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Full Length Research Paper

Experimental analysis of air flow patterns in perfomance of flat plate solar collectors

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Solar drying is one of the promising methods of reducing post-harvest losses in rural areas. Studies have shown that, heat transfer mechanisms in a solar collector influences the performance of solar dryers. This study aims at improving heat transfer in flat plate solar collectors by designing different air flow patterns inside the collector. Three flat plate solar collectors were constructed by using *Pterocarpus* timber (Mninga) and tested for their effect in heat transfer at various flow patterns. Three different flow patterns namely: single duct front pass, double duct parallel flow and double duct counter flow were designed and tested. Experimental results show that collector efficiency of single duct front pass, double duct front pass and double duct counter flow were 30.6, 36.1 and 38.2% respectively. It was found that, double duct flow gives improved performance compared to single duct flow due to the increased heat transfer area. In additional, double duct counter flow showed superior performance compared to double duct parallel flow due to extended heat transfer area and the advantage of air preheating at the inlet which reduces heat losses through glazing. Through this study, it was concluded that, solar collector designs with double duct counter flow can improve collector performance for up to 8.3% compared to single duct front pass.

Key words: Single duct front pass, double duct parallel flow, double duct counter flow, energy, solar intensity.

INTRODUCTION

Solar dryer is an enclosed unit that use solar energy to preserve food by removing water from food materials to the level at which microbial spoilage and deterioration reactions are greatly minimized. Main advantages of solar dryer over sun drying are its ability to keep food safe from birds, insects and unexpected rainfall during drying. In addition, solar dryers reduce drying time and maintains the quality of the products in terms of colour, taste and texture (Tripathy and Kumar, 2008). There are two modes of dryer operation; passive mode and active mode. In passive mode, air is heated and circulated naturally by buoyancy force or as a result of wind pressure or in combination of both. This mode of dryers operation has system efficiency ranging from 10 to 15%. In active mode (forced convection), air is circulated in the system with the help of fans or air blower. The active

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mode improves the efficiency to a range of 20 to 30% which is about twice of that achieved by the passive mode (Fuller et al., 2005). Generally, there are three types of solar dryers namely; direct solar dryer where materials to be dried are placed in transparent enclosure of plastic or glass and receive direct heat from the sun; indirect solar dryer where drying air is heated by the collector and ducted to the dying chamber which is isolated from the direct sun; and mixed mode dryer where material to be dried are heated by direct from solar radiation and by the preheated air coming from the solar collector.

Indirect solar dryers with forced convection flow are one of the best drying technology which can produce high-quality products and eliminate the risk of spoilage during drying (Bennamoun and Belhamri, 2003; Mulokozi et al., 2000). The use of these dryer can reduce drying time by three times compared to other type of dryers and reduce the required collector area by 50. However, several indirect solar dryers have been developed, their applications are still limited due to their unreliable performance and high investment cost relative to production capacity (Janjai et al., 2008). Important criteria dictating the adoption of the indirect solar dryers includes improved quality of products, short drying time and low investment costs. Currently, several indirect solar dryers have been constructed in Tanzania but still they do not meet these adaptation-criteria (Vriens and Van Diesen, 2007). Solar air collectors, although a very important component in the solar drying system, have not received much attention during dryer design (Karim, 2004). In theory, the performance of solar collector depends on several climatic and operating conditions such as collector orientation, thickness of cover materials, wind speed, collector length, collector depth, type of absorber materials and heat transfer mechanisms (Akpinar and Koçyigit, 2010; Benamara et al., 2005; El-khawajah et al., 2011; Kabeel and El-Agouz, 2011; Kundu, 2010). Irrespective of many researches and constructed solar collectors, materials for constructions such as glass size type absorbing materials and heat transfer mechanisms have not been properly considered during design (Mbise, 2008). Therefore, there is a need to study different mechanism of improving heat transfer between air and absorber plate in order to increase collector performance. In this study an attempt to improve heat transfer in the collector by designing different air flow patterns are reported

LITERATURE REVIEW

Flat plate solar collector

Solar collector is a special kind of heat exchangers that transfer heat energy from incident solar radiation to working fluid (Brenndorfer et al., 1985; Ekechukwu and Norton, 1999; Alta et al., 2010). A solar collector performs three functions which are to absorb solar radiation, converting it to heat energy and transfers the energy to a working fluid passing through it (Kalogirou, 2004). Flat plate collectors have been used to deliver heated air for space heating, crop drying and in similar applications that require hot air (Aldabbagh et al., 2010; Gordon, 2001). Flat plate collectors can heat the working fluid to a temperature range of 10 to 50°C above ambient depending on the construction materials and requirements (Struckmann, 2008). The most important advantage of these type of collectors includes low construction costs and slight effect of pressure drops. However, their main drawback is the low heat transfer coefficient between the absorber plate and air stream due to poor thermal conductivity and low heat capacity of air (El-Sebaii et al., 2011a). The principle parts of flat plate solar collector are cover sheet, absober plate and insulation.

Cover sheets (Glazing material)

Glazing is a top cover of a solar collector which performs three major functions: to minimize convective and radiant heat loss from absorber, to transmit the incident solar radiation to the absorber plate with minimum loss and to protect the absorber plate from outside environment (Society, 2009).

