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Comparison of Waste Heat Recovery Performances of Plate-Fin Heat Exchangers Produced from Different Materials

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Abstract

High amount of waste heat emerging from thermal processes performed in the industry can be recovered by means of equipment such as heat pipes, heat exchangers and heat recovery boilers. In this study, thermal performance of a heat recovery device, which enables air-to-air heat transfer, was examined. For this purpose, cross-flow plate-fin heat exchangers were produced by using three different materials, which are aluminum, polymer and cellulose. With the established apparatus, outlet temperatures with different values were obtained for fresh air and exhaust air. Thermal calculations, were performed with the mathematical model developed by using the Effectiveness- Number of Transfer Unit (ε - NTU) method and their results were compared. It was seen that at the same air rate with the same exhaust air inlet temperature and the same fresh air inlet temperature; when the polymer heat exchanger is used, effectiveness value is 12,6% higher on an average than the aluminum heat exchanger. Similarly, when the cellulose heat exchanger is used, effectiveness value is 14,5% higher on an average than the polymer heat exchanger.

Keywords: heat recovery, plate-fin heat exchanger, air to air heat transfer

1 Introduction

Heat recovery equipment used in air conditioning systems enables fresh air, which is taken from the outer environment, to be pre-heated by using exhaust air, so that fresh air temperature is approximated to the conditions of the inner environment. In heat recovery, heat transfer between exhaust air and fresh air can be carried out by means of different tools such as heat wheel and heat pipe. However, the most common method is using cross-flow heat exchangers in which exhaust and fresh air sections are separated from each other by plates [1]. While exhaust air moves along one side of the plates, fresh air is moved along the other side so that heat exchange occurs. For this reason, heat exchanger plates are preferred to be produced from materials of which thermal conductivity coefficient is high [2].

Plate-fin heat exchangers can be produced from any kind of processable materials such as aluminum in particular, paper, plastic and ceramic. Aluminum is the most commonly used plate material because it is non-flammable and durable. Polymer plate heat exchangers are very useful with their resistance to low corrosion and their advantage of low cost as well as heat transfer improved by creating turbulence in channel flow [3], [4]. Plate-fin heat exchangers normally perform sensible heat exchange only. However, total heat exchange can be enabled by performing also latent heat transfer through a plate produced from a humectant material [2, 5, 6]. When processed paper and microcellular polymeric films are used, moisture holding capacity of the plates are significantly increased and total (enthalpy) heat exchanger is obtained [3].

When the literature is examined, numerous articles regarding heat exchangers can be found. However, aluminum heat exchangers are usually researched in the previous studies. In the recent years, different materials have been attempted to be used in heat exchanger production. One of such materials is polymer and the other is cellulose paper; however, there are a limited number of researches on these materials, particularly on paper in the literature. In this article, heat recovery performances of three different heat exchangers, which are made of aluminum, polymer and cellulose paper, were tested and compared to each other. Some of the studies on polymer and paper heat exchangers in the literature are given below. Chen et al. [7] used finned-tube heat exchangers produced from two different polypropylenes (PP) with high heat conductivity and also from ordinary PP material for verification and comparison. They pointed out that when the plastic thermal conductivity can reach over 15 W/m^2 °K, it can achieve more than 95% of the titanium heat exchanger performance and 84% of the aluminum or copper heat exchanger performance with the same dimension. In their studies, Fernandez-Seara et al. [8] examined an air-to-air heat recovery unit created by using polymer plate heat exchangers. They conducted experimental parametric analysis in order to research the impact of changes in working conditions on performance of heat exchanger. In their studies, Joen et al. [9] used very thin polymer structures, constructed both plate-fin and finned-tube heat exchangers and tested their performances when compared to traditional units. They stated that usage of such materials as heat exchanger in heat recovery practices is promising. Cevallos et al. [10], specified that the low thermal conductivity of polymeric materials has been offset by the use of very thin films in mechanically innovative designs that provide sufficient structural integrity to support the prevailing pressure differences. Nasif et al. [11], experimentally evaluated the performance of a Z-type flow heat exchanger utilizing 45-gsm Kraft paper as heat moisture transfer surface. They determined the performance in terms of both sensible effectiveness and latent effectiveness. Lee et al. [12], discussed operation of the total heat exchangers in their article is based on thin fibrous paper. They tested performances of six exchangers made of different functional papers under different flow rates. Zhang [13], constructed and tested one is paper-fin and paper-plate, and another one is paper-fin and membrane-plate, for heat and moisture recovery. Both the experimental data and numerical results indicate that the latent effectiveness of the paper-fin and membrane-plate core is 60% higher than the traditional paper-fin and paper-plate core, due to the high moisture diffusivity in the composite supported liquid membrane.

