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PERFORMANCE EVALUATION OF PARABOLIC CONCENTRATOR WITH THERMAL STORAGE SYSTEM FOR DOMESTIC APPLICATIONS

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ABSTRACT

Solar energy is a free natural resource but its harvesting requires a high capital investment which prohibits its maximum exploitation. A Parabolic Dish Solar Collector (PDSC) with a thermal storage system was been constructed and developed to harness solar beam radiation. The thermal storage system and PDSC were constructed using locally and less cost materials such as galvanized metal sheet and steel rods curved to obey the equation of a parabola then welded together with circular support rings which was then lined with stainless steel reflector pasted for the construction of PDSC. The receiver was made of blackened aluminium material incorporated with coiled copper tube carrying water as the heat transfer fluid. A parabolic dish which acts of a heat collector is used to track and reflects solar radiation at a single point (focus) on a receiver absorber. Heat transfer from the solar collector to the storage tank was done by using thermosyphonic principle to circulate the water (heat transfer fluid) between storage tank and heating system (receiver). The evaluation of thermal storage and analyzing the efficiency of tracking and non-tracking parabolic dish solar collector was carried out during month of June, 2020 for the composite climate of Sokoto. According to the finding, the efficiency of tracking PDSC with thermal storage system and non- tracking PDSC with thermal storage tank were determined and obtained to be 52.9% and 50% respectively.

Keywords: thermal efficiency, parabolic dish collector, solar radiation, storage system and stainless steel reflector.

INTRODUCTION

The rate at which our environment is being exposed to the global warming, ozone layer depletion and desert encroachment as results of human interference cutting down trees for energy needs for cooking is alarming in the developing world (Garba *et al.,* 2010). Parabolic solar dish concentrator are used to achieve high thermal energy and this concentration of sun light in form of solar radiation is achieved by reflecting or refracting the incident flux on the aperture area (reflecting surface of the concentrator) onto a smaller absorber area (receiver) (Flavia *et al.,* 2016). Among solar energy collecting systems, concentrated solar collectors are considered to be more efficient than flat plate collectors (Alibakhsh *et al.,* 2015).

An experimental investigation of solar parabolic dish collector with aperture area of 20m^2, with aim to study its performance with the modified cavity receiver was presented, and the average value of the overall heat loss coefficient for system was found to be about 356 W/m^2 (Reddy *et al.,* (2013). Thermal energy storage is the concept of accumulating thermal energy when available, in storage system for later usage, primarily for domestic heating and industrial processes (Loan and Calin, 2017).

Storage capacity of PCMs can be increased based on material composition, with research from (Mohammad and Kamran, 2018), concluding that introduction of nano particles to PCM mixtures significantly increase performance. Thermal energy storage systems increase overall efficiency by retaining absorbed energy, leading to installation and operating cost reductions as well as lower greenhouse gas emissions (Ibrahim, 2012). Various types of thermal energy storage systems exist such as concrete media storage, molten salt heat transfer fluids, chemical storage and phase change materials (Chan *et al.*, 2013)

Direct steam generation achieving 90% thermal efficiency at 535°C with a parabolic dish and cavity type receiver has been reported based on experimental results using a 500 m^2 dish (Lovegrove *et al.,* 2011). A method of storing thermal energy in a thermo chemical receiver of a concentrated solar collector was proposed by (Zheng *et al.*, 2015). This study developed a methane reforming thermal receiver that when reacted with high temperature steam, produces highly endothermic reactions that can store solar energy in the form of chemical energy.

Solar energy is free energy source and abundant. Using locally available and recycled materials, the construction cost of the solar energy device could be greatly reduced to affordable levels by poor communities (Sadik *et al.,* 2013). In this work, a parabolic dish solar collector with thermal energy storage system was constructed and tested, which can be used to store solar energy for a reasonable amount of time. This stored energy is environmentally friendly and can be used for domestic heating application such as cooking, water heating and room heating applications in the absence of sunlight.

MATERIALS AND METHODS

Materials

The construction of parabolic concentrating collector with thermal storage system was made using locally available and less cost materials, and the specification of the materials used is shown in the table 1. In the selection of materials for the construction, the following were highly considered; local availability, low cost, easy handling during fabrication, lightness of weight for easy handling during use, ability to withstand environmental and operating condition and non-toxic effects.

