Assessment of TiO$_2$ Nanoconcentration and Twin Impingement Jet of Heat Transfer Enhancement—A Statistical Approach Using Response Surface Methodology

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Abstract: Impinging jets are considered to be a well-known technique that offers high local heat transfer rates. No correlation could be established in the literature between the significant parameters and the Nusselt number, and investigation of the interactions between the correlated factors has not been conducted before. An experimental analysis based on the twin impingement jet mechanism was achieved to study the heat transfer rate pertaining to the surface plate. In the current paper, four influential parameters were studied: the spacing between nozzles, velocity, concentration of Nano solution coating and nozzle-plate distance, which are considered to be effective parameters for the thermal conductivity and the heat transfer coefficient of TiO$_2$ nanoparticle, an X-ray diffraction (XRD) and field emission scanning electron microscopy (FESEM) analysis were done, which highlighted the structure and showed that the nanosolution coated the surface homogenously. Moreover, a comparison was done for the experimental results with that of the predicted responses generated by the Design Expert software, Version 7 User’s Guide, USA. A response surface methodology (RSM) was employed to improve a mathematical model by accounting for a D-optimal design. In addition, the analysis of variance (ANOVA) was employed for testing the significance of the models. The maximum Nu of 91.47, where $H = S = 1$ cm; Reynolds number of 17,000, and TiO$_2$ nanoparticle concentration of 0.5% M. The highest improvement rate in Nusselt was about 26%, achieved with TiO$_2$ nanoparticle, when $S = 3$ cm, $H = 6$ cm and TiO$_2$ nanoparticle = 0.5 M. Furthermore, based on the statistical analysis, the expected values were found to be in satisfactory agreement with that of the empirical data, which was conducted by accounting for the proposed models’ excellent predictability. Multivariate approaches are very useful for researchers, as well as for applications in industrial processes, as they lead to increased efficiency and reduced costs, so the presented results of this work could encourage the overall uses of multivariate methods in these fields. Hypotheses: A comparison was done for the predicted responses generated by the Design Expert software with the experimental results and then studied to verify the following hypotheses: Preparation of three concentrations of TiO$_2$ nanosolution was done and studied. The heat transfer rate could be increased by surface coating with TiO$_2$ nanoparticle. The heat transfer could be improved by the impingement jet technique with suitable adjustments.

Keywords: design of experiment (DOE); response surface methodology (RSM); heat transfer; impingement jet; TiO$_2$ nanoparticle; nano coating
1. Introduction

The enhancement of heat transfer is the process of increasing the effectiveness of heat exchanges between two mediums. In industrial applications, jet impingement cooling is widely employed, such as in electronic chip cooling, gas turbine aerofoil cooling and vehicle heat exchangers [1–4]. Jet impingement offers intensive and local heat transfer, which makes it more adaptable to face heat transfer issues with different geometries and conditions. Heat transfer can be greatly enhanced by impinging jets. Designers who employ jet impingement always seek to maintain a balance between driving power and heat transfer, which resulted in many research works regarding jet impingement. In the last century [5,6], summarised the early studies pertaining to jet impingement. Research work before 2001 included many studies regarding single-array jets, single jet and multiple array jets. Correlations resulting from these studies greatly helped in both heat transfer as well as pressure prediction. Florschuetz’s correlation [7] is considered an exceptional and popular portion of these works, which involved a broad range of flow parameters as well as the local impact of cross flow. In the review paper of Zukerman and Lior’s [8], investigations prior to 2005 can be found. As per their summary, impingement is considered one amongst the most effective cooling technologies employed in numerous industrial and engineering applications. Recent studies around jet impingement included new factors that would impact or improve impingement heat transfer.

Studies have been performed to determine the effect of nanoparticle volume concentration on thermal properties of a wide variety of base fluids. Any increase in the nanoparticles volume fraction results in an improvement in the thermal properties of the nanofluid [9–11]. The second part of the paper describes the effect of nano surface coatings on the heat transfer rate with regards to the impingement jet. Experimental investigations regarding carbon nanotubes-coated brass rectangular extended surfaces have been conducted. Then, a comparison was done for the performances of non-coated and coated rectangular brass fins. An average percentage of 12% was found for increase in heat transfer rate with regards to carbon nanocoated rectangular brass fins [12]. Evaluation of heat transfer enhancement was done by [13] by taking AISI stainless steel 304 elliptical annular fin that was coated with carbon nanotube. Based on the result, it was shown that the coated fin’s convective heat transfer coefficient rose by 7%. The efficiency of the fin-shaped tube grew by 6.2%, while the fin effectiveness grew by 21.8%. In an experimental investigation by [14] for nucleate pool boiling heat transfer of R134a on TiO$_2$ coated TF surface, a better heat transfer coefficient was found with the coated surfaces when compared with the uncoated surface because of increment in dynamic nucleation site density as well as augmented roughness. In a study by [15] on the impact of nanostructure coating on the thermal performance of thermostyphon boiling in microchannels, the heat transfer enhancement impact was found to be around 1.0 wt% for both CuO and Al$_2$O$_3$ and around 0.75 wt% for Cu.

This work contributes to the study of influence of altering the plate surface on the heat transfer rate, in which a TiO$_2$ nanosolution is prepared in various concentrations to coat the surface plate and then measure the thermal impact. The second contribution would be to investigate the nanocoating surface solution when the twin impingement jet technique is applied, which is motivated by the significance of this technique in terms of heat transfer rate as well as lack of relevant information in the literature. The third part includes discussion of the results obtained from the parametric study on the correlation of Nusselt number with that of the parameters that are most influential on twin impingement jets. Also, the correlation’s optimum parameters were presented. The current article studies the use of TiO$_2$ nanosolution with various concentrations as well as investigates the improvement in heat transfer rate with regards to the twin impingement jet mechanism.

This work is representative of the serial publication for our previous papers dealing with the enhancement of heat transfer by using twin impingement jet technique and surface coating [2–4] here, we use DOE to analyze the influential parameters studied as the spacing between the nozzles, velocity, concentration of nanosolution coating and nozzle-plate distance, which are considered to be effective parameters for the thermal conductivity and
the heat transfer coefficient of TiO$_2$ nanoparticle. In this article the heat transfer rate could be increased by surface coating with TiO$_2$ nanoparticles. Furthermore, the heat transfer could be improved by the impingement jet technique with suitable adjustments.

From literature reviews, no correlation has been found between the Nusselt number and the significant parameters. Also, investigation regarding the interactions amongst correlated factors was not done before. Moreover, there is still no literature details on such systems, and the impact of utilizing nanocoating in the impingement process has not previously been addressed. To enhance the knowledge on heat transfer characteristics in heating and cooling applications, all these shortcomings should be addressed.

The usage of titanium dioxide (TiO$_2$), due to its physical durability and excellent chemical properties, is popular in many applications such as heat transfer. Furthermore, the TiO$_2$ particles are commercially available and cheap. A further goal of utilizing TiO$_2$ nanoparticles was to be suspended in conventional fluids, commonly used in many types of heat exchangers, including circular tube [16,17], a double tube [18–20] and a shell and tube [21].

