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Multi-Objective Optimization of Plate-Fin Heat Exchanger Using Taguchi-based Grey Relational Analysis

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Abstract

This work involves the investigation of values of design constraints which are optimum and which can be used or helpful in design optimization of Plate-Fin Heat Exchanger (PFHE). Core Area, Core Length Reynolds's Number and Fin Height. Pressure drop (Minimum–Friction factor) and heat transfer (maximum–Nusselt number) are fixed as the responses. The Taguchi method for Design of Experiments (DOE) has been used to frame the number of experiments for the taken values of the factors and Response surface methodology (RSM) has been used as the optimization tool from MINITAB. At the end optimization curves are obtained to find the optimal values of the factors resulting in the desired values of responses MINITAB. A conclusion is made to find out the best statistical model for optimization of performance parameters in a PFHE. For the purpose, Plate fin heat exchanger is considered.

Keywords: *Design constraints, Reynolds's no, Nusselt no, core area, core length, fin height, friction factor, taguchi, Response surface methodology.*

1.0 Introduction

Heat exchangers are majorly used in the transfer of heat (thermal energy) in between two or three fluids or even between fluid and the solid particulates, which are at different temperatures and which are in contact (thermally). The fluid carrying the heat is not transferred and instead only the heat is transferred, which is the most important principle of heat exchangers. This heat exchange (transfer) is due to two processes known as convection and convection. When the classification of heat exchangers are considered, they are basically classified on the mechanisms involved in heat transfer, arrangement of the flow, features of construction, level of compactness, processes involved and number of fluids involved [1].

Among the types of heat exchangers, the Plate Fin Heat Exchanger which is also referred to as compact heat exchanger is one in which heat transfer is through the plates and finned chambers. It is referred to as compact due to the fact that, it is having high ratio of heat transfer surface area to the volume. These kinds of heat exchangers find their applications in aerospace industry due to their superior properties like light weight and compact nature. Also they find applied in cryogenics as they can assist in transferring heat with low temperature differences also [2].

The rearrangement of very easy to be made in PFHE which helps both the fluids to have different types of flows such as: cross flow, counter flow, cross-counter flow or even parallel flow. A counter current arrangement can be obtained in PHFE if the fins are arranged in a good manner [3].

From [4] it can be seen that the very common range for fin thickness is 0.046-0.20 and the range for height is 2-20mm. Thin fins are mostly preferable with large density. Shorter fins possess high column structural strength with high efficiency and can reduce conjugate transfer of heat [5]. The complete details with respect to the PFHEs can be obtained by [6].

Already the design of multi stream PFHE is very much complicated and when an attempt is made to design optimal PFHE with huge numbers of combination of fin geometries it becomes even more complicated. Due to this existing problem [7] has proposed an algorithm which deals with the design issues by treating various fin geometries as continuous variables. Total volume of HE is minimized to fin types which are optimal and the relative design parameters were also brought to the nearest rounded value for the feasibility of the design [8].

When statistics is considered, the relation between variables and the outputs (responses are obtained by using several methods among which RSM is also one. It can be used to maximize the output value by optimizing the variables taken into consideration [9]. Nowadays RSM is used when the DOE is considered and if properly done the results obtained will be of high accuracy not only by RSM but through different statistical tools [10].

Many researchers have worked on the optimization process using RSM either may be in materials or may be in the field of heat exchangers by taking different designs available in the software. Even the software available for the purposes are many [11] [12].

The RSM is considered by [13] and the inputs or the variables are obtained from the CFD analysis done on a specific design of PFHE. The values obtained after the optimization of the variables were very much in contrast with the values observed in the literature. Hence in this work, the PHFE design considerations are taken from [14]. CFD analysis of the design is done through the ANSYS software and the values are used in the optimization process. Here in this work or paper the optimization part is considered and not the CFD analysis part.

2.0 Experimental Work

Extensive literature review has been done before concluding on the design of the PFHE to be considered. Areas of concern were, the PFHE design parameters, dimensions, the fins, core, type of methodology to be used while optimizing and the selection of very important responses. Also operating parameters such as hot and cold mass flow rate, temperature, pressure etc., were fixed based on the review done. CFD analysis is done by ANSYS and the values obtained were considered as the inputs for optimization process. In the optimization process, the DOE is done through Taguchi method and the effects of parameters are studied with the graphs in MINITAB software. The analysis and the optimization is done by the help of RSM. The optimization study is done and the best values are selected. Minimum pressure drop (friction factor) and maximum heat transfer (Nusselt no) are considered as the responses whereas, the parameters considered were Reynolds's no, length and area of core and height of the fin. Once the variables were fixed they were used in the CFD analysis. The material for PFHE was chosen as aluminium and the flowing fluid was considered as nitrogen.

