eliminating terms that were found insignificant to improve the regression model. Hence, the final mathematical models for Nusselt and Reynolds number were shown in Eqs. (7) and (8) as of below:

$$Nusselt\ No. = 4.33 + 0.44A + 0.62B + 0.077AB - 0.22A^2 + 0.3B^2 + 0.24A^2B - 0.13AB^2 \quad (7)$$

$$Reynolds\ \ No. = 114 + 28.67A + 39.28B + 10.25AB - 17.06A^2 + 9.94B^2 \quad (8)$$

Consecutively, ANOVA was also performed for the final mathematical models to evaluate the significance and the results were illustrated in Table 2 as of below:

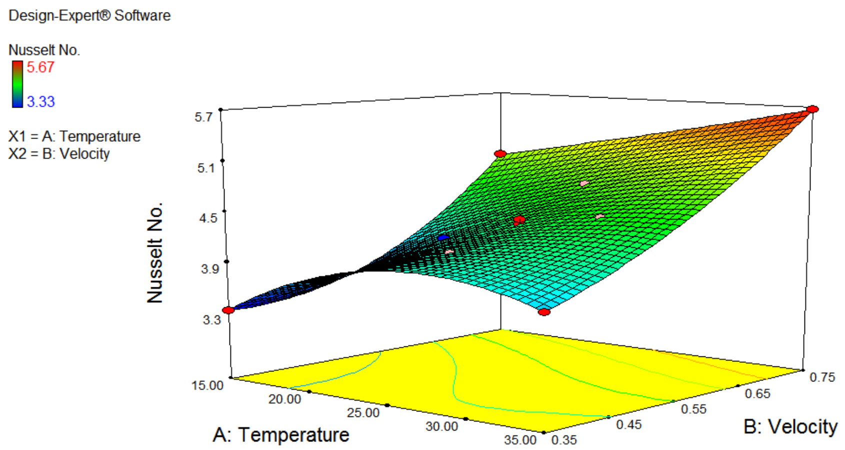
Table 2. Statistical analysis of variance (ANOVA) of responses Nu and Re.

	p-value, Prob. > F	
	Nusselt Number	**Reynolds Number**
Model	< 0.0001, significant	< 0.0001, significant
Factor A: Temperature	0.0002	< 0.0001
Factor B: Velocity	< 0.0001	< 0.0001
AB	0.0046	< 0.0001
A^2	0.0197	0.0025
B^2	0.0054	0.0315
A^2B	0.0042	eliminated
AB^2	0.0444	eliminated
Lack of fit	0.1654, not significant	not significant
R-squared	0.9986	0.9979
Adjusted R-squared	0.9967	0.9964
Predicted R-squared	0.9664	0.9620
Adequate precision	93.681	109.238

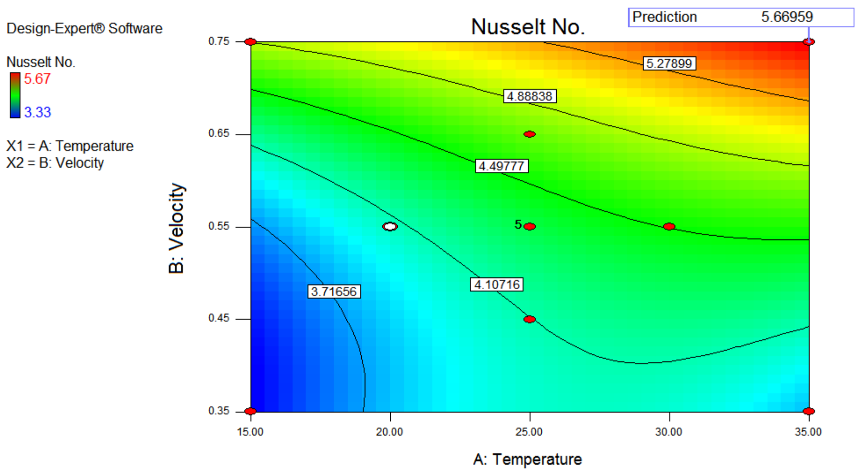
Referring to Table 2, it can be observed that both the models of Nusselt and Reynolds number were significant with p-values of less than 0.0001 (p-value < 0.05 is the indication of significance of model for 95% confidence intervals). The factors of temperature and velocity and their interaction effects (AB) were also found to be highly significant for both models, as their p-values were all less than 0.05. Besides that, the second-order effects (A^2 and B^2) of both the models were also found significant. Lastly, the A^2B and AB^2 factors were found significant for Nusselt number and insignificant for Reynolds number.