In this study, a device was designed and constructed in laboratory environment for recovery of waste heat. In this device, waste heat recovery was enabled by means of a cross-flow plate-fin heat exchanger. Heat exchangers produced from three different materials, which are aluminum, polymer and cellulose, were constructed and their thermal performance values were compared. Air rate and inlet temperatures for fresh air and exhaust air were determined as operation parameters. As a result of the conducted tests, the outlet temperatures for fresh air and exhaust air were obtained and thermal calculations were made on the basis of these values. In conclusion, exchanger type and parameter choice required for an optimum thermal performance were revealed.

2 Installations of the Apparatus

In order to allow hot and cold air to exchange heat without mixing into each other, a cross-flow plate-fin heat exchanger was used. In the apparatus plate-fin heat exchangers, which were produced from three different materials, were used. First one of these was produced by using aluminum, second one was produced by using polymer and third one was produced by using cellulose paper materials. All heat exchangers used in the apparatus were shown in Figure 1. And also characteristics of all the heat exchangers were stated respectively in Table 1.

a) aluminum b) polymer c) cellulose.

Fig. 1 The heat exchangers used in the apparatus

Table 1 Characteristics of aluminum, polymer and cellulose heat exchangers

	ALUMINUM	POLYMER	CELLULOSE
Material of plate	Aluminum	Polypropylene	Cellulose paper
Dimensions of plate	200*200*300mm	200*200*300mm	200*200*300mm
Number of fins	24	50	70
Distance between fins	10 mm	2,6 mm	1,8 mm
Wall thickness	0,8 mm	0,2 mm	0,2 mm
Heat transfer area	2 m^2	4 m^2	5,6 m^2

Ambient air was heated through lamellar resistance heaters so that ambient air with high temperature was obtained. This air, which is also called exhaust air, can be set to different temperature values by means of a temperature control thermostat. In order to obtain cold ambient air, air compressor cooling assemblies were used. The air called fresh air can be set to different temperature values by means of a temperature control thermostat. The compressor cooling assemblies have an air-cooled condenser and the refrigerant circulating in the system is R-22. Two fans with 2500/2700 rpm speed were used. While one of these fans allows the exhaust air moving along the plates to be discharged, the other allows the fresh air, which was heated while moving along the plates, to be given into the inner environment. In the test, effectiveness of the system was researched by using air flows at different speeds. For this purpose, an anemometer was used to measure air speed. In order to ensure that fan speeds were fixed at a desired value and to obtain different speeds, a single-phase speed control device was used. The speed control device has a speed control panel which can control rotation speed of the fan motors used in ventilation systems by changing the voltage to be applied. For temperature control of the heaters that we used to obtain hot air, a temperature control thermostat was utilized. A digital thermostat was used in the compressor cooling assemblies in order to maintain the cold air temperature at a fixed value. This thermostat allows defrosting at regular intervals and durations by stopping the compressor in the systems functioning in positive degrees.

