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Article

Design, fabrication, and performance assessment of a novel solar air heater based on recycled materials

Abolfazl Hajizadeh Aghdam*, Parisa Rezaei, Mohammad Baraheni

Department of Mechanical Engineering, Arak University of Technology, Arak, Iran

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*Corresponding author
Email address:
abolfazl_hajizade@yahoo.com

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ABSTRACT

In this paper, a solar air heater (SAH) is designed using recyclable materials, and its performance is analyzed. The device is composed of an absorbing plate made up of 36 cans of soda and an equal number of tins with bodies covered with black color and has resistivity against high temperatures. The laboratory research revealed that the collector's efficiency is enhanced considerably by increased airflow speed and the heat transfer coefficient between the absorbing plane and air. In addition, the effects of the radiation intensity and mass flow rate on parameters such as the absorbed heat, temperature difference, and thermal efficiency are investigated. The derived results for mass flow rates of 0.0104 (kgs^{-1}) and 0.0078 (kgs^{-1}) indicate that all mentioned parameters increase the radiation intensity. Furthermore, the thermal efficiency and the absorbed heat are increased by increasing the mass flow rate, while a reduced mass flow rate increases the temperature difference parameter. Moreover, studying the charts demonstrates that the tins absorb a larger portion of the sun's radiation and, consequently, enhance thermal transfer compared with the soda cans. Irreversibility increased with increasing radiation intensity. At 300 radiation intensity, the highest thermal and exergetic efficiencies occurred.

1. Introduction

Renewable energy is one of the alternative resources for non-renewable ones, which can be economical in fossil fuels prices. Solar energy is also called green energy, so they are clean energy resources, and their technological effects on the environment are much lower than conventional energy technology. Nowadays, the utilization of solar energy conversion for generating heat and electricity has publicized the development of thermal conversion energy results from a large number of requests for energy. Researchers concentrate on thermal collector studies to improve thermal efficiency cause they have an ordinary structure and are widely used in life from space heating to agricultural drying [1]. Solar Air Heaters (SAH) are usually used as heat exchangers in solar cell applications [2]. Air heating is one of the primary applications of solar heating, which is utilized for heating the environment and the processes in heating systems such as laundry, desalination, drying products, and other drying processes. The common use of energy in procedures leads to raised costs and also environmental contaminations. Utilizing solar energy to heat the air reduces the system's operation cost and regular energy consumption [3]. Tyagi et al. [4] classified solar air heaters according to their tracing, energy storage, wide surface, and number of coverages. The SAHs are divided into three groups: active, passive, and hybrid, based on the mode. The warm air is generated in diverse sections in passive solar air heaters and transferred for final use. On the other hand, passive SAHs are commonly used during the day [5]. The SAH can be categorized into one-pass and two-pass with or without heat storage based on the number of airflow passes [6]. The primary drawback of the SAHs is the low heat transfer coefficient among the absorbing plate and airflow, leading to reduced thermal efficiency. Nevertheless, numerous corrections can be applied to improve the heat transfer coefficient between the absorbing plate and air. In this regard, the influential parameters are the collector length, type of absorbing plate, glass covering sheet, wind speed, etc. Increasing the absorption surface culminates in increased heat transfer to the flowing air. On the other hand, it increases the pressure drop in the collector, leading to raised electricity power consumption for air suction into the collector [7]. one of the solutions for this improvement is the absorbing surface shape. This parameter plays an important role in the designing of solar air heaters. Till now, various kinds of SAHs have been developed and investigated experimentally. It's obvious that material and construction have many effects on the collector's efficiency [8]. Metwally et al. [9] stated the results of experimental investigations on advanced corrugated duct solar collectors. The constituent structure of the collector was a corrugated surface exactly identical with those used for heat exchangers, in which corrugations got the airflow normally. Öztürk and Demirel [10] showed an investigation experimentally from the thermal efficiency of a SAH that its flow channel is covered with raschig rings. They conducted that by increasing the outlet temperature of heat transfer fluid, the energy and exergy efficiencies of this channel increase too. Benli [8] conducted an investigation based on energy and exergy analysis of five types of solar air absorbers (corrugated, reverse corrugated, trapeze, reverse trapeze, and flat plate). The results showed that the shape of the absorbers' surface has a linear relation with the pressure drop and thermal coefficient. Four obstacle shapes and three various configurations in SAHs were numerically tested by Kulkarni and Kim [11]; the highest efficiency goes to a pentagonal obstacle that shows the effect of the shape and arrangement of an obstacle on Nu number. Karsli [12] studies were about the first and second laws of efficiencies of four kinds of flat plate SAHs. The experimental results can be derived that solar radiation and construction are the effective parameters on the performance of SAHs. Özgen et al. [7] studied three types of double-flow SAHs with aluminum cans experimentally and presented that obstacles or cans create a good airflow and turbulence on the absorber plate and diminish the dead zone in the heater. By Concentrating on PVT modules, the total efficiency of a device can be improved if researchers start to use tracking devices, concentrate reflectors, or even use electric and thermal powers in PVT concurrently. Concentrating PVT (CPVT) modules can be used only on greater scales, so the components that constitute the system have significant dimensions. Usually, solar towers, parabolic trough concentrators (PTCs), compound parabolic concentrators (CPCs), and parabolic dish concentrators (PDCs) can be in this category [13].

