International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 9, Issue 1 [Jan. 2020] PP: 01-08

Experimental Investigation of the Diurnal Phase of Hybrid Water Heating/Nocturnal Cooling Flat-Plate Solar Collector in Owerri, Nigeria

O.O. Mong[1], G.N. Nwaji[2++], E.E. Anyanwu[2]
[1]Department of Mechanical Engineering, Federal Polytechnic Nekede, Owerri, Imo State
[2]Department of Mechanical Engineering, Federal University of Technology, Owerri, Imo State
Corresponding author: Nwaji Godswill Nnabuihe

ABSTRACT: *The design, development and experimental performance evaluation of a hybrid flat plate solar collector/nocturnal radiator (SCONOR) with spectral selectivity surface for water heating is presented. The experimental rig comprised a natural circulation open thermosyphon system consisting of the SCONOR coupled with a 300 litre water reservoir at the Department of Mechanical Engineering, Federal University of Technology, Owerri, Nigeria (5.49°N, 7.02°E). Data were collected for several clear sunny and cloudy days. Sample tests on acrylic resin coated on a metallic substrate showed that it has clear spectral absorptivity of 0.7 in the solar heating spectrum. The ambient temperature fluctuated between 27°C and 32°C throughout the period of the experiment. The SCONOR plate attained a maximum temperature of about 80°C during diurnal heating, with a maximum water temperature of about 60°C, while a peak insolation of about 900W/m² was recorded. It was observed that the SCONOR performed best in the heating mode under low flow rate of water. The result shows that the system can be deployed to provide hot water for domestic use and space heating.*

KEYWORDS: *Hybrid flat-plate solar collector; Spectral selectivity; Optical characterization; Dynamic performance; Diurnal Heating*

Date Of Submıssıon: 28-01-2020 Date Of Acceptance: 09-02-2020

Nomenclature

T	Temperature	[K]
Q_i	Energy absorbed	[W]
Q_i	Energy lost	[W]
Q_u	Useful energy	[W]
I	Insolation	[W/m²]
FR	Collector heat removal factor	[-]
η	Efficiency	[-]
U_L	Overall heat transfer coefficient	[W/m°K]
A_c	Area of collector	[m²]
$\dot{m}$	Mass flow rate	[kg/s]
c_{p_w}	Specific heat capacity of water	[J/kgK]

I. INTRODUCTION

The increasing energy demand, insufficient grid electricity supply, increasing costs of fossil fuel resource which have been major drivers of global energy supply coupled with the attendant effects on the environment in form of pollutions, greenhouse gas emissions and general environmental imbalance are current global topical issues among policy makers. In addition, the reports that fossil fuel resources are tending towards exhaustion is reaching governments. According to Toosi [1], the world will run-out of oil in 40 years, natural gas in 60 years and coal in 180 years following the current rate of consumption. Therefore, advocacy is being made towards finding new, viable, environmental friendly and sustainable alternative energy. Solar energy is believed to have the solution to the above challenges, as it is clean and has no adverse environmental effects. Solar radiation is concentrated within 0.2-3μm spectral region known as solar radiation band and solar collectors with enhanced surface absorptivity can absorb much of this energy to be heated up within this band [2]. Worldwide, about 30 million square meters of solar collectors are currently installed [3]. Water flowing through the collector will absorb the heat which can be stored in a reservoir for low temperature applications such as domestic hot water and space heating. Balen et al [4], adjusted a flat plate thermal radiator foe heating purposes and recorded 32°C rise at 25°C ambient condition during diurnal heating during summer clear sky in Irish weather. They used polyethylene/polyphenylenoxid as a glazing material. The system provided a significant proportion of the hot water requirements during the diurnal cycle. It has also been reported that mass flow rate and sky conditions influence the performance of flat plate solar collectors. Under constant mass rate of flow, there is a smooth relationship between the plate variables and time, while time-variant mass rate of flow results in steeper variations. While in the case of constant rate of flow, a maximum temperature of about 55ºC was reached in the storage tank and for the case of time-variation of mass rate of flow yielded a 50^oC maximum storage water temperature [5]. They concluded that a time-dependent mass flow rate has important influences on the behaviour of a flat plate collector and simulations should be done consequently for a correct sizing of the system. The collector efficiency is in the range of 0.4-0.6 [6]. Nosa et al [7] recorded 40% collector efficiency in Warri, Nigeria. Baig et al [10] designed, fabricated and evaluated the efficiency of flat plate solar collector made of mild steel absorber with serpentine galvanized steel coated with zinc as fluid pipes and recorded 13% efficiency. Application of black coating on the mild steel improved the performance by raising the efficiency to about 40% under clear sky conditions. Raja et.al [8] presented investigated the top loss coefficient of flat plate collectors using water as working fluid. For different absorber plate temperatures and plate emissivitie, they reported top loss values in the range $2.5\text{-}7W/m^2K$. Nieuwoudt and Mathews [9] designed and produced a mobile solar water heater for rural households in Southern Africa. Prototype testing revealed that the system produced hot water at 60°C by mid-afternoon on a winter day, and the water still retained the hotness at about 40^oC at 8:00 p.m. on the test day. Hamed et.al [10] investigated the effects of various parameters such as inlet water temperature, water mass flow rate, tube length and number on the performances of a flat plate solar collector using water as heat transfer fluid, in Tunisia.