Thermal insulation

To reduce heat losses to the environment by thermal conduction, the back and edges of the collector must be heat insulated. As the temperature difference between the absorber and the outside air increases the heat losses increases and hence reduces efficiency. It is therefore important to ensure adequate insulation of the thermal solar system (Deutsches, 2005). Thermal insulation must be weather resistant, fireproof, durable and dimensionally stable (Alghoul et al., 2005). Koyuncu (2006) suggest the use of hardwood as collector frame construction which is also used as insulator. Forson et al. (2003) suggest the use of plywood board which serve as absorber materials and insulation.

Absorber materials

Is the main element of a flat-plate collector which covers the full aperture area of the collector and performs three functions: absorb maximum amount of solar irradiance, conduct this heat into the working fluid at a minimum temperature difference, and lose a minimum amount of heat back to the surroundings. Best materials which are suitable for collector absorber plates include copper, aluminum, steels and various thermoplastics (Alami, 2010; Garg and Prakash, 2006).

Heat transfer from absorber plate to air

To increase collector outlet temperature, heat has to be transferred efficiently from the absorber plate to the flowing air (Ion, 2006). Heat transfer coefficient inside the solar collector is one of the important parameter that affects the efficiency of the collector (Aldabbagh et al., 2010). Researchers have attempted various modifications to enhance heat transfer rate in solar collector by incorporating different modifications between absorber plate and glass plate. Most of these research were focused on; increasing the absorber plate characteristics; optimizing design parameters (Martín et al., 2011); reducing the heat loss from the collector by: insulating the collector box, applying special coats on the absorber plate, inserting trans-parent insulation material between the absorber plate and the glaze and applying antireflective coats on the glaze (Hobbi and Siddiqui, 2009). Also other techniques like using absorber with attached fins, corrugated absorber, absorber with packed bed and baffles have been reported in literature (Akpinar and Koçyiğit, 2010). In this study heat transfer in the collector were enhanced by varying the flow patterns of air.

Influence of air flow patterns

Thermal performance of single and double air passes in the collectors have been investigated experimentally and reported in this study. Suggestions for this settings includes: air passing over absorber plate (single duct front pass-SDFP), air enter over absorber plate and exit below it (double duct counter flow-DDCF) and air passing in both sides of absorber plate (double duct parallel flow). Yeh et al. (2002) reported that a considerable improvement in collector efficiency is obtained by employing a double-flow device instead of using a single-flow. The study of Omojaro and Aldabbagh (2010) suggests passing the air from above and below the absorber plate at the same time in a double-flow solar air heater. According to Yeh et al. (2002), the best thermal efficiency can be achieved in a double-flow solar air heater when the cross-section area of upper and lower channels are constructed equally and at the same fixed mass flow rates. However, the thermal efficiency was found to decrease by increasing the height of the first pass for the double pass solar air collector. The experiment by Omojaro and Aldabbagh (2010) showed that, there was an increase of collector efficiency by 4.7% when reducing the height of first pass from 7 to 3 cm. Ramadan et al. (2007) suggested using double pass solar air collector with air passing above the absorber plate before turning to pass below it. Ramani et al. (2010) conducted experimental study involving double and single pass air collector and concluded that, the double-pass design had a thermal efficiency of about 10% higher compared to single-pass design. Likewise, Yousef and Adam (2008) conducted similar experiment and found the performance increase of 10 to 12%. Omojaro and Abdabbagh (2010) reports the performance of double pass solar collector as 7 to 19% higher compared to single pass solar collector. According to El-sebaii et al. (2011b), double duct solar collector gave 7 to 9% performance increase when compared to single pass. Moreover, Chamoli et al. (2012) outlines the performance of double pass solar collector as 10 to 15% more compared to single pass. The use of a double-pass resulted in increased pressure drop across the collector. However, the rise in the operating cost due to the increased pressure drop in the collector was reported to be small.

Mathematical energy balance for single and double duct air flow

The basic physical equations used to describe the heat transfer characteristics in single and double duct air flows are developed from the conservation equations of energy.

Energy balance in single duct front air pass

Energy transferred to the working fluid in single duct front pass depends on the temperature difference between glass and absorber plate (galvanized steel plate) to that of exit air.

$$\dot{m}.C_p.(T_o - T_i) = h_{fg}(T_g - T_o) + h_{fp}(T_p - T_o) \quad [1]$$

Where $\dot{m}$ is the mass flow rate of fluid (air), C_p is the specific heat of air, h_{fg} is the heat transfer coefficient between the glass cover and air, and h_{fp} is the heat transfer coefficient between the absorber plate and working fluid.

Energy balance in double duct air pass

It can be noted that for double duct parallel flow, mass flow in each duct is half of the total flow while in double duct counter flow, whole mass flow is passed in each duct. Energy balance in first pass air stream in double duct flow depends on the temperature differences between glass and plate to that of fluid.

$$\dot{m}.C_p.(dT_{f1}) = h_{f1g}(T_g - T_{f1}) + h_{f1p}(T_p - T_{f1}) \quad [2]$$

Energy balance in absorber plate

$$I.\alpha_p.\tau_{g=} h_{f1p}(T_p - T_{f1}) + h_{f2p}(T_p - T_{f2}) + h_{r,gp}(T_p - T_g) + h_{r,pb}(T_p - T_b) \quad [3]$$

Energy balance in second air flow pass

$$\dot{m}.C_p.(dT_{f2}) = h_{f2p}(T_p - T_{f2}) + h_{f2b}(T_b - T_{f2}) \quad [4]$$

