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Thermal Performance of Flat Plate Solar Collectors for Humid and Unpredicted Weather using Air Properties and Energy Method

Felix Uba[1], Eric Osei Essandoh[2], Gilbert Ayine Akolgo[3] and Charles Nunya Dzikunu[4]

[1,2,3,4]*University of Energy and Natural Resources, Ghana.*
[1]***Correspondence***: felix.uba@uenr.edu.gh

Abstract

Devising technologies to make use of renewable energy such as solar energy is very innovative and progressive since tapping energy from a free source is cost effective in the long-term and totally ecologically friendly. The main aim of solar drying of crops is to preserve them by removing the excess moisture that will cause their deterioration in order to improve their shelf life. Solar drying though found to be a mature, cost-effective and an efficient method of drying especially crops, it has not been widely deployed for crop drying both at the commercial and industrial level in Ghana. The purpose of this research is to produce a solar heat collector for space heating using cheap and available materials and also to demonstrate the importance of incorporating obstacle/fins on plates to improve the efficiency of solar collectors. This study investigates the effect of increased air contact area of various configuration on the efficiency of solar air heaters. Nine different absorber plates (with and without fins) were considered by this research in an experimental study to select the best design that will be suitable for absorbing or providing a high fraction of heat for conditioning humid atmospheric air (lowest relative humidity of the collector air). The best designs of this study had an efficiency between 58% to 72% and maximum absorber temperatures above 80°C, collector air temperature above 70°C and collector air relative humidity below 20% while the worst design had an efficiency between 35% and 50%, collector air temperature bellow 45°C and the lowest collector air relative humidity of 26%. The findings of this research have revealed that increasing the contact area of the air current or circulation and the shapes of the fins attached to flat absorber plates increase their air contact areas and affect the thermal efficiency of the solar collectors. Also, it has revealed that the arrangement of fins contributes positively to the efficiency of solar collectors.

Keywords: Thermal performance; mat black; plates; collector; air properties; heat transfer coefficient

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1.0 Introduction

1.1 Background

Though the deterioration of agricultural produce starts with the presence of unacceptable levels of its own moisture, external conditions such as damp environment and pest attack also contribute enormously to the deterioration or spoilage of agricultural produce (Adom, Dzogbefia, & Ellis, 1997; Fudholi A. , et al., 2015; Schiavone, 2011). The natural method of drying (popularly known as sun or solar or open drying) is extensively used traditionally and is the oldest, easiest and apparently the cheapest method for drying so far. The other method of crop drying (artificial drying) which happens to be more efficient requires devices and standard technologies. This method allows the conditioning of air for product drying thus controlling the drying mechanism in order to produce a good quality product at the end of the drying time. Artificial drying supplies products with conditioned air with less moisture content (humidity level) and creates a condition where the moisture within the product develops a high-pressure against the atmosphere to allow its escape (Adom, Dzogbefia, & Ellis, 1997; Al-Ajlan, Al-Faris, & Khonkar, 2003; Buchinger & Weiss, 2002). Artificial methods require the use of mechanical (solar collectors) and electrical devices(ovens). Ironically, the mechanical type of artificial method of drying which is found to be more efficient than natural or open air drying and much cheaper than electric drying has not been deployed widely in Ghana for socio-economic gains and for this reason, it is imperative for local researchers to pursue this objective in future research.

The most important part of a solar dryer is the cover sheet (collector). The other parts are the absorber plate, insulation film, gasket and seal, inlet and outlet pipes and casing/container.

The basic requirement for the transfer of heat energy from one region to another is temperature difference. To transfer heat energy between two fluids by convective mode without mixing the fluids, heat exchangers are used, and a special type is required when the transfer is between a distance energy source such as the sun and a fluid such as the air. This requires the use of properly designed solar collectors.

The absorber of the solar collector is usually made of high thermal conductivity metal such as copper or aluminum. The aim of solar energy utilisation is to decrease the cost of collecting the energy, reduce construction, installation, operation, decommissioning and obtain high device efficiency. In view of this, air heaters may be designed using fewer valuable metals or even some scraps of virtually no commercial value to reduce cost. To increase the absorbability of the material they are painted with mat black paint to approximate it to a black body (Incropera, Lavine, Bergman, & DeWitt, 2007; Al-Ajlan, Al-Faris, & Khonkar, 2003; Fudholi, Sopian, Ruslan, Othman, & Yahya, 2011).

Because the thermal conductivity of air (0.024 W/m.K) is low, expert suggestions, research and modifications to improve the heat transfer coefficient of the air enclosed between the absorber plate and the glazing material (cover sheet) of the solar collector have become very necessary to the scientific community (Sopian, Alghoul, Alfegi, Sulaiman, & Musa, 2009). Air heaters design factors (i.e., source of energy, number of glazing and glazing type, design of air heater, etc.) have contributed tremendously to its performance (Chaudhri, Kothari, & Panwar, 2009; Enebe & Ezekoye, 2006; Jain & Jain, 2004). Research works have also demonstrated that by providing some turbulence to the convective medium (air) in solar collectors, the amount of heat transferred from the heater (absorber plate) to the air is increased (Verma, Chandra, & Garg, 1991; Yousef & Adam, 2008). Recommendations so far made through research range from introduction of obstacles/fins in the path of the convective medium to the use of complex solar absorbers (heliostats, parabolic concentrators) (Yousef & Adam, 2008). The former requires extending the surface area of the plate (i.e., introducing ridges in the form of fins on the surface of the absorber plate) to increase the contact area of the air passing through the device. The latter method involves the introduction of heat storage, increasing the air passage length, using collector with porous media or V-corrugated collector (Sopian *et al*., 2009; Pradhapraj *et al*., 2010; Dammak *et al*., 2010). A study conducted by Helal *et al.* (2010) on energetic performances of a solar collector system integrated with a back-up solar water heater system has also shown a great improvement of the solar air heater with heat storage over those without heat storage. This development has made the evaluation of various designs, estimation of allowance for improvement, and the need to create various scenarios very paramount as there is no globally acceptable design of solar collectors.

The purpose of this research is to produce a solar collector for space heating using cheap and available materials and to demonstrate the importance of incorporating obstacles/fins on plates to improve the efficiency of solar collectors. Positive findings of this study will inform farmers and other participants in the value and supply chains of the agricultural sector to learn about the best designs of flat plate collectors that may be deployed for effective and efficient drying of crops in humid regions. It intends to investigate the effect of increased air contact area of various configurations on the efficiency of solar air heaters.

1.2 Conceptual Framework

This research work was partially set out to investigate single-pass, low-temperature thermal collectors because the main aim of the study was to tap heat energy from the sun to preheat air specifically for space heating. Air has a specific heat capacity of 0.287 kJ/kg.℃ thus it takes low amount of solar energy while inside the collector which is later transported elsewhere for space heating, one of which application is crop drying. Flat plate solar air heaters are typically employed to satisfy air temperature requirements ranging from 30^{o}C to 80^{o}C with its usual operating efficiency ranging from 30% to 65% (Jesko, 2008). The solar air heater designed and fabricated for this research uses the free convection mode of heat energy transfer thus it uses no device for the circulation of air i.e., it is a passive type of solar collector. Also, per the design principles (simplicity and cheapness) of the solar collector, tracking the sun to collect its radiation is not very necessary.

1.3 Working Principle of Low-Thermal Solar Air Heater

Solar air heaters function by transmitting solar energy through cover sheets to heat absorber plates which in turn increases the internal energy of the air above it and inside the collector for space heating which can be applied for crop drying. Thus, solar air heaters increase the internal energy of the transporting medium (in this case, air) (Ibrahim, Ibrahim, Yatim, & Ruslan, 2013).

