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Optimization of Geometric and Flow Parameters of Circular Heat Exchanger Tube with Square Wing and Combined Solid ring Twisted Tape inserts by Taguchi Method

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Abstract: Optimization techniques in manufacturing sector have been applied to arrive at novel manufacturing product at low cost. The Taguchi method and analysis of variance have been applied to investigate Reynolds number (Re) varied from 5000 to 21000, twisted tape parameters such as ring pitch ratios (d_R/D_T) from 0.5 to 2.0 and wing pitch ratios (P_W/W_T) from 2.0 to 3.5 respectively. The analysis of variance (ANOVA) approach has also being applied to conclude the effects of the various parameters on the turbulent heat transfer and fluid flow inside the circular tube. The experiments are conducted by using Taguchi's L_{18} factorial design experiments, and then each response is changed to signal- noise (S/N) ratio. The investigation revealed that heat transfer is increased around 5.66 times higher than plane circular heat exchanger tube.

Keywords: Heat transfer enhancement • Multiple twisted tapes • Twists ratio • Wing pitch ratio • Ring pitch ratio • Solid rings.

Introduction

The heat exchanger tube is a device fitted with various insert geometries to augment heat transfer rate in most of the mechanical and thermal equipment used in various industrial and house hold appliances. At present many studies have been carried out to enhance the thermodynamic performance of heat exchanger system with intend of energy saving by minimizing the size, cost and power consumption of various heat exchanger techniques. In present era the geometrically compact heat exchanger tube with various swirl generator inserts gained much consideration and was found an efficient way to enhance the performance as well efficiency of various equipment's. The various twisted tape inserts fitted in heat exchanger tube are used on large scale to enhance heat transfer rate and from experimental results it was found that it always achieve better performance than plane tube. In the present study the contribution of numerous investigators has been reported for the innovation of efficient, optimal geometrical shape and new heat exchanger techniques to enhance their thermo hydraulic performance. Bilen et al (2001) applied Taguchi method to get optimal solution of heat transfer rate from a plane surface fitted with rectangular setup of blocks, taking into consideration the angular displacement to its span wise and stream wise disposition. Yang et al. (2009) applied Taguchi method designs of experiments approach and found that feed rate was the major factor affecting the groove difference and the roughness average of milling process. Davim(2003) used the Taguchi technique to optimize the effect of cutting velocity and feed rate and cutting time parameter on drilling metal-matrix composites. Horng et al (2008) applied RSM approach to optimum solution of combined effects of machining parameters, tool angle radius, cutting velocity, feed rate and depth of cut, on the basis of two performance characteristics. Meyer et al. (2018) examined Nu_{rs} and f_{rs} characteristics in the transitional flow regime of TT inserts in a circular tube. A circular tube with an internal diameter of 19.0 mm, length of 5.27m and TT inserts with twist ratios of 3, 4 and 5 were used in experimentation. Skullong et al. (2018) investigated the effect of curved-winglet inserts on thermal and flow behaviours in a circular tube. He Liu et al. (2018) experimentally investigates the Nu_{rs} rate and f_{rs} of a circular tube equipped with cross hollow *TT* inserts of hollow widths of 6, 8 and 10 mm under homogeneous heat flux. Bartwal et al (2018) experimentally investigated passive heat transfer enhancement technique. In this context, novel geometry insert has been developed, which can significantly augment the convective heat transfer rate by the disturbance of the thermal boundary layer. Zheng et al (2018) investigated the flow pattern and heat transfer enhancement of laminar flow in a *HET* equipped with multiple conical strips inserts have been carried out. The experimental and numerical findings show that Nu_{rs} and $f_{rs}$of heat exchanger fitted with various inserts were respectively enhanced by approximately 2.54–7.63 and 2.40–28.74 times compared to the plain tube, and the overall Nu_{rs} performance was found in the range of 1.23–6.05.