Energy balance in bottom (base) plate

$$h_{f2b}(T_b - T_{f2}) + h_{r,pb}(T_b - T_p) + U_a(T_b - T_a) = 0 \quad [5]$$

General efficiency of flat plate solar collectors

The thermal efficiency of a collector is the ratio of the useful thermal energy to the total incident solar radiation averaged over the same time interval. Mathematically, the efficiency (η) of a collector is expressed by Equation 6 (Struckmann, 2008; Luna et al., 2010).

$$\eta = \frac{useful\ energy}{solar\ energy\ available} \quad [6]$$

Useful energy for a solar thermal collector is the rate of thermal energy leaving the collector, usually described in terms of the rate of energy being added to a heat transfer fluid passing through the receiver or absorber (Ekechukwu and Norton, 1999; Farahat et al., 2009).

$$Q_u = m.C_p.(T_o - T_i) \quad [7]$$

The area of the collector on which the solar irradiance falls is called the aperture area of the collector. Therefore, total energy received by collector (optical energy captured) can be described by Equation 8.

$$Q_{in} = I.A \quad [8]$$

Accordingly, absorptance and transmittance are multiple effects of optical energy capture and therefore, these factors indicates the percentage of the solar rays penetrating the transparent cover of the collector and the percentage being absorbed (Farahat et al., 2009).

$$Q_{in} = \alpha.\tau.I.A \quad [9]$$

The rate of useful energy of the collector can be expressed by using overall heat loss coefficient and the collector temperature as Equation 10 (Yogi and Jan, 2000).

$$\dot{Q}_{useful} = \dot{Q}_{in} - \dot{Q}_{loss} = \alpha.\tau.I.A - U_L.A_C.(T_c - T_a) \quad [10]$$

Since it is difficult to define the collector average temperature in Equation 5, it is convenient to define a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature (Struckmann, 2008). This quantity is known as "the collector heat removal factor (F_R)" and is expressed by Equation 11.

$$F_R = \frac{\dot{m}.Cp.(T_o - T_i)}{A.[\alpha.\tau.I - U_L.(T_i - T_a)]} \quad [11]$$

Finally, equation for efficiency of flat plate solar collector can be given by "Hottel- Whillier-Bliss equation" (Karatasou et al., 2006)

$$\eta = F_R.\alpha.\tau - F_R.U_L.\left(\frac{T_i - T_a}{I}\right) \quad [12]$$

If it is assumed that τ and α are constants for a given collector and flow rate, then the collector efficiency is a linear function of the three parameters defining the operating condition: Solar irradiance (I), Fluid inlet temperature (T_i) and collector outlet temperature (T_o). Thus, the performance of a flat-plate collector can be approximated by experimentally measuring these three parameters, and the efficiency can be calculated by using summarized Equation 13 (Ekechukwu and Norton, 1999).

$$\eta = \frac{\dot{m}.Cp.}{A} * \left[\frac{(T_o - T_i}{I}\right] \quad [13]$$

MATERIALS AND METHODS

Three flat plate solar collector models were constructed by using *pterocarpus* timber (hardwood) of thickness 2 inches with black painted marine plywood as bottom heat absorbing plate. Other materials used were galvanized steel plate of 2 mm. The specifications of collectors were: collector length to width ratio 2 (length 1.2 m and width 0.6 m) and depth 15 cm. All collectors were oriented to north-south direction and tilted to an angle of 10° with the ground toward north direction. This experiment was conducted by designing single and double air passes in the collector namely: single duct front pass (SDFP), double duct parallel flow (DDPF) and double duct counter flow (DDCF). With single duct front pass air passes over the surface of the plate as shown in Figure 1, while in double duct parallel flow, air pass from both side of the absorber plate simultaneously (Figure 2a). Similarly, in double duct counter flow, air enters the collector at the top duct and exit at the bottom duct as shown in Figure 2b. In double ducts settings, top to bottom depth ratio were kept at 1:1. Outlet temperatures from collectors were measured by using PT940 thermocouple temperature sensors which were connected to XR5-SE multi-channel data logger. Ambient temperatures were measured by using digital CEM DT-172 temperature and humidity data logger.

On the other hand, solar intensity and air flow rate were respectively measured using PCE-SPM solar radiation meter and Testo 425 Hot Wire Thermal Anemometer. Air flows in each collectors were 1.27 m^3/min. Air flow rates were aided by extract fans which were controlled by variable voltage control switch.

Efficiencies of the collector models were established by testing each collector with 5 mm glass thickness which is the common used glass thickness. The aim of testing collector with same glass

Table 1. ANOVA for collector with similar glass thickness.

Collector	Sum of squares	df	Mean square	F	Significance
Between Groups	1.427	3	0.476		
Within Groups	4.428	12	0.369	1.289	0.323
Total	5.854	15			

thickness was to ensure that variation of the efficiencies during other experiments were not due to design variations. The duration for each experiment was 5 days for collector with similar glass thickness and for different flow patterns. Time of experiment was from 7:30 am to 6:00 pm with a 10 min interval for data sampling. The experiments were conducted at the University of Dar es Salaam in College of Engineering and Technology. All collector models were placed on top of block-Q building situated at the Department of Chemical and Mineral Processing.

RESULTS AND DISCUSSION

Collectors performance with similar glass thicknesses

The main objective of this experiment was to find out if there was significant performances difference between designed collector models with similar characteristics. Each collector model was tested for its performance by using 5 mm glass thickness.

Temperature and energy profile of collectors with same glass thickness

Figure 3 show the variation of ambient and outlet temperature of four collector models while Figure 4 shows the rate of outlet flow of energy from collector recorded from 7:30 am to 06:00 pm on 12/09/2011.

