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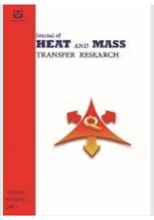

Statistical Analysis of Nanofluid Heat Transfer in a Heat Exchanger Using Taguchi Method

Behrouz Raei[*]

Department of Chemical Engineering, Mahshahr Branch, Islamic Azad University, Mahshahr, Iran

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ABSTRACT

In this study, a statistical experimental design method (the Taguchi method with L_9 orthogonal array robust design) was performed to optimize experimental conditions such that to maximize the Nusselt number of Al_2O_3-water nanofluids in a double tube counter flow heat exchanger. The controllable factors were selected at three sets of conditions including temperature (45, 55, and 65°C), concentration (0, 0.05, and 0.15 vol.%), and flow rate (7, 9, and 11 l/min) of the nanofluid. Analysis of the obtained results revealed that the flow rate plays a key role in the Nusselt number of nanofluid with 63.541%. The optimal levels were defined for the three factors including the nanofluid concentration of 0.15 vol.%, the nanofluid temperature of 65°Ç and the nanofluid flow rate of 11 l/min. The predicted Nusselt number of nanofluid under these conditions was 322.633. The confirmation test was also performed at the optimal conditions, by which good consistency was found between the experimental and the predicted results.

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1. Introduction

By the fast development of modern nanotechnology, micrometer-sized fluids are now replaced with nanofluids (fluids with the particle size of less than 100 nm). Choi [1] in 1995 proposed the term nanofluid for the first time, and it became popular since then. Numerous studies have been performed on the flow properties and heat transfer behavior of different nanofluids with various nanoparticles and base fluid in different heat exchangers. In the following sections, several articles published on using nanofluids are described. Abbasian and Amani [2] assessed pressure drop and turbulent heat transfer of TiO_2 (30 nm)-water nanofluid for various concentrations (0.2-2 vol.%) and different Reynolds numbers within the range of 8000-50000 in the double tube heat exchanger. According to their results, thermal performance of heat exchanger were enhanced by Reynolds number and nanoparticle concentration and the maximum thermal performance factor of 1.8 was attained at a Reynolds number of 47000 and a concentration of 2 vol.%. Zamzamian et al. [3] assessed the impacts of forced convective heat transfer coefficient with CuO-EG and Al_2O_3-EG nanofluids in a plate and double pipe heat exchangers. They found that elevating the temperature and nanoparticle concentration could improve the nanofluid's convective heat transfer coefficient and result in a 2% to 50% improvement in convective heat transfer coefficient of the turbulent and laminar flow regime. Ali [4] performed an experimental investigation on internal convective heat transfer of SiO_2-water nanofluids in a copper tube for a fully turbulent regime. This author investigated the local convective heat transfer coefficient at various positions along the tube at varying Reynolds number. The highest improvement was 8-9% at 0.001 vol.% of SiO_2 nanoparticles. However, at 0.007 vol.% of SiO_2 nanoparticles, a 27% increase was found in the convective heat transfer coefficient. Farajollahi et al. [5] investigated the turbulent flow of TiO_2-water and Al_2O_3-water nanofluids in a double tube heat exchanger for the Peclet numbers within 20000-60000. They indicated the optimal nanofluid concentration where the heat transfer is the highest. The effect of inserting an innovative curved turbulator and utilizing two types of hybrid nanofuids on thermal performance in a helical double-pipe heat

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[*] *Corresponding Author: Behrouz Raei, Department of Chemical Engineering, Mahshahr Branch, Islamic Azad University, Mahshahr, Iran*
Email:b.raei@mhriau.ac.ir