2. Materials and Methods
2.1. Plate Coating

2.1.1. Preparation of the TiO$_2$ Nanoparticles

The sol-gel method was used to prepare TiO$_2$ nanoparticle [22]. TiO$_2$ (2 g) was stirred at 60 °C and was dissolved in purified water (100 mL). Then an aqueous trisodium citrate solution (8% w/v) was applied to the above reaction mix in the drop way at a 0.42 mL/min feed rat to preserve the titanium and trisodium citrate ratio at 1:4. On the other side, we changed the previous process by raising the temperature to 60 °C for 4 h to keep the solution more stable and homogeneous, then the solution achieved was dried overnight from 80–110 °C in a convection oven.

2.1.2. Surface Coating

TiO$_2$ has been dispersed in (de-ionized water:ethylene glycol): (80:20), with three different concentrations of ethylene glycol (EG). This solution was sonicated at 100 W for 120 min in the ultrasonic bath, with an ultrasonic pulse rate of 40 kHz to ensure uniform dispersion of nanoparticles. Afterwards it was stirred on a hot plate at room temperature at a speed of 450 rpm for 15 min. This method of sonification increased suspension stability, as the nanoparticles were precipitated for a longer period (≥120 min). The plate was then cut into three sections and fixed to a scale of 1 cm$^2$. The surface of the aluminum plate was cleaned and polished. As the next step, the plate was coated using TiO$_2$ nanosolution with three different concentration via dr. blade method [23]. As a final point, the coated plates were placed in the oven for 120 min at 65 °C.

2.2. DOE Based on Response Surface Methodology

The parametric experimental study was designed with the DOE approach that employed response surface methodology (RSM), which also forms a part of the current work. This study was designed to correlate influential factors (Re, H, S and Ø) with that of the heat transfer as well as to present optimum conditions that result in higher heat transfer rates. Design Expert software, Version 7 User’s Guide, USA was employed to design and analyse these experiments. The analysis of variance (ANOVA), a helpful technique for statistical deduction, is widely employed in DOE to study the impact of input parameters on experimental observations as well as to analyse the variation occurring in the measured data. The ANOVA hinges on the assumption that the normal distribution of the errors includes constant variance and mean zero. The user’s guide outlines the statistical analysis behind this software [24].

In this study, Nusselt number is the favorable response, which will likely be impacted by the parameters that are under consideration. In RSM, the relation of the desired response that can be impacted by natural input variables can be presented for the current case as [25]:

$$\text{Nu} = f(\text{Re}, \text{S}, \text{H}, \theta) + \epsilon$$  \hspace{1cm} (1)
where \( f \) represents the unknown response function and \( \varepsilon \) denotes the source of noise or error, which has not been accounted for in \( f \). Statistically, \( \varepsilon \) is considered to be distributed normally along with variance and mean zero [26]. In the present work, suggestion of the second order polynomial regression, also known as the quadratic model, has been done because of its ease to predict model parameters and high flexibility apart from its well performance as indicated practically [26]. Accordingly, the representation of the response surface can be done as follows:

\[
y(\text{Nu}) = \beta_0 - \beta_1 x_1 - \beta_{ii} x_2 - \beta_{ij} x_3 + \beta_{ij}
\]

(2)

where \( \beta_0 \) represents a constant and \( \beta_1, \beta_{ii} \) and \( \beta_{ij} \) denote the coefficients of linear, quadratic and interaction term pertaining to the second order model, respectively.

RSM is aimed at determining such polynomial coefficients that provide optimal response surface (\( y \)). The ‘x’s signify the coded variables that correspond to the actual parameters that are being considered. Here, \( x_1, x_2, x_3 \) and \( x_4 \) denote the coded representation for \( \text{Re}, S, H \) and \( \delta \) parameters, respectively. \( \Delta \text{Re}, \Delta S, \Delta H \) and \( \Delta \delta \) indicate the differences of the considered parameters between the higher and lower values. Under RSM, various experimental designs can be classified based on their use for optimisation purpose. However, the most commonly applicable ones are face cantered cube design (FCD), central composite design (CCD) and D-optimal design [27]. In particular, CCD employs extra levels out for the specified range of factors that are under consideration in order to attain the property of rotatability [26]. In fact, physically, this condition cannot be applied for the case study because of the restriction of limited factor levels like in the case of Nano concentration, in which there is no level higher than its maximum limit, and less than its lower limit as a result of this factor’s periodic behaviour. On the other hand, few of the factors offer more flexibility in terms of modifying their levels but continue to face physical constraint of the experimental setup, which makes the FCD’s cuboidal region feature unsuitable for the case under investigation [26]. Moreover, this work specifies that 50 run each is generated by FCD and CCD generate, while the goal of the current experimental work was achieved by D-optimal algorithm in just 28 runs. The attractive feature of D-optimal is that it increases the accuracy of the estimated polynomial coefficients (\( \beta \)’s), while the maximum variance is minimized as a result of maximization of the determinant for matrix in which \( |X^T X| \) is the design matrix by [27]. Consequently, the adoption of D-optimal design is done to configure an optimum relation between the influential parameters and the response since it is considered as a preferable selection for approximating the surface response by [28].

In general, the experimental data is required to construct the DOE models based on a particular experimental design. In this study, combination of the D-optimal design is done with three levels factors (low of \(-1\), Medium and high of \(+1\)) D-optimal suggested 25 experiments. The feasible ranges of the identified parameters are shown in Table 1. Also, DOE plan of twin jets impingement heat transfer is showed in Table 2.

| Parameter                        | Ranges and Levels | Units |
|----------------------------------|-------------------|-------|
| Reynolds number (Re)             | 9000 13,000 17,000| -     |
| Nozzle to nozzle spacing (S)     | 1 2 3           | cm    |
| Nozzle to plate distance (H)     | 1 6 11          | cm    |
| Nano particle concentration (\( \delta \)) | 0.1% 0.5% 1% | M     |

Table 1. The experimental ranges and levels of the considered parameters.
Table 2. The DOE plan of twin jets impingement heat transfer.

