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Assessment of Solar Thermal Energy Potential as a Source of Energy for Drying Applications.

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Abstract

Solar energy can be tapped to produce directly the two widely sought forms of energy- heat and electricity. Solar energy is routinely used in the developing countries to dry up food crops and medicinal plants by spreading them in the open sun but this practice leads to severe losses, both in quality and quantity, of the products and requires long periods to dry up. Further, in Kenya there is a general trend where people are now reverting back to what nutritionists call Africa Indigenous Vegetables (AIV) and value addition through drying is necessary for longer storage or exportation without spoilage. Solar air heaters (SAHs) are technologies that can be used to heat up ambient air to produce hot air for drying or heating applications and there is still scope to improve on them. The performance of a SAH system of the convectional type with airflow above the absorber plate in the tropics is reported. The plane-of-array (POA) solar radiation on the collector varies between 800-1200 Wm^2 on clear sky days with ambient temperature range of 20-30 ^{o}C. The thermal efficiency under natural airflow operation was evaluated to be about 38%.

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1. Introduction

Many countries all over the world are fast-tracking their policies to integrate renewable energy into their primary energy mix to meet the ever rising demand and curb climate change. Solar energy is an appealing alternative energy source, with acclaimed advantages of being non-polluting, renewable and widely distributed. The sun always shines, even on cloudy days and pours forth an enormous amount of energy onto the planet earth. All our present energy sources, with the exception of nuclear energy, are essentially from the sun in one way or another. For example, fossil fuels are residues of past animal and plant populations whose basic energy and growth were derived from the sun, and have been buried under the earth's crust for millions of years ago. Wood fuels derived their energy from sunlight through photosynthesis while wind energy is produced by uneven heating of the earth's atmosphere by solar energy. Energy is consumed in almost every facet of our lives ranging from food production to recreations and there has been an upward trend in demand for energy services driven by rapid population growth, improving living standards of the people and economic growth. The question now is where will the necessary energy come from? Better utilization of solar energy, by use of solar technologies, is considered by many to be the best potential source of this needed energy. The sun's energy can be converted directly into heat (using solar thermal collectors) and electricity (using photovoltaics systems). The current work deals with the conversion of solar energy into thermal energy.

The simplest and most direct method of harnessing solar energy is to convert the incident solar radiation into heat using solar thermal technologies. In any solar energy application, it is beneficial to analyze the performance of a prototype model of any given solar-energy system, either experimentally or analytically, before constructing a commercial system. This is necessary because the performance of any solar-energy conversion device depends on the prevailing climatic conditions and the amount of solar radiation on the plane of the array (POA) at any given time and site. Since the weather pattern and solar radiation varies with the geographical location and season of the year, it is advisable to have real measurements on the climatic data of a site and evaluation of the performance of a prototype model of a given solar energy system to help in sizing optimized systems both in energy production and cost. The performance results may be extrapolated for larger practical systems while the climatic data collected are useful for developing and validating theoretical models that have greatly eased the design of solar energy systems using the now relatively cheap and fast computers.

The SAH systems use ambient air as heat transfer fluid and generate heat (hot air) from the incident solar radiation from the sun. The hot air can be used in several applications requiring low to moderate temperatures (60-70 ^{o}C), such as dehydration of industrial products (e.g. textiles or paper) and agricultural products (vegetables, fruits, grains, medicinal plants, lumber, tobacco, fish) as well as space heating in building interior or greenhouses. These systems are relatively simple to construct and analyze but has low thermal efficiency due to poor thermo-physical properties of air such as low volumetric heat capacity, low density and low thermal conductivity. Thus, there is a need to improve the thermal efficiencies of SAH systems and one way of doing so is to increase the absorber plate area. However, the absorber plate area determines the cost of the system where large area collectors are of high cost hence not cost-effective. Market deployment of solar energy systems depends not only on government decisions but also on cost-effectiveness and consumer acceptance. The high cost of large area air collectors is the major hindrance to their widespread adaptation for large scale applications. Efforts should therefore be made to design more economical solar air heaters as there is still scope to improve their performance. The shape of the flow channel is entirely arbitrary but when the cost and ease of construction is considered then a rectangular cross-sectional duct is usually preferred, since it is simple to construct using cheap and locally available materials. However, the design of a complete SAH is, on the surface, deceptively easy but the hidden complexities become apparent only when the design procedure is commenced. Charters (1971) have outlined the requirements for designing any SAH system.