Turgut et al (2013) developed optimum parameter for concentric heat exchanger tube equipped with various injector turbulators using Taguchi method of orthogonal array. Zeng et al. (2010) compared the special effects of elevation of vortex generator, different attack angles, and length of vortex generator, fin width, fin pitch ratios and circular tube pitch ratios on circular heat exchanger tube using numerical method. Senthilkumar et al (2014) investigated the performance of cemented carbide inserts with different geometrical configuration by applying Taguchi grey relational techniques. The examination of heat transfer rate from heat exchanger tube equipped with rectangular blocks by using Taguchi method, considering angular displacement of the block with span and stream wise disposition. The findings of the investigation reveal that the Taguchi method is a suitable approach to get optimal solution for various parameters used in heat exchanger tube fitted with various inserts Kotcioglu et al (2013), Bilen et al (2001)The deviation between experimental values and the required values can be calculated by application of loss function in Taguchi approach and further the value of loss function is converted into S/N ratios(η_F) Asilturk and Akkus (2011), Koksoy and Muluk (2004), Datt et al (2018&2019).

Twisted Tape Geometry and Parameters Range

Experimental procedure

In this investigation we have carried out various experiments on heat exchanger tube equipped with rings and various square wings twisted tape inserts to determine the variation in Nusselt number and friction factor. Experimental setup equipped heat exchanger tube with solid rings and square wings twisted tape inserts has been developed for investigating heat transfer rate and flow characteristics of heat exchanger tube having twisted tape inserts with rings and multiple perforated wings. The experimental outcomes of heat exchanger tube with multiple square wing twisted tape inserts with solid rings have been validated with data for smooth heat exchanger tube.

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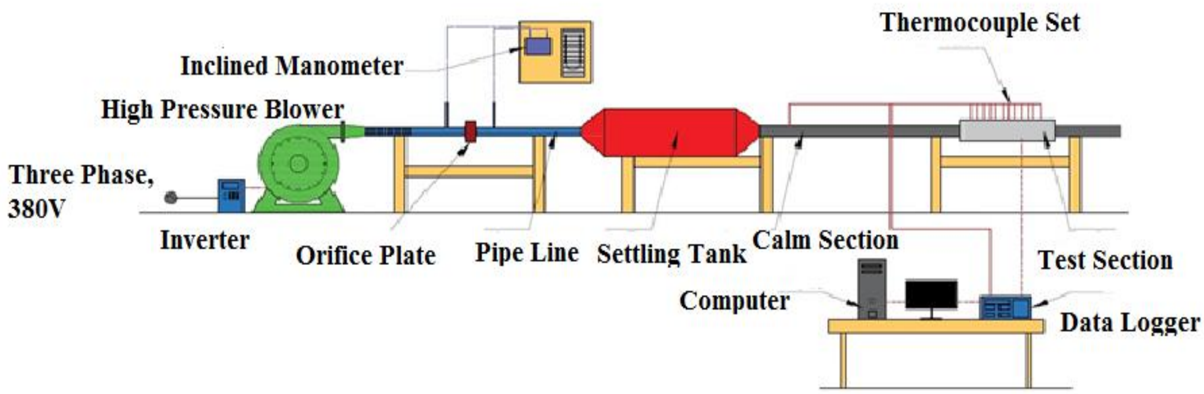

Fig1: Schematic of experimental setup.

Data reduction

The variuos parameters applied in this research to manage the fluid flow parameter in the varius square wings twist tape(TT) inserts with solid rings are evaluated by wings with width (P_W),distance between rings iinserted in the tube (d_T), diameter of the tube *(D_T)*, width of the tape *(W_T)*, inner diameter of the variuos ring (d_{IR}), outer diameter of the iserted ring *(d_{OR})* and twist tapes length (L_T) .

these different parameters have been expressed in the form of dimensionless parameters, viz., wing pitch ratios (P_W/W_T) and ring pitch ratios(d_R/D_T). The steady state condtions of the experiment for the given air mass flow rate (m), heat the transfer rate with heat transfer coefficient (h_{TT}), Nusselt number (Nu_{TT}) and friction factor (f_{TT}) have been evaluated by using the following parametric equations:

The toatal vlaue of the local wall temperature parameters T_{rs} inside of the tube is the average temperature of all the thermocouples inserted in the main domain of the experimental setup.

$T_{TT} = \frac{1}{13}\sum_{i=1}^{12} Tc_i$, Where $Tb_{TT} = \frac{T_i + T_o}{2}$ is bulk mean temperature of the fluid parameters.

