Semnan University

Journal of Heat and Mass Transfer Research

Journal homepage: http://jhmtr.journals.semnan.ac.ir

Investigation of shell and tube heat exchangers by using a design of experiment

S. Balamurugan*, D.P. Samsoloman

Department of Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore – 641 014, Tamilnadu, INDIA

PAPER INFO

History:
Received 5 March 2014
Received in revised form 13 April 2014
Accepted 9 June 2014

Keywords:
Shell and Tube Heat Exchanger
DOE
Experiment

A B S T R A C T

Heat exchangers are one of the most important devices of mechanical systems in modern society. Most industrial processes involve the transfer of heat and more often they require the heat transfer process to be controlled. A heat exchanger is the heat exchanged between two media, one being cold and the other being hot. There are different types of heat exchanger, but the type which is widely used in industrial application is ~~the~~ shell and tube. In this study, experiments conducted based on fully replicable five-factor, five-level central composite design. Regression modelsare developed to analyse the effects of shell and tube heat exchange process parameter such as inlet temperature of hot fluid and flow rates of cold and hot fluid. The output parameters of a heat exchanger are used for analysing the direct and interactive effects of heat exchange process parameters.

1. Introduction

The most commonly used type of heat exchangers is the shell-and tube heat exchanger that finds widespread use in refrigeration, power generation, heating, air conditioning, chemical processes, manufacturing, and medical applications [1]. Performance of a heat exchanger is assessed by the overall heat transfer coefficient method which requires detailed calculations and knowledge of the geometry of the exchangers [2]. Modelling is a representation of physical or chemical process by a set of mathematical relationships that adequately describe the significant process behaviour. Improving or understanding process operations is a major objective for developing a process model. These models are often used for process design, safety system analysis, and process control [3]. In experimental studies and engineering applications of the thermal science, researchers and engineers expect to reduce experimental data into one or simpler and more compact dimensionless heat transfer correlations [4]. The disadvantages of the correlation methods are that heat transfer coefficients strongly depend on their definitions and temperature differences, and inevitably need iterative method to obtain correlations when fluid properties are dependent on the fluid temperature [5, 6]. The design experiments are conducted using prior knowledge to modify several variables and the study is conducted under the same condition and expected to give the best result. A scientific approach to planning the experiment is analyzing the data by statistical methods and objective conclusions [7]. Using the results of the experiments to correlate process parameters whit output response parameters, mathematical models can be developed [8]. These models can be used to automate the process which can be helpful for consistently producing high quality with few demands on skills. In this paper, details about the development of mathematical models for predicting the direct and interactive effects of process parameter

Corresponding author: S. Balamurugan, Department of Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore – 641 014, Tamilnadu, INDIA. *E-mail: balu74_cit@yahoo.co.in*

variables on output response from the experimental data have been obtained.

2. Design of Experiments

It is necessary to consider the resources that can be devoted to the experiment and are useful to outline the form of the analysis to ensure that the experimental data can be analyzed in a meaningful way. Paying attention to the way in which results are reported is helpful in identifying whether the objectives were clearly formulated. The design of experiments deals with the procedure of selecting number of trials and conditions for running those. DOE involves making a set of representative experiments with regard to a set of input variables. A common approach in DOE is to first define an interesting standard reference experiment and then new representative experiments are performed on it. The central composite design (CCD) quadratic model was employed. It is commonly called a central composite design contains an imbedded factorial design with central points that is augmented with a group of star points that allow the estimation of curvature. The star points represent new extreme values (low and high) for each factor in the design [9]. These new experiments are laid out in a symmetrical fashion around the standard reference experiment. Hence, the standard reference experiment is usually called the central point

2.1 Identification of Process Control Variables

The independently controllable process parameters were identified to enable the accomplishment of the experimental work and the development of mathematical models: They are inlet temperature of hot fluid and flow rate of cold and hot fluids which are identified as control variables. Trial runs were carried out by varying one of the process parameters whilst keeping the rest of them at constant values. The upper limits of the factors were coded as + 1.682 and the lower limits as -1.682. The coded values for intermediate ranges are then calculated from the following relationship, $X_i = 1.682\ [2X - (X_{max} + X_{min})] / [X_{max} – X_{min}]$, where, X_i is the required coded value of a variable X; X is any value of the variable from X_{max} to X_{min}; X_{min} is the lower limit of the variable, X_{max} is the upper limit of the variable. The decided levels of the selected process parameters with their units and notations are given in Table 1.

