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Cylindrical Solar Cooker with Automatic Two Axes Sun Tracking System

Essam Abdallah [a], Mohammed Al_Soud [b], Ali Akayleh [b], and Salah Abdallah [c]

[a] *Department of Mechanical Engineering, Al – Balqa Applied University, Jordan,*

[b] *Department of Electrical Engineering, Tafila Technical University, Jordan*

[c] *Department of Mechanical and Industrial Engineering, Applied Science University, Jordan*

Abstract

All concentrating solar cookers were found to provide adequate temperature needed for cooking. But the common problem of these systems is the need for frequent tracking, and standing in the sun while cooking. This problem could be tackled if one goes in for automatic sun tracking. In this work a cylindrical solar cooker with two axes sun tracking system was designed, constructed and operated. Mechanical system; which consists of two parts, one for altitude tracking and another for rotating around vertical axes was designed and constructed.The hardware and software components of the two axis sun tracking system were designed. The programming method of control with open loop system was employed. The programmable logic controller (PLC) was used to control the motion of surface on which the solar cooker was mounted. A continuous test during different days in the year 2008 from 8:30 am to 4:30 pm was performed. The test showed that the using of cylindrical solar cooker system with two axes tracking can increase water temperature up to 90 ^{o}C.

Keywords: Cylindrical Solar Cooker, Automatic Control, Tracking System, PLC

1. Introduction

The energy section in Jordan depends heavily on the imported oil and gas products. This energy policy put the country in tough economic situations and slowed down the economical growth in the last years. This situation is worsening by the dramatic increase in the crude oil prices worldwide and in the increased demand on energy consumption. Jordan lies in high solar insulation band, where the average insulation intensity on horizontal surface is approximately 5 – 7 KWh/m^2/d, which is one of the highest in the world [1].

Solar cooking is often considered a solution looking for a problem. Solar cookers have long been presented as an interesting solution to the world's problem of dwindling fuel wood sources and other environmental problems associated with fuel demand for cooking. The use of solar cookers resulted in appreciable fuel and time savings as well as increased energy security for households using commercial fuels [2].

In [3], a one year comparative field test of seven different types of solar cookers involving 66 families in 3 study areas in South Africa has been conducted. Overall, families use solar cookers on 38% of all days and for 35% of all cooked meals; they express clear preferences for certain cooker types. Solar cookers, together with wood (stoves and open fires, used on 42% of all days), are the cooking appliances most used. Fuel consumption measurements show overall fuel savings of 38% resulting in estimated pay – back periods (through monetary fuel savings) from 8 months onwards, depending on the type and region.

Solar cooking in boarding schools and communal centers in isolated areas demands the heating of large quantities of food. In [4], 3 different kinds of absorbers were presented. They were optimized to fulfill different functions in a concentrator of an area of 2 m$^{2.}$ These alternatives allow the possibility of satisfying the needs of a communal dining center, cooking for up to 30 children, once each concentrator has been installed.

In [5] and [6], the policy formulation for cooking energy substitution by renewable energy is addressed in multi – criteria context. A survey is conducted to know the perceptions of different decision making groups on present dissemination of various cooking energy alternatives in India. Nine cooking energy alternatives are evaluated on 30 different criteria comprising of technical, economic, environmental, social, behavioral and commercial issues. It is found that liquefied petroleum gas stove is the most preferred device, followed by kerosene stove, solar box cooker (SBC) and parabolic solar cooker (PSC).

In [7], the simply designed the low cost parabolic type solar cooker was made and tested. The energy and exergy

* Corresponding author. akayleh_em@yahoo.com

efficiencies of the cooker were experimentally evaluated. The energy output of the SPC varied between 20.9 and 78.1 W, whereas its exergy output was in the range 2.9 – 6.6 W. It is found that the energy and exergy efficiencies of the SPC were in the range of 2.8 – 15.7 and 0.4 – 1.25 respectively.

In [8], for the first time, the SPC of the cylindrical trouph shape is analyzed from the exergy viewpoint. Equations for heat transfer between the three surfaces: cooking pot, reflector and imagined surface making up the system, were derived. The exergy efficiency of the SPC was found to be relatively very low (~1%), and to be about 10 times smaller than the respective energy efficiency which is in agreement with experimental data.

In (9), a fresnel type domestic concentrating cooker was designed. The cooker has an aperture area of 1.5 m^2 and a focal length of 0.75 m. It was found to provide an adequate temperature needed for cooking, frying and preparation of chapattis.

The majority of researchers used box type cooker in their works [10-22]. In [10], a transient mathematical model is presented for a box – type solar cooker with one step outer reflector hinged at the top of the cooker. To validate the model, the temperature distribution obtained by computer simulation is compared with experimental results. Good agreement between experimental and theoretical results is observed.

In [11], the performance of a box – type solar cooker with auxiliary heating was studied and analyzed. This is done with the help of a built – in heating coil inside the cooker or a retrofit electric bulb in a black painted cylinder. It is found that the use of auxiliary sources allows cooking on most cloudy days.

In [12], a simple mathematical model is presented for a box – type solar cooker with outer – inner reflectors. The cooker performance is investigated by computer simulation in terms of the cooker efficiency as well as characteristics and specific boiling items. The overall utilization efficiency of the cooker is 31%.