Glazed flat plate collectors are reputed for higher efficiencies, lower heat losses and high working temperatures in the range of $80\text{-}120^oC$. However, they are associated with high initial costs [11]. According to Duffie and Beckman [6], selective coatings have been shown to effectively maximize absorption of incident solar radiation while limiting losses in the infrared region. Invariably, highly selective coatings may be used to reach higher operating temperatures. Wang et al [12] in a combined solar heating and nocturnal radiant cooling study in Tiajin, China, using two different kinds of acrylic resins as selective coating materials, reported daily average heating efficiencies of about 50% and 30% for two kinds of resin employed. Spectral absorptivity within the solar radiation band greatly influences the efficiency and performance of solar collectors. High absorptivity and low heating losses improve the performance of collectors optimally [2, 13]. Mingke et al [13] proposed a spectral selectivity surface for both solar heating and nocturnal radiative cooling applications. They coated polyethylene terephthalate film with a titanium-based solar absorber on an aluminum substrate. An average temperature of about 109^oC was recorded during diurnal heating phase with the selective surface, with a maximum irradiation of $925W/m^2$. The present investigation seeks to develop an understanding of the dynamic performance of the diurnal phase of a hybrid flat plate solar collector/nocturnal radiator for heating of water heating for low temperature applications in the tropics.

II. METHODOLOGY

2.1 Assumptions and design conditions

(i). The SCONOR is uniformly heated during the day
(ii). The heating phase occurs for an average of 10 hours from 8am to 6pm.
(iii). No energy losses from the bottom and edges of the collector

2.2 Sizing and Thermal Design of SCONOR components

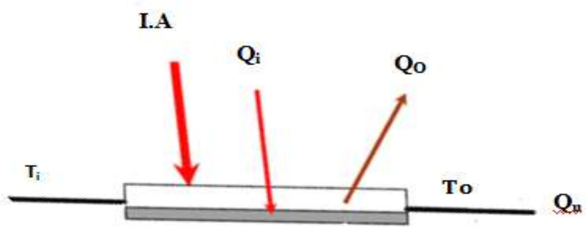

Fig 1.0: Schematic diagram of the SCONOR showing the various heat components

A transverse section of the SCONOR plate is as shown in Fig. 1.0. Solar radiation in the amount, I**,** is incident on the aperture plane of the collector having a surface area, **A**. Water enters the SCONOR at temperature, T_i and leaves at temperature T_o. According to Duffie and Beckman [17], the incident solar energy on the solar collector is expressed as:

$$Q_i = AI \qquad 1$$

where A_c is the area of the solar collector and I is the hourly incident global solar radiation on a horizontal surface.
Also, the collector energy loss is expressed as:

$$Q_o = U_L A(T_i - T_a) \qquad 2$$

where U_L is the overall heat loss coefficient, T_a is the ambient temperature and T_i is the water inlet temperature.
Therefore, the useful energy absorbed by the SCONOR can be estimated as the incident energy minus the energy loss from the surface.

$$Q_u = AIF_R - U_L AF_R(T_i - T_a) \qquad 3$$

Where F_R is the SCONOR removal factor.
The useful energy absorbed by the SCONOR may be measured by means of the amount of heat carried away by the water flowing through the tubes underneath [5, 14], in which case:

$$Q_u = \dot{m}c_{p_w}(T_o - T_i) \qquad 4$$

This is the useful energy absorbed by the water, where $\dot{m}$ is the mass flow rate of water and c_{p_w} is the specific heat capacity of water at constant pressure.
According to Ismail [15, 19], the area of a flat plate solar collector can be estimated from:

$$A = \frac{Q_u}{\eta t I} \qquad 5$$

Where η is the collector efficiency, t is is time and I is the average hourly global incident solar radiation on the collector surface.

