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Empirical investigation of small-scale aluminium wool packed solar air heater made with waste material

Atık malzemelerden yapılan küçük ölçekli alüminyum yün dolgulu güneş destekli hava ısıtıcısının deneysel incelemesi

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Empirical Investigation of Small-scale Aluminium Wool Packed Solar Air Heater Made With Waste Material

Highlights

- *Performance analysis of small-scale solar air heaters fabricated with waste metal.*
- *Analysis of the effect of aluminium wool integration on the thermal performance.*
- *Average thermal efficiency was obtained in the range of 42.69-56.98%.*

Graphical Abstract

In this study, two solar air heaters made with scrap metal elbows were designed, fabricated and empirically analyzed. Also, impact of aluminium wool packing on the thermal performance was investigated.

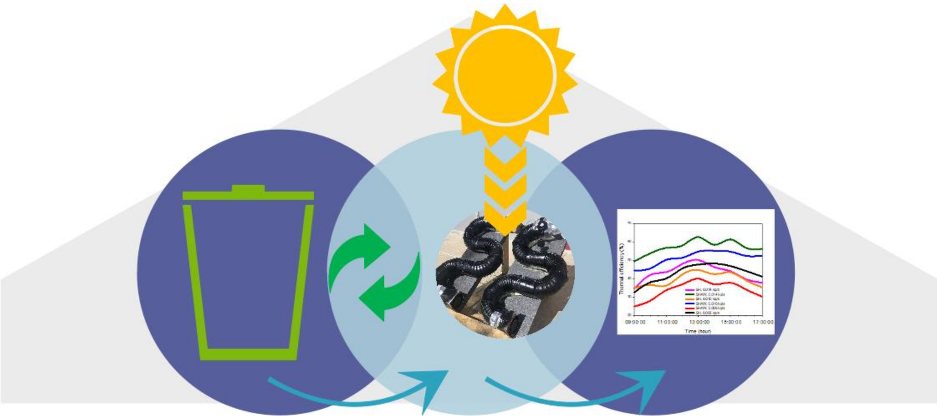

Fig. A. Graphical Abstract

Aim

Manufacturing and testing of sustainable solar air heating system with recycled materials.

Design & Methodology

Two tubular small-scale solar air heating systems were desinged and manufactured. One of them was packed with aluminum wool. Both heaters were tested in three different air mass flow rates.

Originality

Unusual materials such as scrap metal elbows and aluminum wool were used in the solar air heater manufacturing process for sustainable thermal energy production and waste management.

Findings

The thermal efficiency values for hollow heater and modified heater were obtained in the range of 33.63-42.90% and 42.69-56.98%, respectively.

Conclusion

Designed and tested system shows that waste materials can be used in sustainable thermal energy systems effectively.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Empirical Investigation of Small-Scale Aluminium Wool Packed Solar Air Heater Made with Waste Material

(This study was presented at 2nd International Conference on Technology and Science / Techno-Science 2019.)

Research Article / Araştırma Makalesi

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ABSTRACT

Waste production is an important problem for the developing world and globalization. The waste materials can be reused through recycling process and its environmental effects can be minimized. Utilizing renewable energy sources at the maximum level is also an important issue for a sustainable development in future as well as waste management. In this study, small-scale solar air heating systems were produced from waste materials to analyze the usability of waste material in renewable energy systems. Scrap metal elbows were used in the production of heaters. The first solar heater is hollow (SH) and the second one was modified by filling it with aluminum wool (SHAW). Both heaters were tested simultaneously at different flow rates (0.014, 0.010 and 0.006 kg/s). According to the experimental results, the thermal efficiency values for SH and SHAW were found in the range of 33.63-42.90% and 42.69-56.98%, respectively. In addition, it was observed that a low cost modification such as using aluminum wool can significantly increase thermal performance of the solar heating system.

Keywords: Solar air heater, solar energy, scrap metal elbow, aluminium wool, recycling.

