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A Taguchi approach for optimization of flow and geometrical parameters in a rectangular channel roughened with V down perforated baffles

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ABSTRACT

This study presents the optimum design parameters of the rectangular channel with V down perforated baffle turbulators using a Taguchi experimental design method. The experimental investigation for the established rectangular channel involves V down perforated baffles attached to the one of the broad wall of the channel having various roughness parameters. The effects of the four design parameters such as Reynolds number, open area ratio, relative roughness height and relative roughness pitch are investigated. In the Taguchi experimental design method, Nusselt number and friction are considered as performance parameter. An L_{16} (4^4) orthogonal array is chosen as an experimental plan for the design parameters. The analysis of Taguchi method conducted with the goal of optimization process for minimum friction factor (minimum pressure drop) and maximum Nusselt number (maximum heat transfer) for the designed V down perforated baffle roughened rectangular channel. The optimum configurations of control factors for Nusselt number and friction factor are $A_4B_2C_1D_4$ and $A_4B_1C_4D_3$, respectively. Experimental results validated the suitability of the proposed approach.

1. Introduction

The primary objective of the design of modern thermal systems is the achievement of the compact and effective heat exchanger systems. Heat transfer enhancement is one of the most important aspects of researchers and scientists working in the area of thermal systems design. The higher heat transfer rates achieved through various enhancement techniques results in substantial energy savings, with higher thermal efficiency and compact system design. Frequently used heat transfer enhancement techniques include extended surfaces, turbulators and winglets. The turbulators create turbulence in the core fluid flow leading to higher heat transfer rate from the roughened surfaces. A question arises with the roughened channels, as how much should be the modification required in roughened parameters for the optimization. The most of the research in this field is considering the aspect of heat transfer enhancement; on the contrary, optimization of heat transfer devices is the topic that has just been improving. The investigations pertaining to heat transfer enhancement in rectangular channel include various rectangular channels roughened with turbulators having different geometries and geometrical parameters. The heat transfer enhancement is also accompanied with increase in the pressure drop within the rectangular channel. Numerous researches have been carried out concerning the effect of turbulators on heat transfer and pressure drop in a

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Nomenclature

A_o	area of orifice meter (m^2)
A_p	surface area of absorber plate (m^2)
C_d	coefficient of discharge
C_p	specific heat of air (J/kg K)
D_h	hydraulic diameter of duct (m)
e/H	relative roughness height
f	friction factor
G_{air}	mass velocity of air (kg/s m^2)
h	heat transfer coefficient (W/m^2 K)
L	length of test section (m)
$\dot{m}$	mass flow rate of fluid (kg/s)
Nu	Nusselt number
P/e	relative roughness pitch
ΔP	pressure drop across test section (Pa)
ΔP_o	pressure drop across orifice plate (Pa)
Q_u	useful heat gain (W)
Re	Reynolds number
T_f	bulk mean temperature of flowing fluid (K)
T_i	temperature of fluid at inlet (K)
T_o	temperature of fluid at outlet (K)
T_p	mean temperature of absorber plate (K)

Greek symbols

β	open area ratio
ρ_{air}	density of air at bulk mean air temperature (kg/m^3)
Ψ	ratio of orifice diameter to pipe diameter

roughened rectangular channel [1–10]. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varies. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources. Another advantage is that optimal working conditions determined from the experimental work can also be reproduced in real applications [11–16].

Bilen et al. [17] used Taguchi approach to analyze the heat transfer from a surface equipped with rectangular blocks, taking into account the angular displacement of the block in addition to its span wise and stream wise disposition. The Taguchi analysis reveals that the most efficient parameter is the flow Reynolds number then the angular displacement. The study also reveals that the Taguchi method is a suitable approach for implementing in the heat transfer problems. A comparative study of effects of attack angle, length of vortex generator, height of vortex generator, fin material, fin thickness, fin pitch and tube pitch on fin performance of vortex generator fin and tube heat exchanger using numerical method was carried out by Zeng et al. [18] and the parameters are optimized using Taguchi method. The two optimal conditions were determined as $A_1B_3C_3D_2E_1F_2G_1H_3$ and $A_2B_2C_2D_3E_1F_2G_1H3$. Gunes et al. [19] applied Taguchi method to determine the optimum values of the design parameters viz. distance between the coiled wire and test tube wall to tube diameter (s/D), pitch ratio (P/D), ratio of the side length of equilateral triangle to tube diameter (a/D) and Reynolds number (Re) on the basis of heat transfer and friction characteristics in a tube with equilateral triangular cross sectioned coiled wire inserts. The contribution ratio to each parameter is determined and the optimum combination was found to be $s/D=0.0357$, $P/D=1$, $a/D=0.0714$ and $Re=19{,}800$. An optimum design parameter of the concentric heat exchanger with injector turbulators using Taguchi experimental design method was carried out by Turgut et al. [20]. The effects of injector shaped turbulators having different angle, diameter and the numbers on heat transfer and pressure drop were investigated using L_{16} orthogonal array and it was found that the numerical and experimental results are in good agreement with each other. The effect of six design parameters viz. ratio of duct channel width to height, the ratio of the winglets length to the duct channel length, inclination angles of the winglet, Reynolds number, flow velocity and pressure drop were investigated in a delta winglet roughened rectangular channel carried out by Kotcioglu et al. [21] using Taguchi and it was found that Taguchi approach is suitable in determining the optimum values of the control factors in heat transfer problems.

