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Design and Sensitivity Analysis of Photovoltaic/Thermal Solar Collector

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Abstract – Energy is required in almost every aspect of human activities and development of any nation in the world. Increasing fossil fuel price, energy security and climate change have important bearings on sustainable development of any nation. The renewable energy technology is considered one of the drastic approaches which taken over the world to reduce the energy problem. The preservation of vegetables by freezing is one of the most important methods of retaining quality in agricultural products over long-term storage periods. Freezing factories show high demand of energy for both heat and electricity; the hybrid Photovoltaic/Thermal (PV/T) systems could be used in order to meet this requirement. This paper presents PV/T system design for freezing factory. Also, the complete mathematical modeling and MATLAB SIMULINK of PV/T collector is introduced. The sensitivity analysis for the manufacturing parameters of PV/T collector is carried out to study their effect on both thermal and electrical efficiency.

Keywords – Hybrid PV/T system, renewable energy, sensitivity analysis, MATLAB modeling, MATLAB SIMULINK.

1. INTRODUCTION

The use of solar energy conversion systems in industry is limited, but it could be broadened, mainly for the photovoltaics, if PV/T systems are used instead of the basic PV modules. In the late 1970's however, a number of studies began to investigate the incorporation of both photovoltaic and solar thermal collector into a single device [1]. These new solar systems are of practical interest for industrial applications, as they can effectively contribute to cover both the electrical and thermal industrial loads. The temperature of PV modules is increased by the absorbed solar radiation that is not converted into electricity, causing a significant decrease in their efficiency. It is well known that for mono and polycrystalline silicon PV-cells, their efficiency decreases with increasing temperature by approximately 0.5%/°C. This undesirable effect can be partially avoided by a proper heat extraction with a fluid circulation. In hybrid PV/T solar systems, the reduction of PV module temperature can be combined with useful fluid heating. There are two benefits of PV/T: firstly, the efficiency of PV cells can be increased by actively cooling them using the solar thermal collector system. Secondly, by incorporating both systems into a single unit, the area dedicated to solar energy systems can be reduced [2].

Today, industrial buildings such as freezing factories could be representing a new field that needs to both photovoltaic and thermal solar energy conversion system. Solar energy applications in a new field related to the integration of PV and PV/T systems [3-5]. Freezing process is one of the oldest and most widely used methods for vegetables preservation, which allows preservation of taste, texture, and nutritional value of vegetables better than any other method [6]. The freezing process is a combination of the beneficial effects of low temperatures at which microorganisms cannot grow, chemical reactions are reduced, and cellular metabolic reactions are delayed. Washing vegetables stage with warm water is considered as one of the main stages in the frozen vegetables factories to remove chemical residue from the product.

This paper presents the design results of PV/T system used to cover both the electrical and thermal loads of a small freezing factory. The characteristics parameters of PV/T collector are calculated by means of analytical equations. The variation on the behavior of PV/T system with its parameters is presented. The results of the PV/T system design which can be used to supply both the electrical and thermal loads of a small vegetables freezing factory are discussed.

2. VEGETABLE FREEZING FACTORY DESIGN

Figure 1 shows the layout of the suggested freezing factory. It consists of seven rooms; washing room, drying room, sterilization room, packing-weighting room, control room, pre cooling room and complete freezing room [7]. Immediately after cleaning, the vegetables are subjected to a series of washing processes. Washing is carried out generally by a flexible nozzle. The hot water is pumped from the storage tank of the collector to the nozzle. In the drying room, the vegetables are dried using dehydrated apparatus with fan. Sterilization can be achieved by ultra violet sterilization equipment where all the living microorganisms and bacterial spores are killed. The electrical load of this equipment includes lower and upper conveyers, two ultra violet lamps, elevator and vibrating apparatus. Also, the lightning lamps of the factory are considered. There are several factors should be considered in packaging of frozen vegetables process, which include protection from atmospheric oxygen, prevention of moisture loss, retention of flavor, and rate of heat transfer through the package. Packaging is done immediately after sterilization in vacuum or in

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gas mixture of 20% CO_2 + 80% N_2. The control room operates the conveyor and all equipments of the factory. It includes temperature monitoring equipment and other inspection equipments. The pre-cooling room contains a refrigerator which has a capacity of 500 liter. The complete freezing process is the final stage which contains two deep freezers, each of which has a capacity of 750 liter.

3 SITE CHARACTERISTICS

Kharga Oasis in the south Egypt is the chosen zone for freezing factory installation. It is the largest oasis and the capital of the New Valley Governorate in the Western Desert of Egypt. It is located about 240 km southward Assiut Governorate, and about 580 km away from Cairo. The latitude and longitude of Kharga Oasis are 25° 27' N, 30° 32' E respectively. The major economic resources for the city are tourism and agriculture since the water supply and advanced technology is available in Kharga Oasis rather than any other oasis. The most important agricultural products from Kharga Oasis are dates, rice and some vegetables. Therefore, it is preferable to install a small vegetable freezing factory in Kharga Oasis and use one of the renewable energy sources such as PV/T collector to supply both the electrical and thermal energy to this factory.

