Optimization of Process Parameters of the Plate Heat Exchanger

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Abstract- The aim of this study is to determine the importance of the operational factors affecting the recovery performance in air-to-air heat recovery application where heat exchanger is used. The Taguchi experimental design method has been applied to show the effects of the factors and obtain the optimum process parameter combination. Thermal effectiveness has been determined as a performance characteristic. Experiments have been carried out at varying air flow rate, fresh and exhaust air inlet temperatures. Taguchi's $L_9(3^3)$ standard orthogonal array has been chosen as an experimental plan. The significance level of the control factors has been obtained by using analysis of variance (ANOVA). The results show that air flow rate is the most significant factor among the three factors that influences the thermal effectiveness. The results prove that Taguchi method is an easily applicable optimization tool for heat recovery systems.

Keywords Air to air heat recovery, plate heat exchanger, effectiveness, Taguchi method

1. Introduction

The energy policy of the world countries is focused on sustainability. Fossil-based fuels cause non-renewable sources are wasted day by day. The increase in consumption of these resources means more harm to the environment. There are various ways to reduce energy consumption, and one of them is to recover the waste heat. Especially, industrial systems that use high amounts of energy have a large heat recovery potential. By the way recovering and reusing of rejected heat instead of purchasing energy, waste heat recovery applications improve both efficiency and reduce energy costs [1].

There are several types of equipment that can be used for heat recovery. One of them is a heat exchanger. It is a device that can transfer the heat from one fluid to another at different temperatures in thermal contact. Usually, they are used in heating and cooling applications, such as space heaters, refrigerators and air conditioners. Plate type exchanger is one of the most widely used exchanger type for heat recovery. In this type, the two fluids are separated from each other by a thin plate and the heat transfer between the fresh and the exhaust fluid takes place without contacting each other.

The Taguchi method, one of the experimental design methods, can be used to determine which input factor influences the experimental result on what level and also obtain the optimum process parameter combination. Performance characteristics can be optimized through the setting of process design parameters and variability of a process can be reduced by selecting the optimal values of controllable factors. This method has been widely used nowadays because it lets to achieve desired results with less experimentation, in less time and with less cost. In addition, the optimum working conditions obtained from laboratory study can be reproduced at different times and also in different working environments.

Optimization studies for various heat exchangers are available in the literature. Jeom- Yul Yun and Kwan-Soo Lee [2] presented the determination of optimum values of the design parameters in a heat exchanger with a slit fin by using

Taguchi method. The effects of the various design parameters on the heat transfer and friction factor for the heat exchanger having enlarged and contracted oriented rectangular fins were analysed using the Taguchi method by Şahin et al.[3]. Yakut et al.[4] systematically analysed the effects of the various kinds of design parameters on the heat transfer and friction factor for heat exchangers having hexagonal fins using the Taguchi method. Qi et al. [5] determined five experimental factors affecting the heat transfer and pressure drop of a heat exchanger with corrugated louvered fins. The overall heat transfer, friction factor and the effect of the various design parameters on the heat transfer and friction factor for the heat exchanger equipped with square cross sectional perforated pin fins were investigated experimentally by Şahin and Demir [6]. Turgut et al. [7] studied the effect of the geometrical parameters on the performance of the concentric heat exchanger with injector turbulators using Taguchi experimental design method. Hsieh and Jang [8] optimized the parameters of louver finned-tube heat exchangers by the Taguchi method. Kotçioğlu et al. [9] invested experimentally the effects of six design parameters to reach minimum pressure drop and maximum heat transfer for a plate-fin type heat exchanger. An experimental study on a plate fin heat exchanger with navy fins has been conducted by Jungi et al. [10]. Jamshid et al. [11] carried out an experimental investigation to study the heat transfer characteristics in shell and helical tube heat exchangers by using of Wilson plot and Taguchi method. Du et al. [12] applied the Taguchi method to investigate the influence of various geometric parameters on heat transfer and flow resistance characteristics of overlapped helical baffled heat exchanger. Bilen et al. [13] studied the effect of flow rate, coil diameter and coil pitch on the heat transfer rate in plate type heat exchanger by the use of Taguchi Method.