The literature study shows that there are lots of heat transfer enhancement studies on turbulators [1–10]. Therefore, the present article is focussed on the determination of the optimum roughened parameters of V down perforated baffle roughened rectangular channel by using Taguchi method. As it is quite exhaustive to determine the effects of all parameters affecting the heat transfer and friction factor processes in detail because it requires a wide range of experiments, which extremely increase the experimental cost and the experimentation time. But, the quantitative estimations of the various parameters influencing the performance of the system and the principal factors for optimum design need to be determined by an optimization approach.

2. Experimental test setup

The experimental test setup used to study is shown in Fig. 1. The main features of the experimental detail and data reduction are given elsewhere Chamoli and Thakur [9]. The experimental apparatus mainly consists of inlet, test and outlet section of 700, 1300 and 400 mm length respectively. The rectangular channel duct has an aspect ratio of 10, with width of 350 mm and height of 35 mm the channel. The components of the experimental setup are a blower, wooden rectangular duct, electric heater, GI pipe, control valves, orifice plate, U tube manometer, micromanometer, variable transformer,

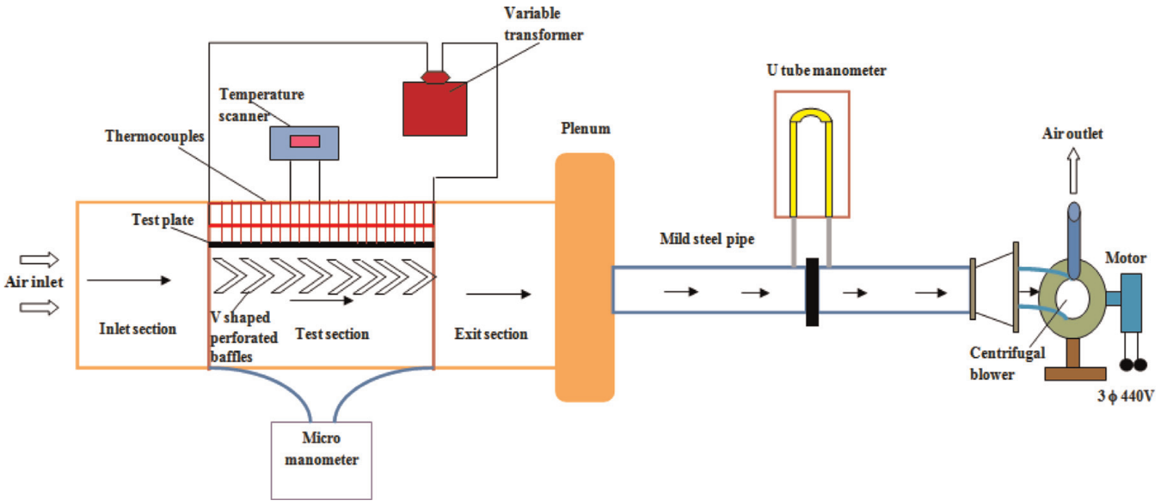

Fig. 1. Schematic diagram of the experimental test rig.

thermocouples and temperature scanner as shown in Fig. 1. An electric heater having size of 1300 mm × 350 mm is fabricated by combining series and parallel loops of heating wire on a thick asbestos sheet of 5 mm thickness. A mica sheet of 1 mm thickness was placed over electric heater wire to have a uniform heat flux over the test plate. The heat flux of intensity 1000 W/m^2 is provided over the test plate with the help of variable transformer. The T type copper constantan thermocouples were used to measure the test plate, inlet and outlet temperatures. The mass flow rate of air is measured by means of calibrated orifice meter attached with a U tube manometer. The control valves were provided to change the flow Reynolds number. A temperature scanner was used to measure the temperatures and pressure drop across the test section was measured with the help of a digital micro manometer. The roughened test plates are fabricated with 0.9 mm thick GI sheet. The V down perforated baffle turbulators were used as a roughness element with different configurations viz. Relative roughness pitch (P/e), relative roughness height (e/H) and open area ratio (β). The schematic diagram of the V down perforated baffle is shown in Fig. 2.