The rate of the flow parameter air mass parameter is governed by using the following governing equation:

$$\dot{m} = C_d A_o \left[\frac{2.\ \rho_{TT}.(\Delta P)_0}{1-\beta^4}\right]^{0.5}$$

Where $(\Delta P)_0 = 9.81.(\Delta h_{TT})_0.\rho_{TT} sin\theta$.

The heat transfer rate coefficient of the fluid flow in the test tube section is evaluated using the governing equation: $Q_u = \dot{m} C_p [T_o - T_i]$,

$$h_{TT} = \frac{Q_u}{A_0 (T_{TT} - Tb_{TT})}$$

Where, the term Tb_{TT} represents the arithmetic average of the inlet and the outlet temperature of the air flowing through the test tube section.

Nusselts Number of the fliud flow area is evaluated from the equation: $Nu_{TT} = \frac{h_{TT}\ D_{TT}}{K_{TT}}$.

The velocity of the fliud flow in the heat exchanger tube is evaluated by using the parametric equation: $V_{TT} = \frac{\dot{m}}{W_T.H_{TT}.\rho_{TT}}$.

The Reynolds number of the fliud flow in the tube is calculated from equation: $Re_{TT} = \frac{V_{TT}.\ D_{TT}.\rho_{TT}}{\mu_{TT}}$.

The friction factor parameter of the luid flow in the test tube section is calculated from the pressure drop ratio as: $f_{TT} = \frac{2.(\Delta P)_d\ D_{TT}}{4.\rho_{TT}.L.V_{TT}^2}$,

Where, $(\Delta P)_d = 9.81 \times (\Delta h_{TT})_d.\rho_{TT}$

The thermal and the hydraulic performance of the fluid flow in a multiple square wing twisted tape with variuos inserts is compared with the plain tube by using the equation:

$$\eta_p = \frac{\left(\frac{Nu_{TT}}{Nu_{SS}}\right)}{\left(\frac{f_{TT}}{f_{SS}}\right)^{\frac{1}{3}}}$$

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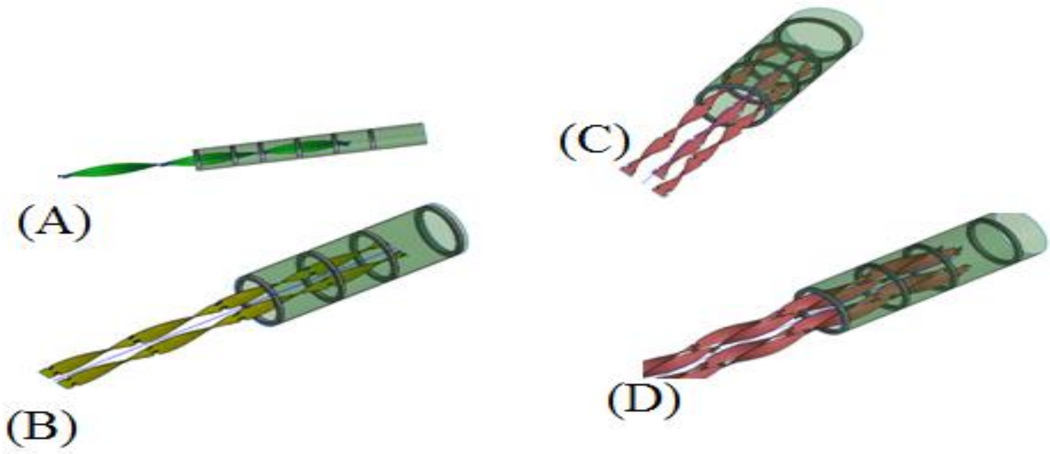

Fig 2: Schematic of twisted tape inserts with square wings perforation and solid rings tube (A) single twisted tapes (B) Double twisted tape (C) Triple twisted tape (D) Multiple (Four) twisted tape.

THE TAGUCHI METHOD AND DESIGN OF EXPERIMENTS

Taguchi method design of experiment is as one of the powerful design widely used to design and conduct the experiments with smallest amount capital and resources. Taguchi techniques employ orthogonal which reduces the number of tests and minimizes the effects of uncontrolled factors. Test design using orthogonal array creates an efficient and concise test suite with fewer test cases without compromising test coverage. The Taguchi Techniques calculate the variation between the experimental values and the desired values by using the application of loss function. Usually, the analysis of S/N is done by using three different quality characteristics, namely the smaller is the better, the larger the better, and the nominal-the-best Gupta et al. (2011)In the present work, L_{18} orthogonal array design is applied to set the control parameters to evaluate the performance of various experimental parameters.