As mentioned in the literature review, Taguchi optimization technique has been used in numerous studies, but the application of this method for the energy recovery based system has been scarce [1]. Another noteworthy difference is that previous investigations are mainly concerned with the optimization of geometric design parameters of exchangers. As different from previous experimental works, in the present study, optimization of the process design parameters of an air to air waste heat recovery application was achieved by means of Taguchi technique. The influence of three operating parameters on the thermal effectiveness was detailed. Contribution ratio and the optimum design value of each parameter was presented. By this way, the optimum combination of the parameters was determined. Differently, variance analysis (ANOVA) was applied to obtain the significance grade of the process parameters. The results of this study will be useful for designers who determine the parameters of the waste heat recovery process. And also these test data will expand the database of air to air heat recovery.

2. Experimental Set-Up

Schematic diagram of the heat recovery device used in the study is shown in Fig. 1. The working principle of the system is as follows: The fresh air passes through one side of the plates and at the same time the exhaust air passes through the other and heat transfer takes place. When the system starts to work, fresh air with a higher temperature than the outside air is given to the interior. The thermal energy load of the exhaust air is transferred to the fresh air by means of heat exchanger. [14,15]

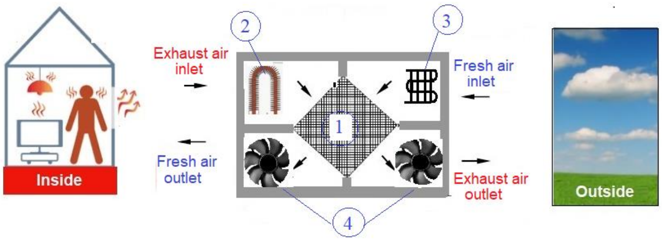

Fig. 1. Schematic display of the experimental apparatus: (1) heat exchanger, (2) heater, (3) evaporator, (4) fan.

The main components of the experimental apparatus were the heat exchanger, heater, evaporator, fans and data acquisition system. The outside of the test section was covered with a glass wool layer to provide insulation against heat loss to the surrounding air. The aluminium plate heat exchanger with 20 x 20 x 30 cm size was fitted in the center of the apparatus. The photo and geometric dimensions of the heat exchanger were shown in previous studies [14, 15].

Fresh and exhaust air were used as working fluids. The tests were carried out at different values for air flow rate, fresh and exhaust air inlet temperatures. For this purpose, the waste heat recovery system was designed with two 2500/2700 RPM fans, one to suck exhaust air and the other to blow fresh air. An anemometer was used in to determine the velocity of the air flow entering into the system and the speed of the fans was adjusted by using a single-phase speed controller. Lamellar resistance heaters were used to get hot air and air compressor cooling apparatus was used to get cold air. The inlet and exhaust air temperatures were set to different temperatures by means of digital thermostats. The devices and their accuracies are given in Table 1.

Table 1. Uncertainty of measurement devices

Measurement Device	Name	Range	Accuracy
Anemometer	Prova AVM-07	0-45/ m/s	± 3%
Thermostat	Emko ESM-3710	(-40) / (+85) °C	± 1%
Thermostat	Evko EVKB 21	(-50) / (+130) °C	± 1%

3. Materials and Methods

3.1. Heat Transfer

In this experimental work, thermal effectiveness (efficiency) has been selected as the performance statistic. Pressure drop and latent heat transfer were neglected and it was assumed that there was no heat loss to the external atmosphere. The thermal effectiveness can be defined as the ratio of the actual heat transfer to the maximum possible heat transfer. Thermal effectiveness is calculated by the following equation (1) [10, 15]:

$$\varepsilon = Q/Q_{max} \tag{1}$$

The amount of actual heat transferred can be found from the heat given by the hot fluid or taken from the cold liquid:

$$Q = C_h(T_{hi} - T_{ho}) \text{ or } Q = C_c\,(T_{co} - T_{ci}) \tag{2}$$

$$C_h = \dot{m}_h C_{ph} \tag{3}$$

$$C_c = \dot{m}_c C_{pc} \tag{4}$$

$$Q_{max} = C_{min}\,(T_{hi} - T_{ci}) \tag{5}$$

The $\mathrm{Q_{max}}$ can be defined as the maximum amount of heat transfer can be possible. This value can be found by selecting the smaller of the $\mathrm{C_h}$ and $\mathrm{C_c}$ and multiplying it with the difference between the inlet temperatures of the cold and hot fluids. For further information, previous studies can be reviewed [14-15].

