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Research paper

Numerical Analysis and Optimization of Design Parameters of a Plate Heat Exchanger using Different Fluids

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Abstract

The main purpose of this work is to examine the effect of design factors on the heat transfer and hydraulic performance of the plate-heat exchanger. Also to use Taguchi optimization technique to optimize the design parameters for maximization of heat transfer rate and minimization of pressure drop. A numerical analysis of plate heat exchanger (PHE) using different fluids (i.e. milk, orange juice and water) is presented in this paper by using COMSOL Multiphysics. The different fluid systems which are considered for this present study are case-1 (milk-water), case-2 (orange juice-water) and case-3 (water-water). Different models are built by varying the design parameters of the plate heat exchanger. In this present study, 600 chevron angle corrugated plates are considered. The different design parameters which are taken for this study are, length of the plates (L), space between each plate (S), amplitude of corrugation on the plate (A) and pitch of corrugation on the plate (P). L16 orthogonal array system of Design of experiments (DOE) is adopted to conduct the numerical analysis. From various models, the influence of design parameters on the performance of plate- heat exchanger for all the fluids are studied. The results of all the three cases are also presented in this paper. Also, in this paper, an attempt is made to optimize the design parameters by using Taguchi optimization technique, in order to minimize the pressure- drop and maximize the rate of heat transfer to The Taguchi optimum setting design parameters for heat transfer coefficient for case-1 (Milk-water) is found to be Length= 32 cm, Space= 0.5 cm, Amplitude= 0.3 cm and Pitch= 0.65 cm and for pressure drop is found to be Length= 28 cm, Space= 0.2 cm, Amplitude= 0.6 cm, Pitch= 0.65 cm. In the process industry like fruit juice processing or milk pasteurization, in order to maximize the heat transfer and minimize the pressure drop during processing, optimum sized plate heat exchanger should be used. The present work will provide the optimum geometrical parameter of the plates to achieve desired output for different inlet temperatures.

Keywords: *Plate Heat Exchanger (PHE); Heat transfer coefficient (h); Pressure drop (ΔP); Design of experiments (DOE); COMSOL; Taguchi*

1. Introduction

Heat exchangers are the specially designed equipment used to transfer thermal energy between two fluids at different temperatures. Due the excellent heat transfer characteristics, very compact in design and flexibility, Plate-heat exchangers are widely used to heat, cool and to regenerate heat in applications like chemical industries, milk, food process and medicine industries. Plate heat exchangers (PHEs) are ease to clean and dismount for maintenance. The PHE consists of a pack of thin corrugated plates hard-pressed into a frame. In order to promote the turbulence inside the flow passage, corrugations are developed on the plate. Compared to shell&tube heat exchanger and double pipe heat exchanger, plate- heat exchanger has very large area density. Plate- heat exchangers are appropriate for liquid- liquid heat transfer duties that need uniform and fast rate of heat transfer, often in the case when handling thermally delicate fluids such as fluids used in fruit juice industries.

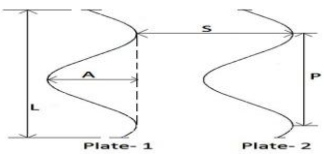

Fig 1: Geometrical Parameters

2. Literature of Knowledge Flow Enabler

Few literatures have reported about Plate Heat Exchanger [5-14]. A large number of analysis based on numerical and experimental analysis of precipitation and particulate fouling in a corrugated-plate- heat exchangers with various geometrical parameters were investigated by Wei Li, Hong-xia Li [5]. Method for selecting the optimal plate pattern of the PHE for minimizing the heat transfer area was presented by Focke [6], a step-wise design procedure for rating and sizing of a plate- heat exchanger was developed by Shah and Focke [7]. The hydro-dynamic character and circulation of flow in two cross-corrugated channels of plate heat exchangers had been examined by Ying-Chi Tsai, Fung-Bao Liu [8]. Rate of heat transfer and pressure-drop of ice slurry in plate heat exchanger was studies by J. Bellas, I. Chaer, S.A. Tassou [9]. Using computational fluid dynamics (CFD), numerical simulations of stirred yoghurt treating in a plate-heat exchanger were performed by Carla S. Fernandes, Ricardo Dias [10].
Optimization of parameters which influence the process has been analyzed by Taguchi Method: Catalytic degradation of liquid fuel like polypropylene has been studied by Achyut K. Panda, R. K. Singh [11]. Taguchi design of experiment method was used to recognise the factors and their exchanges that may affect the thermo-catalytic degradation of waste to liquid fuel in a reactor. Optimization of heat transfer using CFD simulation for concentric