2.2 Developing the Design Matrix and Conducting the Experiments

In factorial design, the experiments are conducted for all possible combinations of the parameter levels and these combinations are written in the form of a table, where the rows corresponding to different trial and the columns corresponded to the levels of the parameters, form a design matrix. The selected design matrix is shown in Table 2. There is are five-level central composite rotatable designs consisting of 20 sets of coded conditions are composed of a full factorial $2^3 = 8$ plus 6 centre points and 6 star points. In the matrix, twenty simulation runs provide ten estimates for the effect of three parameters.

3. Experiment Setup

The thermal analysis of a shell and tube heat exchanger involves the determination of the overall heat-transfer coefficient from the individual film coefficients. The experimental setup is shown in Fig.1

3.1 Mathematical Model

The response function representing any of the dimensions like the inlet temperature of the hot fluid, mass flow rate of cold and hot fluids can be expressed as

$$\mathbf{Y} = f(T_{hi},\ \dot{m}_{c,}, \dot{m}_h) \quad (1)$$

where, Y is the response.

The second order polynomial (regression) used to represent the response surface for k factors is given by

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i,j=1, j\neq i}^{k} b_{ij} x_i x_j \quad (2)$$

The selected polynomial for three factors could be

SPECIFICATION:	
Inner Diameter of the shell	150 mm
Length of shell	615 mm
Number of tubes	32
Tube Inner Diameter	12.5 mm
Tube Outer Diameter	15.5 mm
Pitch	20mm, square
Baffle spacing	100 mm
Number of baffles	4
Area of collection tank	0.04 m^2
Gap between tubes	4.5 mm

Fig.1 Experimental setup for Shell and Tube Heat Exchanger

Table 1 Process variables parameters

Parameters	Units	Notation	Factors Levels				
			-1.682	-1	0	1	1.682
Inlet hot fluid temperature	^0C	(T_{hi})	45	50	55	60	65
Mass flow rate of cold fluid	lpm	(m_c)	3	6	9	12	15
Mass flow rate of hot fluid	lpm	(m_h)	25	30	35	40	45

Table 2 Design of Matrix for Shell And Tube Heat Exchanger

S.No	T_{hi}	m_c	m_h	U (W/m^2K)	Q, Watt	ε	Δp (Pa)
1	-1	-1	-1	208.73	3694.73	0.37	13.33
2	1	-1	-1	218.03	5407.12	0.38	13.33
3	-1	1	-1	212.67	4171.98	0.21	53.35
4	1	1	-1	226.42	6229.64	0.22	53.35
5	-1	-1	1	213.73	3792.42	0.38	13.33
6	1	-1	1	230.74	5689.23	0.40	13.33
7	-1	1	1	219.02	4321.08	0.22	53.35
8	1	1	1	238.49	6578.69	0.23	53.35
9	-1.682	0	0	198.14	2860.77	0.25	30.01
10	1.682	0	0	246.13	7206.27	0.30	30.01
11	0	-1.682	0	219.30	3642.32	0.62	30.33
12	0	1.682	0	229.05	5338.10	0.18	83.36
13	0	0	-1.682	213.84	4679.88	0.27	30.01
14	0	0	1.682	239.34	5235.20	0.29	30.01
15	0	0	0	227.68	4988.87	0.28	30.01
16	0	0	0	227.71	4988.87	0.28	30.01
17	0	0	0	227.69	4988.87	0.28	30.01
18	0	0	0	227.69	4988.87	0.28	30.01
19	0	0	0	227.69	4988.87	0.28	30.01
20	0	0	0	227.70	4988.87	0.28	30.01

expressed as

$$Y = b_0 + b_1 T_{hi} + b_2 m_c + b_3 m_h + b_{11} (T_{hi})^2 + b_{22} (m_c)^2 + b_{33} (m_h)^2 + b_{12} T_{hi} m_c + b_{13} T_{hi} m_h + b_{23} m_c m_h$$

where, b_0 is the free term of the regression equation, the coefficients b_1, b_2, ...b_k are linear terms, the coefficient b_{11}, b_{22}, ...b_{kk} are quadratic terms, and coefficients b_{12}, b_{13}......$b_{k-1,k+}$ are the interaction terms.