According to NASA [16], the average hourly global solar radiation data for Owerri is given as 4.79kWh/day. For a 60 litre [kg] of water flowing through the collector, assuming water inlet temperature of 25°C and outlet temperature of 65°C, and collector efficiency of 42%, the SCONOR area exposed to the sun can be estimated as:

$$A = \frac{60 \text{ x } 4200\ (65-25)*1}{0.42\text{x}3600\text{x}4790} \cong 1.40\text{m}^2$$

Therefore, the mild steel SCONOOR absorber is made up of a total harnessing area of 1.4 m², measuring 1420 by 980mm, and underneath were welded 13 riser tubes of 12.7mm diameter each spaced at centre to centre distance of 62.5mm. A perfect thermal contact was ensured between the plate and risers. Holes were drilled on the header pipes to allow for brazing of the risers. The SCONOR surface was coated with a spectrally selective acrylic resin to enhance absorptivity within solar spectrum. A glass cover was placed 20mm from the SCONOR during the diurnal heating phase as a glazier to reduce thermal loss and convection losses. The bottom side of the SCONOR was covered with 101.6mm fibre glass to reduce heat transfer by conduction. The headers and riser tubes arrangements is as shown in Fig. 2.

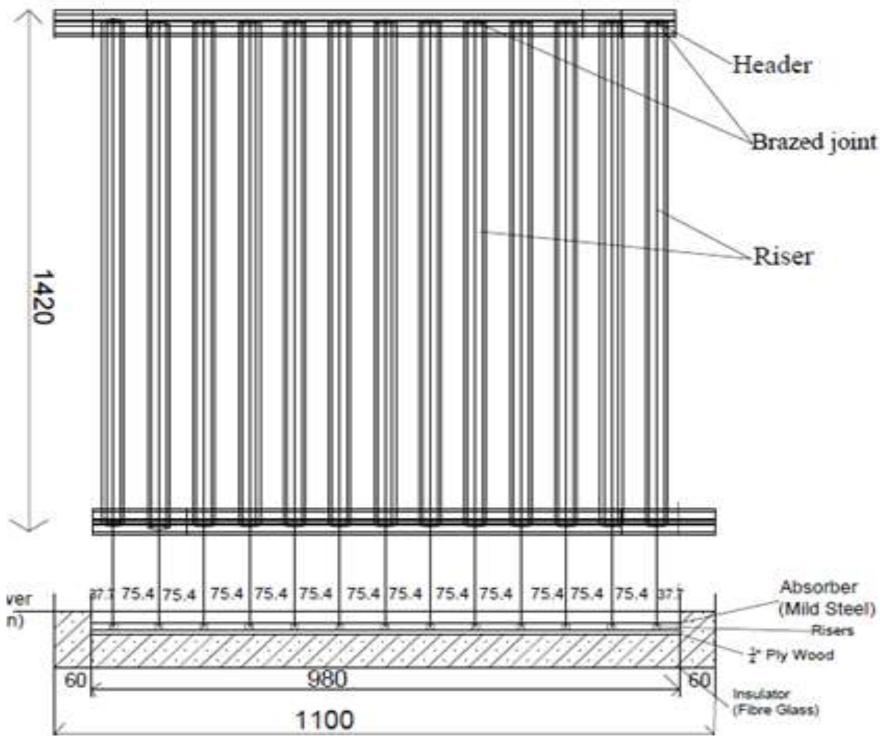

Fig 2: The headers and riser tubes arrangement

III. EXPERIMENTATION

The system was installed at the Department of Mechanical Engineering, Federal University of Technology, Owerri, Nigeria (5.49°N, 7.02°E) and mounted facing south at a tilt angle of 20.49°, in accordance with [17, 18] that the optimum tilt angle is location latitude plus 15°. The set-up comprises a hybrid flat plate solar collector/radiator and vertical storage tank with pipe networks and measuring instruments as shown in Fig. 3. The collector is of single glazed mild steel flat-plate absorber type coated with acrylic resin.

A real time monitoring system comprising several temperature measurements was incorporated. Temperature measurements were taken with K-type thermocouples on the surface of the SCONOR (T_2 and T_3), inlet and outlet positions of the SCONOR (T_1) and (T_5) respectively. The ambient temperature, (T_4) was measured using a digital thermo-hygrometer. Solar radiation data on the plane of the SCONOR was taken using a TES 1333 Solar Power Meter (Solarimeter). A data logger was employed for storing the temperature data as shown in Fig. 4. The experiment was conducted for eight days (between October 2018 to February 2019), twelve hours each day. Data were collected every 30 minutes for each of the days of the experiment.

Fig. 3: Picture of the experimental set-up

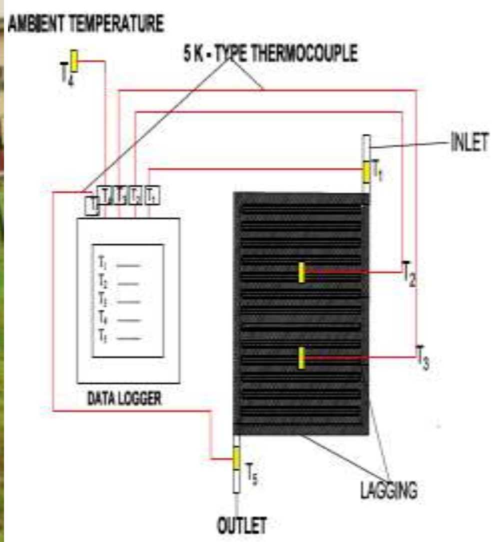

Fig.4: Data logging configuration.