1.4 Classification of Solar Air Heaters

Solar air heaters may be classified according to their construction material into two categories namely, glazed and unglazed solar air heaters. The glazed type is based on air recirculation principles and are usually employed for space heating while the unglazed type is used to heat ambient air for commercial, industrial, agricultural and process applications. They may also be classified according to their air flow paths namely, front-pass, back-pass and through-pass (Mendaza, 2014; Saxena, Batra, & Kesari, 2017)

1.5 Glazed Solar Air Heaters

Solar air heaters that use glass or glazing material to transmit solar energy to an absorber plate are called glazed solar air heaters. They are normally used to produce heat by recirculating conditioned building air. In this system, the absorber plate is heated by an incoming solar radiation and the indoor exhaust air is ducted to come into contact with the absorber plate in order to preheat and reintroduce it into the space. Based on the varying ducting methods of the glazed solar air heater, this device is sub-classified into three categories namely, front-pass, back-pass and through pass as illustrated in Figure 1.

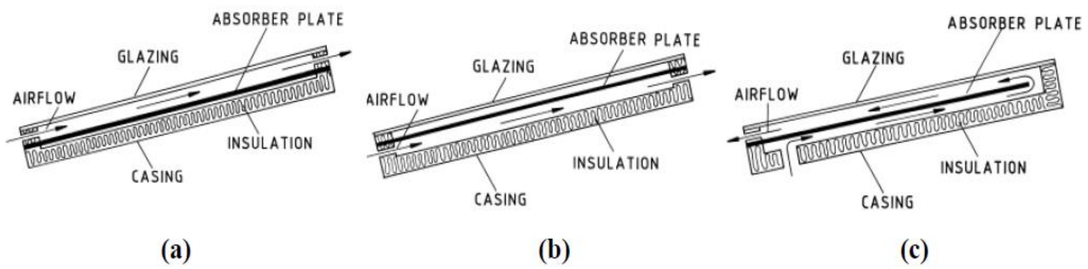


Figure 1: Classification of glazed solar air collectors according to ducting method: (a) front-pass collector; (b) back-pass collector; (c) through-pass collector (Mendaza, 2014)

1.6 *Unglazed Solar Air Heaters*

Unglazed solar air heaters are air heating systems that consist of absorber plates without any glass or glazing on top of the absorber. Unglazed solar air heaters preheat ambient (outside) air instead of indoor air. This type of solar air heater is used for ventilation and crop drying. The commonest type of unglazed solar air heater is the transpired solar air heater (Saxena, Batra, & Kesari, 2017).

2.0 Methodology

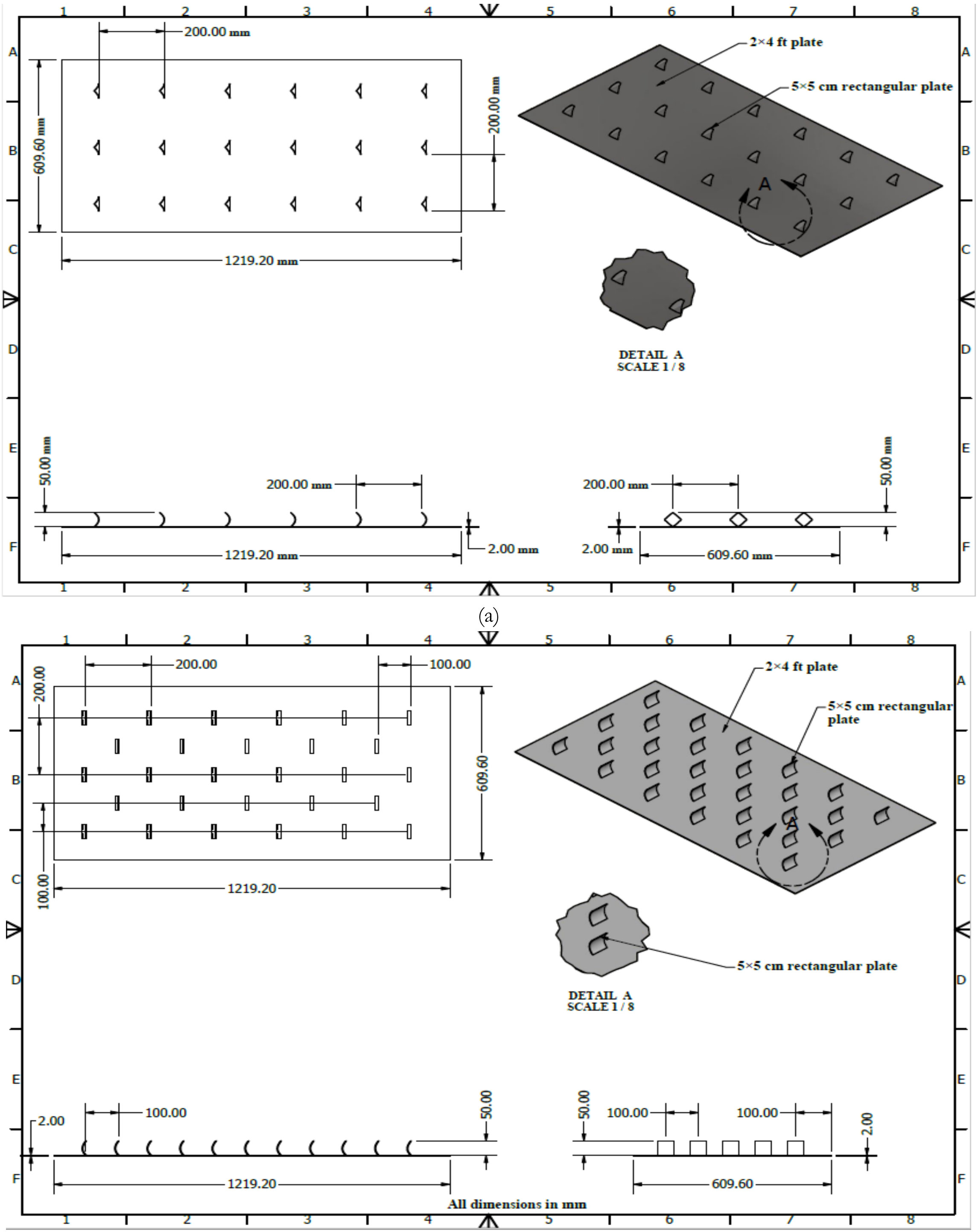
In this research, nine different absorber plates mild steel plates were considered to select the best design that will be suitable for absorbing or providing a high fraction of heat for conditioning the atmospheric air because they are relatively cheaper than aluminum and stainless steel. Figure 2 shows the orientation and shapes of the fins or obstacles attached to the absorber plates. The plates were painted matt black (matt black is a type of paint with high solar absorptivity due to it low level reflectance in the ultra-violet to visible regions of the light spectrum) to increase their absorptivity and are presented in the order they appear in the experiment shown in Figure 2. In all, there were four (4) different fin designs (square, triangular, kite, rectangular which fall under both the uniform and non-uniform types of fins) arranged in two different forms (regular and irregular orientations). Each design was arranged in two ways giving eight orientations. A plane (obstacle free) plate collector (Figure 2(f)) was added to act as a control experiment. The physical properties measured are atmospheric temperature and relative humidity; collector's inside temperature and humidity; solar intensity; absorber plate temperature and air speed. The collectors were constructed and tested on the University of Energy and Natural Resources campus in Sunyani. Arduino sensors were programmed to measure these parameters at time interval of 1 (one) minute. The data picked were also stored in a memory chip and later analysed excel program.

These physical properties were measured at time intervals of 1 minute from 6:00 am to 6:00 pm in the month of May, 2020. An energy analysis was also performed on the plate using the following relations.