The lack of fit, which describes the variation of data around the fitted model, is not significant for both the responses. This implies that the model is fitted well to all data. On the other hand, the R-squared coefficient indicates the proportion of the total variation in the response predicted by the model. R-squared value of close to 1 and a reasonable agreement between predicted R-squared and adjusted R-squared is desirable. For both models, both the criteria were achieved, indicating a satisfactory adjustment of quadratic model to experimental data. Lastly, an adequate precision of greater than 4 represents adequate model discrimination, which was achieved by both equations of Nusselt and Reynolds number [11, 14].

Upon validating both the models, two three dimensional graphs were plotted based on the mathematical models using Response Surface Methodology (RSM) to evaluate the effects of temperature and velocity. The 3D graphs and contour plots of Nusselt number and Reynolds number were illustrated in Figs. 3 and 4, respectively. As seen in the figures, both the Nusselt and Reynolds number augment when the values of temperature and velocity increase. The optimum operating conditions for temperature and velocity in terms of delivering the highest values of Nusselt and Reynolds number in this specific range of study were determined at 35 °C and at 0.75 m/s in accordance to the response surface and contour plots. The maximum values of Nusselt and Reynolds number attained were predicted at 5.67 and 184.5, respectively. The obtain results have shown reasonable agreement from researchers such as Wen and Ding [3], Kim *et al.* [5] and Kwon *et al.* [6] on the effects of temperature and velocity on the Nusselt number.

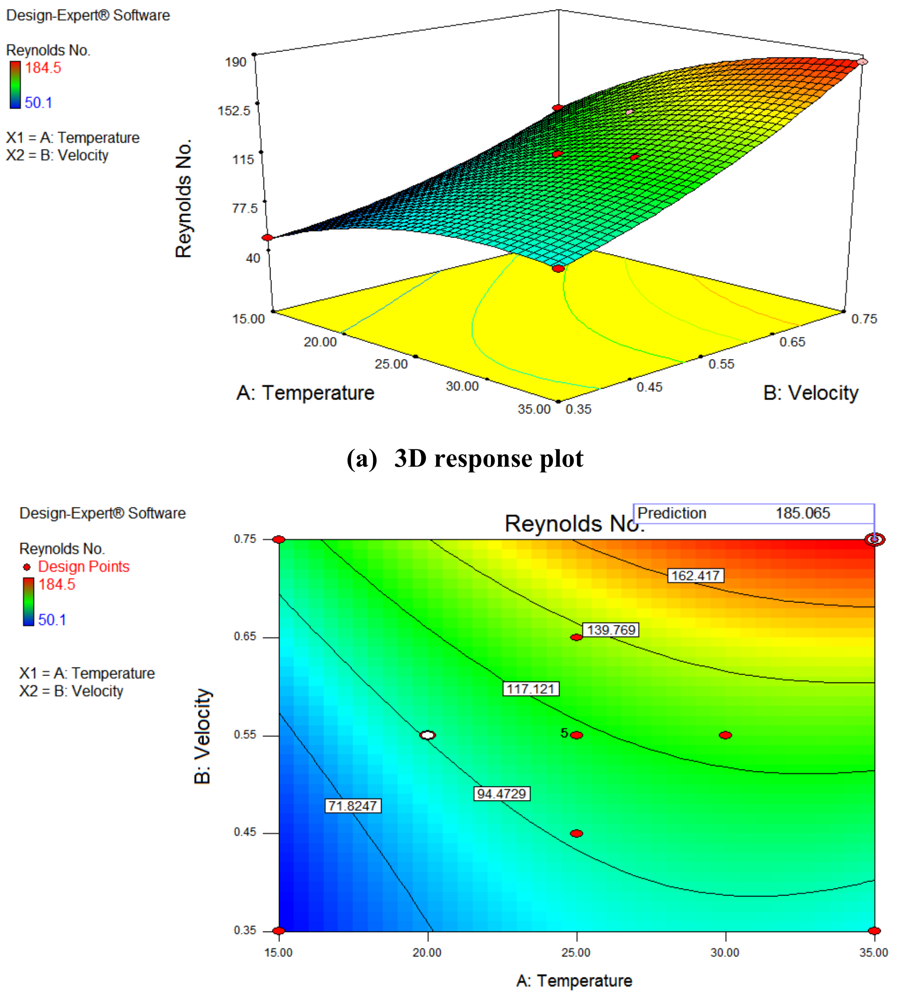


(a) 3D response plot



(b) Contour plot

Fig. 3. 3D response and contour plots in the studied range for Nusselt number.



