International Journal of Engineering Trends and Technology Volume 69 Issue 11, 149-155, November, 2021
ISSN: 2231 – 5381 /doi:10.14445/22315381/IJETT-V69I11P219

Semi-Spherical Solar Oven with Automated Programmed Single Axis Sun Following System

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Abstract *- In this work, a semi-spherical solar oven with auto programmed single-axis sun following system is laid out, built and operated to keep the solar rays vertical to the face of the semi-spherical oven. This system uses the programming open loop method of control. Reflecting mirrors were used to concentrate the sunlight into the focal point in the pot for cooking food.*
The system has experimented under Jordanian climatic conditions. The experimentation results in typical spring days from 9:30 AM to 2:30 PM show that this system can raise the inside temperature of the pot with a water volume of 2.5 litres from 26 C⁰ to 97 C⁰ during 30 minutes. This type of solar oven was used for the preparation of different meals as well as heating water.

Keywords - *semi-spherical solar oven, single-axis sun following system, programming control*

I. INTRODUCTION

A solar cooker uses the thermal effect of sunlight to cook food. Solar cooker prepares meals in an environmentally friendly manner. One of the most significant solar cookers is a Semi-Spherical Solar Cooker (SSC). Such types of cookers can cook quickly and reach higher cooking temperatures than other types of solar cookers, but the amount of food that can be cooked at one time is less due to the size of the cooking pan. The Second drawback of SSC is the complexity in mechanical design and manufacturing. The third disadvantage is that people are close to a strong concentrated solar radiation when using SSC, which may cause burns in the skin and eyes. The fourth and most important drawback of an SSC is a frequent manual adjustment to keep solar radiation perpendicular to the surface. Besides its exergy and energy assessment, a foldable dual reflector paraboloid solar cooker was studied experimentally using water and vegetable oil [1]. It was concluded that it is good for all sorts of cooking. The parabolical dish solar oven's heat loss was discussed. A numerical approach was utilized to propose a new parameter called the cooking pot performance index. To get the input parameter, various experiments were done [2].

An approach for evaluating the performance and design of a solar cooker was proposed [3]. This approach is performed by: (1) valuation of local context, (2) analyses of thermodynamic performance, and (3) design and construction. Nine widely used cooking energy choices were assessed based on thirty criterions [4, 5]. The most preferred alternatives were liquefied petroleum gas stove, that, kerosene oven, Solar over with box type, and solar oven with parabolical shape.

Seven brands of solar ovens were tested [6]. 66 families were involved in this study. The most utilized cookers were solar, wood stoves, and open fires. The percentage of using a solar oven for all days was 38%, and for cooking meals was 35%. 38% fuel saving was found. Cylindric basin form of Parabolic Solar Cooker (PSC) was studied from an exergy viewpoint [7]. Heat transfer among three surfaces was modeled mathematically: i) the system imagined surface, ii) reflector, and iii) cooking pot. In agreement with experimental data, a relatively very low exergy efficiency was found. A low-priced PSC was designed, manufactured, and tested [8].

The exergy and energy efficiencies were in the range of 2.8 – 15.7 and 0.4 – 1.25, respectively. A sample to calculate the cooking power of a solar oven was proposed [9]. Three controlled and three uncontrolled variables were used in this model. The uncontrolled variables were solar insulation, load distribution, and temperature difference. Controlled parameters were solar intercept area, plate thermal conductivity, and heat loss coefficient. The model was based on the energy balance equation. This model can find the solar cookers cooking capacity. It could be employed to estimate the collection of intercept area needed to cook a particular quantity of feed in each environment and heat loss coefficient. The model was validated for the box and concentrating types. From the exergy point of view, the cylindric basin form of the Spherical parabolical cooker (SPC) was tested for the first time in [10]. Heat transfer equations were derived based on reflector, cooking pot, and imagined surface. It was discovered that SPC exergy effectiveness was too small (~1%), 10 times less than the particular energy effectiveness compatible with the experiential datum.

