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EVALUATION OF FLAT-PLATE SOLAR COLLECTOR FOR AGRICULTURAL APPLICATIONS

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ABSTRACT

This work aims to evaluate a collector solar power harvester a domestic small field and greenhouse applications. A liquid flat plat solar collector was chosen because of its low cost, domestic material arability, low technical skills need for construction and operations, and to offer clean, cheap, economical, and available power source to implement post-harvest thermal treatments.

***Keywords.* Green energy, renewable energy, liquid flat plate collector.**

INTRODUCTION

Post-harvest technology is a multidisciplinary field and includes various treatments and operations carried out on harvested crops for the purpose of preservation or enhancement of quality for marketing and consumption (Singhal and Thierstein, 1984).

Fruits continue to live and respire even after they are picked (Biale and Young, 1981). A major economic loss occurs during transportation and/or storage of fresh fruits due to the effect of respiration. The higher the holding temperature, the greater the softening and respiration rate, and the sooner the quality becomes unacceptable. Removing field heat can suppress enzymatic degradation (softening) and respiratory activity; slow down or inhibit water loss (wilting); slow down or inhibit the growth of decay-producing microorganisms (molds and bacteria); reduce the production of ethylene as a ripening agent (Jorge, 2006). The most affecting factors that inhibit the use of field removal technology is the availability of clean, low cost energy source. This work aims to evaluate a domestic solar flat plate collector performance and power capacity as a step in developing a unit for post-harvest thermal treatments.

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Solar flat-plate collector **(FPC)** has been built with major purpose to collect as much solar energy as possible at lower total cost using domestic materials. **FPC** performance tests were conducted at Asyut governorates, Egypt. Latitude 27.19 and longitude 31.18, with 14.08 hours daylong and $G_t = 8200$ W.h /m^2/day for solar declination angle of 23.41°.

FPC Frame and dimensions:

To minimize heat loss from the FPC and to keep its components free from dust, moisture, and other performance affecting factors. A wood casing was built with dimensions to facilitate mobility to the different tested environmental conditions as illustrated in figure 1

Experimental Setup: heat exchanger (flat plate absorber)

The absorber plate which covers the full aperture area of the collector must perform three functions: absorb the maximum possible amount of solar irradiance,. transfer this heat into the working fluid at a minimum temperature difference and lose a minimum amount of heat back to the surroundings.

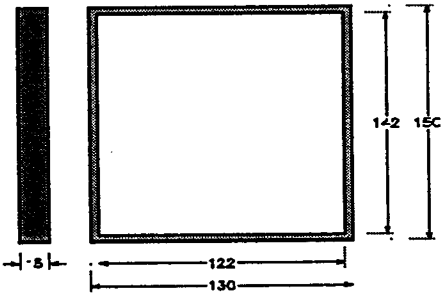


Figure 1: Flat plate solar collector (FPC) overall dimensions in cm.

Absorber with one millimeter thick black coated steel sheet was used to harvest the solar power in form of heat. Absorber gained heat was transmitted to a water (working fluid) running through a steel tube-2.5 cm diameter-forming ten rows, as seen in figure 2, and bounded to the absorber sheet by means of steel clips, figure 3. The liquid tubes were connected at both ends by a 3.81 cm diameter steel header tubes.

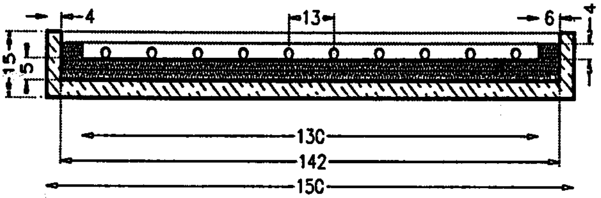
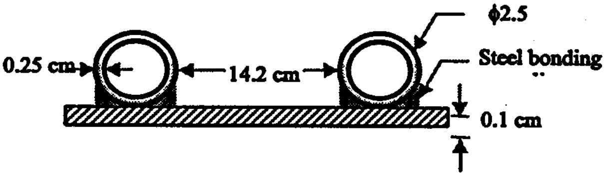


Figure 2: FPC cross section of collector configuration.