exchanger is evaluated numerically by Karouei et al [6]. The considered hybrid nanofuids include silver (Ag) and graphene (HEG) nanoparticles/water and multi-wall carbon nanotubes–iron oxide nanoparticles/water (MWCNT-Fe_3O_4/water). The considered innovative turbulator has 12 blades to create secondary flows. In addition, a hole is considered at the end of the turbulator. Results show that utilizing the present innovative turbulator leads to higher heat transfer rate. As a result, the Ag-HEG/water hybrid nanofuid has better thermal performance at low mass flow rate. Shirzad et al [7] studied the effect of using different nanofluid as a coolant fluid on the thermal performance of Pillow plate heat exchanger (PPHE). The objective of mentioned study was using a new heat transfer enhancement method in PPHE by utilizing nanofluid instead of pure fluid as a heat transfer medium. Accordingly, heat transfer and pressure drop of three water-based nanofluids including Al_2O_3, CuO and TiO_2 are studied by performing three-dimensional numerical simulations by the commercial CFD software. The results indicate that by increasing the nanoparticle volume concentration in the range of 2–5%, the heat transfer coefficient is improved significantly at low Reynolds number.Numerical analysis of the effect of geometrical and operational parameters on the thermal performance of a convergent–divergent tube is done by Hamedani et al [8] .The investigated geometrical parameters include the large and smaller diameters of the cone's wall, the pitch of the cone and the height of the roughness. Obtained results in the first section indicate that the proposed wavy geometry leads to enhanced heat transfer in the pipe. In the second section of the study, instead of pure water, two types of water-based nanofluids, including water/Al_2O_3 and water/CuO, are utilized, and the obtained results are compared with pure water. Results indicate that water/Al_2O_3 nanofluid has better thermal performance than CuO/water and especially pure water. Zaboli et al [9] investigated efficient operational and geometrical parameters in a shell and coil tube heat exchanger. The considered geometrical parameters include helix pitch, coil diameter, and helix height. In addition, the effect of using Al_2O_3, CuO, SiO_2 nanofuids on thermal performance of the heat exchanger is studied numerically. The results show that the geometric parameters of the coil have a significant effect on the heat exchangers of the shell and coil.Hybrid nanofuids flow and heat transfer in a pipe equipped with vortex generator are evaluated numerically by Ajarostaghi et al [10]. At the first part, the impact of the type of working fluid (two various hybrid nanofuids in comparison with pure water at $\varphi = 3\%$) and at the second part, impact of the volume concentration of selected hybrid nanofuid (based on section one) on the turbulence thermal performance of the pipe with innovative vortex generator are evaluated numerically. The considered hybrid nanofuids include silver (Ag) and graphene (HEG) nanoparticles/water and MWCNT–Fe_3O_4/water. The proposed vortex generator has 18 blades to create secondary flows. Also, five output ports are considered at the conical part of vortex generator (four side outputs and one axial one). Results indicated that using both two techniques of heat transfer enhancement in a pipe including proposed vortex generator and hybrid nanofuids leads to higher heat transfer rate. As a result, the MWCNT–Fe_3O_4/water hybrid nanofuid has better thermal performance in all studied Reynolds number.Zaboli et al [11] studied heat transfer and fuid flow in a corrugate coil tube with different lobe-shaped cross-sections are evaluated numerically. Also, spiral twisted tape as turbulator with various geometries is placed in the proposed corrugate coil tube. The examined parameters include the geometry of corrugated coil's cross-section and twisted tape's geometry in corrugated coil tube. Obtained results show that five-lobe cross-section raises the Nusselt number and pressure drop by 9.1% and 3.7%, respectively, in comparison with three-lobe case. Furthermore, increasing the area of spiral twisted tape in the five-lobe corrugated tube leads to growth in Nusselt number and pressure drop by 30.7% and 37.1%, respectively.

Rheological characteristics of Al_2O_3, CuO and TiO_2 nano particles were investigated in oil as the base fluid at 1 and 2 wt.% by Jamal-Abad et al [12].Results indicated that the nanofluid viscosity decreased by increasing the concentration. Oil showed shear thickening behavior while nanofluids showed shear thinning behavior. Moreover, the mentioned study showed that the effective viscosity of fluids would be decreased by nanoparticle addition at some wt.% and some shear rates. Furthermore, results showed that the classic models for nanofluid viscosity couldn't predict their real values of nanofluid viscosity, as the measured values are less than the predicted ones.Bozorgan and Shafahi [13] numerically investigated of the heat transfer and pressure drop of a water-based γ-Al_2O_3 nanofluid gasketed plate heat exchanger to specify its optimum conditions. The results showed that, based on the heat exchanger's performance index, the optimal volume concentration of γ-Al_2O_3 is approximately 0.016. The heat transfer rate at the optimal concentration of nanofluid is approximately 12.3% higher than that of pure water (base fluid), while the pumping power increased by 1.15%. The thermal performance and flow characteristics of CuO/water nanofluids in a mini tube with a circular cross-section under constant heat flux were numerically studied by Aminian et al [14] . Five nanoparticles such as spherical, cylindrical, platelet, brick, and blade were studied. The numerical results indicated that the heat transfer coefficient and Nusselt number of nanofluids would increase with the Reynolds number and volume fraction of nanoparticles. These characteristics for nanofluid containing platelet nanoparticles were the highest compared with other nanofluids. According to CFD simulations, it was found that the Nusselt number of nanofluid with platelet nanoparticle increases about 16% compared to that of the spherical nanoparticle. Furthermore, an increase up to 7.6%, 1.4% and 1% in nanofluids using cylindrical, blade and brick nanoparticles were observed, respectively. The thermal conductivity of liquid paraffin based nanofluids with alumina nanoparticles was experimentally performed by Farsani et al [15] . Data was taken in the temperature range of 20–50°C and solid volume fractions of 0, 1, 2, and 3%. Results showed that the nanofluids thermal conductivity increases with an increase in volume fraction and temperature. It also was concluded that thermal conductivity variations are more significant for the higher volume fractions. Furthermore, the maximum increase (about 19.42%) in thermal conductivity associated with the temperature of 30°C and the solid volume fraction of 3%.