Solar salt was used as a heat storage media for solar cooking [11]. This solar salt was a eutectic mixture that stored and released heat during phase change. 110 minutes were necessary to melt this salt at 220 C⁰. 17 minutes were needed to fry 0.25 kg of potato chips at 170-180 C⁰ from one heat charge. Two successive batches of 20 minutes each were used for cooking 0.6 kg of rice. These batches were performed from one charge. In [12], two axes sun-seeking system of the parabolical solar oven was patterned, manufactured, and used. Results of experimentation displayed that the temperature of water in the cooking tube reached 90 C⁰ in normal summertime, while 36 C⁰ was the extreme temperature of the surrounding. Abu-Malouh et al. [13] studied the impact of two axes sun following system on the performance of spherical solar cooker. Experimental outcomes presented that the temperature in the cooking pot arrived at 93 C^o when the utmost surrounding temperature reached 32 C^o. Abdallah and Nijmeh [14] designed, constructed, and operated a single-axis sun following system. The system used was an open loop with the programming control. To cog the movement of the sun-tracking surface, the PLC system was utilized. The gathered energy measured was correlated with a constant surface tilted 32º to the south. Turning around the vertical axis, north-south axis, and east-west axis were the sun following techniques studied. The outcomes pointed out that the solar energy gathered on the movable was over and above the constant one. There were rises of 24.5%, 23.3%, and 19.7% for the tracking as mentioned above systems, respectively, compared with the 32º inclined surface to the south.

Abdallah and Nijmeh [15] designed, constructed, and operated two axes of the sun following the system. They performed empirical research to inspect the influence of two axes tracking on solar energy production. The outcomes of experimentation showed that the surface with two axes tracking increased the energy collection up to 42.34 % by comparison with the immobile surface. The behavior of active sustainable solar still was studied combined with a PV system and flat-surface solar collector. Two axes sun-seeking system was sketched and constructed for the solar collector to follow the sun's location. The system was checked in (Malaysia, Sarawak) in different weather conditions [16]. Mailani et al. [17] drafted, fabricated, and experimented with an innovative solar still that utilized concentration to raise the received heat energy. Therefore, an adjusted traditional solar basin was still coupled with a Parabolical Trough Concentrator (PTC) and attached to an iron structure. This new structure permitted the solar distiller to alter its direction and follow the sun's disc from the sun up to sundown. The productivity of the suggested solar still was 3.76 l/day. A compound parabolical concentrator-assisted tubular solar production increased, whereas the investment cost decreased by 7%.

A low-priced two axes solar following system was designed and implemented in [18]. It was a closed-loop system. The inputs used were Light Dependent Resistor (LDR) sensors. A digital logic design of the sensors' participation was applied in a pseudo-azimuthal system to twirl the east-west and north-south axes. In the experimental procedure, both the suggested system and the constant flat surface system were tested. The results showed that the suggested system raised the electric energy production by nearly 44.89%, compared to the other one. Two smart single and two axes solar seeking systems founded on Adaptive Neural Fuzzy Inference System (ANFIS) were proposed in [19]. The research confirmed that ANFIS could be employed to layout and carry out the following solar systems. ANFIS was utilized to predict the best slope and direction angles effectively. The simulation outcomes obtained minimum error and a high prediction amount. Applying five membership functions gained the best effectiveness likewise. The conclusion uncovered that ANFIS could do better in driving solar photovoltaic systems to follow the sun's path against both neural networks principles and fuzzy. The most important drawback of SSC is standing under the sun and manually adjusting slope angle and surface azimuth angle. This problem can be solved by utilizing an automatic sun tracking system. In this work, a programmed PLC automatic single-axis sun tracking system is patterned, constructed, and operated to keep the solar radiation perpendicular to the face of SSC. This system keeps the surface of SSC perpendicular to solar radiation and captures the maximum possible heat from the sun's disc.

II. MECHANICAL DESIGN AND CONSTRUCTION

To capture the maximum possible heat power from the sun, the face of SSC has to be continuously regulated so that it is pointed exactly at the sun's disc. For this purpose, it is necessary to use one type of sun following system. Single-axis following systems are simple in mechanical design and construction, easy operation and maintenance, and cheaper. On the other hand, the effectiveness of these systems is less than the two axes tracking systems.

The proposed SSC's mechanical design, with its real dimensions, is shown in Fig (1). This system consists of an oven flat at the focus of a semi-spherical dish made of steel held to the dish by two holding arms. At the top of the oven flat, the cooking pot is replaced. For the dish, the diameter and the depths are 1.5 m and 0.3 m, respectively. The focal distance is 0.47 m.