An energy balance on the collector gives (Sukhatme, 1993; Farahat, Sarhaddi, & Ajam, 2009)

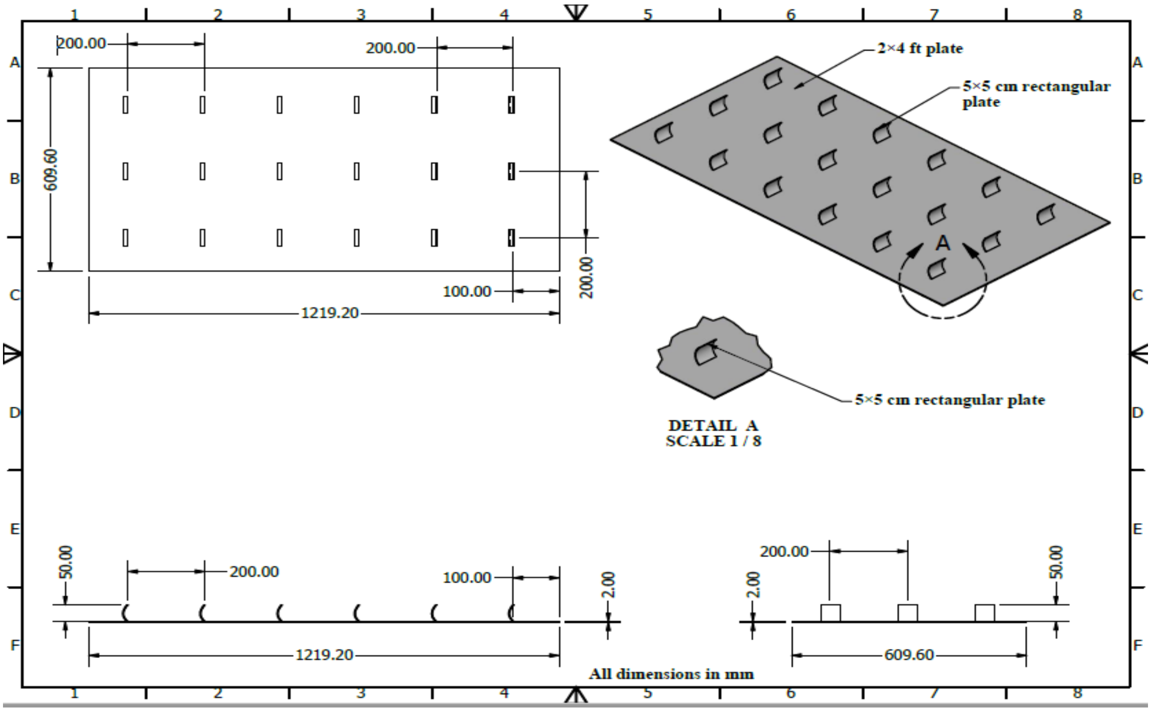
$$\dot{Q}_u = \tau\alpha I_T A_c - U_L A_c (T_c - T_a) \tag{1}$$

where, $\dot{Q}_u$ is the useful energy released by plates; τ, and α are optical and surface properties of the glass cover and plate respectively; I_T is solar intensity on the surface of collector; A_c is collector surface area; U_L represent overall heat transfer coefficient of the absorber in (W/m^2.K); T_c collector temperature and T_a ambient air temperature.



(b)

Figure 2: Collector Plates with different arrangements



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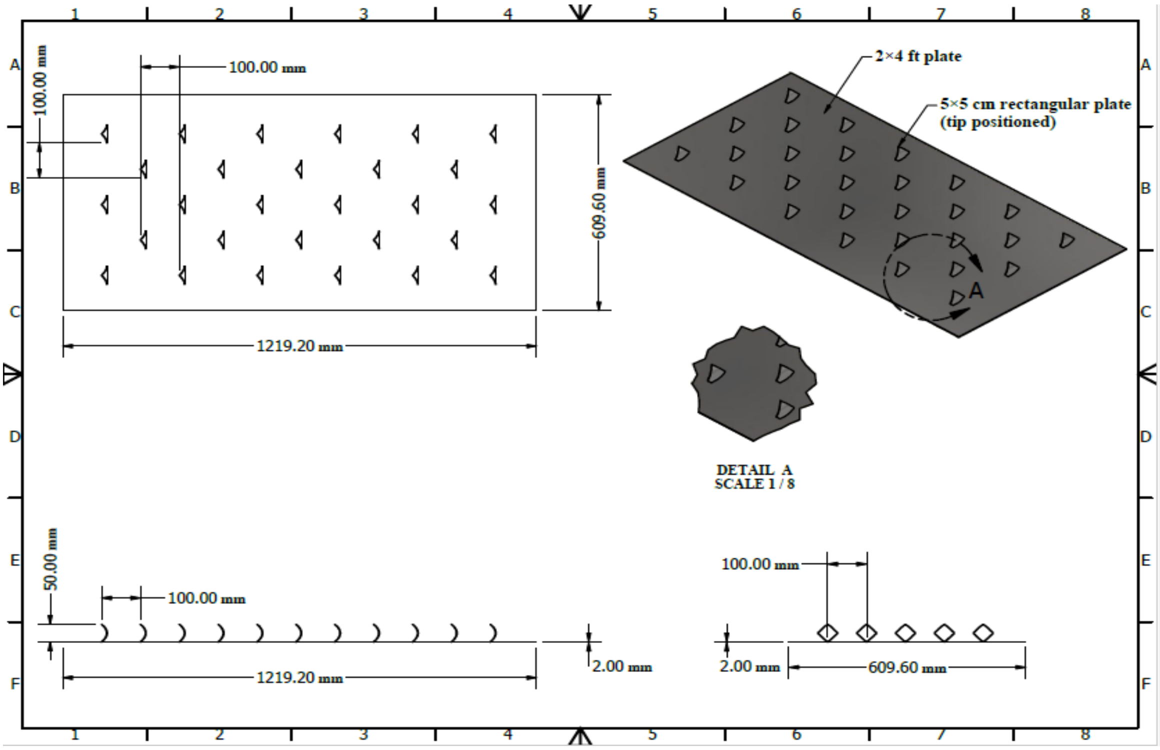
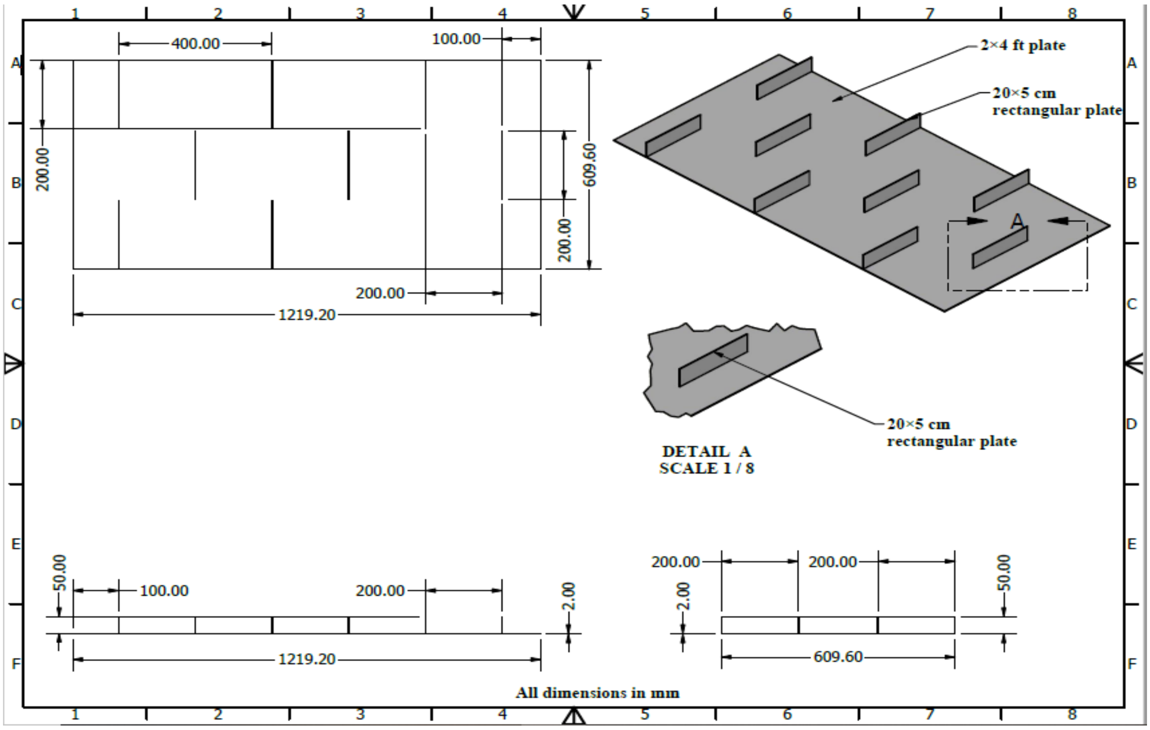
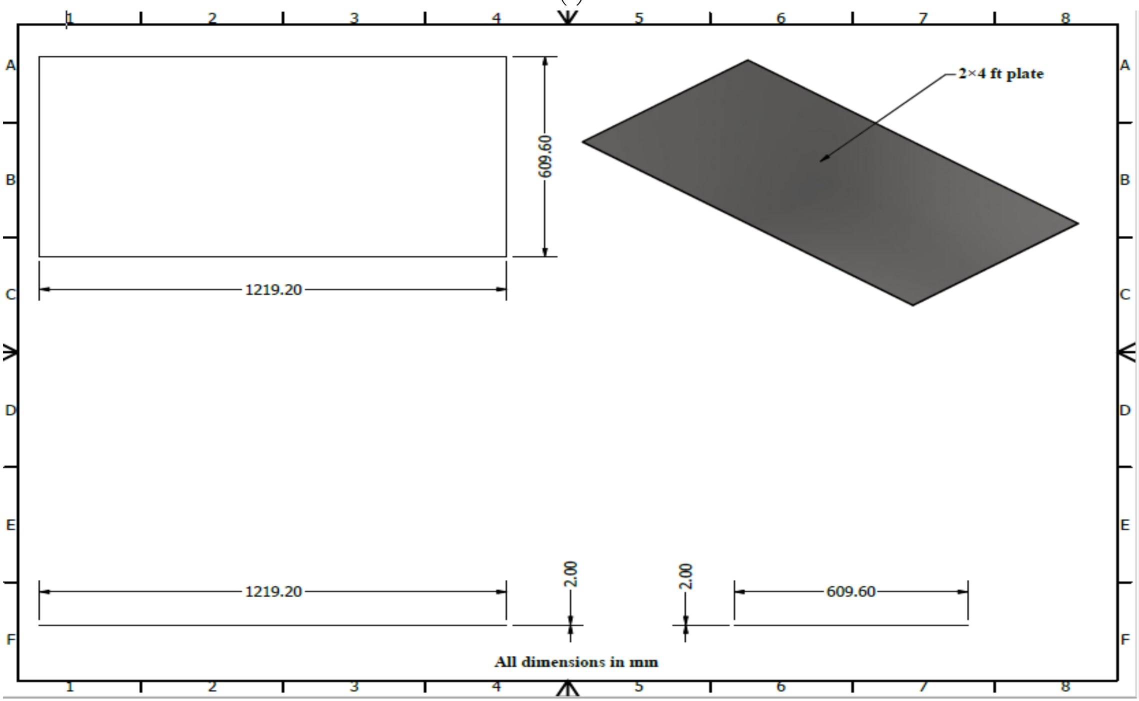