The system was constructed in three batches or stages one after the other; the first stage was parabolic concentrating collector, receiver absorber and the storage system as a third stage, which was later assembled together and placed on the manual tracking mechanism or system.

Detailed list of the materials, their specifications and quantities used for the construction of the system is shown in Table 1

Experimental Set up and instruments used

During the experimental tests, The rate of flow of HTF was measured using volume flow rate meter and conversions done to mass flow rate, and fluid temperature, solar irradiation, and weather conditions (ambient temperature and wind speed) were measured. The instruments used during instrumentation, includes the following listed in Table 2.

Table 1: Specifications and Quantity of Materials Used for Construction of the thermal storage system

MATERIAL	SPECIFICATION	QUANTITY
Galvanized metal sheet	10.0m	2.0
Aluminium plate sheet	10.0m	1.5
Copper pipe tube	0.40m	8.0
Elbow joint (arms)	0.35m	6.0
Control valves	0.81m	4.0
Glass wool or glass fibre	0.30m by 0.23m	1.2kg
Aerogel or Styrofoam	5.00m	2.0

Table 2: List of Instruments and their Specification

PARAMETER MEASURED	INSTRUMENT USED
Solar irradation	Pyranometer
Wind speed	Anemometer
Flow Rate	Flow rate meter
Ambient temperature	Mercury in glass
Fluid temperature	Thermocouple thermometers

Methods

Geometrical Design of the Parabolic Concentrating collector

The concentration of solar radiation in a concentrating system was designed based on the geometry of the dish concentrator. The parabola shape reflector is the locus of a point that moves so that its distances from a fixed line and a fixed point are equal. Figure 1, shows geometry of the parabola. Where *x* and *y* are coordinates in aperture plane. While figure 2, (a) plate 1 and (b) plate 2 are the measuring of parabolic dish geometry and parabolic dish collector before assembled respectively

The standard mathematical equation of parabola was used similar method was employed by (Fareed, 2012).

$$y = ax^2 + bx + c \qquad (1)$$

Where a, b and c are constants of the parabola equation

The simple form of the equation (1) can be written in form of equation (2) stated

$$y = ax^2 \qquad (2)$$

Where the vertex is at (0, 0) and symmetry is on the y-axis

For the simple prototype parabolic dish the equation was simply made to be equation (3)

$$y = \frac{1}{360}x^2 \qquad (3)$$

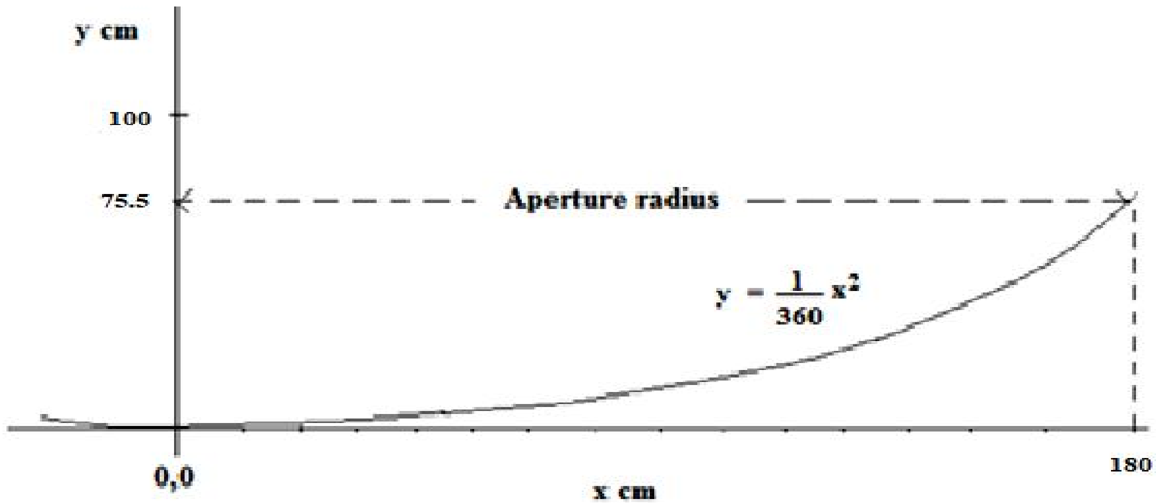

Figure 1: Geometry of the parabola shape

Figure 2: (a) Plate 1, Measuring parabolic dish geometry . (b) Plate 2, Parabolic dish collector before assembled

The focus of the parabola was obtained using equation (4). Where a is the coefficient of the equation and

$$a = \frac{1}{360} \quad (4)$$

Design description of Storage system

The storage system (tank) was made up of two different material sheets, these are, galvanizes sheet of metal and sheet of aluminum materials; the system consists of two cylindrical tanks named as internal and external tank which was made up of aluminium sheet and galvanize metal sheet respectively, in between them there is a space or separate gap. The internal tank also known as PCM tank contains the PCM tubes while the other tank is used as an external tank.

