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Thermal absorber material selection for solar thermal Bi-Metallic multilayer crosses absorber

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ABSTRACT

The energy gain term determines the level of energy received by the solar absorber from solar radiation and various methods have been implemented to increase the collector performance using a bi-metallic cross absorber. Experiments have been conducted to determine suitable material pairing between the bi-metallic cross absorber and black coated flat-plate absorber. Five types of solar thermal absorbers are investigated under condition 525 W/m^2 of solar radiation and with 0.52 m/s air flow speed in terms of heating and cooling performance. Four set stainless steel cross absorbers achieved best energy retention capability by obtaining the slope value of -0.1520 during the cooling phase while during the heating phase, coated flat plate performed well with a slope value of 0.4909. The profile of the thermal absorber with thermal absorption and thermal buffer can be summarized using a spider chart with distance index bar-chart, and the result shows that a bi-metallic, aluminium and stainless steel cross absorber exhibit the optimal balanced thermal profile. With the implementation of the material selection method could minimize the material selection process for cross absorber application.

1. Introduction

Rapid technological and sociological advancement incur massive energy usages and contribute to environmental problems (Bakar and Othman, 2013). Despite increased mobility and unprecedented innovation and achievement, it comes with its own toll on humanity that can threaten future generations (Ahuja and Tatsutani, 2009).

Consumption of fossil fuels releases unwanted and harmful by-products into the Earth's ecosystem in the forms of greenhouse gasses of carbon dioxide, methane, nitrous oxide and other harmful gasses emitted by the industrial sectors into the atmosphere.

The overwhelming dependency and reliance to fossil fuels is slowly depleting the natural energy reserves, triggering a new race towards new technology to harness renewable energy to support the ever-growing energy needs.

Solar energy is an attractive option for space heating and drying purposes as it can effectively conserve energy, is economically feasible for long term usage, and is virtually maintenance free. Solar energy technologies greatly assist global efforts to combat excessive carbon dioxide and other greenhouse gas emissions by substituting the fossil energy with renewable energy resources.

Energy gain determines the level of energy received by the solar absorber from the solar radiation and is essential for calculating collector efficiency (Duffie and Beckman, 1980). To increase energy gain by solar air collector, surface areas of the flat-plate have to be increase horizontally resulting in wider space requirements. Flat-plate design has a fixed angle which causes the collector performance to be susceptible to sun position and output air temperature fluctuates based on weather condition, given that no active solar tracking function is implemented (Chan et al., 2010; Duffie and Beckman, 1980). Multilayer cross absorber implementation could overcome this problem by expanding vertically to increase surface areas and subsequently increase the energy gain of the solar air collector (Majid et al., 2015; Majid, 2011). An enhancement of the multilayer cross absorber is proposed by Razak et al. (2015) where two materials

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with different thermo physical properties are used in the design to facilitate the output air temperature stabilization and increase the overall thermal performance of the solar air collector. For this, direct contact between the solid storage media and a heat transfer fluid is necessary to minimise the cost of heat exchange in a solid storage medium. Research has yet to focus on the material selection and optimisation factors of the thermal bi-metal cross absorber.

This paper seeks to determine and optimise the material pairing for a dual-material multilayer cross absorber for a balanced thermal absorption profile and buffering behaviour for optimum working condition.

2. Research methodology

Solar intensity levels of a solar simulator is set at 525 W/m^2 with a halogen lamp as solar the radiation source, positioned at 90 degrees above the plane of collector cover as in Fig. 1. A variable base depth solar collector test stand is used in the experiment in order to accommodate the height of different types of thermal absorbers. Forced convection setup is achieved by setting the air flow velocity in the collector at 0.52 m/s with 0.04 kg/s of air mass flow rate. Average ambient air temperature during the experiment is at 27.2 ^{o}C under static ambient air conditions (0 m/s). Temperature values for each absorber set, output and input air were measured by means of K-type thermocouples and logged using Advantech ADAM module data acquisition system.