There are many ways to operate energy for buildings in the middle east region. The most beneficial one is using BIPVT-DSF. Double skin façade (DSF) can be a good solution. The usage of building-integrated photovoltaic thermal (BIPVT) is such an interesting offer for saving measures because it considers both energy efficiency and renewable energy. To endorse this system, some advantages can be explained: a) the photovoltaic module efficiency boosts due to the natural or mechanical ventilation, and b) it has substantial effects on the potential for thermal and/or cooling for the entire system [14]. Thus, the best system for rejecting, absorbing, and reutilizing solar heat is Solar façades. The main heat sources in BIPV are PV panels. Usually, these systems are designed with the consideration of supplying ventilation through the solar chimney principle integrated with a DSF design concept [15]. According to previous studies, the use of recycled materials in solar systems is limited. In the case of solar air heaters, the use of soda cans has been reviewed in a limited number of articles. However, in this paper, the performance of a solar air heater with two types of soda cans and tins was studied and compared. Therefore, the innovation of this experiment is that the experimental analysis of solar air heaters has been done with two types of recycled materials, and the performance of SAH has been compared using these two. In addition, exergy and energy analysis has been performed for these two materials. The novelty of this experiment is the comparison of soda cans and tins in one system. The results for tins were better than soda cans. The objective of the fabrication of this device is to compare the output of warm air from two tins and soda can sections. The schematic and figure of the system are represented in Figures 1 and Figure 2, respectively. As shown in the figures below, the SAH has made from a wooden box in some tins, and soda cans (in equal numbers) are arranged in and separated by a wooden partition, in which each part has its own fan. The box has covered by plexiglass, and two projectors were used as sun simulators. The system is laid out in the degree of 45 for having the best performance.

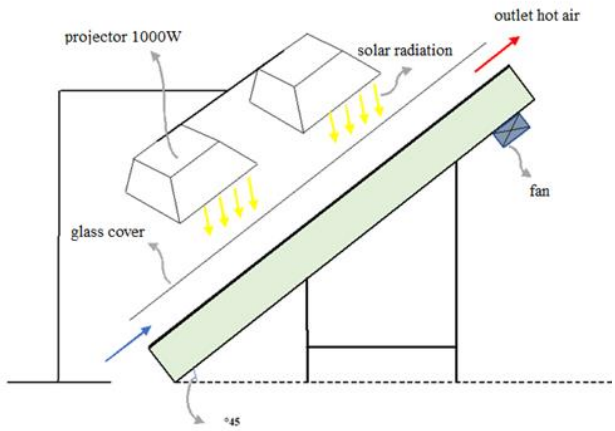


Figure 1. A schematic of the device

Figure 2. Solar air heater

2. Experimental setup

A solar air heater includes the following components:

- Main body: the main body of the device is made of wood with dimensions of 120×66 and a thickness of 0.5cm. Wooden material is selected due to its low price and thermal insulation property. A wooden board is also installed as a partition wall between tins and soda cans.
- Absorbing plate: this plate is the essential element in a solar heater that gathers the solar energy together locally in a thermal form and delivers it to the air. In this case, the rise of the heat transfer is achieved by forced convection and turbulence of the airflow. This surface is made of black-colored aluminium with a thickness of 3mm and connected to the main body.
- Input and output duct: these ducts are used to receive cold air and take out warm air. The ducts with similar diameters are implemented to have equal input flow rates. The output ducts are insulated to prevent thermal loss.
- Transparent glass cover: this cover is made of Plexiglass with a thickness of 4mm. The solar energy passes through this glass cover and is absorbed by the absorbing plate. The generated heat is then transferred into the collector.