Several types of solar air heaters have been proposed, designed and analyzed both theoretically and experimentally on their thermal performance over the years in many parts of the world. Different methods of augmenting the heat transfer coefficient between the flowing air and the channel walls using diverse materials, different dimensions, operating conditions and several shapes have been done. Theoretical analyses of the convectional type SAHs include the works of Wijeysundera (1978), Reddy and Gupta (1980), Parker (1981), Prasad and Mullik (1983), Ong (1995), among others. Studies on the improvements of the flow channel include the use of double-pass airflow (Bhargava et al, 1990), use of non-metallic absorber plate (O'Brien-Bernini and McGowan, 1984), use of packed-flow air passage (Demirel and Kunc, 1987) and use of fins (Garg et al, 1989; Ho- Ming, 1994; Pottler et al, 1999; Naphon, 2005). Yadav et al (1995), Hegazy (1999) and Karwa et al (2002) considered the effects of several thermo-hydraulic parameters and operating conditions on the performance of SAHs systems while Hachemi (1997) compared two SAHs with and without selective absorber plates. Most of the above studies use forced flow air circulation. Use of natural airflow operation studies have been published also. Fath (1995) compared the performance of two thermosyphon SAHs, one with phase-change-material (PCM) heat storage and the other without and showed that mass flow rate lies between 0.006-0.035 kgs^{-1}. Several studies on the use of solar air collectors for drying applications have been reported and include the works of Reddy and Gupta (1980), Diamante and Munro (1993), Chauhan et al (1996), Ekechukwu and Norton (1997), Gao et al (2000), Toure (2001), Panganhane et al (2002), Karim and Hawlader (2004) among others.

The level of knowledge and deployment of solar thermal technologies in Kenya is still relatively low and has not been embraced by the people though the country is endowed with high solar radiation year round. In addition, the Kenyan economy is claimed to be dependent on agricultural sector and the huge post-harvest losses of the crops especially in the rural areas could be reduced by using well-designed solar drying system hence ensuring food security. There is, therefore, a need for the Kenyan Government to support solar thermal technologies through proper legislation and R&D projects throughout the country. In this study, a simple air collector has been designed and built at the Department of Physics, Moi University and tested outdoors under natural airflow operation to determine its thermal performance under the local climate. The thermal efficiency is evaluated as 38% with solar radiation of 800-1200 Wm^2 on clear sky days with threshold value of 178 Wm^2 and ambient temperature between 20-30 ^oC.

2. Structure and Analysis of the Experimental Model

The cross-sectional view of the constructed and tested SAH system is shown in Fig. 1(a). The collector is tilted at an angle β^o to the horizontal as shown in Fig.1 (b,c), to create pressure difference (head) which together with temperature difference sets up a buoyancy force that causes air to flow from inlet at the bottom to outlet at the top of the collector, Fig.1(c). The flowing air is heated up by the absorbed incident solar radiation producing hot air that can be ducted to do useful work. Incident solar radiation strikes the black-painted absorber surface, get absorbed and as a result becomes hot. This thermal energy is partially transferred to the air flowing over the absorber plate. The air temperature increases and achieves maximum temperature at the collector output (Fig. 1(c)). The increase in the air temperature (T_{out}-T_{in}) generates the driving pressure, which sets up an upward draft as a result of density difference between the colder ambient air at the inlet and the hotter air at the exit. The thermally induced flow depends on the level of solar radiation, weather conditions, geometry and orientation of the system and the characteristics of the glazing-absorber combination.

One way of specifying the performance of the solar thermal collector is to measure the instantaneous efficiency when the solar radiation is incident perpendicularly to the absorber surface. The collector is usually exposed to the solar radiation and two types of information are sought. First the inlet T_{in} and outlet T_{out} air temperature together with the mass airflow rate $\dot{m}$ are usually measured and the useful heat gain is then calculated from the equation (Duffie and Beckman, 1991):

$$Q_u = \dot{m} c_p (T_{out} - T_{in}) \text{ ....(1)}$$

where Q_u is the useful heat gained by the heated air and c_p is the specific heat capacity of air. Eq. (1) gives the useful output heat of the collector. Secondly, the solar radiation on the plane of the collector (POA), G, the ambient temperature T_a and wind speed are also measured. These are the operating conditions that produce thermal output or heat.