3.2. Application of Taguchi Method

When the number of process parameters increases, it is necessary to carry out a large number of experiments. Taguchi approach presents experimental plans that simplify and standardize these experiments. The objective of this method is acquiring data in a controlled way and thus, getting information about the behavior of the process [16]. Taguchi's method is based on an orthogonal array, and some of the advantages that these arrays offer to designers are: influence of multiple controllable factors on the quality characteristics and the variations can be analyzed, optimum parametric combinations can easily be found out [1]. Also, the maximum and minimum value ranges of the results of untested experiments can be estimated using this technique [17]. For these reasons, this approach has been applied in a wide variety of fields.

According to Taguchi, process performance is influenced by both controllable and uncontrollable factors. Variables such as part size, fluid temperature, material type, flow rate, and electric current are called controllable factors and the levels can be selected by the researchers. On the other hand, variables that are difficult to control, such as moisture, noise, vibration, dust, product wear, are called uncontrollable factors [18]. The main focus of the Taguchi method is to determine the optimal levels of controllable factors and to reduce the variability that derives from uncontrollable factors. Thus, it is possible to take precautions against the factors that cause variation before the production begins [6].

The signal-to-noise ratio (S/N) has been developed as a basic statistical criterion for evaluating performance indicators in the Taguchi approach [12]. The signal(S) is also called as controllable factor and represents the actual value taken from the system. The noise (N) is called as uncontrollable factor and represents the proportion of undesired factors in the test result [19]. There are some S/N ratios available depending on the type of performance characteristic: “Larger is better”, “lower is better” and “nominal is best”. Regardless of which S/N ratio is used, the larger S/N ratio is always selected. Because the Taguchi technique aims to keep to minimize the effects of uncontrollable factors (N) while maximizing the effects of controllable factors (S)[7]. The S/N ratio can be calculated by using the data in the test sample array. The objective of this study is the maximization of thermal effectiveness, which has been determined as a performance characteristic. For this purpose, “Larger is better” was selected and so S/N ratio was evaluated by using the following equation:

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{6}$$

In the given equation, y is the calculated value of the performance characteristic and n is the number of experiments carried out under these experimental conditions. ANOVA can be performed to obtain statistics of the calculated S / N values and to determine which experimental factor influences the test result at what level [19].

4. Results and Discussion

In the present work, three factors were selected related to the heat transfer characteristic. These factors are fresh air inlet temperature, air flow rate and exhaust air inlet temperature. Three levels determined for each factor are presented in Table 2.

Table 2. Factors and levels

	Factors	Level 1	Level 2	Level 3
A	Fresh air inlet temperature	0 °C	5 °C	10 °C
B	Air flow rate	1,2 m/s	1,6 m/s	2 m/s
C	Exhaust air inlet temperature	28°C	34°C	40°C

Table 3. Confirmation test

Optimum Levels			
Effective Factors	Level	Value	Average S/N
Fresh air inlet temperature	1	0 °C	30,95
Air flow rate	1	1,2 m/s	31,16
Exhaust air inlet temperature	3	40 °C	31,06
Mean of S/N ratios	30,863		
	Expected		Actual
Expected S/N ratio	31,44		31,36
Optimum effectiveness value	37,34		37

If the traditional experimental method had been used, it would have been necessary to perform 3^3= 27 experiments to test all factors and levels. In this study, Taguchi method was implemented and the L_9 (3^3) orthogonal array was selected as experimental plan. Thus, the number of experiments that need to be done was reduced to 9. The L_9 orthogonal array used for the experiments is given in Table 4. The numbers 1, 2, and 3 on each line indicate the levels of the factors.

