Enhancement of heat transfer utilizing γAl_2O_3-water nanofluid designed by Taguchi method

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Abstract: Enhancement of heat transfer in a channel utilizing γAl_2O_3-water nanofluid with an array of impinging jets has been designed and predicted using Taguchi method. Variations of heat transfer were investigated at different Reynolds numbers (Re=50, 100, 150, 200), nanofluid volume fraction (φ=0,1, 3, 5%) and jet–to-cross flow velocity ratio (R=1, 2.5, 5, 7.5). Five in-line jets subjected to across-flow were also used in this study. To use Taguchi method, first the strongest factor on heat transfer were determined as Re, φ and R. Then, different levels of each factor were recognized as 4 levels and orthogonal arrays were prepared for design. the results of the analysis showed that the Nusselt number is optimized at maximum Reynolds number and nanoparticles' volume fraction and minimum velocity ratio in the range of designed factors. The prediction results of Nusselt for randomly selected combinations of the factors and optimum choice showed that the error was rather small and the method could successfully be used to design and prediction of heat transfer enhancement in the channels.
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1. Introduction

Forced convection in a channel is one of the most important subjects in many technological applications like high performance boilers, chemical catalytic reactors, solar collectors and power plants. Management of heat transfer for its enhancement or reduction in these systems is an essential task from an energy saving perspective [1,2].

On the other hand, a single fluid jet or an array of jets, impinging normally on a surface is an effective technique for heating or cooling solid surfaces. In many industrial systems, jet impingement used an effective method of cooling, such as tempering of glass, drying of paper and textiles, cooling of the metal sheets, micro-electronic components and turbine blades. Impinging jets are generally used to enhance the rate of heat transfer between a fluid and solid, and are quite often employed to produce enhanced and controlled localized cooling or heating effects on surfaces, as compared with non-impinging flows. It is necessary to use multiple or an array of jets to cool/heat a large area in many applications. In an array of jets, the impingement of a jet on the surface of a plate results in the formation of a wall jet, which flows radially away from the impingement point along the plate surface. The interaction of this wall jet with the exhaust from the upstream jets results in the formation of a horseshoe vortex upstream of the impinging jet, which plays an important role in the cooling/heating performance. In addition, the interaction between the jets influences the rate of cooling/heating performance. Several investigators have studied the effect of a cross-flow on jet cooling. Krothapalli et. al. [3] studied showed the horseshoe vortex formation at the upstream of a rectangular jet in cross-flow. They reported that the formation and roll-up of the horseshoe vortices could be a periodic phenomenon, which occurs at a frequency similar to the periodic vortices in the wake. Kelso and Smits [4] also observed unsteady horseshoe vortex system in the case of round jet in cross-flow. Some further observations of the horseshoe vortices were reported by Fric and Roshko [5], Shang et al. [6], Krothapalli and Shih [7] and, Kelso et al. [8]. The horseshoe vortex, which formed around each impinging jet, was also observed by Barata et al. [9] and Barata [10] with multiple jets in a cross-flow, Kim and Benson [11] with row of jets in the cross-flow, and Abdon and Sunden [12] with round jet in cross-flow. Many researchers considered Nanotechnology as the most important driving moment for the major industrial revolution of this century. The low thermal conductivity of conventional fluids such as air, water, oil, and ethylene glycol mixture is considered as the primary obstacle to enhance the performance of heat exchangers. Addition of Nano-particles to the pure fluid, the so called “Nano-fluid”, can improve the thermal conductivity of the mixture. The Nano-fluids make larger thermal conductivity compared to the pure fluids [13]. Choi [14] is the first who used the term Nano-fluids to refer to the fluids with suspended Nano-particles. Several researches [15-17] have indicated that with low (1 to 5% by volume) Nano-particle concentrations, the thermal conductivity can be increased by about 20%. Xuan et al. [17] experimentally obtained thermal conductivity of copper-water Nano-fluid up to 7.5% of solid volume fraction. Several studies were performed on natural convection using Nano-fluids in cavities. Khanafer et al. [13] investigated the heat transfer enhancement in a two-dimensional enclosure utilizing Nano-fluids for various pertinent parameters. Jou and Tzeng [18] used Nano-fluids to enhance natural convection heat transfer in a rectangular enclosure. They indicated that volume fraction of Nano-fluids causes an increase in the average heat transfer coefficient. Hwang et al. [19] investigated the buoyancy-driven heat transfer of water-based Al2O3 Nano-fluids in a rectangular cavity. Some authors have studied numerical studies on forced convection using Nano-fluids. Xuan and Li [20] have experimentally investigated the heat transfer and flow field of copper-water Nano-fluid flowing through a tube. They have conducted their study for a range of Re (10,000 to 25,000) and φ(0.3 to 2%). Yang et al. [21] have investigated experimentally the convective heat transfer of graphite in oil Nano-fluid for laminar flow in a horizontal tube heat exchanger. Santra et al. [22] shows the heat transfer due to laminar flow of copper-water Nano-fluid through two-dimensional channel with constant temperature walls. They conclude that the rate of heat transfer increases with the increase in flow Reynolds number as well as the increase in solid volume fraction of the nano-fluid.