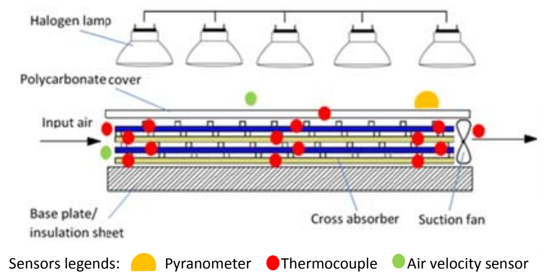

Fig. 1: Experimental setup for solar thermal absorber testing

Four types of cross absorbers were tested under the same conditions in which, 1, 2, 3 and 4 sets of cross absorbers with single material and a bi-metal combination of aluminium and stainless steel (Fig. 2(a-d)) were tested and later compared with aluminium flat-plate absorber setup.

The material dimensions used in cross absorbers are hollow square metal with diameter of ¾ inch, wall thickness of 1 x 10-3 m and with length of 1.2 m. All absorbers are coated with flat black paint to increase solar radiation absorption by the material (Majid et al., 2015). Cross absorbers comprise of one to four layers of hollow square metal absorbers stacked in crossed form as shown in Fig. 2. Experiments are conducted for 20 minutes for heating and cooling phases respectively.

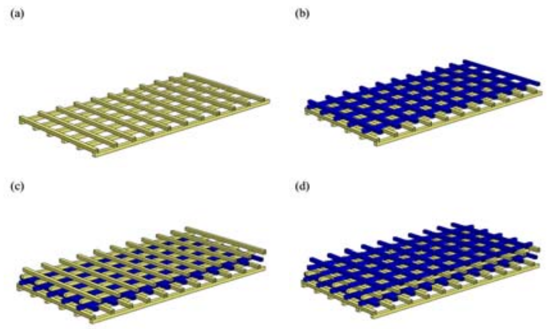

Fig. 2: Cross absorbers with bi-metal setting (a) 1 set (b) 2 set (c) 3 sets (d) 4 sets

3. Results and discussions

Each absorber setup exhibits significant peak temperature at the 20-minute mark. The highest peak temperature is achieved by using an aluminium flat-plate with flat black coating at 38.7 ^{o}C. This is followed by one, two, three and four sets of cross absorber as indicated in Fig. 3 where the lowest is the aluminium cross absorber. Flat black coating is important for reducing the reflectivity while increasing the absorptance of solar radiation to aluminium sheet. Without coating, increase of losses is expected due to reflectivity of metal surface i.e. aluminium and stainless steel. Predetermined values of flat-black coating and uncoated unoxidized aluminium surface have emissivity values of 0.970 and 0.026 respectively.

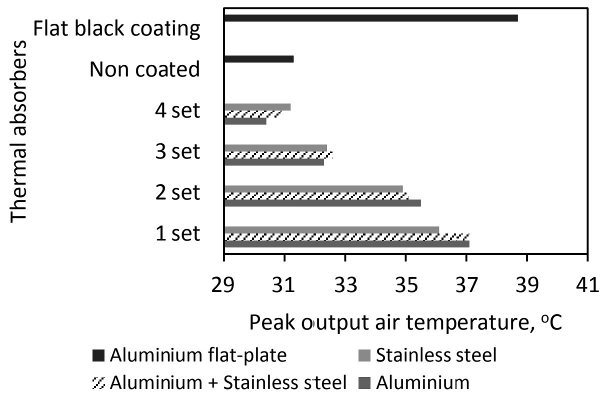

Fig. 3: Peak output air temperature for different thermal absorber type (525 W/m^2)

An important trend in number of layers is detected where the increase number of layers defined by number of sets at each arrangement, resulted in a reduction of maximum air temperature output. The highest useful energy extracted by air flow is 12.8 J/kg by coated aluminium flat plate and the lowest value was obtained by four set cross absorbers, bi-metallic and single material absorbers.

Base collector depth is changed according to height of the absorbers and air flow speed is then re-set to 0.52 m/s causing the volume of air flow is changed due to increase of speed and volume of air for thick absorbers and vice versa for thinner absorbers influencing the peak output air temperature. Specific energy transfer from absorber to air flow is also reduced which is related to the energy absorbed by the absorber (Fig. 4). This is because the mass of absorber materials increase with each increment of layer causing higher thermal mass. Thus, it will prolong the time for thermal energy from solar radiation to heat the thermal absorber to reach peak temperature because more energy is absorbed by the absorber layers. However, in terms of heat capacity, energy content of the cross absorber is higher than in the flat plate absorber.

