Experimental Investigation of a Solar Baking System Using Parabolic Trough Solar Collector

H. H. El-Ghetany
Solar Energy Department, National Research Centre, Dokki, 12622, Giza, Egypt

S. A. Hassan
Solar Energy Department, National Research Centre, Dokki, 12622, Giza, Egypt

M. Z. Metias
Solar Energy Department, National Research Centre, Dokki, 12622, Giza, Egypt

Abstract – The aim of this work is to develop an innovative solar baking system using parabolic trough solar collector. An experimental investigation under various weather conditions is conducted. The experimental pilot unit was installed in Solar Energy Department, National Research Centre, Giza, Egypt. Several test runs are performed to measure all assigned parameters that affect the system performance are conducted. The system is designed to provide thermal energy in the volume enclosure of the baking area that located in the line focus parabolic trough solar collector. The results showed good performance of the solar baker to bake breads and cakes. The tested system can positively contribute in baking purposes in rural and isolated communities where the required ordinary fossil fuel is not available. It is found that to reach the desired moisture content for baking process (35%-40%), it is needed amount of solar radiation dose ranged from 3.7 – 4.0 kWh/m^2. it is noted that in autumn and winter seasons the solar radiation dose and the ambient temperature are relatively low if they are comparing with the corresponding values in spring and summer seasons. The lower solar radiation decreasing the solar energy input to the system while lower ambient temperature increasing the overall heat losses and consequently increasing the baking time to reach the desired moisture content.

Index Terms – Parabolic Trough Collector, Solar Radiation Dose, Moisture Content, Performance Evaluation.

1. INTRODUCTION

The present study aims to find a solution of the thermal energy shortage for cooking and baking in the rural areas and poor communities. The conventional source of thermal energy in that areas is the burning of wood or using the available fossil fuel which will cause two major environmental problems. The first one is deforestation or desertification of the land by cutting the trees to be used as fuel. The second one is the global warming and climatic change problem that resulting from the excess greenhouse gases in the atmosphere as a result from the exhaust gases contaminants of the fossil fuel. Solar energy is the unique solution to overcome the previously mentioned problems. It is a clean source of energy, abundant, available with a significant values of solar radiation dose with a yearly average value of 5.5 kWh/m^2/day. Even the hot box solar cooker is a simple technology to be used for cooking process, it cannot be used for baking process due to it relatively low thermal energy stored in its air enclosure. Therefore, looking for solar energy equipment that provide high thermal energy needed for baking is the optimal solution. Solar bakeries utilize the ultimate renewable resource, sunshine, to cost-effectively provide a needed food. Sun Bakeries, experiences and research will be leading to large projects somewhat on a level that benefits the country as another source of energy [1]. Large scale concentrating solar systems can convert solar thermal energy into electrical power [2]. The concentrated solar energy collectors can provide high concentrated thermal energy that capable to be used for baking process. There are four main types of solar energy concentrating technologies namely; Point focusing solar parabolic dish, Line focusing solar parabolic trough, Central tower receiver, and Fresnel lenses collectors. In this study, the line focusing solar parabolic trough collector (PTC) is used to provide the required thermal energy for baking process as it is considered the most widespread technology. PTCs focus direct solar radiation onto a focal line on the collector axis where a rectangle baking receiving plate is installed; the receiving plate absorbs the concentrated solar energy and the bread placed on the plate is baked. PTC applications can be divided into two main groups: concentrated Solar Power (CSP) plants and applications that require temperatures between 80 and 250^{o}C. The thermal energy stored inside the PTC from the absorber plate and the hot air in the PTC enclosure is utilized for baking process. The present work experimentally verify the behavior of the possibility of using the Parabolic Trough as a Bakery (PTB). Designing the PTB for a specific working condition requires determination of several parameters. According to the daily required load energy and the meteorological data collected, the solar bakery system can be designed. The parameters include geometric design parameters, heat losses coefficient, pressure and temperature inside and outside the PTC and efficiencies. Solar baker is extended with a mirror in one side of the north–south axis to increase the concentration of the sun's rays on the baking plate linear receiver all time. The PTB is designed to investigate the thermal performance and experimentally verify the baking process under the actual meterological conditions of ambient temperature, wind speed and solar radiation. All these paramerters are measured in addition to the temperatures inside the enclosure and the receing absorber plate surface.