There is Styrofoam and glass wool insulation between the internal tank and external tank. The bulk amount of heat (latent heat) used to change the phase of PCM can be stored by using effective insulation.

The storage tank was also connected to a heating application by using pipes. Valves are used to direct the flow of HTF (H_2O) within the receiver tank and storage tank to store the energy during the availability of the solar energy and from storage tank to the heating application when the stored energy is to be used. Figure 3 (a) Plate 3 and (b) plate 4 shows the solar thermal system during construction and after assembled. The design parameters of the solar thermal storage system and heat transfer fluid (HTF) are shown in table 3 and 4 respectively.

Figure 3: (a) Plate 3, Measuring parabolic dish geometry (b) Plate 4, Parabolic dish collector before assembled

Table 3: Design parameters of the storage system

Parameters	Values
External diameter of cylinder, d_e	0.300m
Internal diameter of cylinder, d_i	0.250m
External diameter of copper pipe tube, r_e	0.025m
Internal diameter of copper pipe tube, r_i	0.028m
Length or height of storage tank, l_{st}	0.800m
Internal radius of storage tank, R_i	0.200m
Cross sectional area of inlet pipe tube, A_i	0.00125m^2
Cross sectional area of outlet pipe tube, A_o	0.00128m^2

Table 4: Design parameters of heat transfer fluid (HTF)

Parameters	Values
Mass of water required or used, M_w	20.00kg
Specific heat capacity of H_2O, C_w	4200Jkg^{-1}k^{-1}
Density of H_2O, ρ_w	1.000gcm^{-3}
Initial temperature of water (HTF), T_i	Measured (^{0}C)
Final temperature of water (HTF), T_f	Measured (^{0}C)
Volume of water , V_w	2000cm^3
Required flow rate pump	2.5 x 10^{-5}m^{3}s^{-1}

System operational method

The parabolic dish was made up of stainless steel reflective materials which reflect the solar radiation at a single point known as the focal point. At the focal point, the receiver-absorber tank was placed which contains the heat transfer fluid which is heated up through the sunlight directed toward it. This heat transfer fluid moved from receiver- absorber to the storage tank with the help of flexible rubber pipes tube which was used to incorporate (integrate) the receiver absorber and storage tank so that, the concentrator can rotate freely on two axes. A copper coil pipe tube which utilizes the stored energy was connected to storage tank by steel pipes. In order to circulate the HTF in the system, a heat transfer from the solar collector to the storage tank was circulated using thermosyphonic principle to circulate the water (heat transfer fluid) between storage tank and heating system. Two control valves were used to direct the flow of the HTF into the two thermal circuits (outlet and inlet). Two dial temperature sensors are attached to the receiver tank and at outlet of the storage tank to measure the temperature in the respective tanks. The schematic diagram of assembled system was shown in Figure 4.

Determination of thermal (Heat) energy stored

Thermal energy storage can be classified by storage mechanism (sensible, latent or chemical) or by storage concept (active or passive). Thermal storage can utilize sensible or latent heat mechanisms or heat coming from chemical reactions. Sensible heat is the means of storing energy by increasing the temperature of a solid or liquid. The latent heat, on the other hand, is the means of storing energy via the heat of transition from a solid to liquid state for melting process or transition from liquid to gas for vaporizing materials. The comparison between latent and sensible heat storage shows that when latent heat storage is used, storage densities of 5 to 10 times higher can be achieved (Energy Technology Systems Analysis Program, 2013).

The ability to store thermal energy is given evaluated using equation (5).

$$A = \frac{Q_s}{V} = \frac{mC_P\Delta T}{V} = \rho C_p \Delta T \quad (5)$$

Where m is the mass of storage material in kg, Q_s is thermal energy calculated from the heat capacity, V is the volume in m^3, and ρ is the density in kg/m^3.