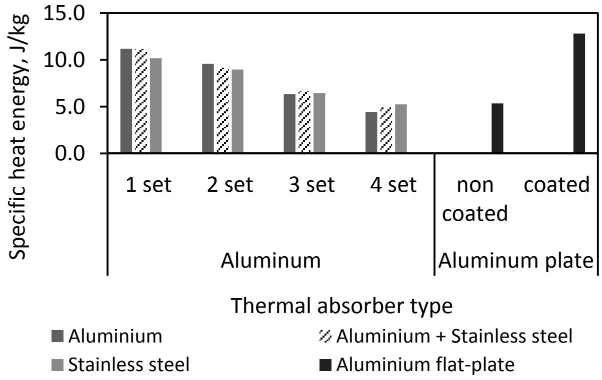

Fig. 4: Useful specific thermal gain of air for different thermal absorber type (525 W/m^2)

With the increased thermal mass, advantages can be seen here where a thermal buffer system is established and assists in covering thermal energy lacking for hot air during intermittent weather conditions or lack of solar radiation.

Table 1 shows the slope values during the cooling phase of the absorbers. Slope values show how fast the heat is extracted from the absorber material, and higher slope values means faster heat transfers from the absorber to surroundings (Razak et al., 2015). Flat plate aluminium with flat black coating exhibit highest peak temperatures and fastest heating times at 38.7^{o}C but due to its high value of emissivity of 0.98.

Table 1: Cooling phase: comparison of slope values

	Absorber type	Slope value	Thermal buffer level
1	FP coat	-0.438	Least
2	2s Al	-0.3789	↓
3	2s Al SS	-0.3774	
4	1s Al	-0.3715	
5	1s SS	-0.2959	
6	2s SS	-0.2797	
7	3s Al	-0.2437	
8	3s SS	-0.2341	
9	3s Al SS	-0.2304	
10	FP no coat	-0.209	
11	4s Al	-0.1972	
12	4s Al SS	-0.1566	
13	4s SS	-0.152	Highest

Lower thermal mass and wide exposure surface to heat transfer fluid resulted in a sharp drop from peak temperature to 26^{o}C ambient temperature with gradient of -0.438. It has least thermal buffer capabilities compared to other thermal absorber types. The highest thermal buffer is recorded by four sets stainless steel cross absorber with -0.152 gradients. With an increase in the number of layers, the thermal mass of the absorber also increases linearly. Temperature slope plays a significant role in determining the thermal buffer capabilities in absorbers (Majid et al., 2015).

In contrast with slope values during the cooling phase, steepness of gradient during the heating phase produces an indicator of solar radiation absorption of absorber whereby a high inclination means a better absorption rate and vice versa for lower values (Table 2). Best absorption rate is achieved by flat plate aluminium with flat black coating, followed by 1 set aluminium and 1 set stainless steel cross absorber.

From both cooling and heating phase slope values, it can be seen that a fast heating material does not necessarily have good thermal buffer properties as shown by the flat plat aluminium with coating and 0.4909 heating slope and -0.438 cooling slope. These three absorber types have almost the same heating performance with relatively low difference of 0.2 % and 1.06 % for 1 set aluminium and 1 set stainless steel cross absorber to the flat plat coated slope value respectively.

Table 2: Heating phase: comparison of slope values

	Absorber type	Slope value	Thermal absorption level
1	FP Al no coat	0.1504	Least
2	4s Al SS	0.1515	↓
3	4s SS	0.1697	
4	4s Al	0.2272	
5	3s Al SS	0.2439	
6	3s SS	0.2442	
7	3s Al	0.2651	
8	2s Al	0.3385	
9	2s Al SS	0.3676	
10	2s SS	0.3748	
11	1s SS	0.4857	
12	1s Al	0.4899	
13	FP Al coat	0.4909	Highest

Both cooling and heating gradient values are plotted together in a spider chart in Fig. 5 (a) where the characteristics and trend of various types of thermal absorbers can be determined. Outer points are for the thermal buffer and the internal line is the thermal absorption. A combination of both trends can determine the capability of the thermal absorber to absorb solar radiation energy and release it and to store the energy in the absorber.

