Numerical Analysis and Optimization of Thermo-Hydraulic Performance in Tube Provided with Thin Wire Rib Roughness using Taguchi Approach

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ABSTRACT

Presence of roughness element on the inside surface of tube enhance heat transfer and pressure drop. The present work deals with numerical investigation and optimization of thermo-hydraulic performance of artificially roughened tube. The roughness is provided in the form of thin wire ribs. The effect of geometrical parameters such as, rib angle of attack (α = 30°, 45°, 60°), rib height (e = 0.5mm, 1mm, 1.5mm), rib pitch (p = 50mm, 46mm, 40mm) and Reynolds number (Re = 6788, 9051, 11313) on thermo-hydraulic performance factor (η) is investigated using Taguchi approach. Nusselt number and pressure drop are considered as performance parameters to find out the thermo-hydraulic performance of artificially roughened tube. An orthogonal array of L9 (3^4) is considered as experimental plan. The goal of study is to obtain maximum Nusselt number and minimum pressure drop. Signal-to-noise ratios and contribution rations of each parameters is calculated. The results indicate that maximum thermo-hydraulic performance is obtain for α = 30°, e = 1 mm, p = 46 mm and Re = 9051

Keywords: Roughness, Numerical Investigation, Optimization, Taguchi Approach, Thermo-hydraulic performance

I.INTRODUCTION

The heat exchange between the two mediums is typically low due to formation of static boundary layer of fluid over the tube wall which offers higher convective resistance in the path of heat transfer. To overcome the aforesaid situation, several heat transfer enhancement techniques have been tested over the several years such as helical roughened tubes, dimpled tubes, grooved tubes, twisted tape, wire coil, circular ring. Principally all these methods are based on creation of disturbance near the wall that reduces the thermal barrier and thereby leads to higher heat transfer. As a result of the enhancement in heat transfer, the size of the heat exchange device is reduced to a large extent with the considerable improvement in its performance.

Boelter et al. [1] in their experimental work collected data for heat transfer and pressure loss. The used strips soldered at certain angle to the flow direction in a duct. The pitch of metal strips was 25.4 mm, while height of strips as 3 mm and 10 mm respectively. They found that there was almost 200 % increase in heat transfer coefficient as compared to smooth duct with considerable increase in pressure drop. Heat transfer and frictional losses in tubes having roughness in the form of helical wire coil inserts was experimentally investigated by **Sethumadhavan and Raja Rao [2]**, they considered helical angles of 30°, 40°,55°, 60°, and 75° and found out that the maximum thermo-hydraulic performance was seen for helix angle of 55°. **Pawan Singh Kathait, AnilkumarPatil [3]** experimentally shown for roughened tubes the maximum value of thermo hydraulic performance is obtained as 1.95 corresponding to roughened tube with pitch to height ratio 10 at Reynolds number of 7343. **Pethkool et al. [4]** they experimentally found that the maximum thermal performance factor is 2.33 obtained for pith ratio 0.27 and rib height ratio 0.06 also Nusselt number and friction factor are 3.10 and 2.14 times above the smooth pipe.

The Taguchi approach is one of the foremost optimization techniques which reduce overall time and experimental cost permits us to minimize the variation around the target when bringing the performance value close to target value. It also helps to determine the optimum values of the working conditions. Taguchi approach for optimization of flow and geometrical parameters for roughened rectangular duct is presented by **Sunil Chamoli [5],** an orthogonal array of L_{16} was chosen as experimental plan. Optimum parameters for Nusslet number and friction factor were found for $A_2B_2C_1D_4$ and $A_4B_1C_4D_3$.Similar approach was used by **Halit Bas and Veysel Ozceyhan [6]** in their investigation for heat transfer and pressure drop in tube assisted with twisted tape inserts. Optimum values for heat transfer and pressure drop were found to be at Reynolds number for 18,400 and 5200 respectively. **Gunes et.al [7]** using Taguchi approach investigated the optimum design parameters for tube with wire coil inserts. The optimum results were found to be s/D= 00357, P/D= 1, a/D= 0.0714 and Re= 19800

Literature review shows that there are many heat transfer enhancements techniques. However little information is available regarding the determination of optimum values of roughness in the form of thin wire ribs orientated at different angle of attacks, pitch and height. With this regards present numerical analysis and optimization of thermo-hydraulic performance in tube provided with thin wire rib roughness using Taguchi approach.