In [13], the thermal analysis of a hot box solar cooker which is manufactured in Istanbul Technical University has been done using the fourth order Ronge – Kutta method. The results obtained have been given comparatively with the experimental results measured from the cooker.

In [14] a model to predict the cooking power of a solar cooker based on three controlled parameters (solar intercept area, overall heat loss coefficient and absorber plate thermal conductivity) and three uncontrolled variables (insulation, temperature difference and load distribution) is presented. The model was validated for commercially available solar cookers of both the box and concentrating types.

In [15], a simple wooden hot box with one reflector solar cooker was designed, fabricated and tested. Maximum inner temperature reached 160°C under field conditions of Giza, Egypt.

In [16], a series of tests were carried out during nine days to make comparison of the Sudanese box – type solar cooker against the other Indian designs. Sudanese solar box cooker showed better thermal performance. Using internal, external reflectors and sloping of the top cover added significantly to the thermal performance indicated by the amount of heat absorbed and hence the achieved plate temperature.

In [17], a method is outlined to find out a reflector performance factor and an orientation factor that depend upon the elevation angle of the sun, the solar surface azimuth angle and the reflector tilt. The analysis is applied to a cooker placed at Aden in Yemen. The results indicate that with proper cooker orientation. The improvement in the performance of the cooker due to the reflector reached during winter is more than 100% at lower elevation angles and is more than 60% at higher elevation angles.

In [18], the influences that govern solar box cookers: HS7534, HS7033 and the newest design HS5521 were described. Its volume is only 35% of the volume of HS7033 and cheaper. The performance comparison of the last two solar cookers is described based on the data collected during testing with and without load.

In [19], the design philosophy, construction and measured performances of a plane – reflector augmented box – type solar energy cooker are presented. The experimental solar cooker consists of an aluminum plate absorber painted with black matt and a double glazed lid. Predicted water boiling times using the two figures of merit compared favorably with the measured values. The performance of the cooker with the plane reflector in place was improved tremendously compared to that without the reflector in place.

In [20], a hot box solar cooker with used engine oil as a storage material has been designed, fabricated and tested so that cooking can be performed even in the late evening. The performance and testing of a storage solar cooker was investigated by measuring stagnation temperatures and conducting cooking trials. The efficiency of the hot box storage solar cooker was found to be 27.5%.

In [21], the top heat losses that constitute the major losses from the box type solar cooker have a strong influence on the thermal performance. To predict or evaluate the thermal performance of a cooker, the top heat loss coefficient U_{tw} for a water loaded cooker should be known. The conducted investigations reveal that the pot water requires less time to reach a certain temperature with an increase in solar radiation level, while, as expected, it takes longer time with higher values of load of water in the pots. However, the effect of wind speed on the time required for certain rise in pot water temperature is marginal.

In [22], the performance of conventional box type solar cookers can be improved by better designs of cooking vessels with proper understanding of the heat flow to the material to be cooked. An attempt was made to arrive at a mathematical model to understand the heat flow process to the cooking vessel and thereby to the food to be cooked. The mathematical model considers a double glazed hot box type solar cooker loaded with two different types of vessels, kept either on the floor of the cooker or on lugs. It is found from the experiments and the modeling that the cooking vessel with a central cylindrical cavity lugs results in higher temperature of the thermal fluid than that of a conventional vessel on the floor or on lugs.

In [23], a box type solar cooker with one or four cooking pots was constructed and tested in Tatna (Egypt) prevailing weather conditions. Experiments were performed during July 2002 using the cooker with or without load. The suggested cooker is able to cook most kinds of food with an overall utilization efficiency of 26.7%.

In [24], a novel design of solar cooker is introduced in which the absorber is exposed to solar radiation from the top and bottom sides. A set of plane diffuse reflections is used to direct the radiation onto lower side of the absorber plate. The performance of the new cooker and the conventional box type solar cooker is investigated. Results under the same operating conditions show that the absorbers of the box type solar cooker and the double exposure cooker attain 140°C and 165°C respectively.

In [25], the thermal performance of a prototype solar cooker based on an evacuated tube solar collector with phase change material (PCM) storage unit is investigated. Cooking experiments with PCM storage processes were carried out simultaneously. The cooker performance under a variety of operating and climatic conditions was studied at Mie, Japan.

In [26], the concept of conical focus is revealed and the design of a solar cooker is explained. The cooker was practically tested for grilling both white and red meat in a record time. A method for obtaining real boiling of water (100°C) using a solar heater is described.

In [27], the role of the vessel inside the solar cooker was discussed. Raising the vessel by providing few lugs will make the bottom of the vessel a heat transfer surface. This change improves the performance of the system by improving the heat transfer rates in booth heating and cooling modes.

All types of concentrating solar cookers were found to provide adequate temperatures needed for cooking, frying and preparation of chapattis. But the common problem of all concentrating cookers with manual tracking, like the need for frequent tracking, and standing in the sun. This problem could be tackled if one goes in for automatic sun tracking [9, 28, 29].

In this work cylindrical solar cooker with two axes, sun tracking, PLC controlled system was designed and constructed. The system was characterized by a fairly simple electromechanical setup. This reduces cost, maintenance and the possibility of failure.