FPC absorber dimensions length [L_p] :	**142**	**cm**
FPC width [w_p] :	**122**	**cm**
FPC gross area [Ac] :	**1.95**	**m^2**
FPC absorber area [A_p] :	**1.73**	**m^2**
number of tubes:	**10.0**	
tubes inner diameter:	**2.0**	**cm**
tubes outer diameter:	**2.5**	**cm**
tube-to-tube spacing:	**14.2**	**cm**
fluid material: water		
fluid volumetric flow rate:	**0.13**	**L/min**
fluid inlet pressure:	**101.2**	**kPa**
plate – tube bond conductance:	**42**	**W/m° K**

Figure 3: FPC absorber plate components and overall dimensions.

Control of Heat losses from FPC edges and back cover

To minimize the heat losses from the FPC, a wooden frame and glass wool layers were used to cover back and sides of the collector, figure 4. Heat transfer overall thermal conductivity will be the sum of the values of conductivity of air, wood glass wool, and absorber layers showed in figure 5, and solved by equations 1, and 2 (Awady, 1999).

$$R = \frac{1}{UA} = \frac{1}{A_1 h_a} + \frac{X_1}{A_1 K_1} + \frac{X_2}{A_2 K_2} \cdots \frac{X_n}{A_n K_n} + \frac{1}{A_n h_b} \text{------------ } \textit{Equation 1}$$

$$R = R_a + R_1 + R_2 .. R_n + R_b \text{------------ } \textit{Equation 2}$$

$$R_{overall} = R_{glass\ wool} + R_{wood} \text{------------ } \textit{Equation 3}$$

where **R** is the thermal resistance of insulation (°K/ W), R_1 is the thermal resistance of inner layer of insulation (°K/ W), R_2 is the thermal resistance of second layer of insulation (°K/ W), R_n is the thermal resistance of n^th^ layer of insulation (°K/ W), R_S is the thermal resistance of outer surface of insulation (°K/ W), U is the overall heat transfer coefficient (W/m^2 °K), A_n is the absorber area (m^2) of n layers, h_b is the surface coefficient of outer surface (W/m^2 °K), h_a is the surface coefficient of inner surface (W/m^2 °K), k_1 is the thermal conductivity of inner layer of insulation (W/ m °K), k_2 is the thermal conductivity of second layer of insulation (W/ m° K), and k_n is the thermal conductivity of nth layer of insulation (W/ m °K).

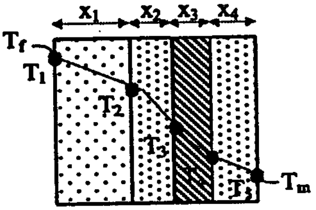
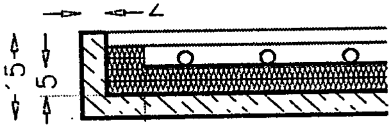


Figure 4: Heat transfer through layers of air, wood, glass wool, and absorber plate.

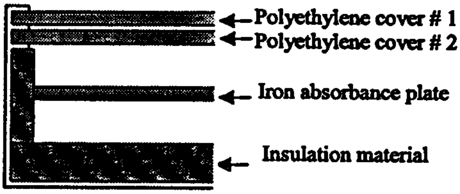


Thickness of the collector back insulation:	4.00 cm
Total Conductivity of the collector back layers insulation:	0.17 W/ m °K
Conductivity of the collector edge layers insulation:	0.17 W/m °K

Figure 5: FPC insulation configuration and characteristics.

Transparent cover

Two transparent polyethylene covers were used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the transparent covers. It also reduces radiation losses from the collector as the covers are transparent to the short wave radiation received by the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate (greenhouse effect). Polyethylene covers are limited in the temperatures they can sustain without deteriorating or undergoing dimensional changes, and the ability of polyethylene to withstand the sun's ultraviolet radiation for long periods. These drawbacks of using polyethylene as FPC covers can be recovered by its low weight and cost with its ability to withstand shocks without being broken. Polyethylene covers configuration and characteristics are illustrated in figure 6.



