Numerical Studies on the Performance of Finned-Tube Heat Exchanger

Praveen Kumar S P, Bong-Su Sin, Kwon-Hee Lee

Abstract**—**Finned-tube heat exchangers are predominantly used in space conditioning systems, as well as other applications requiring heat exchange between two fluids. The design of finned-tube heat exchangers requires the selection of over a dozen design parameters by the designer such as tube pitch, tube diameter, tube thickness, etc… Finned-tube heat exchangers are common devices; however, their performance characteristics are complicated. In this paper numerical studies have been carried out to analyze the performances of finned tube heat exchanger (without fins considered for experimental purpose) by predicting the characteristics of temperature difference and pressure drop. In this study, a design considering 5 design variables and also maximizing the temperature difference and pressure drop was suggested by applying DOE. During this process, L_{18} orthogonal array was adopted. Parametric analytical studies have been carried out using ANOVA to determine the relative importance of each variable with respect to the temperature difference and the pressure drop. Following the results, the final design was suggested by predicting the optimum design therefore confirming the optimized condition.

Keywords**—**Heat Exchanger, Fluid Analysis, Heat Transfer, Design of Experiment (DOE), Analysis of Variance (ANOVA).

I. INTRODUCTION

HEAT exchanger is a device that is used for transfer of thermal energy (*enthalpy*) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at differing temperatures and in thermal contact, usually without external heat and work interactions. The fluids may be single compounds or mixtures. Typical applications involve heating or cooling of a fluid stream of concern, evaporation or condensation of a single or multicomponent fluid stream, and heat recovery or heat rejection from a system.

As for the fin-tube heat exchanger, the structure is simple and easy to produce. It is predominantly used in space conditioning systems, as well as other applications requiring heat exchange between two fluids. One important widespread use is in residential air conditioning systems. Also, maintenance is easy and can be designed in various sizes. Moreover, it has the merit of being operable under a wide range of temperature and pressure. In general, fin tube heat exchangers are used for high temperature operations with temperatures greater than 400°C [1]-[2].

The design of finned-tube heat exchangers requires specification of more than a dozen parameters. This design optimization is characterized by a *trade-off between temperature difference and pressure drop*. Thus, it is necessary to predict or calculate those responses in the design process [3].

There have been many researches to improve the performance of the finned tube heat exchanger; however, they all are much concerned only with the fins and its design and arrangements. In this paper, the fins are neglected (plain tubes) for experimental purpose and the study is majorly focused on the tubular arrangements and tube parameters to determine the optimal design as per the request by a Z manufacturer.

In this study, the task of this finned-tube heat exchanger is to increase the temperature of the fluid (oil) flowing through the pipes and decreasing the temperature of the other fluid (gas) flowing over the pipes. Based on this phenomenon, the five design variables were defined to determine an optimum design, maximizing the performance of heat exchanger. The design variables were selected by assuming that they were the most significant factors with respect to temperature difference and pressure drop. This temperature difference and pressure drop are calculated by estimating the difference in temperature and pressure at the inlet and outlet of the oil using numerical analysis [4].

First, preliminary design was completed using SolidWorks then the temperature and pressure in the inlet and outlet were calculated using numerical analysis. The five design variables are selected and an L_{18} orthogonal array was constructed and evaluated using Design of Experiments (DOE). This orthogonal array is utilized because the minimum number of experiments would have an effect that approximates the full factorial experiments. The sensitivity information of design variable with respect to the temperature difference and the pressure drop was calculated using ANOVA table, quantitatively. After that, the optimum level which maximizes this finned tube heat exchanger performance was predicted, statistically. Finally, the confirmation analysis on the predicted optimum design was performed. In this work, the heat transfer and fluid flow characteristics were performed using ANSYS-CFX.