The proposed procedure for solving the multiple response problems is described in the following steps:

The smaller the better quality for friction factor characteristic was used as shown in equation

$\eta_p = \frac{S}{N_S} = -10\ log_{10}\left(\frac{1}{K}\sum_{i=1}^{K} Y^2{}_{ir}\right)$ (STB).

And larger the best for the Nusselt numbers and thermo hydraulic performance as given in equation: $\eta_p = \frac{S}{N_S} = -10\ log_{10}\left(\frac{1}{K}\sum_{i=1}^{K} Y^2{}_{ir}\right)$ (LTB)

Where Y_i is the observed data at the ith experiment and n is the number of observations of the experiment Mandal et al. 2011). The Reynolds number (Re), ring pitch ratios (d_R/D_T) and wing pitch ratios (P_W/W_T) were selected as a control factor with their different level to find the optimum value of Nu_{TT} and f_{TT} is depicted in Table 1.

Table 1: The control factors at different levels measured for multiple performance description.

Factors	Levels		
	1	2	3
Reynolds number(Re)	5000	19000	-
Ring pitch ratios (d_R/D_T)	0.5	1	1.5
Wing pitch ratios (P_W/W_T)	2	2.5	3

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The orthogonal array of Taguchi L_{18} $(2^1 \times 3^2)$ was selected to explore optimal parameter for heat exchanger tube to enhance the overall performance. The different experiment was conducted by using mixed L_{18} $(2^1 \times 3^2)$ orthogonal array as shown in Table 2. Table 4 shows the different experimental values of the S/N ratios used to find the highest Nu_{TT}, η_P and lowest value of f_{TT} were especially significant for the performance improvement.

Table 2: Analysis of the signal- noise (S/N) ratios by using L_{18} orthogonal array.

Exp.No	Control factors			Responses and S/N ratios					
	A: (Re)	B:(d_R/D_T)	C:(P_W/W_T)	Nu_{TT}	S-N	f_{TT}	S-N	η_P	S-N
1	5000	0.5	2	76	37.616	0.52	5.596	1.9623	5.855
2	5000	0.5	2.5	77	37.729	0.54	5.352	1.9823	5.943
3	5000	0.5	3	88	38.889	0.59	4.582	2.1362	6.592
4	5000	1	2	79	37.952	0.52	5.679	2.0589	6.273
5	5000	1	2.5	87	38.790	0.53	5.514	2.1362	6.592
6	5000	1	3	93	39.369	0.56	4.928	2.2909	7.200
7	5000	1.5	2	73	37.266	0.53	5.432	1.9423	5.766
8	5000	1.5	2.5	74	37.384	0.54	5.272	1.9552	5.824
9	5000	1.5	3	80	38.061	0.55	5.051	2.0310	6.154
10	19000	0.5	2	227	47.120	0.50	5.916	1.7922	5.068
11	19000	0.5	2.5	230	47.234	0.52	5.646	1.8012	5.111
12	19000	0.5	3	246	47.818	0.50	6.020	1.8381	5.287
13	19000	1	2	229	47.196	0.43	7.330	1.8022	5.116
14	19000	1	2.5	248	47.889	0.45	6.878	1.8837	5.500
15	19000	1	3	256	48.164	0.47	6.429	1.9206	5.669
16	19000	1.5	2	221	46.887	0.42	7.452	1.7822	5.019
17	19000	1.5	2.5	229	47.196	0.43	7.330	1.8237	5.219
18	19000	1.5	3	236	47.458	0.45	6.763	1.8464	5.326

Analysis and evaluation of experimental results

The efficiency of twisted tape inserts is measured by using thermal hydraulic parameter η_P in terms of Nu_{TT} and f_{TT} via the experimental design for each possible combination of control factors Reynolds number (Re), ring pitch ratios (d_R/D_T) and wing pitch ratios (P_W/W_T) at different level by Taguchi method.