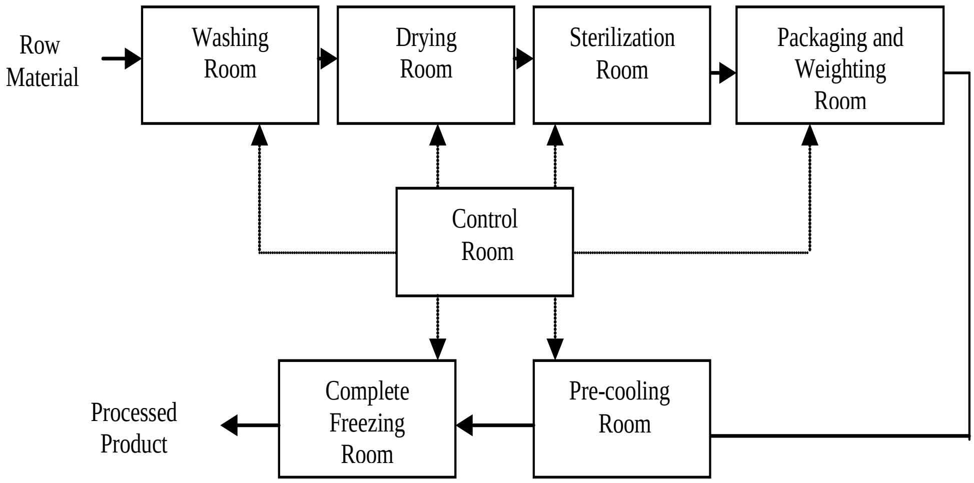

Fig.1. Sequence of operations employed in vegetable freezing process.

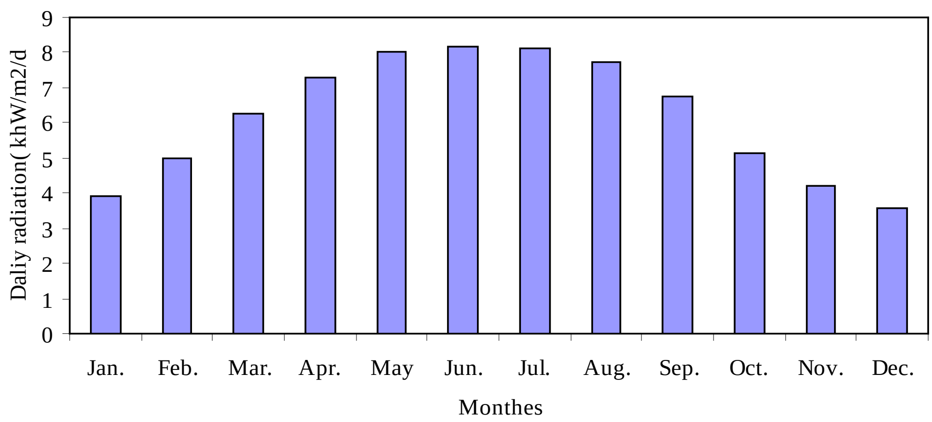

Fig. 2. Monthly average solar irradiation.

4. ENVIRONMENTAL CONDITIONS

Kharga Oasis is known as a rich area of wind and solar energy. The available wind and solar resources greatly influence both the configuration and the cost of power system. Monthly average solar insolation and wind speed data for the selected area are shown in Figure 2 and Figure 3 respectively [8]. It is noticed that the highest values of the solar insolation are during the summer months (May, Jun., Jul, and August) and the lowest values are during the winter months (November, December and January).

The minimum and maximum ambient temperatures for our sit are shown in Figure 4.

5. LOAD ESTIMATION

The electrical load profile of vegetable freezing factory is shown in Figure 5. The thermal load calculations as follows:
The number of washing cycles for one vegetable tray = 3 with flow rate = 5 liter/ min = 300liter/hour
The time of the first cycle = 1 min
The time of the second cycle = 3/4 min
The time of the third cycle = 1/2 min
The capacity of one vegetable tray =10 kg
The hot water temperature for washing = 40 ^{o}C
The total quantity off vegetable produced per day= 500 kg
The number of trays for one shift = 500/10 = 50 trays
The hot water capacity = 50*(1+0.75+0.5)*5liter/min
=562.5 liter
The capacity of hot water tank = 700 liter
The hot water load = 300*20 kcal = 6000/1.1630 kW
=5.2kW
Hence, the freezing factory requires a storage tank of capacity 700 L needed for freezing 500 Kg of vegetables during a day. The thermal load profile of the factory is shown in Figure 6.

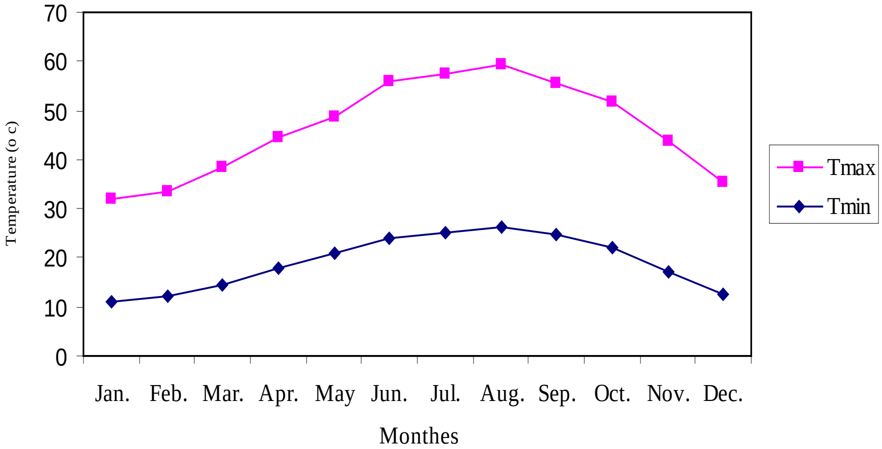

Fig. 4. The monthly maximum and minimum temperatures of Kharga Oasis.

