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CHARACTERISTICS OF SOLAR THERMAL ABSORBER MATERIALS FOR CROSS ABSORBER DESIGN IN SOLAR AIR COLLECTOR

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ABSTRACT

The solar thermal absorber is an integral component of a solar air collector, especially in determining the overall performance of a solar air thermal system. The type and shape of material will have a direct impact on the operating temperature and thermal energy storage effect of the solar air thermal collector. This paper focused on the investigation of aluminum and stainless steel hollow square rods in terms of their solar thermal absorber performance. Comparisons between different materials and coatings were conducted in order to determine their impact in solar thermal absorber applications. Experiments were conducted on both materials with flat-black coated and non-coated surfaces of aluminum (6063) and stainless steel sets respectively. Both sets were exposed under 585 W/m^2 radiation and the temperature response was recorded. A significant improvement was shown to result from the application of flat-black coating against non-coated material, with maximum temperatures of 67.2^{o}C and 48.3^{o}C respectively. It was observed that for the hollow square metal absorber the heating and cooling characteristics can be established by means of the relation between the surface and inner air temperatures of the absorber. This method can assist in temperature profiling of hollow square metal for solar thermal application.

Keywords: Solar air collector; solar absorber; thermal absorber; hollow square metal.

INTRODUCTION

Energy has become one of the most important issues in the world. Fossil energy sources in the form of petroleum and coal are being used extensively and it is predicted that from 2015 energy resources will begin to become scarce [1]. The energy crisis which is being caused by the depletion of energy resources has led to the instability around the world both politically and economically [2–4]. The open burning of fossil fuels releases harmful emission gases to the atmosphere which directly affect the environment and the existing natural ecosystem in an adverse way, as well as contributing to global warming [5,6]. To mitigate the growing environmental problems caused by the excessive use of fossil fuels, the interest in renewable energy sources in the world community has increased significantly, and much research to harness such energy types is being pursued especially in the area of solar energy [7,8]. There are two types of solar thermal air collector – concentrating and non-concentrating. In general, non-concentrating solar collectors consist of four main components: the transparent cover, solar thermal absorber, collector base and heat transfer medium. The transparent cover allows solar radiation to pass through and reach the absorber while reducing the convective and radiation losses [9,10]. The material used must be transparent to short-wave solar radiation and opaque to long-wave solar radiation [11]. It can be enhanced by using multiple transparent cover layers and applying selective glazing in order to further decrease the top losses. When solar rays strike the surface of the solar thermal absorber, it will absorb and convert the energy received into heat and transfer it to the heat transfer medium by means of convection.

The material from which solar thermal absorbers are made is very important in determining the performance of the solar air collector because it functions to absorb and transfer heat to the operating medium depending on its thermophysical characteristics [12]. In the existing literature, research on non-concentrating solar collector absorber materials has been done mainly on a single solar thermal absorber material with a flat absorber configuration, namely mild steel, stainless steel and copper [13–15]. Although copper is widely used due to its high thermal conductivity, it is not economical compared with other cheaper materials, with a slight trade-off in performance. This is supported by research done by [16], who found that copper provides a 3% performance improvement compared with aluminum. Despite this small performance increase, the relatively high cost of using copper against aluminum means that aluminum is a better material, suitable for most heating applications in terms of economic and performance considerations. Majid et al. [17] has successfully implemented hollow square aluminium as the heat sink instead of copper for photovoltaic system with considerations of thermal conductivity, material density and cost while Al-Kayiem [18] using matte black coated aluminum for hybrid biomass solar drying. In a solar water heating system, however, the heat absorbed by the absorber is transferred to the water by conduction and this necessitates an absorber plate with high thermal conductivity, where copper is generally preferred [19]. The type and shape of the material will have a direct impact on the operating temperature and thermal energy storage effect of a solar air collector. A single material absorber is commonly used for developing solar air collectors, although this kind of configuration is heavily dependent on the conditions of direct and diffused solar radiation, especially during intermittent weather conditions, which are a common natural phenomenon.