Table 4. The orthogonal array L_9 (3^3)

	FACTORS AND LEVELS		
Experiment No	A	B	C
	Fresh air inlet temp. (°C)	Air flow rate	Exhaust air inlet temp. (°C)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

L_9 test plan prepared in accordance with the L_9 orthogonal array is given in Table 4. As can be seen from this table, 9 different experiments would be implemented using combinations of the three factors selected at different levels. Other factors were kept constant. Thermal effectiveness ε was taken as the signal factor and the noise factor was ignored. Each experiment was repeated twice under the same conditions at different times in order to detect the effect of noise sources on the heat transfer. Statistical and graphical analyses were performed with the Minitab software program.

The average S/N values obtained for each experiment are presented in Table 5 and the S/N ratio of every factor in every level is given graphically in Fig. 2. As mentioned above, S/N values can help researchers to determine the effect of parameters. The greatest S/N values at all levels of the parameters provide optimum performance. Considering Fig. 2, S/N ratio decreases by increasing fresh air inlet temperature and air flow rate and also increases by increasing exhaust air inlet temperature. Recent studies proved that heat exchanger effectiveness decreased as the air flow rate increased [15, 20-23] Mardiana and Rıffat [20] stated that; reducing air flow rate always increases efficiency in any heat recovery system and the effectiveness is decreased with increasing inlet fresh temperature [24]. The following values can be selected as the optimum parameters: 0 °C (A_1), the first level of fresh air inlet temperature; 1.2 m/s (B_1), the first level of air flow rate and 40 °C (C_3), the third level of exhaust air inlet temperature. $A_1B_1C_3$ has the largest S/N ratio, that's why this can be defined as the optimum parameter combination for this study.

Table 5. S/N ratios

Experiment no	Factors			Effectiveness	S/N
	A	B	C		
	Fresh air inlet temp. (°C)	Air flow rate (m/s)	Exhaust air inlet temp. (°C)		
1	0	1,2	28	35,8	31
2	0	1,6	34	35	31
3	0	2	40	35	31
4	5	1,2	34	36,1	31
5	5	1,6	40	35,7	31
6	5	2	28	33,4	30
7	10	1,2	40	36,5	31
8	10	1,6	28	33,6	31
9	10	2	34	33,4	30

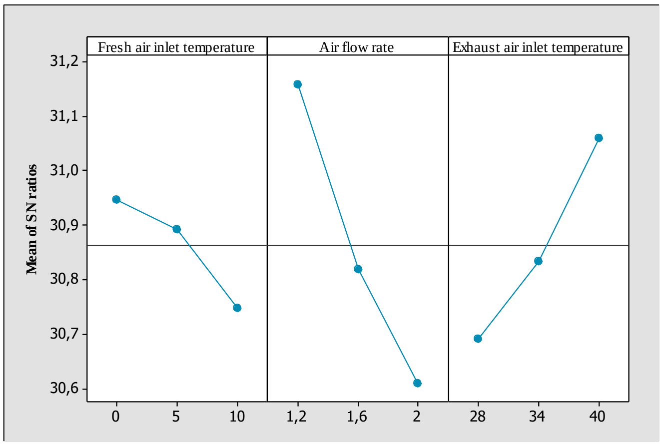

Fig. 2. Main effects plot for SN ratios

Following, the analysis of variance (ANOVA) is used to evaluate the experimental data. This statistical method makes the analysis results more significant and reliable [12]. ANOVA is frequently used to determine how the parameters affect the targeted performance characteristic and how the different levels of parameters change this effect. ANOVA was performed using the S/N ratios given in the Table 5. For this analysis, the mean of the S / N ratios is separately taken to determine the effect of each level of the factors. For example, if the first level (0 °C) of the fresh air inlet temperature is selected, 1, 2 and 3 numbered experiments of Table 5 must be taken into account. Then, the S/N ratio average is determined as (31,08+30,88+30,88) /3 = 30,95. When the first level (1,2 m/s) of the air flow rate is selected, 1, 4 and 7 numbered experiments of Table 5 must be taken into account. The S/N ratio average is calculated as (31,08+31,15+31,25) /3 = 31,16. As the first level (28 °C) of the exhaust air inlet temperature is selected, 1, 6 and 8 numbered experiments of Table 5 must be taken into account. The S/N ratio average is found as (31,08+30,47+30,53) /3 = 30,69. The mean of the S/N ratios of other levels of each factor was calculated in this way. These calculations are shown in Table 6. To find out the mean of all S / N ratios, the arithmetic average of the 9 values shown in bold is found. As a result, the mean of the S / N ratios is determined as 30,863.

