Heat Recovery Optimization

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***Abstract* - In this study, changes in the heat recovery performance of the system under different operating conditions are investigated. A waste heat recovery device was installed for the experimental setup. A cross-flow plate heat exchanger made from cellulosic material is placed and thus heat transfer is ensured. Three different operating parameters were determined. Optimum conditions were determined by giving different values to these parameters. Statistical design of experiment (DOE) method was used for analyzes. As a result of the study, the values to be set for each parameter are explained in order to maximize the thermal effectiveness.**

***Keywords* – Design of experiment, Plate heat exchanger, Cellulosic, Waste heat recovery, Thermal effectiveness.**

I. Introduction

The rapid development of industry leads to the depletion of natural resources. For this reason, the *sustainability* of energy resources is very important. While meeting today's energy needs, on the one hand, resources to be transferred to future generations should be kept as much as possible.

Industrial systems that use very high amounts of energy have large heat recovery potential. With energy savings to be made in such systems, it will be possible to realize an environmentally sensitive production and to contribute to the country's economy. Waste energy can be reused by means of various equipments and one of the most preferred equipment for heat recovery is the plate heat exchanger. In this type of exchanger, hot air passes from one side of the plates while cold air is sent from the other side. At this point, some of the heat in the hot air is transferred to the cold air.

It is desirable that the heat exchanger plates are manufactured from materials having a high heat transfer coefficient. Therefore, aluminum is one of the most preferred materials in plate manufacturing. However, it is exposed to corrosion effects, especially in moist and chemical environments. For this reason, companies have turned to alternative materials. In recent years, materials such as polymers, ceramics, and cellulose have been used for this purpose. In this way, we can benefit from the positive properties of these different materials. For example; when micropore polymeric membranes or processed paper with moisture retention characteristics are used, latent heat transfer as well as sensible heat can be obtained and highest efficiency achieved [1, 2].

When we review the literature, studies on heat exchangers produced from paper or cellulose materials are very limited. Nasif et al. have experimentally evaluated the thermal performance of the heat transfer surface using a heat exchanger made of kraft paper [3]. Kocabas and Savaş, compared the waste heat recovery performance of a plate heat exchanger made of three different materials, aluminum, polymer and cellulosic [4].

In this study, different from the literature; the recovery performance of air to air waste heat was statistically investigated using a heat exchanger consisting of cellulosic plates. The purpose of this study is to reveal the best working parameters for waste heat recovery using the statistical design of experiment method.

II. MATERIAL AND METHODS

The present experiment simulates the process of transferring the heat contained in the exhaust air to the fresh air before the exhaust air is directed to the outer atmosphere. For this simulation; a system consisting of two fans to generate hot and cold air currents, resistors to generate hot air and a compressor to generate cold air is designed. In order to obtain exhaust air and fresh air at different temperature values, temperature thermostats which can set the desired value are used. In addition, a single-phase speed controller is preferred to control the speed of air supplied to the system [2].

A cross-flow plate heat exchanger is used in the system where heat transfer from air to air will be ensured. This system prevents dirty and clean air from mixing with each other. The heat exchanger consisting of cellulosic plates used in the experiment is given in Fig 1.

Figure 1: Cellulosic heat exchanger used in the experiment.

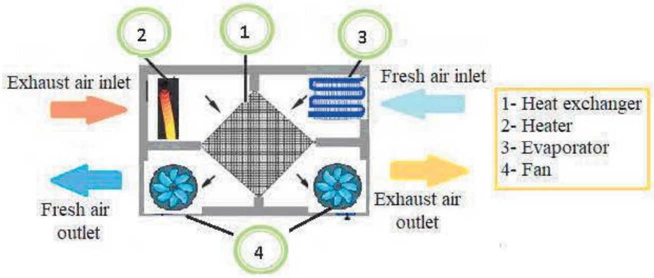

Figure 2: Schematic diagram of the heat recovery system.

The operating principle of the system is as follows: When exhaust air is sent from one side of the plate, fresh air passes by the other side. The fan is used to provide this air flow. The heat flow is synchronous. Fresh air and exhaust air do not come into contact with each other during heat transfer. Thus, the only heat transfer takes place. When the system is operated in winter conditions; warmer air is sent instead of cold fresh air towards the interior. So, by providing heat recovery; we have improved both thermal effectiveness and got energy saving [4].