(d)

Figure 2: Collector Plates with different arrangements. *conti.*

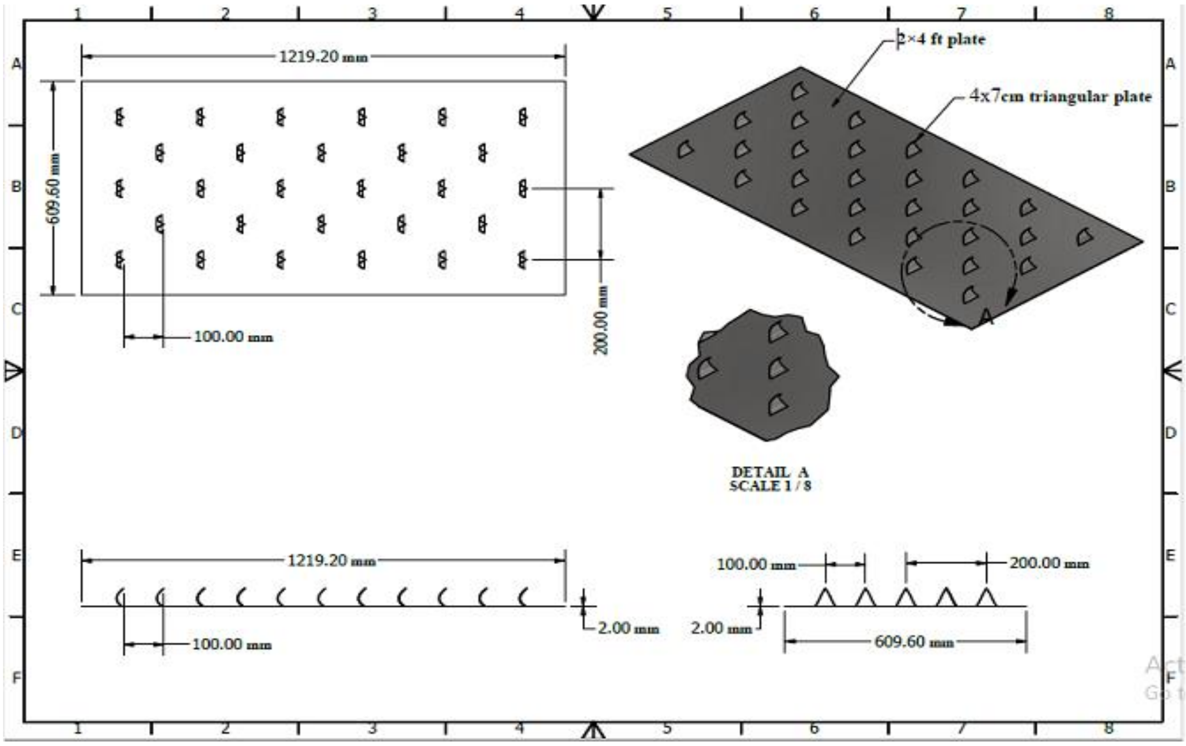


(e)