- Tins and soda cans: 36 soda cans and equally 36 tins are used as fins that are stuck to the absorbing plate in 4 columns and 9 rows. The top and bottom of the aluminium cans are opened, and their internal and external surfaces are decontaminated. Moreover, they are covered with black color to have a higher absorption coefficient. The soda cans are made of aluminium, and the tins are tinned-plated.
- Fan: two 220 V, 15W fans are utilized on the other side of the cans for airflow suction (W_{fan}=15 W).
- Projector: The existing projector with the power of 1000W in the workshop acted as the sun in a way its radiation intensity was adjustable using an implemented dimmer on it.

The equipment used to measure the radiation intensity and the ambient and output temperatures are described in what follows:

Radiometer: this equipment (Figure 3) used to measure the radiation intensity is TES 132 solar power meter (data logging) with the accuracy of, whichever is greater in sunlight. As represented in the figure, the attached sensor to the equipment is placed over the glass cover. The radiation intensity is measured twice, once at the bottom of the plate for the bottom projector and once at the upper part of the plate for the upper projector.

Figure 3. Radiation intensity measurement by model radiometer TES

Thermometer: this equipment (as shown in Figure 4) is lotron HT-3007SD with accuracy $\pm 0.8°C$ and $\pm 1.5°F$ for measuring temperature. By using this thermometer, the ambient and output temperatures are measured from hose ducts in a way that the thermometer is placed in the middle of the hose ducts for 10 seconds, and the final temperature is recorded. If the test is to be performed in 6 minutes, the temperature should be recorded every 2 minutes, and the thermometer must be placed in the environment to reach its periphery temperature and then start the new test.

3. Energy Analysis

The law of conservation of heat energy is defined as follows:

$$\alpha_0 I A_c = M_P C_{P,C}\left[\frac{dT_{p,ave}}{dt}\right] + \dot{m}_a C_{p,a}(T_{out} - T_{in}) + U_C A_C(T_{p.ave} - T_e) \quad (1)$$

Where α denotes the proportion of solar radiation absorbed by the absorber plate and represents the optical yield. Heat losses from the heater are represented by U_C, which is the overall heat transfer coefficient between the environment and the heater.

Figure 4. Measure the outlet temperature of the device with a thermometer

Also, the first and second phrases of equation (1) are defined as useful heat absorbed (Q_s) and the value of energy increased (ΔU), respectively. The heaters' thermal efficiency is defined as follows [16]:

$$\eta = \frac{\dot{m}_a C_{air}(T_{out} - T_{in}) - \dot{w}_{fan}}{I A_c} \quad (2)$$

The total amount of heat transmitted to the fluid is described as:

$$\dot{Q}_u = \dot{m}_a C_{p,a}(T_{out} - T_{in}) \quad (3)$$

Heat is transported from the absorber plate to the air via convection and is calculated as:

$$\alpha = \frac{\dot{Q}_u}{A_C(T_{p,ave} - T_{a,ave})} \quad (4)$$

The mass flow rate of air is computed as follows:

$$\dot{m} = \rho A_h V \quad (5)$$

Thermophysical properties of air are determined according to the average air temperature between entrances and exits of the heater. The velocity of air flowing through the duct is calculated from the knowledge of the mass flow rate and cross-sectional area of the duct. The mean air velocity V is calculated as V_{max} for the flat surface heater with the following equation:

$$V_{max} = \frac{\dot{m}}{\rho A_{per_{max}}} \quad (6)$$

V_{max} indicates the maximum velocity, and A_{per} is the area perpendicular to the flow direction between the two obstacles. As a result, the Reynolds number of the flat absorber plate heaters is computed. The air duct is 150 mm high (H) by 900 mm wide (W). The blockage ratio (BR) is the ratio of the area of the conical components to the cross-sectional area of the air channel [16].