II. NUMERICAL METHOD OF SOLUTION

A. Model Description

A finned tube heat exchanger *without fins* is considered in

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this study. Oil flows inside the tubes while gas flows across the plain tube bundle. There are many parameters to describe the configuration of the heat exchanger. Among these parameters, *tube pitch orientation, tube diameter, tube thickness* are considered as geometrical variables in this study. Meanwhile, number of rows, transverse pitch and length of tubes are typically assumed constant. This heat exchanger is used in oil industry produced by Z manufacturer, which aims in increasing the temperature of the oil flowing through the pipe. The gas at high temperature is made to pass over the oil pipe from bottom to top of the oil pipe in transverse direction.

The preliminary model of the finned tube heat exchanger without fins was designed using SolidWorks is depicted in Fig. 1. The tube material is assumed as steel *whose total length is 8540 millimeter and the number of tube is 484*. The process of designing this tube with fins is a tedious process and requires a high-end computer memory; also the Z manufacturer is much interested only in the tube optimization rather than the fins for the given design. In order to conserve time for numerical analysis the model has been simplified during the preliminary design phase. The diameter for both the inlet and outlet of the oil pipe is 10mm. The material property of the tube is depicted in Table I.

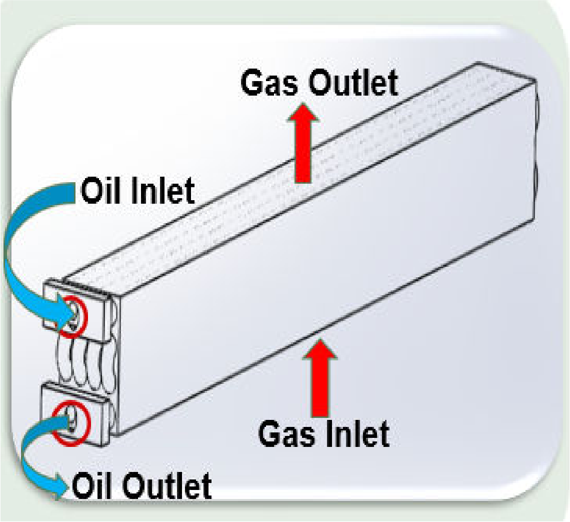

Fig. 1 Model of Finned-Tube Heat Exchanger

TABLE I
MATERIAL PROPERTIES OF STEEL

	Density	Specific Heat Capacity	Thermal Conductivity
Steel	7854kg/m^3	4.34×10^2J/kg·K	60.5W/m·K

B. Initial and Boundary Conditions

A grid system filled with *tetrahedral cells* is generated in the computational domain with 1740899 grids and 131169 meshes using CFX mesh under ANSYS Workbench environment. Heat transfer and fluid flow analysis was conducted under steady state, incompressible and turbulent flow environments. Built-in k-ε model in CFX was chosen as the turbulent model. The governing equations for the numerical analysis are continuity equation, *Navier-Stokes equation and energy equation*.

The temperature of the oil entering the tube is 215°C and flows at 77.74 lb. /s through the pipe. The inlet temperature of the gas is 922.5°F flowing at 77 lb. /s over the pipe. In order to facilitate heat exchange through interaction between these two fluids, the DOMAIN INTERFACE condition available in *CFX* is used between the pipe (*solid domain*) and oil (*fluid domain*). This DOMAIN INTERFACE also implemented between the gas (*fluid domain*) and pipe (*solid domain*), thereby enabling heat exchange through all surfaces. The boundary conditions and the fluid properties are listed in Tables II and III respectively [5].

TABLE II
BOUNDARY AND INITIAL CONDITIONS

	Oil	Gas
Inlet	215 [F]	922.5[F]
Outlet	Atmospheric Pressure	Atmospheric Pressure

TABLE III
FLUID PROPERTIES

	Density [lb./ft^3]	Specific Heat Capacity [Btu /lb. °F]	Thermal Conductivity [Btu/hr.ft.°F]
Oil	56.41	0.4559	0.0643
Gas	0.0240	0.2735	000313

C. Analysis Results

The temperature difference and pressure drop are the two phenomenons which helps us to clearly understand the heat exchange between two fluids in heat exchanger. The results of temperature difference and pressure drop of fluids are extracted from the postprocessor of ANSYS CFX. The result of the analysis is depicted in Figs. 2 and 3