The inner side of the semi-spherical dish contains small mirrors with the dimensions of (10 x 10) cm each- adhered to using silicon glue. Mirrors reflect and focus the incident solar radiation into the pot. The semi-spherical dish is attached to a vertical shaft by a flexible joint, and the dish can rotate around the horizontal axis manually, making a slope angle. The selected value of the slope angle is 65º. The vertical shaft is welded to a mechanical base with four supporting bearings so that it can hold the heavy load of the semi-spherical dish, which in turn sits on a table. On the other hand, an electric motor rotates the vertical shaft along with the table according to the orders of the control system.

The proposed mechanical design uses the following principles: 1) reflecting and concentrating sunlight on a cooking pot. 2) transforming solar radiation to heat by using a blackened cooking pot. 3) tracking the disc of the sun by rotation around the vertical axis.

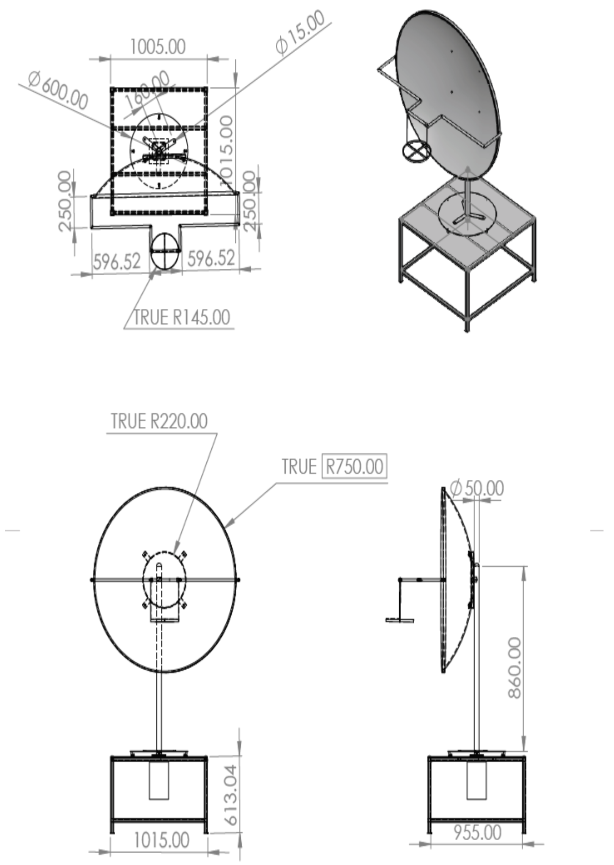

Fig (1). Different views for proposed SSC

The mechanical design of SSC with single axis following system was constructed conforming to the proposed layout in the work-shop of Applied Science Private University in Amman-Jordan. Fig (2) shows the system after manufacturing. This mechanical structure has two flexible joints, one of them is driven by AC motor for following the sun about the perpendicular axis, and the other one is for tracking the altitude of the sun by manual rotation around the horizontal axis.

Fig (2). Front view of SSC after manufacturing and without reflecting mirrors

III. ELECTRIC DRIVE SYSTEM

The electric drive system of the proposed single axis sun following system is based on one driving motor M as shown in Fig (3), which operates the joint rotating the oven around the vertical axis. The motor M tracks the solar azimuth angle γs. Relay R1 is used to operate this motor in forward direction to track the solar azimuth angle by rotation around vertical axis during daylight time, and relay R2 is used to reverse the motion of this motor to the starting point to meet the starting position of the coming day. This electromechanically designed system consists of two bridge rectifiers, PS1 and PS2, that convert 220 VAC into 24 VDC. PS1 powers motor M and PS2 powers the PLC system.