2. EXPERIMENTAL SETUP

The PTC is designed to install small prototype as a demonestration prototype to perform the test procedures. The layout of the PTB is illustated in Fig. 1. The apreature area is about 1 m^2 provided with a support of 0.90 m height with a plane reflector with 1 m^2 area to enhance the incident solar radiation inside the PTB. As per the prescribed design, the PTB components are manufactured, assymbeled, and field tested under the metrological conditions of Cairo, Egypt. The final shape of the prototype is shown in Fig. 2. The reflected surafce is made from curved glass mirriors that illustrate the parabolic shape.

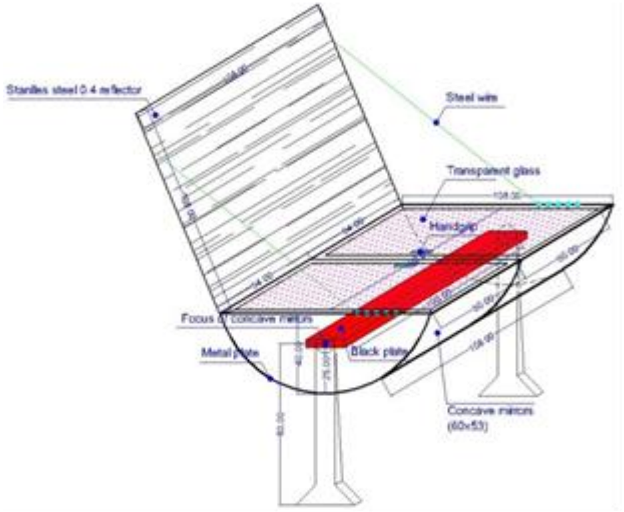

Fig. 1 A layout of parabolic trough solar bakery (PTB)

Fig: 2 Parabolic trough solar bakery (PTB)

A well-sealed glass window is fixied on the aperature area by such a way to allow opening and closing process for entering the bread dough and handling the baked bread. It is sealed with silicone rubber to reduce the convective heat loss from the receiver, and hence reducing the heat loss coefficient. The surface of the receiving plate is painted with a selective coating that has a high absorptance for solar radiation but a low emittance for thermal radiation loss. The plan reflector made from stainless steel is fixed to surface of the PTB to enhance the falling solar radiation on the PTB. The metallic iron frame is designed and manufacture to make the system manually adjusted to facing source with appropriate tilt angle to ensure the perpendicularity of the solar ray to fall on the PTB surface. Eight thermocouples are fixed inside the PTB system. Four of them to measure the air temperature inside the enclosure between the curved parabolic surface and the flat glass sheet window on the aperture area. While another four thermocouples are fixed on the absorber receiving plate surface. The ambient temperature is measured as well as the solar radiation falling on the system is measured though out the experiments.

3. RESULTS AND DISCUSSIONS

Several runs are made to investigate the thermal performance of the system. The temperature distribution of the air enclosure and hence the average air temperature inside the PTB is measured during summer and winter. By the same manner, the temperature distribution of the absorber receiving plate surface is measured and the average absorber plate temperature is estimated. The weight of the bread dough is recorded on periodical basis until reaching the final stage of the baked bread, then the moisture content variation is estimated through out the experiment. The solar radiation variation is recorded throutout the experiment and the solar radiation dose is calculated. Finally the moisture content variation (%) is expressed as a function of the solar radiation dose (kWh/m^2). The daily extraterrestrial radiation on a horizontal surface (Ho), at a day of year, n, can be calculated using following equation [3].

