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MULTI - OBJECTIVE OPTIMIZATION of A THREE-DIMENSIONAL INTERNALLY FINNED TUBE BASED ON RESPONSE SURFACE METHODOLOGY (RSM)

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ABSTRACT

In the present work, computational fluid dynamics (CFD) together with multi-objective optimization study of an internally finned tube has been performed using the response surface methodology (RSM). For the optimization, the Box-Behnken of response surface methodology (RSM) is exploited from the Design Expert 7.0.0 software. The effects of the fin height, fin width and the fin number on the heat transfer enhancement in the form of Nusselt number (Nu) and friction factor multiplied by Reynolds number (fRe) have been investigated. The results of the numerical model are compared with the analytical results for validation of the model. Finally a non-dominated sorting genetic algorithm (NSGA) has been proposed for the multi objective optimization of the responses. It was found that numerical and RSM can be applied for optimization of heat transfer analysis of internally finned tube. The results show that at the lower level of fin height, the Nusselt number has an increasing trend with the increase in fin number but decreases beyond fin number of 7. Similar trend is also observed at higher level of fin height. Moreover, it is found that the contribution of fin thickness, for variations of Nusselt number (Nu) and (fRe) , is not significant as compared to fin height and fin number.

NOMENCLATURE

A_c minimum heat exchanger flow area (m^2)
Adj R-Squared Mean square value of Multi-Objective Optimization
D_h hydraulic diameter (m)
f frictional resistance coefficients
H_f height of fin (m)
h_{avg} average heat transfer coefficient (W/m^2K)
k thermal conductivity (W/m.K)
M Mach number
$\dot{m}$ Mass flow rate of air (kg/s)
Nu_{avg} average Nusselt number
Δp pressure drop (Pa)
P wetted perimeter (m)
Pred R-Squared Mean square value of Multi-Objective Optimization
q uniform heat flux (W/m^2)
Re Reynolds number
T_{mavg} mean fluid average temperature (K)
T_{savg} tube surface average temperature (K)
u Velocity (m/s)
V_{in} inlet velocity (m/s)

Greek Symbols

ρ fluid density (kg/m^3)
ν kinematic viscosity (m^2/s)

Subscripts

f fin
h hydraulic

Abbreviations

RSM response surface methodology
NSGA non-dominated sorting genetic algorithm

1. INTRODUCTION

The modelization and optimization of mixed convection flow through an internally finned tube is a complicated task due to its complex geometry and flow pattern. Advancement of layout for modelling and optimization may direct to quick and successful commercialization of heat transfer enhancement. Internally finned tubes have been extensively studied by many researchers in recent years due to their widely used in an industrial applications. They are commonly used in engineering applications as an effective and efficient means to improve convective heat transfer in compact heat exchangers. In the light of recent economic and environmental concerns, many researchers are regressively working for new methods of heating or cooling improvement of heat exchangers attached externally or internally with various types of fins taking account of application area. In fact , internally finned attached to various type of heat exchangers are generally used in, heating or cooling of oils, heating of circulating fluid in solar collectors, and heat transfer in compact heat exchangers , etc. The main purpose of augmentation of the internal fins is to enhance the heat transfer and break the thermal boundary layer. Generally, there are three categories of heat augmentation techniques: (i) active techniques which require an external power input and (ii) passive techniques which do not require an external power input (iii) Compound techniques which are a combination of both passive and active types. The insert of fin internally is a passive heat transfer enhancement method. Insertion of twisted tapes and stripes [1-5], coil wire and helical wire coil [6-9] are some example of a passive heat transfer enhancement. When advancement in the process of heating or cooling is recommended, then the suitable design of fins compactness and optimization of dimensions of fin geometry are very essential. The heat transfer to the fluid flowing through a finned tube can be studied mainly using the method of heat transfer by forced convection. A wide review on analysis of heat transfer rate and pressure drop characteristics from tubes having fins of various shapes (rectangular, triangular, T-sectional, and twisted) was performed in earlier studies[10-15]. However, measurements of velocity, pressure and analysis of flow pattern inside a finned tube are very difficult and expensive also with experimental techniques. Thus, computational fluid dynamics (CFD) may be used to solve and analyse such type of highly nonlinear and complicated geometry cases due to its high accuracy and stability.