| Standard Order | Run Order | Re   | S   | H   | Ø   | Nu   |
|----------------|-----------|------|-----|-----|-----|------|
| 14             | 1         | 17,000 | 3   | 6   | 0.5 | 88.19|
| 5              | 2         | 17,000 | 1   | 11  | 1   | 81.10|
| 9              | 3         | 13,000 | 3   | 11  | 1   | 65.03|
| 15             | 4         | 13,000 | 2   | 1   | 0.5 | 60.86|
| 23             | 5         | 9000   | 1   | 1   | 0.1 | 66.07|
| 8              | 6         | 9000   | 1   | 1   | 0.5 | 73.08|
| 16             | 7         | 17,000 | 1   | 1   | 1   | 90.80|
| 21             | 8         | 9000   | 2   | 6   | 0.5 | 60.31|
| 2              | 9         | 9000   | 1   | 1   | 1   | 69.98|
| 10             | 10        | 17,000 | 2   | 1   | 1   | 70.10|
| 20             | 11        | 13,000 | 1   | 6   | 0.5 | 75.01|
| 25             | 12        | 17,000 | 2   | 11  | 0.5 | 81.90|
| 1              | 13        | 13,000 | 1   | 6   | 0.1 | 71.3 |
| 18             | 14        | 13,000 | 3   | 6   | 0.1 | 69.6 |
| 12             | 15        | 17,000 | 3   | 1   | 0.1 | 66.24|
| 7              | 16        | 17,000 | 2   | 11  | 0.1 | 76.3 |
| 13             | 17        | 9000   | 3   | 1   | 1   | 50.24|
| 4              | 18        | 9000   | 3   | 11  | 0.1 | 53.07|
| 3              | 19        | 9000   | 1   | 11  | 0.5 | 52.87|
| 22             | 20        | 13,000 | 3   | 11  | 0.5 | 67.84|
| 17             | 21        | 9000   | 3   | 1   | 0.1 | 48.02|
| 19             | 22        | 13,000 | 2   | 11  | 1   | 69.91|
| 11             | 23        | 9000   | 2   | 6   | 1   | 54.18|
| 24             | 24        | 17,000 | 1   | 1   | 0.5 | 94.7 |
| 6              | 25        | 17,000 | 1   | 1   | 0.1 | 85.2 |

2.3. DOE for Twin Impingement Jets Heat Transfer Correlation

For twin impingement jet, analysis of the heat transfer experiments with DOE technique was carried out to estimate the improvement of heat transfer. A comparison study for the cases based on TJIM is required. Also, the DOE technique aims at establishing the correlation between the four factors that were mentioned above and the Nusselt number as well as to optimise that correlation as well. These experiments were performed to define the experimental steps pertaining to heat transfer enhancement consideration:

1. The experiments were designed based on the DOE software (Design-Expert 7) along with RSM.
2. The software was fed with both low and high levels of each parameter, which added midlevel to make each factor as three levels as described in the previous section.
3. Specific design (plan) of 25 experiments was suggested by the DOE software to allow obtaining the corresponding Nusselt number from these experiments.
4. Suggestion of a quadratic polynomial model was done, and the DOE software was employed to perform analysis of variants (ANOVA), a statistical analysis based on minimising error, to build the empirical model (the correlation).
5. RSM could conduct model optimization, which could be achieved by employing the DOE software to set response (Nusselt number) as maximum.
6. As presented in Figure 1, schematic representation, in which fixing of the impingement plate on the traverse system was done in front of twin jet and as presented in Figure 3, arrangement of the experimental setup was done.
7. On the plate at midpoint of nozzle-nozzle spacing, fixing of the micro heat flux-temperature sensor was done.
8. At jet breathing exit, the thermocouple was fixed for measuring the temperature of air jet.
9. The air jet thermocouple and micro sensor were linked to multi-channel data logger, which remained connected to the computer that allowed recording the heat transfer data (heat flux, surface temperature, and air jet temperature).
(10) Switching of the plate heater was done, in which the temperature was set at 100 °C.
(11) Based on center jet velocity, measurement of Reynolds number by flow meter and Pitot tube was done.
(12) A digital caliper was employed to set the nozzle-nozzle spacing at S = 1, 2, 3 cm
(13) As presented in Figure 2, the impingement surface was fixed at H = 1, 6, 11 cm between plate and nozzles.
(14) The traverse system was moved to set the nozzle-plate distance, which employs the MiniCTA software to carry the impingement plate to the desired distance.
(15) Three different concentrations were employed for Nano coating plate.
(16) Data logger software was employed to give the measurement start order which, after acquiring 3000 data samples at a sampling frequency of 10 sample/s, would stop automatically.
(17) The parameters were reset based on the design suggested by the DOE software and measurements were repeated.
(18) After completing all 25 experiments, the results based on the calculated Nusselt number were fed to the DOE software for further analysis.
(19) The adjustment of the plate was done in which placing of the micro sensor was done at the midpoint of nozzle-nozzle spacing.
(20) The aluminum plate was coated with the Nano solution at three concentrations (0.1%, 0.5% and 1%) M.
(21) With the help of the multichannel data logger software, the heat transfer data acquiring process was started with 3000 samples per measurement point at a sampling frequency of 10 sample/s.
(22) Adjustment of the plate was done, in which the micro sensor was placed at the midpoint of nozzle-nozzle spacing.
(23) Setting of the Reynolds number was done with regards to the centre velocity as determined by the Pitot tube near the jet exit and a flow meter sensor for confirming the velocity.

Figure 1. Schematic of twin impingement jets tests setup.
Experimental Procedures and Methodology

Figure 1 provides a schematic illustration showcasing the experimental setup used in this research work. Compressed air of 4 psi (0.275 bar) was supplied through the main compressor. The compressed air is stored in an air reservoir, whose release is controlled by a ball valve. The moisture from the compressed air is removed with the help of a refrigerated air dryer. Pressure gauge and regulator were employed to manage air pressure, which also helped to avoid unwanted fluctuation due to cyclic on/off of the main compressor. The rated airflow is measured via a digital air flow meter (Model VA 420 procured from CSI Instruments (Dantec Dynamics, Skovlunde, Denmark)). Through the two identical pipelines, the air is made to pass prior to entering the twin jets impingement mechanism (TJIM). The control of each of the lines and that of the twin jets’ identical flow properties is ensured by a ball valve.

The tightly held aluminum foil ensures maintenance of a flat impingement surface. On the front surface of the aluminum foil, a high conductivity heat sink compound is employed for the installation of a heat flux microsensor and a Kapton tape to mitigate the impact of air gaps present between the sensor and the measured aluminum surface. The thermal data were collected by employing a Graphtec GL820 multichannel data logger (Dantec Dynamics, Skovlunde, Denmark). Towards the front of the aluminum foil, recording of the temperature distribution was done by employing a Ti25 infrared thermal imager (Dantec Dynamics, Skovlunde, Denmark). It was also found to be compatible with different types of thermocouples (i.e., J, T, K, E, S, R and B types [29]). In this paper, two K-type thermocouples have been used, which were fixed on to the aluminium plate and placed at a distance of 120 mm to observe the temperature of the plate.

Data pertaining to room humidity, temperature, static pressure (pitot tube), atmospheric pressure and dew point were collected from all other sensors with the help of a comet, model H7331. Maintaining of uniform temperature distribution was done because of small thickness of aluminium foil as well as foil thickness that has high thermal conductivity (k), which allows measuring the temperature near the surface accurately [30].

To perform the experimental procedures, the following main steps were used. First, in the case of steady jet, the air flow was set by determining the velocity for twin jets center point close to the nozzle exit by using Pitot tube to achieve Reynolds numbers of 17,000, 13,000 and 9000 for every jet. Second, a digital air flow meter was installed in the TJIM to...
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measurement, recording of a total of 1350 samples was done, in which the average value was taken into account. For jet impingement heat transfer issues, we need to account for fluid mechanics and heat transfer. Consequently, the associated dimensionless numbers also need ascertainment.