$$Ho = \frac{24 \times 3600\, Gsc}{\pi}\left(1 + 0.033\cos\left(2\pi\frac{n}{365}\right)\right)\left(\cos\Phi\,\cos\delta\,\sin\omega_s + \omega_s\,\sin\Phi\,\sin\delta\right) \quad (1)$$

The extraterrestrial radiation on a horizontal surface for an hour period can be estimated by integrating equation (1) for a period between hour angles ω1 and ω2 which define an hour (where ω2 is the larger) [3],

$$I_0 = \frac{12 \times 3600\, Gsc}{\pi}\left(1 + 0.033\cos\left(2\pi\frac{n}{365}\right)\right)\left(\cos\Phi\,\cos\delta\,\sin(\omega_2 - \omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180}\sin\Phi\,\sin\delta\right) \quad (2)$$

The thermal efficiency of a PTC can be defined as the ratio of heat gained by the collector, q_u, to the total incident radiation, $I_{irradiance}$, that is incident on the aperture of the collector [4]

$$\eta_{th} = \frac{q_u}{A_a \; I_{irradiance}} \tag{3}$$

Where the useful heat gained, q_u, represent the amount of thermal energy stored in the absorber receiving plate and can be expressed as follow:

$$q_u = mc_p \; \frac{dT_{RP}}{d\tau} \tag{4}$$

The useful heat collected by the receiver can also be expressed in terms of optical efficiency, heat loss coefficient, heat removal factor, and receiver plate temperature [5]

$$q_u = F_R A_a \left[S - \frac{A_r}{A_a} U_L \left(T_p - T_a\right)\right] \tag{5}$$

The thermal efficiency can be rewritten using equations (4) and (5):

$$\eta_{th} = F_R \left[\frac{S}{I_b} - U_L \left(\frac{(T_p - T_a)}{I_b C}\right)\right] \tag{6}$$

The annual monthly average values of daily solar energy incident on horizontal surface is shown in Fig. 3.

Table 1 The items and it's specification for the bakery.

Item	Specification
Aperture with (W)	1 m
Aperture length (L)	1 m
Aperture area	1 m^2
Focal length (f)	0.257 m
Rim angle	90^o
Reflectivity ( )	0.95
Intercept factor (γ`)	0.90
Receiver material	Stainless steel iron sheet
Absorptivity ($\alpha_r\alpha_E$)	0.90
Emissivity (E_r)	0.20
Length	1 m

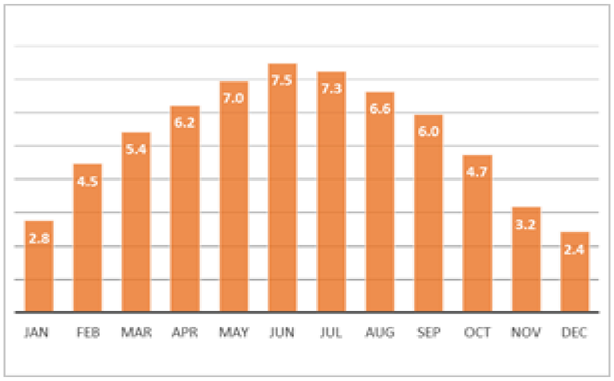

Fig. 3 The monthly average values of daily solar energy incident on horizontal surface

It is clear from the figure that solar energy provides good potentials for utilization in thermal applications throughout the year. Several experiments have been run to evaluate the thermal performance of the solar PTB system. The temperatures inside and outside the solar baker are recorded and the solar radiation falling on the PTB surface is measured throughout the experiments. A sample of the experiments is shown in Fig. 4.

Fig. 4 A photographic view of the baked bread inside the PTB

The eight thermocouples are distributed inside the PTB to measure the temperature of the air enclosure and the receiving absorber plate as shown in Fig. 5.