A cross solar thermal absorber design for a solar air collector was initially proposed by Zafri et al. [20] with the goal of maximizing the solar radiation received by the solar collector. The thermal absorber employed in the work was hollow aluminum with one inch diameter, focusing on maximizing the absorption of solar radiation. Although a single material absorber is commonly used for developing solar air thermal collectors, intermittent weather conditions can have a severe effect on the performance of a single material. The prospect of having a collector with a good thermal absorber and good short-term thermal storage is possible by diversifying the cross absorber concept by means of the thermal absorber materials. This paper focuses on the investigation of aluminum and stainless steel hollow square rod in terms of their solar thermal absorber performance. Comparisons with different materials and coatings were conducted in order to determine their impact in solar thermal absorber applications.

EXPERIMENTAL SETUP

In this paper, the effect of square hollow aluminum and stainless steel with and without flat-black coating was investigated in the scope of solar thermal absorber applications.

The materials for the single solar thermal absorber employed in the experiment were aluminum (6063) and stainless steel square hollow with dimensions of 400 mm length x 19.1 mm diameter x 1 mm thickness, as shown in Figure 1.

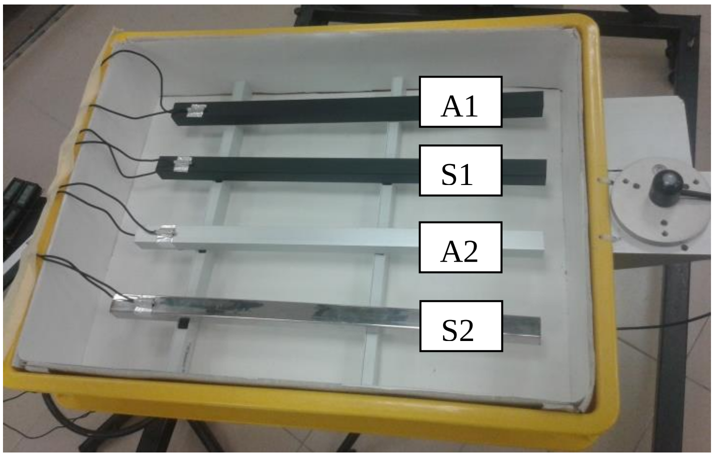

Figure 1. Solar thermal absorber materials (aluminum and stainless steel).

A summary of selected thermophysical properties of each material is given in Table 1.

Table 1. Thermophysical properties of solar thermal absorber material [21,22].

Material	Density , kg/m^3	Thermal conductivity, W/mK	Specific heat capacity, J/kg K	Thermal diffusivity, x 10^6, m^2/s
Aluminum (6063-T5)	2700	200	900	64
Stainless steel	8000	16.2	500	4.2

Table 2. Experiment material and properties.

Parameters	Length	Emissivity	Position
Aluminum non-coated	40	0.77	A2
Aluminum coated	40	0.95	A1
Stainless steel non-coated	40	0.59	S2
Stainless steel coated	40	0.95	S1

Figure 2 shows an experimental setup with solar simulator. An experiment was conducted for non-coated and coated hollow rod material testing. The parameters and properties involved in the experiments are given in Table 2. For each material, data on the surface temperature and for inner air temperature at the center of the hollow rod were collected. Solar irradiance measurement of the solar simulator was taken using a pyranometer. Each setup was exposed to short wavelength radiation under a solar simulator with 585 W/m^2 for 30 minutes, of which 15 minutes is the heating period and the next 15 minutes is for cooling under 0 m/s^2 wind speed. Readings for each parameter were recorded in one minute sequences. Experimental procedures were divided into two stages, for heating and cooling the absorber. This was done in order to determine the radiation absorption rate of each solar thermal absorber material at the heating stages, as well as the heat storage effects shown during the cooling down period.