From Figure 3 it can be seen that there is no variation in temperature between collectors however, temperature varies according to the fluctuation of solar intensity. Fluctuations of temperature during the morning are high when compared to afternoon due to high clouds coverage which results to low solar intensity reaching the earth. Similar characteristic were observed in energy profile in Figure 4. The efficiencies of the solar collector were evaluated by finding the area under energy curve. Statistical analysis of the thermal efficiency of solar air collector with the same glass thickness were analysed with SPSS program with confidence interval of 95%. Efficiency mean of collector models 1, 2, 3 and 4 were 29.6, 29.8, 30.3, and 30.3% respectively. A one-way between subjects ANOVA (Analysis of Variance) was used to compare the efficiencies of collector models and reported in Table 1. The main objective was to determine if there is a significant difference between collector efficiencies when operated with the same glazing materials.

From Table Table1, the significance value is 0.323 ($p<0.05$). Therefore, it can be concluded that there were no statistical significant difference between the means of collector efficiency with the same glass thickness, and that, their minor variations are due to changes in environmental conditions and not due to design variations.

Collectors performances with different air flow pattern

Here, the effect of flow pattern on the performance of solar collector by improving the capability of heat capture from absorber plate was discussed. Performance of single pass were studied by designing single duct with air passing over the surface of absorber (Single Duct Front Pass-SDFP) while double pass were studied by designing double duct parallel flow (DDPF) and double duct counter flow systems (DDCF) as elaborated in Figures 1 and 2.

Temperatures profiles for single and double air pass

Figure 5 shows variation of measured collector and ambient temperatures with time for single duct front flow, double duct parallel flow and double duct counter flow on 22/11/2011. Collector temperatures increased with increase in solar intensity and reached maximum between 12:00 am to 13:00 pm. Temperature difference between double and single air pass collectors during the morning were small while at noon and at sunset the differences were significant.

Generally, there was high fluctuation of temperatures during the morning due to high variation of solar intensity. The fluctuations of temperatures were appearing to decrease from noon due to stability of solar intensity and the fact that the system is in equilibrium. However, there was some variation of solar intensity during the afternoon which was not clearly depicted in temperature measured. This was due to the fact that, absorber plate acts as heat storage and therefore at a short time variation in solar intensity the stored energy was transferred to air.

Double duct counter flow solar collector attained the highest maximum temperature of 59.4°C, double duct parallel flow 55.6°C while single duct front pass gave the least maximum temperature of 50.3°C as shown in Figure 6.

Double duct counter flow solar collector produced the

Figure 1. Schematic view of single duct solar collector.

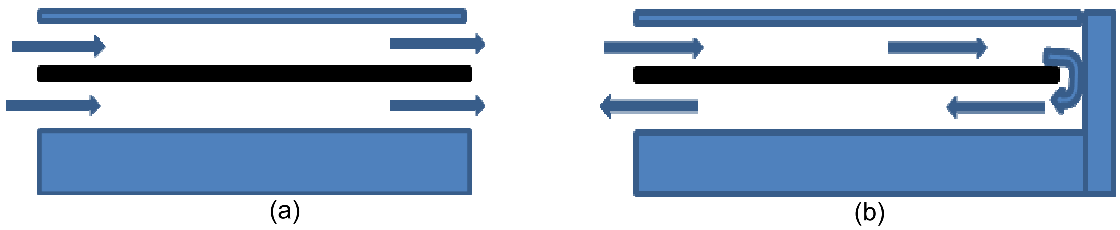

Figure 2. Schematic view of (a) double duct parallel flow (b) double duct counter flow.

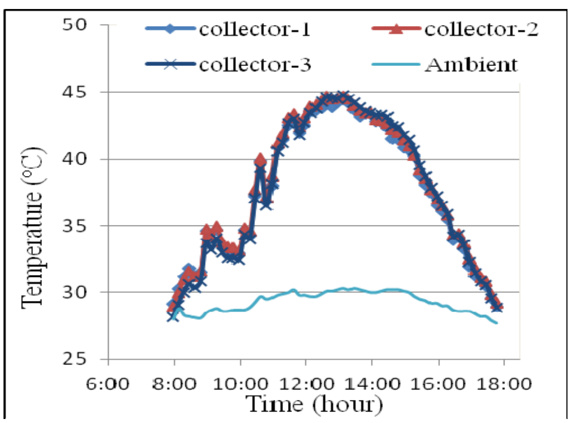

Figure 3. Temperature profile of collector with similar glazing thickness.

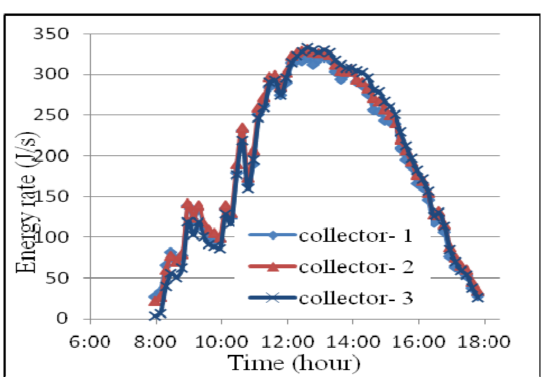

Figure 4. Energy profile of collector with similar glazing thickness.

highest average temperature of 47.2°C while double duct parallel flow and single duct front pass were 44.5 and 41.9°C respectively as shown in Figure 7.