3. Experimental design

3.1. Taguchi method

The Taguchi method is being extensively used in industrial and engineering problems due to its wide range of applications. The Taguchi method is the commonly adopted approach for optimizing design parameters. The method was originally proposed as a means of improving the quality of products using the application of statistical and engineering concepts. This methodology is based on two fundamentals concepts: First, the quality losses must be defined as deviations from the targets, not conformance to arbitrary specifications, and the second, achieving high system quality levels economically requires quality to be designed into the product. To achieve desirable product quality by design, Taguchi suggests a three-stage process: system design, parameter design and tolerance design. System design is the conceptualization and synthesis of a product or process to be used. To achieve an increase in quality at this level requires innovation, and therefore

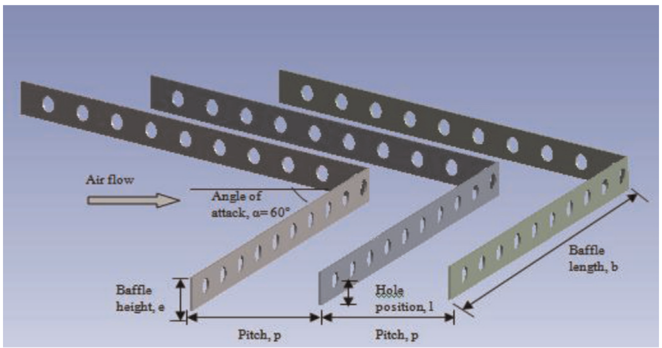

Fig. 2. Schematic diagram of the roughness geometry.

improvements are not always made. In parameter design the system variables are experimentally analyzed to determine how the product or process reacts to uncontrollable “noise” in the system; parameter design is the main thrust of Taguchi's approach. Parameter design is related to finding the appropriate design factor levels to make the system less sensitive to variations in uncontrollable noise factors, i.e., to make the system robust. In this way the product performs better, reducing the loss to the customer. The final step in Taguchi's robust design approach is tolerance design; tolerance design occurs when the tolerances for the products or process are established to minimize the sum of the manufacturing and lifetime costs of the product or process. In the tolerance design stage, tolerances of factors that have the largest influence on variation are adjusted only if after the parameter design stage, the target values of quality have not yet been achieved. Since the experimental procedures are generally expensive and time consuming, the need to satisfy the design objectives with least number of tests is clearly an important requirement. Once the levels are taken with careful understanding four parameters with four levels are used for the established experiments. Table 1 shows the factors to be studied and the assignment of the corresponding levels.

The Taguchi Robust Design method uses a mathematical tool called Orthogonal Arrays (OAs) and signal to noise ratio (SNR) to study a large number of process variables with a small number of experiments [13,14,22].

In the Taguchi method the orthogonal array facilitates the experimental design process and caters a method for fractional factorial experiments. The choice of the correct orthogonal array for the success of experimental design is essential and it depends on the degree of freedom required to study the main and interaction effects of control factors, objective of the experiment, resources and budget availability and the constraints for time. The orthogonal array contributes to study the effect of main and interacting parameters via minimizing the number of experimental trials. The Taguchi analysis is performed with Minitab 16.0 software. The array chosen for the present experimental design is L_{16} with degree of freedom 15. Four parameters each at four levels would require $4^4=256$ runs in a full factorial experiment, whereas Taguchi's factorial experiment approach reduces it to 16 runs only offering a great advantage.

According to the Taguchi design concept L_{16} orthogonal array is chosen for the experiments as shown in Tables 3a, 3b. As indicated in the table, the observed values of the relative roughness pitch (A), relative roughness height (B), open area ratio (C) and Reynolds number (D). Each experimental trail is performed as per L_{16}. The optimization of the observed values is determined by comparing the standard method and Analysis of Variance (ANOVA).

3.2. Analysis of variance (ANOVA)

Taguchi suggests two different routes to carry out complete analysis of the experimental data. In the first approach, results of a single run or the average of repetitive runs are processed through main effect and ANOVA analysis of the raw data. The second approach, which Taguchi strongly recommends, is to use Signal-to-Noise (S/N) ratios for the same steps of the analysis. The S/N ratio is generally represented by η and is a concurrent quality metric linked to the loss function. By maximizing the S/N ratio, the loss associated with the process can be minimized. The S/N ratio determines the most robust set of operating conditions from variation within the results. It is treated as a response parameter (transform of raw data) of the experiment. The experimental observations are transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristics. The S/N ratio characteristics can be divided into three categories given by Eqs. (1)–(3) when the characteristic is continuous:

$$\text{Smaller is the better characteristic: } \frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right) \tag{1}$$

$$\text{Nominal the better characteristic: } \frac{S}{N} = -10\log\frac{1}{n}\left(\sum\frac{\bar{Y}}{S_Y^2}\right) \tag{2}$$

$$\text{Larger the better characteristic: } \frac{S}{N} = -10\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right) \tag{3}$$

where $\bar{Y}$ is the average of observed data, S_Y^2 is the variation of y, n is the number of observations, and y is the observed data. “Higher is better” (HB) characteristic with the above S/N ratio and “Lower is better” (LB) characteristic with the above

Table 1
The parameters and their values corresponding to their levels.