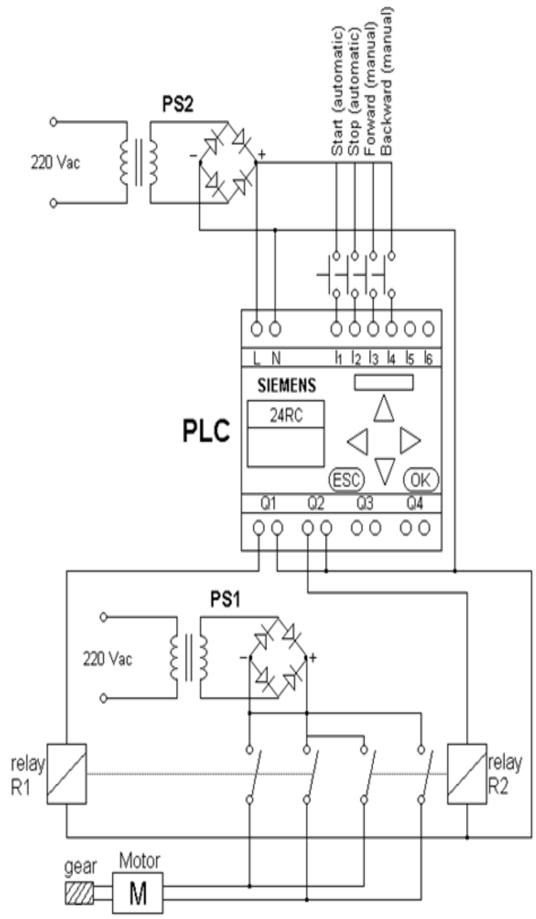

Fig (3). The electric drive of one axis sun following system

IV. CONTROL SYSTEM AND SOFTWARE COMPONENTS

PLC controller (LOGO-24 RC) controls the work of the motor; therefore, it will follow the location of the disc of the sun. In this work, an open-loop programmed method of the control function of the time is utilized. This method uses the function of the solar angle of time for the Amman capital of Jordan. In the case of tracking around the vertical axis, to keep the face of the semi-spherical concentrator perpendicular to the solar radiation all the time, the following equation must be applied:

$$\gamma = \gamma s \qquad (1)$$

Where γ is surface azimuth angle, and γs is solar azimuth angle.
According to Duffie and Beckman [20] δ is the declination angle can be found by using the following equation:

$$\delta = 23.45 \sin (360\, ((284+n)/365)) \qquad (2)$$

Where n is the number of the day in the year.

$$\cos \omega ew = \tan\delta / \tan\phi \qquad (3)$$

Where ωew is the east-west hour angle, and ϕ is the latitude angle. For Amman, $\phi = 32^o$.

$$\gamma s = C1C2\, \gamma's + \{C3(1-C1C2)/2\}*180 \qquad (4)$$

Where:

$$\tan \gamma's = \sin\omega /(\sin\delta \cos\omega - \cos\phi \tan\delta) \qquad (5)$$

Where ω is the hour angle.

$$C1 = \{1 \text{ if } |\omega| \leqslant \omega ew, \; -1 \text{ if } |\omega| > \omega ew\} \qquad (6)$$

$$C2 = \{1 \text{ if } (\phi - \delta) \geqslant 0, \; -1 \text{ if } (\phi - \delta) < 0\} \qquad (7)$$

$$C3 = \{1 \text{ if } \omega \geqslant 0, -1 \text{ if } \omega < 0\} \qquad (8)$$

The calculated values of time's surface azimuth angle function ought to be included as a functional block diagram program into the PLC microcontroller. The PLC program controls the work of the motor so that it will follow the location of the sun. This tracking system operates in all-weather situations regardless of heavy cloudy or dusty.
The daylight time is divided into four equal time intervals. Time intervals T1 and T2 before solar noon, and T3 and T4 after solar noon. Motor speeds were determined experimentally for each interval of time in (degrees per second). PLC program was made based on calculated solar angles according to Amman and motor speeds according to different time intervals.
The PLC control program of the machine following the sun around the perpendicular axis is shown below. The control program is divided into two subprograms, according to the two kinds of motion in the forward direction as shown in Fig (4) and backward direction as shown in Fig (5). From previously calculated surface azimuth angles, it is shown that the motion in the forward direction will cover four periods of time T4, T3, T2, and T1. The programmed blocks B16, B14, B11, and B07 are clocks according to the above periods. The clocks operate the recyclers B17, B12, B09, and 05, which are on-off timers. The programmed block B19 runs the vertical sun following backward motor direction after sun downtime to meet the start of a new day.