In this study the effects of some parameters such as volume fraction of the nanofluid (φ), Reynolds number (Re) and jet-to cross flow velocity ratio (R) on heat transfer enhancement in a channel including jet impinging have been investigated by Taguchi method. Design of the effective parameters and prediction of the results have been carried out using Taguchi method and comparison shows the small error of the predictions and satisfactory performance of the method.

2. Geometrical configuration and governing equations

The present work deals with a two-dimensional channel with five in-line square jets in a cross-flow, the opening height H and length L, as shown in Fig. 1, through which the nano-fluid flows.

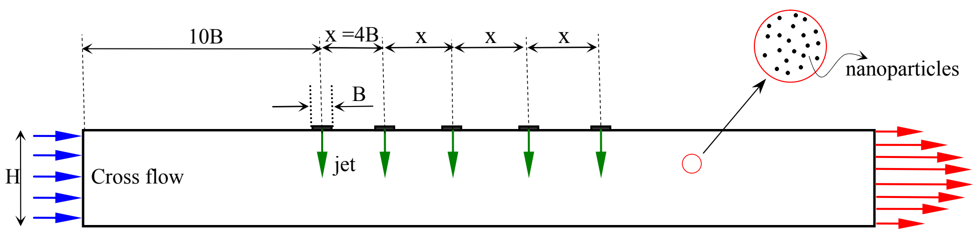

Fig. 1. Schematic diagram and geometrical configuration of the channel

The Nano-fluid in the duct is taken to be Newtonian, incompressible, and laminar. The Nanoparticles are assumed to have a uniform shape and size. Moreover, it is assumed that both the fluid phase and Nano-particles are in thermal equilibrium state and they are significantly small in sizes so the slip velocity between the phases is ignored. The temperature of the bottom wall, T_w, is taken such that $T_w > T_{in}$; where T_{in} is the fluid temperature at the inlet plane.

The continuity, momentum, and energy equations can be expressed as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\upsilon_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \qquad (2)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\upsilon_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \qquad (3)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \qquad (4)$$

Where

$$\upsilon_{nf}=\frac{\mu_{nf}}{\rho_{nf}} \qquad (5)$$

$$\alpha_{nf}=k_{nf}/(\rho C_p)_{nf} \qquad (6)$$

3. Physical properties of the nano-fluid

By assuming that the nanoparticles are well dispersed within the base fluid i.e. the particle concentration can be considered uniform throughout the domain and, knowing the properties of the constituents as well as their respective concentrations, the effective physical properties of the mixtures studied can be evaluated using some classical formulas as well known for two-phase fluids. In the following equations, the subscripts 'p', 'bf' and 'nf' refer, respectively, to the particles, the base-fluid and the nano-fluid:

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_p \quad (7)$$

$$(C_p)_{nf} = (1-\varphi)(C_p)_{bf} + \varphi(C_p)_P \quad (8)$$

$$\mu_{nf} = (123\varphi^2 + 7.3\varphi + 1)\mu_{bf} \text{ for water- nano } \gamma Al_2O_3 \quad (9)$$

$$k_{nf} = (4.9\varphi^2 + 2.72\varphi + 1)k_{bf} \text{ for water- nano } \gamma Al_2O_3 \quad (10)$$

Eqs. (7) and (8) are general relationships used to compute the density and specific heat for a classical two phase mixture [23]. Eq. (9) for computing the dynamic viscosity of nanofluids have been obtained by performing a least-square curve fitting of some scarce experimental data available for the mixtures considered [24-26]. The reason of such a choice resides in the fact that, although there exists some formulas such as the one proposed by Einstein and later improved by Brinkman [27] as well as the one proposed by Batchelor [28] that can be employed, it has been found that these formulas drastically underestimate the viscosity of the nanofluids under consideration with respect to the measured data, as shown by Maïga et al. [29].