Friction factor and Nusselt number have been fixed as performance parameters for this study. These parameters were calculated from following formulae by applying results from analysis in [14].

$$f = \frac{\Delta p}{[0.5 * \rho U^2][\frac{l}{h}]} \quad \text{... (1)}$$

$$Nu = \frac{h * H}{k} \quad \text{... (2)}$$

Table 1: Factors and their levels

Parameters	Labels	Levels		
		1	2	3
Reynolds's no	A	1200	1460	1650
Core length	B	1.346	1.895	2.836
Fin Length	C	0.0731	0.0881	0.0962
Core area	D	0.019268	0.042287	0.053288

Where, ‘Δp’ is the pressure difference between upstream and downstream (bar); ‘ρ’ is the density of fluid (kg/m^3); ‘h’ is the heat convective coefficient (W/m2K); ‘k’ is the thermal conductivity of material (W/mK); ‘L’ is the length of core (m); ‘U’ is the velocity of flow (m/s); ‘H’ is the height of core (m).

The factors with their levels considered for the analysis are given in the Table 1:

3.0 Results And Discussions

The Taguchi method is used for the design of experiments and the L27 orthogonal array is used for the analysis. The table shows the L27 array with 27 combination of experiments with 27 combination of variables. Design layout and the analytical results are as shown below:

The analysis is done for the values of responses and the factors affecting the responses by getting the Response table and S/N graph (Fig.1).

Response Table for Signal to Noise Ratios

Smaller is better (Table 3)

Smaller is better response is considered as the friction factor must be as less as possible. The response table shows clearly that the important factor responsible for the variation in friction factor is core length followed by core area, then fin length and the

Table 2: Taguchi design and the response values

RN	CL	FL	CA	FF	NN
1200	2.836	0.0962	0.053288	0.28524	6.66785
1650	2.836	0.0962	0.053288	0.23756	6.20485
1650	1.895	0.0881	0.042287	0.22658	5.7612
1200	1.346	0.0731	0.053288	0.19354	5.96586
1460	1.895	0.0881	0.042287	0.21589	6.85296
1650	1.895	0.0881	0.042287	0.26845	6.89563
1650	1.346	0.0962	0.053288	0.23863	6.02884
1460	1.895	0.0731	0.042287	0.28125	6.65895
1460	1.895	0.0881	0.042287	0.28651	6.85986
1460	1.895	0.0881	0.019268	0.23125	6.23584
1200	2.836	0.0731	0.019268	0.2289	6.12583
1460	1.895	0.0731	0.042287	0.42825	5.65423
1460	1.895	0.0881	0.042287	0.21823	6.97685
1650	1.346	0.0731	0.053288	0.24203	5.98756
1460	1.895	0.0881	0.042287	0.34651	5.60235
1650	2.836	0.0731	0.053288	0.25345	6.30215
1650	1.346	0.0962	0.019268	0.38254	6.72384
1200	1.346	0.0962	0.019268	0.33786	6.23584
1200	2.836	0.0731	0.053288	0.18224	5.95102
1200	1.346	0.0731	0.019268	0.38652	6.2541
1460	1.895	0.0881	0.042287	0.38387	6.20158
1650	2.836	0.0731	0.019268	0.16788	5.80021
1460	1.895	0.0881	0.042287	0.23689	6.13021
1460	2.836	0.0881	0.042287	0.25012	5.98102
1650	1.346	0.0731	0.019268	0.23689	6.23175
1200	1.346	0.0962	0.053288	0.23865	6.33318
1460	1.895	0.0881	0.042287	0.24898	6.217895

Table 3

Level	RN	CL	FL	CA
1	11.84	11.25	12.35	11.37
2	11.13	11.15	11.95	10.98
3	12.20	12.92	11.01	12.70
Delta	1.07	1.77	1.35	1.72
Rank	4	1	3	2