The characterization of a collector can also be performed using parameters that indicate how the collector absorbs and losses energy to the surroundings. In such a case, if the collector is operating under steady state conditions then the heat gain is given by Hottel-Whillier-Bliss model as:

$$Q_u = A_c F_R[G(\tau\alpha) - U_L (T_{in} - T_a)] \text{......(2)}$$

where A_c is the collector absorbing surface, $(\tau\alpha)$ is transmittance-absorptance product (with τ being transmittance of the glass cover and α is the absorptivity of the collector plate), F_R is the heat removal factor and represents the ratio of the actual useful heat gain to the maximum possible useful heat gain while U_L is the overall heat loss coefficient of the collector.

The instantaneous thermal efficiency η_{th} of a solar thermal collector is given

$$\eta_{th} = \frac{Q_u}{A_c G} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

and substituting for Q_u from Eq. (1) and Eq. (2) we get the instantaneous thermal efficiency as

$$\eta_{th} = \frac{\dot{m} c_p (T_{out} - T_{in})}{A_c G} \quad \ldots\ldots\ldots\ldots\ldots (4)$$

and $$\eta_{th} = F_R(\tau\alpha) - \frac{F_R U_L (T_{in} - T_a)}{G} \quad \ldots\ldots(5)$$

In Eq. (5), the first term on the right hand is an indication of how the incident solar radiation is absorbed by the collector and the second term indicate how the collector losses energy to the surrounding. Eq. (5) is widely employed to characterize solar thermal collectors (both water-type and air- type). A graph of the efficiency η_{th} against the reduced temperature ratio $\Delta T/G$ (where $\Delta T = T_{in}-T_a$) is usually plotted from experimental data. In this work, the mass flow rate is estimated from a mathematical model developed by the first author (Tonui and Tripanagnostopoulos, 2008) and used in Eq. (1) and then Eq. (4) to find η_{th} and the corresponding $\Delta T/G$ evaluated. For stagnation operation, there is no air flow in the channel hence $\eta_{th} = 0$ and $\Delta T = T_p-T_a$ (T_p is absorber plate temperature). The values of F_R and U_L can then be determined from slope and y-intercept of the graph.

3. Experimental Test of the Collector

An experimental prototype model with rectangular air duct was designed and fabricated at the Department of Physics, Moi University and investigated under outdoor test conditions. The air flows between the absorber plate and the top glass cover in a single-pass mode as shown in Fig.1(c). The absorber plate was made from the ordinary roofing corrugated iron sheet with rectangular profile (to increase surface area of the collector) and painted black, with ordinary black paint, on its front surface to ensure high absorptivity of incident solar radiation. The bottom and sides of the collector were made from wooden box and insulating material was placed between the casing and absorber plate rear and side surfaces to reduce bottom and side heat losses respectively by conduction. The absorber plate measures 100 cm by 50 cm with the air channel depth of 15 cm. A single glass cover, made from low iron glass (ordinary window glass) of thickness 0.3 cm, was used as the top cover and helps to reduce the top heat loss by convection and radiation to the ambient as well as acting as the top surface of the duct. The inlet and outlet (8 cm diameter) vents were provided at the bottom and top respectively as shown in Fig.1(c). The Fig. 2 shows the picture of the experimental ring.

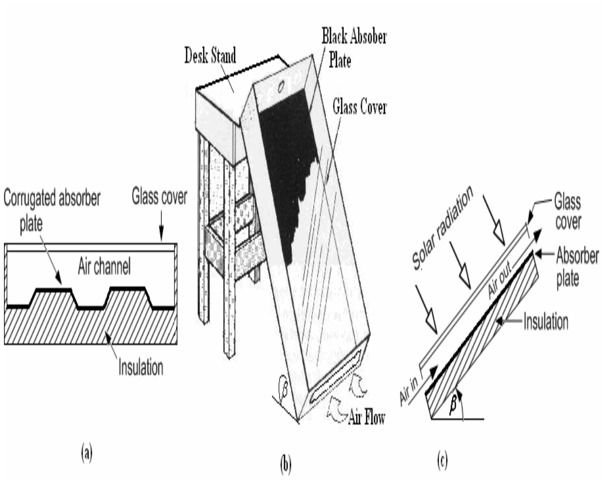

Fig.1 Experimental model (a) cross-sectional view (b) experimental set up (c) airflow plenum