Thermal absorption points that diverge far from the centre indicate good thermal absorption and vice versa for thermal buffers. Slope value for each setup signifies the energy absorption and energy storage capability of each arrangements (Majid et al., 2015) where lower values show least absorption and least storage characteristics and vice versa. The distance between two points (thermal absorption and thermal buffer slopes value) shows the weightage of both characteristic to the absorber that can be defined from Fig. 5 (b). A combination of 4 sets aluminium and stainless steel in cross absorber exhibits 0.3081 distance index, which is lower than other absorbers with 30.9ºC output air temperature which is favourable due to a balanced profile of absorption and buffer index. Cost factor can be minimised by utilising the selection charts in terms of procuring the material that suit the system requirements.

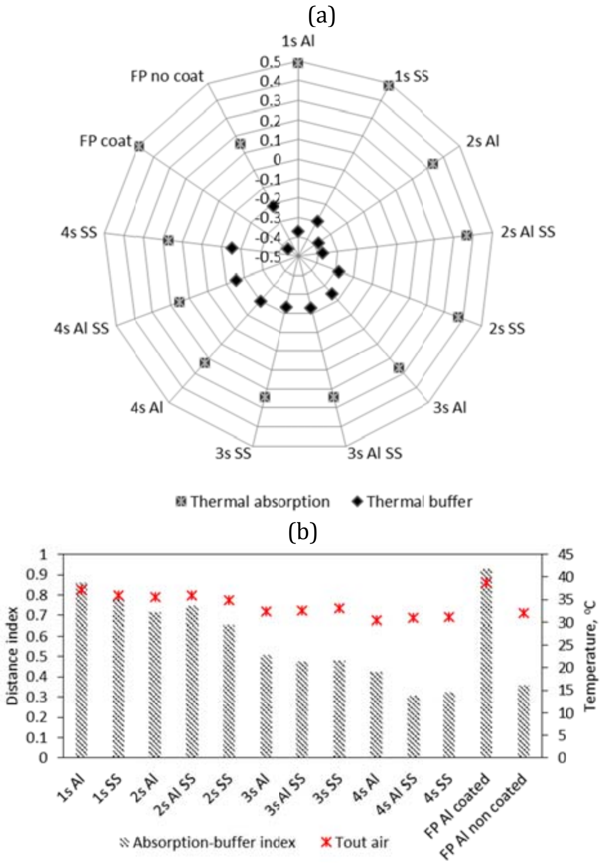

Fig. 5: (a) Combination heating and cooling slope values (b) Absorption-buffer slope index

It is important to note that thermal diffusivities, *D*, plays an important role in determining the temperature behaviour of each material besides the thermal conductivity, *k* during the thermal conduction process between different materials and within the materials itself. Materials with high thermal conductivity and high thermal diffusivity are suitable for solar radiation absorbing surface while high *k* and low *D* are suitable as buffer materials. Thermal conductivity defines the extraction rate of energy from a thermal source and thermal diffusivity shows the rate absorber energy diffused though the material.

Thermal buffer terminology is used to differentiate its characteristics against thermal storage which indicates the material will release the energy or act as a "buffer" when the low input energy source situation i.e. sun is covered with cloud, to prevent a steep drop of hot air temperature during the period of operation.

4. Results and discussions

Thermal buffering in cross absorbers have a significant influence in stabilising the output air temperature of solar air heaters during intermittent solar radiation conditions. Appropriate selection of materials could assist greatly in designing cross absorbers for solar air heaters in achieving good absorption and buffer characteristics.

By implementing collected data into the spider-chart and supported by distance index bar-chart, the relation and influence between two different materials in a cross absorber setup can be determined. A combination of aluminium and stainless steel setup exhibits the best choice for cross absorber application with a balanced profile of absorption and buffering and considering the useful peak output air temperature. Cost factor can be minimised by utilising the selection charts in terms of procuring the material that suits the system requirements.

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