IV. RESULTS AND DISCUSSION

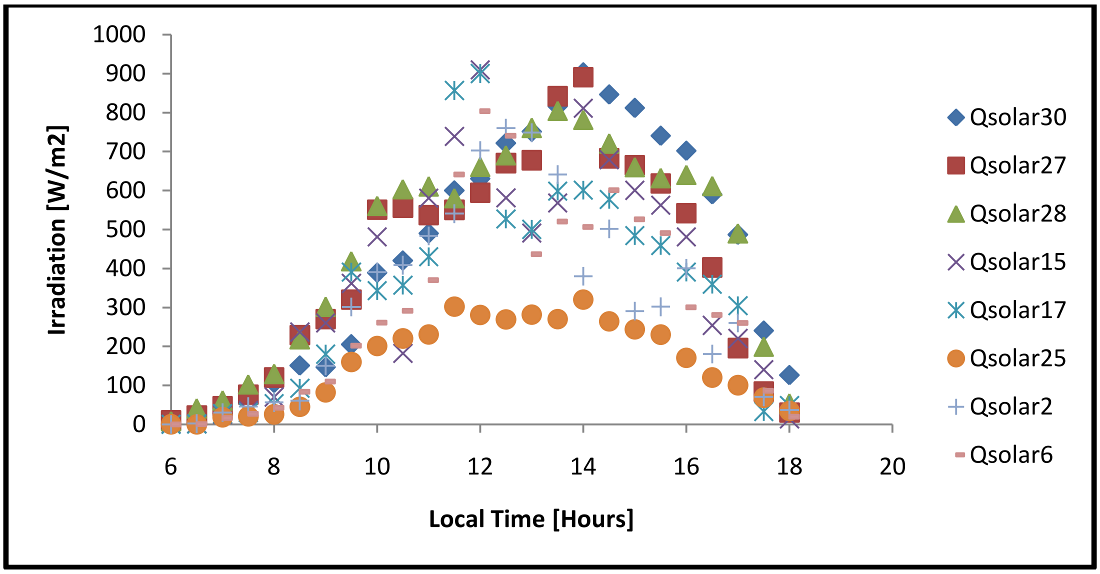

Fig. 5: Time variation of Irradiation over the experimental period

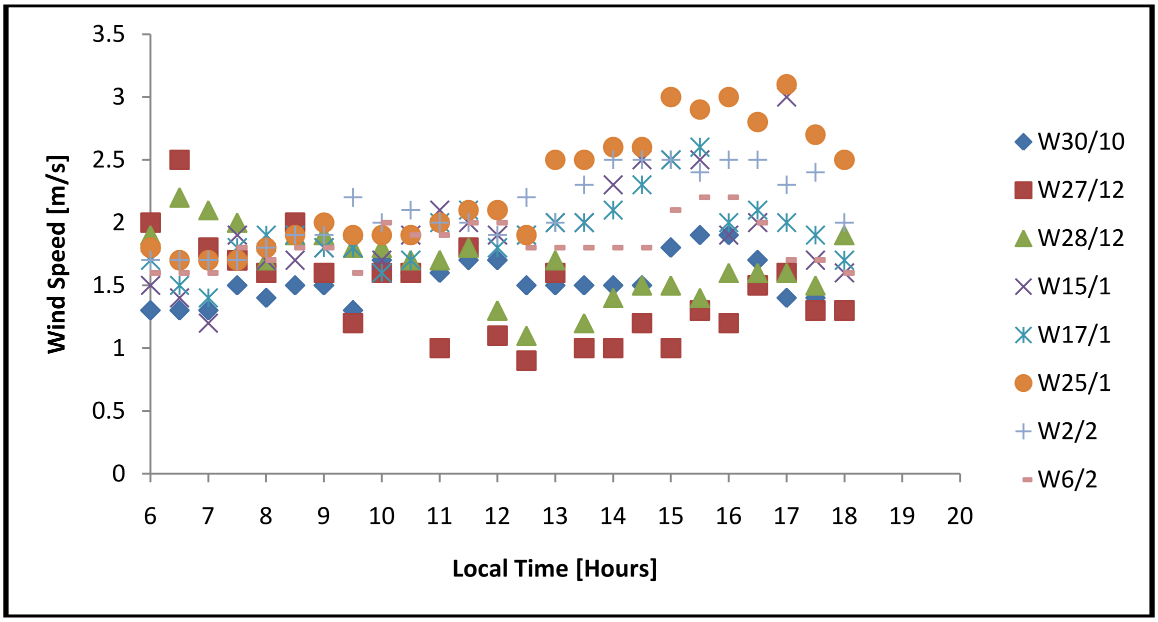

Fig. 6 Time variation of wind speed over the experimental period

The variation of hourly global solar radiation over the experimental period is as shown in Fig 5. The variation of the solar irradiance follow the same trend for the test location with maximum occurring on the 17th of January, followed by October, December and February respectively. However, the peak times of occurrence differ. The peak occurred around 12:00 hours in January while it occurred around 14:00 hours at other periods. As is expected, after mid January, the insolation decreased drastically due largely to harmattan haze and dust associated with the period. Nevertheless, the amount of insolation around the period is 320W/m^2, which is still enough to produce domestic hot water. This means that solar thermal energy devices can function effectively during the harmattan period in the tropical city of Owerri, Nigeria and other locations having similar climatic condition. As can been seen in Fig. 6, the periods of high wind intensity correspond to the periods of low irradiation. Therefore, solar intensity much depends on the prevailing wind speed in any particular location.

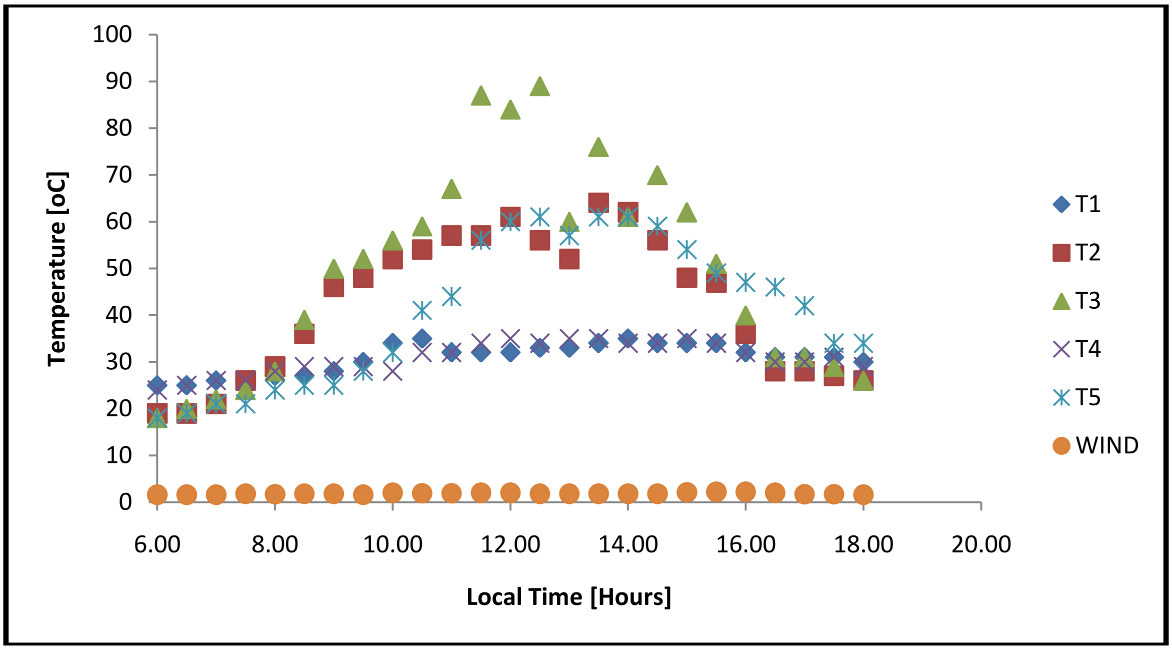

Fig. 7 Temperature variation with local time on a test day

The variation of temperature with time for a chosen test day is shown in Fig. 7 while the maximum temperatures recorded for each of the days within the test period is shown in Fig. 8. It is evident from Fig. 7 that the inlet water temperature (T_1), SCONOR temperatures (T_2 and T_3), outlet water temperature (T_5) and ambient temperature (T_4) respectively increases as the insolation. The peak SCONOR plate temperature reached a value of about 89°C at 13:30 hours on the test day while the maximum outlet water temperature was about 62°C exactly at the time of peak plate temperature. The ambient and inlet water temperatures fluctuated between 20 and 35°C throughout the test period, indicating that the SCONOR has been able to raise the water temperature by 32°C. From Fig. 8, the SCONOR plate, outlet water, inlet water and ambient temperatures decreased progressively from the first day of the experiment, October 30, 2018 to the last day, February 6, 2019. The highest outlet water temperature was 70°C in October while the least outlet water temperature of 45°C was recorded in February. It is obvious that the performance of the system was affected by wind speed and cloud cover. The day of highest wind speed corresponds to the day of lowest insolation. The performance of the system is much enhanced at low wind speeds. This is consistent with the fact that the increase in wind velocity increases the convective heat loss to environment.