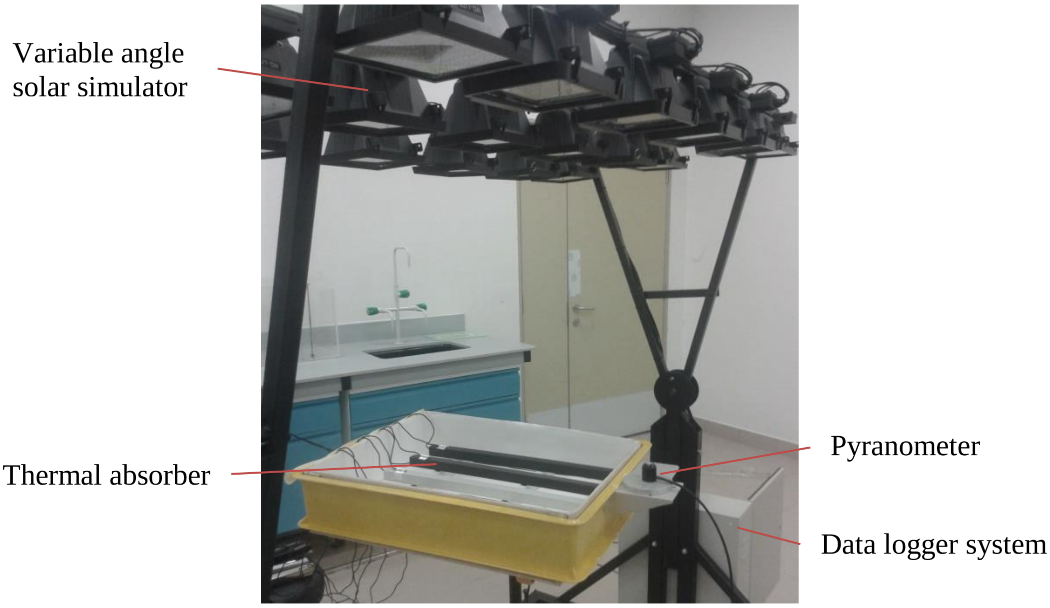

Figure 3. Experimental setup with solar simulator.

RESULTS AND DISCUSSION

Non-coated solar thermal absorber properties

To determine the original characteristics of the absorber material without any additional enhancement, the temperature profiles during heating and cooling of both materials were recorded. From the profile in Figure 4, aluminum's temperature increased rapidly from 0 to 10 minutes to 46^{o}C. The high thermal conductivity of aluminum of 200 W/mK contributed to the thermal energy dispersed to all parts of the material and hence increased the conversion of solar radiation to thermal energy [23]. Meanwhile, stainless steel has low thermal conductivity of 16.2 W/mK with low specific heat at 500 J/kgK, as well as low thermal diffusivity of 4.2 x 10^{6} m^{2}/s, compared with aluminum with 64 x 10^{6} m^{2}/s. The thermal diffusivity value is important in determining the solar thermal absorber's characteristics and whether it can be a good absorber or provide thermal energy storage. Stainless steel can absorb a high amount of thermal energy but has a lower energy propagation rate, and vice versa for aluminum, which has a high value of thermal diffusivity [24]. With the advantage of good thermal energy storage, stainless steel reached a maximum temperature of 50.1^{o}C because of the momentum energy gain from the storage; conversely, aluminum reached a peak temperature of 48.3^{o}C at the same time. During the cooling phase with no solar radiation source, the aluminum temperature dropped dramatically and at 30 minutes it reached a minimum temperature of 31.8^{o}C. Stainless steel displays a gradual and consistent drop of temperature, shown by the steepness of the slope shown in Figure 4. The final minimum temperature of stainless steel was 34.5^{o}C. This shows that stainless steel exhibits good thermal energy storage compared with aluminum, while aluminum possesses a good thermal energy absorption rate.