Atık Malzemelerden Yapılan Küçük Ölçekli Alüminyum Yün Dolgulu Güneş Destekli Hava Isıtıcısının Deneysel İncelemesi

ÖZ

Atık üretimi gelişen dünya için önemli bir sorundur. Atıklar geri dönüşüm yoluyla tekrar kullanılabilmekte ve çevresel etkileri en aza indirgenebilmektedir. Yenilenebilir enerji kaynaklarından maksimum düzeyde faydalanılması da atık yönetimi gibi sürdürülebilir gelecek için önemli bir konudur. Bu çalışmada atık malzemelerden üretilmiş küçük ölçekli güneş destekli hava ısıtma sistemleri, bu malzemelerin yenilenebilir enerji sistemlerinde kullanılabilirliğini analiz etmek için üretilmiştir. Isıtıcıların üretiminde hurda metal dirsekler kullanılmıştır. Üretilen ilk ısıtıcı içi boş yapıdadır (SH). İkinci güneş destekli ısıtıcı ise alüminyum yün ile doldurularak modifiye edilmiştir (SHAW). Her iki ısıtıcı da aynı anda farklı debilerde denenmiştir (0.014, 0.010 ve 0.006 kg/s). Deneysel sonuçlara göre SH ve SHAW için termal verim değerleri sırasıyla 33.63-42.90% ve 42.69-56.98% aralığında bulunmuştur. Bulgulara göre alüminyum yün gibi düşük maliyetli bir modifikasyonun güneş destekli ısıtma sisteminin termal performansı önemli ölçüde arttırdığı gözlemlenmiştir.

Anahtar Kelimeler: Güneş destekli hava ısıtıcı, güneş enerjisi, hurda metal dirsek, alüminyum yün, geri dönüşüm.

1. INTRODUCTION

Due to the growing world population and global promotion, using scrap materials can be considered as one of the primary problems for a sustainable environment. Industrialization, quickly urbanization and consuming habits that change day by day are the important factors which have negative impacts on the environment [1]. This huge volume of increasing wastematerials and consequently their environmental impacts has been reached risky and dangerous levels. The volume of solid waste changes according to the general socio-economic conditions and structure of the countries and territories. However, depending on the social and cultural features in different cities within the borders of country, consumption habits of the nation differ [2].

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Waste management and sustainable development are mostly encountered in the field of waste management research, which evaluate environmental and also sustainable development subjects from various perspectives. Limited natural resources in the global levels make it necessary to discover suitable solutions and sustainable development [3,4].

In the field of recycling waste materials, metal wastes are considered to be recycled in various processes and they could be used in different applications after recycling. There are a number of studies provided in literature, which studied reusing and recycling electronic wastes [5-7] and reutilizing metal wastes [8-10]. Giving priority for using clean energy sources is an important issue in environmental sustainability and development. Solar energy as a renewable and sustainable energy source has a remarkable potential to be used in different fields to provide required energy [11,12].

Heat energy produced from solar energy is wildly utilized in many countries around the world. Solar thermal systems are basically classified to solar water and solar air heaters depending on used heat transfer fluid. Solar heaters are often employed to use in space heating, drying applications and air conditioning systems [13-15]. Experimental and numerical study of indirect solar dryer which was modified using iron mesh [16] and performance analysis of a manufactured greenhouse dryer [17] are other outstanding studies on solar energy utilization provided in the literature.

On outstanding method for increasing thermal performance of solar heaters is utilizing packing materials with high thermal conductivity. In a study done by Chouksey and Sharma (2016) wire screen was utilized to enhance the efficiency of solar heater [18]. In another study, Singh et al. (2015) packed bed heat storage system was investigated. They used rock pebbles for energy storage and compared it with phase change materials [19]. Dhiman et al. (2012) analyzed the effect of using wire matrix in different heaters. They compared the performance of the heaters and stated that the modified heater with counter flow was the highest performance [20]. Prasad et al. (2009) utilized wire mesh with the aim of improving the efficiency of solar heater. They investigated the effect of porosity value on the heat transfer and obtained the efficiency in the range of 77-90% [21]. Investigating packed bed solar heaters packed with various materials showed the successfulness of this technique. Aluminum wool can be a good candidate to be used in solar heaters because it is light and has high thermal conductivity.

In this study, two small-scale solar-powered air heaters were produced from waste materials. One of them is hollow and the other one is filled with aluminum wool. The main purpose of this study is to demonstrate the production of sustainable thermal energy from waste or scrap materials and also to increase its thermal performance with a low cost modification. General structure of the present work is shown in Fig. 1.