Parameters	Levels			
	I	II	III	IV
A, relative roughness pitch (P/e)	1	2	3	4
B, relative roughness height (e/H)	0.287	0.4	0.514	0.6
C, open area ratio (β)	12	24	36	44
D, Reynolds number (Re)	4100	8500	14,800	18,600

S/N ratio transformation is suitable for maximization of Nusselt number and minimization of friction factor.

All of the experiments are listed in a plan given in Table 2. Contribution ratio of all factors on performance criteria depending on the SNR values are given in Tables 3a, 3b and 4a, 4b. Using these tables the optimal combination of the control factors can be predicted. Using Tables 3a, 3b and 4a, 4b the optimal combination of the process parameters can be predicted. The optimum values of the factors are determined by maximizing the Nusselt number and minimizing the friction factor, given in Table 5. The performance statistics (SNR) are selected as optimization criteria using Eqs. (1) and (3).

4. Experimental plan for the optimization

The heat transfer and friction factor characteristics are generally used to predict the performance of V down perforated baffle roughened rectangular channel. The outcome of the study reveals that the friction factor values increases with increase in heat transfer rate. The simultaneous effect of both the heat transfer and friction factor was taken into consideration in the present study and thus the study is based on higher heat transfer rate with minimum friction factor. The planned experimental runs are based on Taguchi method to investigate the main effects of the working parameters of on Nusselt number and friction factors characteristics of roughened channels, with objective of performing ANOVA to establish the optimal geometrical and flow parameters. The main effect of each parameter on Nusselt number and friction factor is shown in Figs. 3 and 4, respectively. The performance values and results of ANOVA are presented in Tables 3a, 3b and 4a, 4b, while the optimal condition of controlling factors are presented in Table 5.

4.1. Data reduction

The raw experimental data have been reduced to obtain the average plate temperature, average air temperature, mass flow rate and Reynolds number. These data were then used to determine the heat transfer coefficient, Nusselt number and friction factor.

The heat transfer coefficient for the heated section is calculated from the equation

$$h = \frac{Q_u}{A_p(T_p - T_f)} \tag{4}$$

where the heat gained by the air Q_u is given as

$$Q_u = \dot{m}C_p(T_o - T_i) \tag{5}$$

Mass flow rate $\dot{m}$ of air has been determined from the pressure drop across the orifice plate using the following equation

$$\dot{m} = C_d A_o \left[\frac{2\rho_{air}\,\Delta P_o}{1-\psi^4}\right]^{0.5} \tag{6}$$

Heat transfer coefficient has been used to calculate the Nusselt number using the equation

$$\mathrm{Nu} = \frac{hD_h}{K_{air}} \tag{7}$$

Table 2
Experimental plan of L_{16} orthogonal array for Nusselt number and friction factor with their SNR values.

Experiment run	*A*	*B*	*C*	*D*	Nu	*S–N*	*F*	*S–N*
1	1	1	1	1	35.00	30.8820	0.0550	25.1985
2	1	2	2	2	63.88	36.1075	0.0499	26.0390
3	1	3	3	3	94.43	39.5022	0.0637	23.9157
4	1	4	4	4	99.09	39.9208	0.0808	21.8538
5	2	1	2	3	100.72	40.0624	0.0337	29.4537
6	2	2	1	4	133.14	42.4862	0.0436	27.2170
7	2	3	4	1	35.57	31.0205	0.0713	22.9399
8	2	4	3	2	64.85	36.2380	0.0918	20.7391
9	3	1	3	4	108.22	40.6861	0.0304	30.3502
10	3	2	4	3	91.70	39.2475	0.0332	29.5895
11	3	3	1	2	70.19	36.9253	0.0662	23.5779
12	3	4	2	1	36.25	31.1850	0.1023	19.8058
13	4	1	4	2	49.99	33.9774	0.0303	30.3764
14	4	2	3	1	31.50	29.9649	0.0484	26.3089
15	4	3	2	4	100.75	40.0652	0.0514	25.7853
16	4	4	1	3	84.95	38.5836	0.0722	22.8319

Table 3a
Analysis of variance for *S*/*N* ratios for Nusselt number.

Source	DOF	Seq SS	Adj MS	*F*	*P* (%)
A	3	7.107	2.369	71.79	2.84
B	3	0.918	0.306	9.27	0.37
C	3	2.943	0.981	29.73	1.18
D	3	239.099	79.7	2415.15	95.58
Error	3	0.099	0.033		0.04
Total	15	250.166			

Table 3b
Response table for *S*/*N* ratios for Nusselt number.