3 Operation Principles

While the exhaust air with high temperature is sucked by one end of the heat exchanger and diagonally crosses to the other side, the cooled fresh air is similarly sucked by the other end and diagonally crosses to the other side, in order to be discharged to the outer environment. The hot and cold air passing between the plates, only exchange heat without mixing into each other. The purpose is to allow high amount of thermal energy in the exhaust air to be used in heating the fresh air. Hence heat recovery will be achieved and energy will be saved. Schematic drawing of the system is given in Figure 2 and its actual picture is given in Figure 3.

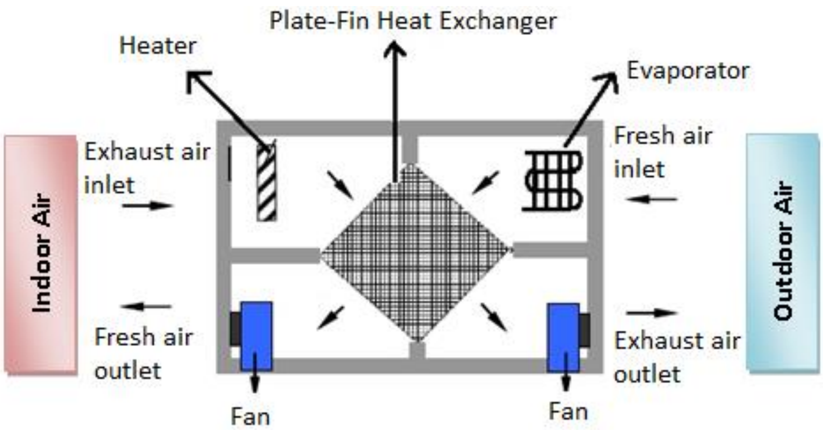

Fig. 2 Schematic representation of the testing apparatus

Fig. 3 The heat recovery device used in the test

Two methods, one of which is log mean temperature difference (LMTD) method and the other is effectiveness number of heat transfer units (ε-NTU) approach, were developed in order to be able to make calculations for a heat exchanger. If a heat exchanger will be designed, LMTD method would be much more useful. Through this method, desired temperature of one of the hot or cold fluids as well as inlet temperatures and flows of the hot and cold fluids are known. Afterwards, an appropriate type of heat exchanger is selected and heat transfer to provide the desired outlet temperature, surface area and hence the size of the heat exchanger are determined. ε-NTU method is preferred when the heat exchanger type and size, fluid flows and inlet temperatures are determined and outlet temperatures and heat transfer performance are intended to be found [14]. In addition, this method enables the heat exchangers that can be used for the same purpose to be compared to each other and allows selection of the most appropriate heat exchanger among these [15].

The most accepted method for thermodynamic analysis of heat exchangers in the literature is ε-NTU method [16]. In this study, ε-NTU method was preferred because we compared performances of different exchangers. In the calculations, latent heat transfer and pressure drops were neglected and it was assumed that no heat loss to outer environment occurred. Effectiveness of a heat exchanger is defined as the ratio of heat transfer occurring in any heat exchanger to maximum possible heat transfer and it is shown as ε [17], [18].

$$\varepsilon = \frac{Q}{Q_{max}} \qquad (1)$$

The heat amount in question can be calculated with heat given by the hot fluid or taken by the cold fluid.

$$\mathrm{Q} = \mathrm{C}_1(\mathrm{T}_{h1} - \mathrm{T}_{h0}) \quad \text{or} \quad \mathrm{Q} = \mathrm{C}_2(\mathrm{T}_{co} - \mathrm{T}_{ci}) \qquad (2)$$

$$C_1 = \dot{m}_h c_{p,h} \quad \text{(The heat capacity of the hot fluid)} \qquad (3)$$

$$\mathrm{C}_2 = \dot{m}_c c_{p,c} \quad \text{(The heat capacity of the cold fluid)} \qquad (4)$$

Q_{max} value, which is defined as maximum possible heat transfer amount, is found by multiplying C_1 or C_2 thermal capacity flow rate, whichever is smaller, with the temperature difference between hot fluid inlet and cold fluid inlet [17], [18].