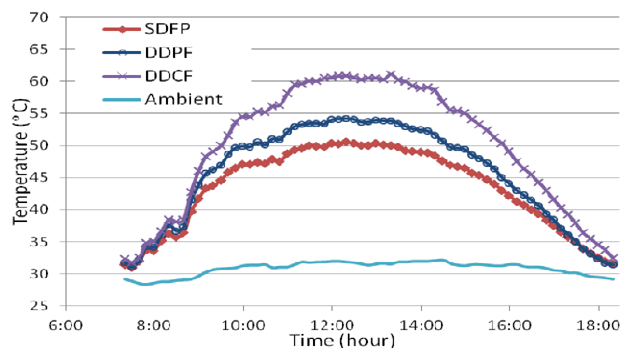

Figure 5. Temperature profiles of collectors with different flows patterns 22/11/2011.

Figure 8 shows the solar intensity versus standard time of the days the experiments were carried out. Solar intensities increased from the early hours at about 200 to 300 W/m^2 at 8:00 am to peak values at noon. Solar intensity curves can clearly give the weather status of the day in terms of clouds coverage. On 22/11/2011 the sky was almost clear from morning to noon while on 24/11/2011 the sky was highly covered by clouds. The highest daily solar radiation obtained during the experiments with single and double air pass was 1350 W/m^2 on 23 November, 2011 while the average solar intensity was 992 W/m^2.

Energy profiles of collectors with similar glass thicknesses

Figure 9 shows variation of solar energy for each collector model on 22/11/2011. Generally, characteristics of energy profiles in Figure 9 are similar to that of temperature profiles reported in Figure 5. From the

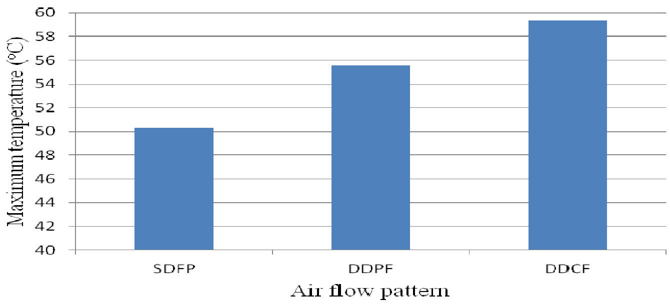

Figure 6. Maximum temperature reached in single and double air pass solar collector.

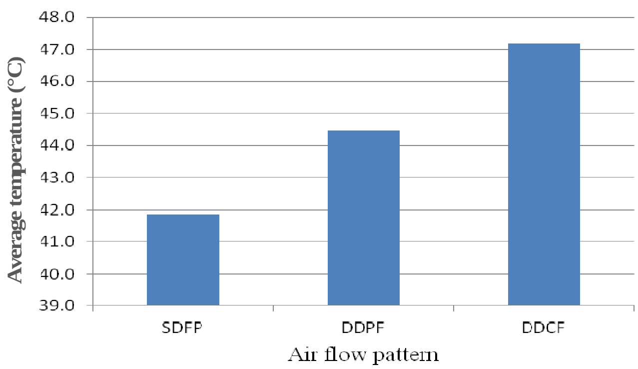

Figure 7. Average temperature for single and double duct solar collector.

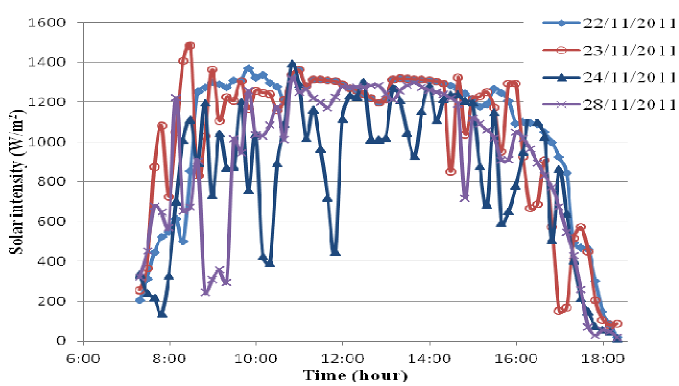

Figure 8. Comparisons of solar intensity for different days of the experiments.

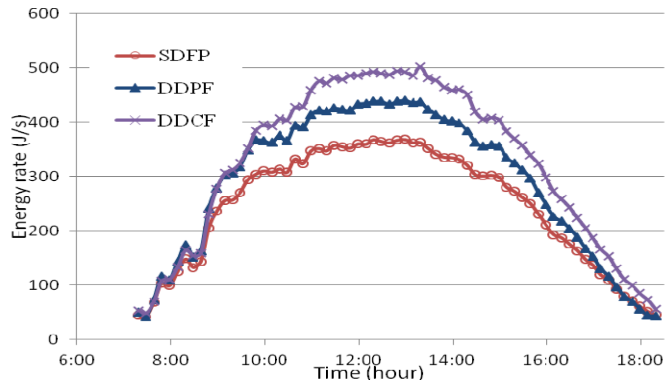

Figure 9. Energy profiles of collectors with different flows patterns 22/11/2011.

figures it was clear that, collector energy depends on the solar intensity and varies with solar intensity fluctuations. Energy delivery starts from lowest value during the morning and start rising to maximum during the noon and then reduced towards sunset.

Low energy during the morning were caused by low angle of incidence of solar radiation on the collector surface (normally at 0 to 60°) and the fact that part of the collected energy were used in pre-heating collector and its components (Das and Chakraverty, 1991). However, with the stabilization of available energy with energy stored in the absorber, from noon the energy does not fluctuate as much as solar intensity.