II. NUMERICAL ANALYSIS

All the flow domains of roughened tube are created in CATIA v5. The geometrical parameters of tube are shown in Table 1. The numerical domain of 30° rib angle of attack is shown in Figure 2.

Table 1 Geometrical specifications of roughened tube

Sr. No	Parameter	Value
1.	Tube diameter (D)	28 mm
2.	Tube length (L)	1.68 m
3.	Rib height (*e*)	0.5, 1, 1.5 mm
4.	Rib length (*l*)	15 mm

5.	Initial Rib pith (*p*)	50, 46, 30 mm
6.	Rib angle of attack (α)	30°, 45°, 60°

The meshing of the roughened flow domains is carried out in ANSYS meshing module. Unstructured tetrahedral mesh is used to discretize all the roughened domains. Figure 2 shows the meshing of the roughened tube for 60° rib angle of attack. All the roughened tubes were meshed in similar way. Grid independence is performed for the flow domain having rib angle of attack 30°. To obtain more accurate results the mesh near the wall of tubes and the ribbed surface is made finer.

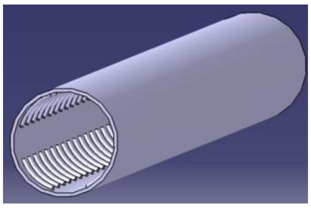

Fig.1 Numerical domain of tube with 30° rib orientation (e=1mm, p=50mm)

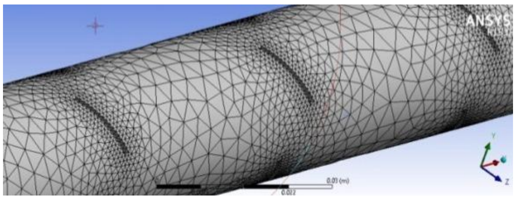

Fig.2 Mesh of tube with 60° angle of attack

To predict the accuracy of the results obtained by simulation grids having different elements, with 863102, 1000591, 11,3825 and 12,49731 are used for grid independence test for Re = 9051. All the boundary conditions used in analysis are given in Table 2. Since it is steady state analysis the solver settings are set to be default. For the pressure-coupling SIMPLE scheme is used with discretization scheme of second order upwind to get the solution of Continuity, Momentum and Energy equations.

Table 2 Boundary conditions details

Sr. No	Face	Type of boundary condition	Velocity/ Pressure magnitude	Temperature
1.	Inlet	Velocity Inlet	- Three Reynolds numbers (6788, 9051, 11313) are used.	314 K
2.	Outlet	Pressure Outlet	Pressure Outlet (Atmospheric pressure)	-
3.	Wall	Constant wall temperature	- No slip condition.	325 K

III.TAGUCHI METHOD

Taguchi method consists of three design stages which are system, parameters and tolerance design. In present study the parameters design stage of Taguchi technique is used. Parameter design provides the optimum values of the design parameters for the system. Tolerance design is used to decide the optimum tolerances for the design parameters. SNR (S/N) is a measure of the performance variability of parameters selected in presence of noise factors. SNR is a measure of performance criteria is defined as signal-to-noise ratio where S stands for mean and N stands for standard deviation. The quality of products improves as SNR gets higher. Hence the ultimate target is to maximize the SNR by minimizing the effect of random noise factor which have impact on

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overall process performance. An orthogonal array is important tool used in Taguchi technique to study the number of design parameters by single quality characteristics. An orthogonal experimental is carried out to find the optimum level for each controllable factor and to find the significance of individual parameters in terms of their main effects on response. The steps involve in Taguchi technique used in present study are as follows:

Step 1: Identification of objective

The objective of the present work is to determine the optimum values of design parameters in tube with thin wire rib roughness.

Step 2: Selection of characteristics

There are 3 characteristics in Taguchi technique, higher is better, nominal is best and lower is better. In present study the first goal is to maximize the Nusselt number therefore it is higher the better. The second goal is to minimize the pressure drop hence it is lower the better problem.

Step 3: Selection of controllable and Noise factors

In present study the controllable factors are rib height (e), rib pitch (p), rib angle of attack (α) and Reynolds number (Re), while heat transfer and pressure drop are the noise factors. The controllable factor for present study is shown in Table 3.