Equation (3) presents the computation for the air jet’s Reynolds number, which is related to the inertial forces due to the viscous forces of the fluid [31]:

\[ \text{Re} = \frac{\rho v d}{\mu} \]  

(\(\mu\) represents the dynamic viscosity of fluid (N·s/m² or Pa·s or kg/(s))), \(\rho\) symbolizes the fluid density (kg/m³) and \(v\) denotes the kinematic viscosity (\(v = \mu / \rho\) (m²/s)).

In Equation (4) representing jet impingement heat transfer, the forced convection seems to be dominated. The heat transfer coefficient (\(h\)) can be counted with the Newton’s law equation \(Q = h (T_s - T_j)\), resulting in:

\[ h = \frac{q}{T_s - T_j} \]  

where \(T_j\) = jet temperature, \(T_s\) = surface temperature, \(q\): denotes the amount of heat transferred (heat flux, W/m²) Equation (5). The Nusselt number equation can be employed to calculate the ratio of convective to conductive heat transfer:

\[ \text{Nu} = \frac{h d}{k} \]  

where \(k\) = fluid’s thermal conductivity, \(d\) = pipe diameter and \(h\) = convective heat transfer coefficient.

4. Results and Discussion

4.1. Thermal Images

Infrared thermal imaging can be considered as a valuable tool. It allows visualization as well as improves the understanding regarding physical phenomena from thermal physics, mechanics, optics and radiation physics, and electromagnetism, both qualitatively and quantitatively [32]. As the hot aluminum plate is impinged by the twin jets, the plate starts cooling up and displays certain temperature distribution based on the jets’ characteristics and configuration. Figure 4 shows the temperature distribution occurring on the impingement plate, pertaining to the following cases (a, b, c, d, e, f, g, h, i, j). The temperature values are then labelled as max, min and average for the images. The steady jet cases presented below signify the nine models. For all models, nine pictures were captured, in which one picture was taken for each model at \(\text{Re} = 17,000\). The first model yielded lower temperature of 59.1 °C and higher temperature of 67.4 °C, when \(S = 1\) and \(H = 1\). Few observations were quite distinct; on the twin jets, the temperature was distributed, which denotes the stagnation regions that were formed when both wall jets would clash together, signifying the impingement impact of hot twin circular jets. The steady jet case allowed achieving higher temperature rates due to high flow rates for the jets. When \(S = 1\) cm and \(H = 1\) cm, the first model yielded lower temperature of 55.2 °C and higher temperature of 95.6 °C. A good consistency was displayed by the analytic results, which pointed towards the established model’s rationality.
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Figure 4. Thermographic distribution of aluminum flat plate model (1) to (9) at Re = 17,000.

4.2. Structure of the TiO$_2$ Material

As per Figure 5, X-ray diffraction (XRD) analysis showcased the X-ray diffraction (XRD) patterns for the synthesized TiO$_2$ sample based on the sol-gel method. At 2θ value, peaks could be seen at 25°, 37°, 38°, 47°, 54°, 55°, 62°, 69° and 75° with (JCPDS-01-075-2553), which verifies the anatase phase formation. Meanwhile, the peaks at various 2θ values verified crystallinity as well as high purity of the particles. The average crystalline size reached 32.12 nm. Moreover, the unit cell parameter recorded as a (Å) = 3.8040, b (Å) = 3.8040, c (Å) = 9.6140, Alpha (º) = 90.0000, Beta (º) = 90.0000, and Gamma (º) = 90.0000, respectively.

The morphology of the films still greatly affects the electrical and mechanical properties of the prepared samples. FESEM images in Figure 6 present the surface micrographs of coatings that were cultivated at 0.1 M, 0.5 M, and 1.0 M. All films had a closely packed structure, flat, homogeneous and uniform, with an average grain size of 62.05 nm. This structure is also free from crystal defects such as cracks and pin holes. Furthermore, less void and fewer inclusions were discovered. The effect of various concentrations on the film thickness and grain size as the concentration increased from 0.1 M to 1.0 M was clearly observed. Moreover, Figure 6 shows all the films observed through the cross-sectional images. The mechanism of grain growth is considered in the GRIGC grain coalescence mechanism [33,34]. Recent studies have examined the process of grain growth in nanocrystalline materials and suggested a growth mechanism: grain-rotation-induced grain coalescence. This typically demonstrates that the rotation of grains among neighboring grains produces a coherent grain-grain interface (the same crystallographic orientation is assumed by the grains) which results in the neighboring grains coalescing through the eradication of common grain boundaries, therefore creating a single larger grain. Under low concentration, clusters of grains of varying sizes were present while a large cluster of grains was formed in the film. In the 0.5 M and 1.0 M films, the cluster of grains is transformed to isolated grains. However, between the grains of films at 0.5 M, more compaction is observed compared...
to that of 0.1 M and 1.0 M. It appears that the clusters of grains were just starting to be transformed into isolated grains for the films at 0.5 M, as demonstrated in Figure 6c.

Figure 5. X-ray diffraction (XRD) analysis.

Figure 6. FESEM micrographs of the surface coated aluminum plate (a) uncoated; coated with TiO$_2$ at (b) 0.1 M, (c) 0.5 M, and (d) 1.0 M.
4.3. Correlation of Twin Jets Impingement Heat Transfer

This section presents and talks about the results corresponding to the parametric study conducted based on the (DOE) technique. The design of the experiment was generated using the Design Expert software. The test was performed to determine the Nusselt numbers that correspond to the designed experiments that are given in Table 2. Based on these results, the quadratic model that the equation represented was suggested by the DOE technique. This section also presents the model adequacy checking results. Also, it states and discusses the correlation gathered from these experiments. To validate the correlation, it also reported a comparison with experimental results. This section also presents the optimum levels of the factors that gathered from model optimization. This was illustrated by a demonstration of response surface representation. Lastly, this section also discusses the interaction among factors at optimum conditions. The Nusselt number correlation with the factors being examined is given a full definition. It can then be well understood after completely examining the following details.

4.4. Model Adequacy Checking

One can achieve the appropriate checking of model adequacy by studying the residuals, which equates to the difference between the observation and the estimation that corresponds to it. First of all, one can check the normality assumption by plotting the normal probability of residuals, as demonstrated in Figure 7a. As these plotted points move basically into a straight line, it can provide a general indication of the normality of the distribution of errors. Furthermore, Figure 7b shows the difference between the actual and predicted. The two lines found below and above the zero horizontal line stands for the limits of a well-distributed residual band. In this representation, the residuals found beyond this band (or outliers) are not seen. Furthermore, proper randomization of the experiments was done nearby the zero-residual line. The last finding is an indicator that it has perfectly achieved the independence of errors. Also, some factors, including the expected response and the run number, should not be linked to the residuals of the correct model. Figure 7c,d illustrate the independence of residuals on the run number as well as the predicted response, respectively. Clearly seen that is no distinguished pattern exists that serves as proof of the independence of residuals. These studies have shown that the correlation model is appropriate for the experimental data provided by the experiments. These experiments were formulated in conjunction with the DOE plan.