2. Mechanical Design of Cylindrical Solar Cooker.

The amount of power produced by a solar system depends upon the amount of sun light to which it is exposed. As suns position changes throughout the day, the solar system must be adjusted so that it is always aimed precisely at the sun, as a result, produces the maximum possible power. Single axis tracking systems are considerably cheaper and easier to construct, but their efficiency is lower than that of two axes sun tracking systems. On the other hand, some solar systems require only two axis tracking [30,31,32].

Fig.1 and fig. 2 show front view and side view of schematic diagram for a proposed solar cooker. Cylindrical solar cooker consist of half cylinder made of steel. In inner side of half cylinder small mirrors with a dimension of 6cm * 6cm are distributed and sticked by a silicon material. A blackened steel tube with 10cm diameter was replaced on the focus line in the half cylinder. The mirrors inside the half cylinder reflect and concentrate the sunlight on a tube.

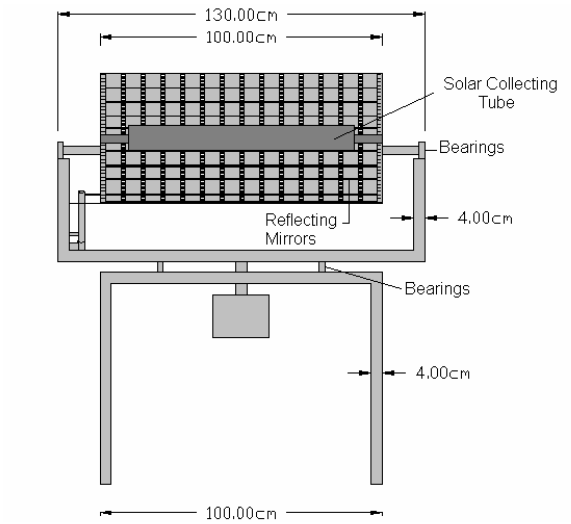


Fig.1 Cylindrical Solar Cooker Front View

This cooker works as follows: The liquid is poured through an opening into the cylindrical tube, where it is cooked there for a suitable time. When the cooking is done, the same opening is used to let the food out. When dirty, the tube can be easily removed for cleaning.

The drive motor M1 for tracking around vertical axes was designed to track the slope angle β, which is the angle between the plane of the surface in question and the horizontal. The drive motor M2 was designed to track the surface azimuth angle γ, which is the deviation of projection of normal to the collecting surface on the horizontal surface to the north south axis. The positions of tracking motors M1 and M2 are shown in fig.1 and fig.2

In this mechanical design four principles were used:

1. Concentrating sunlight into a small area
2. Converting the light to heat where a blackened tube will absorb almost all of the sunlight and turn it into heat.
3. Trapping heat by using plastic bag to cover the half cylinder with blackened tube
4. Tracking the sun disk by means of tracking motors M1 and M2.

3. Electromechanical System Description:

The electromechanical system consists of two drivers , the first for the joint rotating about the vertical axis to track the solar azimuth angle γ_s and the second one for the joint rotating about the horizontal axis to track the zenith angle θ_z as shown in figure 3.

The system has two bridge rectifiers, the first one PS1 that converts the 220 VAC of the supply network into 24 VDC to power the PLC, and the second rectifier PS2 which converts 220 VAC of supply network into 24 VDC to provide the electrical motor M2 with 24 VDC. FI is a frequency inverter which is used to provide the electrical motor M1 with controlled voltage and frequency. The FI is used as an electrical gear to reduce the speed of M1 to the suitable value (33,34 & 35).

