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Heat Transfer Through Porous Materials (Aluminum Foam) Empirical Optimization of a Heat Exchanger

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Abstract

Latest developments in the manufacturing technology have led to development of advance lightweight materials for thermal applications. Heat transfer(q)optimization through Aluminum Foam(AlSi7Mg)has gained significance in industrial as well as academic research. In this paper Heat transfer optimization through Aluminum Foam heat exchanger, has been presented. The experimental data was used to calculate and then optimize the Nusselt number (Nu).The models selected for optimization were log-log linear, exponential and polynomial model. The Nusselt number for the heat exchangers was calculated at u = 0.3–1.5 m/s cold fluid velocity, whereas hot fluid temperature was varied from 30-50 ºC. The best performance for response variable was exhibited by heat exchanger at effectiveness ε = 30%, at u =0.3 m/s. The co-efficient of determination $R^2$was 99.80 for log-log linear model. The results of optimization can be further validated using artificial neural networks, fuzzy logic or genetic algorithms.

Nomenclature:

Keywords: *Aluminum foam, Nusselt number, optimization.*

Introduction

Saving material and energy are main objectives for optimization. The important issues that should be defined during the design process, taking in to consideration the cost of material, is the optimization of the heat transfer. The optimization process can consider minimum weight for a specified heat flow, for a set of specified conditions (such as the heat dissipation from the fin faces, minimum mass, minimum pressure drop etc). In order to intensify the heat transfer from the heat exchanger surface to fluid, it is possible to increase convection coefficient (by increasing the fluid velocity), increasing temperature difference between hot and cold fluid or increase the surface area across which convection occurs. Aluminium foam heat exchangers are used in applications where the need of increasing the heat transfer between a surface and an adjacent fluid exists. The objective of the experiment was to measure the performance of the Aluminum Foam heat exchangers and its optimization in a cross-flow arrangement. The concept was to supply the cold air at ambient temperature to flow through a square duct in which the Aluminum Foam heat exchanger is placed, occupying the entire cross-section of the duct. The experiment of the Aluminum Foam heat exchangers included measuring the coolant temperature and the pressure drop(Δp) across the heat exchangers for various coolant flow rates. At the end, empirical relationship between the dependent and independent variables was developed using the experimental data collected. The data collected was further used for optimization of response variable.

1. Experimentation

The experiment was conducted as per the classical plan of experimentation and setup was fabricated to facilitate variation of π terms, the experimental setup is shown in figure 1.The dimensions of the heat exchangers, number of pipes, and pipe diameters were kept the same during the experimentation process.

Table 1. Thermo-physical parameters for aluminum foams (ERG Aerospace) [3]

Sr. No.	Particular	Specification
1	Pore density (PPI)	20
2	Porosity, ε	0.90
3	Heat conductivity, k(W/m-K)	165
4	Density, (kg/m^3)	230
5	Specific surface, σ (m^2/m^3)	1500
6	Height, H (mm)	101
7	Length, L (mm)	101
8	Width, W (mm)	10

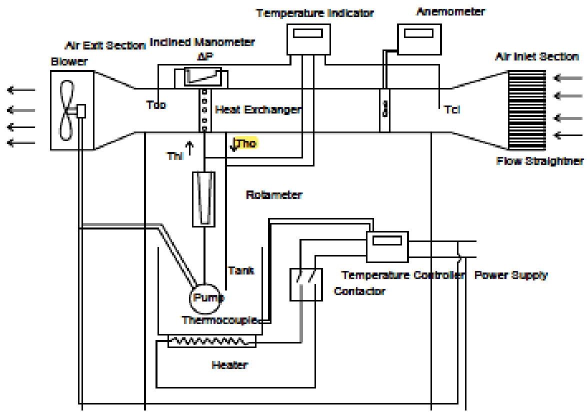

Fig. 1. Heat exchanger and setup used in experiment. [2]

2. Constant Parameters in the Experimentation [2,3]

The hot fluid (water) Mass flow rate ($\dot{m}_h$), Porosity of aluminum foam as specified by manufacturer (ε_f=0.90), The number of tubes parallel to the flow direction, N_T = 5,The number of tubes perpendicular in the flow direction, N_L = 1, The distance between the tubes perpendicular to the flow direction, S_T = 0.01 m, The number of tubes, N_t = 05, Aluminum Tube inside diameter, d_i = 0.0085 m, Aluminum Tube outside diameter, d_o = 0.009 m, Hydraulic diameter, d_h = 0.101 m, Perimeter of the duct, P =0.404m, The duct cross-section area, A_c = 0.101m x0.101 m =0.010 m^{2,}The length of upstream side of the square duct = 0.914 m, Number of passes =1,Total length of the duct, =2.10m.[2,3].