![Figure 7](image_url)

Figure 7. Model adequacy checking by examining (a) the normal probability of residuals, (b) the predicted vs. actual, (c) the independence residuals on run, and (d) the independence residuals on predicted response.
4.5. Validation of the Model

The validity of the correlation was checked by performing an experimental verification through a comparison of the correlation with experimental data. In Figure 7a,b comparison is made between the Nusselt number that is experimentally obtained, and the Nusselt number that is computed from the correlation provided by Equation (2) and Table 2. The statistical analysis software (DOE) generated a point prediction of the model. It predicted the Reynolds number (17,000, 13,000 and 9000), the spacing between nozzles (1, 2, and 3 cm), Nano coating concentration (0.1%, 0.5% and 1% M), and the distance between the nozzle and the plate (1, 6 and 11 cm). These predicted parameters were tested. For instance, given the optimized factors, the maximum Nusselt number response was obtained at Nano concentrations equal to 0.5 M, Maximum Reynolds number at 17,000, a nozzle-nozzle spacing equal to 1 cm, and the distance between the plate and the nozzle equal to 1 cm. This observed result demonstrated a high correlation degree with the predicted one. The model was therefore considered reliable and accurate. The straight regression line with data points across is an indication of the model’s suitability, the agreement between the actual and predicted values. It also adheres to the assumption of data point representation.

To compute the error percentage between the predicted and experimental Nusselt number based on the optimum model, one can use the equation below to verify the error value. Given the error percentage value equal to 3.41%, it was believed to correspond to a good agreement with the optimum experimental data. This is demonstrated below:

\[
\% \text{ Error} = \frac{\text{Nu}(\text{pred}) - \text{Nu}(\text{exp})}{\text{Nu}(\text{exp})} \times 100\%
\]

\[
\% \text{ Error} = 3.41\%
\] (6)

The Model F-value is equal to 16.02, which is an indicator of the significance of the model. Only a 0.01% chance exists that a “Model F-Value” this large can take place as a result of noise. “Prob > F” values that are less than 0.05 are indicators that the terms of the model are significant. In this case, it is considered that A, B, AC, BC, B2, C2 are significant model terms. This is demonstrated in Table 3. It should be noted that the R-squared value that corresponds to this model equals to 0.9573, which is close to one. This R-squared value is an indicator that the model fits the experimental data design very well.

| Table 3. ANOVA for Response Surface Quadratic Model (Analysis of variance table). |
|-------------------------------------------------|
| Source | Sum of Squares | df | Mean Square | F Value | p-Value | Prob > F |
|--------|----------------|----|-------------|---------|---------|----------|
| Model  | 3717.54        | 14 | 265.54      | 16.02   | <0.0001 | significant |
| A-Re   | 2247.14        | 1  | 2247.14     | 135.58  | <0.0001 |          |
| B-S    | 204.52         | 1  | 204.52      | 12.34   | 0.0056  |          |
| C-H    | 0.33           | 1  | 0.33        | 0.020   | 0.8914  |          |
| D-Ø    | 27.26          | 1  | 27.26       | 1.64    | 0.2286  |          |
| AB     | 1.00           | 1  | 1.00        | 0.060   | 0.8111  |          |
| AC     | 116.61         | 1  | 116.61      | 7.04    | 0.0242  |          |
| AD     | 1.89           | 1  | 1.89        | 0.11    | 0.7423  |          |
| BC     | 440.51         | 1  | 440.51      | 26.58   | 0.0004  |          |
| BD     | 17.17          | 1  | 17.17       | 1.04    | 0.3328  |          |
| CD     | 6.57           | 1  | 6.57        | 0.40    | 0.5431  |          |
| A’2    | 32.48          | 1  | 32.48       | 1.96    | 0.1918  |          |
| B’2    | 96.64          | 1  | 96.64       | 5.83    | 0.0364  |          |
| C’2    | 123.59         | 1  | 123.59      | 7.46    | 0.0212  |          |
4.6. Model Optimisation

The Design Expert software was used to conduct the optimization process. The basis of the optimization criterion was on setting the response (Nusselt number) with a value that was as maximum as possible while the influential factors were set in range, except the Nano concentration. Then, optimization was performed three times, every time at a specific Nano concentration level (0.1%, 0.5%, and 1%) M. Consequently, Table 4 contains the optimum values of the factors that were considered to perform the maximum Nusselt number. Evidently, the maximum Nusselt number was determined and gathered at an optimum frequency of Reynolds number and an optimum nano concentration of 0.5%. In other words, the Nusselt number is higher when the Reynolds number is higher. One can attribute this interesting finding to the vortex formation at interference zone as a result of the velocity gradient that is observed between the twin jets. Since there is a spacing difference between the nozzles and the plate surface, there is also a difference in the surface as a result of the Nano coating due to the effect of the morphology on the prepared samples’ mechanical properties as FESEM images illustrate surface micrographs of coating that were grown at 0.1 M, 0.5 M, and 1.0 M. These can be seen in Figure 6. All the films displayed a tightly packed, flat, homogeneous, and uniform structure. It is also free from crystal defects. The influence of varying concentrations on the film thickness and grain size was noticeable as the concentration increased from 0.1 M to 1.0 M. Moreover, the vortexes that can combine with larger amounts of surrounding air with the spent air were produced from the impingement process. This large mixing can lessen the temperature of wall-jet air. It may also result into heat transfer improvement as a result of the increase in temperature difference between the wall-jet air and hot plate at the centre of interference zone.

Table 4. Optimised factors at maximum response.

| φ   | Re  | S | H | Nu  |
|-----|-----|---|---|-----|
| 0.5 | 17,000 | 1 | 1 | 94.7 |
| 1   | 16,999 | 1 | 1 | 89.28 |
| 0.1 | 17,000 | 1 | 1 | 86.119 |

In order to offer a prolonged explanation of the optimization outcomes, representation of the Nusselt number (response) was done. It was represented as a surface shape arranged by the effect of two different factors for every representation while keeping other factors at optimum values, as shown in Table 4. As previously mentioned, the optimization process was conducted at varying nanoconcentrations. Thus, each response surface representation was separated into three plots (a, b, and c) for the nano concentrations of (0.1, 0.5 and 1%) M, respectively. Contour lines were also drawn for the constant Nusselt number values in the same plots. Figure 8 demonstrates the combined effect of nozzle-nozzle spacing and Reynolds number on response surface shape at varying nanoconcentrations. In general, the Nusselt number surface possesses a convex configuration in nozzle-nozzle spacing axis. Moreover, the slope in Reynolds number axis goes from high to low levels. This slope tends to be insignificant under high nozzle-nozzle spacing level. The constant response lines and convex curvature are indicators of the existence of optimum point, which can be found at S/d ≈ 1 and Re ≈ 17,000.