In the present study, we have introduced Eq. (10) that has been obtained using the model proposed by Hamilton and Crosser [30] which assumes spherical particles. Such a model, which was first developed based on data from several mixtures containing relatively large particles i.e. millimeter and micrometer size particles, is believed to be acceptable for use with nano-fluids, although it may give underestimated values of thermal conductivity. This model has been adopted in this study because of its simplicity as well as its interesting feature regarding the influence of the particle form itself.

4. Boundary conditions

The boundary conditions of the channel for velocity and temperature are defined according to the geometry as follows:

Inlet: $T = T_{in}$, $u = u_c$, $v = 0$ at $x = 0$ and $0 \le y \le H$

Outlet: $\frac{\partial T}{\partial x} = 0$, $\frac{\partial u}{\partial x} = 0$ at $x = L$ and $0 \le y \le H$

Top wall: $T = T_{in}$, $u = v = 0$ at $y = H$

Bottom wall: $T = T_W$, $u = v = 0$ at $y = 0$

The boundary conditions of the jet are also as follows:

$T = T_{in}$, $u = u_j$

5. Taguchi Methods

Taguchi methods consist of 3 phases: designing the experiment, running and analyzing, and confirming and validating the assumptions. After selecting the variables to be studied, Taguchi methods depend on distributing the factors under study in an orthogonal array, which distributes the variables (factors) in a balanced manner. Examining a typical orthogonal array (Table 1), where each factor has 4 levels, reveals that each level has an equal number of occurrences within each column. For each column of the orthogonal distribution below, level 1 occurs four times, and levels 2,3 and 4 occur four times as well [31]. This idea of balance goes farther than meaning simply an equal number of levels within each column. The relationship between one column and another is arranged so that for each level within one column, each level within any other column occurs an equal number of times as well. With reference to Table 1, it can be observed that factor φ is assigned to column 1, and for φ at each level, factor Re with 4 levels is repeated. The ramifications of this orthogonality among columns are the basis of the statistical independence of orthogonal arrays; hence the effect of each factor can be separated from the others. Therefore, an estimation of the effect of any one particular factor tends to be accurate and reproducible because the estimated effect does not include the influence of other factors. Furthermore, each factor can be assigned a significance weight to denote its importance in affecting the end result of the experiment.

Table 1. Number of trials, factors and their levels

Trial	φ	Re	R	Nu
1	0	50	1	2.5
2	0	100	2.5	3.13
3	0	150	5	3.7
4	0	200	7.5	4.21
5	0.01	50	2.5	2.28
6	0.01	100	5	3.06
7	0.01	150	7.5	3.7
8	0.01	200	1	5.17
9	0.03	50	5	2.3
10	0.03	100	7.5	3.17
11	0.03	150	1	4.67
12	0.03	200	2.5	4.87
13	0.05	50	7.5	2.41
14	0.05	100	1	4.03
15	0.05	150	2.5	4.45
16	0.05	200	5	4.96

Each array can be identified by the form $L_A(B^C)$, the subscript L, which is designated by *A*, represents the number of experiments that would be conducted using this design, B denotes the number of levels or concentrations within each column which denotes how many levels or concentrations could be investigated, while the letter *C* identifies the number of columns available within the orthogonal array which indicates how many factors or variables could be included in the experiment [31]. For example the orthogonal array $L_{16}(4^3)$ means that 16 experimental runs are needed to investigate 3 different factors, each of which is set at 4 predetermined levels (Table 1). The statistical independence of these arrays enables the effect of each factor to be separated from the others, the effects to be accurate and reproducible because the estimated effect does not include the effects of other factors and the interactions between these factors to be determined.