3.Performance Analysis of Heat Exchanger [3,14]

The method used for evaluating the heat transfer performance of heat exchanger is discussed here. The details of the experimentation are presented in[2,3].

3.1The ε-NTU Method

In the ε-NTU method, the heat transfer rate from the hot fluid to the cold fluid in the exchanger is expressed as:

$q = \varepsilon C_{min} (T_{hi}-T_{ci}) = \varepsilon C_{min} \Delta T_{max}$................................ (1)

Where ε is the heat exchanger effectiveness, sometimes referred as the thermal efficiency, C_{min} is the minimum of Ch and Cc, ΔT_{max}= (T_{hi} - T_{ci}) is the fluid inlet temperature difference (ITD).

3.2Heat Exchanger Effectiveness (ε)

Effectiveness ε is a measure of thermal performance of a heat exchanger.

$\varepsilon = \frac{q}{q_{max}}$.. (2)

The overall energy balance for the two fluid streams is

$q = C_h (T_{hi}-T_{ho}) = C_c (T_{co}-T_{ci})$ .... (3)

Based on this equation, for $C_h< C_c$, $(T_{hi}-T_{ho}) > (T_{co}- T_{ci})$

The temperature drop on the hot fluid side will thus be higher, and over the infinite flow length the hot fluid temperature will approach the inlet temperature of the cold fluid, resulting in $T_{ho} = T_{ci}$. Thus, for an infinite area counter flow exchanger with Ch < Cc, we get:

$q_{max} = C_h(T_{hi} - T_{co}) = C_h \Delta T_{max}$ ………….……………… (4)

Using the value of actual heat transfer rate q from the energy conservation equation (3) and q_{max} from Eq. (4), the exchanger effectiveness of Eq. (5) valid for all flow arrangements of the two fluids is given by

$\varepsilon = \frac{C_c(T_{co}+T_{ci})}{C_{min}(T_{hi}+T_{ci})}$ ………………....................................... (5)

3.3 Calculation of Heat Transfer Parameters

The heat supplied by the hot fluid,

$q = m_h c_{ph}(T_{hi} - T_{ho})$ ……………………………..………. (6)

The heat received by the cold fluid,

$q = m_c c_{pc}(T_{co} - T_{ci})$ ……………………………………. (7)

If $C_h > C_c$, then $C_{min} = C_c$ .... (8)

The following relation can be used for the effectiveness of the heat exchanger.

$\varepsilon = \frac{q}{q_{max}} = \frac{C_c(T_{co}-T_{ci})}{C_{min}(T_{hi}-T_{ci})}$ ………………………………..….. (9)

The heat transfer coefficient, can be written as,

$h = \frac{\rho_c N_t S_t u_c Cp_c (Tco - Tci)}{(\pi DL) N_t \left(\frac{Thi + Tho}{2} - \frac{Tci + Tco}{2}\right)}$ .... (10)

Nusselt number, $Nu = \frac{hd_h}{k}$ .... (11)

Duct hydraulic diameter, $d_h = \frac{4A_c}{P}$ ………………… (12)

Reynolds number, $Re_{max} = \frac{\rho u d_h}{\mu}$ …………………… (13)

4. Experimental Setup [2]

The experimental setup was designed to vary various π terms as per the plan of experimentation. The temperature of hot fluid was set at 35°C, and the corresponding values of h, k were calculated. The D_h is constant during the entire experimentation. For setting π_2=177.87, the cold fluid velocity was set at 0.3m/s and the cold fluid properties were calculated. for setting π_3=0.713 the cold fluid parameters corresponding to its temperature were calculated, and for setting π_4=4696.34 the temperature difference of cold fluid, velocity of cold fluid and dynamic viscosity were substituted in to the pi term. All the observations were recorded in to a Microsoft excel sheet.The experiment was again performed for the next values of π terms and the observations were recorded.

