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Taguchi Method for Turbulent Analysis of Water-Al_2O_3 Nanofluid

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Abstract-Heat transfer enhancement of a water based Al2O3 nanofluid flowing through the circular cross sectional pipe is numerically investigated and predicted by using optimization technique Taguchi Method. Numerical investigation for heat transfer coefficient were done at three levels of four different parameters like Reynolds Number (Re=20000, 27500,35000); Tube Diameter(D=6, 8 10);Nanoparticle Concentration(φ=2, 3 and 4%) and Nanoparticle Diameter Size(dp=10,20 and 30nm). For experimental analysis L9 orthogonal array was selected. The mesh validation of CFD analysis of water is compared with Gnielinsky correlation. Properties of nanofluid were calculated for numerical solution. The results of orthogonal array is showed considered parameters have significant influence on heat transfer coefficient (h).The results of heat transfer coefficient is optimized at maximum value of Re, φ and minimum diameter of tube with less particle diameter. The predicted experiment shows 40% increment of heat transfer coefficient by using nanofluid flow than water. Further randomly selected combination of parameters were compared with actual results of experiment shows less error and Taguchi method could be successfully used to predict heat transfer coefficient of nanofluid flow.
Key Words -Heat transfer coefficient, nanofluid, Taguchi method, ANOVA, Optimization.

I. INTRODUCTION

Low thermal conductivity of conventional heat transfer fluids such as water, oil, and ethylene glycol mixture is a serious limitation in improving the performance and comp- actness of many engineering equipments such as heat exchangers and electronic devices. To overcome this dis- advantage, there is strong motivation to develop advanced heat transfer fluids with substantially higher conductivity. Nanofluids are a new kind of heat transfer fluid containing a small quantity of nano-sized particles (usually less than 100 nm) that are uniformly and stably suspended in a liquid. The dispersion of a small amount of solid nanoparticles in conventional fluids changes their thermal conductivity remark- ably. Compared to the existing techniques for enhancing heat transfer, the nanofluids show a superior potential for increasing heat transfer rates in a variety of cases [1, 2, 3, 4].

Taguchi techniques are experimental design optimization techniques [12, 13] which use standard Orthogonal Arrays' for forming a matrix of experiments in such a way to extract the maximum important information with minimum number of experiments. Using Taguchi techniques, the number of parameters can be tested at a time with probably least number of experiments as compared to any of the other experimental optimization techniques. Moreover, the technique provides all the necessary information required for optimizing the problem. The main advantage of Taguchi Techniques is not only the smallest number of experiments required but also the best level of each parameter can be found and each parameter can be shared towards the problem separately. The main steps of Taguchi Method are determining the quality characteristics and design parameters necessary for the product/process, designing and conducting the experiments, analyzing th results to determine the optimum conditions and carrying out a confirmatory test using the optimum conditions.

II. GEOMETRICAL CONFIGURATION AND NANOFLUID PROPERTIES

Fig1. Shows the geometrical configuration under consider- tion. It consists of a tube with length (L) of 1 m with different diameter (D). The single phase approach was used for nanofluid simulation. The nanofluid considered is composed of water and Al_2O_3 particles. It is taken to be Newtonian, incompressible and turbulent. The nanoparticles are assumed to have uniform shape and size with thermal equilibrium state. The fluid enters with uniform velocity with uniform temperature. The tube has appropriate axial length in order to obtain fully developed profiles (velocity and thermal) at outlet section (L/D>10). The condition of tube wall is maintained at constant temperature (350 K) for simulation. Also floe and thermal field are assumed to be axis symmetric. Flow and heat transfer are considered by continuity, momentum and energy equation. [5]