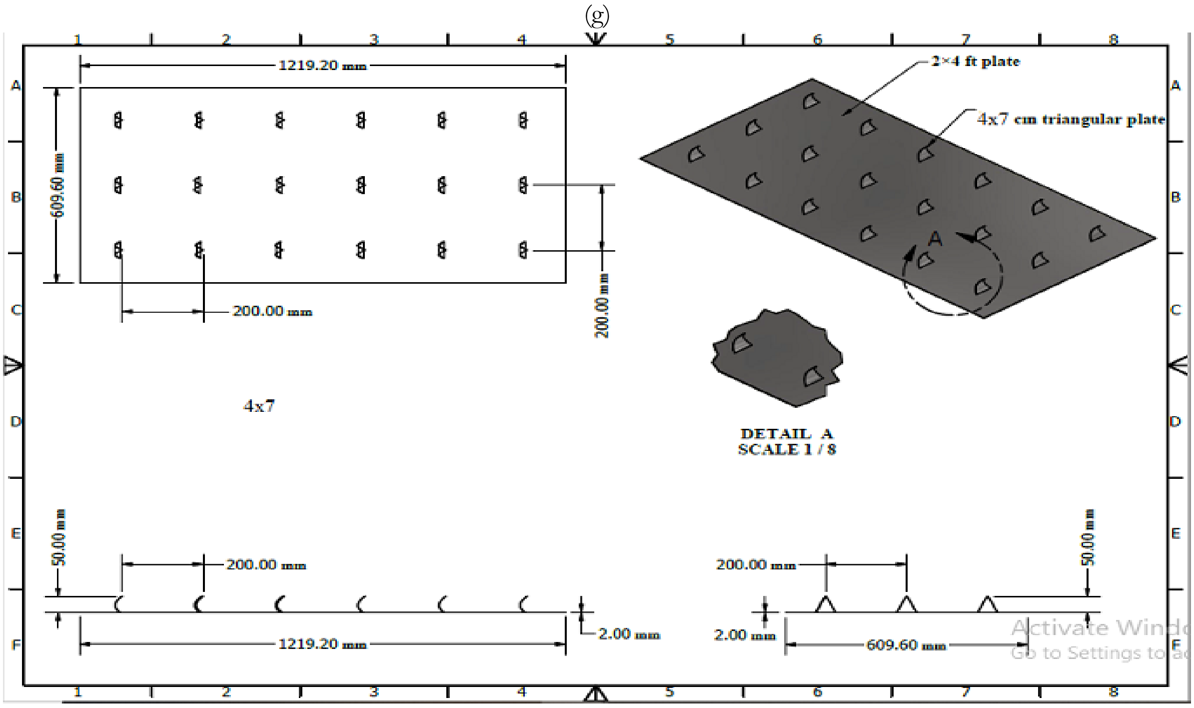


(f)

Figure 2: Collector Plates with different arrangements. *conti.*

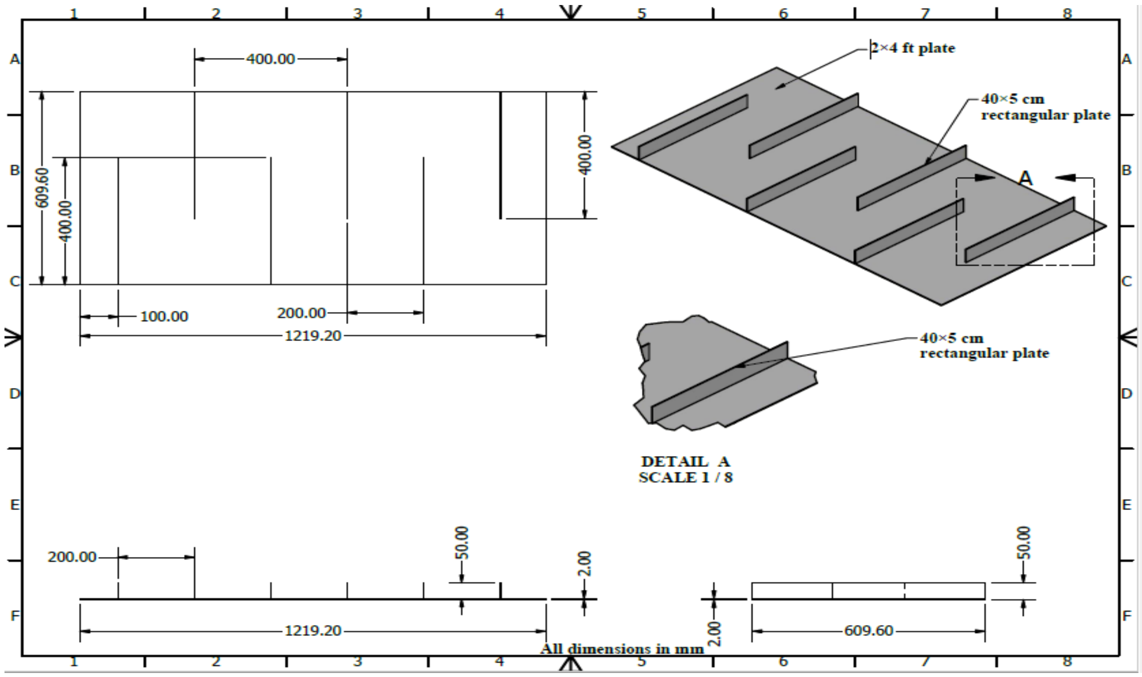


(g)

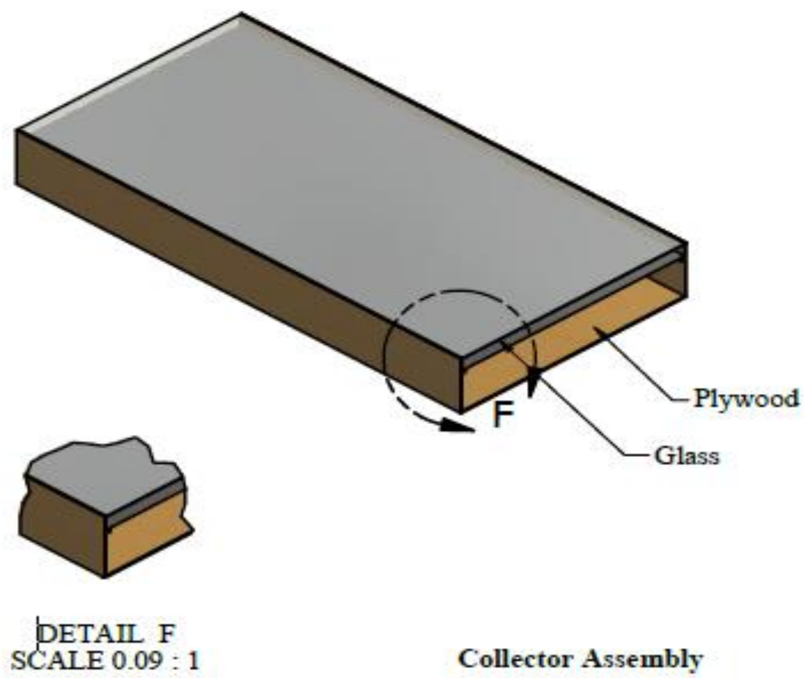


(h)

Figure 2: Collector Plates with different arrangements. *conti.*



(i)



(j)

Figure 2: Collector Plates with different arrangement. *cont.*

Assuming the air leaving the collector is at the same temperature as the absorber plate, T_c. Then the energy gain is expressed as (Pratota, Daguenet, & Zeghmati, 1997);

$$\dot{Q}_g = \dot{m}_a C_{pa}(T_c - T_a) \tag{2}$$

where, $\dot{m}_a$ and C_{pa} represent mass of air leaving the collector per unit time (kg/s) and specific heat capacity of air at constant pressure (kJ/kg.K), respectively. To estimate the fraction of the useful heat absorbed or available from the absorber to the air stream, the term F_R was introduced as a constant (Sukhatme, 1993).

$$F_R = \frac{\dot{m}_a C_{pa}(T_c - T_a)}{\tau\alpha I_T A_c - U_L A_c(T_c - T_a)} \tag{3}$$

From Equations 1 to 3, the heat extracted by the absorber can be expressed as (Sukhatme, 1993; Farahat, Sarhaddi, & Ajam, 2009);

$$\dot{Q}_g = A_c F_R[(\tau\alpha)I_T - U_L(T_c - T_a)] \tag{4}$$

where, F_R, and $\dot{Q}_g$ are the heat removal coefficient of the absorber/the heater efficiency factor and the heat extracted by the absorber respectively.