5. Heat Transfer Model Formulation[14,15,16]

For model formulation graphical rectification of data is carried out. The first step in analyzing the data the value of a dependent variable is plotted on a simple linear graph against the variation of an independent π term.As a next step, data was plotted by taking log of both dependent variable and independent variable. To rectify the function

$y=kx^a$ ……………………………………………… (14)

Where transformation is log y= log k +a log x.

It was observed that the plot on log-log coordinate is nearly a straight line therefore linear model is fitted.

$Y=K (\pi_1)^a (\pi_2)^b (\pi_3)^c (\pi_4)^d$ .... (15)

The second type of graph is semi logarithmic type with log coordinate on y axis and liner coordinate along x axis. This gives a straight line if data are following a function.

$Y=Ke^{ax}$ .... (16)

The transformation of the function is

log y=log k+ax .... (17)

With the polynomial model type, the response variable is transformed into a polynomial series of the specified degree.

$Y = K+a_1\pi_1^2 + b_1\pi_1 + a_2\pi_2^2 + b_2\pi_2 + a_3\pi_3^2 + b_3\pi_3$ ……..… (18)

5.1 Formulation of Log-Log Linear Model

The procedure for formulating log-log linear model for Nusselt number is given below.

Log-log linear model will be of the form given below.

$Nu = K (\pi_2)^a (\pi_3)^b (\pi_4)^c$ .... (19)

Taking log of both sides of above equation we get

$\log_e Nu = \log_e K + a \log_e \pi 2 + b \log_e \pi 3 + c \log_e \pi 4$ .... (20)

The values of a, b, and c are the slopes of log-log plot between Nu and π_2, π_3, π_4, respectively.

Using regression analysis, the values of exponents, a, b, and c were calculated. The regression analysis was performed using statistical software Minitab 17. The values of π terms obtained from experimentation were log transformed and the values of exponents were found out as follows.

5.2 Regression Analysis: log Nu versus log π_2, log π_3, log π_4

Regression Equation

Nu = -0.6517 + 0.8680 π2 + 0.9990 π3 + 0.00001 π4... (21)

Equation 21 is the log-log model for dependent π term with the value of constant is -0.6517 and R^2 =99.80.

5.3 Formulation of Exponential Model

Theprocedure for formation of exponential model for Nusselt number is discussed below.

Nu =$ke^{\alpha 2\pi 2}$ $e^{\alpha 3\pi 3}$ $e^{\alpha 4\pi 4}$……………………………….... (22)

Taking log of both sides of above equation we get,

Nu=Log k+$\alpha_2\pi_2$ + $\alpha_3\pi_3$ + $\alpha_4\pi_4$...................................... (23)

The values of α2, α3, and α4 are the slopes of semi logarithmic graphs between Nusselt numbers and π_2, π_3, π_4.

5.4 Regression Analysis: Nu versus π 2 exp, π3 exp, π4 exp

Regression Equation

Nu = -3.760 + 1.752 π2 + 4.03 π3 + 0.3948 π4 …... (24)

Equation 24 is the exponential model for dependent π term with the value of constant is -3.760 and R^2 =90.21.

5.5 Formulation of Polynomial Model

The Polynomial model is of the form Nu = K+$a_2\pi_2^2$+ $b_2\pi_2$+ $a_3\pi_3^2$+b_3 π_3+ $a_4\pi_4^2$+b_4 π_4, by performing regression analysis the values of exponents a_2, b_2, a_3 $b_3$and a_4 b_4 are calculated.

5.6 Regression Analysis: Nu versus π2, π2^2, π3, π 3^2, π4, π 4^2

Regression Equation

Nu = -31.65 - 0.000003 π 2^2 + 0.062237 π2 + 71.89 π3^2 - 0.00 π 4^2 + 0.000072 π4…………………………... (25)

Equation 25 is the polynomial model for dependent π term with the value of constant is -31.65 and R^2 =99.02.

6. Error Analysis of Model

To establish the accuracy of the model, the error i.e. the difference between actual value of dependent variable and predicted value of dependent variable by substituting the values of independent π terms in experimental setting is evaluated. As the experiment is conducted at 80 different settings the error for only half number of settings is evaluated. On the basis of error, the coefficient of determination (R^2) is evaluated. Coefficient of determination provides a measure of how well future outcomes likely to be predicted by this model. The value of R^2 is calculated by using formula as given below:

$$R^2 = 1 - \frac{\Sigma(yi-ti)^2}{\Sigma(yi-\bar{y})^2} \text{...} (26)$$

Where yi=observed value of dependent variable for i_{th} experimental setup.

ti=predicted value of dependent variable for i_{th} experimental setup

$\bar{y}$=mean of y_i

R^2 = Coefficient of determination.