Properties of cover material -Plastic (Polyethylene)

Solar spectrum refractive index: 1.46
Transmittance: 0.70
Long-wave absorbance: 0.05
Long-wave transmittance: 0.78
Number of covers: 2.00
Cover-plate air spacing: 6.00 cm
Cover 1 – cover 2 air spacing: 2.50 cm

Plate material plain carbon steels

conductivity: 60.50 W/ m K
Thickness: 0.10 cm
Solar spectrum absorbance: 0.88
Long-wave emittance: 0.15

Figure 6: FPC cross section of energy absorption plate and its two transparent polyethylene covers

Open-field weather condition measurements

FPC performance was carried out through various of different environmental conditions. The solar radiation, wind speed, air humidity, and temperature were measured by means of devices and instruments as illustrated in figures (7, 8, 9, and 10).

Device: Pyrometer model PSP
Sensitivity: 9 µV/W m²
Range: 0-2800 W/m²
Accuracy: ± 0.5%

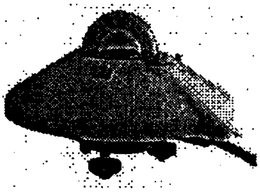


Figure 7: Solar radiation measuring device.

Device: Cup counter anemometer.
Range: 1- 67 m/s
Accuracy: 1 m/s (±5%)

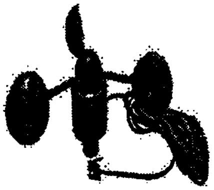


Figure 8: Wind speed measuring device.

Device: Dial hair hygrometer.
Range: 0 to 100%
Accuracy: 1%

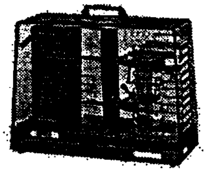


Figure 9: Humidity measuring device.

Device: Glass mercury thermometer.
Range: -10 to 200 °C
Accuracy: 1 °C

Figure 10: Temperature measuring device.

TEST PROCEDURES AND CALCULATIONS

Heat exchanger

Water flow rate was measured by estimating water quantity in 500 ml measuring cup accurate to ±4 at 20 °C and a digital stop watch to measure time accurate to 1/60 s. The general heat transfer equation 4, can be used to calculate the heat load to the fluid at the measured flow rate.

$$\Delta q = \frac{AK}{t}\Delta T,\ k \text{ -- } \textit{Equation 4}$$

Where Δq is the heat difference (W), K is the conductivity (W/m °K), t is the time (sec), and ΔT is the temperature difference(°K).

FPC performance and efficiency

Solar flat plate collector efficiency is a ratio to determine the useful solar energy to the total incident solar energy as shown in figure 5. FPC efficiency represents the total losses to atmosphere by convection and radiation. To evaluate the tested FPC performance, overall heat transfer coefficient (U) was determined by the equations 5,6, and 7 (Awady, 1999).

$$\eta = \frac{\text{Useful energy collected}}{\text{Incident solar energy}} = \frac{Q_u/A}{Q_i/A} = \frac{Q_u/A}{I} \text{———————— } \textit{Equation 5}$$

$$Q_o = UA(T_a - T_m) \text{———————— } \textit{Equation 6}$$

$$Q_u = Q_i - Q_o = I\tau\alpha.A\text{-}\ UA(T_a - T_m) = mC_p(T_h - T_c) \text{ - } \textit{Equation 7}$$

where **η** is the FPC efficiency, **I** is the incident solar energy per unit area (W/m^2), **Q_i** is the collector heat input (W), **Q_u** is the useful energy gain in a solar collector (W), **Q_o** is the the solar collector overall heat losses (W), **T_c** is the temperature of fluid (°K), **T_h** is the temperature of hot fluid (°K), **T_a**: collector average temperature (°K), **T_m** is the temperature of ambient still air (°K), **C_p** is the heat capacity of the fluid (kJ/kg °K).