The air properties were calculated by the following equations:

$$c_p = 975.2 + 0.12468T_i + 3.3132 * 10^{-6}T_i^2 \tag{5a}$$

$$\rho = 1.9049 - 3.04328 * 10^{-3}T_i - 1.3889 * 10^{-6}T_i^2 \tag{5b}$$

The characteristic dimension or equivalent diameter of ducts for solar collectors is given by

$$D_h = \frac{2ab}{(a+b)} \tag{6}$$

where a and b are channel height and width, respectively.

To calculate the thermal efficiency of the collector, it is defined as (Sukhatme, 1993);

$$\eta_c = \frac{\dot{Q}_g}{I_T A_c} \tag{7}$$

3.0 Results and Discussions

The various designs of solar air heaters were tested concurrently, and their results recorded in the order of their arrangement as displayed in Figure 3. The atmospheric air properties were measured before it entered and exited the collector. It was found out that for all the collectors the plates were able to condition the atmospheric air (i.e., increase the temperature and reduce the humidity). Figure 3(a-e) shows the following parameters: temperatures of absorber plates; air temperature of both atmosphere and inside collectors; relative humidity of both atmosphere and inside collectors; relative humidity difference between atmospheric air and inside collector air and temperature difference between collector plates and inside collectors, respectively. The difference in the shapes of the fins affected the speed and flow pattern of the air thus, the differences in results. The plates were found to get hot and simultaneously release the heat to the buoyant air flowing around them (Figure 2). Table 1 shows the Temperatures recorded on the plates simultaneously as they release heat to the surrounding air. The temperature values do not show explicitly the effectiveness of the plates as their heat transfer coefficients are different due to the shape factor of the various fins, so a better case is to use the air inside the collector as a heat sink.

Table 1: Temperatures in ^{o}C of the various Plates for May, 2020

Item	**Plate 1**	**Plate 2**	**Plate 3**	**Plate 4**	**Plate 5**	**Plate 6**	**Plate 7**	**Plate 8**	**Plate 9**
Max.	78.2	71.8	73.0	87.2	78.2	70.0	77.8	80.4	71.8
Min.	25.1	25.2	26.0	25.5	25.3	25.3	25.2	25.4	25.2
Average	47.5	45.5	48.3	51.6	48.0	45.3	48.7	49.9	45.5

Table 2 and Figure 3 (a-e) truly reflect the recommended rates at which absorber plates should be transferring heat to the collector inside air. The information shows that majority of the plates with fins gave air temperatures above 70^{o}C except Plates 3, 6, 7 and 8.

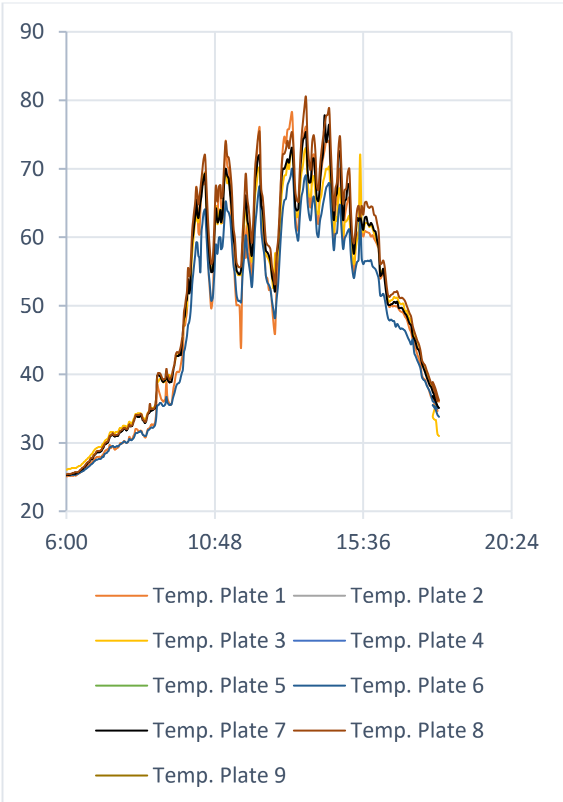
Table 2: Physical Properties of Collector Air and Atmospheric condition for May, 2020

Item	**Atm.**		**Collector 1**		**Collector 2**		**Collector 3**		**Collector 4**	
	T/^{o}C	**RH/%**	**T/^{o}C**	**RH/%**	**T/^{o}C**	**RH/%**	**T/^{o}C**	**RH/%**	**T/^{o}C**	**RH/%**
Max	42	92	73	81	77	85	62	80	73	83
Min	24	37	26	17	25	18	25	25	25	14
Average	31.8	65.4	46.7	40.2	48.4	40.4	41.7	49.2	47.3	38.4

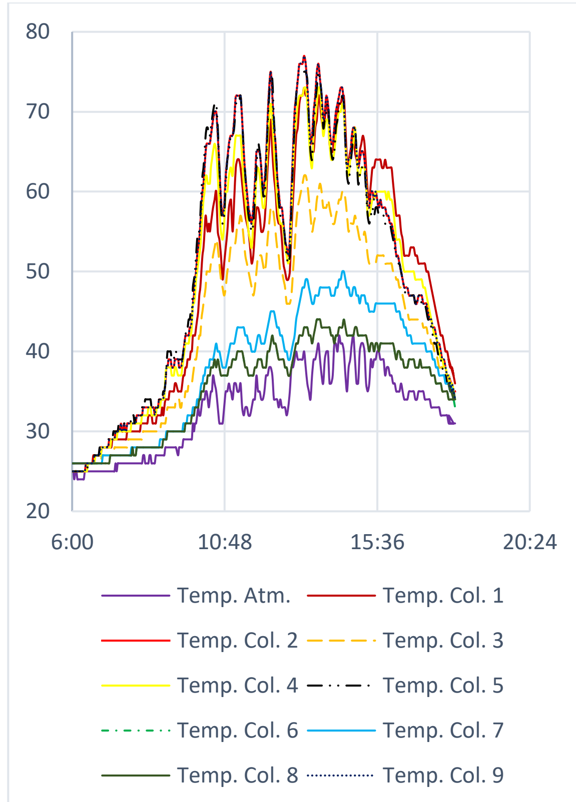
Item	**Collector 5**		**Collector 6**		**Collector 7**		**Collector 8**		**Collector 9**	
	T/^{o}C	**RH/%**	**T/^{o}C**	**RH/%**	**T/^{o}C**	**RH/%**	**T/^{o}C**	**RH/%**	**T/^{o}C**	**RH/%**
Max	75	86	44	83	50	81	45	85	77	80
Min	25	17	26	38	26	32	26	18	25	25
Average	48.2	39.0	34.5	59.3	36.6	56.3	34.6	40.4	48.4	39.2

The control experiment (i.e., Plate 6) which is without fins showed the least maximum temperature (i.e., 44^{o}C) followed by the plates (Plate 3, 7 and 8) with temperatures 62^{o}C, 50^{o}C and 45^{o}C, respectively. Among the last three plates mentioned, the low values of Plates 7 and 8 can be attributed to the nature and size of the fins (i.e., triangular). The triangular obstacles are not able to obstruct the flow to create enough turbulence for mixing and extraction of heat from the absorber plates due to their smaller cross-sectional areas, hence the smaller values for their temperatures. Among the rest of the plates that displayed inside temperatures above 70^{o}C and daily average of 48^{o}C are Plates 2, 5 and 9 which happen to be the fins with irregular arrangement. Also, the least relative humidity (i.e., daily average relative humidity less than 40%) can be obtained from Plates 5 and 9. The dimensions of the fins on Plate 5 and 9 happen to be larger than the fins on the rest of the plates. The fins (Plates 5 and 9) by their nature create the tendency for the air to travel a longer path and create higher turbulence as compared to the rest.