3.1 Uncertainty analysis

Test equipment selection, accuracy, specification, observation, reading, and ambient circumstances may all contribute to test uncertainty. Surface-fluid temperatures, pressure loss, air velocity, and global solar radiation were all measured in the heaters using appropriate instruments. The following equation (Holman equation) was used to estimate relative uncertainty. The thermal efficiency and air flow rate uncertainties are 1.05% and 2.4%, respectively [16].

$$W = [(X_1)^2 + (X_2)^2 + \ldots (X_n)^2]^{\frac{1}{2}} \quad (7)$$

4. Results and discussion

Some charts are derived using the achieved results of the tests, and the comparisons of the mentioned parameters with some of these charts are illustrated.

4.1 Investigation of the effect of radiation intensity on the temperature difference

As is evident (Figure 5), the temperature is raised by increased radiation intensity and also through time. In addition, more temperature increase occurs in the tins. By comparison of two Figures 5 and Figure 6, it can define that the lower mass flow rate cause more temperature differences; in fact, the lower mass flow rate causes more time to heat the fluid.

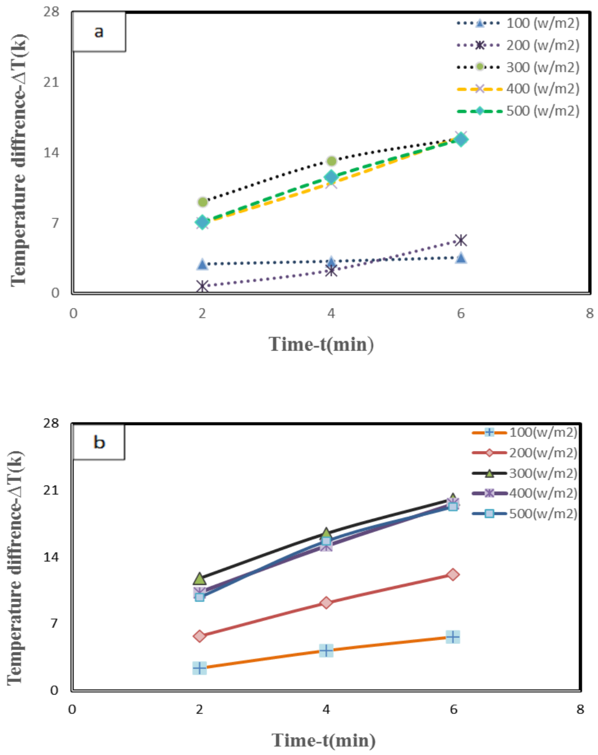


Figure 5. temperature difference – time in terms of radiation intensity for =0.0104kgs^{-1} with 100% dimmer a) Soda cans b) tins

4.2 Investigation of the effect of radiation intensity on the useful heat absorbed

As it is demonstrated in Figure 7, the absorbed heat is increased by increasing the radiation intensity and through time. The maximum value of heat absorption occurs at the radiation intensity of 300. The absorbed heat in the tins is greater compared to the soda cans. It can be due to the difference in material and metal thickness of tins and sodas. As shown in Figure 8, the efficiency is improved by increasing the irradiance intensity and peaks at 300 radiation intensity. Furthermore, the thermal efficiency of the tins is more than soda cans.

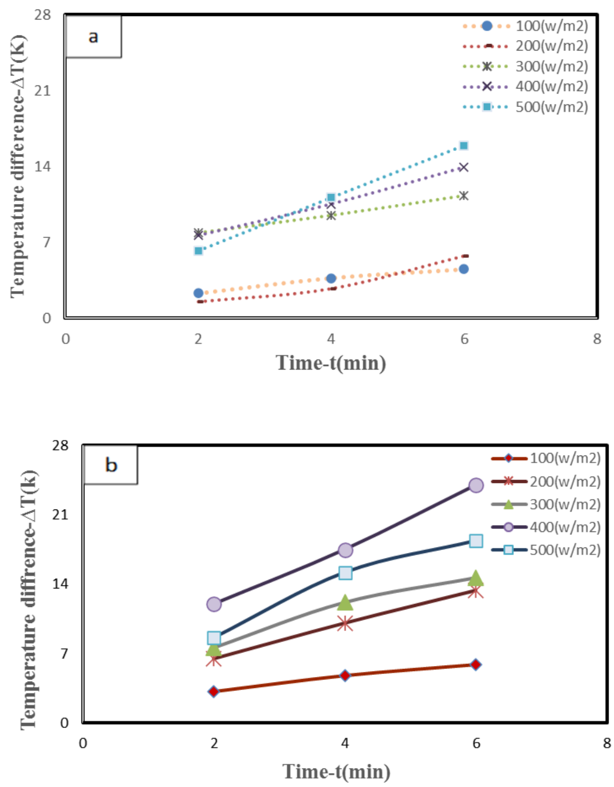


Figure 6. temperature-time difference in terms of radiation intensity for $\dot{m}$=0.0078kgs^{-1} with 80% dimmer a) Soda cans b) tins