A detail review of CFD analysis of heat exchanger using different commercial software packages was reported by Aslam Bhutta et al. [16]. CFD analysis is a time consuming and high computational cost. Therefore , soft computing techniques (Artificial Neural Network (ANN), Fuzzy-logic (FL), Adaptive-Network-Based Fuzzy Inference System (ANFIS), Particle Swap Optimization Technique (PSO) and Genetic Algorithm (GA) can be used as a powerful tools to study and predict the thermal and fluid flow behaviours as discussed by Varol et al.[17] who utilized the soft computing methods ,i.e., Adaptive-Network-Based Fuzzy Inference System (ANFIS) and Artificial Neural Network (ANN) to predict the free convection thermal and flow variables inside a triangular enclosure. CFD approach was used to solve the governing equations and the obtained results were used for training and testing the (ANN) and (ANFIS) methods. The comparison between CFD and soft computing methods explained an acceptable range of error. They also revealed that (ANFIS) was more powerful technique than (ANN) method. Aminossadati et al.[18] were used CFD analysis to testing and validating an (ANFIS) approach of the laminar mixed convection in a two-sided lid-driven enclosure filled with nanofluid. They reported that the predicted results from (ANFIS) were in a good agreement with CFD results within acceptable range of error. Liu et al. [19] used the fuzzy logic method to control the convergence in the numerical fluid dynamic simulation using SIMPLE algorithm. Diaz et al.[20] had used (ANN) technique to control the temperature of air passing over a heat exchanger. This method was used to predict the dynamic behaviour of a heat exchanger. Dragojlovic and Kaminski [21] used the fuzzy logic to guide the under- relaxation of the discretized Navier-Stroke equations during the simulation of turbulent flow and heat transfer problems. The results illustrated that the application of fuzzy logic improved the computational effort of solving various types of CFD problems with different geometries, boundary conditions and material properties. Islamoglu and Kurt [22] and Islamoglu [23] predicted the heat transfer rate using (ANN) approach for a wire on the tube heat exchanger .They also predicted the mass flow rate and outlet temperature for air flow in corrugated channels. In the present work, the diameter and the length of pulse tube and regenerator are considered as variable parameters in the numerical procedure, while the remaining parameters are considered constant. The literature review indicated that no previous work has studied simultaneously the effect of variable fin height, fin number and fin thickness on the performance of the Nusslet number (Nu) and friction factor multiplied by Reynolds number (fRe). Also, in the present work, the effects of fin size and number on the performance of heat exchanger were modelled and optimized based on numerical data collected by Rout et al.[24]. Most of studies concerned with the effects of parameters on the thermal and fluid flow analysis have been performed using a one-parameter-at-a-time method, where this method provides one parameter at a time instead of all simultaneously. This method is time consuming and expensive. To cross over such problems, response surface methodology (RSM) which is one of the statistical design tools can be used for prediction of interaction between many parameters and for process optimization also. RSM defines the effect of independent variables, alone or in combination, on the process [25]. RSM has been tested to be a powerful statistical tool for optimization of thermal and fluid flow processes in many cases [26-38]. In order to get the optimum fin configuration in a three-dimensional internally fined tube, the response surface method (RSM) is used in the present work as a numerical optimization method. This method offers a series of numerical analysis for a given set of design points and generates a response surface of the given input parameter over the design space. The main purpose of the present work is to find an appropriate combination between maximize the heat transfer enhancement and the reduction in friction loss. The application of the response surface method (RSM) to handle with the three-dimensional internally fined tube is not considered previously and this addition represents the original scientific contribution of the present work.

2. MATHEMATICAL FORMULATION

The details of numerical modelling, governing equations, model validation and grid independency test has been described by Rout et al.[24] . A schematic view of the proposed numerical model is shown in Figure 2. The average Nusselt number is expressed as :-

$$Nu_{avg} = \frac{h_{avg} D_h}{k_{air}} \tag{1}$$

Where the average heat transfer coefficient (h_{avg}) is defined by :-

$$h_{avg} = \frac{q}{T_{savg} - T_{mavg}} \tag{2}$$

Where T_{savg} , T_{mavg}, D_h and k_{air} are respectively tube surface average temperature, mean fluid temperature, hydraulic diameter and thermal conductivity of air. The Reynolds number is defined as :-

$$\mathrm{Re} = \frac{V_{in} D_h}{\nu_{air}} \tag{3}$$

The hydraulic diameter of the fin channel is defined as :-

$$\mathrm{D}_h = \frac{4P}{A_c} \tag{4}$$

where (A_c) is the minimum heat exchanger flow area and (P) is the wetted perimeter. The frictional resistance coefficients (f), due to frictional resistance of gas passes through the cross- section can be defined according to Darcy's equation as :-