helical coil heat exchanger for constant wall temperature has been carried out by Sagar Das [12]. Under constant wall temperature condition, thermal optimization in heat transfer of a concentric coiled tube-in-tube heat exchanger, based on fluid fluid heat transfer was intensive in this work. The numerical analysis of heat transfer in a very small heat exchanger using COMSOL Multiphysics [13] was studied that is common in the field of micro electro mechanical systems (MEMS). The performance of underground heat exchangers and storage systems using COMSOL Multiphysics has been studied by David Van Reenen [14]. Effect of flow arrangement on the thermal behaviours of a Micro channel Heat -Exchanger using COMSOL had been investigated by Thanhtrung Dang, Jyh-tong Teng, and Jiann-cherng Chu [15]. Applications of COMSOL Multiphysics software to heat transfer processes by Wei Xiong [16].

3. Methodology

In the present work, a numerical analysis of plate heat exchange with four design parameters of the plate heat exchanger (i.e. length of the plates (L), space between each plate (S), amplitude of corrugation on the plate (A) and pitch of corrugation on the plate (P)) are taken in to consider as shown in the figure 1 to investigate the effect of design factors on the thermal and hydraulic performance of the plate -heat exchanger. Also to use Taguchi optimization technique to optimize the design parameters for maximization of heat transfer rate and minimization of pressure drop.

3.1. Design of Experiment

Design of experiment is generally used to obtain highest possible performance by determining the optimum combination of design factors. This reduces the number of combinations and time as well. In this study Taguchi DOE is implemented using Minitab statistical software package of version- 17.
According to Taguchi's orthogonal array theory, for numerical analysis, L16 orthogonal array is adopted for the analysis of plate heat exchanger. In L16 orthogonal array, 16 geometrical setups are modelled and numerical analysis has been done.
Here in this numerical analysis, 4 control variables such as length of the plates (L), space between each plate (S), amplitude of corrugation on the plate (A) and pitch of corrugation on the plate (P) all input parameters are taken in 4 levels. Number of possible runs for numerical calculation will be 64. But according to the methodology suggested by Taguchi, the numerical analysis can be done by taking L16 orthogonal array. That is with only 16 setups we can complete the analysis with same confidence level. Orthogonal array recommended by Taguchi uses random order to reflect all the levels of control parameters. The four-level suitable design factor has been taken as per the following Table-1 for the experimental analysis.

Table 1: Control -parameters and levels

Control- parameters	Level 1	Level 2	Level 3	Level 4
Length, L (cm)	28	32	36	40
Space, S (cm)	0.2	0.3	0.4	0.5
Amplitude, A (cm)	0.3	0.4	0.5	0.6
Pitch, P (cm)	0.65	1	1.35	2

According to the Taguchi design concept L16 orthogonal array is chosen for the numerical analysis as shown in Table 2.