(a) 3D response plot

(b) Contour plot

Fig. 4. 3D response and contour plots in the studied range for Reynolds number.

4.2. Convective heat transfer enhancement

To evaluate the convective heat transfer enhancement of alumina nanofluids, the convective heat transfer coefficient and Nusselt number of base fluids were firstly determined. The convective heat transfer enhancement was compared on the basis of Reynolds number; hence the Reynolds numbers obtained from Table 1 were adapted. The reason for the comparison being done under the same Reynolds number instead of velocity is that Reynolds number takes the viscosity effects of the fluid into account, therefore providing a more realistic and higher accuracy of results. The repetitions of the center point previously done were excluded as CCD and RSM methods were not used in evaluating the heat transfer enhancement. Upon determining the convective heat transfer coefficient and Nusselt number of base fluids, the heat transfer enhancement of alumina nanofluids were then determined in terms of percentage in enhancement and were illustrated in Table 3.

Table 3. Heat transfer enhancement of alumina nanofluids.

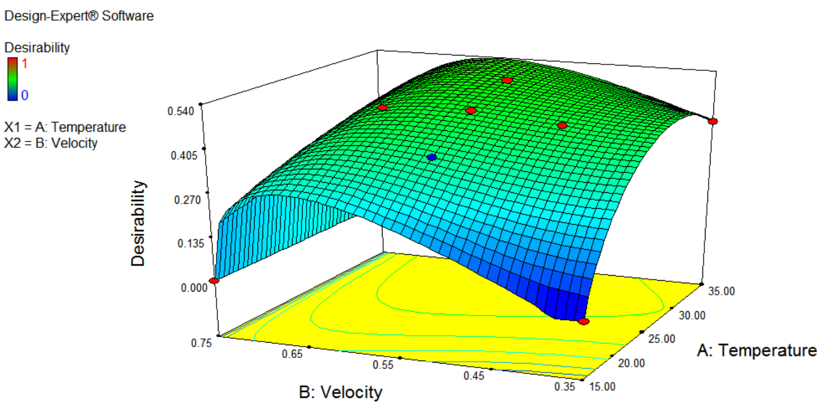
No.	Tin (°C)	Reynolds No.	h_{nf} (W/m²K)	h_{bf} (W/m²K)	h (%)	Nu_{nf}	Nu_{bf}	Nu (%)
1	25	136	493.4	308.4	60.0	4.72	3.02	56.3
2	15	107.5	499.7	306.0	63.3	4.89	3.06	59.8
3	25	115	453.7	279.9	62.1	4.34	2.75	57.8
4	15	50.1	340.3	168.7	101.7	3.33	1.69	97.0
5	30	124.3	475.6	274.1	73.5	4.50	2.67	68.5
6	20	92.3	419.9	286.0	46.8	4.06	2.83	43.5
7	35	184.5	607.3	349.3	73.8	5.67	3.37	68.3
8	25	94.1	429.0	245.2	75.0	4.10	2.40	70.8
9	35	86.1	406.9	188.9	115.5	3.80	1.82	108.8

As seen in Table 3, the enhancement of convective heat transfer coefficient ranges from 46.8% to 115.5%, whereas the enhancement of Nusselt number ranges from 43.5% to 108.8%. The maximum heat transfer enhancement of alumina nanofluids were both observed at a temperature and Reynolds number of 35 °C and 86.1, respectively. This enhancement percentage reported is significantly higher as compared to the results of previous researchers such as Wen and Ding [3], Lai *et al.* [4], Kim *et al.* [5] and Kwon *et al.* [6] who performed alumina nanofluids at different temperatures, concentrations and Reynolds numbers. From the results, it can be concluded that the interaction effects plays a highly significant role in influencing the heat transfer characteristics of alumina nanofluid and thus should not be neglected.