$$f = \frac{-\Delta p}{\rho u^2 / 2} \tag{5}$$

3. RESPONSE SURFACE METHODOLOGY (RSM)

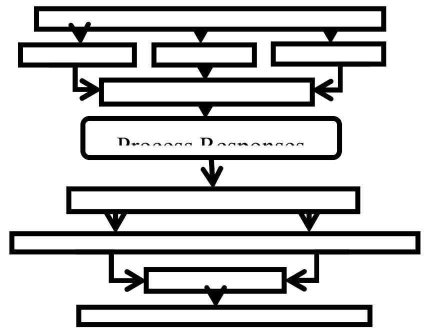
The results of numerical analysis of internally finned tube are obtained through the design of experiment approach (DOE) such as response surface methodology (RSM). The numerical model provides an inexpensive and time saving alternative to study the performance of responses avoiding the experimental error runs. DOE is basically a scientific approach to effectively plan and perform experiments using statistics and it is commonly used to improve the quality of products or processes with less simulation runs. Such approaches enable the user to define and study the effect of every single condition possible in a simulation where several factors are involved [39 and 40]. Response surface methodology is an assembly of statistical and mathematical method useful for developing, refining and optimizing process. It deals with the circumstances where several input variable potentially affects the performance measure or quality of the product or process. The performance measure or quality is known as response. The objective is to establish a suitable approximation of the true functional relationship between independent variables and the process responses through response surface methodology. Generally, a second-order model as given in Eq.6 is utilized in response surface methodology.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{kj}\sum \beta_{ij} X_i X_j + \varepsilon \quad (6)$$

Where (y) is the corresponding response for input variables while , X_i , X_i^2 and X_iX_j are the square and interaction terms of parameters respectively. The β_0, β_i, β_{ii} and β_{ij} are the unknown regression coefficients while (ε) is the error as defined by Rout et al.[24]. Box-Behnken design preferred over central composites as it is match for run the simulation with least number of runs. It accomplishes non-sequential analysis and it has fewer design points. A three factorial and three levels (-1, 0, +1) were used for construction of second-order response surface model. The variables (factors) used in the study are the fin number (A), fin height (B), and fin thickness(C). The real values of the process variables (factors), their variation limits, and number were selected based on the preliminary simulation. The real values along with coded values of the factors are shown in Table 1. A regression model was proposed, and results were studied using Design Expert 7.0.0. The analysis of variance (ANOVA) was performed based on the proposed model to find the interaction between the process variables and response. The quality of the fit for the polynomial model was expressed by the coefficient of determination (R^2), and the statistical significance was checked by the F-value (Fischer variation ratio) and P-value (significant probability value). Model terms were selected or rejected based on the probability value within 95% confidence interval (or 5% significance level). Finally , three-dimensional response surface plots were drawn in order to visualize the individual and the interaction effects of the independent variables on Nusslet number (Nu) and friction factor multiplied by Reynolds number (fRe).The flow chart of the details of the numerical procedure and proposed optimization design is shown in figure 1.

TABLE 1. REAL AND CODED LEVELS OF THE INDEPENDENT VARIABLES

factors	Real values of coded levels		
	-1	0	1
Fin number	6	8	10
Fin height	0.0125	0.02125	0.0325
Fin thickness	0.02	0.4	0.6



Step 1 we choose the input parameter (fin number, fin height and fin thickness))

Step 2 then we go for numerical analysis

step 3 Find the output (responses) from numerical analysis

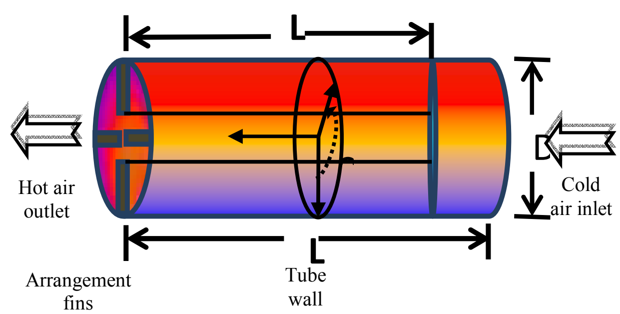
step 4 then we go for regression analysis and compare the numerical responses with predicted responses

step 5 next develop regression equation from regression analysis

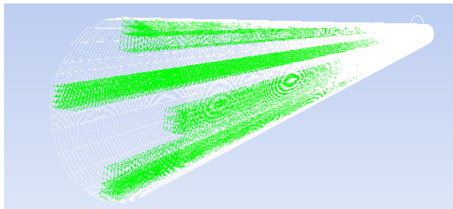
step 6 next go for NSGA optimization

step 7 conformation test from obtain result of NSGA

FIGURE 1. FLOW CHART OF PROPOSED INTEGRATED PROCESS MODEL



(a)