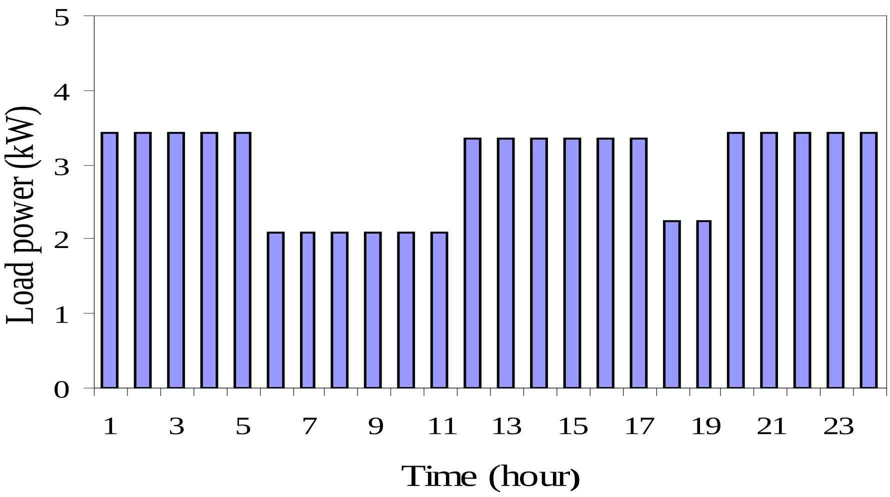

Fig. 5. The daily electrical load profile variation of freezing factory.

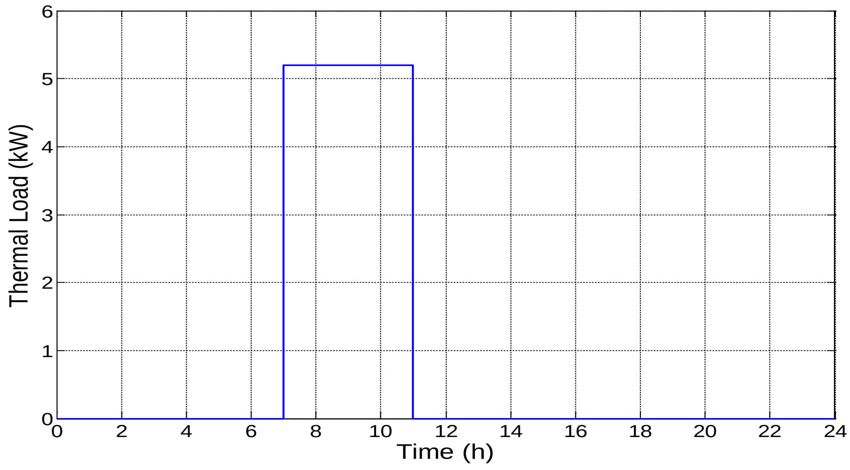

Fig .6. The daily thermal load profile of freezing factory.

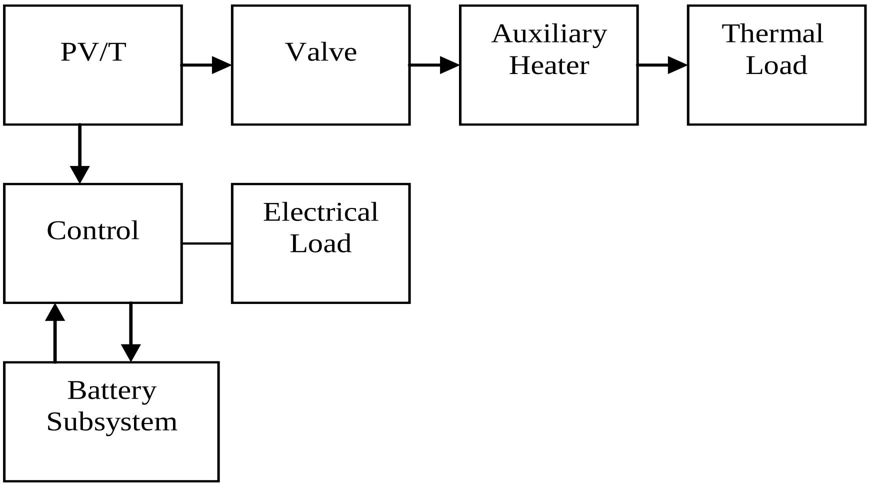

Fig. 7. Freezing factory power system.

6. PV/T SYSTEM SPECIFICATION

Figure 7 indicates the configuration of PV/T collector. In this paper, large size system (active system) with PV/T modules in parallel rows placed on a horizontal building roof with the water storage tank located inside the building and a pump for the water circulation from the collector to storage. A freezing factory power system is shown in Figure 7. It consists of the PV/T collector, thermostatic valve, auxiliary heater to heat the water in cloudy days, a storage battery for supplying the electrical load in cloudy and night periods, and finally a controller unit which control the operation between PV/T, storage battery and the electrical load [9]. The storage tank can be located at any place, like behind the collectors, indoors in a plant room or any other suitable location, and thus, there is an overall improvement in the aesthetics of the system. The design parameters of PV/T collector used in this study are listed in Table 1.

7. MATHEMATICAL MODELING OF PV/T

In order to analyze the thermal and electrical performance of the PV/T, a one dimensional steady state thermal model was developed with the collector treated as a flat plate thermal collector. As such the modified Hottel-Whillier equations presented by [13], [14] were used. The useful heat gain is represented as [9], [13]:

$$Q = AF_R\left[(\tau\alpha)_{PV} * GU_{loss}(T_i - T_a)\right] \quad (1)$$

The useful heat gain (Q) is represented as a function of the collector area (A), the heat removal efficiency factor (F_R), the transmittance-absorptance product of the photovoltaic cells ($\tau\alpha$.), the solar radiation (G), the collector heat loss coefficient (U_{loss}) and the temperature difference between the cooling medium inlet temperature(T_i) and the ambient temperature(T_a).

Table 1. Specification of PV/T collector considered [9].

