Operational Trends of a mini parabolic solar collector for agricultural purposes in a non-active solar environment

M.E. Emetere a,b, S.E. Sanni c, A.O. Dauda a, A.A. Akinsiku d, O.I. Osunlola a and A.D. Adejumo a

a Physics Department, Covenant University Canaan land, P.M.B 1023, Ota, Nigeria
b Mechanical Engineering Science Department, University of Johannesburg, Auckland Park, Johannesburg, South Africa
c Chemical Engineering Department, Covenant University Canaan land, P.M.B 1023, Ota, Nigeria
d Chemistry Department, Covenant University Canaan land, P.M.B 1023, Ota, Nigeria

Abstract

The mode of operation of mini parabolic solar panels made of germanium, mild steel and aluminum were investigated experimentally, as means of providing heated water on a farmland; the process was also modelled. Angular adjustments of the solar collectors from 70-90° were adopted in order to determine, the best material of construction for the parabolic solar collector and the angular orientation with the highest heat collection tendency and absorption rate. The highest quantity of adsorbed heat/best heating effect of the solar collector was obtained at an angular orientation of 80° for mild steel and aluminum. It was also observed that, the parabolic solar collectors have their optimum exposure times, after which, the heating rate drops or there is loss of heat from its surface. The experimental and model estimates, in terms of heat absorption for the mild steel solar collector at 70 and 90° angular tilts, shows that, the optimum heating time was 40 minutes while at 80°, the optimum heating time was found to be 50 minutes.

Keywords
Solar energy, farm, energy, model, parabolic solar collector

1. Introduction

The use of heated water in a farm serves the following, sterilization of equipment, cleaning of animal hutchs, washing of fruits and vegetables alongside processing milk products as well as administering drugs in the poultry [1]. In most site locations in developing
countries, the application of electrical heating to farming is very minimal. Most farmers use Liquefied Propane (LP), or natural gas to heat water for agricultural applications. However, the disadvantage of the former is the likely increase in the release of carbon dioxide into the atmosphere. The continuous burning of this fossil fuel has caused a drastic rise in the earth’s atmospheric carbon dioxide (CO2) level by more than 25% over the past 150 years. The second disadvantage of the use of LP or natural gas for water heating is that they are non-renewable sources of energy, meaning that, they are limited in availability and could cease to exist after a period of time.

In recent time, farmers use heat recovery units, waste oil burners, solar, and/or geothermal energy to heat water and provide supplementary water heating. However, the prospects of waste oil burners and geothermal energy are limited by geographical location. The viable option in tropical region is the use of solar energy. Solar Water Heating (SWH) mainly depends on geographical location, due to the fact that it is more effective in places of abundant sun light [23, 24]. Nevertheless, SWH systems also have the potential to function effectively in countries with less sunlight.

The main aim of this study is to model an efficient heating water source for agricultural use via the design and construction of a prototype parabolic solar collector. Hence, the focus of the study is to:

I. construct a parabolic solar collector using aluminum sheet, reflective coating/mirrors and a central heat pipe.

II. analyze the performance of parabolic solar collector (PTSC) using MATLAB software.

III. advance the functionality of the parabolic solar collector in a conventional environment.

This research serves as an eye-opener to people on the use of renewable source of energy that is more environmentally friendly alongside other derivable benefits.

In the past, few scientists worked on design construction and use of solar devices in rural areas of developing countries. Musa et al. [2] did the design, construction and performance test of a parabolic fresnel concentrator cooker which uses locally accessible materials. The success of the device is hinged on the precise adoption of concentric illustrative rings and glass mirrors. Sulaiman et al. [26] showed the importance of parabolic concentrators for cooking. Ever since, further research on improving solar parabolic collectors has advanced [3-7]. Concentrated solar power is a cost-effective renewable emerging technology. The challenge of continuous heat generation after sun hours often faced by this technology can be overcome by heat storage in oil or molten salt; which is cheaper when compared to energy storage in batteries [8]. From the four optical types of concentrating technologies: parabolic trough, dish concentrating, linear Fresnel reflector and solar power tower, this study focus on parabolic-trough concentration as it gives 1/3 of the theoretical maximum for the design of acceptance angle [9-10]. There is a promising future in this study in rural areas as it is simple and clean.