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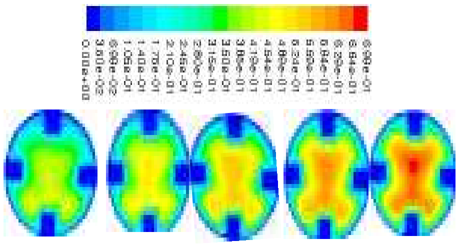


(c)

FIGURE 2 (a) SCHEMATIC DIAGRAM OF COMPUTATIONAL DOMAIN (b) COMPUTATIONAL GRID (c) COMPARISON OF VELOCITY PROFILES IN AXIAL DIRECTION, AFTER A LENGTH of (i) 1m (ii) 2m (iii) 3m (iv) 4m and (v) 5 m.

4. RESULTS AND DISCUSSION

From previous CFD modelling presented by Rout et al.[24], results are used to generate data for optimization in RSM technique. This method reduces the experimental cost and save time. So, CFD is used to obtain % degradation at various simulation conditions as requisite for optimization of heat transfer phenomenon.

4.1 Regression Model and Analysis of Variance (ANOVA)

A total of 17 number sets of runs obtained from the Box-Behnken, and the corresponding output responses are shown in Table 2 using CFD procedure. It is found that, the Nusselt number varies due to presence of fin in between 4 and 18 while friction factor multiplied by Reynolds number (fRe) varies from 11 to 26. The results are analysed using ANOVA (analysis of variance), obtained from design of experiment. It gives the regression equation in terms of coded factors expressed below : -

$$Nu = +12.10 - 2.27 * A + 4.08 * B + 0.42 * C - 0.89 * A * B + 0.12 * A * C - 0.22 * B * C - 1.76 * A^2 - 0.70 * B^2 + 0.081 * C^2 \quad (7)$$

$$fRe = +18.66 - 2.49 * A + 3.93 * B + 0.51 * C - 0.79 * A * B - 0.13 * A * C - 0.17 * B * C - 1.44 * A^2 - 0.12 * B^2 + 0.092 * C^2 \quad (8)$$

Where A, B and C are coded values of fin height, fin number and fin thickness, respectively. Figures 3 and 4 graphically represent the comparison between actual (numerical results) versus predicted results obtained from regression model for the Nusselt number and friction factor multiplied by Reynolds number (fRe) analysis. It was found an 12% degradation of (Nu) number and 10% degradation of (fRe) value of the predicted model well match with the observational results.

Table 3 shows the ANOVA results of the proposed model for Nusselt number prediction. The proposed model significance and accuracy were evaluated using mean square value, Adj R-Squared Value, F-value and P-value respectively. The model is significant as P-value of <0.0001 and corresponding F-value of 58.14. The Model F-value of 58.14 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" could occur due to noise. In the proposed model (R^2) value of 0.9868 and Pred R Squared value of 0.9260 are considered. The "Pred R-Squared" of 0.9260 is in reasonable agreement with the "Adj R-Squared" of 0.9698. The "Lack of Fit F-value" of 0.52 implies the Lack of Fit is not significant relative to the pure error. There is a 69.06% chance that a "Lack of Fit F-value" could occur due to noise. Non-significant lack of fit is good which required for model to fit. As all the model statistics and diagnostic plots are significant, it can be proposed to handle the design space.Table 4 shows the ANOVA results of the proposed model for (fRe) prediction. The proposed model significance and accuracy was evaluated using same procedure as (Nu). The model is significant as P-value of <0.0001 and corresponding F-value of 60.42. The Model F-value of 60.42 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" could occur due to noise. In the proposed model (R^2) value of 0.9873 and Pred R-Squared value of 0.8857. The "Pred R-Squared" of 0.8857 is in reasonable agreement with the "Adj R-Squared" of 0.9709 are considered. The "Lack of Fit F-value" of 1.41 implies the Lack of Fit is not significant relative to the pure error. There is a 36.40% chance that a "Lack of Fit F-value" could occur due to noise. Non-significant lack of fit is good which required for model to fit. As all the model statistics and diagnostic plots are significant, it can be proposed to handle the design space. In order to ensure that the selected model adequately represents the real system, the predicted versus actual value plots, were plotted as shown in Figures 3 and 4 respectively. It is observed from the comparison model that the data is almost normally distributed in an acceptable range of error even though there are some deviations.