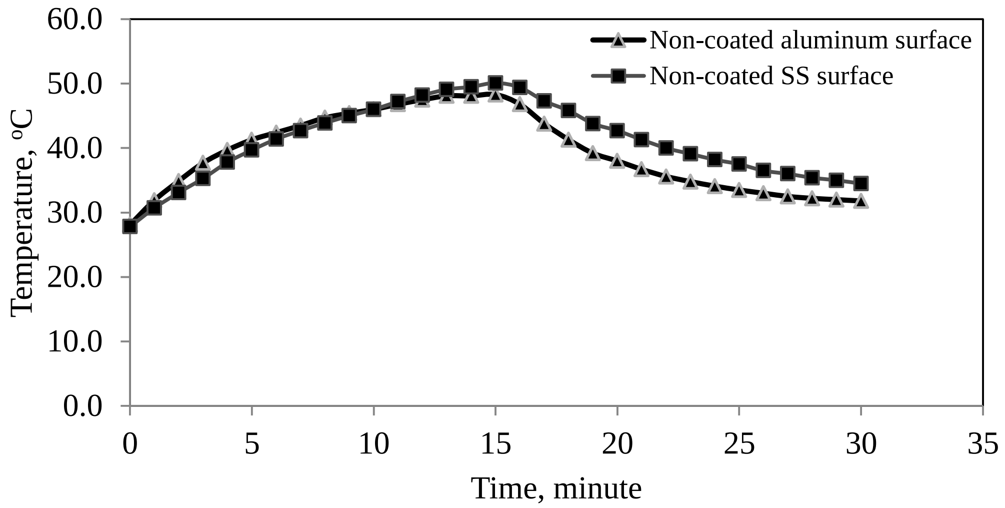

Figure 4. Temperature profile for heating and cooling of non-coated aluminum and stainless steel surface at 585 W/m^2

Relation of Surface and Inner Temperature

The relation of the surface temperature and inner air temperature of aluminum with flat-black coating and without coating has been determined by the slope of the gradient seen in the graph in Figure 5. For the non-coated aluminum, the slope of the heating stage has a steepness of 0.846, while the coated aluminum has 0.826. The lower slope value indicates that the heat transfer rate from the surface to the inner air of the absorber is increased, resulting in a faster temperature increase of the air inside the hollow square metal absorber. Solar irradiance acts as an energy source that causes the metal molecules to vibrate; hence increase of temperature is imminent as the temperature is proportional to kinetic energy, determining the temperature of the material [25]. This behavior is in agreement with Fourier's law of thermal conductivity, where the definitive k-value and temperature differences of two adjacent walls influence the rate of heat transfer from a high temperature plane to a lower temperature plane [24,26]. The maximum temperatures of the coated and non-coated aluminum were 66.8^{o}C and 48.3^{o}C respectively. At the maximum temperature, the air temperature at the inner thermal absorber approaches the same value as the surface, which means that the solar thermal absorber temperature is reaching the terminal temperature of equilibrium of the thermal absorber.

In the cooling period, a high value of slope is preferable because it indicates that the thermal energy is transferred from the inner region to the outer region at a slower pace, creating prolonged heat retention/storage at the solar thermal absorber. The non-coated stainless steel shown in Figure 6 has a better energy storage capacity than the coated aluminum shown in Figure 5, as they have gradient values of 0.949 and 0.798 respectively. Stainless steel generally has a superior heat storage capability but is less sensitive with temperature increase during heating, and vice versa for aluminum. This finding corresponds well with the thermophysical characteristics from Table 1, where the thermal diffusivity of stainless steel is 15.2 times lower than that of aluminum, explaining the phenomenon described above. This is also applicable for the cooling stage of coated and non-coated stainless steel. The highest temperature achieved is at 63.9^{o}C, while with non-coated stainless steel it is 49.5^{o}C. The values of slopes with their corresponding stages and materials are summarized in

Table **3**.