Level	*A*	*B*	*C*	*D*
1	36.60	36.40	37.22	30.76
2	37.45	36.95	36.86	35.81
3	37.01	36.88	36.60	39.35
4	35.65	36.48	36.04	40.79
Delta	1.80	0.55	1.18	10.03
Rank	2	4	3	1
Contribution ratio (%)	13.27	4.06	8.70	73.97

Table 4a
Analysis of variance for *S*/*N* ratios for friction factor.

Source	DOF	Seq SS	Adj MS	*F*	*P* (%)
A	3	9.823	3.274	65.48	5.72
B	3	135.948	45.316	906.32	79.16
C	3	4.497	1.499	29.98	2.62
D	3	21.313	7.104	142.08	12.41
Error	3	0.15	0.05		0.09
Total	15	171.732			

Table 4b
Response table for *S*/*N* ratios for friction factor.

Level	*A*	*B*	*C*	*D*
1	24.25	28.84	24.71	23.56
2	25.09	27.29	25.27	25.18
3	25.83	24.05	25.33	26.45
4	26.33	21.31	26.19	26.30
Delta	2.07	7.54	1.48	2.88
Rank	3	1	4	2
Contribution ratio (%)	14.82	53.97	10.59	20.62

Table 5
Optimum conditions and performance values of tested V down perforated baffle roughened rectangular channel, where superscript a, b, c and d are the sequence of effective parameters.

	Parameters				Value
	A (*P*/*e*)	*B* (*e*/*H*)	*C* (β)	*D* (Re)	
Nu					
Optimum level	2^{b}	2^{d}	1^{c}	4^{a}	133.14
Optimum value	2	0.4	12%	18,600	
f					
Optimum level	4^{c}	1^{a}	4^{d}	3^{b}	0.0265
Optimum value	4	0.287	44%	14,800	

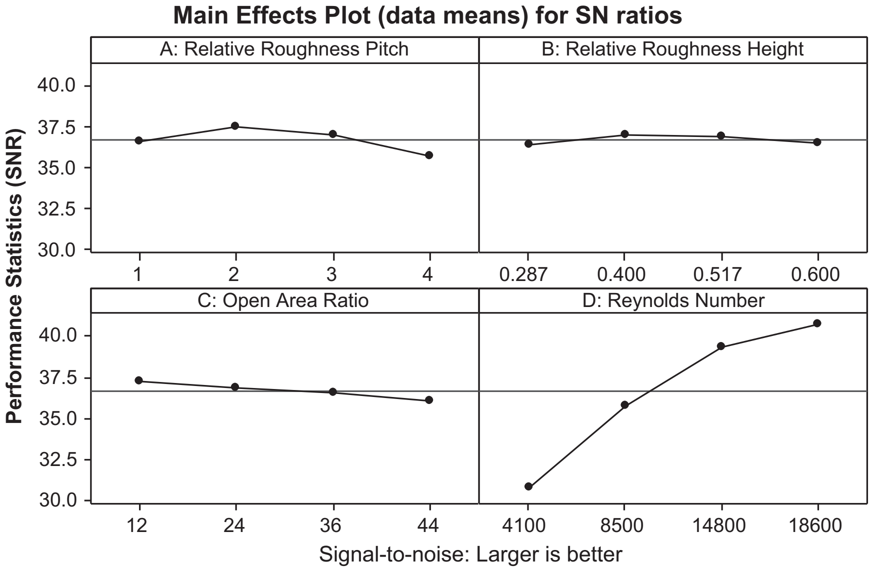

Fig. 3. The effects of design parameters of *A*, *B*, *C* and *D* on Nusselt number.

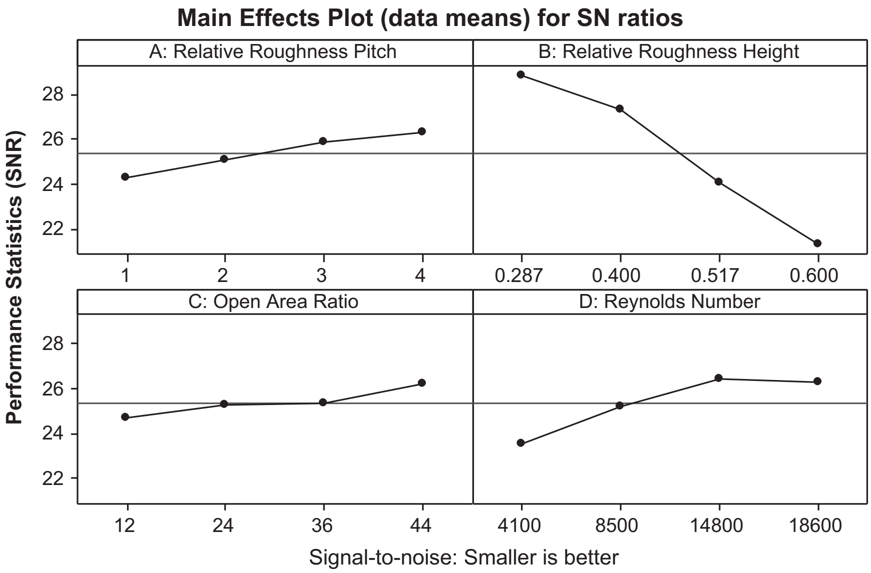

Fig. 4. The effects of design parameters of *A*, *B*, *C* and *D* on friction factor.