6. Results and discussion

6.1. Taguchi analysis

Level average analysis, as described by Taguchi [31] is one of the techniques used to explore the results of the Taguchi methods. The name derives from determining the average effect of each factor on the outcome of the experiment. The goal is to identify those factors that have the strongest effects and whether they exert their effect independently or through interacting with other factors. Presented in table 2 are the levels of the influencing factors and the average results calculated for each level. The relationship between different levels of each factor and the level average results are plotted in figs. 2, 3 and 4. From the figures, the optimum combinations of the factors and levels can be found. In this study, since the obtained curves are fully ascending or descending, the optimum combination contains the maximum or minimum level of each factor.

Table 2. Levels of the influencing factors and the average results

Factor	Level No.	Level quantity	Average Nu results
φ	1	0	3.38
φ	2	0.01	3.55
φ	3	0.03	3.75
φ	4	0.05	3.96
Re	1	50	2.37
Re	2	100	3.34
Re	3	150	4.13
Re	4	200	4.80
R	1	1	4.09
R	2	2.5	3.68
R	3	5	3.50
R	4	7.5	3.37

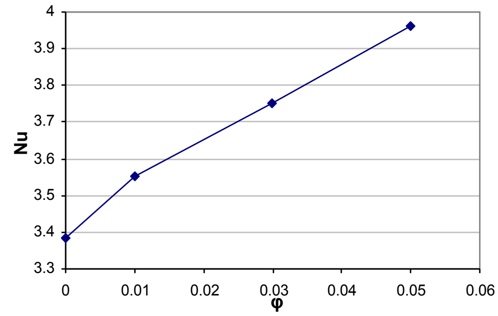

Fig. 2. Variations of Nusselt against volume fraction of nano-fluid

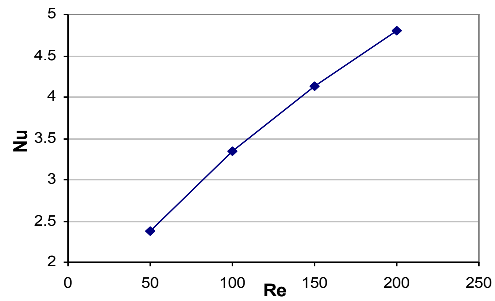

Fig. 3. Variations of Nusselt against Reynolds number

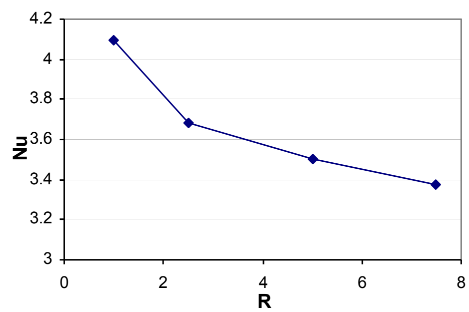

Fig. 4. Variations of Nusselt against velocity ratio

An estimate of the predicted response (Y) based on the selected levels was then computed. The calculations were based on the overall average value (T) and the effect that each of the recommended strong factors has on the overall average, i.e. effect of φ (T_φ), Re (T_{Re}) and R (T_R).

$$Y = T + (T_\varphi - T) + (T_{Re} - T) + (T_R - T) \qquad (19)$$

Further calculations were performed to determine whether the outcome of other combinations could be predicted from the Taguchi design and confirmed by actual results. Three combinations were randomly selected and the combination for optimum (here maximum) Nusselt number was also selected based on the figs. 2,3 and 4 to be calculated by the Eq. 19. The results are shown in Table 3 which shows a close approximation in each case with small error which shows good and rather precise prediction of the Nusselt results by Taguchi method.

Table 3. Comparison of the Taguchi method predictions and actual results

Combination	Nu: Taguchi design	Nu: Actual	Error (%)
φ=0.01, Re=100, R=7.5	2.94	3.01	2.11
φ=0.05, Re=50, R=5	2.51	2.44	3.02
φ=0, Re=200, R=1	4.95	5.04	1.71
φ=0.05, Re=200, R=1 (Optimum)	5.53	5.85	5.44

7. Conclusion

Based on the results obtained in this study, the following concluding remarks may be inferred:

- Heat transfer enhancement in a channel utilizing nanofluid could be designed and predicted successfully and with an acceptable error by Taguchi method.
- Nanofluid volume fraction, Reynolds number and jet-to-cross flow velocity ratio could be considered as effective factors in predicting the heat transfer enhancement in a channel.
- Optimum levels of the influencing factors in heat transfer enhancement could be reliably determined by Taguchi method.

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