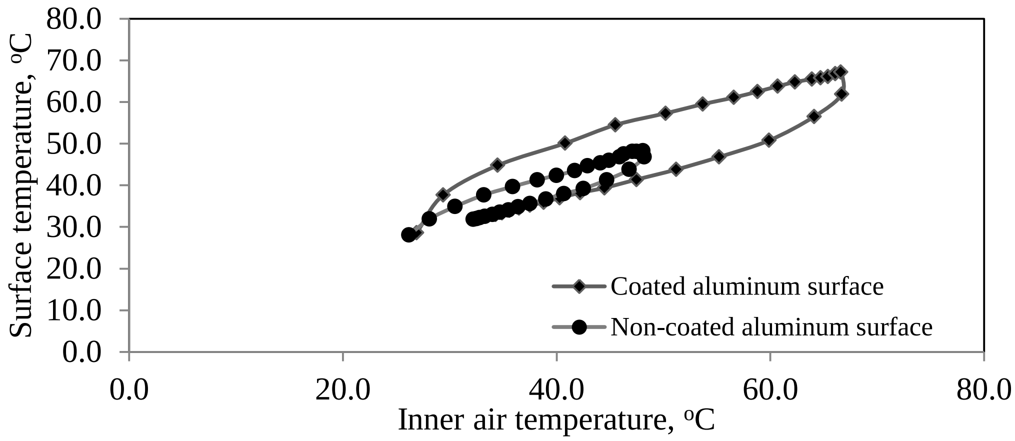

Figure 5. Relation of surface and inner air temperature of coated and non-coated aluminum surface at 585 W/m^2.

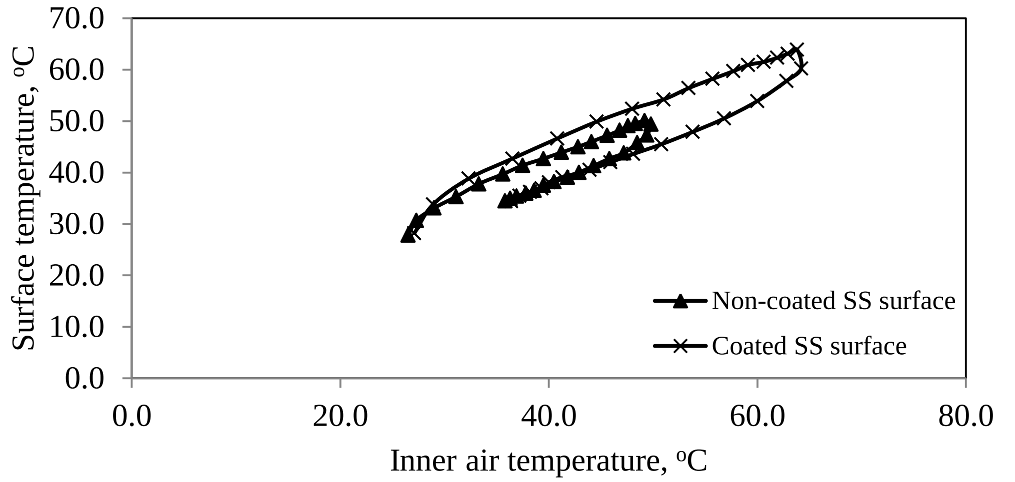

Figure 6. Relation of surface and inner air temperature of coated and non-coated stainless steel surface at 585 W/m^2.

Table 3. Slope values for each stage with material type.

Material	Stage	Slope value	Maximum / minimum temperature, ^{o}C
Aluminum coated	Heating	0.826	67.2
Aluminum non-coated	(in 15 minutes)	0.846	48.3
Stainless steel coated		0.876	63.9
Stainless steel non-coated		0.892	50.1
Aluminum coated	Cooling	0.798	33.0

Aluminum non-coated	(in 15 minutes)	0.916	31.8
Stainless steel coated		0.855	34.4
Stainless steel non-coated		0.949	34.5