6.1 Error Analysis of log- log Model

As per the regression analysis in section 5.14 the coefficient of determination is:

Table 2. Value of R^2 for Log-Log Linear model

S	R-sq	R-sq(adj)	R-sq(pred)
0.00	99.80%	99.80%	100%

The value for R^2=99.80% shows excellent fit for the observed data.

6.2 Error Analysis of Exponential Model

As per the regression analysis in section 5 the coefficient of determination is:

Table 3. Value of R^2 for exponential model

S	R-sq	R-sq(adj)	R-sq(pred)
0.129016	90.21%	89.64%	88.82%

The value for R^2=90.21% shows good fit for the observed data.

6.3 Error Analysis of Polynomial Model

As per the regression analysis in section 5.16 the coefficient of determination is:

Table 4. Value of R^2 for exponential model

S	R-sq	R-sq(adj)	R-sq(pred)
0.032	99.02%	98.89%	98.10%

The value for R^2=99.02 shows excellent fit for the observed data.

7. Optimization of Model

For Optimization of the model R^2 was calculated with all readings and the error was calculated using Minitab-17 statistical package, the values with high error were omitted and again R^2 was calculated until all reading with high value of error were omitted. The procedure was repeated for all the models for maximum value of R^2.

8. Validations of Models

8.1 Log- log Linear Model

The validation of log-log linear model is carried out as it is having highest value of R^2. For validation of model the experimental data for π_2, π_3, π_4 is fed in to the model and predicted values of π_1 are calculate for some of the experimental data.
The log - log linear model for Nusselt number is as under.
Nu = -0.6517 + 0.8680 π2 + 0.9990 π3 + 0.00001 π4 .. (27)
By substituting the values of various independent variables in eq. 27 the predicted values Nusselt number is evaluated.

8.2 Exponential Model

The validation of modelis carried out from the experimental data for π_2, π_3, π_4 is fed in to the model and predicted values of π_1 are calculate for some of the experimental data.
Nu = -3.760 + 1.752 π2 + 4.03 π3 + 0.3948 π4…..…. (28)
The value of constant K is -3.760, and R^2 is 90.21.

8.3 Polynomial Model

The validation of polynomial model is carried out for validating, the experimental data for π_2, π_3, π_4 is fed in to the model and predicted values of π_1 are calculate for some of the experimental data.
Nu = -31.65 - 0.000003 $\pi2^2$ + 0.062237 π2 + 71.89 $\pi3^2$ - 0.000000 $\pi4^2$ + 0.000072 π4……………………… (29)

8.4 Comparison of Models

The values of coo-efficient of determination are calculated and tabulated.

Table 5. Comparison of Models for Nu

Sr. No.	Model	Governing Equation	R^2
1	Log-Log Linear	Nu = -0.6517 + 0.8680 π2 + 0.9990 π3 + 0.00001 π4	99.80
2	Exponential	Nu = -3.760 + 1.752 π2 + 4.03 π3 + 0.3948 π4	90.21
3	Polynomial	Nu = -31.65 - 0.000003 $(\pi2)^2$ - 0.0622 $(\pi2)^2$ + 71.89 $(\pi3)^2$ – 0.00$(\pi4)^2$ + 0.000072 (π4)	99.02

The Table 6 indicates that the coo-efficient of determination R^2 for Nusselt number is maximum for log-log linear model.

9. Interpretation of Model

An attempt was made to fit the following models to observed data generated by the experimentation using classical plan of experimentation.

The co-efficient of determination R^2 for Nusselt number is maximum for log-log linear model. Hence the log-log linear model will be used for predicting value of Nusselt number. The log-log linear model for Nusselt number is given below.
Nu = -0.617 + 0.860 (π2) + 0.999 (π3) + 0.00001 (π4) .... (30)

9.1 Variation of Nu with π 2

It is observed from the model that as the value of π2 is increased the value of Nusselt number goes on increasing. At π2=1900, the value of Nusselt number is maximum. Therefore, the optimal value of π2 for Nusselt number is 1900. As the Nusselt number actually defines the heat transfer performance of heat exchanger the optimal value of π2 is and the velocity of cold fluid is 3 m/s.