$$C_1 < C_2 \rightarrow Q_{max} = C_1 (T_{hi} - T_{ci}) \qquad (5)$$

$$C_2 < C_1 \rightarrow Q_{max} = C_2 (T_{hi} - T_{ci}) \qquad (6)$$

$$Q_{max} = C_{min} (T_{hi} - T_{ci}) \qquad (7)$$

For any heat exchanger, number of heat transfer units (NTU) is an indicator of the heat exchanger size and it is a pure number. NTU is commonly used in thermal analysis of heat exchangers. It is defined as below [19];

$$\mathrm{NTU} = \frac{\mathrm{U\,A}}{\mathrm{C_{min}}} \tag{8}$$

Effectiveness value can be expressed as a function dependent on flow characteristic with number of heat transfer units (NTU) and $\mathrm{C^{*}} = \mathrm{C_{min}}/\mathrm{C_{max}}$ thermal capacity ratio values as below [20];

$$\varepsilon = \mathrm{f}\left(\mathrm{NTU}, \frac{\mathrm{C_{min}}}{\mathrm{C_{max}}}, \text{flow type}\right) \tag{9}$$

Where a cross-flow heat exchanger in which two fluids are not mixed $0 < \frac{\mathrm{C_{min}}}{\mathrm{C_{max}}} \leq 1$, effectiveness is [15], [20];

$$\varepsilon = 1 - \exp\left[\frac{\exp(-\frac{\mathrm{C_{min}}}{\mathrm{C_{max}}}(\mathrm{NTU})^{0{,}78}) - 1}{\frac{\mathrm{C_{min}}}{\mathrm{C_{max}}}(\mathrm{NTU})^{-0{,}22}}\right] \tag{10}$$

Since type and size of the heat exchanger and flow rates of the fluids are known, effectiveness value is found by calculating NTU and ($\mathrm{C_{min}}/\mathrm{C_{max}}$) ratio and using the formula given in Eq. (10). Afterwards, outlet temperatures of the two fluids were calculated by using Eq. (11) and Eq. (12) given below. The calculated values and the values obtained from the test were compared and it was seen that the results were approximately the same. According to these descriptions, effectiveness of a heat exchanger is calculated as below [14], [20];

$$\varepsilon = \frac{\mathrm{C_1}(\mathrm{T_{hi}} - \mathrm{T_{ho}})}{\mathrm{C_{min}}\,(\mathrm{T_{hi}} - \mathrm{T_{ci}})} \tag{11}$$

$$\varepsilon = \frac{\mathrm{C_2}\,(\mathrm{T_{co}} - \mathrm{T_{ci}})}{\mathrm{C_{min}}\,(\mathrm{T_{hi}} - \mathrm{T_{ci}})} \tag{12}$$

4 Results and Discussion

The purpose of establishing the apparatus is to compare heat recovery performances of the plate-fin heat exchangers, in a heat recovery device. In the apparatus, measurements were taken by three different plate-fin heat exchangers, one of which produced from aluminum, one is produced from polymer and one is produced from cellulose material. Heat exchanger material, air rate, fresh air inlet temperature and exhaust air inlet temperature were determined as our parameters. For measurements taken in each test; while one parameter was changed, others were kept fixed.

Outlet temperature values of heat exchanger for each air rate and inlet temperature value were read and recorded. Each heat exchanger were tested at three different air rates which are 1,2 m/s, 1,6 m/s and 2 m/s. Two different fresh air inlet temperatures, which are 0 °C and 10 °C, seven different exhaust air outlet temperatures, which are 28 °C, 30 °C, 32 °C, 34 °C, 36 °C, 38 °C and 40 °C were obtained.