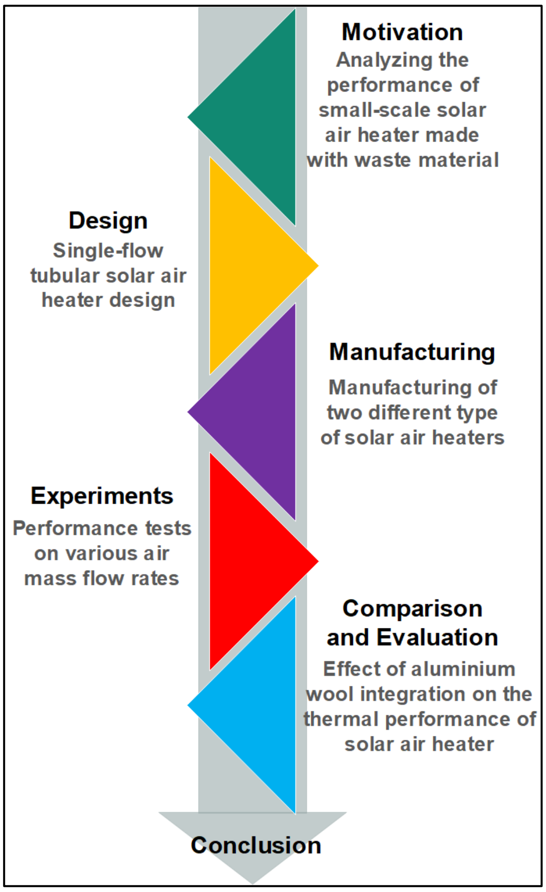

Fig. 1. A view of aluminum wool used in the solar heating systems

2. MATERIALS AND METHODS

In this study, scrap metal elbows were used to generate sustainable hot air from waste materials. Accordingly, 6 elbows were utilized in the first solar air heater (SH). Diameter of elbows is 95 mm. The material thickness is 1 mm. The second air heater (SHAW) has same dimensions and it has been packed with aluminum wool. The utilized aluminum wool has a density of 2700 kg/m^3 and a thermal conductivity value of 237 W/mK. It is aimed to enhance heat transferby adding aluminum wool. Both heaters were coated with matt black spray paint. The surface area of both heaters is 0.16 m^2. A view of aluminum wool used in the solar heating systems is shown in Fig. 2. Thermal insulation material with 50 mm thickness were placed on the bottom side of the heaters to prevent heat losses. Thus, the heat loss from the bottom will be minimized and more accurate measurements will be taken in the experimental study. Low energy consuming AC fans (40 W) with the same features were installed at the inlets of the heaters. A wooden platform was produced to install heaters in desired position. The angle of inclination of the produced platform is 32º.

Experimental studies were carried out in Burdur/Turkey in October. Experiments were started at 09:00 and continued for 8 hours. Experiments were carried out at three different air flow rates (0.014, 0.010 and 0.006

kg/s). All measurements were performed at 15 minutes intervals. A view of experimental setup is shown in Fig. 3. Air temperature measurement was made by utilizing 5 K-type thermocouples (accuracy: ±0.5 ºC). Temperature measurement points can be seen in Fig. 3 (orange circles). Moreover, two dataloggers were used in logging measured temperature data (accuracy: ±0.3 °C). Solar radiation and velocity were measured by utilizing a solarimeter (accuracy: ±10 W/m^2) and an anemometer (accuracy: 2%), respectively.

Fig. 2. A view of aluminum wool used in the solar heating systems

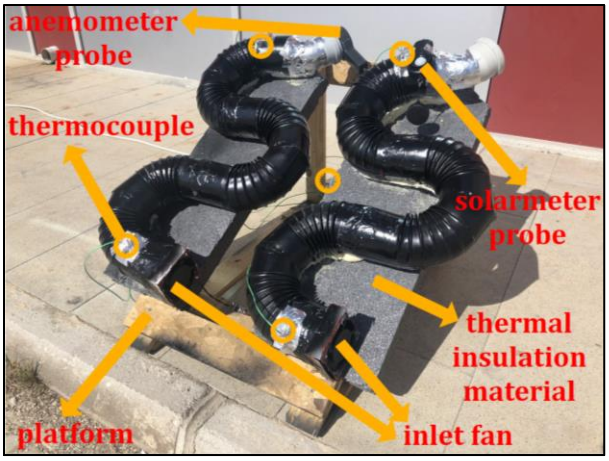

Fig. 3. A view of experimental setup

3. THEORETICAL CALCULATIONS

Mass conservation of air can be defined by using the following expression:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

here, $\dot{m}$ is mass flow rate in the solar air heating system (kg/s) and can be obtained by:

$$\dot{m} = \rho V A \quad (2)$$

Specific heat capacity of air and air density can be calculated by using Eq. (3) and Eq. (4), respectively [22].

$$c_p = 999.2 - 0.1434 \times T + 1.101 \times 10^{-4} T^2 - 6.7581 \times 10^{-8} T^3 \quad (3)$$

$$\rho = 353.44/T \quad (4)$$

where T is temperature (K), ρ is density of air (kg/m^3) and A is area (m^2). Reynolds number can be calculated by using Eq. (5) [23]:

$$Re = (\rho V D_h)/\mu \quad (5)$$

here, V is air velocity (m/s), D_h is hydraulic diameter (m) and μ is dynamic viscosity of air (Pa.s).