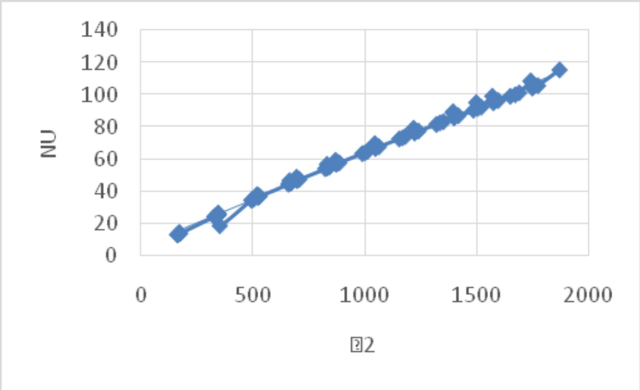

Fig.2 Variation of Nu with π2

9.2 Variation of Nu with π 3

As the terms containing value of π3 is positive the Nusselt number goes on increasing to the maximum value.So, the optimal value of π3 for Nusselt number is 0.727. π3 represents fluid Prandtl number which dependent on the cold fluid temperature. The Prandtl number fairly remains constant for large temperature if the fluid is air.

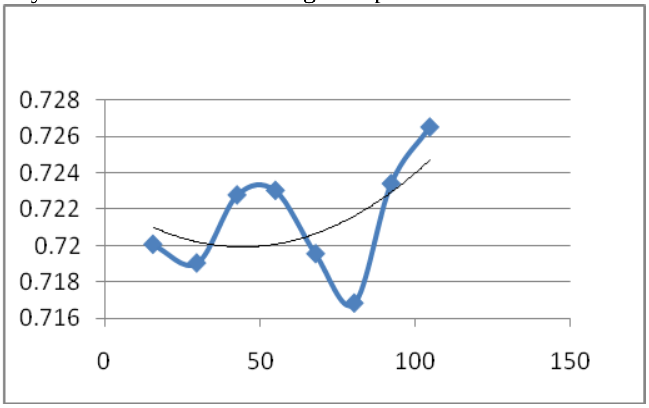

Fig.3 Variation of Nu with π3

9.3 Variation of Nu with π 4

It is observed from the model that as the value of π4 is decreased the value of Nusselt number goes on increasing. As π4 approaches zero, the value of Nusselt number is maximum. π4 represent viscous dissipation in heat exchanger. The optimal value for π4 is close to zero. The viscous forces should be minimum to enhance the heat transfer parameter Nu.

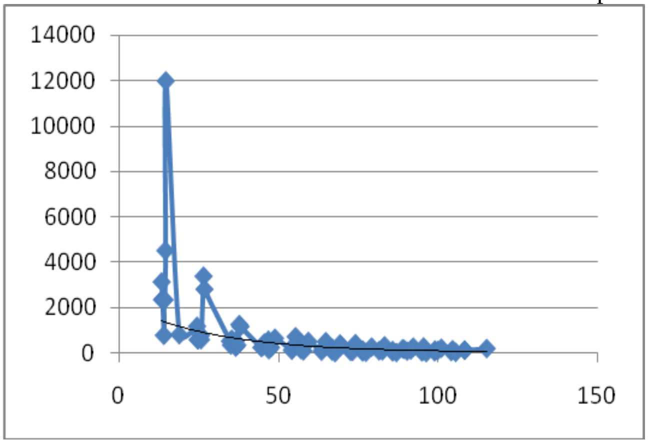

Fig.4 Variation of Nu with π4

10. Sensitivity Analysis

The log-log linear model for Nusselt number indicates that the performance measures are the logarithmic functions of independent π terms π2, π3 π4 defining the various independent variables i.e. Reynolds number, Prandtl number and the Brickman number. As these π terms are varied the Nusselt number also varies. The sensitivity of a π term indicates the percentage change in Nusselt number as the independent π term is changed by 1 %.

10.1 Sensitivity Analysis for π2

The values of the sensitivity analysis at minimum, medium, maximum and average value of π2 i.e.177.87, 711, 1244 and 710.957. The fig. 5 indicates the sensitivity the model at the optimum value of π2 i.e. 710.957. it shows the relationship between π2 and sensitivity of Nusselt number. It is observed that as the π2 increase the sensitivity goes on increasing and the sensitivity was maximum at maximum value of π2 and the optimal value of π2 decreases.