In the first test, the aluminum heat exchanger were inserted into the recovery device and the air rate was set as 1,2 m/s. The fresh air temperature was fixed at 0 °C and the exhaust air with different temperatures starting from 28 °C up to 40 °C were given to the system one by one. For each value, the fresh air and exhaust air outlet temperatures were recorded. Afterwards, tests were repeated with the same plate and at the same air rate by changing only the fresh air temperature as fixed to 10 °C and all the results were recorded. The same process steps were repeated for other air rates as well, thus the tests for the aluminum heat exchanger were completed. Then the polymer and cellulose heat exchangers were respectively inserted to the device and all abovementioned test steps were conducted again. In case of conflicted readings, the tests were repeated and the results were compared to the calculated values. While the fresh air inlet temperature was taken as 0 °C and 10 °C, the exhaust air inlet temperature was gradually increased from 28 °C up to 40 °C and the fresh air outlet temperatures corresponding to different air rates were shown comparatively for the aluminum, polymer and cellulose heat exchangers through the diagrams below. Diagrams presenting the fresh air outlet temperatures obtained from the tests when fresh air inlet temperature was taken as 0 °C and 10 °C are given in Figure 4 and Figure 5.

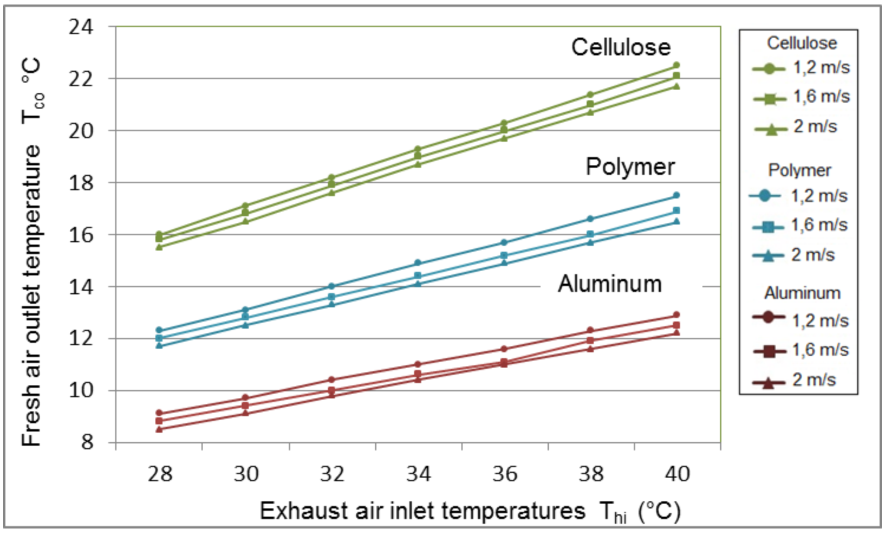

Fig. 4 Comparison of the fresh air outlet temperatures of the aluminum, polymer and cellulose heat exchangers at different air rates when the fresh air inlet temperature is 0 °C

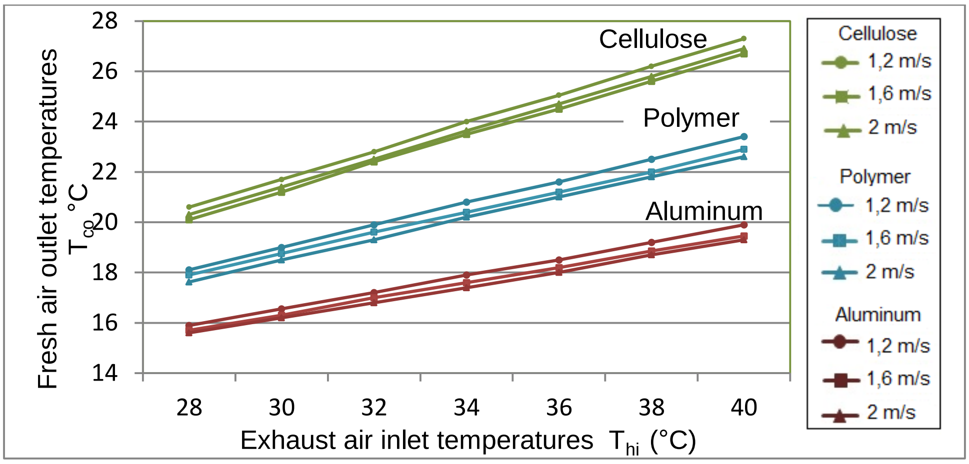

Fig. 5 Comparison of the fresh air outlet temperatures of the aluminum, polymer and cellulose heat exchangers at different air rates when fresh air inlet temperature is 10 °C