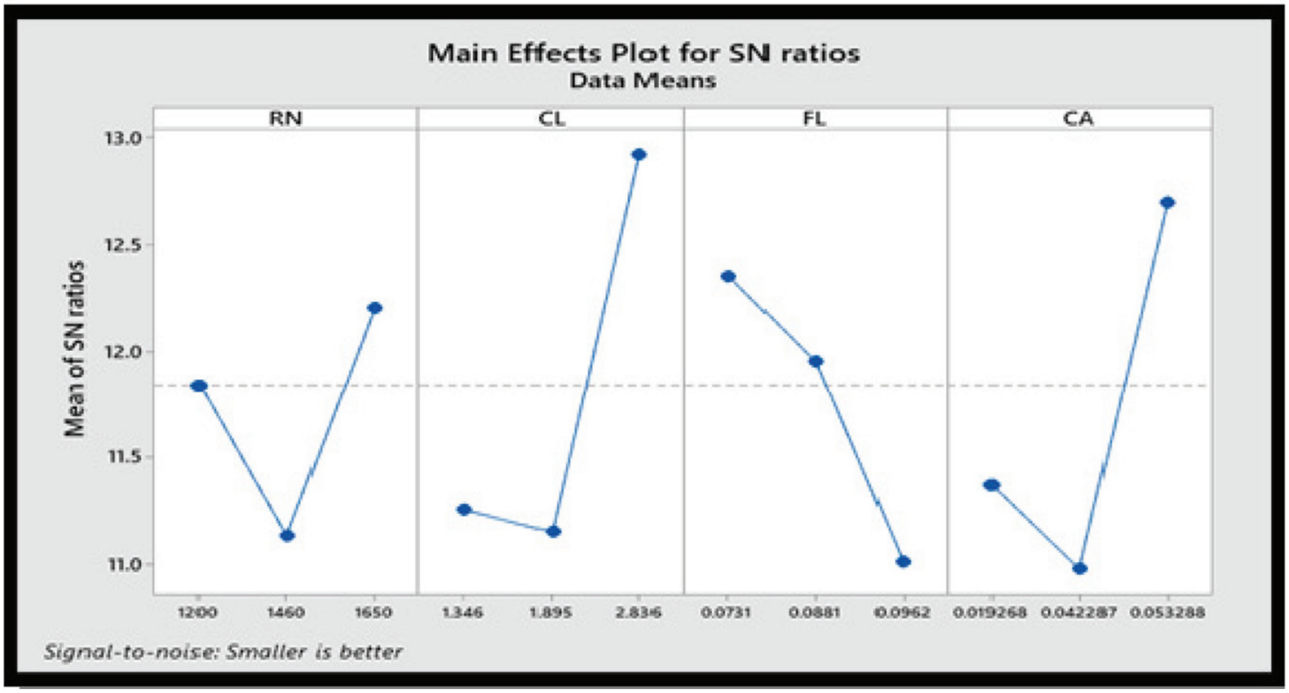

Figure 1: Main effects plot for SN ratios

Reynolds's no. The same can be demonstrated using the S/N curves for different variables as shown below:

The analysis for S/N ratio for friction factor shows that, the friction factor decreases with the increase in the Reynold's no but again starts increasing with the increase in the factor. Similarly increase in core length (up to 1.89m) decrease the friction factor and further increase in the core length the friction factor increases. Factor C (Fin height) decreases the friction factor with its increase (up to 0.08m) but gradually decreases the response with further increase. A drastic decrease in the friction factor can be seen with the increase in core area (up to 0.04m^2) and immediately after that the friction factor increases. These results lead to optimization of the variables to minimize friction factor by selecting the optimized factors. By the response table it is clear that the major effecting factor is the core length.

Similarly the analysis of Nusselt number is also carried out and the results are indicated in Table 4:

Response Table for Signal to Noise Ratios

Larger is better (Table 4)

Larger is better is considered for the analysis as the heat transfer rate is always to be maximum when efficient PFHE is considered. The response table shows that the fin length is the major influencing factor followed by core length and then core area followed by Reynolds's no. The same can be showed by the S/N graph also:

The raise in the Nusselt number can be seen aggressively in fin length as it increases step by step. All the other variables have mixed effect and the same can be seen from the graph.

RSM analysis for friction factor

Table 4

Level	RN	CL	FL	CA
1	15.87	15.87	15.67	15.88
2	15.80	15.89	15.85	15.80
3	15.83	15.77	16.07	15.81
Delta	0.07	0.13	0.40	0.08
Rank	4	2	1	3