The values of the coefficient of the above polynomial were calculated by regression analysis with the help of the QA Six Sigma DOE IV PC software package. From the calculated coefficient of the polynomial, insignificant coefficients were eliminated with the help of back elimination technique which was employed to determine significant coefficients. The final mathematical model was constructed using the significant coefficients.

The adequacy of the models was tested using the analysis of variance technique (ANOVA). According to this technique, if the calculated value of the F ratio of the model exceed the standard tabulated value of the F ratio for a desired level of confidence (say 95%), then the model can be considered adequate within the confidence limit. The results of ANOVA are presented in Table 3.

The values of adjusted R^2 and standard error of estimates are given in Table 4.

It was found that the reduced models were better than the full models, because the adjusted R^2 values and standard error of estimates of the reduced models were higher and lower respectively than that of full models.

The final mathematical model was constructed to determine a significant coefficient. The final regression models determined by the regression analysis are as follows:

$$U = 227.777 + 10.269T_i + 3.06\dot{m}_c + 5.787\dot{m}_h -2.616T_i^2 - 1.896\dot{m}_c^2 1.041\dot{m}_h^2 + 0.864\, T_i\, \dot{m}c + 0.088\, \dot{m}_c\dot{m}_h + 1.679\, \dot{m}_h T_i \quad (3)$$

$$Q = 4893.453 + 1115.342\, T_i + 407.826\, \dot{m}_c +132.667\, \dot{m}_h + 51.283\, T_i^2 - 140.758\dot{m}_c^2 + 24.426\dot{m}_h^2 + 88.259\, T_i\dot{m}_c + 14.794\, \dot{m}_h\dot{m}_c + 48.046\, \dot{m}_h T_i \quad (4)$$

$$\varepsilon = 0.285 + 0.011T_i - 0.102\dot{m}_c + 0.008\dot{m}_h -0.007T_i^2 + 0.037\dot{m}_c^2 - 0.006\dot{m}_h^2 - 0.001T_i\dot{m}_c - 0.001\dot{m}_c\dot{m}_h + 0.002\dot{m}_h T_i \quad (5)$$

$$\Delta p = 30.056 + 21.575\dot{m}_c - 0.29T_i^2 + 4.424\dot{m}_c^2 - 0.291\dot{m}_h^2 \quad (6)$$

Conformity Test

Also, accuracy of the regression models was determined by conducting conformity test runs using the same system. In this procedure, the process variables were assigned intermediate values in order to carry out the conformity test runs and the responses were measured and recorded in Table 5. The results show that the regression models are accurate. The validity of the developed models was once analyzed by drawing the scatter diagram, showing the predicted and observed values of the response dimensions. This diagram drawn for the models is shown in Fig.2

4. Results and Discussions

The experimental results are used to construct a mathematical model using Systat12 DOE software.

Table 3 Analysis of Variance for Testing the Adequacy of Models

parameters	Sum of Squares: Regression	Sum of Squares: Residual	Degree of freedom: Regression	Degree of freedom: Residual	Standard F- ratio	F-ratio	Remarks
T_{hi}	3.651	1.194	11	20	2.31	5.554	Adequate
m_c	1.373	0.346	11	20	2.31	7.161	Adequate
m_h	43.595	9.546	6	25	2.49	20.773	Adequate

Table 4 Comparisons of R^2 Values and Standard Error of Estimations for Full and Reduced models

	Adjusted R^2 values		Standard error of estimate	
	Full model	Reduced model	Full model	Reduced model
T_{hi}	0.427	0.618	0.297	0.242
m_c	0.613	0.685	0.146	0.131
m_h	0.713	0.791	0.728	0.617

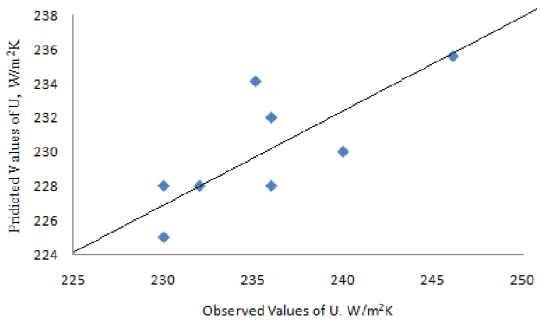

Fig. 2 Scatter diagram for the Overall Heat Transfer Coefficient.