Design of experiment; it is defined as experiments in which the input factors are intentionally changed in order to detect changes in output of a process. Variations in the output of the experiment are observed by giving various values to the factors. It is observed at which value the factors reach the target output. This method is very useful for determining the best or optimum operating conditions, estimating the individual effects of the factors, estimating the output values under optimal conditions, and so on [2, 5].

In order to implement the design of experiment method, quality variable, factors and levels should be determined. Therefore, in this study; thermal effectiveness is chosen as quality variable and it was aimed to maximize the thermal effectiveness value. Three factors have been identified: air flow rate, fresh air and exhaust air inlet temperatures. It is planned to use two levels of these factors. The factors represented by the letters A, B and C and their levels are shown in Table 1.

In the design of the experiment, ready tables which can be selected according to the factor and level numbers are used. By using these tables, we can perform experiments in a certain logic order and explain the results statistically. In the current study, 2 * 2 * 2 = 8 experiments should be performed to test all combinations of factors and levels since there are 3 factors and 2 levels. The ready L8 (2^3) test plan is given in Table 2. The "-" sign on the table indicates the first level and the "+" sign indicates the second level [2].

Table 1: Factors and levels.

Symbol	Factors	Level 1	Level 2
A	Fresh air inlet temperature	0 °C	10 °C
B	Air flow rate	1.2 m/s	2 m/s
C	Exhaust air inlet temperature	28°C	40°C

Table 2: Ready L8 test plan [5].

Fresh air inlet temp.	Air flow rate	Exhaust air inlet temp.	Results
-	-	-	
-	-	+	
-	+	-	
-	+	+	
+	-	-	
+	-	+	
+	+	-	
+	+	+	

III. RESULTS

All experiments were carried out in accordance with the L8 test plan given in Table 2. Using fresh and exhaust air inlet and outlet temperatures, thermal effectiveness are calculated as we explained in our previous studies [2, 4]. Factors, levels and calculated effectiveness values are shown in Table 3.

To find out how much each factor affects the result of the experiment, all the results should be grouped four by four according to two different levels of each factor. The first group is the first four values of the factor corresponding to the first level and the other group is the last four values of the factor corresponding to the second level. To determine the effect of the relevant factor on the test result, it is necessary to take the average of the first four values and compare them to the average of the second four values. For example, when we select the fresh air inlet temperature, which is one of the factors, the effect of the factor is calculated as:

First group average =(62,8+64,4+60,9 +62,1) /4 = 62,55
Second group average=(62,4+63,7+59,5+61,5) /4 = 61,78
Effect of factor = Second group average- first group average = (61,78 - 62,55)= - 0,77 (values taken from table 3)

According to the calculation, the transition from the first level to the second level caused the effectiveness to fall from 62,55 to 61,78. In this case, the effect of this factor is -0.77 which is the difference between the two averages. The meaning of the "-" sign is that changing the factor from level 1 to level 2, reduces the result of the experiment. The effects of all other factors can be found in the same way.

Table 3: Effectiveness results in accordance with L8 test plan [2].

Factors			Effectiveness (%)
Fresh air inlet temp. (°C)	Air flow rate (m/s)	Exhaust air inlet temp. (°C)	
0	1.2	28	62,8
0	1.2	40	64,4
0	2	28	60,9
0	2	40	62,1
10	1.2	28	62,4
10	1.2	40	63,7
10	2	28	59,5
10	2	40	61,5

Table 4: Experimental results show in excel L8 table [2].

Experiment Results	A		B		C		AB		AC		BC		ABC	
	1. Level	*2. Level*	*1. Level*	*2. Level*	*1. Level*	*2. Level*	*1. Level*	*2. Level*	*1. Level*	*2. Level*	*1. Level*	*2. Level*	*1. Level*	*2. Level*
62,8	62,8		62,8		62,8			62,8		62,8		62,8	62,8	
64,4	64,4		64,4			64,4		64,4	64,4		64,4			64,4
60,9	60,9			60,9	60,9		60,9			60,9	60,9			60,9
62,1	62,1			62,1		62,1	0.621		0.621			0.621	0.621	
62,4		62,4	0.624		0.624		62,1		62,1			62,1		62,1
63,7		63,7	63,7			63,7	63,7			63,7	63,7		63,7	
59,5		59,5		59,5	59,5			59,5	59,5		59,5		59,5	
61,5		61,5		61,5		61,5		61,5		61,5		61,5		61,5
Average	62,55	61,78	63,33	61,00	61,40	62,93	62,28	62,05	62,10	62,23	62,13	62,20	62,03	62,30
Effect	-0,77		-2,33		1,53		-0,23		0,12		0,08		0.27	