Table 2: Orthogonal array for L16 design

Setup No.	Length, L (cm)	Space, S (cm)	Amplitude, A (cm)	Pitch, P (cm)
1	28	0.2	0.3	0.65
2	28	0.3	0.4	1
3	28	0.4	0.5	1.35
4	28	0.5	0.6	2
5	32	0.2	0.4	1.35
6	32	0.3	0.3	2
7	32	0.4	0.6	0.65
8	32	0.5	0.5	1
9	36	0.2	0.5	2
10	36	0.3	0.6	1.35
11	36	0.4	0.3	1
12	36	0.5	0.4	0.65
13	40	0.2	0.6	1
14	40	0.3	0.5	0.65
15	40	0.4	0.4	2
16	40	0.5	0.3	1.35

3.2. Numerical Analysis:

Numerical study of the plate heat exchanger has been accomplished by using the COMSOL Multiphysics software, version 4.4 using 'fluid flow module'. The procedure of this software is based on the FEM.
The model focuses on transport of heat in a plate type heat-exchanger that is common in the field of heating & cooling applications. The heat exchanger is constructed by stacking several pleated sheets or plates on side by side of each other while leaving a gap between them. To simplify the modelling process in this study, only a cross section between two plates whose shapes are sinusoidal to provide an optimal heat-transfer area of the heat exchanger. The heating fluid circulates in the gaps between the corrugated walls where the fluid that is to be heated flows.
Assumptions:
For numerical analysis of plate heat exchanger Stationary physics interface is considered in COMSOL Multiphysics. The fluid flow in the gap between the plates is assumed to be steady, non-isothermal and laminar. Radiation heat transfer for the analysis is neglected.
Governing Equations:
A standard computational fluid dynamic (CFD) approach is based on the governing differential equations. The governing differential equations are conservation of mass (Continuity Equation), conservation of momentum (Navier-Stokes Equations) and conservation of energy (Energy Equation). Based on the assumptions, continuity equation, Navier- Stokes equations and energy equation can be written in the following form:

3.2.1. Continuity Equation

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \qquad (1)$$

3.2.2. Navier-Stokes Equation:

X- Momentum Equation:

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = F_x - \frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \qquad (2)$$

Y- Momentum Equation:

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = F_y - \frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \qquad (3)$$

3.2.3. Energy Equation:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (4)$$

Boundary Conditions:
Different boundary conditions are given as shown in the *Table-3*.

Table 3: Boundary Conditions

Name	Expression	Description
T_in	25 [degC]	Inlet Temperature
T_wall	70 [degC]	Wall Temperature
u_avg	25 [cm/s]	Average inlet velocity

Geometry:
The geometry for Setup -1 (Length= 28cm, Space= 0.2cm, Amplitude= 0.3cm and Pitch= 0.65cm) is shown in the Figure- 2

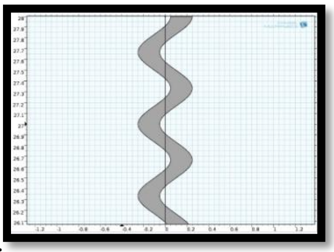

Fig. 2: Geometry for Setup-1

All the thermo-physical values of Milk, orange juice and water are chosen at mean temperature (Density, Dynamic viscosity, Thermal Conductivity, Heat capacity at constant pressure and Ratio of specific heats) from various literatures [17-18].

3.3. Taguchi Optimization for Design Parameters:

Taguchi method is a powerful tools for optimization of process parameters. It is based on the “Orthogonal Array” system which gives a balanced (minimum) set of parameter. The numerical data are examined by a powerful statistical tool(Minitab). All the input variables are well-defined in the software as per their corresponding data and then the responses data are evaluated to optimize the parameters. In Taguchi methodology signal to noise ratio plays a vital role in determining influence of design parameters. Here, the main objective of the problem is to maximize the heat transfer coefficient and to minimize the pressure drop, so accordingly signal to noise ratio is adopted by considering ‘larger is better’ and ‘smaller is better’ criteria respectively for the optimization.
In the present work, two characteristics such as heat transfer coefficient and pressure drop were calculated. Individual optimized parameters were calculated individually by Taguchi technique. Main effect plot for means of both the parameters were drawn and ANOVA table for both the objectives were analyzed.