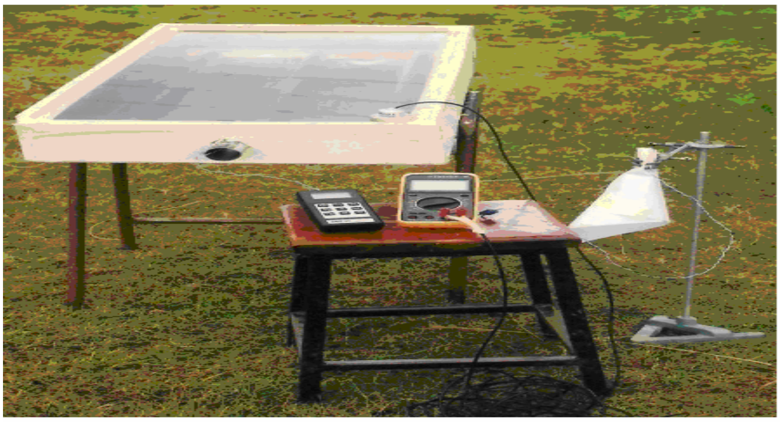

Fig. 2 Picture of the experimental ring.

The system was mounted at a tilt angle of 20° due south (since Eldoret is slightly north of equator) on a support structure and tested outdoor in an open field (to avoid shading from trees or buildings). Type-T (Cu-CuNi) thermocouples (accuracy of ± 1.0 °C) were used to measure the air inlet and outlet temperatures in the channel as well as the ambient and absorber plate temperatures. The thermocouple used to measure the ambient temperature was put in a secured (i.e. shaded) surrounding to prevent direct heating from the sun and the effects of wind. The POA solar radiation on the plane of the collector was measured by using Kipp & Zonen pyranometer. The data were recorded manually at interval of 15 minutes from 9:00 AM in the morning till 3:00 PM in the afternoon. The airflow in the channel was by natural convection.

4. Results and Discussions.

The performance tests were carried out according to the international standard methods (Duffie and Beckman, 1991). For solar applications, experimental study is very important to determine actual performance of the system under the metrological conditions of the place of interest. In this study, the experimental test campaigns were done in the first half of the year 2008 in Eldoret, Kenya. Fig. 3 gives representative mean hourly values of experimental data collected on the POA solar radiation G, the ambient temperature T_a, absorber plate temperature T_p and the inlet T_{in} and outlet T_{out} air temperature on a typical sunny clear day. The figure indicate that the available solar radiation, G varies from about 800 Wm^{-2} in the morning (at about 9:00 AM) and rises gradually to about 1200 Wm^{-2} around midday (12:00 noon) and falls off gradually also to about 800 Wm^{-2} again in the early afternoon (at about 3:00 PM). This shows that there is high solar irradiation over this season of the year hence large amount of thermal energy that can be tapped per day. The ambient temperature, T_a is also moderately high, between 25 °C to 30 °C hence the heat losses are relatively low resulting to high amount of heat (high output temperature of air) which could be channeled for useful drying and heating applications.

The variations of the inlet, T_{in} and outlet, T_{out} air temperatures are also shown in Fig.3. The results show that the temperature rise of air lies between 30 to 40 °C. This is a large temperature rise implying high thermal energy yield that can effectively be used to dehydrate agricultural crops or industrial products, reducing the drying time as well as improving the quality of the products.

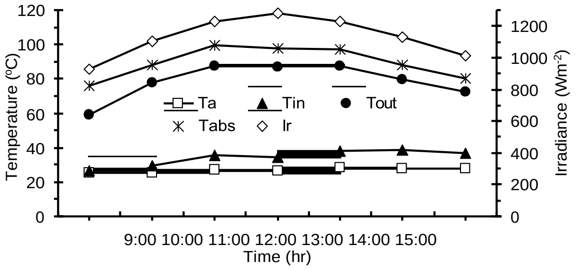

Fig. 3 Typical mean hourly values of solar intensity G, ambient T_a and plate T_p temperatures, inlet T_{in} and outlet T_{out} air temperature results.

The changes in the air temperature rise, $\Delta T = T_{out} - T_{in}$ against POA solar radiation for a typical day is shown Fig. 4. The best fit line is drawn using linear regression and the graph shows that the temperature rise, ΔT, increases linearly with incident POA radiation reaching maximum value at noon (1200 Wm^{-2}). The equation of the trend line gives the threshold value of incident solar radiation G_{Th} for the studied model of about 178 Wm^{-2}. These results are helpful in estimating the fluid temperature for any day of the year if the metrological data are known.