The combined impact of Reynolds number and nozzle-plate distance on Nusselt number surface at various nanoconcentrations is depicted in Figure 9. The response surface is symbolized by the semi-flat surface with curvature through the Reynolds number range. The curved lines signify the response surface’s curvature whereas the straight contour lines symbolize a flat surface shape. Over-all, the surface is oriented towards the low Reynolds number as well as high nozzle-plate distance levels. Thus, the maximum Nusselt number is acquired at a higher Reynolds number of about 17,000 and lower nozzle-plate distance of unity. The optimization at a nanoconcentration of 0.5% M generates greater levels of response.
Figure 8. Nusselt number contours and 3D surface formed by the effect of Reynolds number and frequency at the optimum conditions for the optimization target of maximum Nusselt number and nanoconcentration equal to (a) 0.1% M; (b) 0.5% M; (c) 1% M.

Figure 9. Nusselt number contours and 3D surface formed by the effect of Reynolds number nozzle-plate distance at the optimum conditions for the optimization target of maximum Nusselt number and nanoconcentration equal to (a) 0.1%; (b) 0.5%; (c) 1%.
Figure 10 demonstrates the effect of Reynolds number and nanoconcentration on the Nusselt number at various nanoconcentrations. The response surface constitutes a concave shape that leans towards the low Reynolds number values. Optimization at 0.5% Nano concentration depicts the response surface behavior as indicated. Conversely, the optimization process at a 0.5% nanoconcentration renders a sloping surface towards a 0.1% concentration. The impact of concentration on the Nusselt number exhibits varying behavior as the correlation is optimized at a 0.5% nanoconcentration. Furthermore, the higher Nusselt number is acquired at a 0.5% nanoconcentration and Reynolds number of 17,000 as the optimization is carried out at a 0.5% M nanoconcentration.

Figure 11 illustrates the combined effect of nozzle-plate distance and nozzle-nozzle spacing, which are optimized at varying nanoconcentrations. The 3D surface in (nozzle-nozzle spacing) changing directions is considered the response surface. The surface is inclined from low to high levels of nozzle-plate distance under low levels of nozzle-nozzle spacing. However, as shown in plot (a), the contour lines represent a sloped surface at high levels of nozzle-nozzle spacing. There is an rise in the surface slope with the increase in the optimization target of nanoconcentration, where one can observe the sharper slope as optimization is conducted at a nanoconcentration of 0.5%. As observed, the maximum Nusselt number point is found at $H = 1$ and $S = 1$ cm.

Figure 12 presents information regarding the response surface as influenced by the combined effect of (nanoconcentration) and (nozzle-nozzle spacing) as the optimization takes place at varying nanoconcentrations. The influence of those factors creates different surface shapes. These shapes can be the 3D surface as the nozzle-nozzle spacing changes direction or the 3D surface when there are differences in the nanoconcentration. When the nozzle-nozzle spacing levels are low, the optimization takes place at a nanoconcentration of 0.5%. The optimum point can then be found at the normalized nozzle-plate distance of unity and the normalized nozzle-nozzle spacing of approximately 1 cm.
Figure 11. Nusselt contours and 3D surface formed by the impact of the nozzle-nozzle spacing and nozzle-plate distance at the optimum conditions for the optimization target of maximum Nusselt number and nanoconcentration equal to (a) 0.1%; (b) 0.5%; (c) 1%.

Figure 12. Nusselt number contours and 3D surface formed by the effect of the nozzle-nozzle spacing and phase angle at the optimum conditions for the optimization target of maximum Nusselt number and nanoconcentration equal to (a) 0.1%; (b) 0.5%; (c) 1%.
Figure 13 depicts the combination effects of nanoconcentration and nozzle-plate distance on Nusselt number. This figure is obtained from the optimization process that was performed at different nanoconcentrations. In general, one can characterize the response surface by concave shape as the direction of the nanoconcentration and slope changes with the increase in the nozzle-plate distance. The surface concavity moves its symmetry line from the middle to the low nano concentration levels as the optimization target changes in terms of the concentration of 0.1%, 0.5% and 1%. As previously mentioned, and confirmed in this finding, the maximum Nusselt number was obtained at concentration = 0.5% M and H = 6 cm.

![Figure 13. Nusselt number contours and 3D surface formed by the effect of the nozzle-plate distance and Nano concentration at the optimum conditions for the optimization target of maximum Nusselt number and nanoconcentration equal to (a) 0.1%; (b) 0.5%; (c) 1%.](image)

4.7. Test Results at the Interference Zone of Twin Jets Impingement (Interaction of Factors)

It is vital to examine the interactions among input variables that can serve as a guide in avoiding the conditions that lead to the degradation of heat transfer rates among the application areas. The interaction among factors was taken into consideration for the optimum case that was gathered from the optimization process performed at nanoconcentration of 0.5% (refer to Table 4). Given any two variables, their interaction was drawn by altering one variable at low to high levels and examining the behavior of the other variables while maintaining the rest of the factors at their optimum values. Thus, the effect of one factor is affected by the level of the other factor when there is interaction taking place. Essentially, based on the quadratic correlation under consideration, there are 7 interactions among the factors. One can express these interactions as pairs: Re × Q, Re × S, Re × H, Q × S, S × H, and H × Q.

Figure 14 report the interaction of Reynolds number and the distance between plate (H) and nozzles at optimum condition. Generally, the low nozzle-plate distance and low nozzle-nozzle spacing performs better heat transfer, as illustrated in Figure 14. Also, there is a slight convergence among the distance levels when the Reynolds number increases.
One can therefore say that the effect of the nozzle-plate distance on the Nusselt number at \( Re = 9000 \) is more pronounced compared to that at \( Re = 17,000 \), especially when \( H = 6 \) and \( H = 11 \) cm. On the other hand, Figure 15 illustrates how the Reynolds number affects the Nusselt number when the spacing between the nozzle is equal to 2 cm. No significant change was observed between \( H = 6 \) and \( H = 11 \) cm. Figure 16 shows the effect of distance variance on the Nusselt number under optimum conditions when the nozzles have a spacing equal to 3 cm between them. It is then possible to observe the steady behavior when the Reynolds number is increased on the Nusselt number for the various parameters.

**Figure 14.** Interaction of Reynolds number and nozzle-plate distance levels at optimum levels of other factors at nozzle-nozzle spacing = 1 cm.

**Figure 15.** Interaction of Reynolds number and nozzle-plate distance levels at optimum levels of other factors at nozzle-nozzle spacing = 2 cm.
Nanocoating concentration and nozzle-plate distance interact at optimum conditions, as shown in Figure 17. It was observed that the Nusselt number at low and high Nano concentration levels increases under a concentration of 0.5 M and then drops under 1% M nanoconcentration. As the nozzle-plate distance increases, the Nusselt number decreases. There is a sharper slope of dropping at $= 0.1%$ M than at $= 0.5%$ M. Thus, the convergence of the rates of the Nusselt number rates takes place at high nozzle-plate distance. Furthermore, the variation from 0.1% to 0.5% of the nanoconcentration significantly improves the heat transfer at $H/d = 1$. Also, this figure shows clearly that the heat transfer rate by using nanocoating was higher than the surfaces without coating. Table 5 presents the enhancement ratio of TiO$_2$ nanocoating surface plate in the three different models.