Parvar et al[16] investigated the effect of ZnO nanoparticles to transformer oil on the thermal conductivity and dynamic viscosity. The results indicated that the thermal conductivity of the nanofluidwas higher than that of the pure transformer oil at the temperature of 25°C. Also, a rise in the nanoparticle concentration of transformer oil increased the thermal conductivity of nanofluid. Besides, the thermal conductivity at the volume fractions of 0.05% and 1% increased by approximately 4.61% and 11.53%, respectively. A statistical experimental design method has been implemented to optimize experimental conditions for maximizing the overall heat transfer coefficient of Fe_2O_3–water nanofluid in an air-cooled heat exchanger by Vermahmoudi et al.[17].As observed in the literature, lack statistical analysis exists on the operating parameter. The majority of researchers indicated that nanoparticle concentration, temperature, and nanofluid flow rate directly affect the heat transfer coefficient. Nevertheless, nothing could be understood by comparing the operational parameters.

The present research investigates the effect of some operating conditions on the Nusselt number of a double tube counter flow heat exchanger. To optimize the design of an existing process, it is essential to identify the factors with the greatest interrelationship and influence. Therefore, the analyses utilizing conventional investigational approaches are not efficient. The complex systems were analyzed using the Taguchi method and statistical experimental design [18-21]. The Taguchi approach includes two main areas. First, it determines a group of orthogonal arrays (OAs) for several experimental conditions. Second, it proposes a standard technique for analyzing the results. In using the Taguchi design of experiments, two objectives should be essentially met. The number of trials should be defined and then the conditions for each trial should be quantified [22].Taguchi method allows determining the effective factors simultaneously, effectively, and efficiently. This method can considerably decrease the time needed for the experimental assessment. This is a key step to investigate the impacts of multiple factors on the behavior and the effect of separate factors determining the most and the least effective factors [23]. Therefore, the Taguchi technique determines the optimal level for each factor. Followed by selecting and choosing the optimal, the confirmation and prediction tests should be carried out. The confirmation test is essential to provide direct evidence of the procedure. Within the Taguchi method, the results of the experiment are analyzed and the overall trends of the effective factors are determined by investigating the main effect of the factors separately. In addition, this technique allows controlling the features such that a higher or a lower value of a specific factor creates the desired outcome. Therefore, it is possible to predict the levels of effective factors producing the best results [24].

This research explains a case study to investigate the effective parameters like nanofluid concentration, nanofluid flow rate, and temperature on the Nusselt number of the double tube heat exchanger by the Taguchi method. The main objectives of this study are two-field: 1) to assess the impact of each parameter on the Nusselt number and 2) to apply the statistical Taguchi experimental design method on the optimization of factors and to find a combination of parameters to achieve the maximum value of the Nusselt number.

2. Experimental

2.1 Apparatus

Fig. 1 represents the schematic of the experimental set up. The test loop includes a heater, two reservoir tanks, two flow meters, a digital thermostat controller, one flange, two centrifugal pumps, temperature sensors, control box, a personal computer, data logger, metal valves for closing and opening of flow passes, and a U-shaped manometer. The test set is comprised of a double tube heat exchanger including two concentric tubes. The nanofluid (hot fluid) is passed through an inner tube that is constructed of stainless steel. The thickness and inner diameter of the tube are 6 mm and 12.7 mm, respectively. The distilled water (cold fluid) is passed through the outer tube surrounding the inner tube. The outer tube is constructed of carbon steel with an inner diameter of 63.5 mm and a thickness of 6 mm. The test section has a total length of 60 cm.

The nanofluid is located in a cylindrical 16 l carbon steel reservoir container (with a corrosion-protected inner layer). An electrical heater with a power of 3 kW is installed at the bottom of the tank to heat the fluid over the boiling temperature. The heater is linked to a thermostat to control the temperature as well as a digital display (BR6-FDMP4 model with accuracy of ±0.1℃) indicating and controlling the hot fluid temperature. A 220-V electrical heater supplies the needed energy. After obtaining the needed temperature, a centrifugal pump is used to pump the nanofluid into the test section (HAPPY Company with the highest capacity of 35 l/min, 0.5 hp).