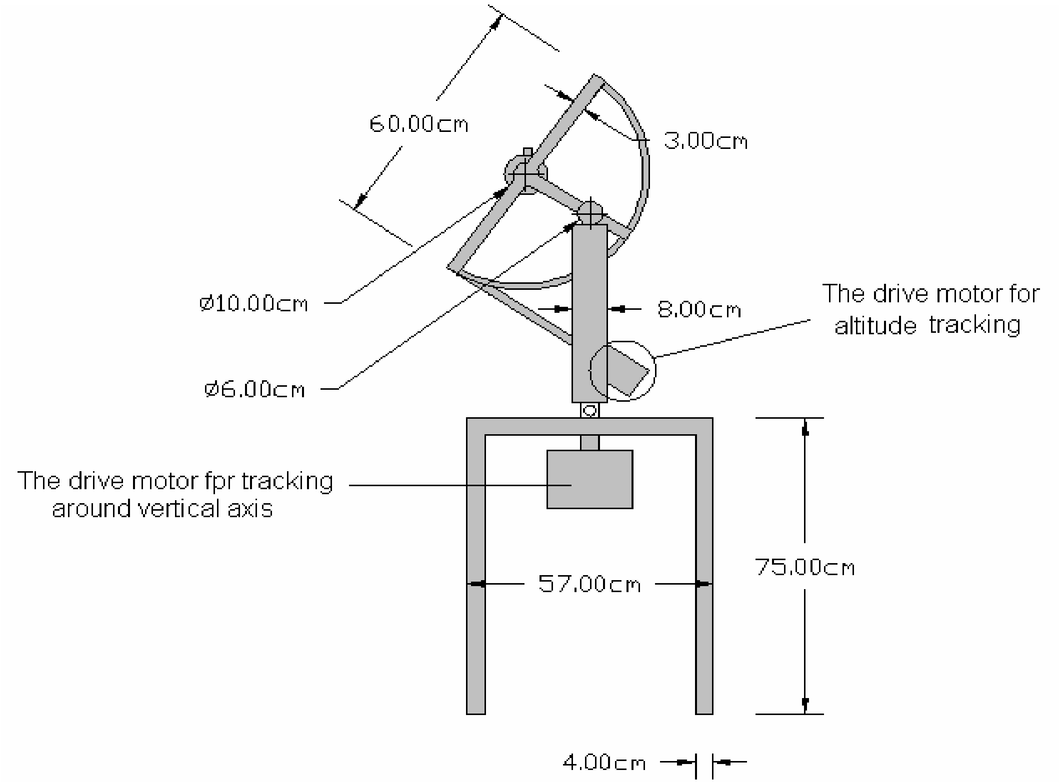


Fig.2 Cylindrical Solar Cooker Side View

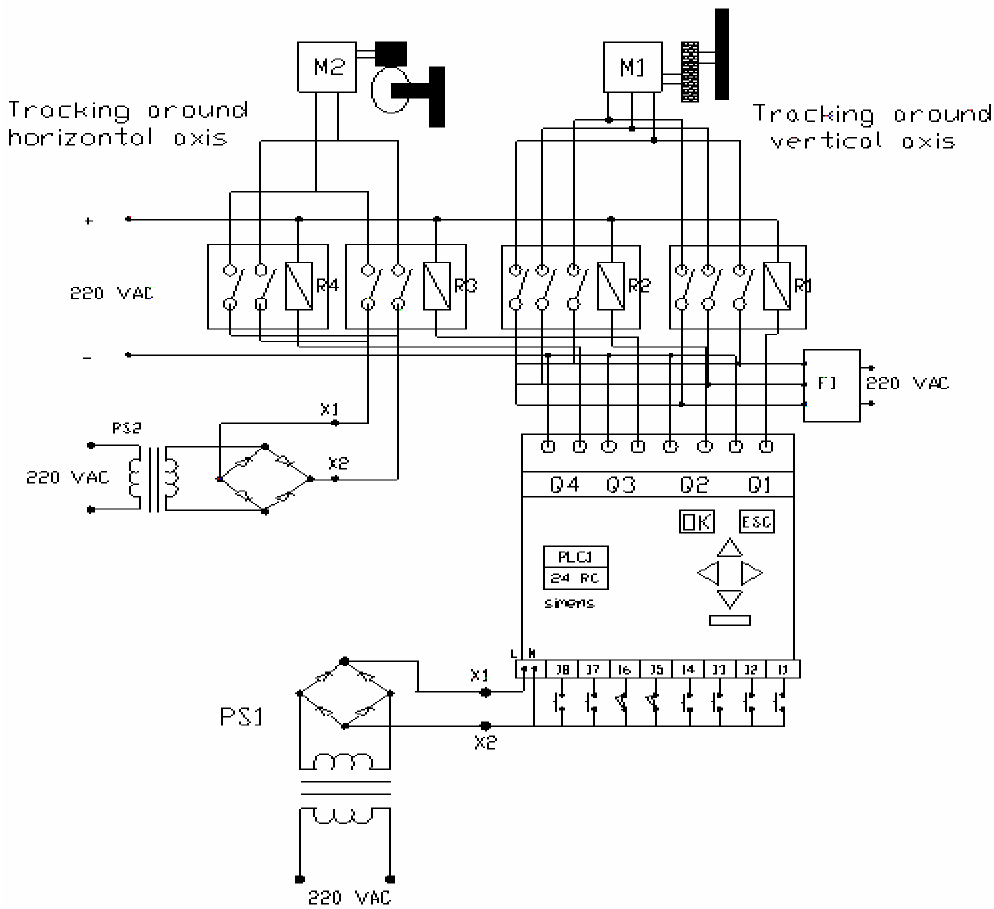


Fig3. The electromechanical circuit for driving of two motors

The PLC has eight inputs, and they are used as the following:

I1-Push button to start automatic mode of tracking

I2 -Push button to stop tracking

I3-Switch for manual operation of tracking in the forward direction for vertical motor M1. It is used to adjust the system.

I4-Switch for manual operation of tracking in the backward direction for vertical motor M1. It is used to adjust the system.

I5-Limit switch, it is used to backward the system to start position (zero position) for vertical motor M1.

I6-Limit switch, it is used to stop the vertical motor M1 at start position

I7-Switch for manual operation of tracking in the forward direction for horizontal motor M2. It is used to adjust the system.

I8-Switch for manual operation of tracking in the backward direction for horizontal motor M2. It is used to adjust the system.

Also the PLC has four outputs, and four outputs were used, these are as following:

Q1-It represents the forward direction of motion through the relay R1 for motor M1 of tracking around vertical axis.

Q2-It represents the backward direction of motion through the relay R2 for motor M1 of tracking around vertical axis.

Q3-It represents the forward direction of motion through the relay R3 for motor M2 of tracking around the horizontal axis.

Q4-It represents the backward direction of motion through the relay R4 for motor M2 of tracking around the horizontal axis.