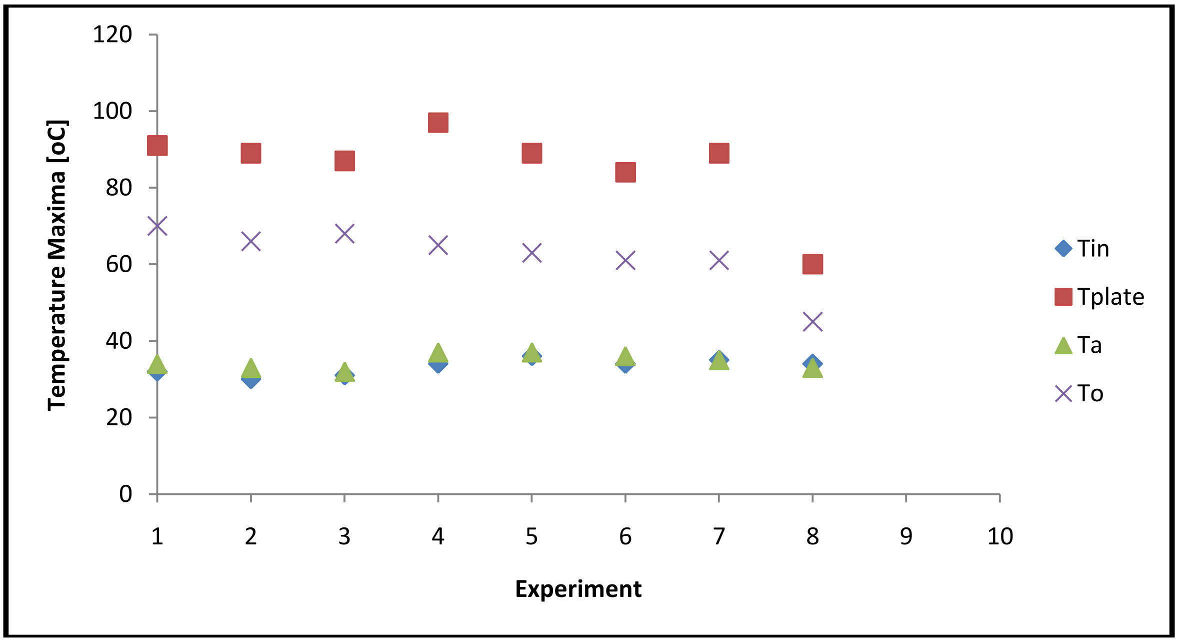

Fig. 8: Variations of daily maximum temperature over the experimental period.