Analysis of performance of collector with different flow patterns

The results of the statistical analysis of variance (ANOVA) for single and double air pass in collector which was carried out to study the significance differences between their individual means are reported in Table 2. Average performance of single duct front pass (SDFP), double duct parallel flow (DDPF) and double duct counter flow (DDCF) were 30.6, 36.1 and 38.9% respectively.

Comparisons of means for single and double pass solar collector

A one way between subjects ANOVA were used to ascertain if there was significance difference between means of single and double pass solar collectors. From Table 3, it is evident that there is statistical significant difference between the means of single and double pass solar collectors with $p=0.002$. However, in order to identify the method to use in multiple comparison of means, Levene test of homogeneity was conducted.

From Table 4, $p>0.05$; therefore equal variance assumed (Turkey) test were used for multiple comparison of collectors means.

It is clear from Table 5 that the thermal performances of double passes solar air collectors were higher when compared to single passes. These results were in agreement with the study of Yeh et al. (2002) who outlines a considerable performance increase when employing a double-flow device instead of using a single-flow. It could be seen that, performance of single duct front pass collector (SDFP) was significant different compared to double duct parallel flow and double duct counter flow. Similarly, there were no statistical significant difference between double duct parallel flow and double

Table 2. Statistical analysis of performance of solar air collector with single and double air pass by using SPSS program.

Statistical parameters		N	Mean	Standard deviation	Standard error	95% confidence interval for mean		Min.	Max.
						Lower bound	Upper bound		
SDFP		4	30.6250	0.96393	0.48197	29.0912	32.1588	29.20	31.30
DDPF		4	36.0500	1.39164	0.69582	33.8356	38.2644	34.00	37.10
DDCF		4	38.8750	3.53777	1.76889	33.2456	44.5044	33.60	41.00
Total		12	35.1833	4.12064	1.18953	32.5652	37.8015	29.20	41.00
Model	Fixed effects			2.26434	0.65366	33.7047	36.6620		
	Random effects				2.42067	24.7680	45.5986		

Table 3. Analysis of variance of collectors with different air flow patterns.

Collectors	Sum of squares	df	Mean square	F	Significance
Between Groups	140.632	2	70.316		
Within Groups	46.145	9	5.127	13.714	0.002
Total	186.777	11			

Table 4. Results of Levene test for single and double air pass solar collector.

Levene statistic	df1	df2	Significance
3.179	2	9	0.090

Table 5. Multiple comparisons test for single and double air pass mean efficiencies.

(I) Air_flow	(J) Air_flow	Mean difference (I-J)	Standard error	Significance	95% confidence interval	
					Lower bound	Upper bound
SDFP	DDPF	-5.42500*	1.60113	0.020	-9.8954	-0.9546
	DDCF	-8.25000*	1.60113	0.002	-12.7204	-3.7796
DDPF	SDFP	5.42500*	1.60113	0.020	0.9546	9.8954
	DDCF	-2.82500	1.60113	0.235	-7.2954	1.6454
DDCF	SDFP	8.25000*	1.60113	0.002	3.7796	12.7204
	DDPF	2.82500	1.60113	0.235	-1.6454	7.2954

*: The mean difference is significant at the 0.05 level.

duct counter flow (p=0.235). In double pass solar collector, air flow was from both sides of the absorber plate, and therefore it doubles heat transfer areas which in turn reduce collector thermal losses. From this study, it can be concluded that, double ducts counter flow gave the best performance and it can improve the performances of the solar collectors by 8.3% compared to single duct front pass (convectional type) as shown in Figure 10. The result was in agreement with results reported by Omojaro and Abdabbagh (2010) and El-sebaii et al. (2011b) in the ranges of 7 to 19% and 7 to 9% respectively. On other hand, the result were in disagreement with the results reported by Chamoli et al. (2012), Yousef and Adam (2008) and Ramani et al. (2010) in the ranges of 10 to 15%, 10 to 12% and higher than 10% respectively. This was due to the fact that the reported studies uses aluminium plates which were superior in thermal conductivity when compared to galvanized steel used in this study. In addition, the first author attempts to use two similar plates in double duct and compared results with single duct which contains single plates while in this study only single plate were used in double and single air passes.

Theoretically, in double duct counter flow, heat energy extracted by the flowing air in the first pass from the glass covers is used as air preheater which in turn decreases

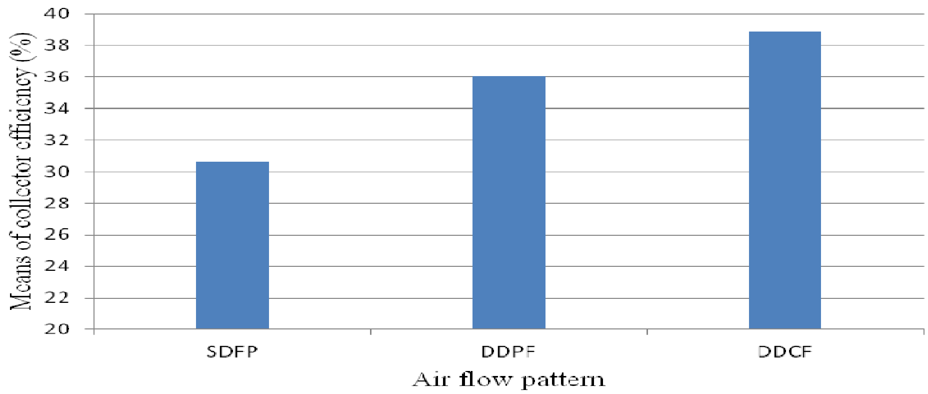

Figure 10. Means plot of performances of solar collectors with different air flow patterns.