The excel table prepared in order to facilitate the above calculation is shown in Table 4. This table is used in practice for the analysis of test results as follows: First, the experiment result column is filled. All values in the row of this column are copied to the empty cells in that row. The averages of all columns are calculated and then saved on the "*Average*" row. Finally, the column averages of level 1 are subtracted from the average of the columns of each level 2 and the results are recorded in the "*Effect*" row [5].

The AB, BC, AC, and ABC columns indicate the interaction between factors. If we accept the first level of each factor as "-" and the value of the second level as "+" as we defined in Table 2, these signs are multiplied to create the sign of the interaction. For example, to find the sign of the first cell in the AC interaction column; The sign (-) on the first cell of A and the sign (-) on the first cell of C are multiplied. Since the multiplication result is "+", the sign of the first cell of the AC column becomes "+" and is saved as the 2nd level. The same method is followed to find the signs of other interactions. In this way; we can find the effects of all factors and interactions. The factor with the higher absolute value in the effect row has a much higher effect. According to this; factor B has the greatest effect, followed by factors C and A respectively.

Minitab program was used to visualize the data in the "*Effect*" row. The normal probability line showing the statistically significant effects is given in Figure 3. Confidence level was taken as 0.05 in statistical calculations. When the normal plot is examined, the significant points are found in the lower left corner of the graph or in the upper right part of the graph. The points near the normal probability line are statistically insignificant. Accordingly; points A, B, and C, which are directly distant, have been identified as significant; the AB, AC, BC and ABC interactions are considered to be insignificant since they are close to the line. The points on the left side of the line have a negative effect. This means that passing from the first level to the second level causes the result of the experiment to fall. Conversely, the points on the right side of the line have a positive effect on the end of result [2].

The Pareto graph showing the order of the points according to their significance levels is given in Figure 4. According to the Pareto graph; B is the factor with the greatest impact, followed by Factors C and A, respectively. If it is desired to improve effectiveness, the focus should first be on the B factor. As we can see in Figure 3, factor B has the (-) effect. Therefore; for the factor B, the first level, 1.2 m / s, should be selected.

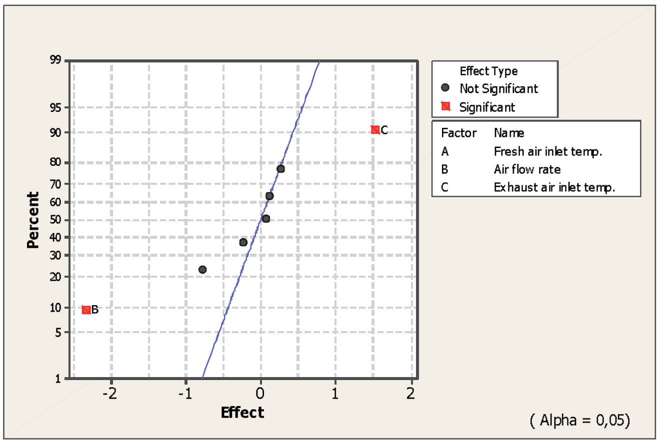

Figure 3: Normal plot of the effects.

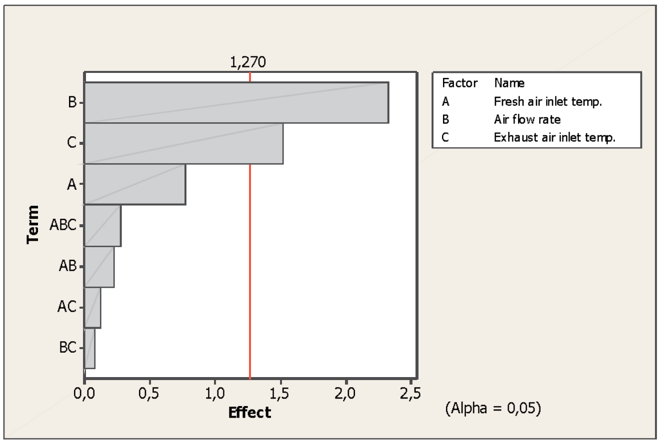

Figure 4: Pareto chart.