Table 3 Design parameters and their levels

Parameters	Levels		
	1	2	3
A: Rib Height (e)	0.5	1	1.5
B: Rib Pitch (p)	50	46	40
C: Rib angle of attack (α)	30	45	60
D: Reynolds number (Re)	6788	9051	11313

Step 4: Selection of Orthogonal array

The sequence of the experiments with combination of factors is determined by an orthogonal array. It help to determine the number of simulations to be performed, with all the levels of factors will be tested an equal quantity. In present study the optimization is performed with statistical software Minitab 15 package. In present work, there are four factors with three levels. Hence there are 8 (4*2) degrees of freedom because of four deign parameters. In present work an orthogonal array of L_9 is chosen instead of L_{27} to minimize the number of runs of simulation.

Step 5: Performing numerical simulation and analysis

All the numerical simulations conducted as shown in experimental plan in Table 4. The combination of the optimum values of process parameters can be predicted. Finally the confirmation test is conducted to verify the optimum process parameters obtained from parameters deign. In present study the objective is to maximize the heat transfer or Nusselt number and minimize the pressure drop. And finally the overall effect of heat transfer and pressure drop is taken into consideration to find the overall thermal and hydraulic performance of the use of roughened tube in terms of thermo-hydraulic performance factor suggested by Webb and Eckert [8]. Thermo-hydraulic performance is given by,

$$\eta = \frac{Nuc/Nus}{(fc/fs)^{1/3}}$$

Contribution ratios of all the factors on Nusselt number, pressure drop and thermo-hydraulic performance factor are defined by the SNR as depicted in Tables 5, 6 and 7.

Table 4 Experimental plan for L_9 Orthogonal array and SNR values

Parameters				Nu	SNRA1	ΔP	SNRA2	η	SNRA3
A	B	C	D						
1	1	1	1	63.18	36.012	90.57	-39.139	0.978033	-0.19293
1	2	2	2	90.62	39.144	172.6	-44.740	1.181166	1.44622
1	3	3	3	111.64	40.957	369.65	-51.355	1.154562	1.24834
2	1	2	3	100.10	40.008	274.69	-48.776	1.09682	0.80271
2	2	3	1	78.67	37.916	136.63	-42.710	1.010583	0.09144
2	3	1	2	108.55	40.713	259.56	-48.284	1.268461	2.06554
3	1	3	2	94.58	39.516	226.34	-47.095	1.021877	0.18798
3	2	1	3	119.62	41.556	346.65	-50.797	1.139456	1.13395
3	3	2	1	81.55	38.229	81.5574	-43.705	0.815633	-1.77011

Table 5 Factorial effect and contribution ratio for Nusselt number

	LEVEL	**A**	**B**	**C**	**D**
SNR	1	38.70	39.97	39.43	37.39
	2	39.55	39.54	39.13	39.79
	3	39.77	38.51	39.46	40.84
R		1.06	1.45	0.34	3.45
Rank		3	2	4	1
Contribution ratio (%)		6.35	13.22	2.45	77.98

Table 7 Factorial effect and contribution ratio for pressure drop

	LEVEL	**A**	**B**	**C**	**D**
SNR	1	-45.08	-47.78	-46.07	-41.85

	2	-46.59	-46.08	-45.74	-46.71
	3	-47.20	-45.00	-47.05	-50.31
R		2.12	2.78	1.31	8.46
Rank		3	2	4	1
Contribution ratio (%)		38.75	5.72	6.02	49.50

Table 6 Factorial effect and contribution ratio for thermo-hydraulic factor

	LEVEL	A	B	C	D
SNR	1	0.8339	0.5146	1.0022	-0.6239
	2	0.9866	0.8905	0.1596	1.2332
	3	-0.1494	0.2659	0.5093	1.0617
R		1.1360	0.6246	0.8426	1.8571
Rank		2	4	3	1
Contribution ratio (%)		21.43	6.49	10.37	61.71

IV.RESULTS AND DISCUSSIONS

The results obtained from numerical simulations are analyzed in Minitab 15.0 software to determine the effect of roughness and flow parameters on heat transfer and pressure drop. Figure 3 shows the effect of each roughness and flow parameter on nusselt number.