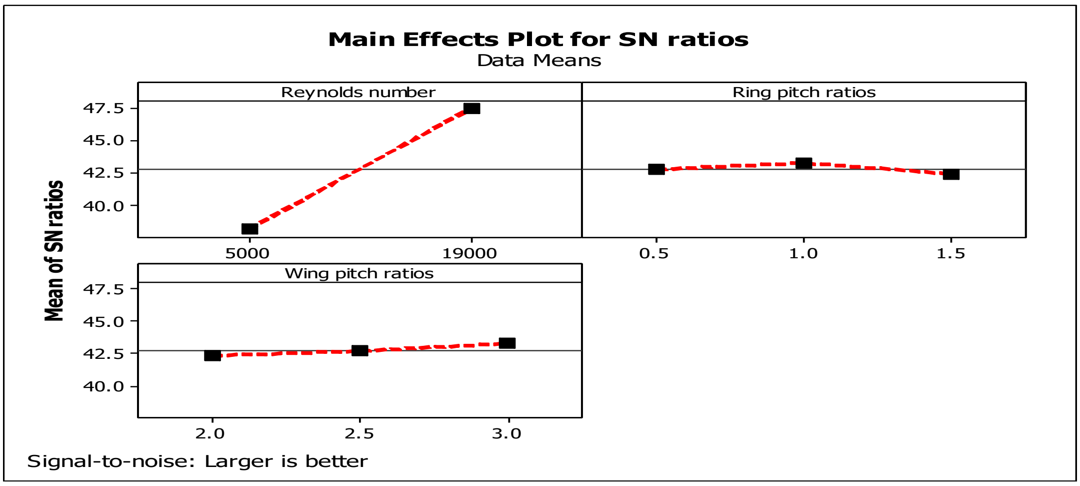

Figure 3: The effects of design parameters Reynolds number (Re), ring pitch ratios (d_R/D_T), and wing pitch ratios (P_W/W_T) on Nusselt number.

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The optimization of various factors was measured in terms of single to noise (S/N) ratios. The highest Nu_{TT}, η_P and lowest value of f_{TT} were especially significant for the performance improvement of heat exchanger tube fitted twisted tape inserts. For this purpose, the ''larger-the-better'' equation was used for the parameters Nu_{TT} and f_{TT} and the ''lower-the-better'' was used to find the f_{TT} factor. Finally the optimum value of Nu_{TT} and f_{TT} were calculated to be 256 and 0.477 respectively. The average Reynolds number (Re), ring pitch ratios (d_R/D_T) and wing pitch ratios (P_W/W_T) were calculated at which the optimized range of Nusselt number and friction factor were obtained.

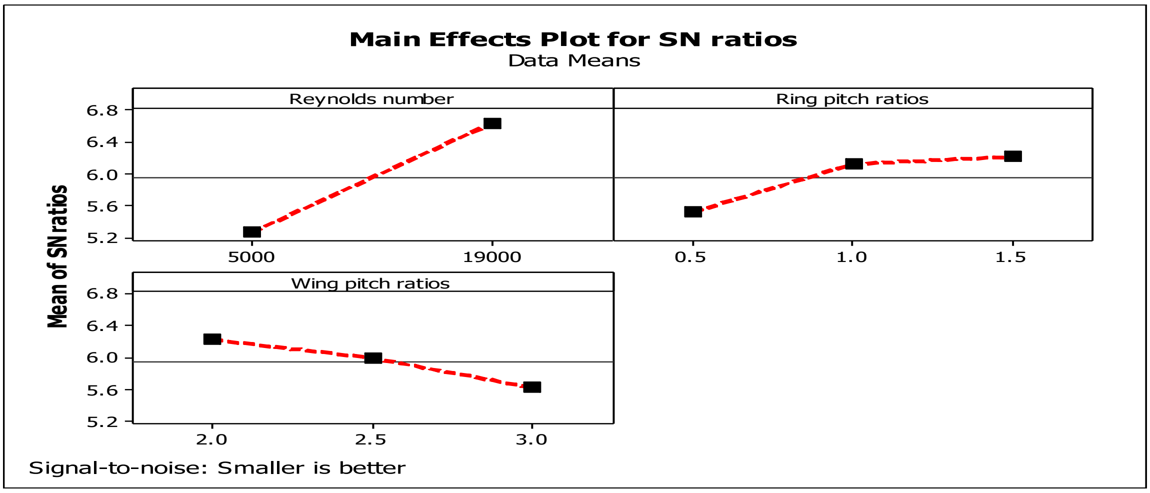

Figure 4: The effects of design parameters of Reynolds number (Re), ring pitch ratios (d_R/D_T), and wing pitch ratios (P_W/W_T) on friction factor.