The distilled water is then transferred into the cold cylindrical container made of PVC with a capacity of 100 l. It is worth noting that the temperature of the cold reservoir container was maintained at 6℃ by a combination of ice and water. At 13 l/min, the cooling fluid flow rate was constant all over the test. After turning

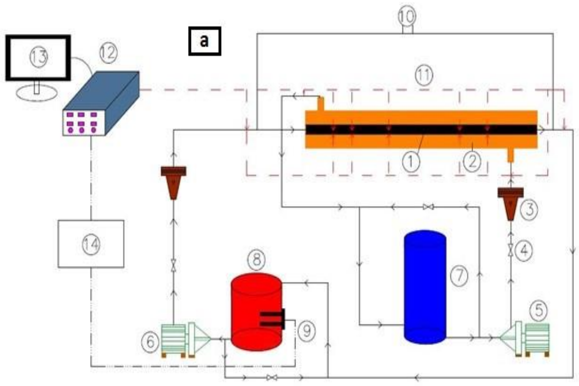

Figure 1. The experimental arrangement: (1) inner tube, (2) annulus, (3) rotameter, (4) control valve, (5) cold water pump, (6) hot water pump, (7) cold reservoir tank, (8) hot reservoir tank, (9) electrical heater, (10) differential pressure gauge, (11) thermocouples, (12) data logger, (13) PC, and (14) PID controller.

on the pump, the cold fluid is passed through the valves. The specifications of the cold fluid pump are the same as those of the hot fluid pump. The flow rates were measured using two flow meters (Technical Groups Model sp.gr.1.0, 1.8-18 l /min). The flow meters had an accuracy of 0.1l/min.

The bulk temperature of the flow was measured using 4 temperature sensors at the outlet and inlet of the annulus and inner tube. Here, the bulk and wall temperatures were determined at the points over the heat exchanger's length for monitoring the alterations in the local convective heat transfer coefficient in the double tube heat exchanger. Eight temperature sensors were placed for this regard within the distance of 5, 10, 20, and 40 cm from the inlet, 4 sensors were inserted into the inner tube thickness to measure the wall temperatures, and 4 other sensors were installed in the inner tube for measuring the bulk temperatures. Hence, the bulk and local wall temperatures were attained at 4 points of the heat exchanger. The accuracy of all temperature sensors was ±0.1℃. The data logger (model TM-1202, TIKA Company) was also utilized to record the temperature data. In Fig 2, the side view of the heat exchanger including the dimensions of the test section and the locations of the embedded temperature sensors are shown. This apparatus had already been used in other studies [25-29] .The measurement uncertainty was determined based on Moffat [30],which indicated the uncertainty of 9.7% in the Nusselt number.

2.2 Preparation of nanofluids

In this study, γ-alumina nanoparticle with 99% purity and 20 nm average particle size was bought from US Research Nanomaterials, Inc., USA. The almost spherical nanoparticles were dispersed mechanically in distilled water as the base fluid. To provide stable nanofluid, no chemical was added to prevent any probable complication.

Different concentrations of nanofluid including 0.05 and 0.15 of vol.% were prepared. These nanoparticles were then added to distilled water as the base fluid. Mixing with a magnetic stirrer for half an hour, and ultrasonication for 3 h guarantees the stability of the nanofluid up to 24 (as previously demonstrated [28]).Also, The repeatability was investigated during tests. Some tests repeated randomly at different times and it was determined that there is very little difference between them. This means that with the passage of time, no changes occurred in test results and it can be concluded that the situation of nanofluid is steady in terms of stability. Over time; randomly sampling was done from certain part of the experimental set up. The samples were then dried in the oven, and its mass was measured to determine the concentration. The results showed that little difference existed between initial concentration and subsequent concentration. Therefore, all these reasons show that nanofluids homogeneously distributed in the heat exchanger and situation of nanofluid is steady in terms of stability.

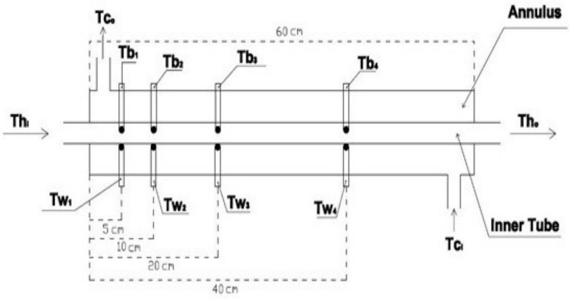

Figure 2. Side view of the double tube heat exchanger and the locations of the embedded temperature sensors.

As previously stated, three methods were used by the researchers for calculating the average heat transfer coefficient within a double tube heat exchanger. A detailed explanation of these three methods was presented elsewhere [25].In this research, a novel technique is employed to calculate the average heat transfer coefficient.

2.3 Design of experiments

Design of experiment (DOE) methods is used to decrease the experiment costs. The most common types of DOE include one-factor designs, response surface method designs, and reliability DOE factorial designs (such as an general full factorial design, two-level fractional factorial designs, Taguchi's orthogonal arrays, two-level full factorial designs, and Plackett-Burman designs)[31].The Taguchi method was utilized to increase the quality of the procedure or product through statistical concepts. This method is extensively utilized in engineering analyses owing to its extensive range of usage. It was verified that the technique is very effective if the appropriate considerations are made [32].