Our interpretations on the above given diagrams that present the fresh air outlet temperatures are as follows:

1. When the aluminum, polymer and cellulose heat exchangers are compared at the same air rate, with the same exhaust air inlet temperature and the same fresh air inlet temperature; the highest outlet temperature for fresh air is obtained from the cellulose heat exchanger. It is followed by the polymer and aluminum heat exchanger.

2. For all the heat exchangers, where air rate and fresh air inlet temperature are kept fixed and exhaust air inlet temperature is increased, fresh air outlet temperatures constantly increase.

3. For all the heat exchangers, where the air rate and the exhaust air inlet temperatures are kept fixed and the fresh air inlet temperature is increased, fresh air outlet temperature increases.

4. For all the heat exchangers, where the exhaust air inlet temperature and the fresh air inlet temperature are taken as a fixed value; while the air rate is being increased, fresh air outlet temperature decreases.

Effectiveness (ε) values were calculated by using the fresh air (T_{co}) and exhaust air (T_{ho}) outlet temperatures that were obtained from the tests. Data regarding the calculated values were shown in diagrams below in Figure 6 and Figure 7.

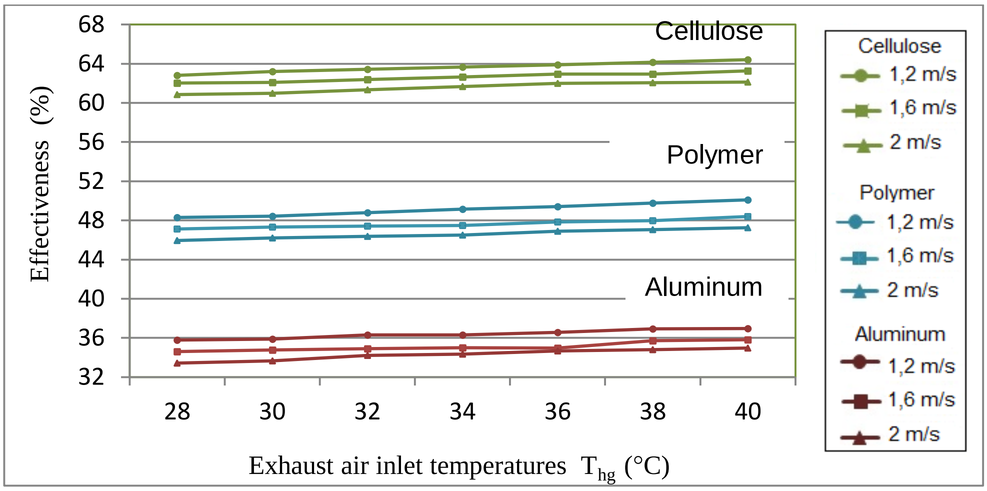

Fig. 6 Comparison of effectiveness of the aluminum, polymer and cellulose heat exchangers where the fresh air inlet temperature is 0 °C at different air rates