Parameter	Symbol	Value	Unit
Number of covers	N_g	1	
Ambient Temperature	T_a	293	K
Emittance of plate	ε_p	0.95	
Emittance of cover	ε_c	0.88	
Number of tubes	n	66	
System flow rate	m	2	lps
Collector area	A	100	m^2
Wind speed	v	2	m^2/s
|PV Trans/Abs [10]	$\tau\alpha_{pv}$	0.74 or 0.78	
Thermal Trans/Abs [11]	$\tau\alpha_T$	0.925	
Absorber thickness	t	0.5	mm
PV thickness	L_{pv}	0.4	mm
PV conductivity [12]	k_{pv}	130	W/mK
Tube Hydraulic Diameters	d_h	9.7	mm
Tube spacing	w	0.1	mm
Ratio of tube width to spacing	d/w	1.5	
Heat transfer coefficient from cell to absorber [10]	h_{pvA}	45	W/m^2K
Insulation conductivity	k	0.095	W/mK
Edge insulation thickness	L_{edge}	0.025	m
Absorber conductivity	k_{abs}	50	W/mK
Heat removal efficiency factor (typical)	F_R	~0.85	
Collector heat losses coefficient (typical)	U_{Loss}	~6 glassed ~ 22 unglassed	W/m^2K
Mounting angle	β	37	degree

The heat removal efficiency factor accounts for the mass flow rate in the collector (m) and the specific heat of the collector cooling medium (C_p) which represented by [9], [13], and [17]:

$$F_R = \frac{mc_p}{AU_{loss}}\left[1-\exp\left(-\frac{AU_{loss}F'}{mc_p}\right)\right] \quad (2)$$

In order to obtain the heat removal efficiency factor however, it is necessary to calculate a value for the corrected fin efficiency (F'). This is done by first calculating the fin efficiency (F) using [9], [13], and [17]:

$$F = \frac{\tanh\left(M(w-d)/2\right)}{M(w-d)/2} \quad (3)$$

The coefficient (M) is a term which accounts for the thermal conductivity of the absorber and PV cell and is represented as [9], [13], and [17]:

$$M = \sqrt{\frac{U_{loss}}{k_{abs}L_{abs} + k_{PV}L_{PV}}} \quad (4)$$

As such, the corrected fin efficiency (F') can be calculated using [9], [13], and [17]:

$$F' = \frac{\frac{1}{U_{loss}}}{w\left[\frac{1}{U_{loss}\left(d+(w-d)F\right)}\right] + \frac{1}{wh_{PVA}} + \frac{1}{\pi d_{h\ fluid}}} \quad (5)$$

Where, h_{PVA} is a heat transfer coefficient to account for the bond resistance between the PV cell and the absorber and h_{fluid} is the forced convection heat transfer coefficient inside the cooling passage determined from the Dittus-Boulter equation.

$$U_{loss} = U_t + U_b + U_e \quad (6)$$

The top loss coefficient (U_t) is calculated using the equation below [9], [13], and [17]:

$$U_t = \left[\frac{\frac{N_g}{C}}{T_{pm}\left(\frac{T_{pm}-T_a}{N_g+f}\right)^e} + \frac{1}{hw}\right]^{-1} + \frac{\sigma\left(T_{pm}+T_a\right)\left(T_{pm}^2+T_a\right)^2}{\left(\varepsilon_p + 0.00591N_g\,hw\right)^{-1} + \frac{2N_g+f-1+0.133\varepsilon_p}{\varepsilon_g} - N_g} \quad (7)$$

Where:

$$c = 520\left(1-0.00005\beta^2\right) \quad (8)$$

$$e = 0.43\left(1-100/T_{pm}\right) \quad (9)$$

$$f = \left(1+0.089hw-0.1166hw\varepsilon_p\right)\left(1+0.07866N_g\right) \quad (10)$$

$$hw = 5.7 + 3.8v \quad (11)$$

The bottom loss coefficient is calculated using the equation below [9], [13], and [17]::

$$U_b = \frac{K_b}{L_b} \tag{12}$$

The edge loss coefficient is calculated using the equation below [9], [13], and [17]::

$$U_e = \frac{(UA)_{edge}}{A_e} \tag{13}$$

$$(UA)_{edge} = \frac{K_e}{L_e}.\, p.\, L \tag{14}$$

The mean plate temperature can be calculated by [9], [13], and [17]::

$$T_{pm} = T_i + \frac{Q_u / A_e}{F_R U_L}(1 - F_R) \tag{15}$$

The electrical efficiency of PV/T system can be calculated based on the difference between the mean temperature (T_{pm}) of the PV/T and the Nominal Operating Cell Temperature (*NOCT*). The electrical efficiency of PV/T system can be calculated as [9], [13], and [17]::

$$\eta_e = 0.15(1 - 0.005(T_{pm} - NOCT)) \tag{16}$$

The thermal efficiency of the PV module can be expressed in terms of the inlet temperature *Ti*, the ambient temperature *Ta*, and the incoming solar-irradiation on the collector surface *G*. The thermal efficiency of the PV/T can be represented by the following equation [9], [13], and [17]::

$$\eta_{thermal} = F_R(S \times \tau\alpha_{PV}) + (1 - S \times \tau\alpha_T) - F_R U_{loss}\frac{T_i - T_a}{G} \tag{17}$$

8. SENSITIVITY ANALYSIS

Several parameters affect PV/T performance such as optimum mass flow rate, absorber plate parameters (i.e. tube spacing, tube diameter, and fin thickness), absorber to fluid thermal conductance and configuration design types. A MATLAB/SIMULINK model which is shown in Figure 8 is carried out to determine how some of these parameters would affect the thermal efficiency of the system. The dependence of thermal efficiency on the ratio of temperature difference between the collector inlet and the ambient (*Ti*-*Ta*) relative to the global solar radiation incident on the collector surface (*G*) is carried out at various PV/T parameters. This allows us to determine the parameters that have the greatest influence on the PV/T performance, and to provide an insight into what gains could be made by changing them.