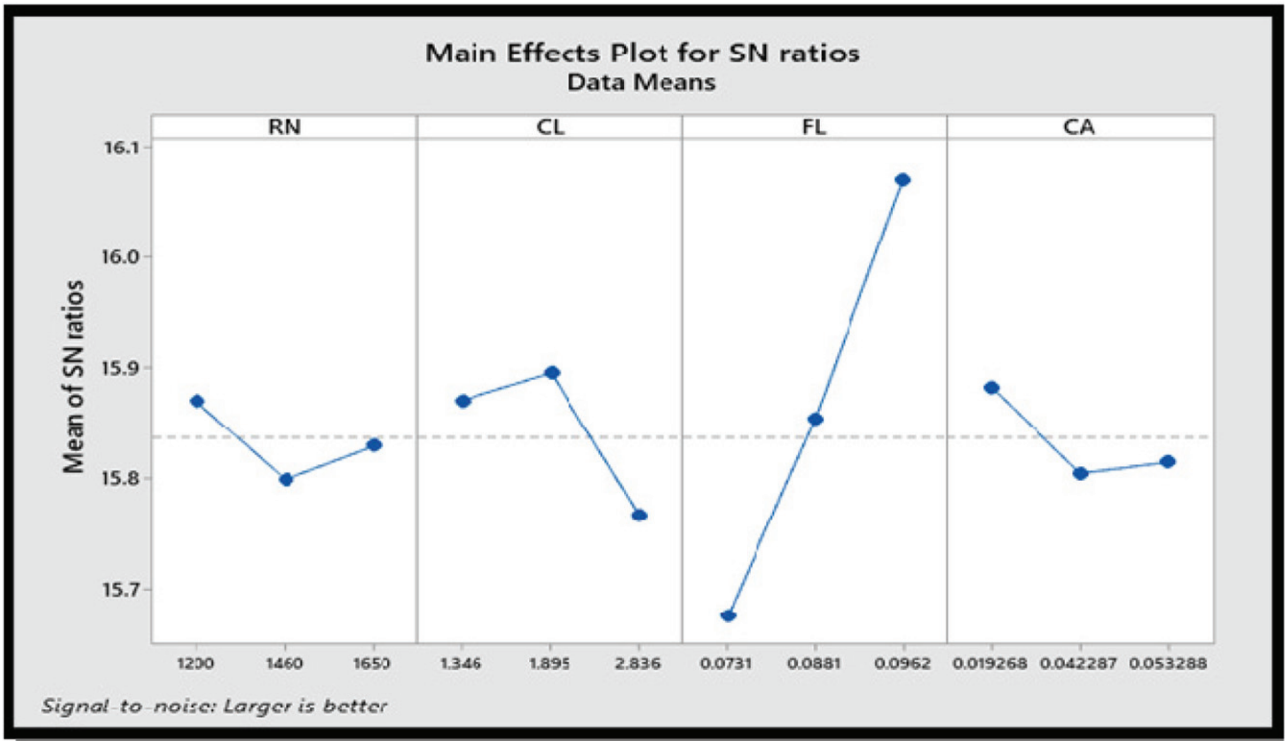

Figure 2: Main effects plot Signal to Noise Ratios

The regression equation obtained is shown below:

FF = 25 + 0.007 RN –1.4 CL –797 FL + 58 CA - 0.000003 RN*RN + 0.10 CL*CL + 4658 FL*FL- 1788 CA*CA – 0.00018 RN*CL + 0.012 RN*FL + 0.032 RN*CA + 5.4 CL*FL + 15.5 CL*CA – 184 FL*CA

The above table shows the analysis of variance by RSM which gives the effect of individual variables and also the combination effect is also shown in Fig.3. The factor core length and cl*cl are major influencing and the same is shown in the Table 5. The remaining parameters and the combination can also be studied.

The competence of the chosen model is investigated by examining the residuals. Difference in the observed and the predicted response is the residual and they can be inspected using probability plots. The model can be declared satisfactory as the residuals in the figure above are not showing any deviations and are following particular trend whereas the errors are distributed normally with no obvious pattern and structure which is unusual.

The contour graphs as shown above shows the values of variables wherein the least or minimum values of response (friction factor) can be obtained. Up to 1.50mm of core length the friction factor is minimum and in a range of 1220-1580 (RN) the friction factor is minimum. Similar graphs can be plotted to show the interactions of all the variables along with the responses.

The above Fig. shows the optimization of response with the optimal variable values. The optimal variables can be listed as follows: RN – 1200, CL – 1.6470, CL – 0.0841 and CA – 0.0533. The optimum

Table 4: Analysis of Variance

Source	DF	AdjDev	Adj Mean	Chi-Square	P-Value
Model	14	0.589407	0.042100	0.59	1.000
RN	1	0.011162	0.011162	0.01	0.825
CL	1	0.048731	0.048731	0.05	0.916
FL	1	0.048339	0.048339	0.05	0.826
CA	1	0.047309	0.047309	0.05	0.828
RN*RN	1	0.006301	0.006301	0.01	0.937
CL*CL	1	0.000798	0.000798	0.00	0.977
FL*FL	1	0.079031	0.079031	0.08	0.779
CA*CA	1	0.055663	0.055663	0.06	0.813
RN*CL	1	0.002706	0.002706	0.00	0.959
RN*FL	1	0.003170	0.003170	0.00	0.955
RN*CA	1	0.046565	0.046565	0.05	0.829
CL*FL	1	0.003967	0.003967	0.00	0.950
CL*CA	1	0.070558	0.070558	0.07	0.791
FL*CA	1	0.002802	0.002802	0.00	0.958
Error	4	0.164436	0.041109		
Total	18	0.753843			