Effect of Coating on Solar Thermal Absorber Performance

There is a significant temperature increase between the coated and non-coated aluminum surfaces, where the maximum temperatures achieved under 585 W/m^2 radiation exposure are 67.2^{o}C and 48.3^{o}C respectively, as shown in Figure 7. The temperature difference at the maximum temperature points of the coated and non-coated aluminum is 18.9^{o}C. By applying flat-black coating, the radiative characteristics of a surface are altered, with lower reflectivity and subsequently increased absorptivity and transmissivity of the solar thermal absorber surface [27]. Such properties are important in the solar thermal absorber [28] as they can significantly increase the heat transfer rate between the absorber material and the air inside the hollow rod due to the high temperature gradient between the absorber and ambient air. It can be seen that the temperature of the inner air lags behind the surface temperature for both coated and non-coated metals. This is most obvious with the coated metal and is caused by the high temperature difference between the surface and inner air, causing the air to reach the equilibrium temperature with the surface at 65.8^{o}C in 12 minutes, compared with non-coated surface which takes 10 minutes to reach equilibrium at 46^{o}C.

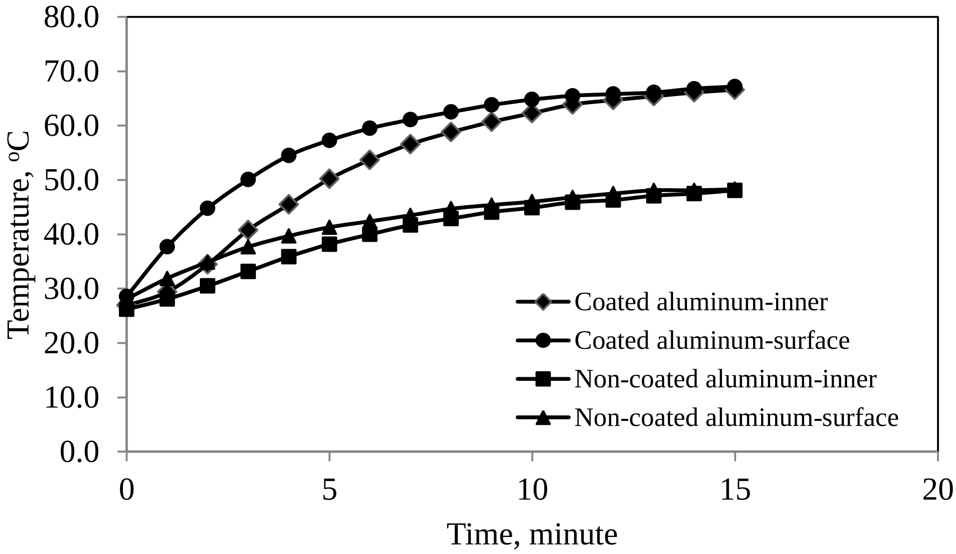

Figure 7. Temperature profile for coated and non-coated aluminum.

CONCLUSIONS

Solar thermal absorber materials, namely aluminum and stainless steel square hollow rods, show promising results for use as alternatives to expensive materials such as copper. Aluminum exhibited good thermal absorption, while stainless steel has good heat storage behavior. Both materials are suitable for dual material combinations for solar air thermal cross absorber design, which could increase the efficiency of the solar air collector. Significant improvement has been shown to result from the application of flat-black coating, and the maximum achievable operating temperature is 67.2^{o}C for coated aluminum, which represents a temperature difference of 18.9^{o}C from the non-coated surface. The relation between the surface temperature and inner air at the center hollow has been established by determining the gradient of the slope. With increasing slope, heat transfer from the surface to the inner air of the absorber also increases, resulting in a faster air temperature increase. It was observed that for the hollow square metal absorber, the heating and cooling characteristics can be established by means of the relation between the surface and inner air temperatures of the absorber. This method can assist in temperature profiling of hollow square metal for application as a solar air cross absorber collector.