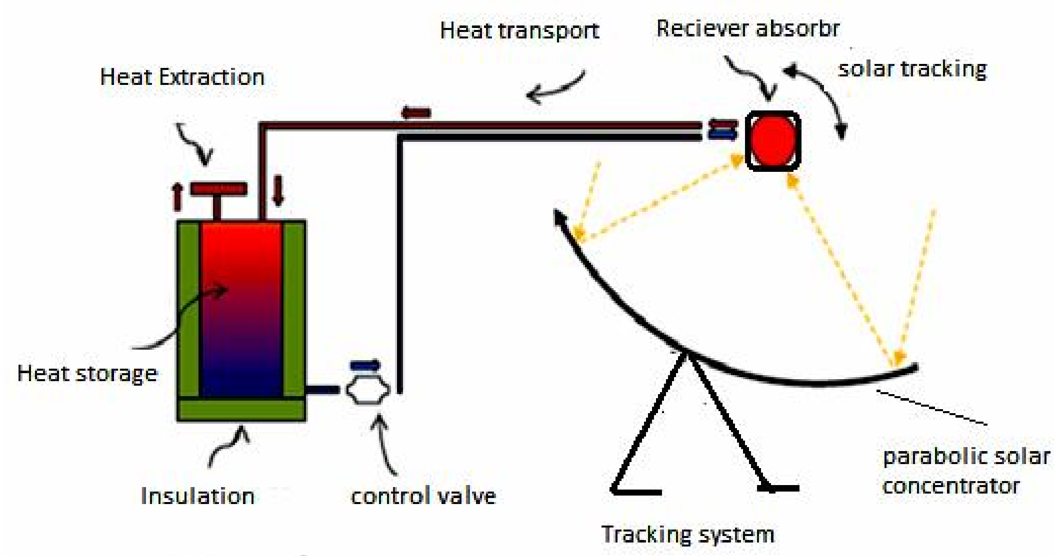

Figure 4: Schematic diagram of assembled parabolic concentrator with thermal storage system

Under steady state conditions, the temperature rise of water was used to determine the heat transferred to the water using the equation of heat gain stated in equation (6) (Ihab *et al.*, 2020)

$$Q = mc_p(T_f - T_i) \quad (6)$$

where m is mass flow rate of the heat transfer fluid, c_p is the heat capacity of water at constant pressure, $(T_f - T_i)$ is the temperature gradient with T_i as the inlet temperature and T_f as the outlet temperature of the heat transfer liquid and Q is the rate of transfer of heat or the power output (Ihab *et al.*, 2020).

The total heat intercepted by the dish was calculated using effective dish aperture area A_a and the prevailing solar constant G_{sc}.

The effective aperture area was determined using equation (7).

$$A_{ae} = A_a r \quad (7)$$

Where A_a is aperture area and r is reflectance of stainless steel reflector = 0.96 (Lucas, 2013). A_{ae} is the effective aperture area.

In the prototype dish the effective aperture area was determined as:

$A_{ae} =$ 7.07 m^2 x 0.96 = 6.787 m^2

The solar energy intercepted by the aperture area per unit time was calculated by:

$$Q_s = G_{sc}A_a cos\theta_i \quad (8)$$

Where G_{sc} is the prevailing direct solar intensity, θ_i is the angle of incidence. For the perpendicular aperture, $cos\theta_i$ = 1

A_a is a design parameter and was calculated from the diameter of the cylindrical absorber using equation (9)

$$A_a = 2\pi ah \quad (9)$$

The radius of the cylindrical absorber was 0.142 m therefore the absorber area was 2.19 m^2

The solar constant G_{sc} at the location of solar harvest was measured using solar power meter in W/m^2.

Determination of maximum efficiency of the PDSC with storage system

The two challenges of energy concentration and storage have a bearing on efficiency (Christopher *et al.,* 2005). The first law of thermodynamics defines efficiency, η as the ratio of useful output energy of a device to the input energy of the device.

$$\eta = \frac{Useful\ output\ energy}{Energy\ input} \quad (10)$$

Therefore, the efficiency of the PDSC with thermal storage system was calculated as the first law efficiency, η which is the ratio of power output (thermal energy gained by water per second) to the power input (solar power intercepted).

$$\eta = \frac{mc(T_f - T_i)}{G_{sc} A_a cos\theta_i} \times 100\% \quad (11)$$

Where solar power intercept calculated using equation (8)

$$Q_s = (G_{sc}) A_a cos\theta_i$$

Therefore, equation (11) can be written as

$$\eta = \frac{mc(T_f - T_i)}{Q_s} \times 100\% \quad (12)$$

However the actual amount of solar radiation that is reflected to the absorber is dependent of the reflectance and smoothness of the reflecting surface. The effective aperture area (A_{ae}) was also calculated using equation (7).