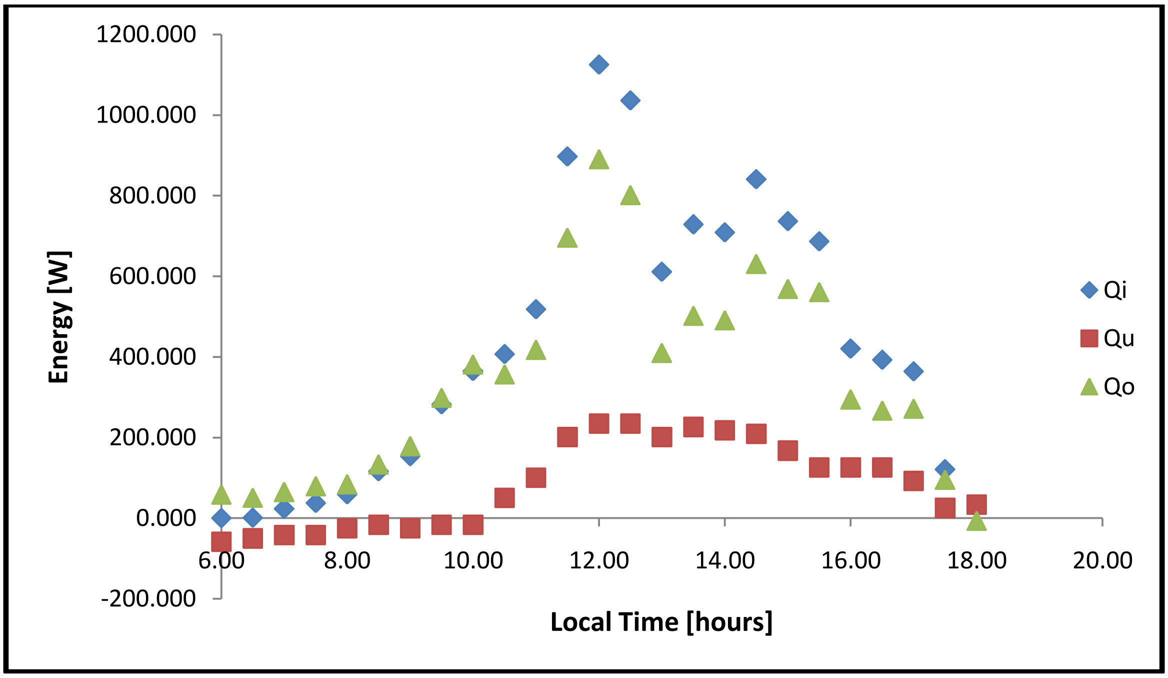

Fig. 9 Energy variation with time

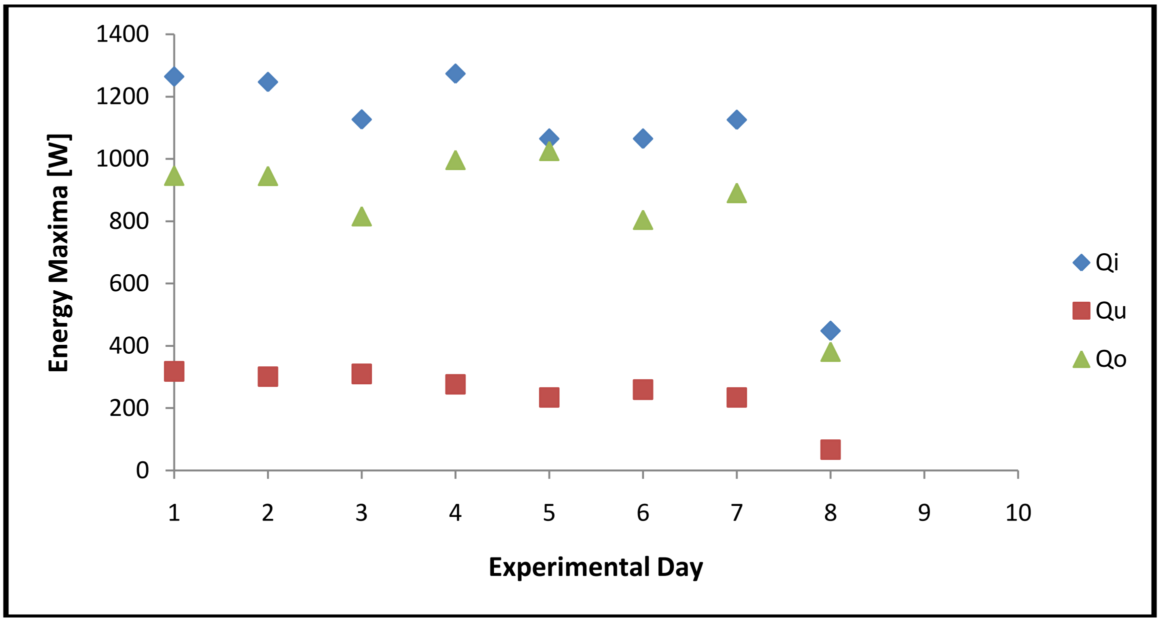

Fig. 10 Variation of thermal energy over the experimental period

From Fig. 9, peak useful energy into the fluid system occurred at peak solar insolation. It is evident that the system was associated with high rate of losses which led to low useful energy reported. The mild steel substrate was not coated with any solar absorbing material. Only the acrylic resin was coated on the substrate and during diurnal heating, the absorptivity was very low, hence, the low energy absorption recorded by the system. The efficiency solar collector depends on the temperature difference between the plate and ambient. For a given rate of solar insolation, the collector efficiency increases with decreasing differences between the plate and the ambient temperature. Fig. 10 reveals that though the system received the highest incident global radiation in January 15, the associated high loss rate limited its performance. Even though the least energy loss occurred in February 6, the best performance was recorded in December. However, the results obtained for the four months show that the system is capable of providing needed output for optimum water heating.

V. CONCLUSION

The thermal evaluation of a hybrid solar collector/nocturnal radiator for diurnal heating of water has been undertaken. The collector is made of mild steel coated with a spectrally selective acrylic resin. The results obtained show a maximum water temperature rise of 32^0C while the ambient temperature ranged from $27\text{-}35^0$C in the test location, except for cloudy days. The hybrid plate attained a maximum temperature of 89^oC and the maximum average water temperature was 62^0C. A peak insolation of 900W/m^2 was recorded throughout the test period. It can be observed that the effect of wind on the system performance is significant. At low wind speeds, convection losses are minimized and hence, the system performed better than at high wind periods or days. Polyethylene as windscreen, instead of glass cover which was placed atop the collector during the day will greatly improve the system performance by reducing wind convection. Also, using a solar absorbing coating of enhanced absorptivity on the mild steel substrate before coating the acrylic resin will improve the thermal performance of the hybrid plate during the diurnal heating. However, integration of the hybrid collector/radiator in a building envelope can ensure preparation of sufficient hot water for domestic applications as well as space heating purposes.