4. Programming of The Control System

The optimal spherical solar cooker positions can be defined by two angles, β & γ, as shown in [36].β is the slope of surface, and γ is the surface azimuth angle. For two axes tracking, the cooker positions are determined as follows:

$$\beta = \theta_z \text{ and } \gamma = \gamma_s. \qquad (1)$$

Calculations have been done to determine the different solar angles for Amman that are required in this work. This allowed the calculation of the optimal poison of tracking surface during the daylight hours.The daylight hours were divided into 4 identical time intervals T1, T2, T3 and T4, during which the motor speeds (deg/s) were determined. Then the PLC programming was done based on the solar angles analysis and motor speed calculations. The PLC controls the intermittent position adjustments made by the motors. This means that the motor for tracking around the horizontal axis will be idle for 10-20 minutes according to the different intervals of time mentioned and works only for a few seconds, the motor for vertical tracking will be idle for 15-35 minutes and works for a few seconds. The LOGO 24 RC PLC system which uses the functional diagram language of programming is used to control the motors operation in this work [37, 38, 39].

The PLC program of the system driving the vertical tracking motor is represented in fig (4). The program consists of two parts related to the two types of motion, forward and backward. From the theoretical calculated results of the solar azimuth angle γ_s, it is deduced the forward motion will cover all the intervals of time T1, T2, T3 and T4. The blocks B7, B11, B14, and B16 are clocks that represent the four above mentioned intervals of time. The clocks actuate the recycles B5 B9, B12, and B17, which represent on – off timers. The clocks must be adjusted to the calculated positions function of time. The block B19 will operate the vertical tracking motor in the backward direction after sunset.

A) Forward Direction

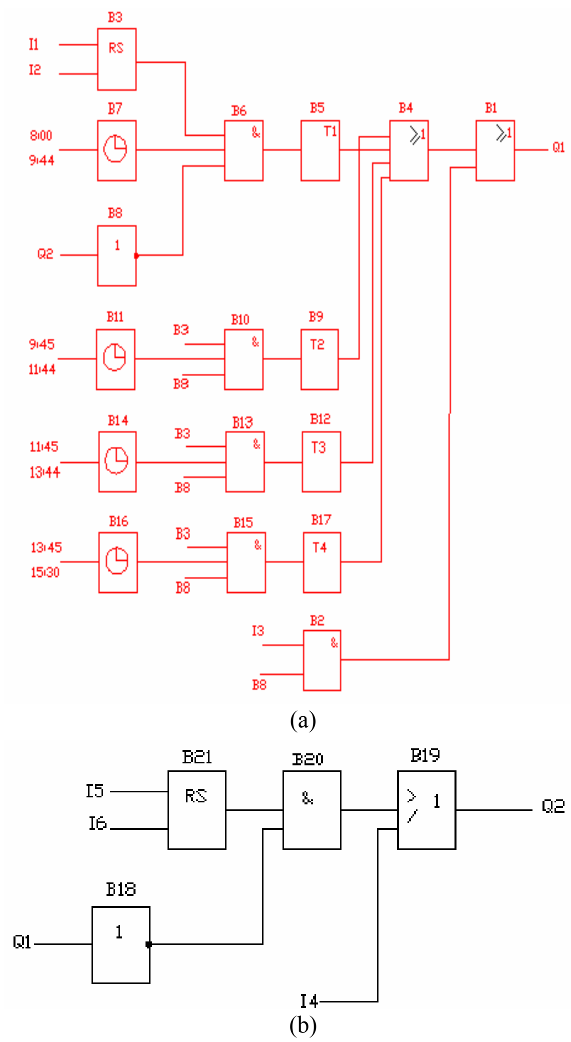
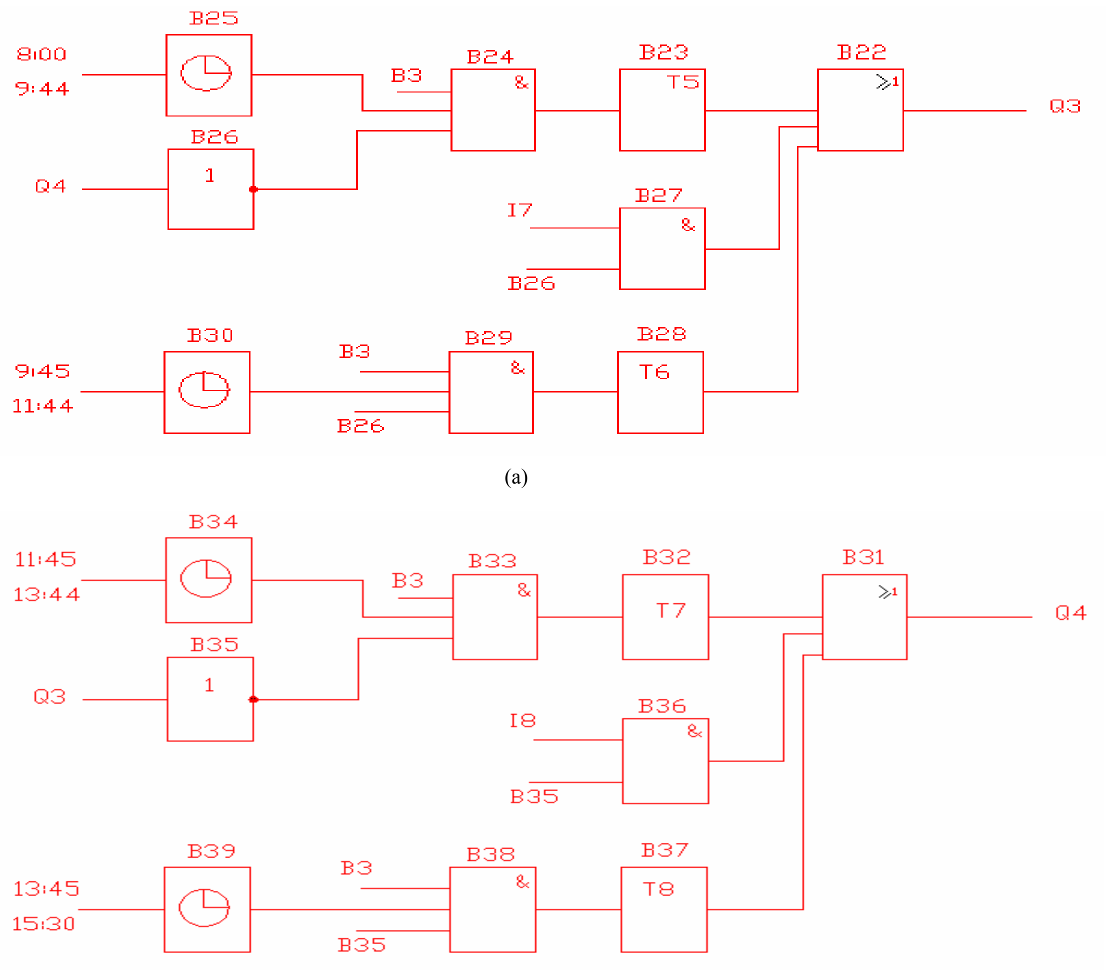