Table 1. The factors and their levels for experiments design

Factor	Factor name	Level	Level Value
C	Nanofluid concentration,vol%	1	0
		2	0.05
		3	0.15
T	Nanofluid temperature, °C	1	45
		2	55
		3	65
Q	Nanofluid flow rate,l/min	1	7
		2	9
		3	11

Table 2. The tests plan of L_9 (3^3) orthogonal array for the system

Factors levels Run no	C	T	Q	Nu
1	1	1	1	160.05
2	1	2	2	220.72
3	1	3	3	294.25
4	2	1	2	217.69
5	2	2	3	283.88
6	2	3	1	216.84
7	3	1	3	267.58
8	3	2	1	224.12
9	3	3	2	282.12

Taguchi's method is an experimental optimization technique using the standard orthogonal arrays to create the matrix of tests. It contributes to obtaining a huge deal of information from the least number of tests and, consequently, result in the best level of each parameter [33]. This method is the best parametric experimental design instrument for choosing various effective parameters with relative features and placing them in to a proper plan table with various levels for each parameter [34].Here, the number of levels and parameters are determined in terms of the present system. After determining the number of control levels and parameters, the proper orthogonal array (OA) is chosen and then the optimal number of tests is defined.

In this work, three controllable factors are considered including nanofluid flow rate, nanofluid concentration, and nanofluid temperature, each with three levels (Table 1). If a full factorial experimental design is employed, the permutations number would be 3^3. Nevertheless, the number of tests was reduced to 9 by the fractional factorial design. An L_9 OA represented in Table 2 is selected, where subscript 9 and L denote the number of experiments and the Latin square, respectively. Each row of the matrix denotes one run. In Table 2, the numbers 1, 2, and 3 represented the 1st, 2nd, and 3rd levels of a factor, respectively. Hence, the experimental results (Nusselt number) in Table 2 are attained by combining the values of levels in Table 1 and the L_9 OA. Consequently, a standard analysis is applied to utilize the average results to assess the empirical results. Generally, for standard analysis, selecting a quality characteristic (QC) is required only to determine the optimal condition. Tree kinds of QCs are appropriate in this regard: 1) lower is better (LB), 2) nominal is the best (NB), and 3) higher is better (HB). Since this study aims to attain the highest value of the Nusslet number of Al_2O_3-water nanofluid within the double tube heat exchanger, the QC with HB is needed.

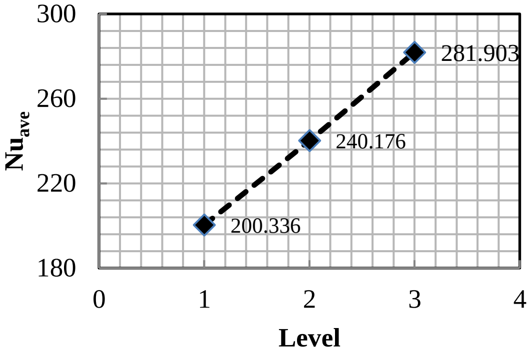

Figure 3. Effect of nanofluid flow rate factor on the Nusselt number

3. Results and Discussion

3.1 Taguchi results

Using Qualitek-4 (QT4) software, the results were analyzed and the conditions were optimized for setting the control factors. QT4 (version 4.75) is the windows version software for the analysis and automatic scheme of Taguchi tests. According to the Taguchi method in Table 2, implementations 1-9 were run. The main impact of control factors in the Taguchi method represents the trend of a factor's effect. The average results were used to calculate the main effects. The impacts of nanofluid flow rate, temperature, and concentration on the Nusselt number are shown in Figs. 3, 4, and 5. Fig. 3 represents the effect of nanofluid flow rate on the average response value. As observed in the fig, by increasing of the nanofluid level from level 1-3 (from 7 to 11 l/min), the average value of the response increases, which is the Nusselt number at each level. The highest value occurs at level 3 (11 l/min), where the average response is 281.903. Hence, to achieve the optimal value of the response, the nanofluid flow rate must be increased.

Fig. 4 represents that increasing the nanofluid temperature level from 1 to 3 (from 45 to 6 65℃) has a positive effect on the average response value at each level. Indeed, to obtain the maximum response value, the nanofluid temperature must be set to the third level (65 ℃). These improvements can be achieved because of two factors: i), improvement of nanofluid's thermal conductivity with temperature and ii) reducing the viscosity of the base fluid with temperature increase. As a result, increasing the nanoparticles'Brownian motion into

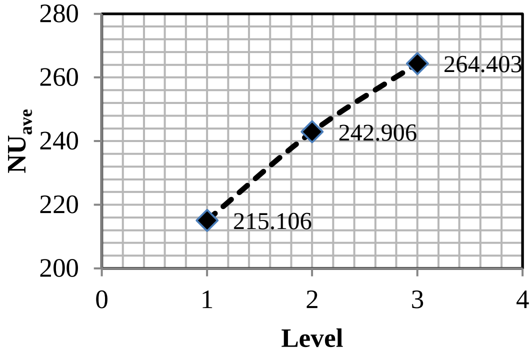

Figure 4. The impact of nanofluid inlet temperature factor on the Nusselt number.