Mason and Reitze developed high performance cost reducing sky trough parabolic trough solar collector [11]. The application of photovoltaic cells in agriculture have been discussed by Liu et al. [27]. They however, mentioned that, shortage of land and desertification are limitations besetting their use. Their novel technology which tends to harness these combined problems, uses the diffractive and interference principles of photovoltaics which helps to split sun rays over transmitted and reflective wavelengths for optimal plant growth and solar power generation respectively. The maximum efficiencies recorded from implementation of this technology as against conventional solar panels is 6-8 %. According to Choo [12] the increased demands for clean energy has led to the increased development of solar energy research ranging from the use of Solar Thermoelectricity (STE) to Dye Sensitized Solar Cells (DSSC), Concentrated Photovoltaic Cell (CPC), Photovoltaic Solar Panels (PV) and Concentrated Solar Power (CSP). According to them, CPC, DSSC and STE are emerging technologies under intensive investigation and may occupy a significant share of the solar market if significant breakthroughs are achieved in terms of their relative pricing with respect to conventional solar panels. Based on the work of Torshizi and Mighani [13], greenhouse solar houses can be built in order to help meet the demands of
agriculture in far reaching rural areas. In their paper, benefits of solar energy in agriculture were also discussed and this includes irrigation, drying, plant growth etc. Kawira et al. [14] investigated the performance of three different designs (i.e. aluminum sheet, car solar and aluminum foil reflectors) of thermal parabolic trough solar concentrators for steam production. The same dimensions of aperture width, collector length and areas were adopted in the designs. The absorber pipe was made of copper that carried water in it as the heat transfer fluid. Their design considerations include considerations for minimal heat losses. A concentration ratio of 128 was adopted for the solar concentrators. The maximum steam temperature obtained was 248.3 °C, while the average steam temperature produced was 150 °C. The efficiencies of the different solar configurations were determined when they were closed and when open. The closed solar concentrator efficiencies in descending order of magnitude are in the order of aluminum sheet, car solar and aluminum foil while for the open solar concentrators, the performances are in the order of car solar, aluminum sheet and aluminum foil in increasing order of efficiencies. Umair et al. [15] designed a parabolic concentrator with wings angled in the east and west directions (surface Azimuth angle), and modelled its performance considering different angular orientations in space of 70-90°. The aim was to determine at several tilt and bend angles, the optimum temperature absorbed by the solar concentrator which is an improvement on the conventional straight types whose wings are angled facing southwards. Based on their findings, the proposed CPC will improve the efficiency of energy-driven solar panels at increased exposure times of 2-3h. Borah et al. [16] succeeded in designing and constructing a compound parabolic solar concentrator for efficient drying via indirect method. A total of six semi-parabolic concentrators were integrated on a receiver plate for direct conversion of solar to thermal energy by absorbing the incident rays upon metallic tubes placed on the principal focus of the parabolas. Their results showed that, the new design gave better performance when compared with fixed CPC and the absorption time was found to increase by 1h 30 minutes for the tilted parabolic concentrators over their fixed counterparts. According to Norton [28], the following are useful design considerations when designing a parabolic solar concentrator for energy storage applications: collector types, aperture cover materials, plate absorbers, line-axis collectors and the need for non-convecting solar panels. Lee [17] constructed a solar drying system (Compound Parabolic Concentrator) with evacuated solar collector, having a storage tank, a water-to-air heat exchanger, an auxiliary heater and a drying chamber whose performance was compared with indoor and outdoor drying methods. However, the results from investigation showed that, solar drying was the most effective for all drying samples considered although, outdoor drying gave comparable results for the drying process of oyster mushroom. Hernandez et al. [18] carried out a review on beneficial and adverse environmental effects of utility-scale solar energy development alongside their impacts on biodiversity, land use, land-cover change, soils, water resources and human health. They highlighted the intention as being motivated by the need to reduce carbon-intensive sources of energy and emission of greenhouse gases. However, they underscored the numerous benefits of the use of solar energy against the very few/negligible disadvantages that they claimed have not been carefully investigated. Despite the underlying economic benefits and potentials in the use of solar energy sources as replacements for fossil fuels, their use still remain relatively low, thus, in order to achieve higher market penetration, there is need to create more awareness on the benefits therein, provide financial aids/control mechanisms that will cover for overhead costs with special advocacy towards the use of solar thermal energy as alternative heating source of energy for fossil fuels for industrial applications [19]. In this research, the acquired knowledge from literature was scaled by 50% to serve a mini farm size. The efficiency of the parabolic solar concentrator is hinged on its concave reflecting surfaces that capture and focus the solar beam radiation onto a smaller receiving area with relatively high energy density which can withstand temperatures between 100-1000°C. Also, another advantage is its flexibility to adapt to electronic structures like trackers.
The advanced application of the parabolic solar concentrator can be found in large power stations, where steam is produced to drive turbine engines [20]. The application of this technology is far reaching in rural communities of developing nations; hence, the originality of the study is in the adoption of common local materials to build solar structures for rural farmers. The prototype of the solar concentrator is as shown in figure 1. Its basic components include the receiver tubes, curved mirror assemblies and the heat transfer fluid [21]. In our design, the heat transfer fluid is water, the curved mirrors are shaped-sliced-glass pieces that are aligned in a curved wooden frame.