Nusselt number can be found by utilizing the following expression:

$$Nu = (h D_h)/k \quad (6)$$

where k is thermal conductivity (W/mK) and h is heat transfer coefficient (W/m^{2}K).

Useful heat energy gained by solar heater can be found as:

$$Q_{us} = \dot{m} c_p (T_{out} - T_{in}) \quad (7)$$

Thermal efficiency of the solar heater can be found as [24]:

$$\eta = \frac{\dot{m} c_p (T_{out} - T_{in})}{I A_{sh}} \quad (8)$$

where A_{sh} is surface area of the solar heater (m^2) and I is solar radiation (W/m^2).

Coefficient of performance can be calculated by utilizing Eq. (9) [17]:

$$COP = Q_{us}/W_t \quad (9)$$

here, W_t is total electrical power. In this study, low energy consuming fans were utilized and this value can be taken as power of fan.

Total experimental uncertainty can be expressed by Eq. (10):

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2 \right]^{1/2} \quad (10)$$

Here, w_1, w_2, w_n are the uncertainties in the independent variables.

Total uncertainly for mass flow rate can be found as:

$$W_{\dot{m}} = \left[\left(\frac{\partial \dot{m}}{\partial V} w_V\right)^2 + \left(\frac{\partial \dot{m}}{\partial D} w_D\right)^2 + \left(\frac{\partial \dot{m}}{\partial \rho} w_\rho\right)^2 \right]^{1/2} \quad (11)$$

Total uncertainty for thermal efficiency can be calculated by using Eq. (12):

$$W_\eta = \left[\left(\frac{\partial \eta}{\partial \dot{m}} w_{\dot{m}}\right)^2 + \left(\frac{\partial \eta}{\partial c_p} w_{c_p}\right)^2 + \left(\frac{\partial \eta}{\partial \Delta T} w_{\Delta T}\right)^2 + \left(\frac{\partial \eta}{\partial A_{sh}} w_{A_{sh}}\right)^2 + \left(\frac{\partial \eta}{\partial I} w_I\right)^2 \right]^{1/2} \quad (12)$$

4. RESULTS AND DISCUSSION

Change of ambient air temperature over time is shown in Fig. 4. Accordingly, average ambient air temperatures for Exp. 1, Exp. 2 and Exp. 3 are 26, 26.62 and 26.34 °C, respectively. Change of solar radiation with time is given in Fig. 5. Accordingly, the average values for Exp. 1, Exp. 2 and Exp. 3 are 804, 818 and 788 W/m^2, respectively. The highest instantaneous solar radiation value for this study is 948 W/m^2 in Exp. 2, which was observed at 13:00.