3.1.1 Optimization for Case- 1 (Milk-Water)

Taguchi Methodology for Heat transfer coefficient
The input parameters which are used to optimize the output parameter (Heat transfer coefficient) are length, space, amplitude and pitch.
Linear Model Analysis: Means versus Length, Space, Amp, Pitch
Estimated Model Coefficients for Means

Term	**Coef**	**SE Coef**	**T**	**P**
Constant	6775.28	102.4	66.175	0.000
Length 28	-596.81	177.3	-3.365	0.044
Length 32	491.37	177.3	2.771	0.070
Length 36	439.59	177.3	2.479	0.089
Space 0.2	-1275.03	177.3	-7.190	0.006
Space 0.3	-44.28	177.3	-0.250	0.819
Space 0.4	126.51	177.3	0.713	0.527
Amp 0.3	4240.69	177.3	23.914	0.000
Amp 0.4	620.99	177.3	3.502	0.039
Amp 0.5	-1870.34	177.3	-10.547	0.002
Pitch 0.65	75.16	177.3	0.424	0.700
Pitch 1.00	4.06	177.3	0.023	0.983
Pitch 1.35	11.04	177.3	0.062	0.954

S = 409.5 R-Sq = 99.6% R-Sq(adj) = 98.2%
Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Length	3	3610110	3610110	1203370	7.17	0.070
Space	3	12265662	12265662	4088554	24.38	0.013
Amp	3	123261625	123261625	41087208	244.97	0.000
Pitch	3	55734	55734	18578	0.11	0.948
Residual Error	3	503161	503161	167720		
Total	15	139696293				

Response Table for Means

Level	Length	Space	Amp	Pitch
1	6178	5500	11016	6850
2	7267	6731	7396	6779
3	7215	6902	4905	6786
4	6441	7968	3784	6685
Delta	1088	2468	7232	165
Rank	3	2	1	4

From the response table it has been clear that, heat transfer coefficient largely depends on amplitude of corrugation on the plates and least depends on pitch of corrugation on the plates.
Table-7 shows values of signal to noise ratio and means for each run.

Table 7: Mean &SN ratio with corresponding factor combinations for heat transfer coefficient: Case-1 (Milk- Water)

Setup No.	Length	Space	Amp	Pitch	h	SNRA1	MEAN1
1	28	0.2	0.3	0.65	9050	79.133	9050
2	28	0.3	0.4	1	6790	76.6374	6790
3	28	0.4	0.5	1.35	4306.88	72.6833	4306.88
4	28	0.5	0.6	2	4567	73.1926	4567
5	32	0.2	0.4	1.35	6901	76.7782	6901
6	32	0.3	0.3	2	11234	81.0107	11234
7	32	0.4	0.6	0.65	4507.74	73.0792	4507.74
8	32	0.5	0.5	1	6423.87	76.1559	6423.87
9	36	0.2	0.5	2	4010	72.0629	4010
10	36	0.3	0.6	1.35	4021	72.0867	4021
11	36	0.4	0.3	1	11863.5	81.4842	11863.5
12	36	0.5	0.4	0.65	8965	79.051	8965
13	40	0.2	0.6	1	2040	66.1926	2040
14	40	0.3	0.5	0.65	4879	73.7666	4879
15	40	0.4	0.4	2	6929.08	76.8135	6929.08
16	40	0.5	0.3	1.35	11916.4	81.5229	11916.4

Figure- 6 shows the variation of Means of heat transfer coefficient values with controllable parameters.
Main effect plot for means in *Figure-6* indicates that length at 2nd level, space at 4th level, Amplitude at 1st level and pitch at 1st level are optimized levels for maximizing heat transfer coefficient. So optimized design parameters for heat transfer coefficient are:

1. Length: 32 cm
2. Space: 0.5 cm
3. Amplitude: 0.3 cm
4. Pitch: 0.65 cm

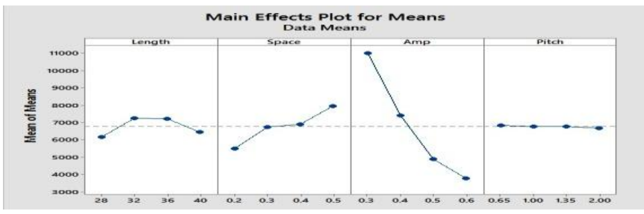

Figure 6: Main Effects Plot for Means of heat transfer coefficient-(Case-1)