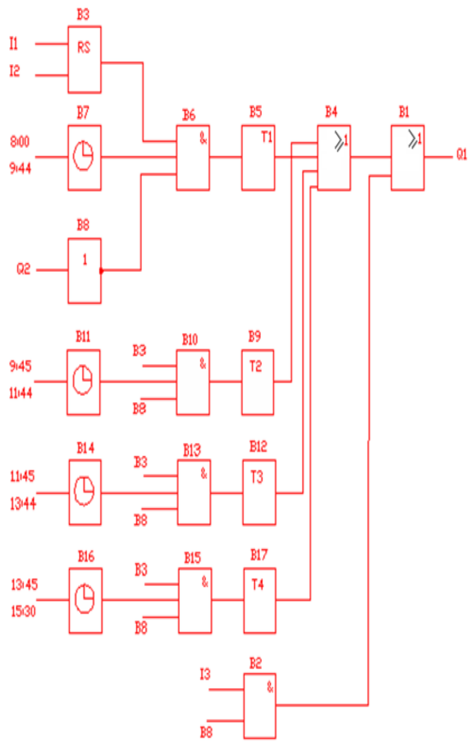

Fig (4). PLC control program to rotate the joint in forward direction

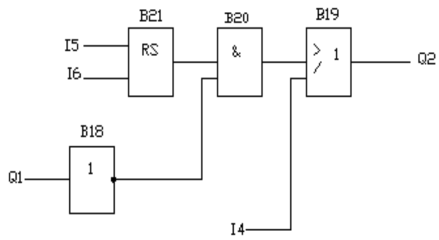

Fig (5). PLC control program to rotate the joint in the backward direction

V. EXPERIMENTATION AND RESULTS

Experimental data are conducted and recorded for one axis sun tracking system from 9:30 AM to 2:30 PM in the energy laboratory at Applied Science Private University for 5 days in May 2021. Fig (6) shows the manufactured, mirror-built, programmed automatic single-axis sun-tracking setup system. On 16th May, data for heating water is illustrated below for one day, noting that water was changed every 30 minutes. Fig (7) shows the temperature of the water inside the pot C^o vs. time. Fig (8) shows the pot outside temperature vs. time. Fig (9) shows the solar radiation vs. time. Finally, Fig (10) shows the atmospheric ambient temperature vs. time. During the other four days, experimental data were recorded in Table 1 for different types of food such as carrot, egg, potato, onion, fish, rice, meat, and chicken. The duration time in hours, maximum pot inner temperature, maximum pot outside temperature, and maximum ambient temperature are recorded for each type of food.