To relates the actual useful energy gain of a collector to the useful gain – in case of the collector surface at the fluid inlet temperature –the collector heat removal factor as reviewed in the equation 8,9, 10, and 11.

$$Q_u = mC_p(T_a - T_m) = F_R(Q_a - Q_o) \text{———————— } \textit{Equation 8}$$

$$Q_i = I.A = I(\tau\alpha).A \text{———————— } \textit{Equation 9}$$

$$F_R = \frac{mC_p(T_h - T_c)}{A(I\tau\alpha - U(T_a - T_m))} \text{———————— } \textit{Equation 10}$$

$$Q_u = F_R\, A(I\tau\alpha - U(T_a - T_m)) \text{———————— } \textit{Equation 11}$$

Where F_R is the heat removal factor, **m** is the fluid mass flow rate (Liters/s), τ is the transmitivity of glass cover system, α is the absorptivity of absorber plate.

FPC performance varies depending on how warm the collector inlet water temperature is relative to the ambient air temperature. FPC efficiency was calculated according to the equation 12.

$$\eta = F_R\tau\alpha - F_R U\left(\frac{T_h - T_c}{I}\right) \text{———————— } \textit{Equation 12}$$

Finally FPC (figure 11), thermal characteristics was determined based on Hottel - Whillier Bliss efficiency curve, figure 12 (Norton, 2006).

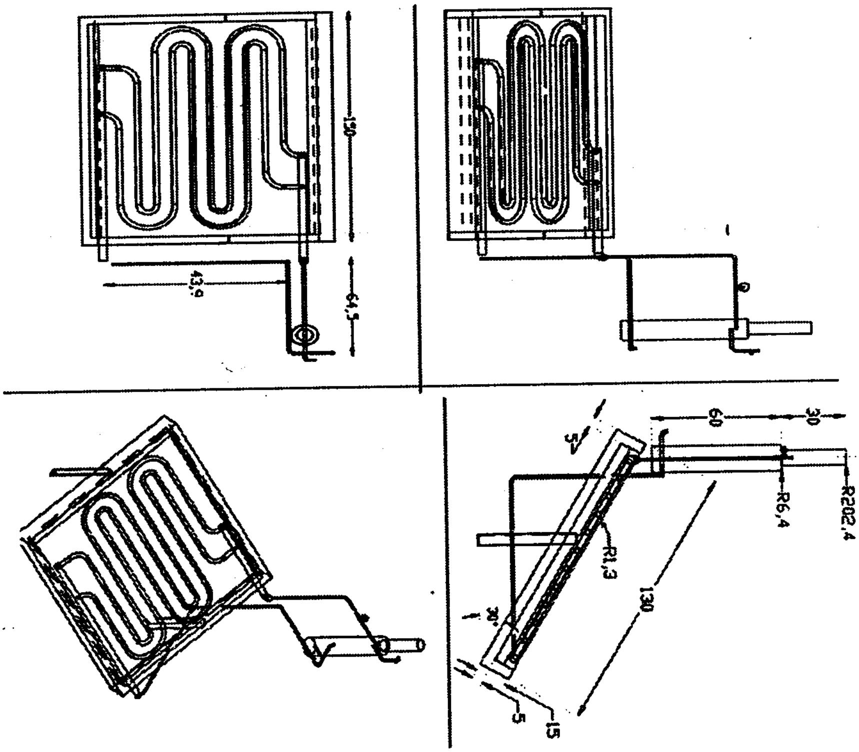


Figure 11: FPC configuration.

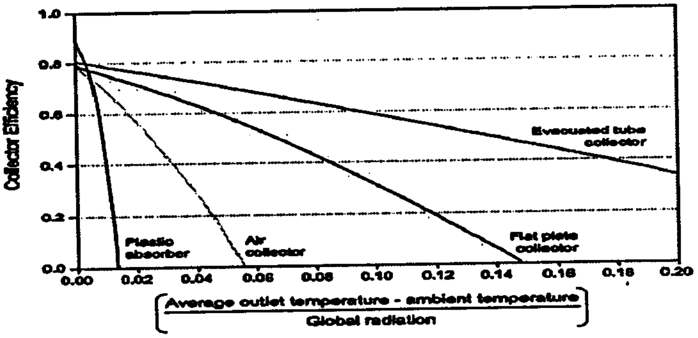


Figure 12: Hottel-Whillier Bliss efficiency curves (Norton, 2006).