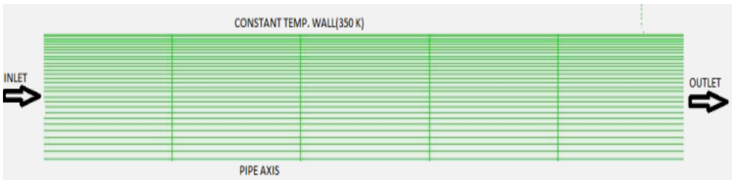

Fig-1: Geometrical configuration of problem

The following equation represents the mathematical formulation of single phase model [18].
Continuity equation:

$$\boldsymbol{div}(\boldsymbol{\rho}\,\vec{\boldsymbol{V}}) = \mathbf{0} \qquad \textbf{(1)}$$

Momentum equation:

$$div(\rho\vec{V}\,\vec{V}\,) = -gradP + \nabla\,(\mu\,\nabla\,\vec{V}) \qquad (2)$$

Energy equation:

$$div(\rho\vec{V}C_p\,T\,) = div(kgrad\,T) \qquad (3)$$

III. PHYSICAL PROPERTIES OF THE NANOFLUID

By assuming that the nanoparticles are well dispersed within the base fluid i.e. the particle concentration can be considered uniform throughout the domain and, knowing the properties of the constituents as well as their respective concentrations, the effective physical properties of the mixtures studied can be evaluated using some classical formulas as well known for two-phase fluids. In the following equations, the subscripts 'p', 'bf' and 'nf' refer respectively, to the particles, the base-fluid and the nanofluid.

A. Density of nanofluid

In the absence of experimental data for nanofluid densities, constant value temperature independent values, based on nanoparticle volume fraction, are used. [10]

$$\rho_{nf} = \varphi\rho_p + (1-\varphi)\,\rho_{bf} \qquad (4)$$

B. Heat capacity

It should be noted that for calculating specific heat of nanofluid some of prior researcher have used the following correlation.[10]

$$C_{nf} = \varphi C_{p_{np}} + (1-\varphi)\,C_{p_{bf}} \qquad (5)$$

C. Thermal Conductivity

The model used here includes various material parameters that can change the effective k of nanofluids. The material parameters that involve the liquid are kinematic viscosity, Prandtl number, liquid thermal conductivity, and Re. One study that is of interest is the impact of the density of the particles. Two extreme cases have been considered Thermal conductivity of the nanoparticle is much larger than the thermal conductivity of the liquid.[11]

$$k_{nf} = k_{bf}(1 + A\,{R_e}^{m}Pr^{0.333}\varphi)\left[\frac{1+2\varphi}{1-\varphi}\right] \quad (6)$$

Where A and m are constants having values 4×10^4 and 2 respectively.

R_e= Brownian-Reynolds number

$$R_e = \frac{1}{\upsilon}\sqrt{\frac{18\,k_b T}{\pi\,\rho_p d_p}} \quad (7)$$

D. Dynamic Viscosity

In this study dynamic viscosity dependence only on concentration (φ), in order to evaluate a least square fitting, based on some experimental data available was performed by Miaga et.al.[6] leading to following equation,

$$\mu_{nf} = \mu_{bf}(123\varphi^2 + 7.3\varphi + 1) \quad (8)$$

IV. TAGUCHI METHOD

Taguchi's methods of experimental design provide a simple, efficient, and systematic approach for the optimization of experimental designs for performance, quality and cost. The main purpose of Taguchi method is reducing the variation in a process through robust design of experiments. 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 varied; it allows for the collection of the necessary data to determine which factors most affect process quality with a minimum amount of experimentation, thus saving time and resources.[12, 13].

A. Selection of Process Variable:

From past literature survey [7] I found that several factors influence the convective heat transfer coefficient. Flow through the heat exchanger is one of the examples of fluid flow through the pipe which is widely used in the industries therefore it is taken for the analysis. The enhancement of convective heat transfer depends upon the many parameters like tube diameter, Reynolds number, nanoparticle concentration, size of nanoparticle, etc. So form the investigation I optimize that parameters which will give effectiveness of the heat exchanger [16].