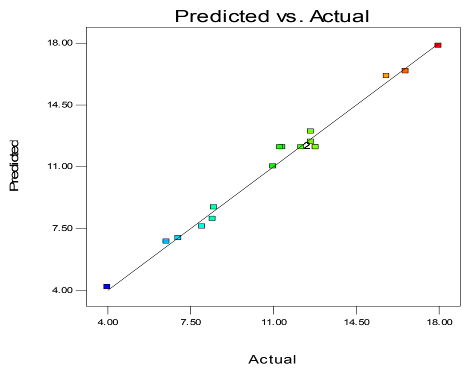


FIGURE 3 OBSERVED VERSUS PREDICTED VALUES FOR NUSSELT NUMBER (Nu).

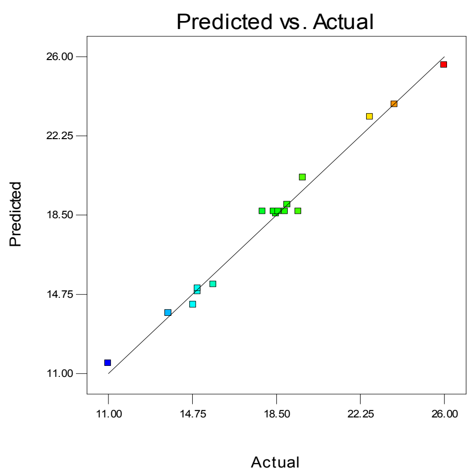
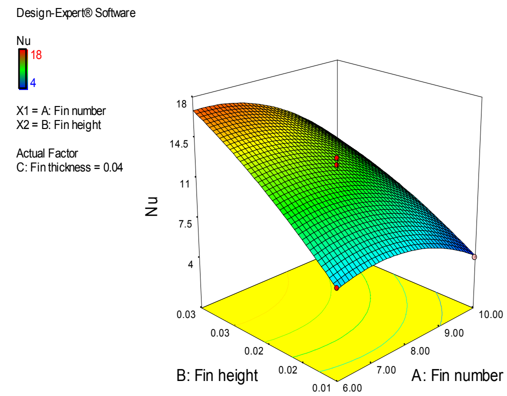
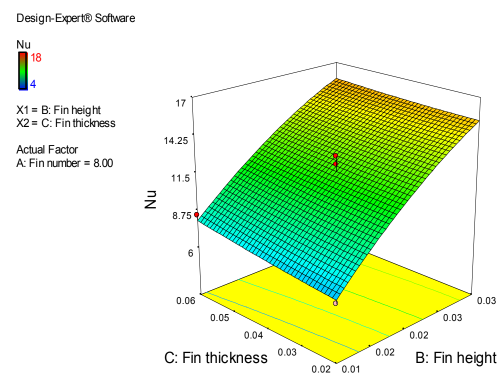


FIGURE 4 PLOT OF OBSERVED VERSUS PREDICTED VALUES FOR FRICTION FACTOR MULTIPLIED BY REYNOLDS NUMBER (fRe).

The 3D response surface plots of the regression model are shown in Figure 5 (a-b) for (Nu) and Figure 6 (a-b) for (fRe). Figure 5 (a) demonstrates the interactive relationship between Nusselt number, fin height and fin number. It shows that , at the lower level of fin height the Nusselt number has an increasing trend with the increase in fin number , but decreases beyond fin number of 7.Similar trend is also observed at higher level of fin height. The Nusselt number (Nu) increases monotonically with increase in fin height. Similarly, figure 5(b) shows the interactive relationship between Nusselt number, fin height and fin thickness. At the lower level of fin thickness, Nusselt number increases monotonically with increase in fin height. Similar trend is also observed at higher level of fin thickness. The Nusselt number (Nu) increases marginally with increase in fin thickness. However contribution of fin thickness, for variation of Nusselt number (Nu), is not significant as compared to fin height and fin number.