RESULTS

FPC was evaluated upon absorber area as well as aperture and gross areas. It is the absorber area that collects solar energy, and so evaluation of the efficiency based on the percentage of solar thermal radiation hitting the absorber and transferred to the thermal fluid loop. FPC efficiency equation 13, was obtained from figure 13, efficiency.

$$\eta = 0.7 - 4.5\frac{\Delta T}{G_T} - 5.9\left(\frac{\Delta T}{G_T}\right)^2 \qquad \text{Equation 13}$$

Where G_t is the incident solar radiation (w/m2), and G_d/G_t is the diffuse radiation proportion.

From efficiency curve, FPC optical efficiency occurs when the fluid inlet temperature equals the ambient air temperature ($T_f = T_a$).

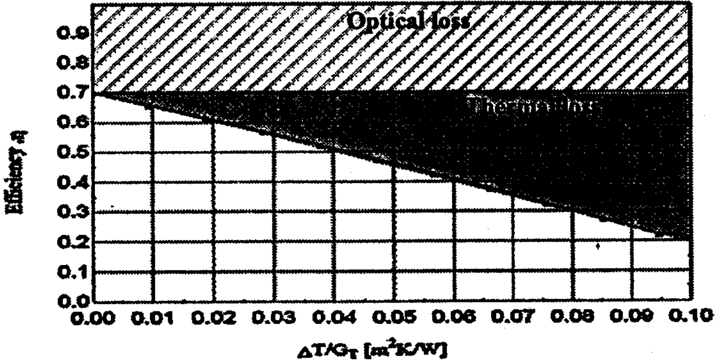


Figure 13: Instantaneous efficiency of collector.

Also, it was found that, at low solar irradiances, the efficiency decreases at faster rate (figures 13, 14).

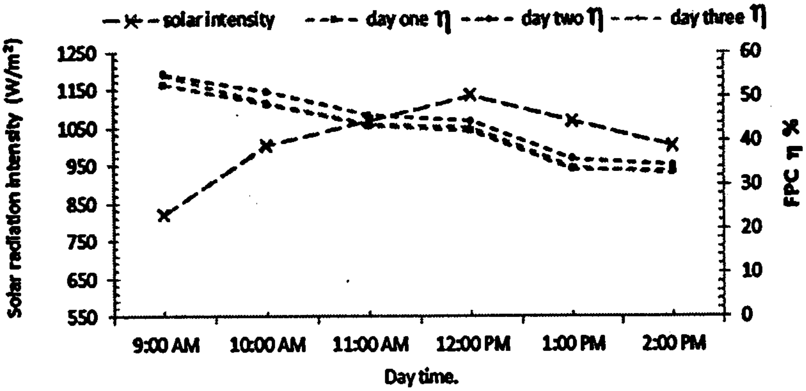


Figure 14: FPC efficiency at different solar radiation intensities for successive three days measurement.

The heat level of the FPC absorber plate affects the total efficiency. Increasing of absorber temperature, decrease the FPC efficiency as shown in figure 15.

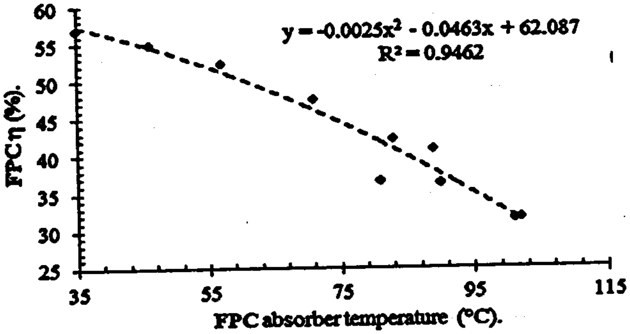


Figure 15: FPC efficiency estimation due to absorber plate temperature.

Increment in FPC ambient air velocity, proportionally increases the total thermal loss according to figure 16.