B. Selection of Process Variable Levels:

From study of literature of past researcher, the varying levels of process parameter (like Reynolds number, tube diameter, its concentration, and size) are selected as three parameters are varying in three levels of Reynolds numbers. The variation levels value for each parameters are given in Table 1.

Table -1: Process Variable Range

Variation level	Re	Pipe Dia.(mm)	Particle concentration (%)	Particle Size(nm)
Lower	20000	6	2	10
Medium	27500	8	4	20
Higher	35000	10	6	30

C. Selection of Orthogonal Array

The selection of orthogonal array for experiment was done by use Minitab-15 statistical software [14]. By putting parameter variation levels as per Table 1 in Minitab-15 statistical software the Mini tab suggest that mix level L9 (1*2, 3*3) factorial orthogonal array is most compatible for our experiment. The experiment table suggested by Minitab- 15 for L9 orthogonal array is shown in Table 2

Table -2: Standard Orthogonal Array Arrangement

Expt. No.	Col 1	Col 2	Col 3	Col 4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The final experiment are designed by proving selected parameters values as per Table 2, suggested by in Minitab- 15 statistical software is shown in Table 3. The experiment suggested by this table is specifying the parameter level value of that particular experiment for find out the response value.

Table -3: Experimental Design for L9 orthogonal array

Expt. No.	Re	Pipe Dia.(mm)	Particle concentration (%)	Particle Size(nm)
1	20000	6	2	10
2	20000	8	3	20
3	20000	10	4	30
4	27500	6	3	30
5	27500	8	4	10
6	27500	10	2	20
7	35000	6	4	20
8	35000	8	2	30

9	35000	10	3	10

D. Analysis of Variance (ANOVA) and Data Analysis

Different factors affect on heat transfer characteristics of nanofluids at different levels. The relative magnitude of factor effect can be decided from table no.3 to better feel for effect of different factor can be obtained by decomposing of variance i.e. analysis of variance(ANOVA).

For experimental data analysis ANOVA larger to better is given by,

Sound to noise ratio(S/N Ratio), $\eta = -10 \log \left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right)$

Where y is output parameter and n is the number of the experiment. In this research, the main objective is to determine main effects of the nanofluid performance parameters to perform ANOVA and to find out optimum condition based on the Taguchi method. Table 4 gives the CFD simulation results for L9 orthogonal array for heat transfer coefficient and S/N ratio (η) [15].

Table -4: Experimental results for L9array and S/N ratio

Expt. No.	Re	Pipe Dia. (mm)	Part conc. (%)	Part. Size (nm)	Heat transfer coeff.	S/N Ratio η
1	20000	6	2	10	17860.43	85.03
2	20000	8	3	20	14295.36	83.10
3	20000	10	4	30	11132.47	80.93
4	27500	6	3	30	24291.26	87.70
5	27500	8	4	10	22287.43	86.96
6	27500	10	2	20	13355.58	82.51
7	35000	6	4	20	35083.64	91.88
8	35000	8	2	30	19649.11	85.86
9	35000	10	3	10	19008.81	85.57

V. RESULT AND DISCUSSION

A. Mesh and data validation

A careful check of independence of numerical solution was done to ensure the accuracy. In order to demonstrate the validity and accuracy of model, heat transfer coefficient of water is calculated from outlet temperature of nanofluid by using Ansys Fluent 13.The calculated heat transfer coefficient of water is compared with the correlation given by Gnielinsky over the traditional Ditus-Bolter equation because errors are usually limited to ±10% [17].

Figure -2 displays the comparison between the values for used grid, our simulations were almost all within the range therefore the numerical procedure is reliable and can predict turbulent forced convection flow in pipe.