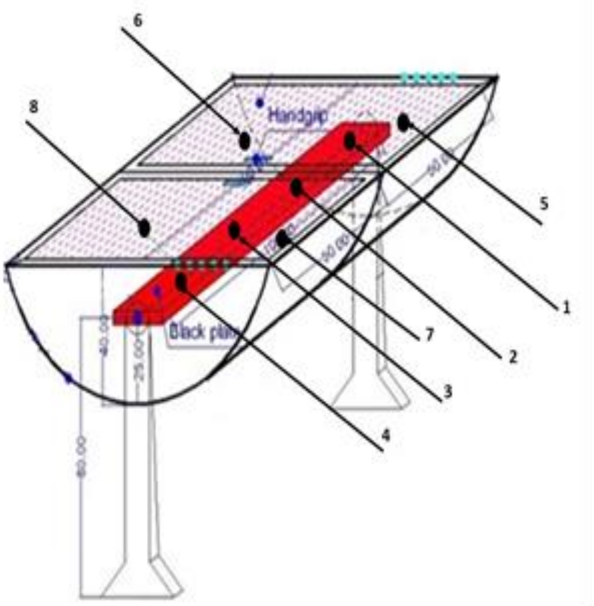

Fig. 5 Distributed Thermocouples inside Baking Chamber

Two test runs are illustrated in this work; one in winter season and the other is on summer season. The temperature variations of the receiving absorber plate and the air enclosure in winter are shown in Fig. 6.

Figure 7 shows the receiving absorber plate temperature distribution while Fig. 8 illustrates the air enclose temperature distributions presented in Fig. 6.

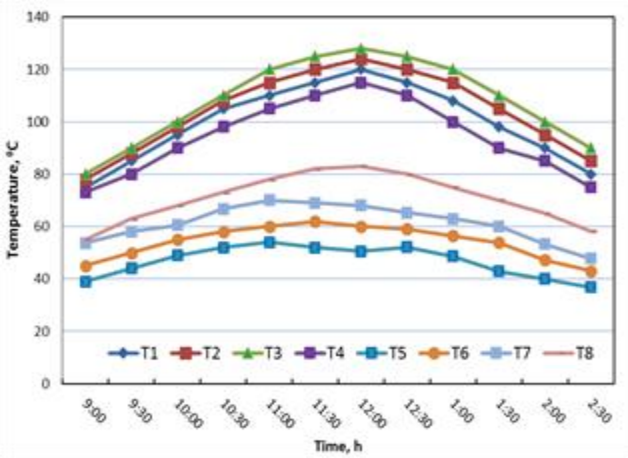

Fig. 6 Variations Temperature of plate and in closed air inside bakery in winter season

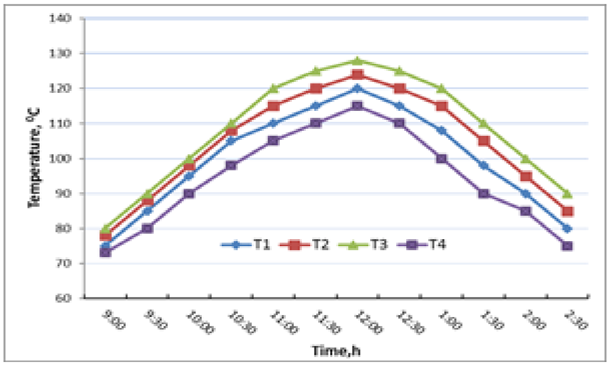

Fig. 7 Variation Temperatures of receiving absorber plate inside bakery in winter season

The same experiments are done in summer season and figures 9-11 represents The temperature variations of the receiving absorber plate and the air enclosure, the receiving absorber plate temperature distribution, and the air enclose temperature distributions respectively

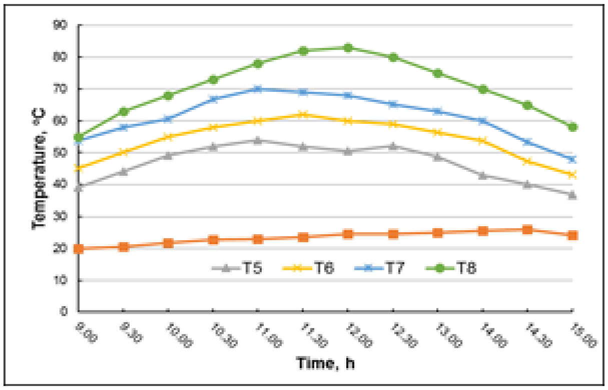

Fig. 8 Variation Temperatures of the air enclose inside and outside PTB in winter season