the temperature of glass covers and heat losses to the surroundings. Therefore, the performance of double pass collectors were found to be superior compared to single pass solar air collector where air flows in one side of absorber plate. However, the application of double duct counter flow in natural convection is limited, since air needs to be forced through the two channels for efficient utilization of the system. Also more power is demanded in forced convection systems in order to overcome the effect of pressure drops due to the increased duct length. For the best performance of double duct counter flow with forced convection, it was recommended by Forson et al. (2007) and Pawar et al. (1994) that the collector length should be limited to 1.5 to 2.5 m while length to width ratio should range between 1.0 and 2.0.

Conclusion

Performances of double duct air flow pattern have been studied and compared to single duct flow pattern. The experimental results show differences in collector efficiency with change in flow pattern. From the results obtained for the different flow patterns examined, it was observed that varying the flow patterns collector efficiency appeared to significantly change. It was also observed that double duct counter flow gave efficiency of 38.2% compared to 30.6% for single duct system.

From these results it can be concluded that collector efficiency can be improved by 8.3% by altering the aerodynamics through the collector. Double pass counter flow seems to have the advantages of increased heat transfer area; reduced heat losses through glazing as well as increased turbulence hence improved heat transfer. Despite this improved efficiency, it is important to also analyse the increased collector cost and do a cost benefit analysis to arrive at an optimal situation.

Conflict of Interest

The authors have not declared any conflict of interest.

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NOMENCLATURE

SDFP: Single duct front pass (air passing over absorber plate.

DDCF: Double duct counter flow (air inter over and exit below absorber plate).

DDPF: Double duct parallel flow (air passing in both sides of absorber plate).

A: Collector area (m^2).

F_R: Collector heat removal factor.

C_p: Specific heat capacity of air (J/Kg.K).

m: Mass flow rate (kg/s).

I: Global solar intensity reaching collector surface (W/m^2).

Q_u: Useful energy gained by air (W).

Q_{in}: Available solar energy on collector surface (W).

T_o: Temperature out of collector (°C).

T_i: Air inlet temperature (°C).

U_L: Heat loss coefficient (W/m^2 K).

α: Absorptivity

τ: Transmissivity

η: Collector efficiency

h_{fb}: Heat transfer coefficient between the fluid and base plate (W/m^2 °C).

h_{fg}: Heat transfer coefficient between the glass and fluid (W/m^2 °C)

h_{fp}: Heat transfer coefficient between absorber plate and fluid (W/m °C)

$h_{r,gp}$: Radiative heat transfer coefficient between glass and absorber plate (W/m^2 °C)

$h_{r,pb}$: Radiative heat transfer coefficient between absorber and base plate (W/m^2 °C)

$T_{f1,2}$: Temperature of air in upper and lower duct respectively (°C)

T_b: Base plate temperature (°C)

T_g: Glass temperature (°C)

T_p: Absorber plate temperature (°C)

U_a: Ambient heat loss coefficient.

REFERENCES

Akpinar EK, Koçyiğit F (2010). Energy and exergy analysis of a new flat-plate solar air heater having different obstacles on absorber plates. Appl. Energy 87(11):3438-3450. doi: 10.1016/j.apenergy.2010.05.017

Alami AH (2010). Experiments on Aluminum-Copper Alloys Properties as Solar Absorbers. JJMIE, 4(6).

Aldabbagh LBY, Egelioglu F, Ilkan M (2010). Single and double pass solar air heaters with wire mesh as packing bed. Energy, 35(9):3783-377.

Alghoul M, Sulaiman M, Azmi B, Wahab MA (2005). Review of materials for solar thermal collectors. Anti-Corrosion Methods Mater. 52(4):199-206.

Alta D, Bilgili E, Ertekin C, Yaldiz O (2010). Experimental investigation of three different solar air heaters: Energy and exergy analyses. Appl. Energy 87(10):2953-2973.

Benamara M, Houcine I, Guizani A, Maalej M (2005). Efficiency investigation of a new-design air solar plate collector used in a humidification?dehumidification desalination process. Renewable Energy 30(9):1309-1327. doi: 10.1016/j.renene.2004.09.019

Bennamoun L, Belhamri A (2003). Design and simulation of a solar dryer for agriculture products. J. Food Eng. 59(2-3):259-266. doi: 10.1016/s0260-8774(02)00466-1

Brenndorfer B, Kennedy L, Bateman COO, Trim D, Mrema G (1985). Solar dryers: Their role in post-harvest processing: Commonwealth Secretariat.

Chamoli S, Chauhan R, Thakur NS, Saini JS (2012). A review of the performance of double pass solar air heater. Renewable. Sustain. Ener. Rev. 16:481-492.

Das S, Chakraverty A (1991). Performance of a solar collector with different glazing materials and their degradation under the condition prevailing in a solar collector. Energy Convers. Manage. 31(3):233-242.

Deutsches GS (2005). Planning and installing solar thermal systems: a guide for installers architects and Engineers. USA: James & James (Science publisher).

Ekechukwu O, Norton B (1999). Review of solar-energy drying systems III: low temperature air-heating solar collectors for crop drying applications. Ener. Convers. Manage. 40(6):657-667.