Figure 3(a) represents the temperatures of the plates whiles they simultaneously convert heat to the collector inside air as it absorbs solar radiation. However, this information does not give a good performance of the plates because it does not give the quantity of heat it has converted into the environment i.e., the collector inside air. Figure 3(b) gives the condition of the air in terms of temperature. The lowest curve (with the least area) represents the atmospheric air temperature. The maximum atmospheric temperature obtained from the curve is 42^{o}C. The rest of the curves on Figure 3(b) were plotted with air temperatures measured after they have passed over the hot plates hence their high temperatures as compared to the atmospheric air temperature. The maximum temperatures happened to be recorded from the plates with large cross-sectional area fins, example, plates 2, 5 and 9. The same trend was recorded for the relative humidity in Figure 3(c). The relative humidity values measured after the air has passed over the plates happened to be lower than that of the atmospheric air. The least value recorded for the atmospheric air is 37 % (i.e., the topmost curve) which is higher than all the values. Figure 3(d) represents the difference in the relative humidity between the atmospheric air and the various collectors' air. It represents the amount of moisture removed from the atmospheric air after it has passed over the plates. The largest difference was recorded from collector 5 which can be attributed to the fact that the air is made to travel a longer path as compared to the other plates and the nature of the fins allows greater turbulence. Figure 3(e) represents the difference between the plates and air temperatures. This information displays the degree of improvement that can be made on the collector and it displays how efficient and effective they are. The largest value was recorded from the control experiment due to the absence of fin to create some turbulence.



(a)



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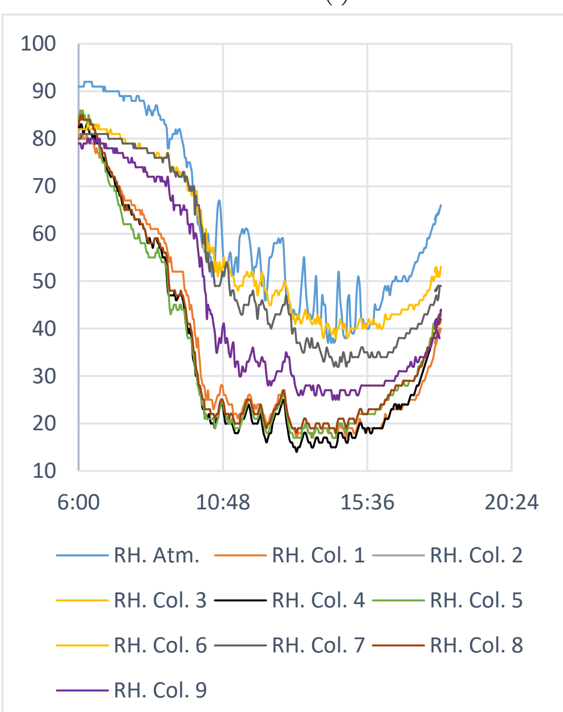

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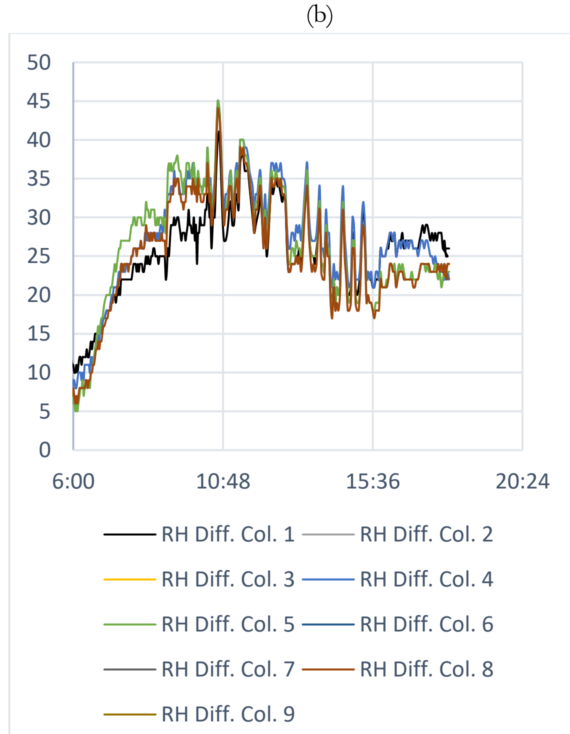
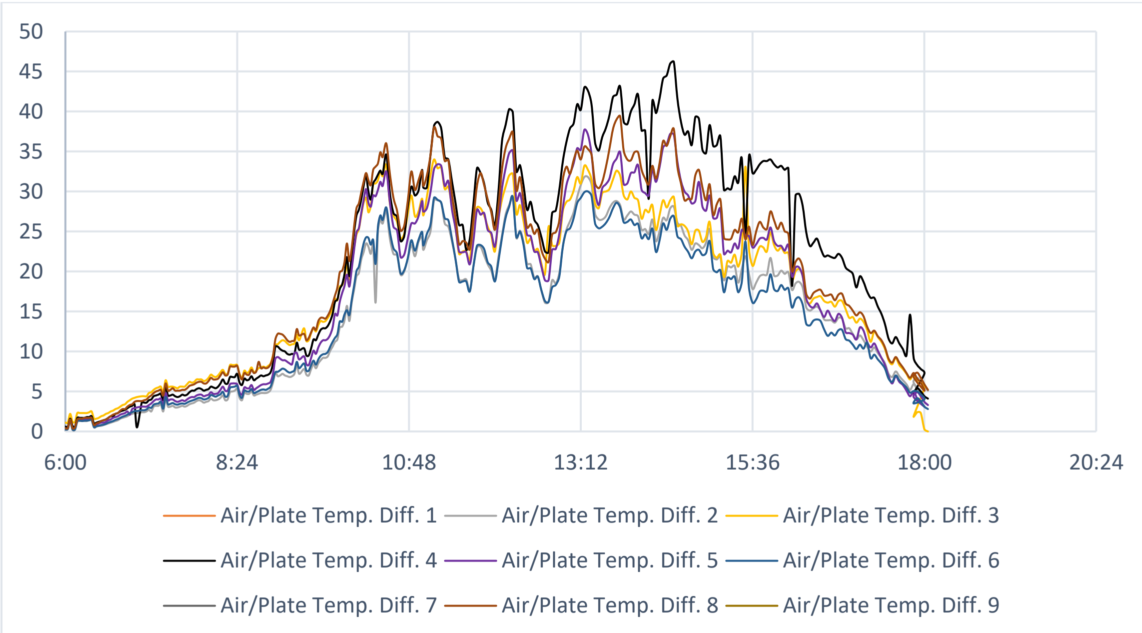


(d)

Figure 3: Physical Properties of both Air and Collector Plates (a- Temperature of Plate, b-Temperature of Collector Air, c- Relative Humidity of both Atmosphere and Collector Air, d- Difference in Relative