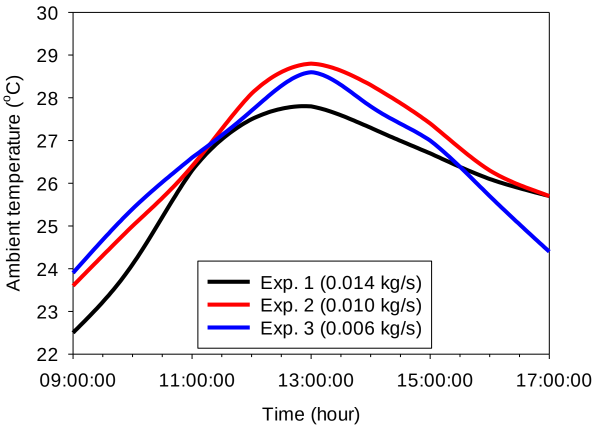

Fig. 4. Time-dependent variation of ambient temperature values

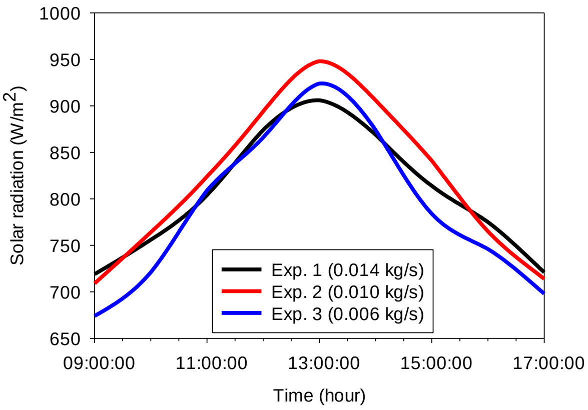

Fig. 5. Time-dependent variation of solar radiation values

The change of temperature values over time is shown in given in Fig. 6. It can be seen that the aluminum wool integration has positive effect in all flow rates. For SH, average temperature difference values for Exp. 1, Exp. 2 and Exp. 3, are 3.97, 4.80 and 6.79°C, respectively. These values for SHAW are 5.24, 6.21 and 8.59°C, respectively. The highest instantaneous temperature difference value was observed as 11.20°C in SHAW at low air flow. In a study by Singh et al. (2019), the average temperature difference values in the heater with single pass and wavy absorber surface were observed between 4-12°C [25]. In other study by Perwez and Kumar (2019), temperature difference values were measured as 4.4-10°C in a single pass and modified heater [26]. It can be seen that the temperature difference values of the heaters with waste materials in the current study are similar to those in the literature [27,28].

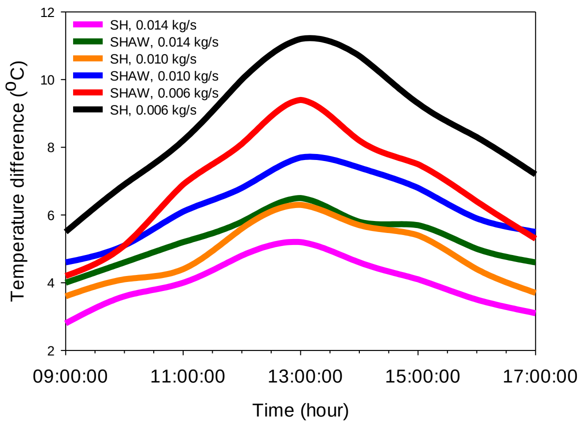

Fig. 6. Time-dependent variation of temperature difference values

Figure 7 shows the change in thermal efficiency values over the test time. Accordingly, the average efficiency of SH obtained as 42.90%, 39.42% and 33.63%, in the experiments carried out at 0.014, 0.010 and 0.006 kg/s flow rates, respectively. In addition, the calculated maximum thermal efficiency values obtained as 50.08%, 44.75% and 39.98%, respectively. Average efficiency values achieved as 56.98%, 51.20% and 42.69% for SHAW, respectively. Moreover, the maximum instantaneous efficiency values calculated for SHAW obtained as 62.61%, 55.09% and 48.25%.

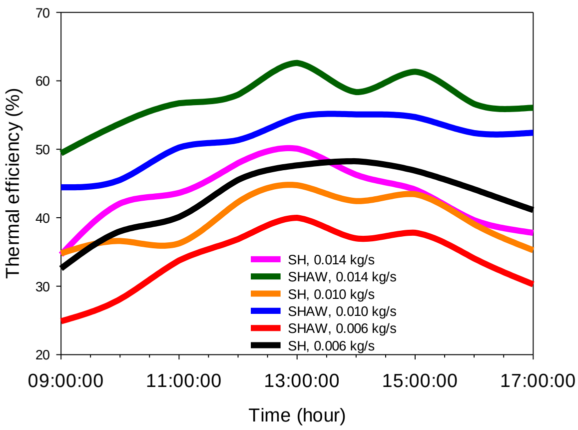

Fig. 7. Time-dependent variation of thermal efficiency values

In a study by Kabeel et al. (2016), the efficiency of the heater using phase change materials was found in the range of 14.4-50% [29]. A heater with corrugated and porous surface was analyzed by Badescu et al. (2019). According to the obtained results, the thermal efficiency value varies in the range of 52.5-66.2% [30]. In the study by Abuşka and Şevik (2017), a heater with v-grooves was designed and tested with absorber surfaces with different materials. According to the results, the average thermal efficiency was obtained in the range of 43-60% [31]. The heaters examined in this study are produced from waste materials and has low cost. It was also operated with fans with 40 W power consumption. Although the heaters examined in this study are small-scale and have appropriate thermal efficiency values when compared with the complex heaters in the literature. At the same time, a significant improvement was achieved in thermal efficiency values with a simple modification by using aluminum wool.