Fig 4. The functional PLC program for the plane rotated about the vertical axis, (a) Forward Direction, (b) Backward Direction.

The PLC program of the system driving the slope angle tracking motor is represented in fig.5. The program consists of two parts also according to the motion, up and down direction. From the theoretical calculated angles values, it is noted that β (slope) decreases from its maximum at sunrise until its reaches its minimum at noon. This represents the up direction motion, which covers the intervals of time T1 and T2. The down direction motion occurs from noon till sunset where β is a maximum. This period of time will cover the intervals T3 and T4.

The blocks B25, B30, B34, and B39 are clocks that represent the four above mentioned intervals of time. The clocks actuate the recyclers B23, B28, B32 and B37, which represents on-off timers. The clocks must be adjusted to the calculated position as a function of time.



(a)

(b)

Fig5. The functional PLC program for the tracking of slope angle, (a) Up Direction , (b) Down Direction.

5. Experimentation and Results.

Experiments done on the cylindrical solar cooker with two axes sun tracking system were carried out on three days; 24/5/2008, 12/6/2008 and 16/8/2008. The experimental work was fully carried out in the renewable energy laboratory at the Applied Science University, in Amman- Jordan. Each experiment started from 8:30 morning to 4:30 afternoon. The measuring electronic parts were tested and calibrated before being used on the various tests. The global solar radiation on a horizontal surface was measured using Kipp and Zonen pyranometer. Calibrated thermocouples (type – K) coupled to digital thermometer are used to measure the temperature. Fig(6) shows different views of the designed and tested system.