RESULTS

The parabolic dish solar collector (PDSC) was located at an open area away from tall obstacles such as trees and buildings which would otherwise obstruct radiation and in effect reduce the solar harvesting period. The tests were carried out at old site of Sokoto Energy Research Centre in the University permanent site under climatic conditions of Dundaye Village in Sokoto State, Nigeria with latitude 13.0514^O and Longitude 5.2314^O. Water was selected as the heat transfer fluid for the solar heater because of its stability at high temperatures, low material maintenance and transport costs, safe to use, and is the most commonly used fluid for domestic heating applications. The tests and results obtained from several experiment done on different days between Wednesdays 2nd to Saturday 4th June, 2020. The measurements were carried out to investigate the performance of the PDSC with storage system and without storage system.

The result of determination of thermal efficiency (η) of the PDSC with storage system was evaluated using equation (12); similar method was employed by (Christopher *et al.,* 2005). The magnitude of the efficiency of the system was found to be 52.9%.

Similarly, the result of determination of thermal efficiency of the PDSC system without thermal storage tank was also evaluated using the same equation (12), and the magnitude of the efficiency without thermal storage tank was found to be 50.0%

Results of performance of Tracking PDSC with thermal storage tank

The experimental test for the performance of parabolic dish solar collector (PDSC) with thermal storage was conducted (tracking system). The measurements were taken between 10:30am to 14:30pm. The general weather was clear and sunny with intermittent windy regime and the values of the Wind Speed, Ambient Temperature, Insolation with the Initial and Final Water Temperatures during the experimental Test were recorded. The flow rate of HTF was maintained at 0.46g/s. The results of thermal performance of the system were shown in figure 5.1a and 5.1b.

Results of performance of non-tracking PDSC with thermal storage tank

Similarly, the experimental test for the performance of non-tracking PDSC with thermal storage was also studied and conducted (non-tracking system). The measurements were recorded between 10:00am to 14.30pm. The general weather was clear and sunny with intermittent windy regime. The flow rate of HTF was maintained at 0.46g/s. The results of the performance of the system without thermal storage tank were shown in figure 5.2a and 5.2b.

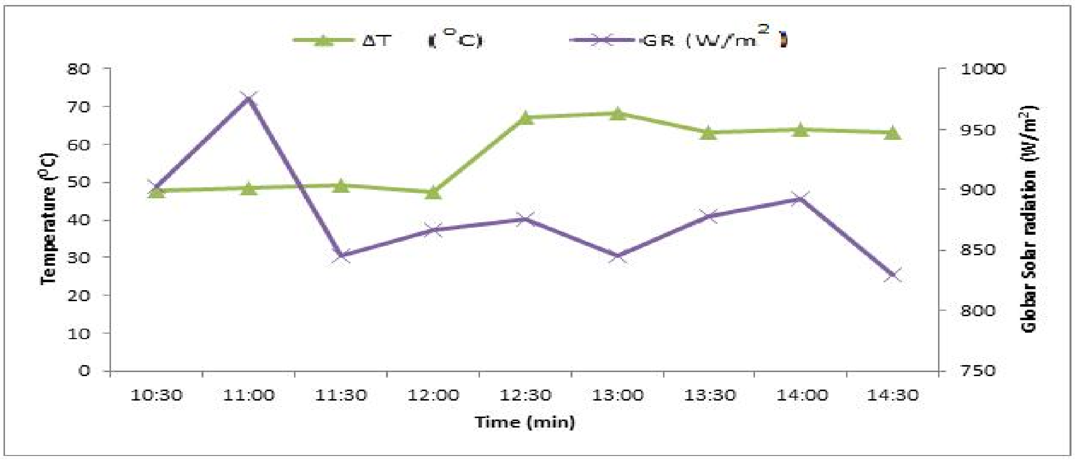

Figure 5.1a: Temperature variation with time and corresponding global solar radiation for tracking PDSC with thermal storage system.