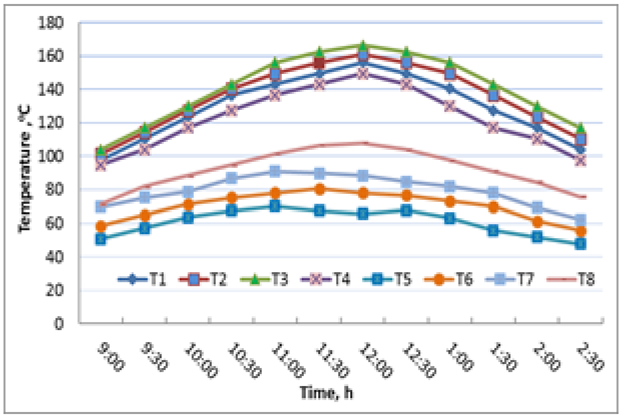

Fig. 9 Temperature variation of the air enclosure and plate inside bakery in summer season

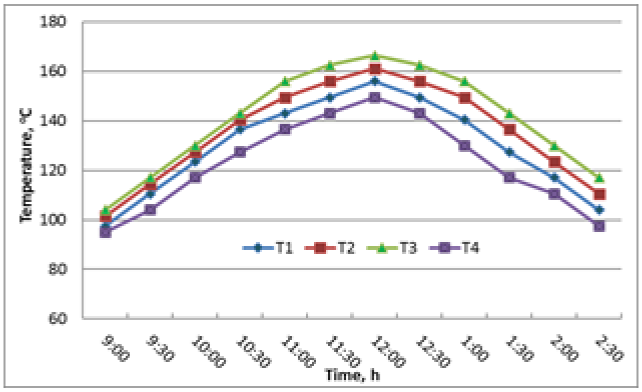

Fig. 10 Temperature variation of the plate inside bakery in summer season

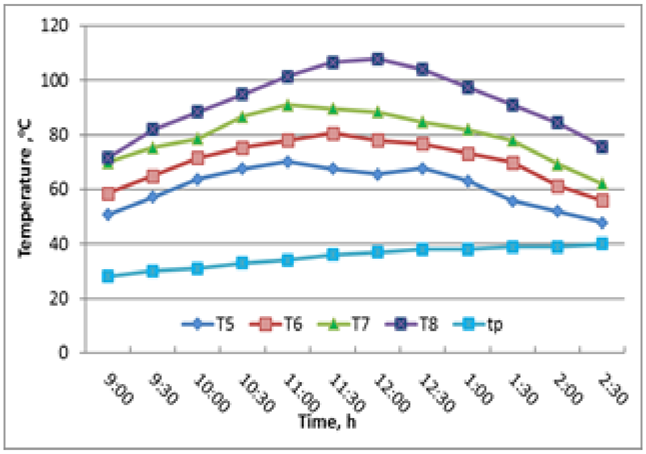

Fig. 11 Temperature variation of the air enclosure inside TPB in summer season

The average ambient temperature variation, average receiving absorber plate variation, and average air enclosure variation for summer and winter seasons is illustrated in Fig. 12.