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REFERENCES

[1] Sopian K. Renewable energy - path for a carbon free future. 8th UN-CECAR International Conference, University Led Development; 2014.
[2] Sopian K. Bringing Renewables into the Mainstream. P8th Malaysian International Chemical Congress. 2006; 234–41.
[3] Janssen R. Renewable energy into the mainstream. Report of International Energy Agency’s Renewable Energy Working Party, Netherland; 2002.
[4] Ahuja D, Tatsutani M. Sustainable energy for developing countries. S.aPIEnS 2009;2:1–16.
[5] Sopian K. Tenaga eterbaharuan – laluan masa depan bebas karbon. Bangi: Penerbit Universiti Kebangsaan Malaysia; 2008.
[6] Yatim B. Inovasi Menghadapi Cabaran Bekalan Tenaga. Penerbit Universiti Kebangsaan Malaysia; 1995.
[7] Chu Y. Review and Comparison of different solar energy technologies. Report Global Energy Network Institute 2011.
[8] Lewis NS, Crabtree G, Nozik AJ, Wasielewski MR, Alivisatos P. Basic research needs for solar energy utilization. Basic Energy Sciences Workshop on Solar Energy Utilization, US Department of Energy, Office of Basic Energy Science. 2005.
[9] Duffie JA, Beckman WA. Solar engineering of thermal processes. Second Edition. John Wiley & Sons, Inc; 1980.
[10] Kalogirou S a. Solar thermal collectors and applications. Progress in Energy and Combustion Science. 2004;30:231–95.
[11] Saxena A, El-Sebaii a. a. A thermodynamic review of solar air heaters. Renewable and Sustainable Energy Reviews. 2015;43:863–90.
[12] Saxena A, Pandey SP, Srivastav G. A thermodynamic review on solar box type cookers. Renewable and Sustainable Energy Reviews. 2011;15:3301–18.
[13] Akpinar EK, Koçyiğit F. Energy and exergy analysis of a new flat-plate solar air heater having different obstacles on absorber plates. Applied Energy 2010;87:3438–50.

[14] Bouadila S, Kooli S, Lazaar M, Skouri S, Farhat A. Performance of a new solar air heater with packed-bed latent storage energy for nocturnal use. Applied Energy 2013;110:267–75.

[15] Alvarez G, Arce J, Lira L, Heras MR. Thermal performance of an air solar collector with an absorber plate made of recyclable aluminum cans. Solar Energy 2004;77:107–13.

[16] Shariah AM, Rousan A, Rousan KK, Ahmad AA. Effect of thermal conductivity of absorber plate on the performance of a solar water heater. Applied Thermal Engineering.1999;19:733–41.

[17] Majid ZAA, Ruslan MH, Sopian K, Othman MY, Azmi MSM. Study on performance of 80 watt floating photovoltaic panel. Journal of Mechanical Engineering and Sciences. 2014;7:1150–6.

[18] Al-Kayiem HH, Yunus YM. Drying of empty fruit bunches as wasted biomass by hybrid solar-thermal drying technique. Journal of Mechanical Engineering and Sciences. 2013;5:652–61.

[19] Close DJ. Solar air heaters for low and moderate temperature applications. Solar Energy.1963;7:117–24.

[20] Majid ZAA. Kajian prestasi sistem pengering pam haba terbantu suria dengan pengumpul suria multifungsi. Universiti Kebangsaan Malaysia, Bangi, 2011.

[21] Salazar A. On thermal diffusivity. European Journal of Physics. 2003;24.

[22] Bagdade SD. ASM ready reference: Thermal properties of metals (Materials Data Series). ASM International; 2002.

[23] Cengel YA. Introduction to thermodynamics and heat transfer. Second Edition. McGraw-Hill Science/Engineering/Math; 2007.

[24] Çengel YA, Turner RH, Cimbala J. Fundamental of thermal-fluid Sciences. 4th ed. McGraw-Hill; 2011.

[25] Halliday D, Resnick R, Walker J. Principles of physics. 10th ed. John Wiley; 2008.

[26] Çengel YA. Heat and mass transfer: A practical approach. 3rd ed. McGraw-Hill; 2006.

[27] Ekechukwu OV, Norton B. Review of solar-energy drying systems III: low temperature air-heating solar collectors for crop drying applications. Energy Conversion and Management. 1999;40:657–67.

[28] Norton B. Anatomy of a solar collector: Developments in materials, components and efficiency improvements in solar thermal collector systems. Refocus 2006;7:32–5.