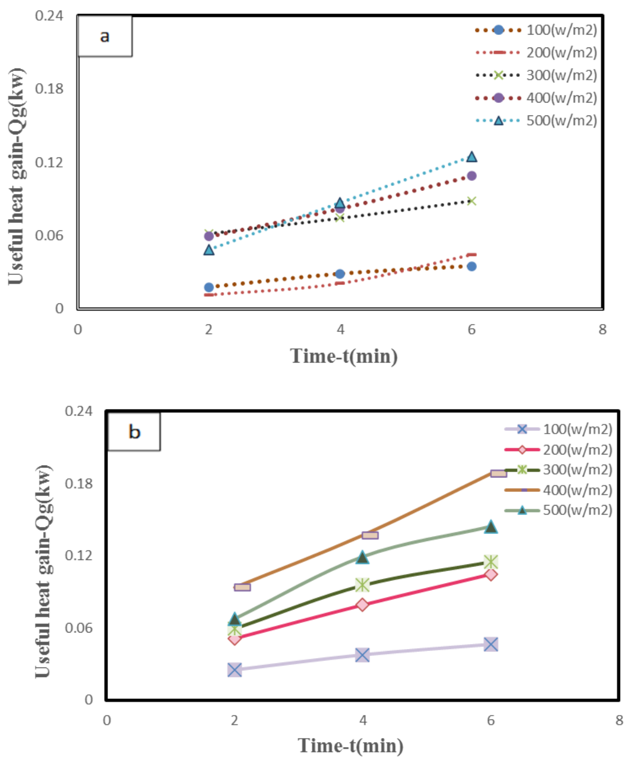
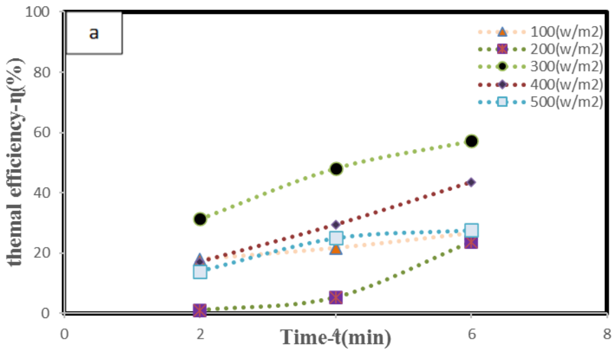


Figure 7. Absorbed heat-time diagram in terms of radiation intensity for $\dot{m}$=0.0078kgs^{-1} with 80% dimer a) soda cans b) tins



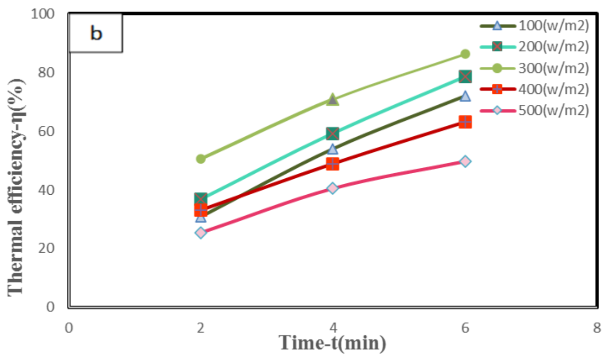


Figure 8. Efficiency-time in terms of radiation intensity for $\dot{m}$=0.0104kgs^{-1} with 100% dimmer a) soda cans b) tins

4.3 Investigation of the effect of radiation intensity on thermal efficiency

Figures 9 (a and b) show the effect of radiation intensity on the thermal efficiency of the SAH made by soda cans and tins. It indicated that the thermal efficiency increases with an increase in radiation intensity while SAH made by tins has better performance than the one made by soda cans.