Fig (6). Semi-Spherical solar oven with auto single-axis sun following system

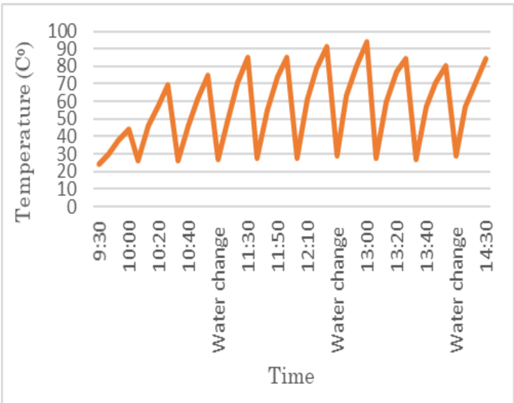

Fig (7). The temperature of the water inside the pot

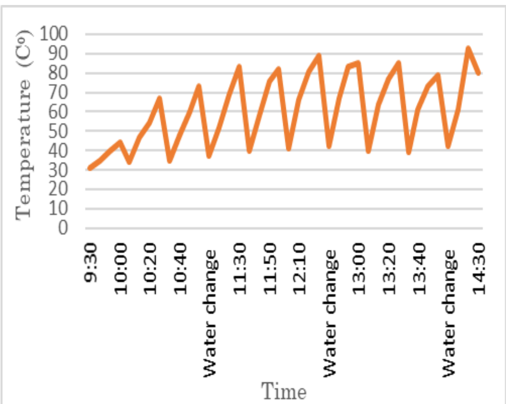

Fig (8). Pot outside temperature

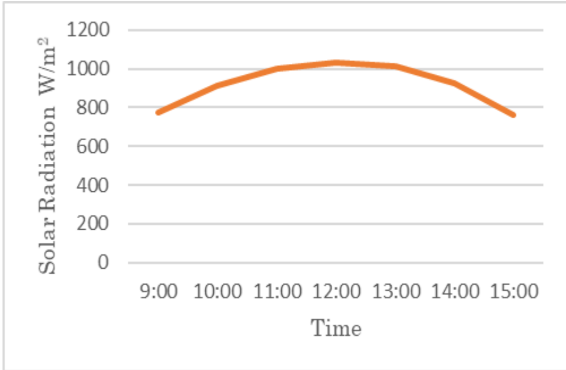

Fig (9). Solar radiation

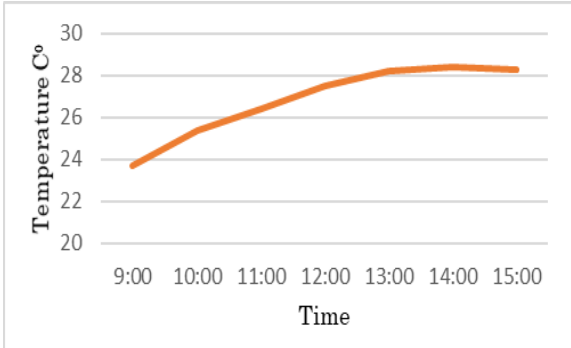

Fig (10). Atmospheric ambient temperature

TABLE 1
RESULTS OF DIFFERENT TYPES OF FOOD COOKED

Food	Start time	Finish time	Period (hr)	Max Temperature(C°) Inside pot	Max Temperature(C°) outside pot
Day 1 2/5/2021 Max Ambient Temperature 28.9 (C°)					
Carrots1	9:35	10:55	1:20	88	86
Carrots2	11:20	12:35	1:15	88	79
Eggs	1:20	1:40	0:20	91	86
Day 2 3/5/2021 Max ambient Temperature 29.1 (C°)					
Potato	9:30	11:10	1:40	97	93
Onion	11:20	12:25	1:05	93	92
Garlic	12:35	1:15	0:40	92	89
Day 3 4/5/2021 Max ambient Temperature 30.1 (C°)					
Chicken	9:30	11:00	1:30	96	94
Meat	11:20	1:00	1:40	97	95
Eggs	1:20	1:37	0:17	93	92
Day 4 10/5/2021 Max ambient Temperature 35.7 (C°)					
Rice1	9:30	11:00	1:30	82	78
Fish1	11:30	12:20	0:50	94	91
Fish2	12:40	1:25	0:45	92	83
Rice2	1:30	2:35	1:05	79	74

The following figures show the different types of food cooked:

Fig (11). Different types of food cooked

After analysis of data recorded and graphed, the semi-spherical solar oven with automatic, programmed single-axis sun following system prototype is capable of heating water and cooking different types of food quickly enough time. The temperature inside the pot can be regulated and decreased in different ways, such as the partial coverage of mirrors or the change of the system's direction towards the sun's disc.

The highest temperatures inside pot water reached around the solar noon when the highest solar intensity values. The experimentation results in a typical spring day from 9:30 AM to 2:30 PM showed that this system can raise the inside temperature of the pot with a water volume of 2.5 liters from 26 Cº to 97 Cº during 30 minutes. This result showed that water temperature inside the pot could still attain further bigger values on summer days.

Many reasons could reduce the productivity of solar ovens, such as ambient temperature, wind speed, cloudy and dusty conditions, time of the day, day of the year, type of tracking system, and type of reflective material. The reflective material which used in this work was reflecting mirrors. The reflectivity of used glass mirrors is about 50%, which is not efficient compared to some special types of reflective materials. The efficiency of reflective foil, specially designed for solar energy purposes, can attain 94% [21] and [22]. Sun following system with open-loop control is more effective in dusty and cloudy conditions, but sun following system with the closed-loop system is more productive in clear sky conditions.

The type of solar ovens suggested in this work was used successfully to prepare different meals and heat water. This is in favor of utilizing this type of solar cookers in countries characterized by high solar radiation and high ambient temperatures.

V. CONCLUSIONS

The current study introduced the draft, manufacture, and experimentation of a semi-spherical solar oven with the programmed single-axis sun following system to solve the issue of the manual following and standing under the sun, which is the major drawback of most manual tracking concentrating solar ovens.

A semi-spherical solar oven with an auto single-axis sun following system has been experimented with under Jordanian climatic conditions. The experimentation results in a typical spring day from 9:30 AM to 2:30 PM show that this system can raise the inside temperature of the pot with a water volume of 2.5 liters from 26 Cº to 97 Cº during 30 minutes.

The proposed semi-spherical solar oven has an easy electric drive system setup that lowers the maintenance price and the chance of failure and can cook various kinds of food.

ACKNOWLEDGMENT

The authors are thankful to the Applied Science Private University, Amman, Jordan, for this research work's complete monetary support.

FUNDING

Applied Science Private University supports this research, Jordan, to cover costs of materials, equipment, and construction of the ergonomic-automated lectern prototype in the university's workshops.

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