![Diagram of solar collector](image)

**Figure 1**: Solar collectors based on parabolic trough system [25].

2. **Design and Construction of the Mini Parabolic Solar Collector**

The physics of the latent heat of the fluid (water) that circulates through a pipe is hinged on the absorbing properties of the pipe. Hence, the improvised curved surface reflects sunlight and focuses it onto the absorber tube. To conserve the heat-gain by the tube, a degree of vacuum is created to ensure maximum transfer of absorbed heat energy to the moving fluid. Sahoo et al. [22] estimated the heat gained by the running fluid within the absorber tubes. The saturated steam parameters reached up to 55 bar/270°C. The initial assessment of the device was done using our previous studies [23, 24]. Different gradients of water storage tanks were adopted to create an open or closed loop. This idea helps to avoid the cost of purchasing a pump for circulating the heated fluid. Based on the design considerations, a parabolic solar concentrator was constructed as shown in Figure 2.
The materials used for the construction of the parabolic solar collector were purchased in accordance with the material specification on the design analysis. The equipment for the construction include a wooden stand, square sized mirrors of sides 10 mm (3 mm thick), bearing seal, ball bearing, receiver pipe, tilting adjuster, cover/top frame, end bar, joint angle piece, metallic stand brazes, edge redressing bar, aluminum steel, germanium steel and mild-steel.

Experimentation
A digital thermometer was used to obtain the temperature of the circulating fluid. The readings were taken at 10 minutes interval for 4 hours daily. The angle of orientation of the concentrator was gradually adjusted from east to west. The information from the experimentation procedure were inputted in the Microsoft excel sheet and the corresponding plots were done using MATLAB. The information entered in the Microsoft excel sheet were day, time, angle of trough, initial heat of the water, heat of water after passing through the central heat-pipe, number of runs. The experimental parameters were optimized using the following mathematical representations:

$$Q = mc(\Delta T)$$  

(1)

here $M =$ mass (kg), $C =$ specific heat capacity (J Kg$^{-1}$ °C$^{-1}$), $Q =$ heat energy and $\Delta T =$ temperature change ($T_2 - T_1$) (°C).

$$T = \frac{M_{AL}C_{AL}T_x + 33.3M_wC_w}{M_wC_w + M_{AL}C_{AL}}$$  

(2)

where $M_{AL} =$ mass of aluminum (kg), $C_{AL} =$ specific heat capacity of aluminum (J Kg$^{-1}$ °C$^{-1}$), $T_x =$ temperature of the central heat pipe (°C), Initial temperature of water = 33.3 (°C), $M_w =$ mass of water (kg), $\Delta T =$ Temperature difference and $C_w =$ specific heat capacity of water (J Kg$^{-1}$ °C$^{-1}$).

3. Results and Discussion
Figure 3 shows the thermal analysis for germanium steel at angles of 90°, 80° and 70° tilt. The number of runs was theoretically calculated since it is very difficult to see it physically. It was observed that the water reached its highest temperature at angle 80°. At higher fluid circulation (number of runs), it was observed that the temperature of fluids at angle 90 and 70° were almost close as seen in Figure 4, which depicts the range for a good model. It was observed that the same trend occurred when the steel was replaced with aluminum (Figure 5). The difference between Figures 3 and 5 is that, aluminum pipes generate more heat than germanium pipes. The adoption of mild-steel would theoretically not be far from...
the trends in aluminum and germanium (Figures 7 & 8).

Figure 3: Graph of temperature against number of runs at 90°, 80° and 70° tilt for germanium steel.

Figure 4: 3D analysis for the sensitivity of germanium steel pipe at 90°, 80° and 70°

Figure 5: Graph of temperature against number of runs at 90°, 80° and 70° tilt for aluminum steel.

Figure 6: 3D analysis for the sensitivity of aluminum steel pipe at 90°, 80° and 70°
The initial temperature of water was higher in germanium steel than aluminium. An excerpt of the raw data obtained for mild steel is displayed in Tables 1-3.

In Figure 9, for the different runs, aluminium gave the highest heating rate followed by mild steel then germanium. This is evident in their relative conductivities i.e. aluminium, mild steel and germanium in order of increasing conductivities. However, it is expected that aluminium will absorb radiation than mild steel and germanium hence, will be the best material of construction of the parabolic solar panel for maximum results and efficient heat utilization. Again, at different times, it was observed that, aluminium still gave the highest heat sensitivity by absorbing the highest quantity of heat. Next to it is mild steel while germanium gave the least heat absorption tendency (Figure 10).