Conflict of Interests

The authors hereby declare that there is no conflict of interests whatsoever with the publication of this paper.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial supports provided at various times by the Tertiary Education Trust Fund (TETFUND) under its Research Grant Scheme.

REFERENCES

[1]. R. Toosi, Energy and Environment: choices and challenges in a changing world, Verve publishers' inc., L.A, USA, (2010) 409.
[2]. C.G. Granqvist, Spectrally Selective Surfaces for Heating and Cooling Applications, SPIE Opt. Engr. Press, Bellingham, USA, (1989).
[3]. N.B. Khedher, Experimental Evaluation of a Flat Plate Solar Collector Under Hail City Climate, Engineering, Technology & Applied Science Research. 8 (2) (2018) 2750-2754
[4]. I. Balen, V. Soldo, D. Kennedy, Analysis of cooling and heating of water with flat-plate solar radiators, Proceedings of Conference on Sustainable Developments of Energy, Water and Environmental Systems, Dubrovnik, Croatia (2003).
[5]. C. Stanciu, D. Stanciu, A. Gheorghian, I. Șoriga, Analysis of a flat plate collector for hot water domestic use -a sensitivity study**,** Materials Science and Engineering 147, (2016) 1-9, doi:10.1088/1757-899X/147/1/012146.
[6]. J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, (4^{th} ed.), New Jersey: Wiley Hoboken, (2013) 188.
[7]. A.O. Nosa, O. Ikponmwosa, J. Julius, Design and construction of a solar water heater based on the thermosyphon principle**,** Journal of Fundamentals of Renewable Energy and Applications 3 (2013), doi:10.4303/jfrea/235592.
[8]. S.Y. Raja, K.V. Sharma, R.M. Basaveswara, Evaluation of heat loss coefficients in solar flat plate collectors, Journal of Engineering and Applied Sciences 4 (5**)** (2009) 15-19
[9]. M.N. Nieuwoudt, E.H. Mathews, A mobile solar water heater for rural housing in Southern Africa, Building and Environment 40, (2005) 1217-1234
[10]. M. Hamed, A. Fellah, B.A. Ben, Parametric sensitivity studies on the performance of a flat plate solar collector in transient behavior, Energy Conversion and Management (2014) 938-947
[11]. S. A. Kalogirou, Solar thermal collectors and applications, Progress in Energy and Combustion Science, 30**,** (2004) 231–295.
[12]. Y. Wang, C. Yong, Z. Li, K. Jianguo, Thermal performance analysis of a solar heating and nocturnal radiant cooling system, Proceedings of 548 ISES Solar World Congress 2007: Solar Energy and Human Settlement, (2007) 545-550.
[13]. H. Mingke, G. Pei, L. Li, R. Zheng, J. Li, J. Jie, Theoretical and experimental study of spectral selectivity surface for both solar heating and radiative cooling**,** International Journal of Photoenergy, Vol 2015, (2015) http://dx.doi.org/10.1155/2015/807875.
[14]. I. Mohd, Y. Anshul, S. Rajnish, K. Anil, Mathematical modelling and performance analysis of singlepass flat plate solar collector, Materials Science and Engineering 404, (2018) 1-11, doi:10.1088/1757-899X/404/1/012051
[15]. S.S. Rao, Utilization, generation and conservation of electrical energy, Khana publishers, Delhi, India (2007) 187.
[16]. National Aeronautic and Space Administration (NASA), Metereological data for Owerri (2002)
[17]. A. Rostamzadeh, M. Adim, S. Sabzi, Experimental and Numerical Study of Forced Circulation Solar Water Heaters, Proceedings of the Global Conference on Global Warming, Lisbon, Portugal, (2011) 1-6.
[18]. S. Kalogirou, Solar Energy Engineering: Processes and Systems, First Edition, Academic Press Publications, USA, (2009).
[19]. M.M. Baig, M.A. Khan, M.K.M. Uddin, M.R. Malik, M.W. Hague, Calculation and fabrication of a solar flat plate collector efficiency using mild steel as absorber plate, International Journal of Science Technology & Engineering 3 (8), (2017) 36-41

Nwaji Godswill Nnabuihe, et.al. "Experimental Investigation of the Diurnal Phase of Hybrid Water Heating/Nocturnal Cooling Flat-Plate Solar Collector in Owerri, Nigeria" *International Journal of Engineering Inventions*, Vol. 09(01), 2020, pp. 01-08.