Figure 9 describes the variation of thermal efficiency with (*Ti* –*Ta*)/*G* for different values of fin ratio (*d/w*). It is observed that, as the value of *d/w* increase (decreasing w) the thermal efficiency increase. Also, it is found that as the value of *d/w* increase, there is a minimal increase in electrical efficiency which is shown in Figure 10. This variation can be attributed to the increase of absorber collector area and a more reduction of the PV module temperature. The gap of spacing (*w*) between the tubes plays an important role in design configuration. Therefore, to obtain a good performance a full covered surface area by absorber collector underneath the PV module is recommended.

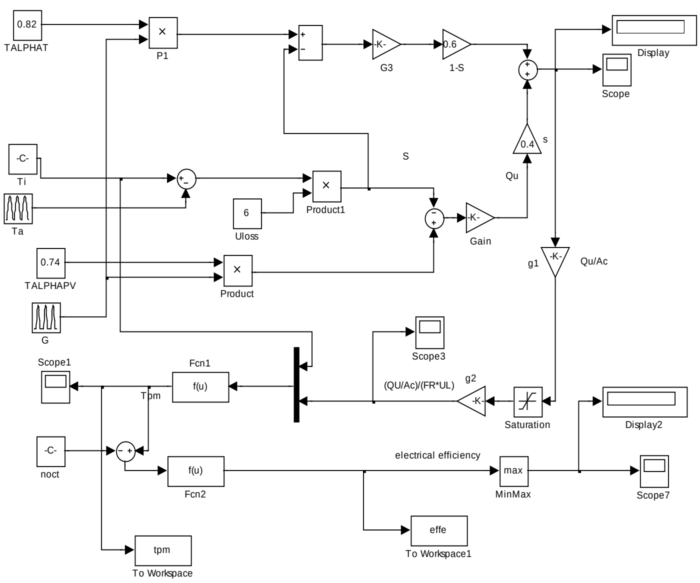

Fig. 8. PV/T collector diagram using MATLAB/SIMULINK.

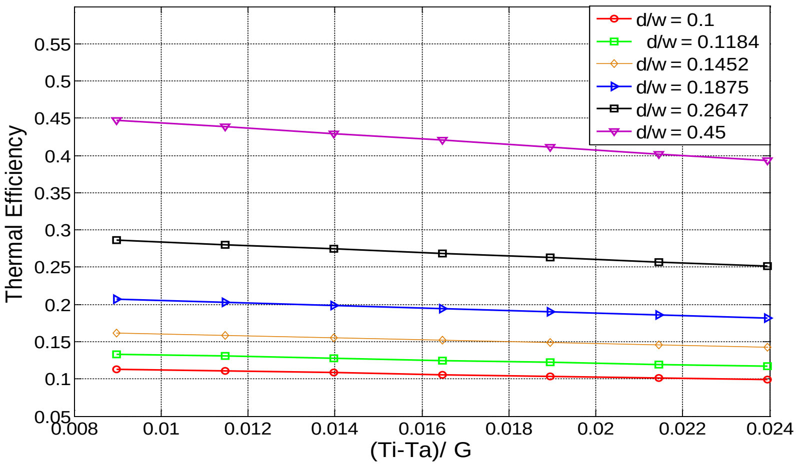

Fig. 9. Thermal efficiency variation with fin ratio.

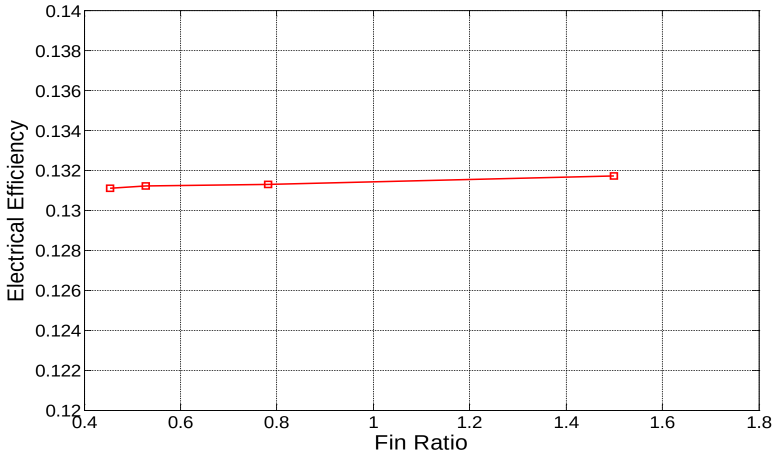

Fig. 10. Electrical efficiency versus fin ratio.

One of the key parameters that affects on the PV/T performance is the transmittance/absorptance product. Figure 11 indicated that, increasing the transmittance/absorptance product improves the thermal efficiency. Typically, silicon PV cells are designed to maximize their absorption of wavelengths where the photoelectric effect occurs in the solar spectrum ranged from 400 nm up to approximately 1200 nm, since the solar spectrum continues to approximately 2500 nm. These long wavelengths tend to be reflected whereas they are absorbed by solar thermal collectors resulting in the increase of thermal efficiency. One of the drawbacks of increasing the absorption of longer wavelengths is that it tends to result in the PV cell temperature being increased thus resulting in a decrease in the electrical efficiency.

The thermal and electrical efficiencies versus packing factor are shown in Figures 12 and 13. A rise in the packing factor means more collector area is covered by the PV cells. Hence, the thermal efficiency decreases along with the increase in the packing factor. However, the electrical efficiency slightly enhanced by the increment in the fraction of absorber plate area covered by the solar cells and reducing the temperature of the PV/T by withdrawing the thermal energy associated with the PV module.

Thermal efficiency versus absorber conductivity is depicted in Figure 14. It is observed that, the thermal efficiency is decreased from 0.64 to 0.6 with the increment of the absorber conductivity; this variation can be attributed to the heat removal factor. Unlike, the electrical efficiency remains approximately 13% with absorber conductivity as shown in Figure 15. Therefore, the electrical and the thermal efficiency do not considerably influenced by the material from which the collector is made.