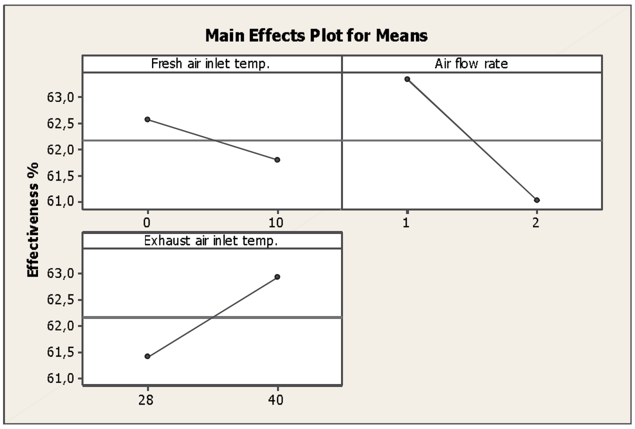

Figure 5: The effect of factors [2].

The change in the effect of bringing factors from the first level to the second level on the effectiveness is shown in Figure 5. The following comments can be made from this figure:

1) For Factor A: Increasing the fresh air inlet temperature from 0 ° C to 10 ° C will reduce effectiveness. This can be explained by the reduction in temperature difference between hot and cold air. The amount of the reduction is given in Table 4 as approximately 0,77%.
2) For factor B: Increasing the air flow rate from 1.2 m/s to 2 m/s led to a rapid fall in effectiveness. This is because there is not enough time for heat transfer when the air flow rate increases. The amount of fall is given in Table 4 as approximately 2,33%.
3) For factor C: Increasing the exhaust air inlet temperature from 28 ° C to 40 ° C will cause the effectiveness to rise slightly. This is due to the increase in temperature difference between hot and cold air. The amount of the increase is given in Table 4 as approximately 1,53%.
4) Air flow rate, represented by the factor "B" has the highest degree of effect on effectiveness. Then the factors "C" and "A" respectively.

IV. Conclusion

In this study, the effect ratios of factors affecting thermal effectiveness in a waste heat recovery system are investigated using full factorial design method L8 (2^3). A plan is created for two different levels of each factor. In analyzes where Minitab's statistical software program is preferred, air flow rate is the most effective factor. This is followed by exhaust air inlet temperature and fresh air inlet temperature, respectively.

These results show that higher effectiveness can be achieved at a low air flow rate, low fresh air inlet temperature and high exhaust air inlet temperature. In this respect, the most suitable working parameters for the system specified in the existing conditions; 0 °C for fresh air inlet temperature, 1.2 m/s for air flow rate and 40 °C for exhaust air inlet temperature. Moreover, this study shows that the experiment design method can be used easily in analyzing and optimizing the waste heat recovery performance.

References

[1] M. S. Owen, *Isıtma, Havalandırma ve İklimlendirme Uygulamaları*. İstanbul: ASHRAE -Türk Tesisat Mühendisleri Derneği, 2007.
[2] C. Kocabaş, “Farklı malzemelerden imal edilmiş plakalı ısı değiştiricilerinin atık ısı geri kazanım performanslarının deneysel analizi”, Master Thesis, Institute of Science and Technology, Bilecik Şeyh Edebali Üniversitesi, 2014.
[3] M. S. Nasif, R. Al-Waked, M. Behnia, M. and G. Morrison, “Modeling of air to air enthalpy heat exchanger,” *Heat Transfer Engineering*, vol. 33, pp. 1010-1023, 2012.
[4] C. Kocabaş and A.F. Savaş, “Comparison of waste heat recovery performances of plate-fin heat exchangers produced from different materials, ” *Contemporary Engineering Sciences*,” vol. 8(11), pp. 453 - 466, 2015.
[5] M. Şirvancı, *Kalite İçin Deney Tasarımı Taguçi Yaklaşımı*. İstanbul: Literatür Yayınları, 1997.