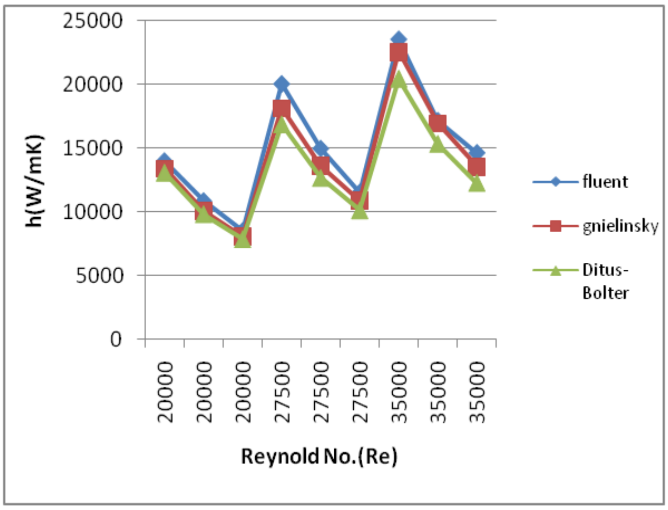

Fig -2: Mesh Validation with correlations

B. Taguchi Analysis and Verification

Level average analysis as described by Taguchi method, is one of the technique to explore the average effect of each factor on the outcome.Figure-3, 4, 5, 6 displays the effect of each factor on heat transfer coefficient. The aim is to find out those factors that have strong effect and whether they exert their effect independently or through interaction with other factor from table number -5, the results are plotted. From figure-3, 4, 5, 6 optimum combinations can be found. In this study, graphs are ascending or descending, the optimum combination contains maximum or minimum level of each factor. An estimated predicted response values (ηopt) [13, 15]

$$(\eta opt) = m + (m_{Re} - m) + (m_D - m) + (m_\varphi - m) + (m_{np} - m)$$

Where, m is overall mean of S/N ratios.

Table -5: Levels of affecting factors and the average results

Factor	Level	Level Quantity	Average Results
Re	1	20000	83.02
Re	2	27500	85.72
Re	3	35000	87.77
D	1	6	88.20
D	2	8	85.31
D	3	10	83.00
Φ	1	2	84.47
Φ	2	4	85.46
Φ	3	6	86.59
dp	1	10	85.85
dp	2	20	85.83
dp	3	30	84.83

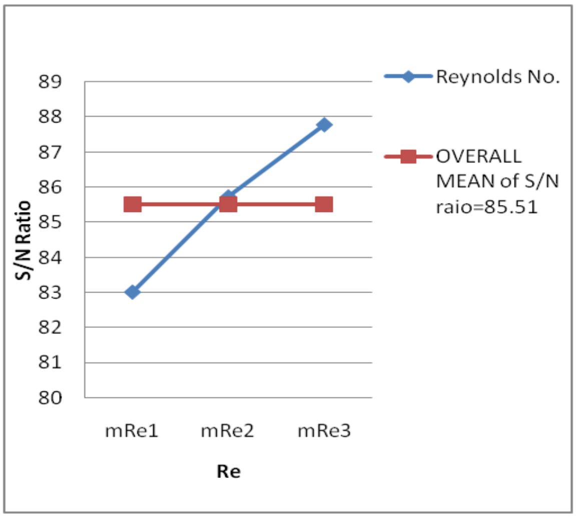

Fig -3: Variations of S/N ratio against Reynolds Number

Further calculations were performed to determine whether the results of other combination could be predicted from Taguchi method and confirmed by the Actual results. Three combinations were randomly selected and combination for optimum here maximum. Optimum heat transfer coefficient also selected based on fig 3, 4, 5and 6 to be calculated by above equation which shows close approximation in each case with small error. This indicates that predications are good and precise of heat transfer coefficient by Taguchi method.[19]