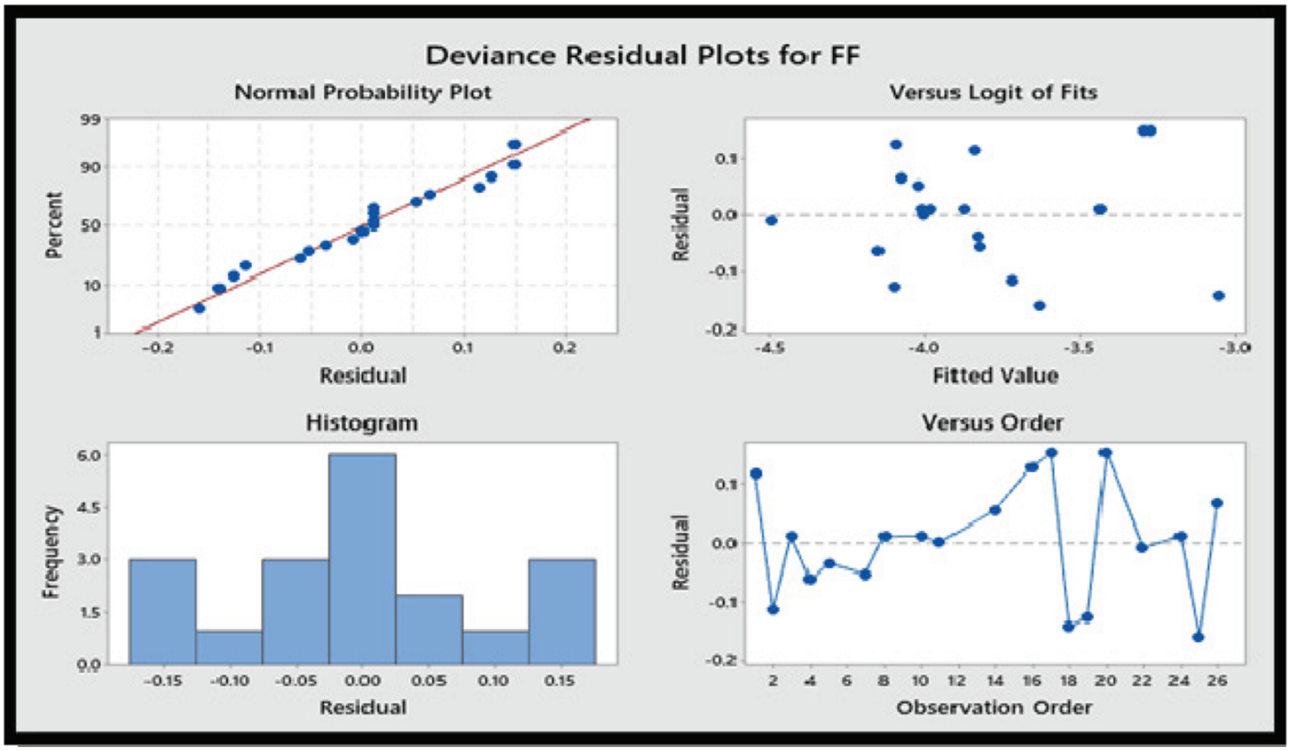

Figure 3: Residual plots for Friction Factor

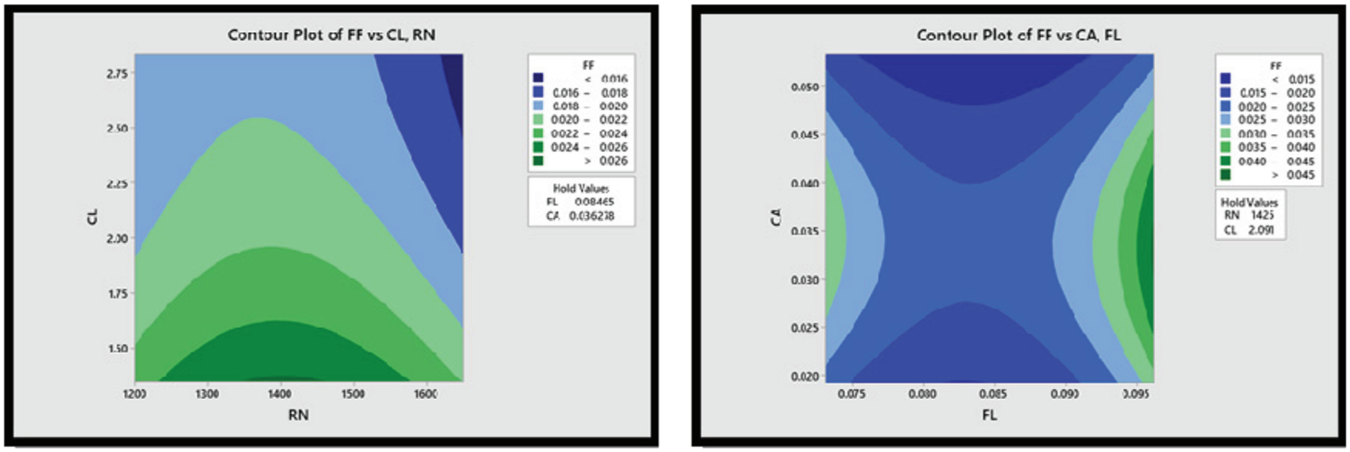

Figure 4 : Contour graphs of friction factor v/s CL, RN, CA and FL

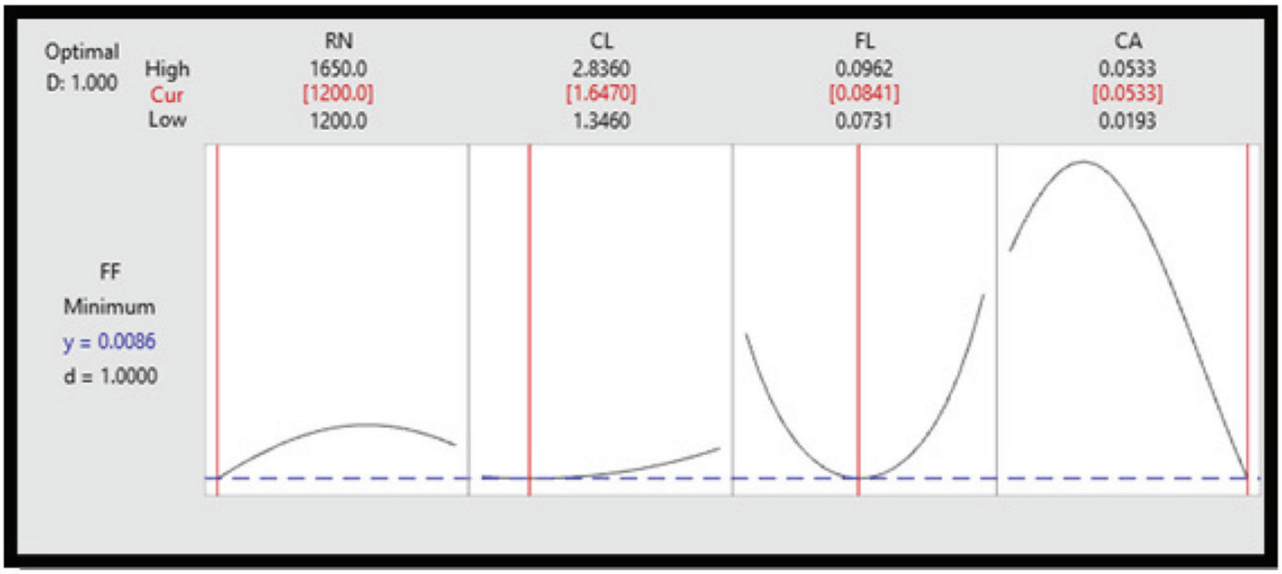

Figure 5: Optimization curves for Friction factor

friction factor obtained for the optimal variable value is FF minimum: 0.1086.The desirability value is 0.929836 almost equal to 1.

RSM analysis for Nusselt number

Regression Equation

NN

1.4 + 0.0081 RN + 0.34 CL – 189 FL – 0 CA – 0.000003 RN*RN – 0.074 CL*CL + 1135 FL*FL – 53 CA*CA – 0.000038 RN*CL – 0.0015 RN*FL – 0.0007 RN*CA – 0.4 CL*FL + 1.4 CL*CA + 31 FL*CA.

The ANOVA table shows the results similar to that of the results discussed in the previous section of taguchi analysis. Residual plots show no deviations and are following particular trend whereas the errors are distributed normally with no obvious pattern and structure which is unusual. Hence the model is adequate. The surface plots show the variation of the response (Nusselt no) with the varying factors. The interaction of variables and the response behaviour can be studied by the surface graphs.