El-khawajah MF, Aldabbagh LBY, Egelioglu F (2011). The effect of using transverse fins on a double pass flow solar air heater using wire mesh as an absorber. Solar Energy 85(7):1479-1487. doi: 10.1016/j.solener.2011.04.004

El-Sebaii AA, Aboul-Enein S, Ramadan MRI, Shalaby SM, Moharram BM (2011a). Investigation of thermal performance of-double pass-flat and v-corrugated plate solar air heaters. Energy *36*(2), 1076-1086.

El-Sebaii AA, Aboul-Enein S, Ramadan MRI, Shalaby SM, Moharram BM (2011b). Thermal performance investigation of double pass-finned plate solar air heater. Appl. Ener. 88(5):1727-1739.

Farahat S, Sarhaddi F, Ajam H (2009). Exergetic optimization of flat plate solar collectors. Renewable Energy, 34(4),1169-1174.

Forson F, Nazha M, Akuffo F, Rajakaruna H (2007). Design of mixed-mode natural convection solar crop dryers: Application of principles and rules of thumb. Renewable Energy, 32(14):2306-2319.

Fuller RJ, Aye L, Zahnd A (2005). Evaluation of a solar dryer in a high altitude area of Nepal. Mechanical Eng, pp.1-10.

Garg P, Prakash J (2006). Solar Energy:Fundamental and application. New Delhi: Tata McGraw-Hill Publishing company limited.

Gordon J (2001). Solar energy: The state of the art: ISES position papers: Earthscan/James & James.

Hobbi A, Siddiqui K (2009). Experimental study on the effect of heat transfer enhancement devices in flat-plate solar collectors. Int. J. Heat Mass Transf. 52(19-20):4650-4658. doi: 10.1016/j.ijheatmasstransfer.2009.03.018

Janjai S, Srisittipokakun N, Bala B (2008). Experimental and modelling performances of a roof-integrated solar drying system for drying herbs and spices. Energy 33(1):91-103.

Kabeel AE, El-Agouz SA (2011). Review of researches and developments on solar stills. Desalination 276(1-3):1-12. doi: 10.1016/j.desal.2011.03.042

Kalogirou SA (2004). Solar thermal collectors and applications. Progress in Ener. Combust. Sci. 30(3):231-295.

Karatasou S, Santamouris M, Geros V (2006). On the calculation of solar utilizability for south oriented flat plate collectors tilted to an angle equal to the local latitude. Solar Energy, 80(12):1600-1610.

Karim M (2004). Development of solar air collectors for drying applications. Energy Convers. Manage. 45(3):329-344. doi: 10.1016/s0196-8904(03)00158-4

Koyuncu T (2006). Performance of various design of solar air heaters for crop drying applications. Renewable Energy, 31(7):1073-1088. doi: 10.1016/j.renene.2005.05.017

Kundu B (2010). Analytic method for thermal performance and optimization of an absorber plate fin having variable thermal conductivity and overall loss coefficient. Appl. Energy 87(7):2243-2255. doi: 10.1016/j.apenergy.2010.01.008

Luna D, Jannot Y, Nadeau JP (2010). An oriented-design simplified model for the efficiency of a flat plate solar air collector. Appl. Thermal Eng. 30(17-18):2808-2814. doi: 10.1016/j.applthermaleng.2010.08.016

Martín RH, Pérez-García J, García A, García-Soto FJ, López-Galiana E (2011). Simulation of an enhanced flat-plate solar liquid collector with wire-coil insert devices. Solar Energy 85(3):455-469. doi: 10.1016/j.solener.2010.12.013

Mbise E (2008). Design of an efficient box type solar dryer for fruits and vegetables. Dar es Salaam.

Mulokozi G, Mselle L, Mgoba C, Mugyabuso J, Ndossi G (2000). Improved solar drying of vitamin A-rich foods by women's groups in the Singida District of Tanzania. International Center for Research on Women P. 5.

Omojaro AP, Aldabbagh LBY (2010). Experimental performance of single and double pass solar air heater with fins and steel wire mesh as absorber. Appl. Ener. 87(12):3759-3765.

Pawar RS, Takwale MG, Bhide VG (1994). Evaluation of the performance of the solar air heater. Ener. Convers. Manage. 35(8):699-708.

Ramadan MRI, El-Sebaii AA, Aboul-Enein S, El-Bialy E (2007). Thermal performance of a packed bed double-pass solar air heater. Energy, 32(8):1524-1535.

Ramani BM, Gupta A, Kumar R (2010). Performance of a double pass solar air collector. Solar Energy, 84(11):1929-1937.

Struckmann F (2008). Analysis of flat–plate solar collector. Project Report, MVK160 Heat and Mass Transport, Lund, Sweden.

Tripathy P, Kumar S (2008). Determination of temperature dependent drying parameters for potato cylinders and slices during solar drying. Ener. Convers. Manage. 49(11):2941-2948.

Vriens M, Van Diesen G (2007). Tanzania, The implementation of an innovation for sustainable economic development in rural areas: the case of solar fruit and Vegetable drying in rural.

Yeh HM, Ho CD, Hou JZ (2002). Collector efficiency of double-flow solar air heaters with fins attached. Energy, 27(8):715-727.

Yogi GD, Jan KF (2000). Principles of solar engineering. USA: Taylor and Francis.

Yousef B, Adam N (2008). Performance analysis for flat plate collector with and without porous media. J. Energy S. Afr. 19(4):33.