4.4 Investigation of the effect of radiation intensity on given heat

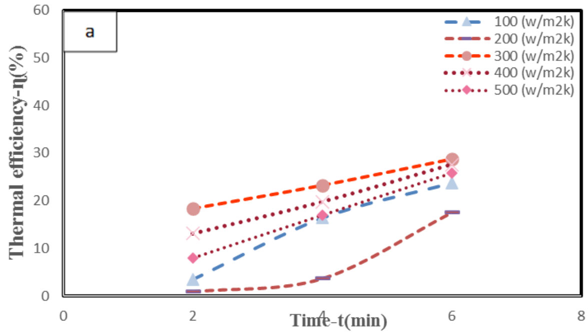
Figure 10 shows the effect of radiation intensity on the given heat of the SAH made by soda cans and tins. It indicated that tins have better performance than soda cans. The given heat is increased by raising the radiation intensity with equal heat transfer cross sections. This value is equal for both tins and soda cans.

4.5 Investigation of the effect of mass flow on thermal efficiency with increasing radiation intensity

Figure 11 shows the effect of mass flow rate on the thermal efficiency of the SAH made by soda cans and tins. It can be seen that by increasing the mass flow rate, the thermal efficiency is increased.

4.6 Investigation of a thermography camera

The following images are captured using the model Testo672 thermography camera, which represents the radiated heat from the heater by radiation intensities mentioned above. Hot surfaces are recognized by red, orange, and yellow color spectrums, and cold surfaces are represented by violet, blue, and green colors. Figures 12 and Figure 13 show temperature profiles on SAH with two different radiation intensities. The pictures are recorded in 6-minute intervals like the previous results, and the units are set in the SI system. As time passes, during photography, the thermography camera shows the temperature contour, which demonstrates the surface temperature of tins and soda cans that match with ΔT results.



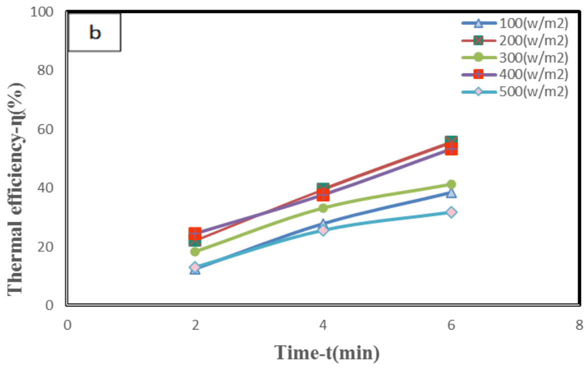


Figure 9. Efficiency-time in terms of radiation intensity for $\dot{m}$=0.0078kgs^{-1} with 80% dimmer a) soda cans b) tins

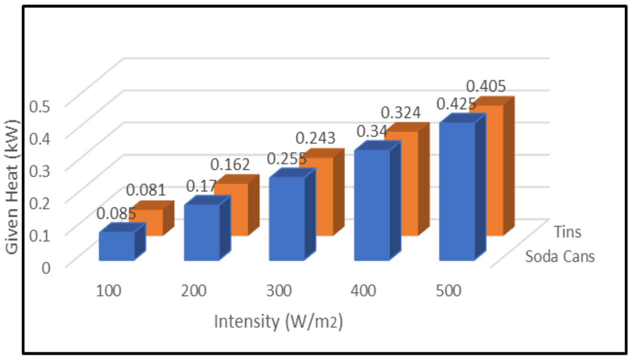
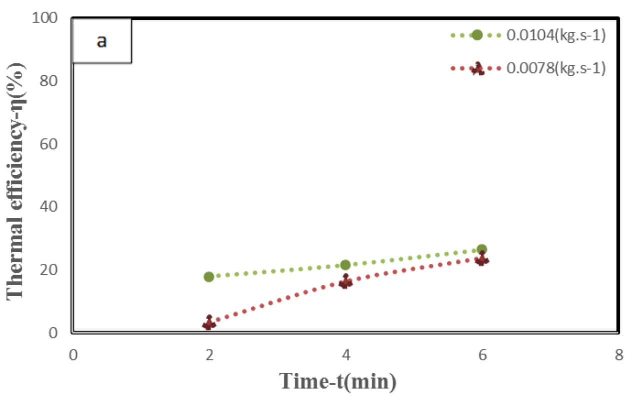