The above Fig. shows the optimization of response with the optimal variable values. The optimal variables can be listed as follows: RN – 1418 and 1818, CL – 2.0233, CL – 0.0962 and CA – 0.0406. The optimum friction factor obtained for the optimal variable values is NN maximum: 6.98521. The desirability value is 0.985486 almost equal to 1.

Table 5: Analysis of Variance

Source	DF	AdjDev	Adj Mean	Chi-Square	P-Value
Model	14	0.185534	0.013252	0.19	1.000
RN	1	0.001462	0.001462	0.00	0.970
CL	1	0.002157	0.002157	0.00	0.963
FL	1	0.005226	0.005226	0.01	0.942
CA	1	0.000390	0.000390	0.00	0.984
RN*RN	1	0.081485	0.081485	0.08	0.775
CL*CL	1	0.006236	0.006236	0.01	0.937
FL*FL	1	0.074360	0.074360	0.07	0.785
CA*CA	1	0.000778	0.000778	0.00	0.978
RN*CL	1	0.001910	0.001910	0.00	0.965
RN*FL	1	0.000765	0.000765	0.00	0.978
RN*CA	1	0.000395	0.000395	0.00	0.984
CL*FL	1	0.000460	0.000460	0.00	0.983
CL*CA	1	0.008814	0.008814	0.01	0.925
FL*CA	1	0.001130	0.001130	0.00	0.973
Error	4	0.073844	0.018461		
Total	18	0.259378			