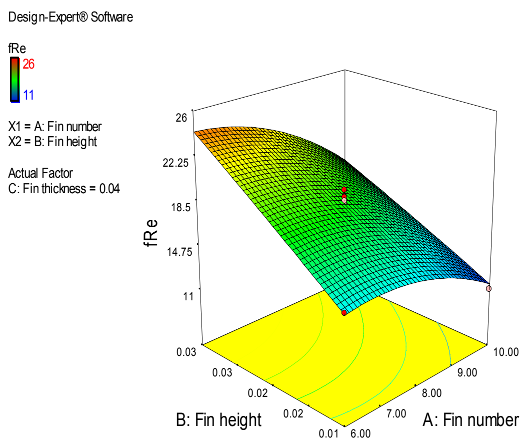
(a)



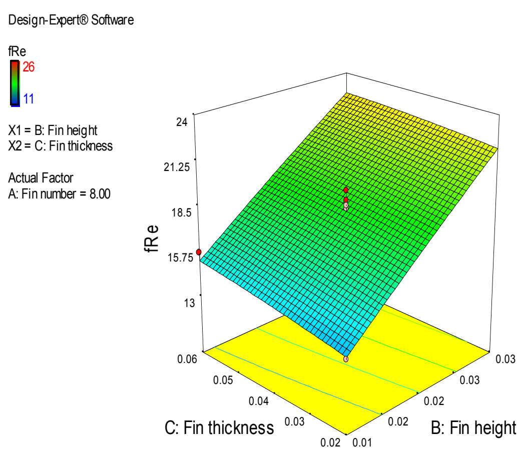
(b)

FIGURE 5 3D RESPONSE SURFACE PLOTS OF THE REGRESSION MODEL FOR NUSSELT NUMBER (Nu).

Figure 6 (a) demonstrates the interactive relationship between friction factor multiplied by Reynolds number (fRe), fin height and fin number. It shows that at the lower level of fin height, (fRe) shows an increasing trend with increase in fin number but shows a decreasing trend further. Similar trend is also observed at higher level of fin height. (fRe) increases monotonically with increase in fin height. Similarly, figure 6(b) shows the interactive relationship between (fRe), fin height and fin thickness. At the lower level of fin thickness, (fRe) increases monotonically with increase in fin height. Similar trend is also observed at the higher level of fin thickness. (fRe) increases marginally with increase in fin thickness. But contribution of fin thickness, for variation of (fRe), is not significant as compared to the fin height and fin number.



(a)



(b)

FIGURE 6 3D RESPONSE SURFACE PLOTS OF THE REGRESSION MODEL FOR (fRe)

4.2 Multi-Objective Evolutionary Algorithms

An evolutionary approach such as a non-dominated shorted genetic algorithm (NSGA) is proposed to optimize multi-objective responses which happen to be contradictory in nature. Unlike single objective optimization, a set of optimal solutions termed as Pareto-optimal solutions is achieved in case of multi-objective optimization. Genetic algorithm (GA) is a category of population based stochastic search technique which is closely modelled on the natural process of evolution with importance on breeding and the existence of the fittest. The algorithm starts with a set of primary solutions instead of starting with a single point. Genetic algorithm operators probabilistic results leading to stochasticity. These operators are accountable for providing the search direction to a GA. Selection operator opts for best solutions and crossover operator unites a good genetic material from two good solutions to form the best solution. Improved strings are produced by altering string locality in mutation operator. Reproduction operator eliminates bad things and if good strings are created, they are highlighted. In multi objective optimization, a set of mutually dominant solution, is generated which is exclusive and distinctive with respect to all objectives. Multi-objective optimization aims at convergence to the Pareto-optimal set and maintenance of diversity and distribution in solutions. The multi-objective evolutionary algorithm based on a non-dominated sorting is known as Non-dominated Sorting Genetic Algorithm (NSGA)[41]. It utilizes elitist non-dominated sorting along with crowding distance sorting to get the non-dominated set. The algorithm is skilled enough to handle constrained multi-objective optimization problems with binary coding and real parameters. Genetic algorithm requires fitness value or objective function for optimization problem. Hence, it is essential that decision variable should be relate with the objective.

In the present work, the objectives are maximization of (Nu) and minimization of (fRe), which are functions of decision variables viz., fin number, fin height and fin thickness. Accordingly, empirical relation between input parameters and process responses obtained in equations 7 and 8 are used as functional relations. The objective functions are given below :-

Objective 1 = 18 x (Nu) (9)

Objective 2 = -26 x (fRe) (10)

However, there are two responses which may not be applicable simultaneously for all industrial applications.The NSGA codes simulation was generated by using the MATLAB tool box. The choice of responses purely depends on the requirement of process engineer and industries. The constrained values were selected from the numerical observations. This results of constrained Pareto-optimal solutions for two combinations of (Nu) and (fRe). An initial population size of 60 was set with simple crossover and bitwise mutation with a crossover probability, Pc = 0.8, migration interval of 20, migration fraction of 0.2 and Pareto fraction of 0.35 respectively. **Error! Reference source not found.**7 shows the Pareto-optimal front solutions for responses for (Nu) and (fRe) combination.