Figure 16. Interaction of Reynolds number and nozzle-plate distance levels at optimum levels of other factors at nozzle-nozzle spacing = 3 cm.

Figure 17. Interaction of nozzle-plate distance and phase angle levels at optimum levels of other factors at nozzle-nozzle spacing = 1 cm.
Table 5. Improvement ratio of TiO\(_2\) nanocoating surface plate.

| Model | Concentration of TiO\(_2\) by Molarity | Nu Values (with Coating) | Nu Values (without Coating) | Improvement Ratio (%) |
|-------|----------------------------------------|--------------------------|----------------------------|-----------------------|
| M1    | 0.1%                                   | 86.2                     | 84.7                       | 10.6%                 |
|       | 0.5%                                   | 93.7                     |                            |                       |
|       | 1%                                     | 90.8                     |                            |                       |
| M2    | 0.1%                                   | 80.14                    |                            |                       |
|       | 0.5%                                   | 84.92                    |                            |                       |
|       | 21%                                    | 83.01                    |                            |                       |
| M3    | 0.1%                                   | 78.63                    |                            |                       |
|       | 0.5%                                   | 83                       |                            |                       |
|       | 1%                                     | 82.1                     |                            |                       |

The geometrical parameters of nozzle-plate distance and nozzle-nozzle spacing organize the interaction presented in Figure 18. This figure was drawn while keeping the other factors at optimum levels. Generally, low to high levels of nozzle-plate distance demonstrate that there is an increase in the Nusselt number until it achieves the peak level at \(S = 1\) cm and \(H = 1\) cm. It then experiences decay with the increase in nozzle-nozzle spacing. At \(H = 1\) cm, the twin jets generate heat transfer rates higher than the rates generated at \(H/d = 11\). However, when \(H/d = 6\) cm, one can find the peak point at the nozzle-nozzle spacing equal to 3 cm. It then experiences a decrease at 2 cm and 1 cm. When the distance of the nozzle-plate is equal to 11 cm, a high Nusselt number can be seen. This then decreases when the spacing between nozzles becomes greater. However, the convergence of the rates of the Nusselt number takes place at low nozzle-nozzle spacing levels.

**Figure 18.** Interaction of nozzle-nozzle spacing and nozzle-plate distance levels at optimum levels of other factors.
Figure 19 demonstrates the interaction of nozzle-plate distance and nozzle-nozzle spacing when the other parameters are at their optimum conditions. Essentially, low and high levels of nozzle-nozzle spacing generate different sloping curves that have varying Nusselt number rates. On the other hand, higher heat transfer levels are observed at \( S = 1 \text{ cm} \) and \( H = 1 \text{ cm} \). As the distance of the nozzle-plate increases, the Nusselt number experiences a slight increase until it reaches \( H = 11 \text{ cm} \). When \( S = 2 \text{ cm} \), the low to high levels of nozzle-plate distance show that there is an increase in the Nusselt number until it achieves the peak level at \( H = 11 \text{ cm} \). When \( S = 3 \text{ cm} \), the values of the Nusselt number increased from \( H = 1 \) to \( H = 6 \text{ cm} \), then experienced a decrease at \( H \) from 6 to 11 cm. The Nusselt number has variations among its rates at nozzle-plate distance levels in the nozzle-nozzle spacing range.

![Figure 19. Interaction of nozzle-plate distance and nozzle-nozzle spacing levels at optimum levels of other factors.](image)

**4.8. Comparison and Discussion**

This study offers an enhancement heat transfer hypothesis at the interference zone of the twin impinging jets as a result of the twin impingement jet effect. This objective can only be met by performing a set of experiments to test the heat transfer of the twin jets at a specific Reynolds number. Table 6 presents the summary of convective heat transfer for the nanoparticle in some applications and the heat transfer enhancements in these studies.

A comparison of enhancements in nanocoating applications have been presented in Table 7 to show the nanoparticle type, surface geometry, research method, main finding, and the heat transfer enhancement.
### Table 6. Comparison of convective heat transfer in Nano particle applications.

| Researchers and Year | Research Technique | Geometry | Base Fluid | Main Outcomes                                                                 |
|----------------------|--------------------|----------|------------|-------------------------------------------------------------------------------|
| Reddy and Rao (2014) | Experimental       | Tube     | EG/W (4:6) | The maximum improvement of the h and friction factor was achieved by 10.73% and 8.73% at 0.02 vol.% loading. |
| Ali et al. (2015)    | Experimental       | Vertical helical coiled | Water           | Heat transfer coefficient improved with increased loading of nanoparticles and Re. |
| Abbassi et al. (2014) | Experimental   | Vertical annulus | Water | The coefficient of heat transfer of nanofluids was higher than water and improved with increased particulate load. |
| Bhanvase et al. (2014) | Experimental | Tube     | EG/W (4:6) | The maximum improvement of (h) was 105% at 0.5 vol.% particle loading. |
| Perarasu et al. (2012) | Experimental | Coiled agitated vessel | Water           | The maximum improvement of h was 17.59% at 0.3 vol.% particle loading. |
| Barzegarian et al. (2016) | Experimental | Brazed plate heat exchanger | Water | The maximum improvement of local h at 0.3%, 0.8% and 1.5% particle weight loading were 6.6%, 13.5% and 23.7% respectively. |
| Arulprakasajothi et al. (2015) | Experimental | Horizontal tube | Water | Nu increased by 10%, 11.2%, 12% and 16.3% at particle volume loading of 0.1%, 0.25%, 0.5% and 0.75% respectively. |
| Chen and Cheng. (2016) | Experimental | Heat exchanger | Water | Nu and friction factor improved with particle loading. |
| Abdolbasg et al. (2015) | Numerical         | Straight channel | Water (6:4), water | (a) The improvement of h improved with an increased in particle loading. (b) The influence of nanoparticles on h was greater in higher Re or heat flux. (c) The enhancement of h was greater for EG/W (6:4) base fluid than pure water. |
| Bakili et al. (2013) | Experimental       | Vertical pipe | EG/W | The enhancements of heat transfer coefficient at 0.5, 1.0 and 2.5 wt.% loading was respectively 11.8%, 23.5% and 24.9%. |
| Chen et al. (2008)   | Experimental       | Vertical tube | Water | (a) A maximum enhancement of h was 21%. (b) h increased as the increase in particle loading and the decrease in particle size. |
| Goutam and Manosh. (2014) | Numerical         | Horizontal pipe | Water | (a) Size of particle plays greater role in the enhancement of convection heat transfer than that in thermal conductivity. (b) Particle migrations on the boundary layer can improve h of TiO$_2$ nanofluids. |
| Salman et al. (2015) | Experimental       | Tube inserted with conic cut twist tape | Water | Heat transfer coefficient increased with rise in nanoparticle loading and Re. |
| Singh et al. (2016)  | Experimental       | Steel plate | Water | CHF increased with the increase of loading of TiO$_2$ nanoparticle in nanofluid (impingement jet). |