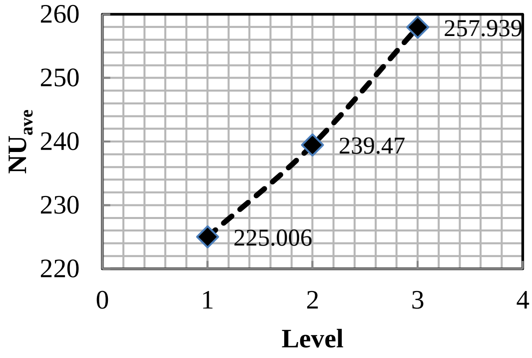

Figure 5. The impact of nanofluid concentration factor on the Nusselt number

Table 3. ANOVA for the Nusselt number

Factor	DOF_F	SS_F	V_F	P_F,%
vol. % C,	2	1634.922	817.461	9.509
T, °C	2	3665.058	1832.529	22.651
Q, l/min	2	9981.472	4990.736	63.541
other/error	2	165.989	82.994	4.299
Total	8	15447.443	-	100

the fluid increased the convection-like impact remarkably leading to increasing the Nusslet number.

Fig. 5 shows the effect of nanofluid concentration on the average value of the response. As predicted, by increasing the concentration level from 1 to 3 (from 0 to 0.15% vol.%), the average response increased at each level and reached the highest value (257.939) at level 3. Based on the previous studies, it is indicated that heat transfer improvement of nanofluids is caused by several issues including the combined impacts of Brownian motion of particles, particles near the wall, particle migration, thermal conductivity improvement, and decreased thickness of boundary layer [35, 36].

3.2 The results of Analysis of Varianc(ANOVA)

ANOVA is another technique to optimize the results proposed by the Taguchi method. These data represent the interaction and the relative effect of the factors on the variation of the results. ANOVA is the same as a regression analysis used for investigating and modeling the association between one or more independent variables and a response variable. Nevertheless, ANOVA is different from the regression in two states: 1) no assumption is made regarding the nature of the relationship and 2) the independent variables are qualitative.

P_F denotes the percentage contribution of each factor as follows:

$$P_f = \frac{SS_f - (DOF_F V_{Er})}{SS_T} \times 100 \qquad (1)$$

In which DOF_F denotes the degree of freedom for each factor that is attained by subtracting one from the number of each factor's level (L). The total sum of squares, SS_T, is

$$SS_T = \sum_{j=1}^{m}\left(\sum_{i=1}^{n} {Y_i}^2\right)_j - mn(\bar{Y}_T)^2 \qquad (2)$$

Where

$$\bar{Y}_T = \sum_{j=1}^{m} \frac{(\sum_{i=1}^{n} Y_i)_j}{mn} \qquad (3)$$

In which m shows the number of tests conducted in this work, n shows the number of repetitions under similar experimental conditions, and Yi represents the value of the measurement results of a definite run. The factorial sum of squares, SS_F [19], is

$$SS_F = \frac{mn}{l}\sum_{k=1}^{L}(\bar{Y}_k^F - \bar{Y}_T)^2 \qquad (4)$$

Where $\bar{Y}_k^F$ is the average value of the measurement results of a certain factor in the kth level. The variance of each factor, V_F, is

$$V_F = \frac{SS_F}{DOF_F} \qquad (5)$$

Also, the variance of error, V_{Er}, is

$$V_{Er} = \frac{SS_T - \sum_{F=A}^{D} SS_F}{m(n-1)} \qquad (6)$$

Initially, $\bar{Y}_k^F$ was attained from the response column in Table 1. By replacing $\bar{Y}_k^F$ and $\bar{Y}_T$ into Eq. (4), the factorial sum of squares, SS_F, for each factor was individually determined. Utilizing Eq. (2), the total sum of squares, SS_T, was calculated. Replacing DOF_F and SS_F in Eq. (5), the variance of each factor was obtained, and the variance of error, V_{Er}, was attained by replacing SS_T and SS_F into Eq. (6). Ultimately, by replacing DOF_F=2, SS_T, and SS_F into Eq. (1), the percentage contribution of each factor, P_F, was defined. These values are demonstrated in Table 3.

The last column of ANOVA represents the effects of interactions and factors allocated to the column to the variations of the results. Also, the other/error row includes the data regarding the sources of results variability.