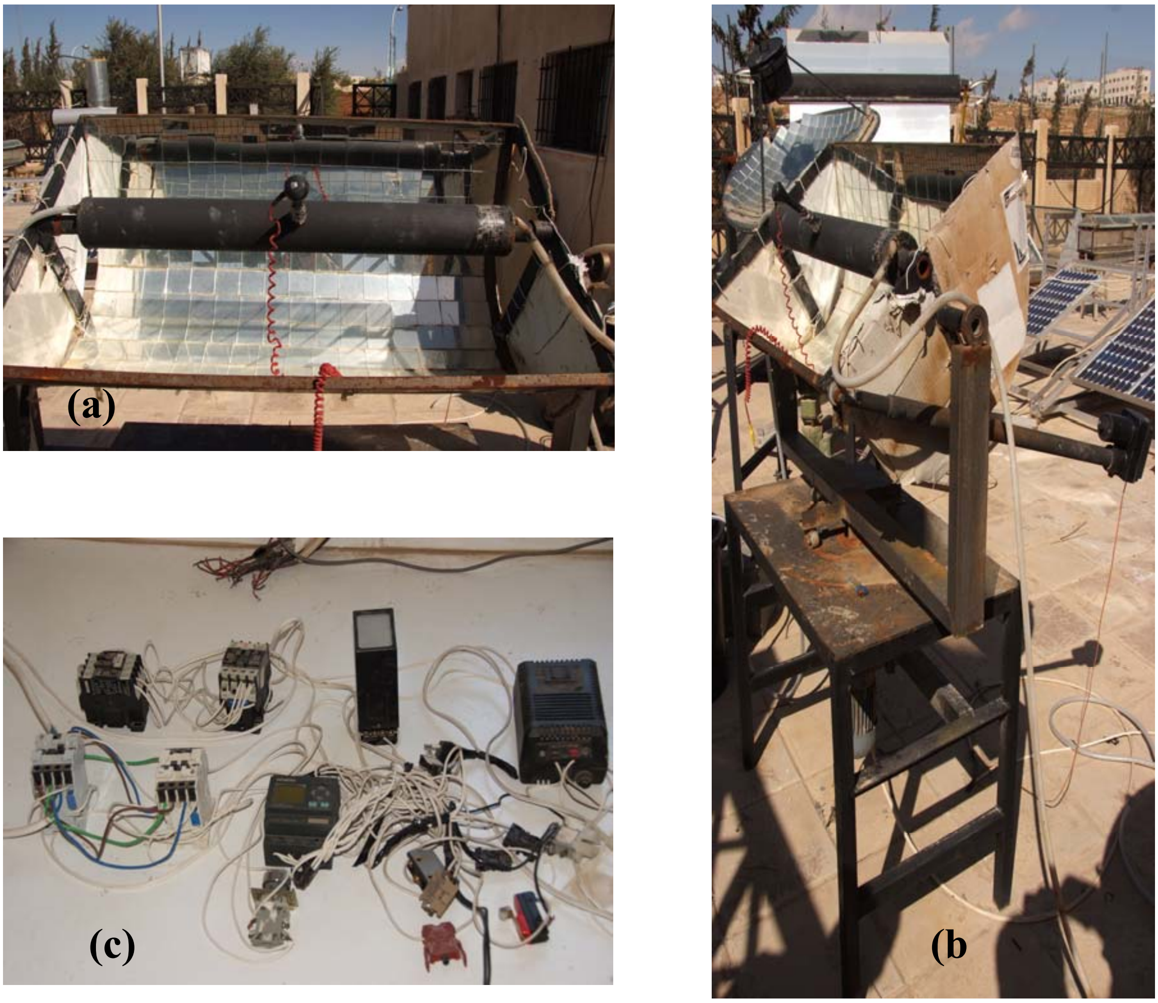


Figure 6.(a) Front view of cylindrical solar cooker .(b) Side view of cylindrical solar cooker with mechanical base and driving motors. (c) The hardware components of the control circuit.

Fig.7 and fig.8 show the variation in ambient temperature and the variation in the solar intensity through three summer days.

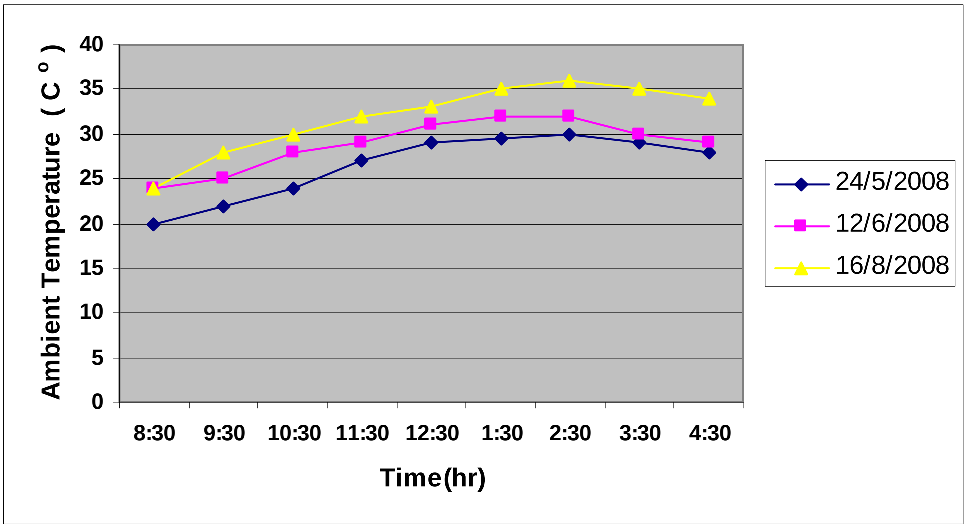


Fig.7 The Ambient Temperature variation function of time

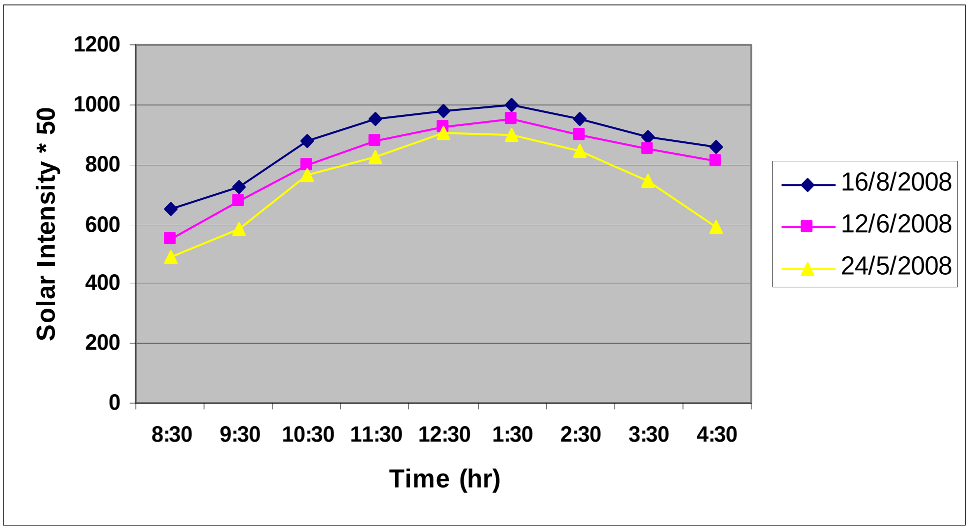


Fig.8 The Solar Intensity variation function of time

Fig.9 and fig.10 show the variation in water temperature function of time inside the collecting tube and the variation of the tube surface temperature function of time. the figures show an increase in the water temperature during early hours of the day until it reaches the maximum values around noon correspondingly to the highest solar radiation and then decreases due sunset.