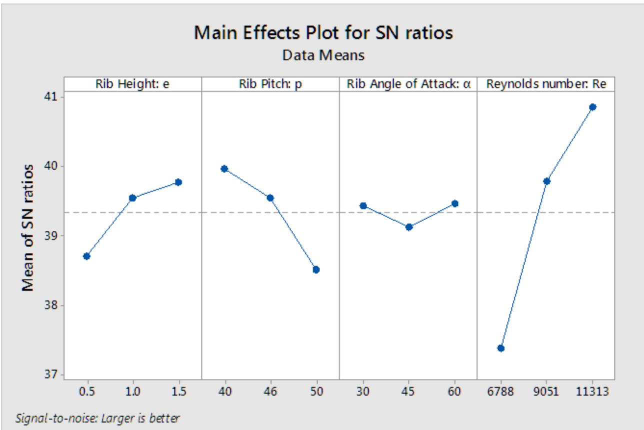

Fig. 3 Effect of individual roughness and flow parameters on Nusselt number

It can be observed that Nusselt number takes it maximum value at third level for parameter of rib height (e). As the height of wore increases it provides the better mixing of fluid neat to boundary layer which results in disturbance in laminar sub-layer. Also Nusselt number is observed to be increase with decrease in pitch of roughness due to increase in turbulence intensity and increase in flow path. The maximum value of Nusselt numbers are observed for the rib angle of attack 60°. It is clear from the Figure 3 that the optimum values of

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parameters for maximum heat transfer are as follows: e= 1.5 mm, p=40 mm, α= 60° and Re= 11313. Hence $A_3B_3C_3D_3$ are the optimum conditions of roughness and flow parameters for maximum heat transfer according to "Larger is better" criteria for Nusselt number.

The effect of roughness and flow parameters on pressure drop is shown in Figure 5. It is observed that the pressure drop decrease with decrease in rib height (e) this is due to since the height of rib increases the surface area increases and hence flow blockage increases with causes overall increase in pressure drop. Increase in pitch of roughness provides more pressure drop due to increase in turbulent intensity due to successive number of ribs placed closed to each other. The optimum values of parameters for minimum pressure drop are as follows: e= 0.5 mm, p=50 mm, α= 45° and Re= 6788. Hence $A_1B_1C_2D_1$ are the optimum conditions of roughness and flow parameters for minimum pressure drop according to "Smaller is better" criteria for pressure drop.

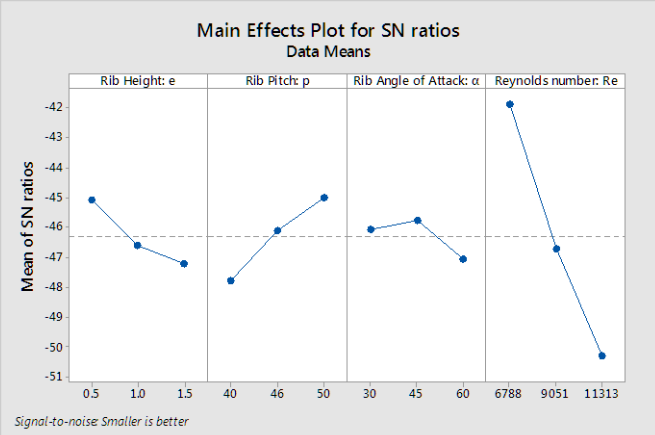


Fig. 4 Effect of individual roughness and flow parameters on pressure drop

It is obvious that the heat transfer will increase with increase in values of roughness and flow parameters and pressure drop tends to decrease with decrease in values of roughness and flow parameters. However it is necessary to analyze the combine effect of heat transfer and pressure drop which will provide the maximum thermo-hydraulic performance. Figure 5 shows the effect of individual roughness and flow parameters on thermo-hydraulic performance factor (η).

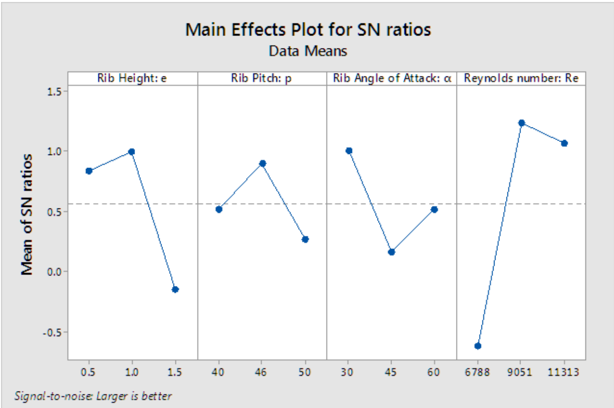


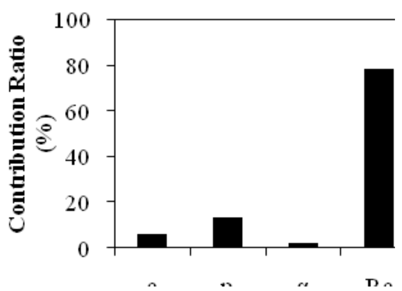
Fig. 4 Effect of individual roughness and flow parameters on thermo-hydraulic performance factor