For ANOVA, Sum of squares of the total, which indicates the total variance of the S/N ratio, needs to be evaluated [25]. The SS_T value is the sum of squares of SS_A , SS_B and SS_C which are the sum of squares of individual factors, and the sum of squares of error (SS_e). The sum of the squares was calculated by the following formulas [12, 26]:

Sum of the squares for total:

$$SS_T = \sum_{i=1}^{n} (\eta_i - \eta_m)^2 \tag{7}$$

Sum of the squares for factor A:

$$SS_A = n_{A_i} \sum_{i=1}^{k_A} (\eta_{A_i} - \eta_m)^2 \tag{8}$$

Sum of the squares for error:

$$SS_E = SS_T - \sum_{i=A}^{E} SS_A \tag{9}$$

η_i = S/N ratio

η_m =mean of S/N ratios

n = total number of experiments

k_A = number of levels of factor A

n_{A_i} = number of experiments at level i of factor A

η_{A_i} = S/N value at level i of factor A

The sum of the squares of all factors was calculated by this way and the ANOVA results are given in Table 7. For instance; the sum of the squares for the factor A (fresh air inlet temperature) is determined as: SS_A= $[(3 * (30{,}95 - 30{,}863)^2 + 3 * (30{,}89 - 30{,}863)^2 + 3 * (30{,}75 - 0{,}863)^2] = 0{,}0626.$

Table 6. The mean of S/N ratios

Fresh air inlet temperature				Air flow rate				Exhaust air inlet temperature		
Level 1	*Level 2*	*Level 3*		*Level 1*	*Level 2*	*Level 3*		*Level 1*	*Level 2*	*Level 3*
31,08	31,15	31,25		31,08	30,88	30,88		31,08	30,881	30,881
30,88	31,05	30,53		31,15	31,05	30,47		30,47	31,15	31,053
30,88	30,47	30,47		31,25	30,53	30,47		30,53	30,474	31,245
30,95	**30,89**	**30,75**		**31,16**	**30,82**	**30,61**		**30,69**	**30,84**	**31,06**
									Mean of S/N ratios	30,863

Degree of freedom of every column is derived from the levels of each control factor minus 1. The sum of the mean squares (MS) was calculated by dividing the sum of squares (SS) of each factor by the degrees of freedom (DF) of that factor [12]. The rank row is the order of factors according to their significance. The contribution ratio of each factor can be evaluated separately using the ANOVA table.

Contribution ratio means the effect of factor on the performance characteristic and it can be found out dividing the sum of the square of this factor by the total. For example, contribution ratio for fresh air inlet temperature (factor A) can be calculated as 0.0626 / 0.7263 = 0.086 (8,6 %). Contribution ratios of each factor are shown graphically in Fig.3.

Table 7. ANOVA table

	Degree of freedom (DF)	Average values			Sum of squares (SS)	Sum of mean squares (MS)	Contribution ratio %	Rank
		Level 1	Level 2	Level 3				
Fresh air inlet temperature	2	30,95	30,89	30,75	0,0626	0,0313	8,6	3
Air flow rate	2	31,16	30,82	30,61	0,4577	0,2289	63	1
Exhaust air inlet temperature	2	30,69	30,84	31,06	0,2055	0,1028	28,3	2
Error	2				0,00046	0,000234	0,1	
Total	8				0,7263		100	

The air flow rate has 63% of total effect, as it can be seen from Fig. 3 and Table 7. This means the parameter B is the most significant factor in heat recovery. The inlet temperature of the exhaust air is the secondary effective factor with the ratio of 28% and the fresh air inlet temperature was the factor with the lowest effect on the result of the experiment with a ratio of 8%. Results are compatible with database and literature. Mardiana and Riffat [20] specified that: air flow rate has a significant effect on all types of heat recovery efficiency or recovered heat and the temperature of the inlet air has a minor influence in the heat recovery system for both sensible and total efficiency. Niu and Zhang [24] submitted that sensible effectiveness does not change much with supply air inlet temperature. Yaici et al. [27] indicated that the outdoor temperature has only minor effects on heat recovery.