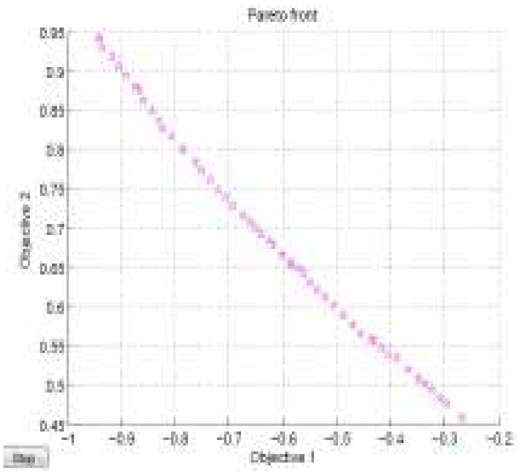


FIGURE 7 PARETO OPTIMAL SOLUTION SET WITH OBJECTIVES FOR (Nu) AND (fRe)

5. CONFIRMATION TEST

In order to verify the accuracy of the generated quadratic model, a confirmation numerical run were performed for (Nu) and (fRe). The residual and the percentage error were found in an acceptable range. The range of percentage error between the numerical and the predicted value of (Nu) and (fRe) lie within 5% and confirmation runs within 95% prediction interval. So, the generated quadratic model is very accurate.

6. SUMMARY AND CONCLUSIONS

A powerful, efficient and highly accuracy optimization methodology coupling (RSM) and (NSGA) is introduced to optimize the layout of the internally fined tube using the numerical approach solution method. The main purpose is to find an appropriate combination between maximize the heat transfer enhancement and the reduction in friction loss. (RSM) and (NSGA) are successfully applied to obtain the Pareto-optimal front and statistically analyze the results. Non-dominated sorting genetic algorithm (NSGA II) is used for multi objective optimization of responses and pareto fronts were obtained for both (Nu) and (fRe). Any solution in the pareto front is considered as an optimal solution. The main conclusions can be summarized as follows :-

1- The proposed response surface methodology is used to analyze the relationship between the process parameters like fin number, fin height and fin thickness to the responses like (Nu) and (fRe), which are tested using ANOVA.
2- The proposed generated heat transfer model is significant as values of the F-test,
   Prob> F, from the ANOVA analysis.
3- The results generated from the response surface methodology revealed that both fin height and fin number have a great significance effect rather than fin thickness on (Nu) and (fRe) values.
4- The present method can also be extended by taking velocity inlet as one of the factors (process parameter) in the response surface methodology.
5- The numerical experiments with the optimum layout of the proposed finned tube were analyzed for the accuracy of the optimization results. This confirm that the present response surface methodology which is considered in this study is effective to optimize the model of the heat transfer inside a finned tube and as a result reduces the experimental cost in optimizing or improvement.
6- Multi-objective numerical optimization combined with response surface methodology provides a reliable and economic means of designing a heat-transfer enhancement of internally finned tube which is tested by conducting a conformation test.

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APPENDIX 1

TABLE 2 BOX-BEHNKEN DESIGN OF EXPERIMENT ALONG WITH OBSERVED AND PREDICTED RESPONSE [FIN NUMBER (A), FIN HEIGHT (B) AND FIN THICKNESS (C)]