This row represents the information regarding the effects from three sources: 1) uncontrollable factors (noise), 2) the factors not involved in the test, and 3) experimental error. The contribution of each factor on

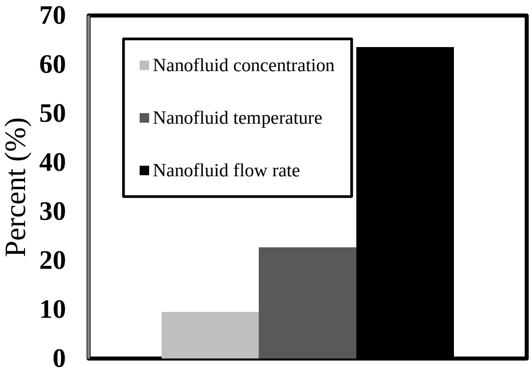

Figure 6. Contribution of each factor on Nusslet number.

Nusselt number P_F is provided in Fig.6. It is observed that the nanofluid flow rate is the most effective factor in the response (Nusselt number) with 63.541%, followed by temperature and concentration of nanofluid with 22.561% and 9.509%, respectively.

A statistical experimental design method has been implemented to optimize experimental conditions for maximizing the overall heat transfer coefficient of Fe_2O_3–water nanofluid in an air-cooled heat exchanger by Vermahmoudiet al [17]. The following controllable factors, each one at three levels, were chosen as operating conditions: nanofluid concentration, nanofluid temperature, nanofluid flow rate, and air flow rate. Analysis of the experiments indicated that the airflow rate and nanofluid flow rate have the most contribution in the overall heat transfer coefficient of nanofluid with 44.3% and 27.12%, respectively. The mentioned results are in consistence with the results of the present study which showed that the nanofluid flow rate is the most important factor in the heat transfer performance.Vermahmoudiet al [17] also showed that the nanofluid concentration has the least effect on the heat transfer performance of nanofluid in in an air-cooled heat exchanger. The mentioned result is in consistence with the results obtained in the present study.

The optimal conditions for the test can be obtained by applying the ANOVA. The performance at the optimal conditions is determined in terms of the selected QCs using the QT4 software. Table 4 represents the best performance and optimal conditions for our case study.

Based on the Taguchi method, the nanofluid flow rate possesses the maximum role in the Nusslet number with 41.097. The best set for control factors is 1) nanofluid concentration 0.15 vol.%, 2) nanofluid temperature 65℃, and 3) nanofluid flow rate 11 l/min.

The current grand average (i.e., arithmetic average for all trials) for the Nusselt number is around 240. 805.Nevertheless, at optimal conditions, the Nusselt number is increased to about 322.633.

Table 4. Optimum conditions and performance of the Nusselt number

Factor	Level Description	Level	Contribution
C, vol. %	0.15	3	17.134
T, °C	65	3	23.597
Q, l/min	11	3	41.097
Total			81.828
Current Grant Average of Performance			240.805
Expected Result at Optimum Condition			322.633

Table 5. Results of confirming the experiment and statistical model at optimum conditions.

Operating conditions			Predicted result	Experimental result
Concentration, vol.%	Temperature, °C	Flow rate, l/min		
0.15	65	11	322.63	315.97

Table 6. Intractions between factors

#	Interacting Factor pairs(Order based SI)	Column	SI (%)	Col	Opt
1	T×Q	2×3	22.74	1	[3,3]
2	C×Q	1×3	22.28	2	[1,3]
3	C×T	1×2	2.05	3	[1,3]

3.3 Confirmation test

After determining the optimal conditions through the statistical analysis, a confirmation test was performed at these conditions to examine the accuracy of the predicted results. Table 5 provided the results. Comparing the results of this experiment with those of the statistical model shows a very good consistency.

This demonstrates a good consistency between the experimental and the predicted values, with only a 2% error, and approves the effectiveness of the experimental design to attain the optimal value of the Nusselt number in only 9 runs instead of 27.

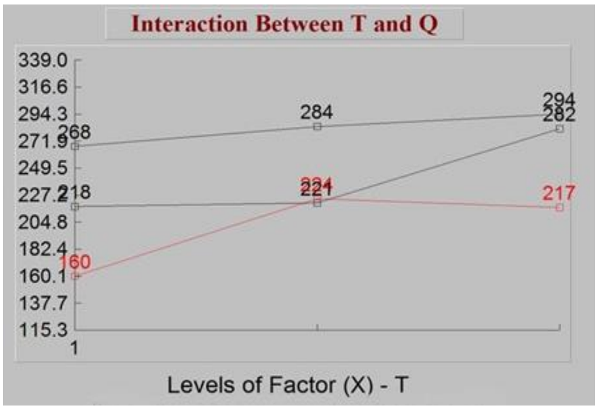

Figure 7. Interaction of nanofluid's temperature and flow rate on each other.