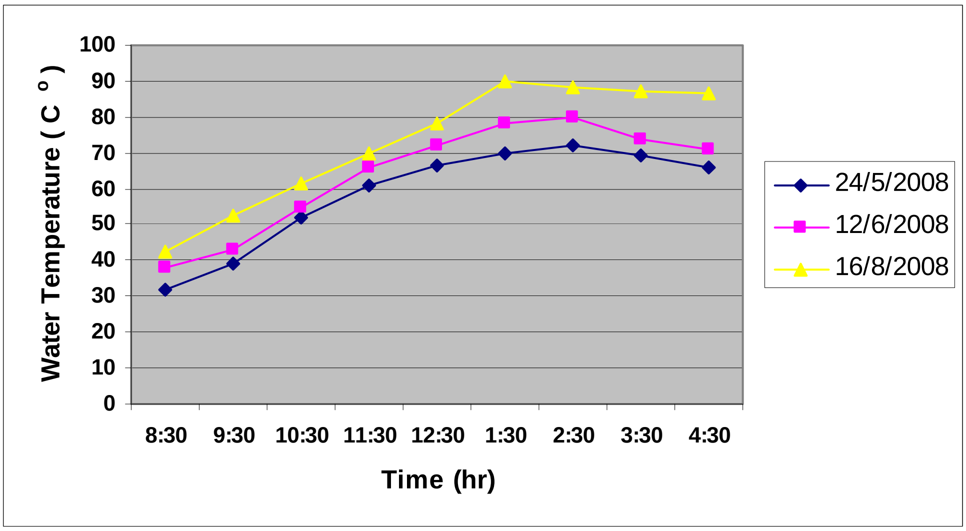


Fig.9 The Water Temperature variation function of time

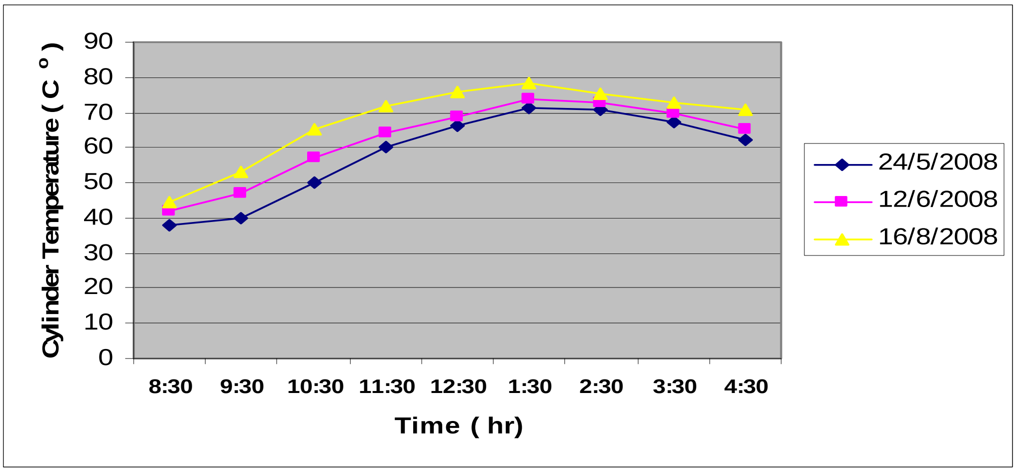


Fig.10 The Outside tube Temperature variation function of time

From the curve of water temperature variation function of time it is seen that the water temperature inside tube reached 90 ^oC in normally summer days, where the maximum ambient temperature registered 36 ^oC. This shows that water temperature inside tube could still reach further higher rates on hotter days. It is noticed after studying all the curves, that the water temperature inside tube increases when the ambient temperature is hotter or where the solar intensity is prevalent.

When using this system for cooking or simply heating water, the latitude of location, season, and wind speed and weather conditions as cloudy days or dusty days should be considered.It should be remembered that food containing moisture cannot get much hotter 100 ^oC in any case, so it is not necessary to cook at the high temperature indicated in standard cookbooks. Because the food does not reach too high temperature, it can be safely left in the cooker all day without burning. This type of cookers can be used to warm food, drinks and can also be used to pasteurize water or milk.

6. Conclusion

In this work a cylindrical solar cooker with two axes sun tracking system was designed, constructed and operated. Mechanical system; which consists of two parts, one for altitude tracking and another for rotating around vertical axes was designed and constructed.The hardware and software components of the two axis sun tracking system were designed. The programming method of control with open loop system was employed. The programmable logic controller was used to control the motion of surface on which the solar cooker was mounted.A continuous test during different days in the year 2008 from 8:30 am to 4:30 pm was performed. The test showed that the using of cylindrical solar cooker system with two axes tracking can increase water temperature up to 90 ^oC.

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