Run	Coded levels of variables			Actual levels of variables			Response(%degradation)		Response(%degradation)	
	A	B	C	A	B	C	Nu Observed	Nu Predicted	fRe Observed	fRe Predicted
1	-1	-1	0	6	0.0125	0.04	7	6.94	15	15.11
2	1	-1	0	10	0.0125	0.04	4	4.18	11	11.71
3	-1	1	0	6	0.0325	0.04	18	16.88	26	24.6
4	1	1	0	10	0.0325	0.04	11	10.56	18.5	17.99
5	-1	0	-1	6	0.02125	0.02	12.6	12.4	19	19.16
6	1	0	-1	10	0.02125	0.02	8	7.62	14.8	14.44
7	-1	0	1	6	0.02125	0.06	12.6	12.9	19.7	20.44
8	1	0	1	10	0.02125	0.06	8.5	8.6	15	15.2
9	0	-1	-1	8	0.0125	0.02	6.5	6.7	13.7	14.2
10	0	1	-1	8	0.0325	0.02	15.8	15.4	22.7	22.46
11	0	-1	1	8	0.0125	0.06	8.45	8.1	15.7	15.62
12	0	1	1	8	0.0325	0.06	16.6	15.8	23.8	23.14
13	0	0	0	8	0.02125	0.04	12.2	12.1	19.0	18.66
14	0	0	0	8	0.02125	0.04	12.4	12.1	18.4	18.66
15	0	0	0	8	0.02125	0.04	12.8	12.1	18.9	18.66
16	0	0	0	8	0.02125	0.04	12.3	12.1	18.1	18.66
17	0	0	0	8	0.02125	0.04	12.5	12.1	18.6	18.66

TABLE 3 ANOVA RESULTS OF THE RESPONSE SURFACE quadratic model for NUSSELT NUMBER (Nu) [FIN NUMBER (A), FIN HEIGHT (B) AND FIN THICKNESS (C)]

Source	Sum of Squares	df	Mean square	F Value	p-value Prob> F	
Model	43.06	9	4.78	67.45	< 0.0001	significant
A-Ip	30.42	1	30.42	428.81	< 0.0001	
B-T_{on}	6.02	1	6.02	84.87	< 0.0001	
C-τ	1.46	1	1.46	20.61	0.0027	
AB	3.53	1	3.53	49.82	0.0002	
AC	0.09	1	0.09	1.27	0.2971	
BC	0.084	1	0.084	1.19	0.3123	
A^2	0.65	1	0.65	9.1	0.0195	
B^2	0.87	1	0.87	12.21	0.0101	
C^2	0.014	1	0.014	0.2	0.6658	
Residual	0.5	7	0.071			
Lack of Fit	0.24	3	0.079	1.21	0.4148	not significant
Pure Error	0.26	4	0.065			
Cor Total	43.56	16				

TABLE 4 ANOVA RESULTS OF THE RESPONSE SURFACE quadratic model for friction factor multiplied by Reynolds NUMBER (fRe) [FIN NUMBER (A), FIN HEIGHT (B) and FIN THICKNESS (C)].

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F	
Model	220.3621	9	24.48468	58.14073	< 0.0001	significant
A-Fin number	41.0585	1	41.0585	97.49653	< 0.0001	
B-Fin height	146.3015	1	146.3015	347.4039	< 0.0001	
C-Fin thickness	1.413038	1	1.413038	3.355366	0.1097	
AB	4.13187	1	4.13187	9.811439	0.0166	
AC	0.0625	1	0.0625	0.148411	0.7115	
BC	0.252735	1	0.252735	0.600138	0.4639	
A^2	12.98701	1	12.98701	30.83863	0.0009	
B^2	3.365113	1	3.365113	7.990715	0.0255	
C^2	0.027796	1	0.027796	0.066004	0.8046	
Residual	2.947895	7	0.421128			
Lack of Fit	0.827895	3	0.275965	0.520689	0.6906	not significant
Pure Error	2.12	4	0.53			
Residual	2.947895	7	0.421128			

TABLE 5 PARETO-OPTIMAL SOLUTIONS USING NSGA

Sl no	Fin number.	Fin height	Fin thick ness	Nu	fRe
1	6	0.03	0.059995	18.07344	23.79503
2	6	0.029236	0.050866	17.70819	23.11431
3	7	0.028795	0.048298	17.22085	22.31508
4	8	0.02619	0.030276	15.75081	22.4044
5	7	0.022929	0.047951	15.17802	22.00132
6	8	0.022231	0.037288	14.11657	18.67375
7	8.	0.022535	0.036798	13.77127	18.30243
8	9	0.024543	0.052716	13.17919	17.78051
9	7	0.01573	0.047543	11.86729	17.02766
10	8	0.016144	0.035108	11.57736	16.30548
11	9	0.0177	0.041602	9.710957	14.3223
12	9	0.015023	0.043254	8.929118	13.65624
13	9	0.011241	0.03544	8.02074	13.09845
14	9	0.012957	0.033549	7.83051	12.76863
15	9	0.010388	0.023392	7.144143	12.36675
16	10	0.012761	0.027962	6.112278	11.22496
17	10	0.010428	0.027283	4.96425	10.33782