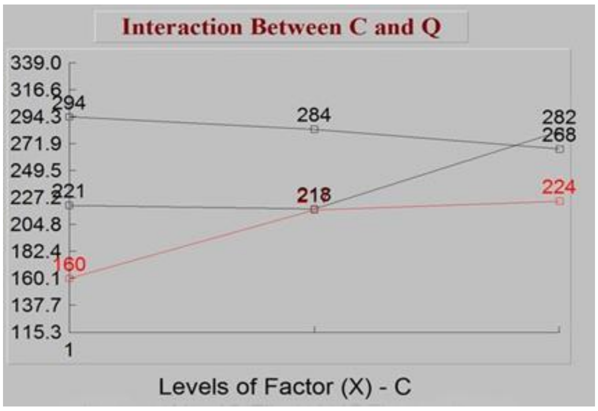

Figure 8. Interaction of nanofluid's concentration and flow rate on each other.

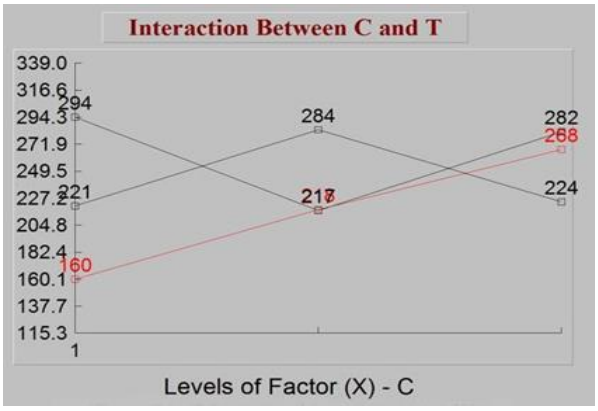

Figure 9. Interaction of nanofluid's temperature and concentration on each other.

3.4 Interaction

Factors A and B interact with each other when changes in level A alter the effect of B and vice versa. In this section, the effect of each factor on another is investigated. The results are provided in Table 6. Some explanations regarding the columns are briefly provided as follows.

Columns: represent the column number of the mentioned factors.

SI%: indicates the percentage of the severity index of the interactions of the mentioned factors, which are 100% for the interaction angle of 90 degrees and zero for the two parallel lines.

Opt: shows the level of factors that are closer to the optimal value calculated by Taguchi method. In this example, the highest value is obtained in experiment 3 (the third row of Table 2) as 294.25 closer to the optimal value calculated by Taguchi method (322.633).

Fig. 7 represents the interaction diagram between Q and T factors. Here, the x-axis is the value of the T-factor levels and the y-axis represents the value of the Q-factor response at different levels. For example, for the value 294, (having levels X3= 65℃and y3= 11 l/min), which are close to those of the optimal value of 322.633; hence, it is put in the Opt column. Fig. 8 represents the effect of flow rate factors and nanofluid concentration and Fig. 9 represents the impact of the factors with the least effect on each other, namely nanofluid's temperature and concentration. In Fig. 8, the angle between the lines is smaller, indicating the ineffectiveness interactions of the concentration factors and the nanofluid temperature on each other.

Conclusions

This experimental study was conducted to assess the convective heat transfer coefficient of Al_2O_3-water nanofluid in a double tube heat exchanger. The impacts of the following controllable factors on the Nusselt number were investigated utilizing the Taguchi method under the following conditions: nanofluid temperature (45, 55, and 65℃), nanofluid concentration (0,0.05, and 0.15 vol.%), and nanofluid flow rate (7,9, and 11 l/min). It was observed that the Nusselt number of Al_2O_3-water nanofluid increased by an increase in the flow rate, concentration, and temperature of the nanofluid. It was found that the nanofluid flow rate is the most effective parameter on the Nusselt number of Al_2O_3-water nanofluid. The optimal operating conditions to maximize the Nusselt number of nanofluid were determined as a nanofluid temperature of 65℃, the nanofluid concentration of 0.15 vol.%, and the nanofluid flow rate of 11 l/min. A confirmation test was also performed and found that the prediction error of the statistical model is about 2%. This approves a good consistency between the experimental and the predicted values. Utilizing the Taguchi method for designing the tests, the optimal value of the Nusselt number of nanofluid was attained in only 9 runs instead of 27.

It is worth mentioning that adding even a small quantity of a nanoparticle to working fluid to obtain a very small increment in heat transfer performance is not costly. It would be more practical and less costly to increment the nanofluid flow rates to obtain the same increment in the heat transfer coefficient. Nevertheless, numerous challenges exist that should be recognized and overcome. Nanofluid production cost and stability are the major factors hindering the commercialization of nanofluids. By solving these problems, it is expected that nanofluids can affect substantially as working fluid in heat exchanging devices.

Nomenclature

Q	nanofluid flow rate, [l/min]
T	temperature, [°C]
Abbreviation	
l	liter
L	level
m	number of experiments
n	number of repetitions
P	percent of contribution
PC	personal computer
PID	proportional–integral–derivative
PVC	polyvinyl chloride
Re	Reynolds number
V	variance
Y	value of results
$\bar{Y}$	average value of results
Subscripts	
Er	error
F	factor

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