Table 5 Results of Conformity Experiments

Sl. No	Parameters			Measured values				Predicted values				% Error			
	T_{hi}	m_c	m_h	U	Q	ε	Δp	U	Q	ε	Δp	U	Q	ε	Δp
1	53	10	37	227.6	4981.5	0.28	30.01	232.4	4975.1	0.29	28.7	-2.03	0.12	-3.45	4.31
2	65	7	32	246.1	3694.7	0.37	13.33	235.2	3782.8	0.34	13.8	4.61	-2.32	8.82	-4.03
3	58	14	43	236.4	7201.2	0.27	30.00	235.5	7198.1	0.29	28.7	0.38	0.04	-7.40	4.49
				Average								0.98	-0.72	-0,67	1.59

$$\% \text{ Error} = \left\{\frac{\text{actual value} - \text{predicted value}}{\text{Predicted value}}\right\} \text{x } 100$$

Graphs are plotted to identify the influence of independent variables (T_{hi}, $\dot{m}_c$ & $\dot{m}_h$) on the dependent variables (U, Q, ε and Δp).

4.1 DIRECT EFFECTS

4.1.1 Inlet Temperature of the Hot Fluid (Thi)

The Inlet Temperature of the hot Fluid does not have any considerable impact on the shell side pressure drop and effectiveness of the shell and tube heat exchanger. The Overall heat transfer co-efficient increases with an increase in the inlet temperature of the hot fluid. But, it is the heat transfer rate that is much affected by the Inlet temperature of the hot fluid. As the inlet temperature of the hot fluid increases, the heat transfer rate increases accordingly.

4.1.2 Mass Flow Rate of the Cold Fluid (ṁc)

The mass flow rate of the cold fluid does not have any considerable impact on the overall heat transfer co-efficient, though it increases with increasing mass flow rate. However, the heat transfer rate increases drastically as the mass flow rate increases. The pressure drop also increases considerably with increasing mass flow rates. The effectiveness of the heat transfer also drops down with increasing mass flow rates of the cold fluid.

4.1.3 Mass Flow Rate of the Hot Fluid (ṁh)

The Mass Flow Rate of the Hot Fluid does not have any considerable impact on all the four dependent variables.

4.2 INTERACTION EFFECTS of the OVERALL HEAT TRANSFER CO-EFFICIENT (U)

The overall heat transfer co-efficient has its maximum value for the highest inlet temperature of the hot fluid. In addition, the maximum heat transfer co-efficient is also associated with the mass flow rate of the cold fluid which is 12 lpm in this case. The highest mass flow rate of the cold fluid (15 lpm in this case) does not have any impact on the heat transfer co-efficient.

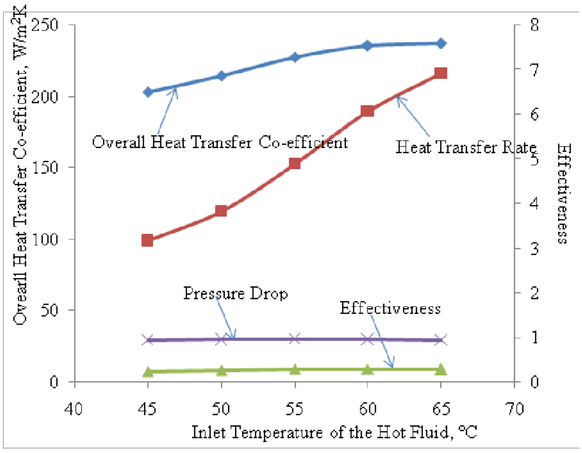

Fig. 3 Direct effect of T_{hi} on dependent variables

4.2.2 Effect of $\dot{m}_c$ and $\dot{m}_h$ on 'U'

The overall heat transfer co-efficient is maximum for the highest mass flow rate of the hot fluid. In addition, the heat transfer coefficient increases as the mass flow rates of the both fluids increase. Except for the high mass flow rate of the cold fluid, the heat transfer co-efficient drops.