3.1.2 Taguchi Methodology for Pressure Drop

The input parameters, which are used to optimize the output parameter (Pressure Drop), are length, space, amplitude and pitch.
Linear Model Analysis: Means versus Length, Space, Amp, Pitch
Estimated Model Coefficients for Means

Term	Coef	SE Coef	T	P
Constant	7836.0	192.3	40.742	0.000
Length 28	-1120.8	333.1	-3.365	0.044
Length 32	-296.4	333.1	-0.890	0.439
Length 36	991.9	333.1	2.978	0.059
Space 0.2	-2183.7	333.1	-6.555	0.007
Space 0.3	656.6	333.1	1.971	0.143
Space 0.4	523.6	333.1	1.572	0.214
Amp 0.3	5254.9	333.1	15.775	0.001
Amp 0.4	1991.8	333.1	5.979	0.009
Amp 0.5	-2653.3	333.1	-7.965	0.004
Pitch 0.65	-1101.6	333.1	-3.307	0.046
Pitch 1.00	504.5	333.1	1.515	0.227
Pitch 1.35	1181.3	333.1	3.546	0.038

S = 769.3 R-Sq = 99.4% R-Sq(adj) = 96.9%
Response Table for Means

Level	Length	Space	Amp	Pitch
1	6715	5652	13091	6734
2	7540	8493	9828	8340
3	8828	8360	5183	9017
4	8261	8840	3243	7252
Delta	2113	3187	9848	2283
Rank	4	2	1	3

From the response table it has been clear that, pressure drop largely depends on amplitude of corrugation on the plates and least depends on length of the plate.
Table- 8 shows values of signal to noise ratio and means for each run for pressure drop

Table 8: Mean &SN ratio with corresponding factor combinations for pressure drop: Case-1 (Milk- Water)

Setup No.	Length	Space	Amp	Pitch	h	SNRA1	MEAN1
1	28	0.2	0.3	0.65	9035.56	-79.1191	9035.6
2	28	0.3	0.4	1	9845	-79.8643	9845.0
3	28	0.4	0.5	1.35	5968.04	-75.5166	5968.0
4	28	0.5	0.6	2	2012	-66.0726	2012.0
5	32	0.2	0.4	1.35	8000	-78.0618	8000.0
6	32	0.3	0.3	2	13068.1	-82.3242	13068.1
7	32	0.4	0.6	0.65	2345	-67.4029	2345.0
8	32	0.5	0.5	1	6745	-76.5796	6745.0
9	36	0.2	0.5	2	3383.55	-70.5875	3383.6
10	36	0.3	0.6	1.35	6423	-76.1548	6423.0
11	36	0.4	0.3	1	14581.9	-83.2763	14581.9
12	36	0.5	0.4	0.65	10923	-80.7668	10923.0
13	40	0.2	0.6	1	2190	-66.8089	2190.0
14	40	0.3	0.5	0.65	4634	-73.3191	4634.0
15	40	0.4	0.4	2	6929.08	-80.4594	10543.2
16	40	0.5	0.3	1.35	11916.4	-83.9058	15678.0

Figure- 7 shows the variation of Means of pressure drop values with controllable parameters.

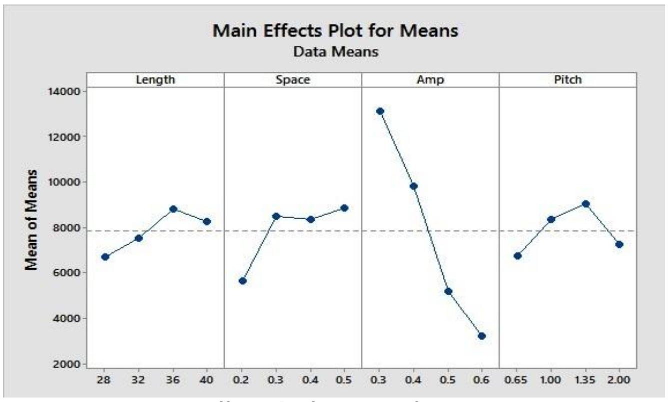

Figure 7: Main Effects Plot for Means of Pressure Drop-(Case-1)