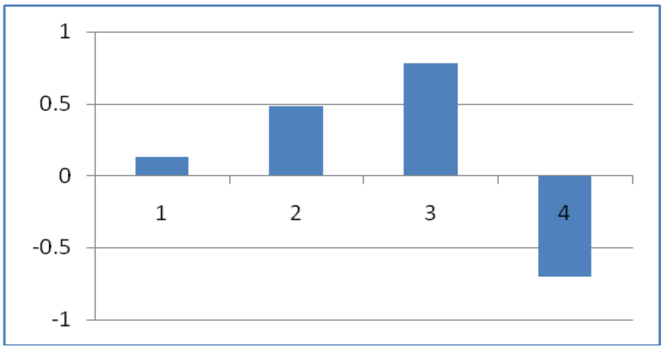

Fig. 5 Sensitivity graphs of π2

10.2 Sensitivity Analysis for π3

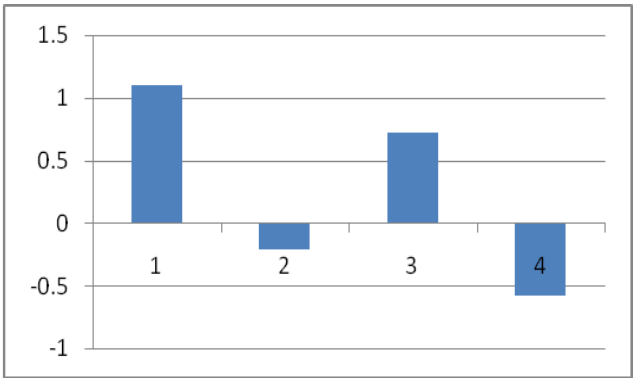

Fig.6 Sensitivity graphs of π3

Fig.6 shows the values of the sensitivity analysis at minimum, medium, maximum and optimal value of π3 i.e. 0.711, 0.713, 0.745 and 0.723. The fig. also indicates the sensitivity of the model at the optimum value of π3 i.e. 0.723. It shows the relationship between π3 and sensitivity of Nusselt number. It is observed that as the π3 increase the sensitivity goes on decreasing and the sensitivity was maximum at minimum value of π3.

10.3 Sensitivity Analysis for π4

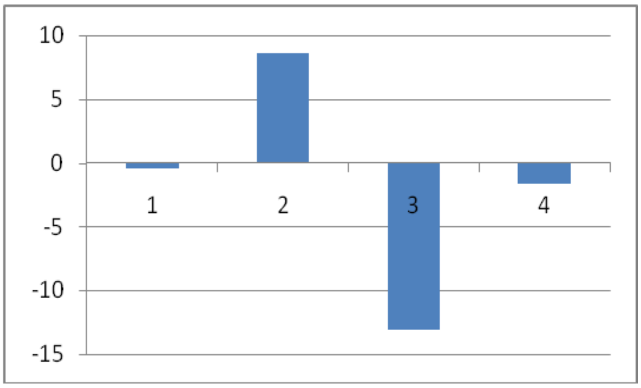

Fig.7 Sensitivity graphs of π4

Fig. 7 shows the values of the sensitivity analysis at minimum, medium, maximum and optimal value of π4 i.e. 810.12, 93.91, 31.29 and 311.77.It indicates the sensitivity of the model at the optimum value of π4 i.e. 311.77. It shows the relationship between π4 and sensitivity of Nusselt number. It is observed that as the π4 increase the sensitivity increases then again decreases. The sensitivity was maximum at minimum value of π4.

11.Results

At π2=1900, the value of Nusselt number is maximum,Therefore, the optimal value of π2 for Nusselt number is 1900 at cold fluid velocity of 3 m/s. The optimal value of π3 for Nusselt number is 0.727,π3 represents fluid Prandtl number which fairly remains constant for large temperatures if the fluid is air.It is observed that as the value of π4 is decreased the value of Nusselt number goes on increasing. As π4 approaches zero, the value of Nusselt number is maximum. π4 represent viscous dissipation in heat exchanger. The optimal value for π4 is close to zero. The viscous forces should be minimum to enhance the heat transfer parameter Nu.