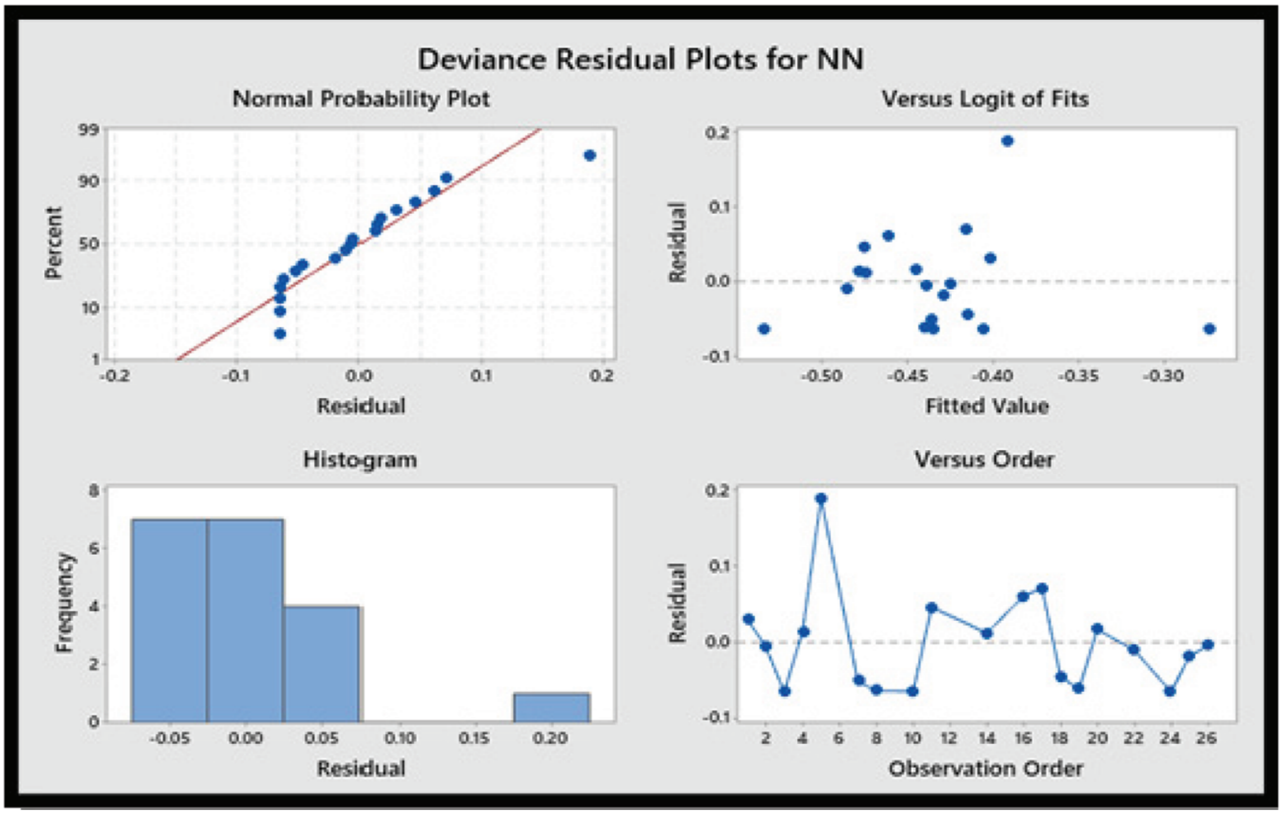

Figure 6: Residual plots for Nusselt number

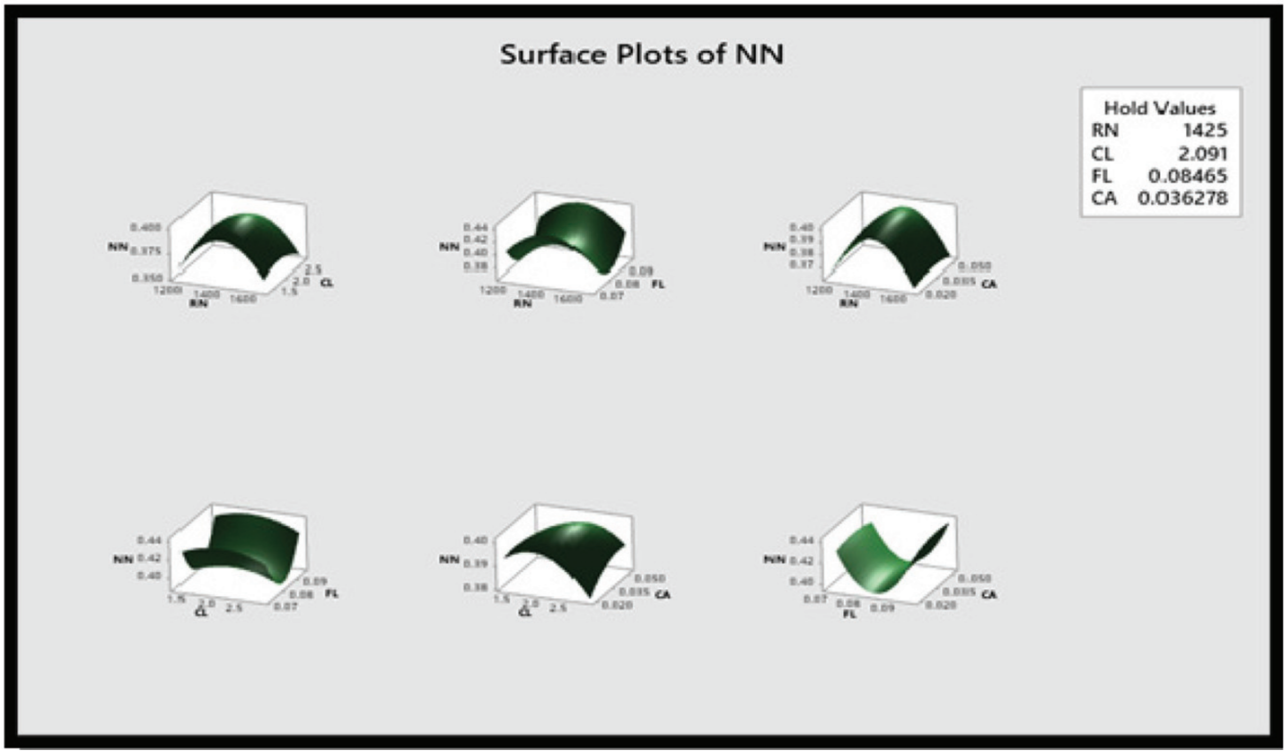

Figure 7: Surface plots for NN v/s the variables

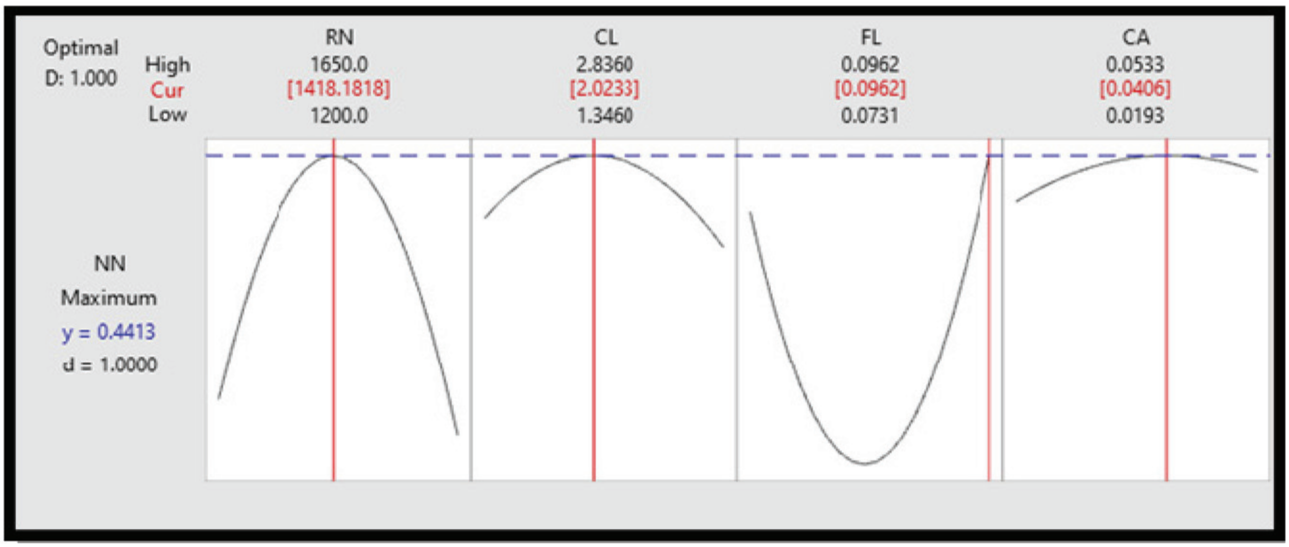

Figure 8: Optimization curves for Nusselt Number

4.0 Conclusions

Analysis and optimization of PFHE has been carried out in this research using MINITAB 15.0 software and the optimal values of variables and the corresponding responses have been found out. The same values can be further considered for the design optimization using MATLAB with the use of Genetic Algorithm (GA) or Differential Evolution (DE) algorithm. The following conclusions can be made with the results obtained:

1. Model generated for evaluation, prediction and optimization is fit as the residuals do no deviate and follow particular trend.
2. Effects of design constraints over the

performance parameters are studied successfully using Taguchi and Response Surface Methodology.

3. The optimized values of the design constraints (variables) for minimizing the Friction factor are RN-1200, CL-1.6470, CL-0.0841 and CA-0.0533. The optimal value of friction factor (minimum) obtained using RSM is 0.1086.
4. The optimized values of the design constraints (variables) for maximizing the Nusselt number are RN – 1418 and 1818, CL – 2.0233, CL – 0.0962 and CA – 0.0406. The optimal value of Nusselt number (maximum) obtained using RSM is 6.98521.

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