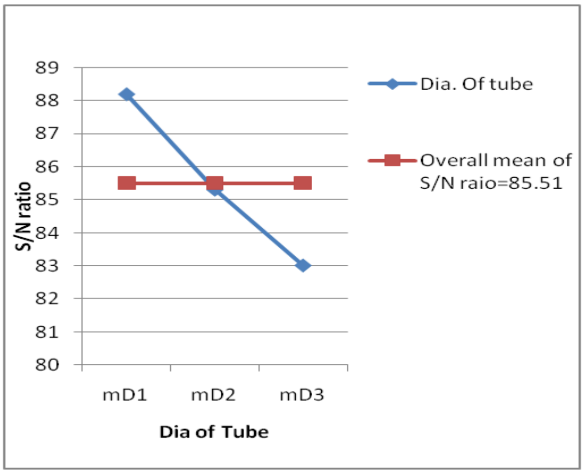

Fig -4: Variations of S/N ratio against Reynolds Number

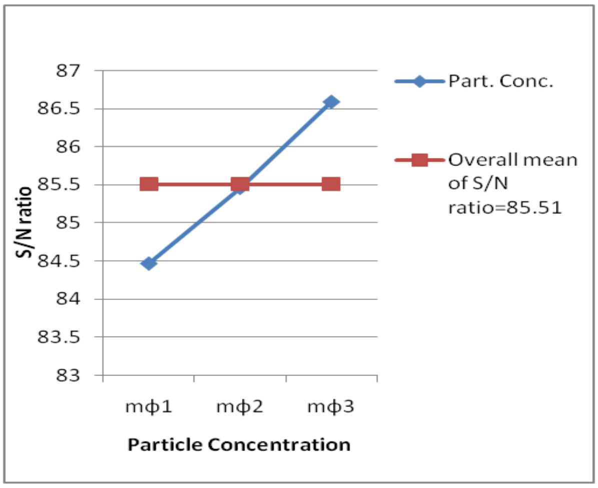

Fig -5: Variations of S/N ratio against particle conc.

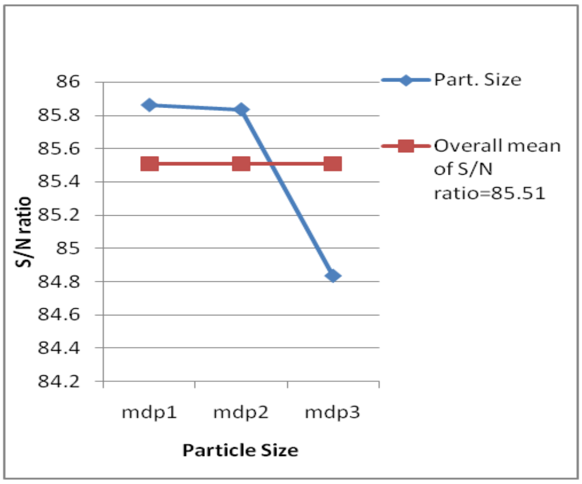

Fig -6: Variations of S/N ratio against Particle Size

Table -6: Taguchi method Prediction and actual Result

Combination	ANSYS Fluent **h**(W/m^{2}K)	Taguchi method **h**(W/m^{2}K)	Error (%)
Optimum Re=35000;D=6mm; φ=6%; dp=20 nm	39266	39355	0.002
Re=27500;D=10mm; φ=4%; dp=30 nm	15170	15183	0.008
Re=35000;D=10mm; φ=3%; dp=10 nm	19008	18836	0.009

CONCLUSIONS

Based on the results obtained in the numerical study, the following conclusions are summarized.

- The combinations of all working parameters -Reynolds number, tube diameter, nanoparticle concentration, and size in flow through the circular pipe have equal importance.

- Heat transfer enhancement in pipe using nanofluid could be designed and predicted successfully with acceptable error by Taguchi method.
- Optimum level gives the better result for nanofluid flow by Taguchi method and also reduces number of experiments that are required for finding its performance.
- Optimum level of nanofluid flow gives the maximum heat transfer coefficient with increment 40% than water result.

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