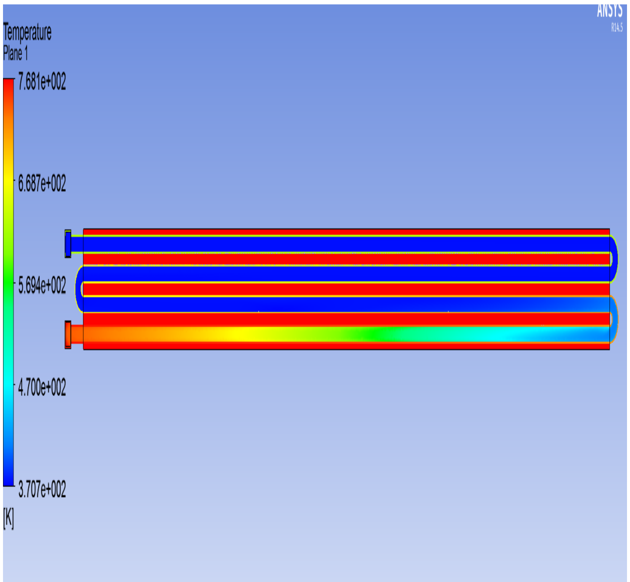

Fig. 2 Temperature distribution of the oil along the pipes

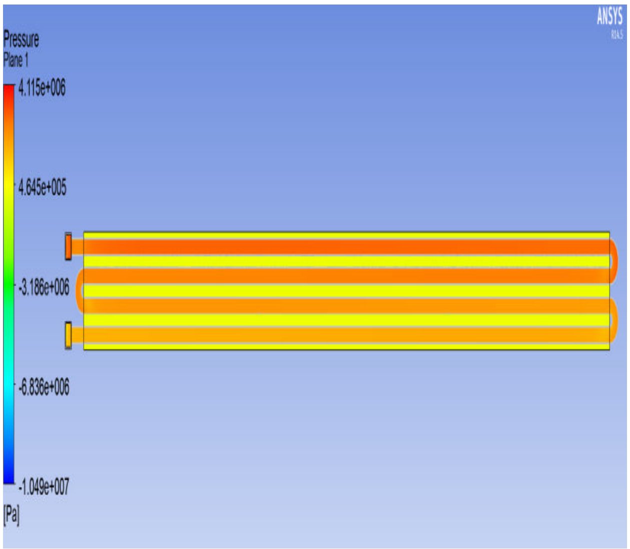

Fig. 3 Pressure distribution of the oil along the pipes

III. EVALUATION ON THE EFFECTS OF DESIGN VARIABLES USING DESIGN OF EXPERIMENTS

Design of experiments (DOE) or experimental design is the design of any information-gathering exercises where variation is present, whether under the full control of the experimenter or not. However, in statistics these terms are usually used for controlled experiments. Also it involves with designs regarding how the experiments will be conducted, how the data will be gathered and how should the data be statistically analyzed so as much information can be derived from the least number of experiments.

A. Definition of Design Variables

The five design variables were defined to find a design maximizing the performance of finned tube heat exchanger. They are the *inner diameter of the tube*(A), *the thickness of the tube* (B), *the velocity of the oil* (C), *the velocity of the gas* (D) and *the pitch orientation of the tubes* (E) were chosen.

B. Implementation of DOE Using Orthogonal Array

For *four design variables*, the number of levels is set to be three. The second level is set to the *initial variable*. The first and third levels are fixed by the lower and upper ones around the initial value, respectively. The levels of design variables for an orthogonal array are determined as shown in Table IV. Then, an appropriate orthogonal array is selected. TheL_{18} ($2^1 \times 3^7$) orthogonal array can *replace 35×21=486 full-combinational experiments.*

The orthogonal array is implemented in-order to *reduce the tedious computation time*. The time taken to complete one CFD simulation is around 3-4 hours. To complete 486 full combination experiments using ANSYS-CFX, the required time will be around 3 months which is usually a long time.