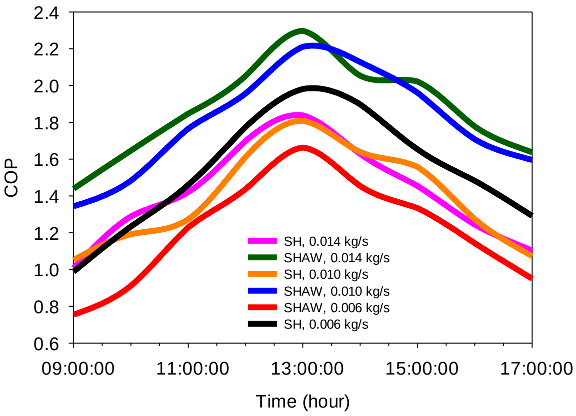

Fig. 8. Time-dependent variation of COP values

Time dependent change of COP values is shown in Fig. 8. For SH, average COP values for Exp. 1, Exp. 2 and Exp. 3, are 1.41, 1.39 and 1.21, respectively. These values for SHAW are 1.86, 1.79 and 1.53 respectively. Large differences were observed in the thermal efficiency due to the variation in the air mass flow rate. However, the data calculated for COP are close to each other. The reason for this is that the decrease in mass flow is performed by fan operation control. Fan power should be reduced in order to reduce the mass flow rate. This issue directly affects the COP value of the system. The heaters examined in this study are in small scales, which were produced and tested to demonstrate sustainable hot air production from waste materials. Therefore, COP values are somewhat lower than current studies in the literature. However, it is compatible with many studies in the literature in terms of thermal efficiency. Uncertainty values are given in Table 1. It can be said that they are in applicable range [16, 24, 32].

Table 1. Uncertainty values

Parameter	Unit	Uncertainty
Air velocity	m/s	±0.27
COP	-	±0.13
Solar radiation	W/m^2	±0.50
Temperature	˚C	±0.56
Thermal efficiency	%	±0.89

Table 2 demonstrates some studies which investigated packed bed solar heaters. As it can be seen, obtained thermal efficiency in the present study is in acceptable range when compared to related studies. Also, it should be indicated that developed solar heater in this study has simple structure and low investment cost which make it compatible with more complex solar heaters.

Table 2. Some studies which investigated packed bed solar heaters

Reference	Application	η
Buchberg and Edwards [33]	honeycomb	43-62%
Ramani et al. [34]	double-pass, wire mesh	58.4-78.2%
Ho et al. [35]	double-pass, wire mesh	42-62%
Ming et al. [36]	offset strip fin	40-45%
Thakur et al. [37]	packed bed with low porosity	54-77%
Gupta et al. [38]	transverse rib surface	47-65%
Akhtar and Mullick [39]	single glazing	47-68%
Varshney and Saini [40]	wire mesh	57-78%
El-Sebaii et al. [41]	double-pass, limestone and gravel	48-69%
Sopian et al. [42]	double-pass, iron scrap	60-70%
This study	single-pass, made with waste material	33.63-42.90%
	single-pass, made with waste material, aluminum wool packed	42.69-56.98%

5. CONCLUSION

Effective utilization of renewable energy sources and waste management are two key points for a sustainable development in future. In this study, two solar air heaters produced from waste materials were experimented. According to the results, it has been observed that the use of aluminum wool can significantly increase thermal performance of solar heater. The average thermal efficiency values of the unmodified heater were calculated in the range of 33.63-42.90%, and the thermal efficiency of the aluminum wool integrated heater was calculated in the range of 42.69-56.98%.

The surface area of the produced collectors was quite small. In future studies, thermal performance can be remarkably increased by increasing the surface area and also increasing the air residence time. In addition to aluminum wool, different fin and baffles can also be integrated into these heaters. Improved versions of heaters examined in this study can be a considerable alternative for economical air heating systems. In addition, it is considered to be a short term solution for sustainable heated air production for less developed countries and regions.

Besides, since waste materials were used in these heaters, it can be stated that waste materials can contribute positively to our developing world regarding environmental sense. It can be concluded that these systems produced from waste materials can be used in different processes such as space heating and drying.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Ataollah KHANLARI: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing.

Azim Doğuş TUNCER: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing.

Ceylin ŞİRİN: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing.

Faraz AFSHARI: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing.

Afşin GÜNGÖR: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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