Figure 10. Given Heat-intensity variation, blue) soda cans, red) tins



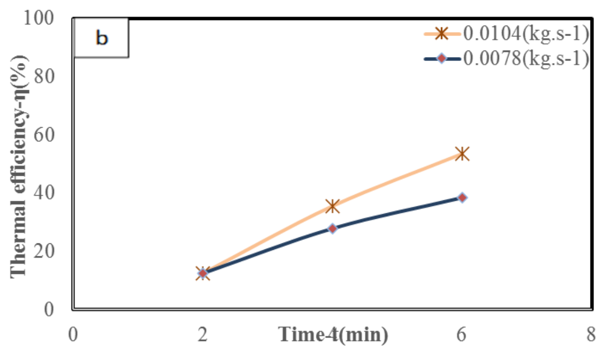


Figure 11. Thermal efficiency-time diagram for two different flow rates a) soda cans b) tins

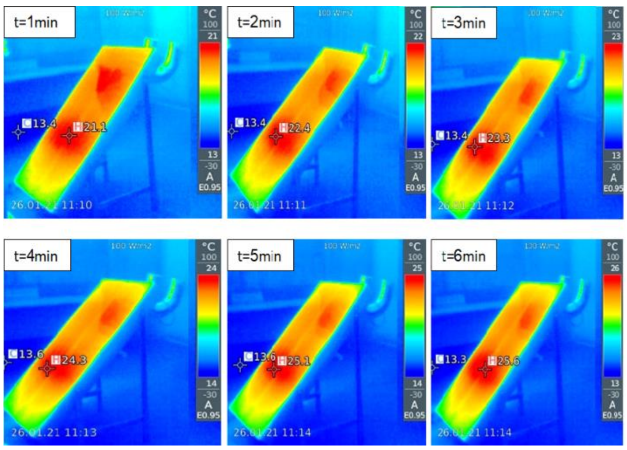


Figure 12. Thermal images of radiation intensity 100(w/m^2)

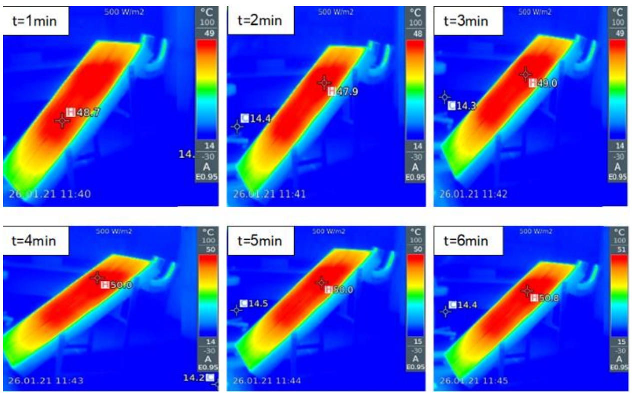


Figure 13. Thermal images of radiation intensity 500(w/m^2)

5. Conclusion

By analyzing the derived results, the following could be realized:

- The absorption heat is improved by increased irradiance intensity from 100 to 500 w/m^2 through the specific time (6 minutes); its maximum occurs at the irradiance intensity of 300. The absorbed heat in tins is about 0.01 Kw greater compared with soda cans.
- Since the sucked air has a low velocity as a consequence of reduced fan velocity, it has more opportunity to get warmer, and more heat is absorbed by the soda cans and tins. However, this absorbed heat still has a larger value in the case of tins, about 5%.
- With equal heat transfer cross-sections, the delivered heat increases by raising the radiation intensity and is similar for both cans and tins cases.
- By reducing the mass flow rate from 0.0104 to 0.0078 kg/s over time, the temperature difference increased about 4%. This increase also depends on the rise in radiation intensity.
- The thermal efficiency is enhanced by raising the mass flow rate and radiation intensity. this enhancement for 100 w/m^2 and 0.0104 kgs^{-1} for soda cans is about 20% and for 500 w/m^2 and 0.0104 kgs^{-1} is about 15%. the greater enhancement could be observed for tins at 100 w/m^2 and 0.0104 kgs^{-1} about 40% . Also, at 500 w/m^2 and 0.0104 kgs^{-1} the increment of 25% is recognizable.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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