It is assumed that the interaction with respect to variable should not be very large. In general, L_{18} ($2^1 \times 3^7$) orthogonal array is *mixed level array*, in which it is assumed that the first column is with 2 levels and the remaining columns with 3 levels. Furthermore, the interactions between design variables in the array are almost evenly distributed to other columns which help in reducing the probability of misuse of orthogonal array by neglecting any interaction. The experiments were set up as Table V. The variable, E in the first column denotes either the staggered or straight orientation of the tube pitch. The variables A, B, C and D are assigned from second to sixth column and remaining columns are filled with errors.

TABLE IV
LEVELS OF DESIGN VARIABLES

levels	A (mm)	B (mm)	C (ft./s)	D(ft./s)	E
1	47.25	3.51	112.5	157.5	Staggered
2	52.5	3.9	125	175	Straight
3	57.5	4.29	137.5	192.5	

TABLE V
EXPERIMENTS USING ORTHOGONAL L_{18} ($2^1 \times 3^7$) ARRAY

Exp. No	E	A	B	C	D	error	error	error
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

A. Experimental Result Analysis and ANOVA

Numerical analysis was conducted for 18 cases using the conditions in orthogonal array as depicted in Table V. The temperature difference and pressure drop for 18 cases is obtained from the numerical analysis. The results are depicted in Table VI.

Based on the analysis results, *the relative importance of each variable with respected to temperature difference and pressure drop* is obtained using ANOVA. The ANOVA table for temperature difference and pressure drop is depicted at Tables VII and VIII. From the table, it can be seen that the pitch orientation and inner diameter of the tube are *significant variables* and remaining variables doesn’t have much sensitive to temperature difference. Also from the ANOVA for pressure drop table, it can be seen that inner diameter of the tube is much *sensitive to pressure drop* where the remaining being insensitive. This also clearly shows that the velocity of the both the fluids which is also one of the five design variable doesn’t affect both the temperature difference and pressure drop [6].

TABLE VI
TEMPERATURE DIFFERENCE AND PRESSURE DROP AT OIL OUTLET OF THE HEAT EXCHANGER

Cases	Temperature Difference (F)	Pressure Drop (MPa)
1	340.089	4.30164
2	351.701	3.74316
3	342.418	5.29221
4	36.5532	3.08033
5	25.447	5.790569
6	37.57	3.80133
7	629.844	2.94321
8	627.062	2.40278
9	630.6504	3.59323
10	524.125	4.6578
11	543.7824	4.42603
12	552.782	3.57546
13	294.09	4.20279
14	306.47	6.14886
15	258.8838	2.868162
16	701.0646	3.64014
17	674.421	2.61361
18	678.3324	2.17327

TABLE VII
ANOVA TABLE FOR TEMPERATURE DIFFERENCE

Factor	*S*	*Ø*	*V*	*F*
E	127111.61	1	127111.61	31.07
A	745862.06	2	372931.03	91.16
B	79.95	2	39.97	0.01
C	293	2	146.68	0.04
D	191.40	2	95.70	0.02
Error	32727.82	8	4090.98	

TABLE VIII
ANOVA TABLE FOR PRESSURE DROP

Factor	*S*	*Ø*	*V*	*F*
E	0.02	1	0.02	0.03186
A	8.18	2	4.09	5.68
B	1.23	2	0.62	0.86
C	2.24	2	1.12	1.56
D	4.02	2	2.01	2.80
Error	5.76	8	0.72	

IV. CONCLUSION

In this paper, numerical analysis on finned tube heat exchanger (without fins) was performed to estimate the temperature difference and pressure drop in-order to analyze the performance of heat exchanger. The DOE using L_{18} $(2^1 \times 3^7)$ orthogonal array was performed to select the dominant design variable. Based on results it can be concluded as:

1) The significant factor which affects the temperature difference in our fin tube heat exchanger is the straight arrangement of tubes (squared array) rather than the staggered arrangement. Also the inner tube diameter combined with this straight tube influence further temperature difference.
2) With the pressure drop in fin tube heat exchanger, the tube inner diameter affects significantly irrespective of the tube arrangements.
3) The optimal solution can be obtained with lesser experimental trial by using the orthogonal array table for the finned-tube heat exchanger analysis.

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