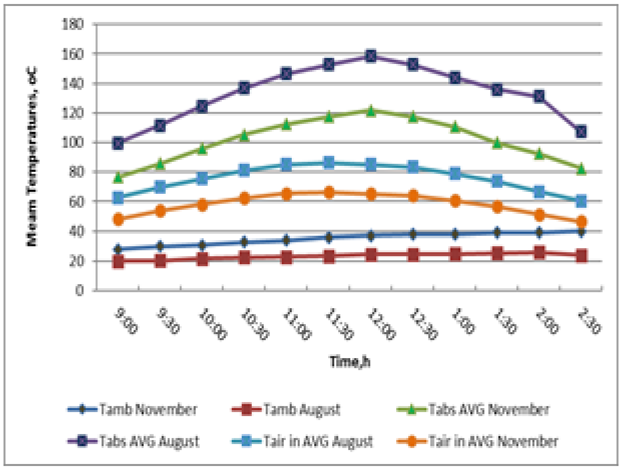

Fig. 12 Average temperatures variations of the air enclosure, ambient and absorber receiving plate in winter and summer

To check the validity of the system to perform baking process, the weight of the bread dough is recorded on periodical basis until reaching its final stage of the baked bread, then the moisture content variation is estimated through out the experiment. The solar radiation variation is recorded throtout the experiment and the solar radiation dose is calculated. Finally the moisture content variation (%) is expressed as a function of the solar radiation dose (kWh/m^2) as shown in Fig. 13.

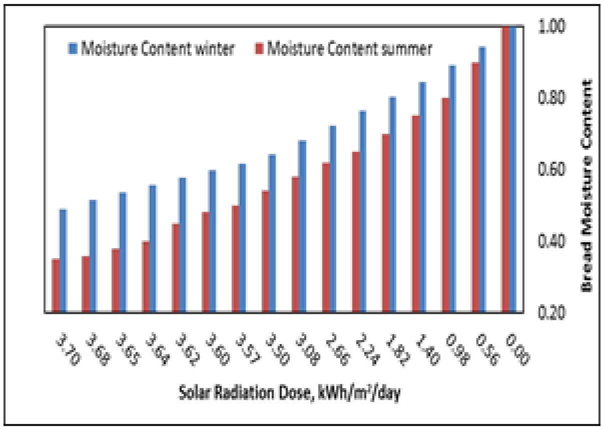

Fig. 13 Moisture content variation (%) as a function of the solar radiation dose (kWh/m2)

4. CONCLUSIONS

The innovative solar baking system using parabolic trough solar collector showed good significant values for performing baking process using only solar fuel. Such kind of technology solves a lot of problems in rural and insulated communities as the presented system can be used as solar baker and solar cooker as well. Through several test runs, it is found that the system is affected by the amount of incident solar radiation dose and ambient temperature throughout the experiment. It is found that to reach the desired moisture content for baking process (35%-40%), it is needed amount of solar radiation dose ranged from 3.7 – 4.0 kWh/m^2. it is noted that in autumn and winter seasons the solar radiation dose and the ambient temperature are relatively low if they are comparing with the corresponding values in spring and summer seasons. The lower solar radiation decreasing the solar energy input to the system while lower ambient temperature increasing the overall heat losses and consequently increasing the baking time to reach the desired moisture content.

REFERENCES

[1] Christoph Müller, Fundación EcoAndina" Solar community bakeries on the Argentinean Altiplano" International Solar Food Processing Conference 2009.
[2] SouravKhanna, Suneet Singh, Shireesh B. Kedare "Effect of angle of incidence of sun rays on the bending of absorber tube of solar parabolic trough concentrator" India Energy Procedia 48 (2014) 123 – 129
[3] Duffie, J.A. and Beckman, W.A., Solar Engineering of Thermal Processes, 2nd Edition, John Wiley & Sons, 1991.
[4] Winter, Francis de. Solar collectors, Energy storage, and Materials. USA: The MIT press, 1991
[5] Garg, H P and J Prakash. Solar energy, fundamentals and application. New Delhi: Tata McGraw-Hill, 2006

Author

Dr. Hamdy has an extensive experience in the field of mechanical engineering for 32 years either academically or professionally. Professionally, he is an electromechanical designer and reviewer for the pipe lines, storage tanks, heat exchanger, water treatment and solar energy systems of several projects. Academically, he is recognized both internationally and nationally in the area of solar energy applications. He is the author of more than 40 scientific research articles published in leading international journals and international and national conferences.