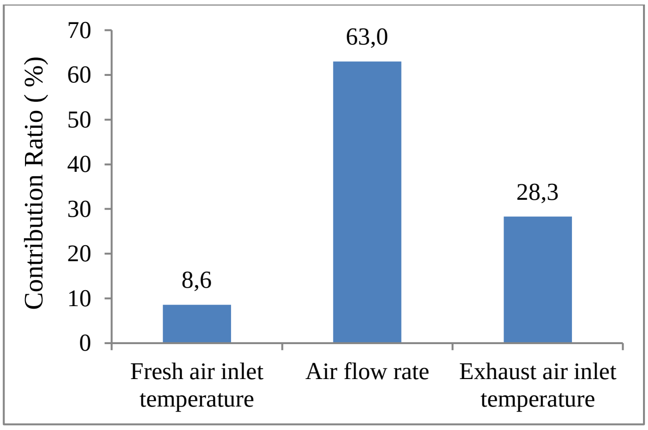

Fig. 3. Contribution ratios

After the ANOVA was carried out, the confirmation tests should be performed on the optimum parameter values. For this purpose, the optimum process parameters are selected. The second step is to predict and verify the improvements of the performance characteristic [7]. The test sample was prepared for optimal conditions ($A_1B_1C_3$). The results of the confirmation test are shown in Table 3. In order to test the predicted results, confirmation experiments were conducted within 95% significance level confidence (5% error). In order to find the expected S/N ratios following equation can be used [26]:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{k} (\bar{\eta}_i - \eta_m) \qquad (10)$$

$\hat{\eta}$ = expected S/N ratio

η_m = mean of S/N ratios

$\bar{\eta}_i$ = average S/N ratio at the optimum level

k = number of important factors affecting the performance

Since all three factors were determined as significant in the above analysis, each factor needs to be included in the calculation. By using the above equation, the expected S/N ratio was found 31,44 and the optimum effectiveness was found 37,34. The actual and expected S/N ratio and effectiveness values are shown comparatively in Table 3. When Table 3 is examined, it is observed that the expected and actual values are quite compatible with each other. And also results presents, the determined optimum process parameter shows better performance than the previous observations. Confirmation results proved the validity and reliability of the Taguchi approach used in the optimization of parameters.

5. Conclusion

In this article, the influence of various process parameters on waste heat recovery performance of plate heat exchanger was investigated experimentally. A device was installed in a laboratory environment where air to air waste heat recovery was enabled by means of a cross-flow plate-fin heat exchanger. The fresh air inlet temperature, the air flow rate and the exhaust air inlet temperature were determined as operating parameters. Three levels were selected for each parameter. Thermal effectiveness ε was taken as the performance indicator. The influence of three operating parameters on the thermal effectiveness was analysed. The optimum process conditions were determined by using the Taguchi method. The experiments were planned in accordance with Taguchi's L_9 orthogonal array and each trial was performed under different conditions of air flow rate, fresh and exhaust air inlet temperatures. The factors and levels were examined by using the signal-to-noise ratios and ANOVA methods. Minitab statistical software program was used for analysis. Results indicate that higher effectiveness can be achieved at a low fresh air inlet temperature, low air flow rate and high exhaust air inlet temperature. Based on the ANOVA results, all control factors have a significant impact on the quality characteristic. The most significant parameter has been found as air flow rate (63%). The second parameter is the exhaust air inlet temperature (28%) and the last one is the fresh air inlet temperature (8%). The optimum process parameter combination has been obtained as (A_1, B_1, C_3). At the end of the study, the validity of the Taguchi method was tested by performing the confirmation test. Compared the other trials, the highest thermal effectiveness (37%) is achieved when the optimum parameter combination is used. The results show that the Taguchi approach can be used to improve the effectiveness of air-to-air recovery. The predicted and experimental results are in very good agreement with each other. This show, the optimum conditions determined by the Taguchi method can be used reliably for real heat recovery applications.

Abbreviations

c	cold air
h	hot air
hi	hot air inlet
ci	cold air inlet
co	cold air outlet
ho	hot air outlet
$\dot{m}$	mass flow
C_{ph}	specific heat of the hot air
C_{pc}	specific heat of the cold air

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