4.2.3 Effect of $\dot{m}_h$ and T_{hi} on 'U'

The overall heat transfer co-efficient increases with an increase in both the inlet temperature of the hot fluid

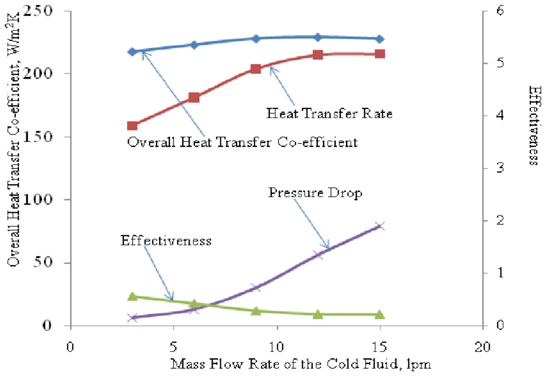

Fig .4 Direct effect of $\dot{m}_c$ on Dependent Variables

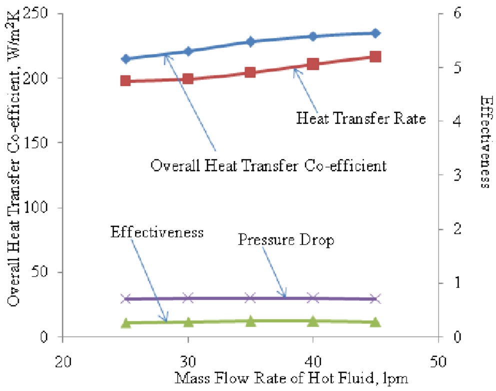

Fig. 5 Direct effect of $\dot{m}_h$ on dependent variables

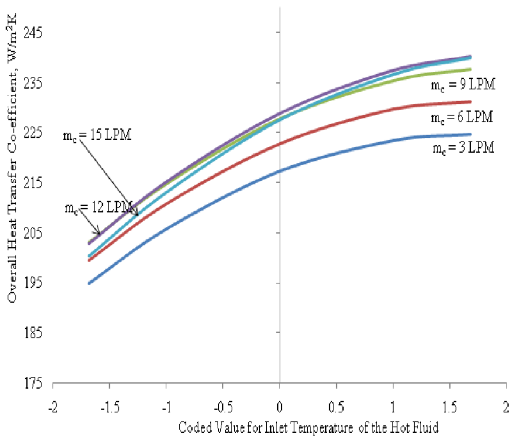

Fig. 6 Interaction Effect of T_{hi} and $\dot{m}_c$ on 'U'

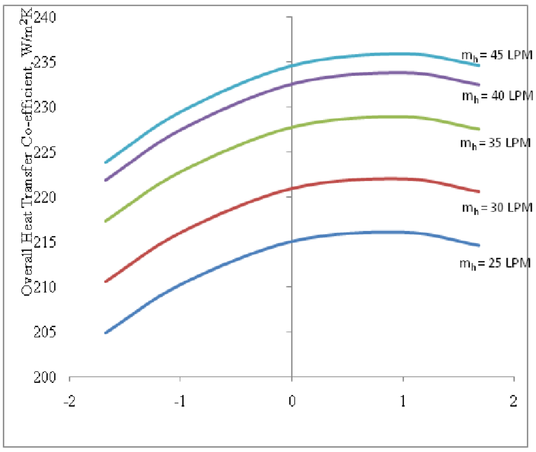

Fig. 7 Interaction Effect of $\dot{m}_c$ and $\dot{m}_h$ on 'U'

and the mass flow rate of the hot fluid. This coefficient statistic is maximum when both the inlet temperature of the hot fluid and the mass flow rate of the hot fluid are maximum.

It can be concluded that with the highest inlet temperature of the hot fluid and the highest mass flow rate of the hot fluid, the highest overall heat transfer co-efficient can be attained. The mass flow rate of the cold fluid has to be chosen carefully since very high values can minimize the heat transfer co-efficient values.

4.2.4 Effect of T_{hi} and $\dot{m}_c$ on 'Q'

The heat transfer rate increases with an increase in both the inlet temperature of the hot fluid and the mass flow rate of the cold fluid.

4.2.5 Effect of $\dot{m}_c$ and $\dot{m}_h$ on 'Q'

The heat transfer rate increases with an increase in the mass flow rates of hot and cold fluids.

4.2.6 Effect of $\dot{m}_h$ and T_{hi} on 'Q'

The heat transfer rate increases with an increase in the inlet temperature of the hot fluid.