The friction factor determined from the flow velocity 'V' and the pressure drop 'ΔP' across the test section of 1.3 m length using the Darcy–Wiesbach equation as

$$f = \frac{2\Delta P \rho_{air} D_h}{4LG_{air}^2} \tag{8}$$

The uncertainties of experimental measurements were determined by using the method introduced by Kline and McClintock [23]. The maximum uncertainties in the values of non dimensional numbers viz. Reynolds number, Nusselt number and friction factor computed are $\pm 2.5\%$, $\pm 4.9\%$ and $\pm 4.7\%$, respectively.

5. Results and discussion

For the experimental analysis of performance prediction of V down perforated baffle roughened rectangular channel the considered parameters are flow Reynolds number, relative roughness pitch, relative roughness height, open area ratio and parameter have four levels given in Table 1. A systematic approach was used to obtain the optimal condition of control factors followed by contribution of individual factors and the response under optimal conditions. In order to establish these conditions, the experimental data for Nusselt number and friction factor collected and presented in the form of SNR in Table 2. From Table 2 overall mean for the S/N ratio of the Nusselt number and friction factor are found to be 36.68 db and 25.37 db, respectively. Figs. 3 and 4 show the effect of four control factors on Nusselt number and friction factor. It is seen from Fig. 3 that the Nusselt number takes its local maximum value at the second level and increases from 36.6 to 37.45 and then decreases to 37.01 at the third level for parameter A (P/e), this is due to the reason that on increasing relative roughness pitch values beyond 2 the mixing of the jet impinging flow with mainstream fluid flow is reduced, which leads to low heat transfer rate from the surface. For parameter B (e/H), the Nusselt number increases with increase in relative roughness height up to the second level and after that it start decreasing, this is due to the fact that the mainstream flow reattachment is reduced, which was accompanied with the heat transfer area shifting in further downstream direction leads to lower rate of heat transfer. The Nusselt number tends to decrease with the increase of parameter C (β) due to the fact that with increase in open area ratio, the quantity of fluid flow through the perforation increased, which results in the jet impingement reduction accompanied with the interference between the jets, leads to lower heat transfer rate. For parameter D (Re), the Nusselt number increases with the increase of mean fluid velocity, as expected. The analysis of the results gives the combination factors resulting in maximum heat transfer rate among the investigated test plate configurations are as follows: $P/e=2$ (A_2), $e/H=0.4$ (B_2), $\beta=12\%$ (C_1) and Re$=$18,600 (D_4). Consequently, $A_2B_2C_1D_4$ is defined as the optimum condition of design parameters related to the heat transfer according to the “higher is the better” situation for Nusselt number. The optimal value of Nusselt number is presented in Fig. 7.

The effect of each parameter on friction factor is presented in Fig. 4. The friction factor decreases with increase in control factor (A) i.e. increase in relative roughness pitch values, this is due to the reason that, with increase in relative roughness pitch the pressure drop across the channel is reduced, leading to lower friction factor values. The friction factor tends to increase with the increase of parameter B (e/H) due to the fact that large height baffle produced higher surface area and flow blockage associated with spent of the dynamic pressure of the fluid. The similar trend of friction factor was observed for control factor C (β), the value of friction factor decreases with increase in open area ratio; this is due to the reason that with increase in open area ratio the flow blockage for fluid flow is reduced, which results in lower friction factor values. The values of friction factor decreases with increase in mean fluid velocity i.e. the control factor D (Re). The optimum values of the parameters for minimum friction factor condition as follows: $P/e=4$ (A_4), $e/H=0.287$ (B_1), $\beta=44\%$ (C_4) and Re$=$14,800 (D_3). Consequently, $A_4B_1C_4D_3$ is defined as the optimum condition of design parameters related to the friction factor according to the “lower is the better” situation for friction factor. The optimal value of friction factor is presented in Fig. 7.