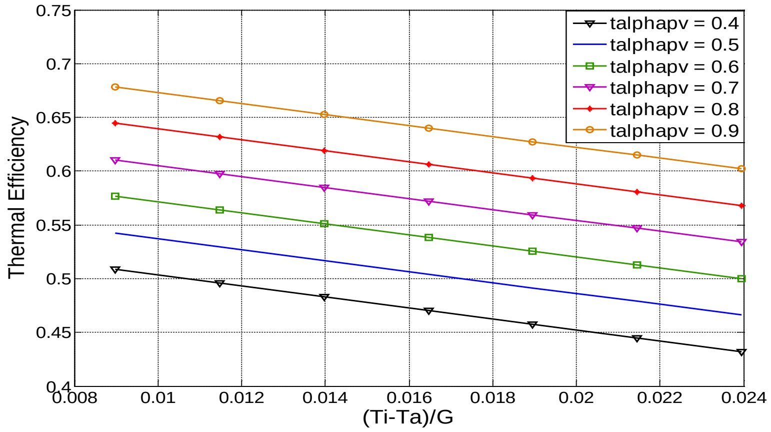

Fig. 11. Thermal efficiency variation with PV Transmittance/absorptance product.

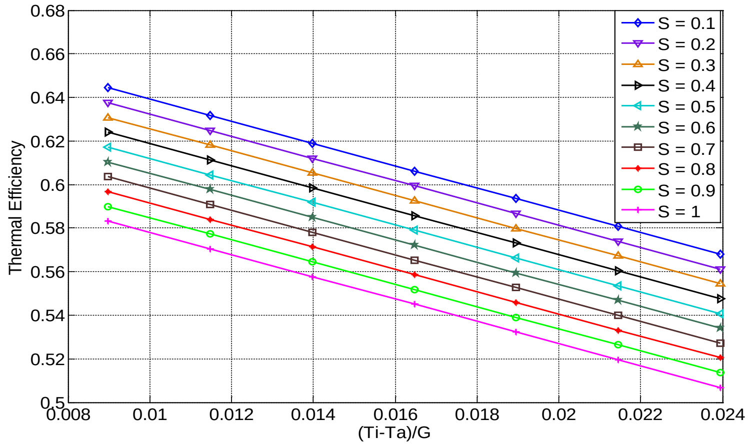

Fig. 12. Thermal efficiency variation with packing factor.

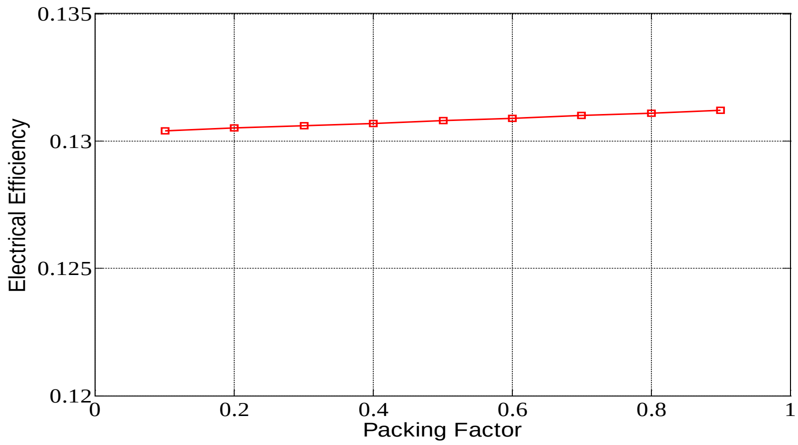

Fig. 13. Electrical efficiency versus packing factor.

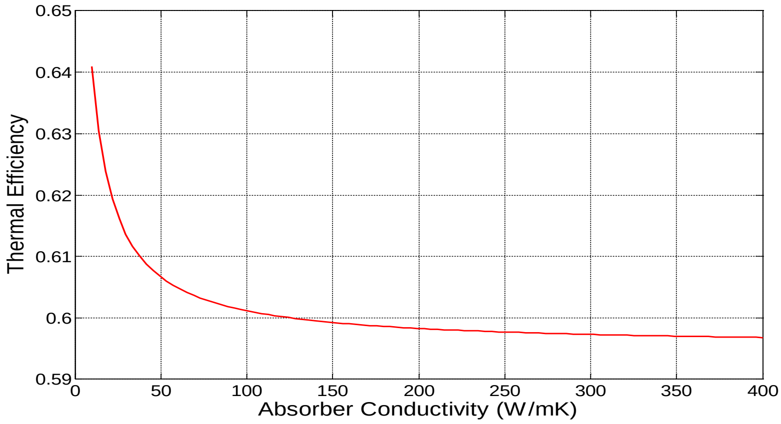

Fig. 14. Thermal efficiency variation with absorber conductivity.

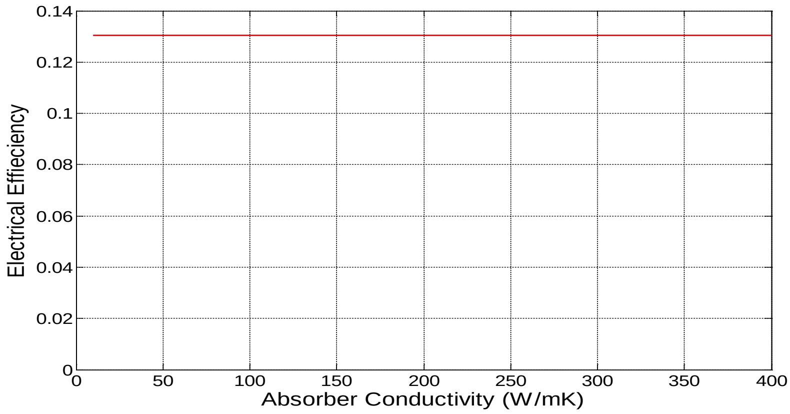

Fig. 15. Electrical efficiency versus absorber conductivity.