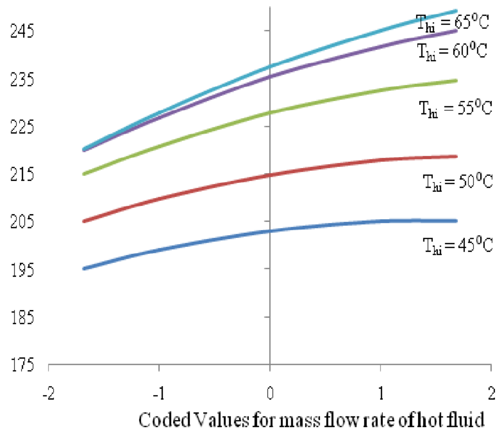

Fig. 8 Interaction Effect of $\dot{m}_h$ and T_{hi} on 'U'

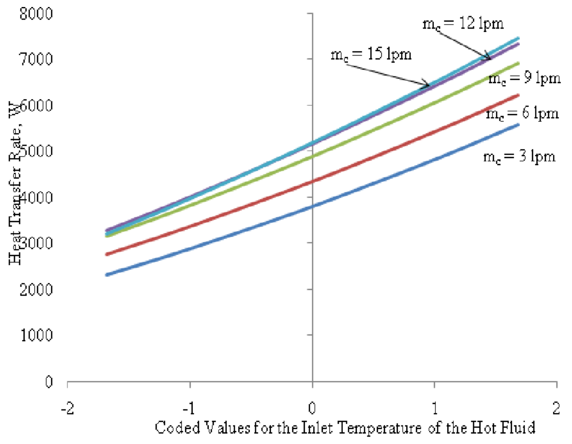

Fig. 9 Interaction Effect of T_{hi} and $\dot{m}_c$ on 'Q'

It can be concluded that with an increase in all the three variables, the heat transfer rate increases. However, a considerable increase in the heat transfer rate is seen with an increase in the inlet temperature of the hot fluid and the mass flow rate of the cold fluid. The heat transfer rate is the maximum and minimum when the mass flow rate of the cold fluid and the inlet temperature of the hot fluid are the maximum and minimum, respectively.

4.2.7 Effect of T_{hi} and $\dot{m}_c$ on 'ε'

Effectiveness of heat transfer increases with a decrease in the mass flow rate of the cold fluid. It can also be seen that the effectiveness drops with an increase in the inlet temperature of the hot fluid.

4.2.8 Effect of $\dot{m}_c$ and $\dot{m}_h$ on 'ε'

Effectiveness decreases with an increase in the mass flow rate of th e cold fluid as it is already could be seen in the previous graph (Fig 4.10). The mass flow rate of the hot fluid does not have any significant impact on the effectiveness.

4.2.9 Effect of $\dot{m}_h$ and T_{hi} on 'ε'

Both the inlet temperature of the hot fluid and the mass flow rate of the hot fluid do not have any considerable impact on the effectiveness.

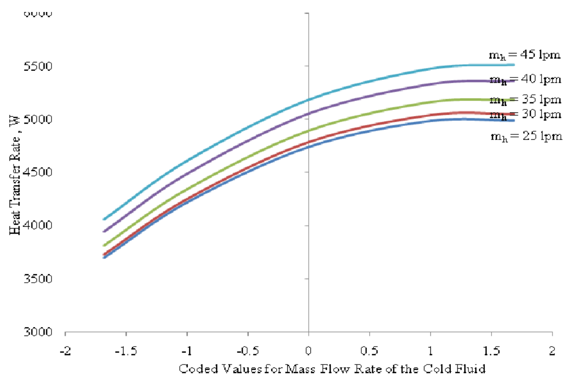

Fig. 10 Interaction Effect of $\dot{m}_c$ and $\dot{m}_h$ on 'Q'

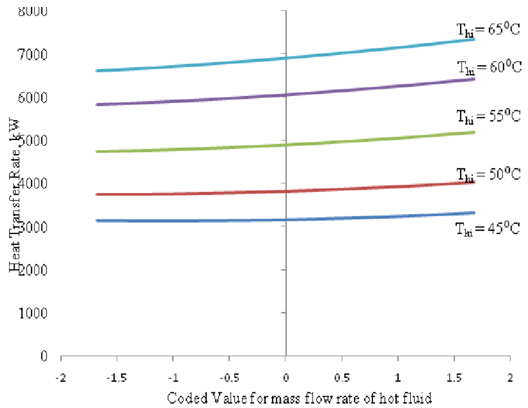

Fig. 11 Interaction Effect of $\dot{m}_h$ and T_{hi} on 'Q'