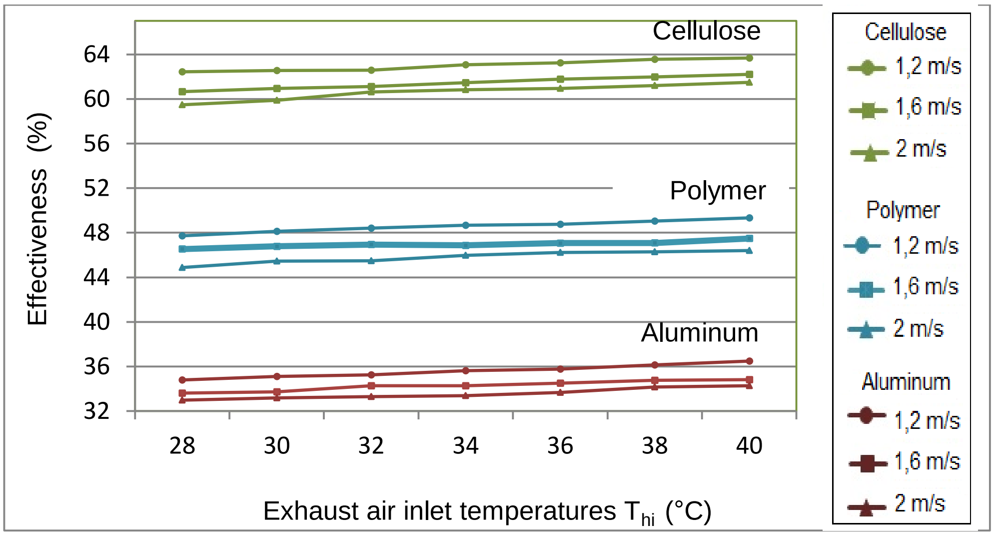

Fig. 7 Comparison of effectiveness of the aluminum, polymer and cellulose heat exchangers where the fresh air inlet temperature is 10 °C

Effectiveness ε values were calculated individually for the aluminum, polymer and cellulose heat exchangers and shown through the diagrams above. Our interpretations on these diagrams are as follows:

1. When the aluminum, polymer and cellulose heat exchangers are compared at the same air rate, with the same exhaust air inlet and fresh air inlet temperatures; the highest effectiveness ε values are obtained from the cellulose heat exchanger. This is because the highest fresh air outlet temperature under the same conditions is reached when the cellulose heat exchanger is used. It is followed by the polymer and aluminum heat exchangers respectively.

2. In all the heat exchangers, for which the air rate and the fresh air inlet temperature are kept fixed and the exhaust air inlet temperature is increased, effectiveness ε values increase.

3. In all the heat exchangers, for which the air rate and the exhaust air inlet temperature are kept fixed; while the fresh air inlet temperature is increasing, effectiveness ε values decrease.

4. In all the heat exchangers, for which the exhaust air inlet temperature and the fresh air inlet temperature are taken as a fixed value; while the air rate is being increased, effectiveness ε values decrease. This is because while the air rate is being increased, the fresh air outlet temperature decreases.

4 Conclusion and Suggestions

In this study, a heat recovery apparatus using a plate-fin heat exchanger was designed and constructed. The apparatus system was operated individually for three heat exchangers, each produced from different materials which are aluminum, polymer and cellulose. The fresh and exhaust air outlet temperatures obtained from each test were recorded and thermal calculations were made by using these values.

When these three different heat exchangers are compared to each other at the same air rate, with the same exhaust air inlet temperature and the same fresh air inlet temperature; the highest fresh air outlet temperature and the highest effectiveness ε value were obtained from the cellulose heat exchanger. It is followed by the polymer and aluminum heat exchangers respectively. At the same air rate with the same exhaust air inlet temperature and the same fresh air inlet temperature; when the polymer heat exchanger is used, effectiveness value is 12,6% higher on an average than the aluminum heat exchanger. Similarly, when the cellulose heat exchanger is used, effectiveness value is 14,5% higher on an average than the polymer heat exchanger. When the aluminum heat exchanger and the cellulose heat exchanger are compared; the difference between them reaches up to 27% on an average. In this case, when we insert the cellulose heat exchanger into the same cross-section area instead of the aluminum heat exchanger; effectiveness value would increase by 27%.

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