Thermal efficiency versus heat transfer coefficient from cell to absorber is presented in Figure 16. When the heat transfer coefficient from cell to absorber is increased up to 350 W/mK, the thermal efficiency is increased to approximately 68%. While the electrical efficiency is slightly improved with heat transfer coefficient from cell to absorber as indicated in Figure 17.

One of the essential parameters which must be specified in order to achieve the most promising performance of the system is the water mass flow rate through PV/T collectors. Vividly, increasing the water mass flow rate results in more heat removal from the PV/T collector which in turn raises the electrical energy output. Figures 18 and 19 show the variation of the thermal and electrical efficiency of the system versus the water mass flow rate respectively. As can be seen, increasing the water mass flow rate from 2 to 25 lps results in the increment in the electrical efficiency from 13.06 to 13.09% and the thermal efficiency increases from 59 to 62.5%. As can be seen, the output electrical energy from the PV panel slightly increases as the flow rate increases; this is due to the fact that the panel is working at a lower temperature.

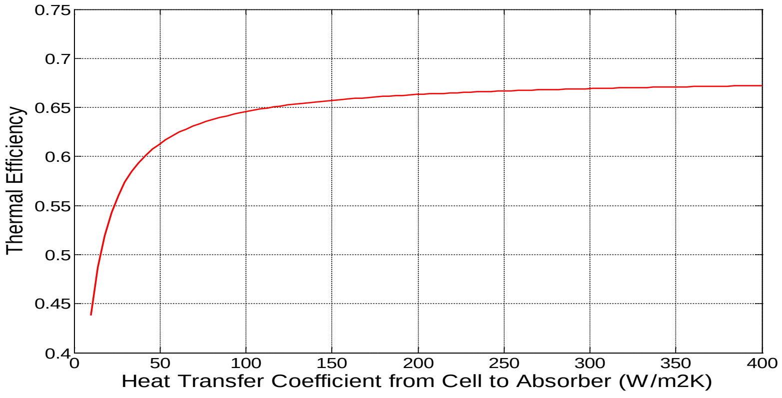

Fig. 16. Thermal efficiency variation with heat transfer coefficient from cell to absorber.

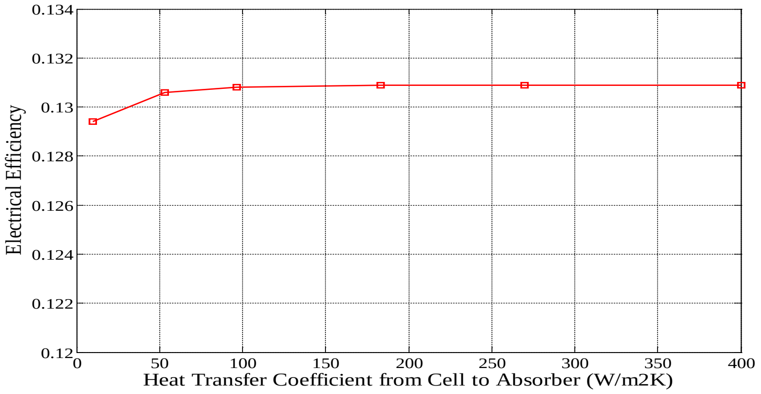

Fig. 17. Electrical efficiency variation with heat transfer coefficient from cell to absorber.

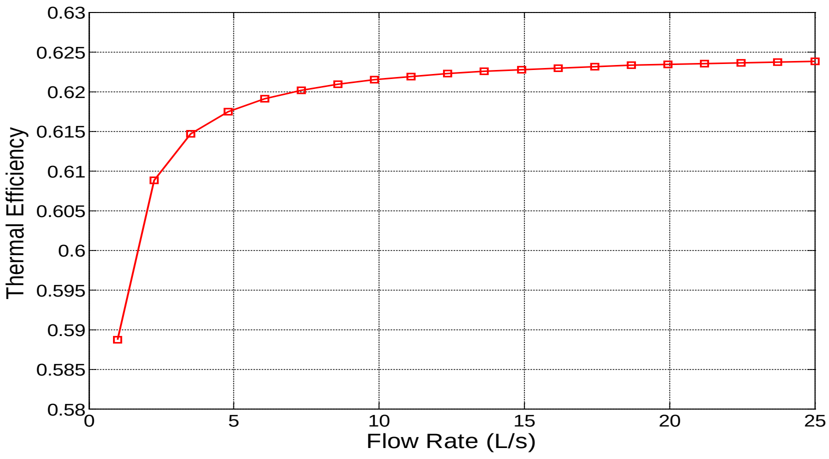

Fig. 18. Thermal efficiency variation with mass flow rate.

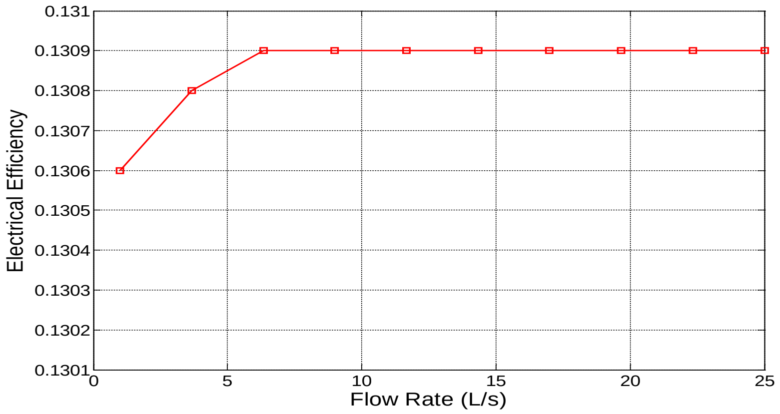

Fig. 19. Electrical efficiency variation with mass flow rate.