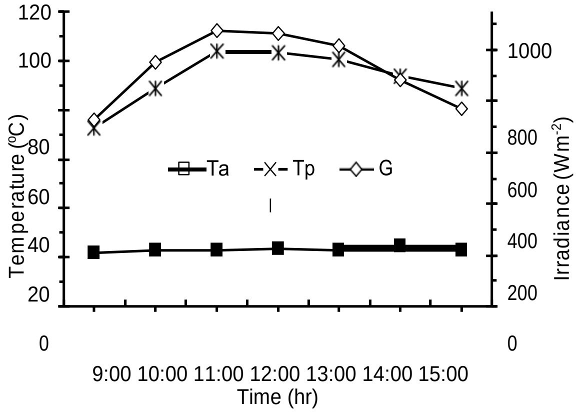

Fig. 5 Typical mean hourly stagnation results (no airflow).

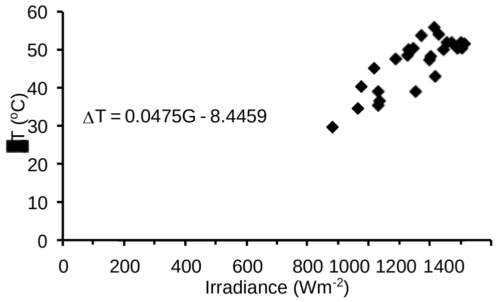

Fig. 4 Typical variation of ΔT with the incident solar radiation results.

Eq. (5) was used to analyze the thermal performance of the prototype solar air collector. The task here is to evaluate the mass flow rate. Since the air circulation was by natural convection, the model developed by the first author was modified and validated against the experimental data and used to evaluate the air mass flow rate. An iteration loop in the program fixes the mass flow rate when the predicted output air temperature equalizes that of the measured output temperature. Several correlations equations exist in many literatures that can be adopted for any solar collector. Detailed heat transfer equations between the collector components and air-flow in the channel as well as between the collector and surrounding can be obtained from the reference Duffie and Beckman (1991). The estimated air mass flow rate from the program is about 4.33 x 10^{-3} kg/s, which is comparable to those given by Fath (1995). The stagnation results which were used to evaluate the reduced temperature ratio, $\Delta T/G=(T_p-T_a)/G$, is given in Fig. 5, where the absorber plate temperature, T_p is seen to be over 100 ^{o}C on a clear sunny day.

Fig. 6 gives the performance curve of the prototype model and the corresponding thermal performance equation is

$$\eta_{th} = 0.38 - 5.56\frac{(T_{in} - T_a)}{G} \ldots\ldots(6)$$

The heat removal factor can be obtained from Eq. 6 from the *y*-intercept and assuming typical value of ατ-product as 0.85, gives the value of F_R ~0.44, which is relatively high given that natural airflow is used. The value of total heat loss coefficient U_L is determined from the slope of the performance curve as U_L = 12.6 Wm^{-2}K^{-1}, which is reasonably low.

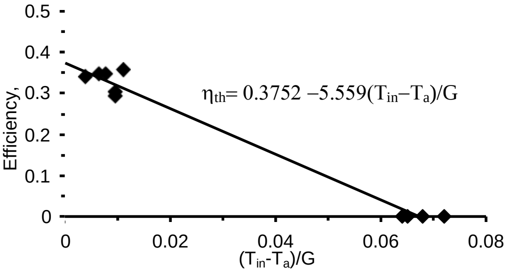

Fig. 6 Typical performance curve of the prototype model.

5. Conclusion.

The performance of a SAH system with natural air flow between the glass cover and the absorber plate made from a rectangular corrugated roofing iron sheet but painted black on its front surface has been demonstrated as capable of heating air to such a temperature that can be used effectively for heating or drying applications. The results show that the global solar radiation on the plane of the collector (POA) can vary from 800 to 1200 Wm^{-2} depending on the time of a clear day and the threshold value required to produce hot air is about 178 Wm^{-2}, hence there is abundant solar energy that can be tapped for useful applications. The corresponding ambient temperature is relatively high (between 20–30 °C) hence minimal heat losses from the collector as depicted by the relatively low value of U_L (12.6 Wm^{-2}K^{-1}), ensuring high thermal efficiency. From the estimated flow rate, the thermal efficiency was found to be about 38% hence reasonable fraction of the incident solar radiation above threshold valued can be converted into useful work. The results are very useful in Eldoret region since it is an agricultural zone, producing a lot of grains (maize, wheat, beans etc) and vegetables and the period when the experiments were performed is also the harvesting season. The hot air produced could be used effectively for drying purposes, which will ensure good post harvest yields unlike the present practice where maize and wheat are dried in the open air.

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