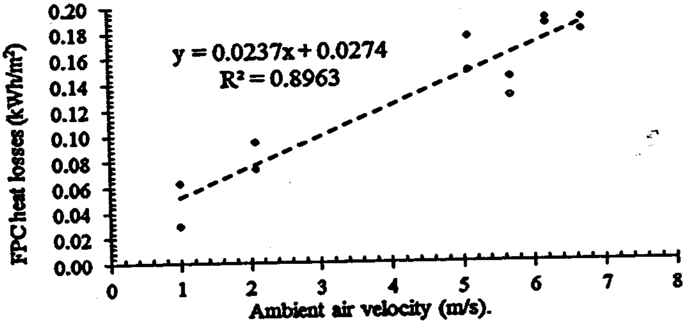


Figure 16: The variations of the energy efficiency versus the wind speed.

DISSCUSSION

Because of its characteristics, FPC was selected to evaluate its efficiency as a design factor in designing a power source for field crop heat removal post-harvest treatment, for a small and medium crop production areas – widely found in Egypt. Small and medium crop production areas in Egypt have no or low economical potential for using post-harvest treatments as essential treatment to minimize crop damage and to maintain its quality and marketing value, especially for thermal sensitive crops. The FPC is easy to construct and to operate with low maintenance and technical skills. Also, FPC is suitable as a power source for in-field application of post-harvest crop heat removal treatments, where the crops are harvested during long period of time in relatively small quantities. The field crops can form a wind breaks to minimize the heat losses from FPC, with positive impact in its performance. FPC is thermal self-compensating power source, as it depends on solar thermal radiation figure 13, 14. As the harvested crop gain more heat because of the increasing of solar power, the more power will be applied to the chiller crop cabinet. FPC is thermal self-compensating power source that it is almost, thermal self-regulating power source. FPC could be used as a double fold field thermal power in heating and cooling treatments as envisaged.

CONCLUSION

FPC built from domestic low cost materials performed close to the performance level of the traditional known FPC systems. For better performance in designing applications such as a domestic field chiller, it must have a high performance heat exchanger to extract most of the thermal power and to maintain the FPC thermal fluid as much as close to the level of ambient air temperature.

FPC orientation is one of the factors affecting the system performance. FPC efficiency will decrease at faster rate when system is not oriented accurately. So, system design for in field use, must consider ease of the system mobility, avoiding stationary design in any further work.

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المخلص العربى

تقييم أداء مجمع شمسى مسطح للاستخدام فى التطبيقات الزراعية.

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يهدف البحث لتقييم كفاءة وحدة مسطحة لتجميع الطاقة الشمسية، لأغراض التدفئة أو التبريد بما يتلاءم و التطبيقات الزراعية المختلفة. وبما يتسق مع توفير الاحتياجات الحرارية للوحدات الزراعية الصغيرة والمتوسطة ووحدات الزراعات المحمية، زهيدة التكلفة، و بما يتناسب و الاشتراطات البيئية. ونحو السعى لتحقيق الهدف، عمد البحث على استخدام المواد المتوافرة محليا، فى إنشاء وحدة تجميع شمسى تجريبية بإطار خشبى، بأبعاد ١٣٠ سم ×١٥٠ سم، ومغطى بطبقتى من البلاستيك المستخدم فى التطبيقات الزراعية للحماية من الفقد الحرارى. وصنعت وحدة الامتصاص الحرارى من أنابيب مثبته على لوح امتصاص من معدن الحديد المكسو بطلاء أسود ومحاط بالصوف الزجاجى بسمك ٤ سم، لزيادة كفاءة عمليات امتصاص الحرارة وتقليل الفاقد الحرارى. وقد روعى فى وحدة الاختبار، أن لا تحتاج إلى مهارات خاصة فى التصنيع أو التشغيل أو الصيانة. وجد من خلال مجموعة التجارب التى جرت تحت الظروف المصرية المختلفة ، تحقيق وحدة التجميع الشمسى محلية التصنيع كفاءة تشغيل تقارب كفاءة التشغيل لوحدات التجميع الشمسى القياسية والتى قاربت ٧٠%، عند تساوى درجات حرارة دخول المياه ودرجة الحرارة المحيطة. وقد سجل تناقص فى كفاءة عمل وحدة التجميع الشمسية المسطحة، بزيادة درجة حرارة دخول المياه بالنسبة إلى درجة حرارة الهواء الجوى المحيط بالوحدة الشمسية.

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