12.Conclusion

As per the planning of experimentation the experimental setup was fabricated, trial run was conducted. Modifications in the experimental setup were carried out. Experimentation was conducted within the test envelope and results were calculated. The quantitative analysis of the data was carried out. The model was prepared from the experimental data. Three different models were tested. Optimum model was log-log linear model. Validation of model was carried out. The sensitivity analysis was done to check the robustness of the model.

Future Scope

Theoptimization results can be further validated using artificial neural networks, fuzzy logic and genetic algorithms.

References

1. V. V. Calmidi, R. L. Mahajan "Forced Convection in High Porosity Metal Foams" Journal of Heat Transfer, AUGUST 2000, Vol. 122 / 557.
2. BrijendraSingh Bhaskar[1],S.K.Choudhary[2], "Planning of experimentation for performance evaluation of Porous Media Heat Exchanger". International Journal of Mechanical Engineering Research. ISSN 2249-0019 Volume 6, Number 1 (2016), pp. 31-39.
3. Brijendra Singh Bhaskar[1], S.K. Choudhary[2] "Experimental Investigation of Heat Transfer through Porous Material Heat Exchanger" International Journal of Engineering Research and Technology. ISSN 0974-3154 Volume 10, Number 1 (2017), pp. 51-60
4. Ahmet Ali Sertkaya, BurakAkbaba, "Experimental and Numerical Analysis of Two Dimensional Heat Transfer On Open Cell Aluminum Foams", International Journal of Arts & Sciences, 6(1):205–216 (2013).
5. Hilbert Schenck Junior, Theory of Engineering Experimentation, McGraw Hill, New York (1961).
6. Ken I. Salas and Anthony M. Waasy, "Convective Heat Transfer in Open-Cell Metal Foams", 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 1 - 4 May 2006, Newport, Rhode Island.
7. Tamayol, K. Hooman1, "Thermal Assessment of Forced Convection through Metal Foam Heat Exchangers", Journal of Heat Transfer, Transactions of the ASME, November 2011, Vol. 133 / 111801-1.
8. Simone Mancin, Claudio Zilio, Alberto Cavallini, Luisa Rossetto, "Heat transfer during air flow in aluminum foams", International Journal of Heat and Mass Transfer 53 (2010) 4976–4984.
9. Gamal A. Amhalhel, Piotr Furmański, "Problems of Modeling Flow And Heat Transfer In Porous Media", BiuletynInstytutuTechnikiCieplnejPolitechnikiWarszawskiej, Nr 85 1997.
10. Abed Alrzaq, S. Alshqirate, Mohammad Tarawneh, Mahmoud Hammad, "Dimensional Analysis and Empirical Correlations for Heat Transfer and Pressure Drop in Condensation and Evaporation Processes of Flow Inside Micropipes: Case Study with Carbon Dioxide (CO2)" J. of the Braz. Soc. of Mech. Sci. & Eng. ABCM January-March 2012, Vol. XXXIV, No. 1 / 89.
11. Kenan Yakut, Nihal Alemdaroglu, Bayram Sahin, CaferCelik, "Optimum design-parameters of a heat exchanger having hexagonal fins", Applied Energy 83 (2006) 82–98.
12. J.H. Lin, C.Y. Huang, C.C. Su, "Dimensional analysis for the heat transfer characteristics in the corrugated channels of plate heat exchangers", International Communications in Heat and Mass Transfer 34 (2007) 304–312.
13. M.E.Nakhchi,"Experimental optimization of geometrical parameters on heat transfer andPressure drop inside sinusoidal wavy channels", Thermal Science and Engineering Progress, 9 (2019) 121–131.
14. D. S. Deshmukh, M. S. Deshmukh," Optimization Technique Focused on Back-Pressure Production Occurrences of Fixed 4-Stroke Diesel Generator using ANN & DA Modeling", Turkish Online Journal of Qualitative Inquiry (TOJQI), vol.12, issue-10 (2021), 194-212.
15. Dr. M. S. Deshmukh, New Mathematical model for the Diesel Exhaust Particulate Filter Efficiency, 17762/2018-CO/L (2019), COPYRIGHT
16. Dr. M. S. Deshmukh, Dr. D. S. Deshmukh, Performance and emission parametric study using novel diesel particulate filter for VCR CI Engine, International journal of Advanced and Innovative Research ISSN No-2394-7780, UGC Journal No :63571, (2019), vol-06, issue-02,19-27.