### Table 7. Comparison of nanocoating application enhancements.

| Authors (Year) [Reference] | Research Method | Geometry | Nanoparticle | Main Findings |
|----------------------------|-----------------|----------|--------------|---------------|
| Senthilkumar et al. (2013) | Experimental    | Brass Surface | CNT | The enhancement ratio was around 12% |
| Mayilsamy (2014) [13]      | Experimental    | Finns    | CNT | Finns effectiveness increased by 21.8%. Heat transfer rate increased by 7%. Finns efficiency increased 6.2% |
| Ray (2017) [14]            | Experimental    | Cooper surface | TiO$_2$ | Surface Coated by TiO$_2$ and R134 in 2 thickness 100 and 200 nm. Coated surface is better than uncoated surface due to augment the roughness |
| Li et al. (2018) [51]      | Experimental    | Hot surface | Cu+ Al$_2$O$_3$ | Significantly increase the heat transfer rate |
| Mitrovic and Hartman (2004) [52] | Experimental | Finns Electrocoating | Micro-fin structured R-141 | Significantly Improve the heat transfer rate by using electrocoating for Finns |
The interaction of Nusselt number values and Reynolds number for different research work is showed in Figure 20, it’s also illustrated the current work values is higher than others [53–60]. Interaction of the thermal conductivity with nanofluid concentration has been illustrated in Figure 21 comparing with many researchers to validate the current research work [57–60]. Figure 22 presents the interaction of Nusselt number values with different concentrations of nanofluid, the figure shows that the current work is higher than Arjun work in both laminar and turbulent velocity flow [61]. Based on the results of the flow characteristics, one can obtain higher turbulence intensity at a higher velocity. Also, based on the previously presented results of the parametric study, a Reynolds number equal to around 17,000 is considered the optimum value for obtaining the highest Nusselt number. Therefore, that Reynolds number was used to obtain the current results and examine the higher heat transfer enhancement levels. The outcomes of the heat transfer enhancement test are discussed from different viewpoints. Firstly, this section has been discussed the study of the impact of the twin impingement jet on the Nusselt number obtained through these experiments. Furthermore, this section has presented a discussion of the effect of a nanosolution coating on the Nusselt number enhancement factor. There is also an explanation regarding the influence of jet configurations on the heat flux enhancement factor. All these areas support the creation of a clear view regarding the assessment of heat transfer enhancement as a result of twin impinging jets. The Nusselt number’s behavior is considered based on the normalized nozzle-plate distance and changes from one to eleven for twin jets. The figures above present the Nusselt number determined at the interference zone centerline of twin jets and for the various cases. The nanoparticle concentrations have taken into account three levels of concentration (0.1 M, 0.5 M, and 1 M) and three values for the Reynolds number (9000, 13,000 and 17,000). It was evident that the concentration (especially at 0.5 M) was almost successful in achieving a Nusselt number that is higher compared to the others. However, at H = 1 cm, it was observed that the steady jet had better performance compared to others at S = 1 cm. Therefore, the two wall jets produced by the impinging of twin jets on the hot plate served as the only cooling air source at secondary stagnation point found between the twin jets. Hence, from the main stagnation point, the heat removing action significantly affects the removal of heat from the secondary stagnation point. Since it was proven by previous studies that steady single jet are better at generating heat transfer than the pulsating jet at stagnation point [62], it can also be said that the heat removing action of the steady jets from the secondary stagnation point is better than pulsating jets for that given case. Velocity increment takes place at the centerline of the interference zone, which increases the velocity and results into heat transfer and Nusselt number augmentation [63–65].
Figure 20. Interaction of Nusselt number and Reynolds number.

Figure 21. Interaction of the thermal conductivity with Nanofluid concentration.

There is a significant improvement in the result of Nusselt number as against other results such as [29,66–69]. There was a consistency in the results for the heat transfer rate for the surface coated by TiO$_2$ solution in the most cases compared to other results like [68,70,71] as shown in Figure 23.

Figure 22. Interaction of Nusselt number values with different concentrations of Nanofluid.

Figure 23. Interaction of nozzle-plate distance levels with Nusselt number values.
5. Conclusions

This article presented and discussed the results of the study about the impact of nanocoating concentration on the heat transfer enhancement within the interference zone of the twin impingement jets mechanism. The manuscript presented the application of RSM studies by D-Optimal design in optimization study to improve the heat transfer coefficient. The article is organized into three parts. The first part presented the heat transfer enhancement that was examined and assessed by the determination of heat flux and Nusselt number. The second part included the nanopreparations, field emission scanning electron microscopy technique (FESEM), and X-ray diffraction analysis (XRD) that were performed to examine the structure and surface homogeneity of the surface coating. The third part explained the fundamental theory of the DOE technique for the purpose of the parametric study. This research optimized all the correlated parameters for maximizing the Nu number. The results indicated that the Nu number was highest at the optimal nano-concentration of 0.5% M and the nozzle spacing was 1 cm. Thus, the Nu number increases with lower nozzle spacing. This interesting fact was attributed to the development of a large vortex at the interference zone. This led to an increased mixing, which could decrease the temperatures of the wall-jet air and increase the heat transfer by increasing the temperature differences between the wall-jet air and hot plates at the interference zone centers. However, an interaction of all factors indicated that these parameters could show a different effect on the heat transfer if they were changed. Based on the results of the factor interaction, the research concluded that a high Re number could change the optimal nano-concentration from a low to high level. The highest rate of enhancement in Nusselt number is around 26% which is achieved using TiO₂ nanocoating process. Results reported also the successfully application of RSM and its validation with including ANOVA studies on the quality of the model. Generally, the model optimization process offered information regarding the optimal conditions which increased the heat transfer rate, so the presented results of this work could encourage the overall uses of multivariate methods in these fields.

6. Future Scope

The nanofluid (nanoparticle) is seen to have a high future scope in the field of industrial, engineering, and research and development. The surface coating is one application that enhances the performance and heat transfer of numerous thermal systems. In the impingement jet techniques, nanotechnology applications have a very promising future and require more investigation. The effect of utilizing another nanocoating such as CNT, Al₂O₃, ZNC, CU, etc. on the flow characteristics and heat transfer rate in various applications can be examined. Some new critical nanotechnology applications must be formulated. The lack of information about the heat transfer kinds of nanofluids such as high temperature and high-pressure applications, jet impingement, and spray, etc. are of interest and worth exploring. The challenges presented above have also presented new opportunities and study directions for studies in the heat transfer applications of TiO₂ nanotechnology in the future.

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