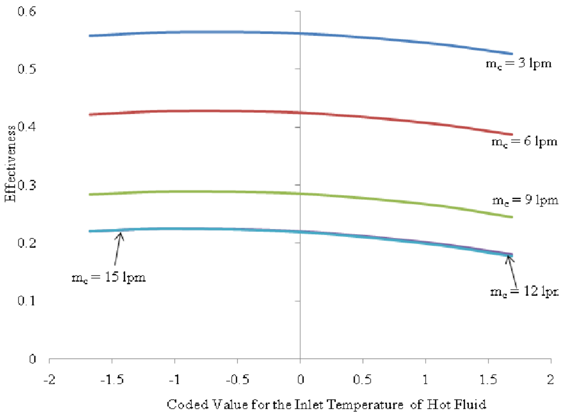

Fig.12 Interaction Effect of T_{hi} and $\dot{m}_c$ on 'ε'

In conclusion the effectiveness of the heat exchanger is dependent on the mass flow rate of the cold fluid. To achieve high effectiveness, the mass flow rate of the cold fluid has to be of a low value. Low effectiveness is attributed to the fact that the mass flow rate of the cold fluid is very high.

4.2.10 Effect of T_{hi} and $\dot{m}_c$ on 'Δp'

The pressure drop increases as the mass flow rate of the cold fluid increases. The inlet temperature of the hot fluid does not have any impact on the pressure drop.

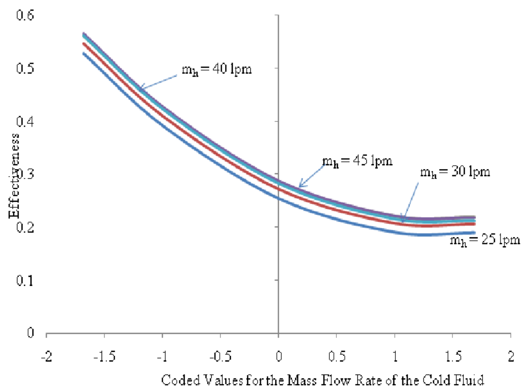

Fig. 13 Interaction Effect of $\dot{m}_c$ and $\dot{m}_h$ on 'ε'

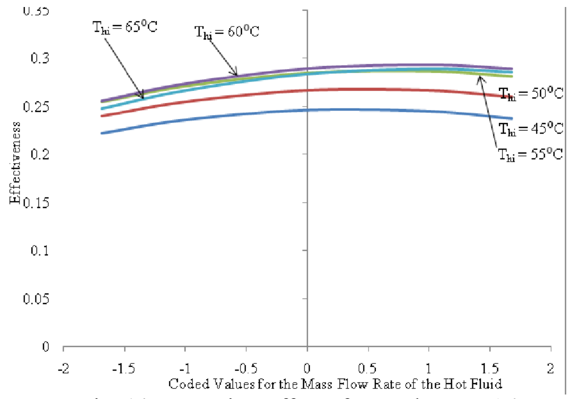

Fig. 14 Interaction Effect of $\dot{m}_h$ and T_{hi} on 'ε'

4.2.11 Effect of $\dot{m}_c$ and $\dot{m}_h$ on 'Δp'

The mass flow rate of the hot fluid has no effect on the effectiveness of the heat exchanger.

4.2.12 Effect of $\dot{m}_h$ and T_{hi} on 'Δp'

The plot shows that a considerable pressure drop occurs at the intermediate values of both the inlet temperature of the hot fluid and the mass flow rate of the hot fluid. However, it can be concluded that high pressure drops are attained at high mass flow rates of the cold fluid.

5. Conclusions

From the experiment, it can be concluded that;

- The Inlet Temperature of the hot fluid has a great impact on the heat transfer rate. As the inlet temperature of the hot fluid increases, the heat transfer rate increases drastically.
- The inlet temperature of the hot fluid does not have any impact on effectiveness and pressure drop.
- The mass flow rate of the cold fluid has a very high impact on effectiveness, i.e., the effectiveness drops as the mass flow rate of the cold fluid increases.