Based on the 3D plots of Figures 4, 6 and 8, it is clear that, the parabolic solar collector made of aluminium is the most sensitive to solar radiation while mild steel is next, with the solar collector made of germanium being the least temperature sensitive, hence, the difference between the three pipes is in direct relation to the predicted properties of the metal (Figure 9). The raw temperature modulation of the circulating fluid is shown in Figure 10. The graph shows the thermal variation at 80° tilt.
In Table 1, the external surface temperature of the metal (mild steel) varied between 44.3 and 33.3 °C between 10 and 70 minutes while the internal temperature of the metal varied between 38.6 and 33.3 °C between 10 and 70 minutes. The temperature readings were found to increase with the number of runs from 10-40 minutes along the rows but decreased along the columns for each run (this agrees with the model results in Figures 3-5). From 50-60 minutes, the recorded temperatures seemed to show only little differences for the 58th run while, the 59th and 60th runs gave similar outlet temperatures. Comparing the results with those of the internal and external temperatures, when the solar mirror angle is 90°, the maximum heat that can be reflected from the surface of the metal is 33.3 °C at 70 minutes, although it is higher at other times.

From Table 2, it is evident that, when the angle of tilt of the mild steel solar collector was 80°, the external temperature increased from 44.2 to 45.6 °C within the first 30 minutes but dropped slightly by 0.3 °C at the 40th minute. The external surface temperature rose to 46 °C at 50 minutes and dropped by 0.9 and 3.8 at 60 and 70 minutes respectively; this then implies that, maximum heating of the external surface of the solar mirrors at the tilt angle of 80 °C, is 50 minutes after which the temperature at the metal surface begins to drop. Considering the internal surface temperature of the metal, a maximum heating rate can only be achieved when the parabolic solar mirror is exposed to the sun for 30-60 minutes; this is because, the maximum attainable temperature at such time range is 42.3 °C since it dropped to 40.7 °C at the 70th minute. Based on the temperature readings taken for the 58th and 59th runs, the lowest attainable solar temperature were 39.04 and 39.09 °C respectively. The temperature profile for these two runs are quite similar based on the trend established by the temperature changes recorded for every 10 minutes of exposure time of the solar panel to the sun; this is also validated by the model results in Figures 3-5. This then implies that, the maximum temperature reflection of the mirror were obtained after 50 minutes giving temperatures of 41.49 and 41.57 °C respectively, while for the 60th run, the maximum attainable temperature was also obtained after 50 minutes to be 41.65 °C. At further exposure times, the temperature profile showed reductions for all runs. Generally, at all times for 80° tilt angle of the solar mirror, the temperature of the metal increased for all the runs across the rows at all times.

When the tilt angle of the mild steel solar collector was 70°, the temperature of the mild steel increased to 44.7 °C and was lower than this value for the next 30 minutes; a similar trend was also observed in the values recorded for the internal temperature of the metal. For all the different runs, it is clear that, the maximum attainable temperature is 40.79 °C and this is at 40 minute since lower temperatures were recorded at further times. However, the 58th run seems to give the least temperature after 70 minutes of exposure time of the panel to solar radiation.

Considering the results for all angle orientations, this then implies that, the metal cannot receive/retain/reflect much heat at 70° like other solar angle orientations (i.e. 80 and 90° solar tilt angles) in space; this agrees with the model results shown in Figure 7). The highest heating rate was obtained at 80° angular tilt of the solar panel; this agrees with the results in Figures 9 and 10.

**Conclusion**

In the study we encountered few challenges that are suggested for further work i.e. solar tracking
errors and low transmissivity of the glass cover. The thermal analysis trends of the metallic pipes show that they are good candidates for the specified purpose. However, the low temperatures recorded were as a result of the low surface temperature associated with the convectional environment where the research was done. However, at higher runs, a farmer within such location can get his/her desired heated water for the day’s work. This research is prescribed for the rural communities in developing nations. Based on the findings, it is also evident that the farmer needs to maintain an angular tilt of 80° for maximum heating rates. This event occurs is because the highest temperature was obtained at 80° tilt of the panel relative to other angular orientations. The results obtained are also indicative of the optimum exposure times for the solar panels; it is 40 minutes for the 70 and 90° angle of tilt, while it is 50 minutes for the 80° angular tilt, hence, it is recommended to adopt these heating times for these angular orientations for maximum heating rates to be achieved.

<table>
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<tr>
<th>Time (min)</th>
<th>Exterior temp. of pipe (°C)</th>
<th>Interior temp. (°C)</th>
<th>Temp. at 58th run (°C)</th>
<th>Temp. at 59th run (°C)</th>
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Table 2: Table showing the values for first day at 80° tilt and number of runs

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Table 3: Table showing the values for first day at 70° tilt and number of runs

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