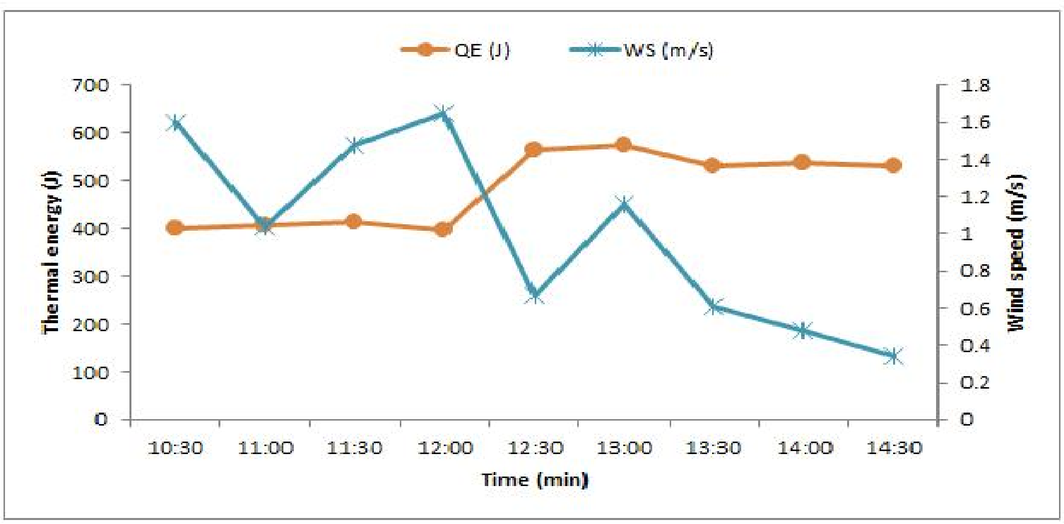

Figure 5.1b: Thermal energy variation with time and corresponding wind speed for tracking PDSC with thermal storage system

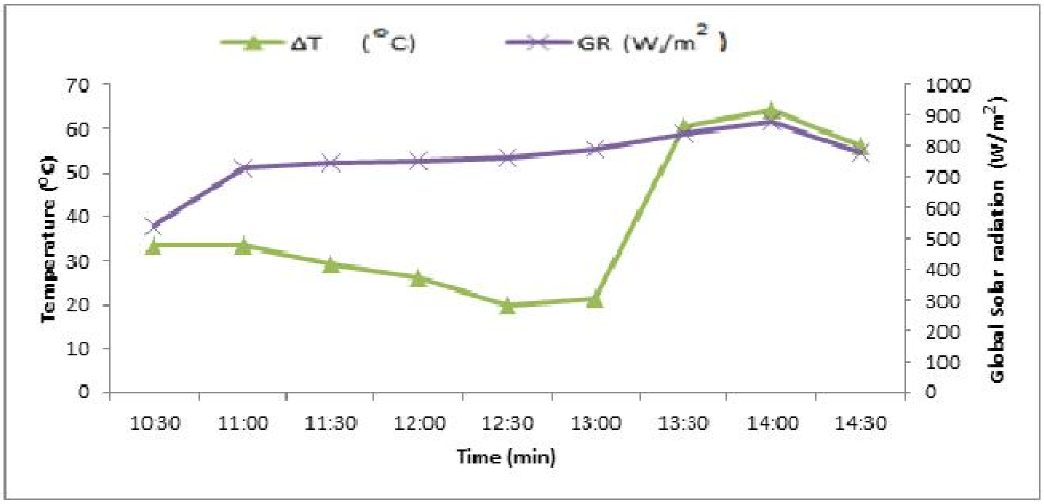

Figure 5.2a: Temperature variation with time and corresponding global solar radiation for non-tracking PDSC with thermal storage system.