Main effect plot for means in *Figure- 7* indicates that length at 1st level, space at 1st level, Amplitude at 4th level and pitch at 1st level are optimized levels for minimizing pressure drop.
So optimized design parameters for pressure drop are:
1 Length: 28 cm
2 Space: 0.2 cm
3 Amplitude: 0.6 cm
4 Pitch: 0.65 cm
The same procedures are followed for Case-2 (Orange Juice-Water) and Case-3 (Water-Water) for the optimization of design parameters using Taguchi Technique.

3.2 Optimization for Case- 2 (Orange Juice-Water)

3.2.1 Taguchi Methodology for Heat Transfer Coefficient

The optimized design parameters for heat transfer coefficient are:
1 Length: 40 cm
2 Space: 0.2 cm
3 Amplitude: 0.6 cm
4 Pitch: 0.65 cm
3.2.2 Taguchi Methodology for Pressure drop
The optimized design parameters for pressure drop are:
1 Length: 28 cm
2 Space: 0.5 cm
3 Amplitude: 0.6 cm
4 Pitch: 2 cm

3.3 Optimization for Case- 2 (Water-Water)

3.3.1 Taguchi Methodology for Heat Transfer Coefficient

So optimized design parameters for heat transfer coefficient are:
1 Length: 40 cm
2 Space: 0.2 cm
3 Amplitude: 0.5 cm

4 Pitch: 0.65 cm

3.3.2 Taguchi Methodology for Pressure drop

The optimized design parameters for pressure drop are:

1 Length: 28 cm
2 Space: 0.5 cm
3 Amplitude: 0.3 cm
4 Pitch: 0.65 cm

4. Conclusion

- This present work is basically intended for heating of food fluids in food processing industries during their packing. Numerical analysis of plate heat exchanger with different design parameters has been carried out and the followings conclusions are made. The heat transfer and pressure drop increases with increase in length of the plates and amplitude of corrugation on the plates, whereas heat transfer and pressure drop decreases with increase in space between the plates and pitch of corrugation on the plates.
- Heating of milk, orange juice and water in a plate heat exchanger has been done using hot water as a secondary fluid.
- The optimization of design parameters has been done by using Taguchi optimization technique in order to maximize the heat transfer rate and to minimize the pressure drop.
- The Taguchi optimum setting design parameters for heat transfer coefficient for case-1 (Milk-water) is found to be Length= 32 cm, Space= 0.5 cm, Amplitude= 0.3 cm and Pitch= 0.65 cm and for pressure drop is found to be Length= 28 cm, Space= 0.2 cm, Amplitude= 0.6 cm, Pitch= 0.65 cm. Similarly for case-2 (Orange Juice-water), the Taguchi optimum setting design parameters for heat transfer coefficient is found to be Length= 40 cm, Space= 0.2 cm, Amplitude= 0.6 cm and Pitch= 0.65 cm and for pressure drop is found to be Length= 28 cm, Space= 0.5 cm, Amplitude= 0.6 cm and Pitch= 2 cm. For case-3 (water-water), the Taguchi optimum setting design parameters for heat transfer coefficient is found to be Length= 40 cm, Space= 0.2 cm, Amplitude= 0.5 cm and Pitch= 0.65 cm and for pressure drop is found to be Length= 28 cm, Space= 0.5 cm, Amplitude= 0.3 cm and Pitch= 0.65 cm. It is clear from the Taguchi response table that, both heat transfer coefficient and pressure drop largely depends on amplitude of corrugation on the plates.
- Plate heat exchangers have progressed significantly since they were invented and this development will certainly continue to further expand their industrial applications. However, in order to achieve this, there are still some challenges related to their construction and performance. The construction of plate heat exchangers includes the development of new plate units by using new design concepts.

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