The delta is the difference of the maximum and minimum of the SNR for every control factor. The contribution ratio is equal to the ratio of the delta values of each factor to the total delta value of all factors as presented in Tables 3b and 4b. The contribution ratio of each control factor to Nusselt number is shown in Fig. 5. It is seen from the figure that the Reynolds number contributes to 73.9% percentage of the total effect. This means that the parameter D is the most effective one on heat transfer. Based on the Fig. 5, it can be concluded that the second, third and fourth effective parameters on heat transfer are A, C and B, respectively. As seen from Fig. 6, the parameter B is the most effective parameter on friction factor with a contribution ratio of 53.97% percentage of the total effect. The factors D, A and C contribute to 20.62%, 14.82% and 10.59% of the total effect on friction factor, respectively. The optimum level of control factors for Nusselt number and friction factor are A_2^b, B_2^d, C_1^c, D_4^a and A_4^c, B_1^a, C_4^d, D_3^b, respectively shown in Table 5. Here the coefficients a, b, c and d symbolize the importance level of each parameter and indicate the first, second, third and fourth effective parameter, respectively. ANOVA of the data

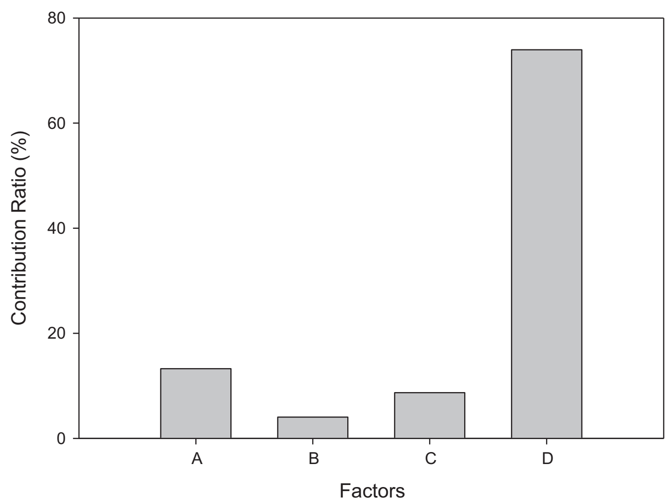

Fig. 5. The contribution ratio of each parameter to Nusselt number.

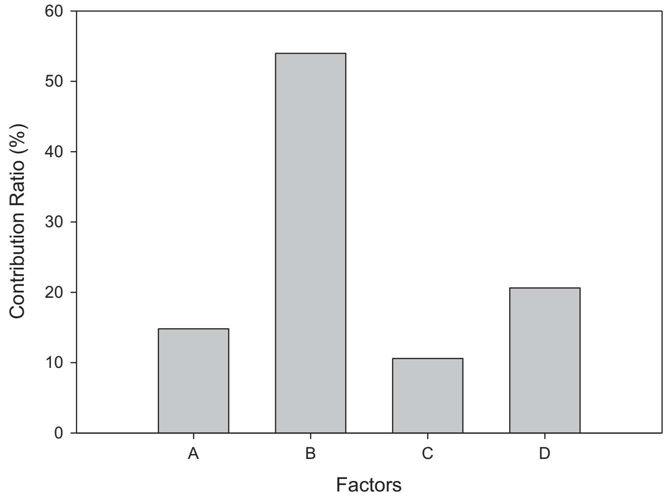

Fig. 6. The contribution ratio of each parameter to friction factor.

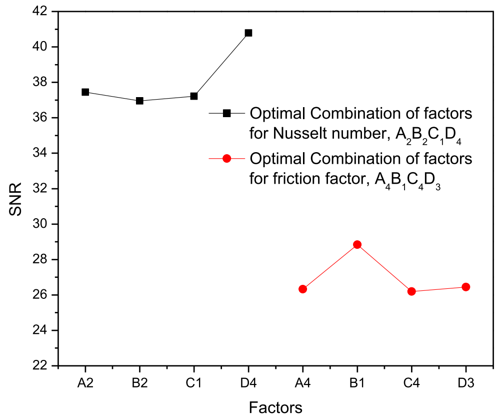

Fig. 7. optimal combination of control factors for Nusselt number and friction factor.

was done for Nusselt number and friction factor with the objective of analyzing the influence of relative roughness pitch (A), relative roughness height (B), open area ratio (C) and Reynolds number (D) on the total variance of the results. ANOVA allows analyzing the influence of each control factor on the total variance of the results. Tables 3a and 4a show the result of ANOVA for Nusselt number and friction factor, respectively. It can be observed from ANOVA Table 3a for Nusselt number that the (D) Reynolds number (P=95.58%) have greater influence on the Nusselt number and thus this parameter is physically and statistically highly significant. However the parameter (A) relative roughness pitch, (B) relative roughness height and (C) open area ratio has significantly less effect with the proportion of P=2.84%, P=0.37% and P=1.18%, respectively. For ANOVA result for friction factor from Table 4a, it is observed that the parameter (B) relative roughness height, (A) relative roughness pitch, (C) open area ratio and (D) Reynolds number have greater influence in the order of P=79.16%, P=5.72%, P=2.62%, and P=12.41%, respectively. The parameter (B) relative roughness height has the most significant effect on the friction factor in comparison to the other control factors A, C and D.