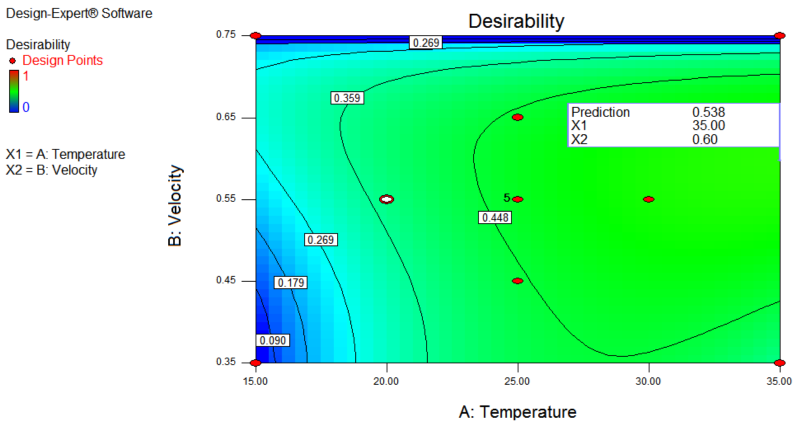
4.3. Optimization of heat transfer enhancement

Upon determining the heat transfer enhancement, optimization was performed to investigate the optimum operating conditions. Optimization is a process that determines the optimum desirability depending on the boundary conditions, or "goals" set for each of the factors and responses. In the present investigation, the goal for temperature was set to "in range", whereas the goal for velocity was set to "minimize". On the other hand, Nusselt and Reynolds number were set at goals of "maximize". The main reason why velocity was limited to a minimum value is because as the velocity increases, the pumping power required in pumping nanofluid will also augment, ultimately increasing the operational cost and thus deemed undesirable. Upon setting the boundary conditions, the 3D desirability plot and contour plot were then generated using RSM as seen in Fig. 5.

As seen in Fig. 5, the highest desirability was determined at a value of 0.538 at the temperature and velocity of 35 °C and 0.60 m/s, respectively. In order to evaluate the accuracy of the prediction, the experiment was re-performed with alumina nanofluids at the mentioned parameters in order to determine the uncertainty. Table 4 illustrates the predicted desirable points, experimental results and the uncertainty of the prediction.



(a) 3D desirability plot



(b) Contour plot

Fig. 5. 3D desirability and contour plots for optimum heat transfer enhancement of alumina nanofluids.

Table 4. The evaluation of goals and predicted points for corresponding factors and responses of alumina nanofluid

Factor / Response	Goal	Lower Limit	Upper Limit	Predicted Points	Exp. Data	Error (%)
Temperature	In range	15	35	35	35	-
Velocity	Min.	0.35	0.75	0.6	0.60	-
Nusselt No.	Max.	3.33	5.67	4.8	4.74	1.27
Reynolds No.	Max.	50.1	184.5	138.6	138.6	-

The results obtained in Table 4 shows that the modeling and optimization performed in this investigation were able to predict the aforementioned conditions of nanofluid successfully up to an accuracy of 1.27%. Therefore, it can be concluded that all the results obtained were deemed adequate and accurate, and the optimum operating condition in accordance to the desired goals falls at temperature and velocity values of 35 °C and 0.6 m/s, respectively.

5. Conclusions

This investigation is concerned with the study of influence of the temperature and velocity, along with optimization on the heat transfer enhancement of non-aqueous alumina nanofluids using both experimental and analytical techniques. In terms of experimental study, the investigation was performed with nanofluids flowing through a circular copper tube under a constant heat flux condition and a laminar flow regime. The experiment was performed according to the design matrix generated using Design Expert (version 7.0) with varying ranges of temperature from 15 °C to 35 °C and velocity of 0.35 m/s to 0.75 m/s. Nusselt number and Reynolds number were chosen as responses to evaluate the heat transfer enhancement. In terms of analytical techniques, the multifactorial design method, Design of Experiments (DOE) which includes techniques of Central Composite Design (CCD) and Response Surface Methodology (RSM) were applied. Statistical analysis of variance (ANOVA) was also performed in order to evaluate the significance of models created. Some concluding observations from the investigation were given as of below.

- The highest heat transfer coefficient and Nusselt number was reported at values of 607.3 W/m^2K and 5.67, respectively at temperature and velocity of 35 °C and 0.75 m/s, respectively.
- From ANOVA, the interaction effects between temperature and velocity was found to be highly significant in influencing the heat transfer enhancement of alumina nanofluids. Therefore, interaction effects between parameters should not be neglected. Further studies should be performed on other influencing parameters such as concentration, particle size, etc. to further determine the significance of interaction effects.
- The maximum heat transfer enhancement was recorded at a value of 115.5% for heat transfer coefficient and 108.8% for Nusselt number, which were both significantly higher than the results reported by previous researchers, hence further proving the significance of the interaction effects between temperature and velocity.
- Through optimization, the optimum desired operating condition in this range of study in accordance to the desired goals set was found at a temperature of 35 °C and a velocity of 0.6 m/s.

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