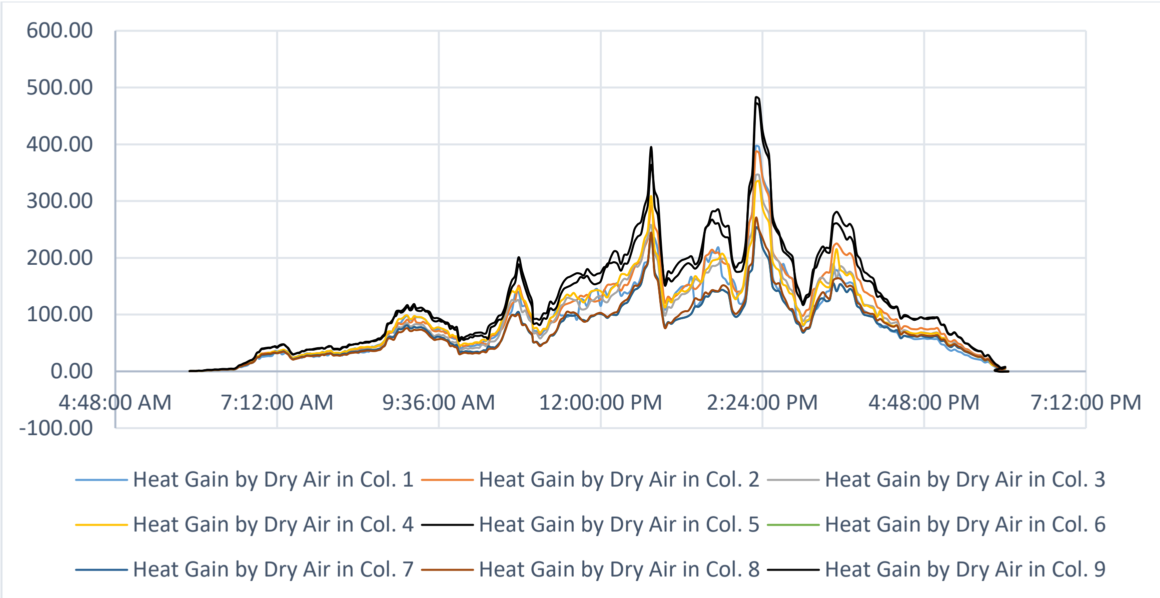
Humidity between Collector Air and Atmosphere, e-Difference in Temperature between Collector Air and Plate)



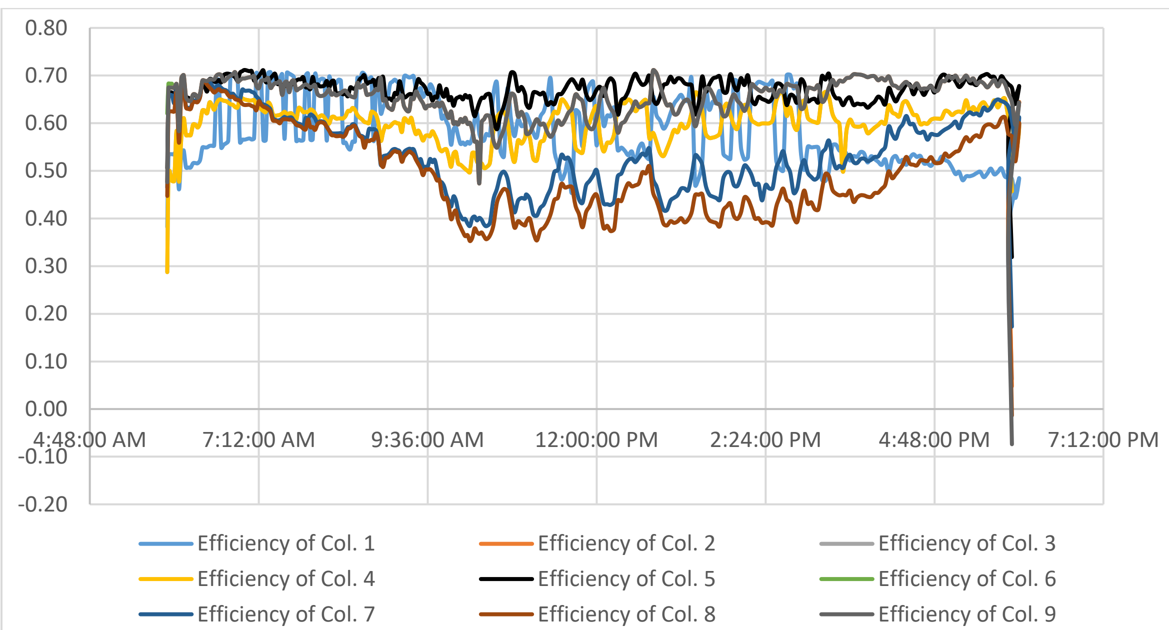
(e)

Figure 3: Physical Properties of both Air and Collector Plates Physical Properties of both Air and Collector Plates (a- Temperature of Plate, b-Temperature of Collector Air, c- Relative Humidity of both Atmosphere and Collector Air, d- Difference in Relative Humidity between Collector Air and Atmosphere, e-Difference in Temperature between Collector Air and Plate) ***cont.***

The experiment has also shown that the use of fins/obstacles on absorber plates increases efficiency and thermal performance of collectors as displayed by the energy analysis in Figures 4. Collectors with Plates 2, 5 and 9 were found to have the air with the highest heat gain and with the highest efficiency (i.e., from 59 to 72 %) as shown in Figure 4(b).



(a)



(b)

Figure 4: Energy Analysis (a. Heat Gain by Dry Air in the various collectors and b. Efficiency of collectors)

5. Conclusion

This paper designed and constructed nine (9) solar air heaters with or without ridges or fins. The inclusion of these fins is meant to create turbulence and good mixing for convective heat transfer to occur. The main parameters measured are outlet air temperature and pressure, inside physical properties of the air stream (plate temperature and air temperature and relative humidity). Other major dependent properties are the shape and size of the fins. The fin designs incorporated into the solar air heaters designed and fabricated by this study were of the following four geometrical shapes: square, rectangular, kite and triangular. Each of these four fin designs was arranged on two different flat absorber plates in two different orientations giving eight different configurations of solar air heaters. The ninth design which was made flat and finless (conventional flat plate collector) was used as the standard for comparison with the other eight designs of the solar air heater. The motivation of this research was to investigate these various solar air heaters in order to establish the most cost-effective and efficient design for air heating or crop drying in humid regions or zones. The intended application of the solar air heaters designed and fabricated by this study is crop drying. This research conducted experiments that involved the natural or free mode of convection heat transfer to determine the properties (temperature, relative humidity, air velocity, flow pattern) of the collector air and the respective efficiencies of the nine solar air heater designs. The findings of this research have revealed that increasing the contact area of the air current or circulation increases the efficiency of solar air heaters. It also revealed that the shapes of the ridges or obstacles or fins attached to the surfaces of the flat absorber plates increase their air contact areas and affect the thermal efficiency of the device. However, critical comparison of the various designs of the solar air heaters based on the respective layouts or configurations was not done by this present study and has been reserved for future studies. Average temperature and relative humidity of the atmospheric air of 31.8℃ and 65.4% respectively were recorded during the study. Critical analysis of the successful experiments conducted by this study established the values of the following parameters: heat extracted from the sun by the absorber plates; the temperature and the relative humidity of the collector air of each of the nine different solar air heater designs; and the thermal efficiencies of the devices. The best solar air heater design is the one that attains the lowest relative humidity of the collector air. Thus, in descending order, the best three designs developed by this study are Collector 5, 9 and 2 which attained average collector air temperatures and humidity of 48.2^{o}C and 39.0%, 48.4^{o}C and 39.2% and 48.4^{o}C and 40.4% respectively. On the other hand, the thermal efficiencies for these plates happen to fall between 58 % and 72 %. It is also revealed by this study that the solar air heater that produced the lowest collector air humidity was not the design that extracted the greatest amount of heat from the solar radiation. It is very interesting to note that the solar air heaters designed and constructed by this research satisfy air temperature and operating efficiency requirements of 30℃ to 80℃ and 30% to 70% respectively provided by literature.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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