6. Experiments confirmation

The confirmation experiment is the final step in the design of experiment process. The confirmation experiment is conducted to validate the interference drawn during the analysis phase. The confirmation experiment is performed by considering the new set of factor settings $A_2B_2C_1D_4$ to predict the Nusselt number, while $A_4B_1C_4D_3$ for predicted the friction factor. The results of confirmation tests conducted with the optimum design parameters are presented in Tables 6 and 7. The estimated SNR for Nusselt number can be calculated with the help following predictive equation:

$$\eta_1 = \overline{T} + \left(\overline{A_2} - \overline{T}\right) + \left(\overline{B_2} - \overline{T}\right) + \left(\overline{C_1} - \overline{T}\right) + \left(\overline{D_4} - \overline{T}\right). \tag{9}$$

where η is the predicted average, T is the average result of 16 runs and $A_2B_2C_1D_4$ is the mean response for factors at

Table 6
Results of the confirmations experiment for Nusselt number.

	Initial parameter	Optimum parameters	
		Prediction	Experiment
Level	$A_1B_1C_1D_1$	$A_2B_2C_1D_4$	$A_2B_2C_1D_4$
S–N ratio (dB)	30.8	36.68	42.48

Improvement of *S–N* ratio for Nusselt number = 11.68 dB.

Table 7
Results of the confirmations experiment for friction factor.

	Initial parameter	Optimum parameters	
		Prediction	Experiment
Level	$A_1B_1C_1D_1$	$A_4B_1C_4D_3$	$A_4B_1C_4D_3$
S–N ratio (dB)	25.19	25.37	28.63

Improvement of *S–N* ratio for friction factor = 3.44 dB.

designated levels. The SNR value of Nusselt number by the predictive equation was found to be 36.68 and from the experimental results value of SNR is found to be 42.48. The resulting model seems to be capable of predicting Nusselt number to a reasonable accuracy. An error of 13.6% for the SNR of Nusselt number is observed.

Similarly a predictive equation is developed for estimating SNR of friction factor is given by the equation:

$$\eta_2 = \overline{T} + \left(\overline{A_4} - \overline{T}\right) + \left(\overline{B_1} - \overline{T}\right) + \left(\overline{C_4} - \overline{T}\right) + \left(\overline{D_3} - \overline{T}\right). \tag{10}$$

where η is the predicted average, T is the average result of 16 runs and $A_4B_1C_4D_3$ is the mean response for factors at designated levels. The SNR value of friction factor by the predictive equation was found to be 25.37 and from the experimental results value of SNR is found to be 28.63. The resulting model seems to be capable of predicting Nusselt number to a reasonable accuracy. An error of 11.37% for the SNR of Nusselt number is observed. However, the error in SNR values for Nusselt number and friction factor by predicted equation can be further reduced, if the number of measurements is increased. This validates the development of the mathematical model for predicted the measures of performance based on knowledge of the input parameters. According to the above comments and explanations, the results proved that the Taguchi method is a reliable and easily applicable optimization tool for researchers studying heat transfer enhancement.

7. Conclusions

In this study, the optimal parameters have been designed to maximize the heat transfer and minimize the pressure drop by Taguchi method. The selected parameters for performance prediction of V down perforated baffle roughened rectangular channel are relative roughness pitch (P/e), relative roughness height (e/H), open area ratio (β) and Reynolds number (Re). The significant results of the present work are summarized as follows:

1. The most important parameter with the aspect of heat transfer is Reynolds number, as the Reynolds number shows the contribution ratio of the order of 73.97%. Thus heat transfer can be improved by controlled change of flow Reynolds number. Optimum condition of design parameters is $A_2B_2C_1D_4$ and the optimum values of the parameters for maximum heat transfer condition are given as follows: $P/e=2$, $e/H=0.4$, $\beta=12\%$ and Re = 18,600.
2. If the Taguchi optimization method is concerned only with respect to friction factor, among the effective parameters on system performance, e/H and Re are understood to be the most effective ones. The contribution ratios of e/H and Re are 53.97% and 20.62% on friction factor, respectively. The optimum condition of design parameters is $A_4B_1C_4D_3$ and the optimum values of the parameters for minimum friction factor condition are determined as follows: $P/e=4$, $e/H=0.285$, $\beta=44\%$ and Re = 14,800.
3. The analysis of variance ANOVA was performed to determine the variance of each control factor on the overall results and it was found that the most important parameter for variance is Reynolds number and relative roughness height corresponding to Nusselt number and friction factor, respectively.
4. The confirmation of experimental test was performed and an error of the order of 13.6% and 11.37% between experimental and predicted values of SNR for Nusselt number and friction factor was obtained, respectively.
5. The results shows that in order to optimize the geometrical and flow parameters of V down perforated baffle roughened rectangular channel for heat transfer and friction factor there is no need to perform all 256 experiments ($4^4=256$). Because performing all the experiments consume too much time and is not appropriate with respect to the experimental

cost. Therefore, the Taguchi method was successfully applied to the present work, with a very limited number of experiments and short span of time.

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