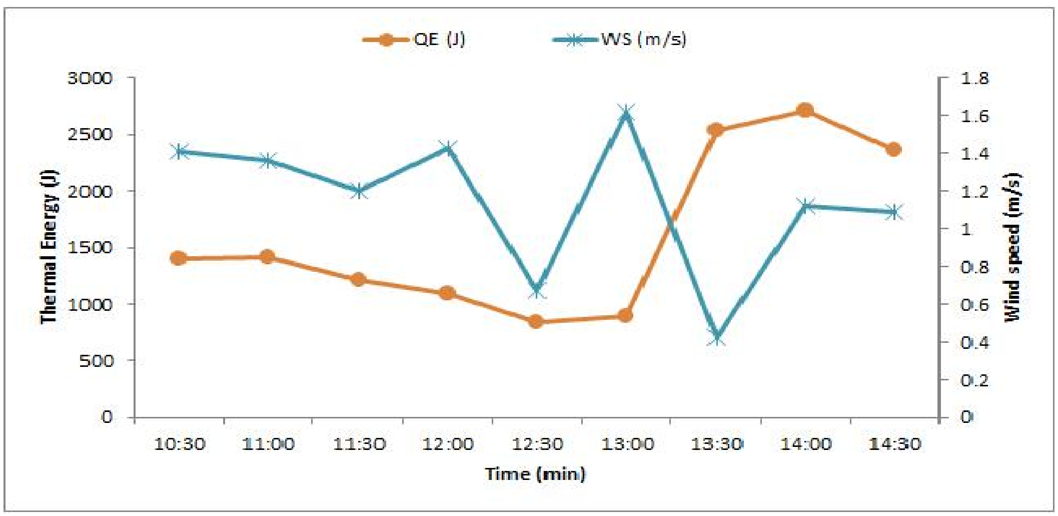

Figure 5.2b: Thermal energy variation with time and corresponding wind speed for

DISCUSSION

The experiment test results obtained of the performance of tracking PDSC with storage system were depicted in figure 5.1a and 5.1b. The results shows that, the highest change in temperature variation with time was 99.2^{O}C at 13.30pm and the highest thermal energy value obtained at that time was 532.6J, while the corresponding global solar radiation and wind speed were measured to be 878 W/m^2, 0.61m/s respectively. Low temperature and thermal energy output were realized in the morning hours which then increased drastically to a maximum when the sun was at zenith between 13:00 hrs and 14:30 hrs as indicated in figure 5.1a and 5.1b. There was a sharp decrease in solar power in the period between 13:00hrs and 13:30 hrs due to cloud cover. The power output then continued to decrease in the afternoon hours when the solar beam was not perpendicular to the aperture. The thermal energy output of the PDSC is dependent on the intercept factor, γ which was considerably low in the early morning and late afternoon hours. The intercept factor was high when the sun was at zenith resulting to a good proportion of the perpendicular beam being reflected to the absorber. Therefore, the maximum temperature required for domestic heat process was achieved, and significant limestone was also achieved compared to temperature of 100^{O}C obtained by (Ibrahim 2012).

Likewise for the performance of non-tracking PDSC with thermal storage system was conducted, and the experimental test results were shown in figure 5.2 and 5.2b. The results revealed that, the highest change in temperature variation with time was 95.4^{O}C at exactly 14:00pm and the highest thermal energy output recorded at that time was found to be 2704.8J, while the corresponding global solar radiation and wind speed were measured to be 880 W/m^2, 1.12m/s respectively. The graphs of the two results in figure 5.2a and 5.2b shows that, both temperature and thermal energy outputs were directly resonating with the fluctuating solar radiation respectively. However, there is observable delay in response to the solar fluctuations. The graph indicates a region of sharp decline in solar flux between 13:30 hrs and 14:30 hrs yet not accompanied by a sharp decline in the energy output. This can be attributed to the heat capacity of the HTF itself and a slight contribution of heat capacity of the material encasing the HTF. The receiver absorber device shows steadier thermal energy output even during drastic swings in the solar intensity as indicated by figure 5.2a and 5.2b.

CONCLUSION

A parabolic dish solar collector with thermal storage system was constructed and tested using water as (HTF) heat transfer fluid. The thermal efficiency performance of tracking PDSC with storage system and non-tracking PDSC with thermal storage system was also investigated under different solar harvesting conditions it was clear that, the best results of efficiency performance were obtained when the system was sun tracking and having the thermal storage component compared to non-tracking PDSC. The variation of thermal energy and temperature results obtained in some days during experimentation could be as a result of both optical and thermal losses from the reflector and receiver. Furthermore, the results of the tests conducted were obviously hindered by the fluctuation of the atmospheric parameters as a result of the cloud cover which diminishing the intensity of solar radiation being one of the uncontrolled atmospheric parameter. Therefore, the system can serve the economy in terms of foreign exchange, as we don't need to import.

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