It can be seen that the optimum values for thermo-hydraulic performance factor are e= 1 mm, p=46 mm, α= 30° and Re= 9051. Hence $A_2B_2C_1D_2$ are the optimum conditions of roughness and flow parameters for thermo-hydraulic performance according to “Higher is better” criteria for thermo-hydraulic performance factor.

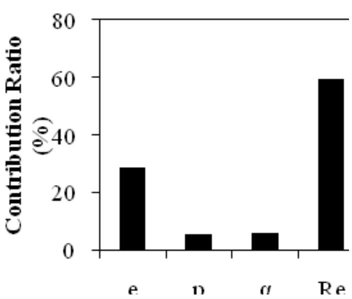
The optimum conditions for heat transfer, pressure drop and thermo-hydraulic performance factor are predicted using 95% significance level as shown in Table 7. The confirmation tests are conducted at optimum conditions to check the predicted results. The contribution ratio of each parameters on Nusselt number, pressure drop and thermo-hydraulic performance factor is shown in Figure 5 (a-c). It can be seen that for Nusselt number the Reynolds number is the most effective parameters which contributes to overall heat transfer with 78%. Rib height (*e*) plays important role in pressure drop which is second most effective parameter with contribution ratio of 39%. The contribution ratio of e, p α and Re on thermo-hydraulic performance is 21.43%, 6.49%, 10.37% and 61.71% respectively.

Table 7 Optimum conditions and performance values for tested models

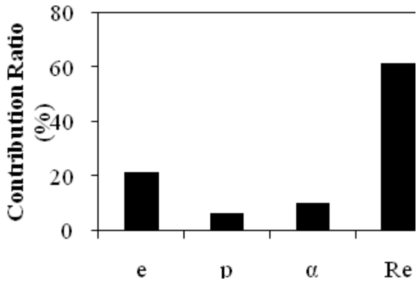
		Parameters				**Nu**		**ΔP**		**η**	
		e	p	α	Re	Predicted	Real	Predicted	Real	Predicted	Real
Nu	Optimum level	3	3	3	3	123.70	125.24	453.79	455.43	1.001	0.985
	Optimum value	1.5	40	60	11313						
ΔP	Optimum level	1	1	2	1	70.80	72.31	121.79	124.16	0.955	0.9612
	Optimum value	0.5	50	45	6788						
η	Optimum level	2	2	1	2	94.41	96.14	149.89	152.41	1.11	1.091
	Optimum value	1	46	30	9051						



(a)



(b)



(c)

Fig.5 Contribution ratios of each parameters on Nu, ΔP and η

V.CONCLUSION

In present study the optimum values of roughness and flow parameters are determined using Taguchi technique for thermal and hydraulic performance for tube provided with roughness. The significant results of present work are summarize as follows:

1. Nusselt number is observed to increase with increase in roughness and flow parameters. The optimum values of parameters were obtained as e= 1.5 mm, p=40 mm, α= 60° and Re= 11313. And optimum condition of design parameters was $A_3B_3C_3D_3$.
2. Pressure drop decreases with decrease in rib height and rib pitch. The optimum values of parameters were obtained as e= 0.5 mm, p=50 mm, α= 45° and Re= 6788. Hence $A_1B_1C_2D_1$ are the optimum conditions of design parameters.
3. The optimum values of parameters for thermo-hydraulic performance factor are obtained as, e= 1 mm, p=46 mm, α= 30° and Re= 9051 with $A_2B_2C_1D_2$ as optimum design condition.
4. Amongst all the factors the Reynolds number is the most effective parameter contributing to overall thermal and hydraulic performance for roughened tube, while rib height is the second most effective parameters amongst the other.
5. The results show that there is no need to perform all 81 simulations to find the optimum parameters affecting the heat transfer and pressure drop. Hence Taguchi method is successfully applied in present work reducing the overall numerical simulations and reducing the overall time.

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