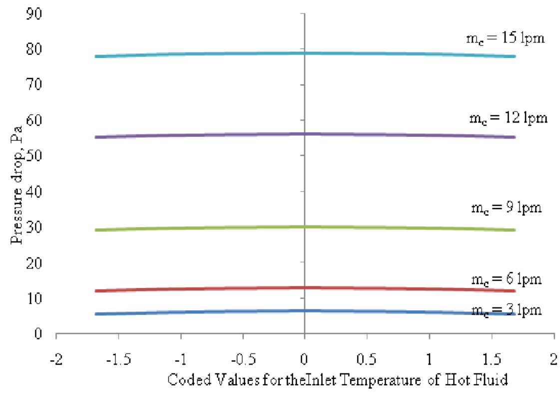

Fig. 15 Interaction Effect of T_{hi} and $\dot{m}_c$ on 'Δp'

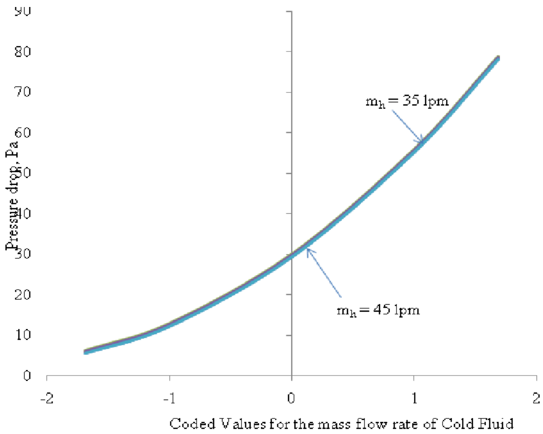

Fig. 16 Interaction Effect of $\dot{m}_c$ and $\dot{m}_h$ on 'Δp'

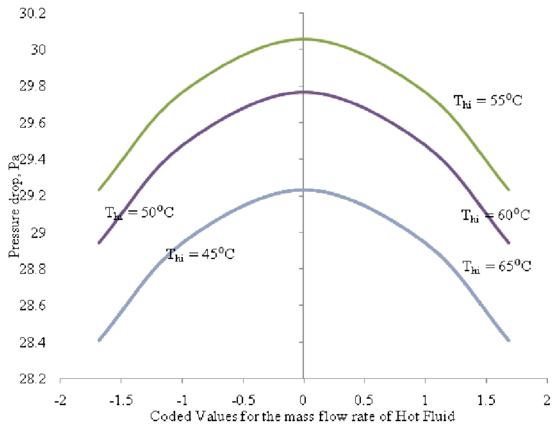

Fig. 17 Interaction Effect of $\dot{m}_h$ and T_{hi} on 'Δp'

- The mass flow rate of the cold fluid also has a considerable effect on the pressure drop, i.e., as the mass flow rate of the cold fluid increases, the pressure drop increases accordingly.
- As the mass flow rate of the cold fluid increases, the heat transfer rate also increases. However, the mass flow rate of the cold fluid doesn't seem to have a high impact on overall heat transfer co-efficient.
- The mass flow rate of the hot fluid does not have any impact on the overall heat transfer co-efficient, heat transfer rate, effectiveness, and shell-side pressure drop.

References

[1]. Y. Ozcelik, Exergetic optimization of shell and tube heat exchangers using genetic based algorithm, Appl. Therm. Eng., vol. 27, pp. 1849- 1856, (2007).

[2]. P. Vijaysai, M.D. Osborn, S.S. Au, K. Ravi Chandra Reddy, Prediction of performance assessment of heat exchangers for proactive remediation, IEEE trans, 3055-3060,(2006)

[3]. Q. Wang, G. Xie, M. Zeng and L. Luo, Prediction of heat transfer rates for shell and tube heat exchangers by artificial neural networks approach, J. Therm. Sci., vol.15, no.3, pp. 257-262,(2006).

[4]. X. Zhao, Performance of a single-row heat exchanger at low in-tube flow rates, Master Thesis, University of Notre Dame, (1995).

[5]. [5] C.Ahilan, S.Kumanan, N.Sivakumar, Prediction of Shell and Tube Heat Exchanger Performance using Artificial Neural Networks, Proc. of the International Conference on Advanced Computing and Communication Technologies (ACCT 2011), ISBN: 978-981-08-7932-7, pp 307 -312, (2011)

[6]. W.G.Cochran and G.M. Cox, 'Experimental design'; India, Asia Publishing House, (1963).

[7]. O.L.Davis, The design and analysis of industrial experiments, New York, Long mount, reprint,(2010).

[8]. P. Harris , B.L Smith , Factorial technique for weld quality prediction", Metal Construction, Vol.15, pp. 661 – 666, (1983).

[9]. D.C Montgomery, Design and analysis of experiments, 2nd Edition', John Wiley and Sons Inc., New York, pp.537, (2001)