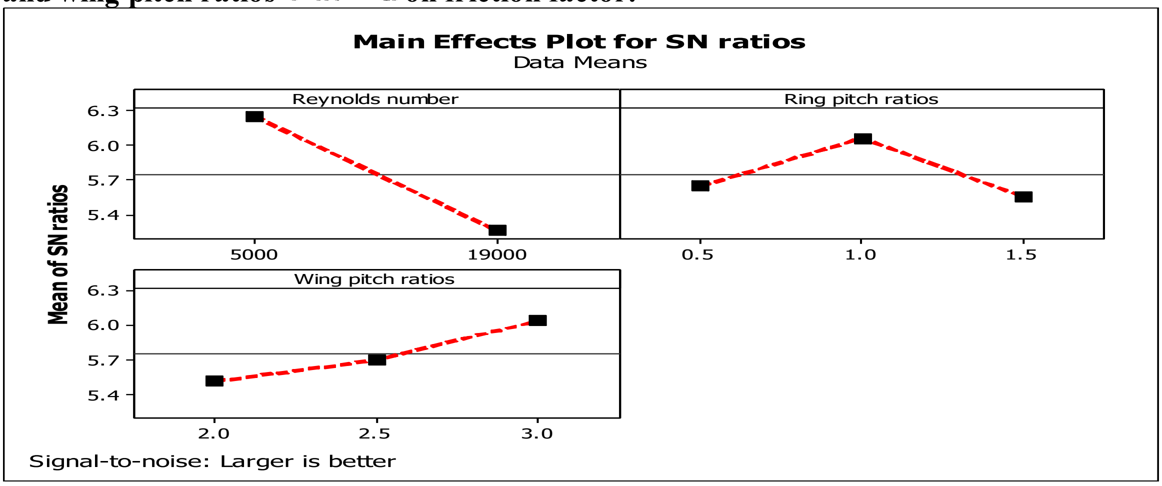

Figure 5: The effects of design parameters of Reynolds number (Re), ring pitch ratios (d_R/D_T), and wing pitch ratios (P_W/W_T) on thermal hydraulic performance.

Taguchi Analysis: Nusselt number versus Reynolds number, Ring pitches, and Wing pitch ratios.

Table 3: Response Table for Signal to Noise Ratios Larger is better

Level	Reynolds	Ring pitch ratios	Wing pitch ratios
1	38.12	42.73	42.34
2	47.44	43.23	42.70
3	-	42.38	43.29
Delta	9.32	0.85	0.95
Rank	1	3	2

Taguchi Analysis: Friction factor versus Reynolds number, Ring pitch and Wing pitch ratios.

Table 4: Response Table for Signal to Noise Ratios Smaller is better.

Level	Reynolds	Ring pitch ratios	Wing pitch ratios
1	5.268	5.519	6.235
2	6.641	6.127	5.999
3	-	6.217	5.630
Delta	1.373	0.698	0.605
Rank	1	2	3

Taguchi Analysis: η versus Reynolds number, Ring pitch ratios and Wing pitch ratios.

Table 5: Response table for signal to noise ratios larger is better.

Level	Reynolds	Ring pitch ratios	Wing pitch ratios
1	6.245	5.643	5.517
2	5.258	6.059	5.699
3	-	5.552	6.039
Delta	0.987	0.507	0.522
Rank	1	3	2

Table 6: Results of ANOVA for Nusselt numbers and parameters.

Source	Degree of freedom	squares SS	F ratio	P	Contribution (%)
Reynolds number	1	108113	6447.35	0.000	71.2
Ring pitch ratios	2	528	15.75	0.000	14.4
Wing pitch ratios	2	742	22.12	0.000	15.4
Error	12	201	-	-	
Total	17	109584			

S = 4.09494 R-Sq = 99.82% R-Sq(adj) = 99.74%

Table 7: Analysis of Variance for η, using Adjusted SS for Tests.