9. CONCLUSIONS

The solar energy conversion into electricity and heat with a single device (called hybrid photovoltaic thermal (PV/T) collector) is a good progress for future energy demand. This paper presented a PV/T collector fed a small freezing factory in a remote area in Egypt. The factory needs the electricity and hot water for operation, so using PV/T collector is promising idea. A complete design of the vegetable freezing factory is represented in this study. The factory is used for 500 Kg vegetables and a 2.975 kW electrical load. A mathematical model of PV/T collector is used to carry out multi parameters analysis and predict quite well the thermal and electrical performance of a PV/T collector using MATLAB/SIMULINK. PV/T collectors are very promising devices. If the overall energy production of the units increases, the hybrid system have better chances of success. Future work should be focused to improve the efficiency of PV/T collectors and to reduce the total cost, through this achievement, it will be more competitive.

NOMENCLATURE

A	Collector area
Cp	Specific heat of water (4190 J/Kg °C)
d_h	Tube Hydraulic Diameters
W	Tube spacing
d/w	Ratio of tube width to spacing
D	the tube width (d)
G	Intensity of solar radiation W/m$^{2.}$
F_R	The collector heat removal factor
F’	The corrected fin efficiency
h_{pvA}	Heat transfer coefficient from cell to absorber
hw	Wind heat transfer coefficient w/m^2 °C
k_{abs}	Absorber conductivity
k_{pv}	PV conductivity
K	Insulation conductivity
L_b	The back insulation thermal thickness cm
L_e	The edge insulation thermal thickness cm
L_{pv}	PV thickness
m	System flow rate
n	Number of tubes
N	Number of covers
$NOCT$	The Nominal Operating Cell Temperature
Q	The useful heat gain
t	Absorber thickness
T_a	Ambient Temperature
T_i	The cooling medium inlet temperature
T_{pm}	The mean temperature
S	Packing factor
U_b	Back collector overall heat transfer coefficient W/m^2 °C
U_l	Collector overall heat transfer coefficient W/m^2 °C
U_t	Top collector overall heat transfer coefficient W/m^2 °C
w	the tube pitch

Greek symbols

β	Mounting angle
ε_p	Emittance of plate
ε_c	Emittance of cover
σ	The Stefan-Boltzmann constant.
$\tau\alpha_{pv}$	PV Trans/Abs
$\tau\alpha_T$	Thermal Trans/Abs
v	Wind speed

REFERENCES

[1] Jiang F., Seng T.P., and Hua G.L., 2011. development of solar a-si pv/thermal (pv/t) system for tropical region. In *Proceeding of ISES Solar World Congress.* August 28 to September 2, Kassel, Germany.

[2] Kalogeria S.A. and Y. Tripanagnostopoulos. 2006. Hybrid PV/T solar systems for domestic hot water and electricity production. *Energy Conversion and Management* 47: 3368-3382

[3] Charalambous P.G., Maidment G.G., Kalogirou, S.A. and Yiakoumetti K., 2007. Photovoltaic thermal (PV/T) collectors: A review. *Applied Thermal Engineering Journal* 27: 275–286.

[4] Seng T.P., Fan J., and Hua G.L., 2012. Solar photovoltaic/thermal (pv/t) test-bed. In *Proceedings of International Congress on Informatics, Environment, Energy and Applications (IEEA)*, Singapore. Pages 69-74.

[5] Kim J-H., Chun J-A. and Kim J-T, 2011. The experimental performance comparison of two different types of unglazed pv/t collector. In *Proceedings of ISES Solar World Congress*, Kassel, Germany. Pages 124-130.

[6] Gustavo V., Cánovas B., Altunakar B., and Mejía-Lorío D.J., 2005. Freezing of fruits and vegetables. an agribusiness alternative for rural and semi-rural areas: Food and Agriculture Organization of the United Nations, Rome.

[7] Process plant for vegetables (VE00), 2005. Accessed online on 2013 at http://www.edibon.com/products/catalogues/cn/systems/technicalinformation/12/-VE00.pdf.

[8] New and Renewable Energy Authority, Ministry of Electricity and Energy, 1998. *Egyptian solar radiation atlas*, Cairo, Egypt.

[9] Anderson T.N., Duke M., Morrison G.L. and Carson J.K., 2009. Performance of a building integrated photovoltaic/thermal (bipvt) solar collector. *Solar Energy* 83: 445-455.

[10] De Vries D.W., 1998. *Design of a photovoltaic/thermal combi-panel*. PhD thesis, Eindhoven University, The Netherlands.

[11] Weerakoon A.N., 2008. *Use of corrugated panels as transpired solar collectors.* Unpublished PhD Thesis, University of Auckland, New Zealand.

[12] Krauter S.C.W., 2006. *Solar electric power generation: Photovoltaic energy systems.* Springer-Verlag, Heidelberg.

[13] Anderson T.N. and M. Duke. 2007. Analysis of a photovoltaic/thermal solar collector for building integration. In *Proceedings of SB07: New Zealand Sustainable Building Conference*, 14-16 November, Auckland, New Zealand. Pages 1-11.

[14] Vokas G., Christandonis N., and Skittides F., 2006. Hybrid photovoltaic-thermal systems for domestic heating and cooling-A theoretical approach. *Solar Energy* 80(5): 607-615.

[15] Duffie J.A. and W.A. Beckman. 2006. Solar engineering of thermal processes. Wiley, New York,

[16] Wei H., Chow T.-T., Ji J., Lu J., Pei G. and Chan, L.-S., 2006. Hybrid photovoltaic and thermal solar-collector designed for natural circulation of water. *Applied Energy* 83(3):199-210.

[17] Calise F., d'Accadia M.D., and Vanoli L., 2012. design and dynamic simulation of a novel solar trigeneration system based on hybrid photovoltaic/thermal collectors (PVT). *Energy Conversion and Management* 60: 214–225.