Source	Degree of freedom	Squares SS	Mean Square (MS)	F ratio	P	Contribution (%)
Reynolds number	1	0.223329	0.223329	90.18	0.00	66.12
Ring pitch ratios	2	0.047795	0.023898	9.65	0.003	17.2
Wing pitch ratios	2	0.045140	0.022570	9.11	0.004	17.7
Error	12	0.029719	0.002477	-	-	
Total	17	0.345983	-	-	-	

S = 0.0497652 R-Sq = 91.41% R-Sq(adj) = 87.83%

Results and Discussion

From Fig.3 it can be seen that the value of Nusselt number (Nu_{T1}) increases significantly with the enhancement of Reynolds number (Re) from 5,000 to 19,000 and consequently it increases the turbulent flow rate through heat exchanger tube. It can also be seen that the value Nu_{T1} increases with ring pitch ratios (d_R/D_T) from 0.5 to 1.0 and wing pitch ratios (P_W/W_T) from 2.0 to 3.0 respectively. The maximum value of Nu_{T1} were found at d_R/D_T= 1.0 and P_W/W_T=3.0. From experimental results it is evident that the smaller range of ring pitch ratios and wing induces swirl flow near the boundary wall of heat exchanger tube and generated additional turbulent flow along with traditional flow and consequently there is significant growth in heat transfer rate. The effects of control factors on friction factor and thermal hydraulic performance are presented in Fig.4 and Fig.5. Figure 4 shows the value of Nusselt number (Nu_{T1}) increase significantly with rise in the value of Reynolds number (Re) and friction factor decreases with the increase in fluid velocity. The average value of the S/N of Taguchi approach of various factors for each level of flow parameter is summarized in Table 2. The purpose of S/N ratio in Taguchi approach is to measure the deviation of the experimental design. The highest S/N ratio gives the best result. From Fig.3, it can also be seen that the highest S/N ratio was found for the 15th investigational run with optimum parametric permutation.

An analysis of variance (ANOVA) techniques was used to find a relation between control factors and possible experimental outcomes. The significant flow and geometric parameters are identified with the help of ANOVA. The ANOVA is performed with the confidence of 95% to find the significance level of various geometric parameters. The various outcomes of the ANOVA are shown in the table 6 and table7. The result revealed that Reynolds number, ring pitch ratios (d_R/D_T) and wing pitch ratios (P_W/W_T) influence Nusselt number (Nu_{TT}) with 71.2%, 14.4% and 15.4% respectively.

Conclusion

This study highlights the use of Taguchi method to find the optimum solution of flow and geometric parameters of heat exchanger tube equipped with combined square wings and solid rings twisted tapes. The different experimental runs were conducted by using Taguchi's L_{18} orthogonal array and further analyzed by using ANOVA techniques. The performance of heat exchanger tube by and large depends upon flow pattern and geometry of the various parameters used in the present investigation.

- Thermal performance of heat exchanger tubes is significantly affected by the flow and geometrical parameters. To obtain maximum thermal hydraulic performance, flow and geometrical parameters must be taken priority while designing industrial and domestic heating devices.
- From the result it is evident that Reynolds number, ring pitch ratios (d_R/D_T) and wing pitch ratios (P_W/W_T) play significant role in the performance of heat exchanger tube as well on the thermal performance factor.
- The optimum value of the various experimental run was obtained at experimental run16 for the possible combination $A_2B_3C_1$.
- The overall thermal hydraulic performance at experimental run16 is 1.92, obtained by the contribution of Nu_{TT}=256 with S-N ratio 48.1648; friction factor 0.477; ring pitch ratios (d_R/D_T) =1.0 and wing pitch ratios (P_W/W_T) =3.0 respectively.

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Nomenclature

D_T	Diameter of Tube, (m)
L	Length of tube, (m)
h_{TT}	Heat transfer rate coefficient
Nu_{TT}	Nusselt number (hD/k)
Re_{TT}	Reynolds number
W_T	Width of tape
P_W	Pitch between wings
d_{TT}	Director diameter,(m)
f_{TT}	Friction factor
Greek	Symbols
η_p	Performance evaluation factor (Dimensionless parameter)