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Study of a passive solar air heater using palm oil and paraffin as storage media

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ABSTRACT

This study evaluated a passive solar air heater using different storage media. The heater, which is very useful in low temperature applications like agricultural produce drying and heating of buildings, is made up of a double-glaze solar thermal collector of a flat plate type coupled with thermal storage medium. The heater was replicated using paraffin and palm oil as storage medium for systems 'a' and 'b' respectively. The evaluation of the systems without load under 24-h periods were carried out experimentally in Nsukka, Enugu State, Nigeria, within the weather temperature and daily radiation of 23.6–32.4 °C and 11.6–21.1 MJ m^{-2} respectively. The peak cumulative efficiencies were 57.3% for system 'b' and 46% for system 'a'. Similarly, the mean efficiencies were 38.4% and 41.0% for systems 'a' and 'b' respectively. The results prove that for low temperature applications the systems can successfully be implored. From the study, it can be concluded that the use of palm oil as storage medium for solar air heaters is a good substitute for paraffin which is a non renewable medium with its future uncertainties due to depleting global crude oil reserves.

1. Introduction

As the exhaustibility of conventional energy forms are well established, it is imperative to utilize renewable sources of energy to satisfy the global energy demand [1]. Renewable energy is seen as one clean source whose effective use reduces negative impact on the environment and is sustainable [2]. Solar energy is the basic and most available non-conventional source of energy and its most viable use is supplying of heated air for mainly agricultural drying and space heating operations for low-temperature applications [3–5]. However, as a result of intermittent nature of solar energy, the use of it in this form is limited. Hence, thermal energy storage system can help in effective use of solar energy based systems. Solar thermal storage is mainly used in active air heaters for supply of heated air when sun sets [2,6]. Accessing solar energy using active systems is relatively costlier than passive [5]. One challenge facing the widespread use of passive systems is reduced energy production when the sun sets. Hence, solar thermal energy storage provides a workable solution to this.

Recent studies favor the use of paraffin as a thermal storage medium for low temperature systems [7–11]. However; the authors have not really considered the fact that paraffin is non-renewable with its future uncertainties. Therefore, there is the need for further work on sustainable storage media.

Palm oil, with its characteristic thermal properties [12] and ease of accessibility as a biomass resource have not been considered in the literature. Use of palm oil as a storage medium is therefore considered for this study.

Ojike [12] has designed a solar air heater which was used to incubate poultry eggs. This air heater has inbuilt paraffin as a storage

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Nomenclature		*Subscript*	
A	area (m^2)	c	solar collector
C	specific heat ($J\ Kg^{-1}K^{-1}$)	amb	ambient
G	Solar radiation at the plane of the solar air heater ($w\ m^{-2}$)	p	paraffin
		po	palm oil
m	mass (Kg)	ig	inner glass cover
T	Temperature (K)	og	outer glass cover
V	Volume (m^3)	t	absorber plate
Q	Thermal quantity (J)	s	storage medium
ρ	density ($kg\ m^{-3}$)	l	collector outlet
η	cumulative efficiencies (%)	cm	mid-chamber
		co	chamber outlet

medium. In this study, this design shall be considered by comparing the use of paraffin and palm oil as storage media. This is to determine the output temperature of the heated air and useful thermal efficiencies.

2. Description of the solar air heater

Fig. 1 shows the solar air heater photograph considered in the study. The heating chamber housed the solar collector with thermal storage in addition to air-heating column. The air heater was replicated twice as systems 'a' and 'b' which used paraffin and palm oil as thermal storage medium respectively. The thermo-physical properties of storage media are shown in Table 1.

System 'a' made of paraffin, with mass of 11.5 kg, is contained in a rectangular steel box neatly laid so that its top formed absorber plate with selective surface with the side and bottom parts of the box well insulated using fiber glass. The rectangular walls of the box with depth as 0.03 m act as thin fins. Hot air is generated at the gap between the top of the absorber plate and the inner glass cover (Fig. 2).

As shown in Fig. 2, air at ambient conditions enters the solar collector where it is heated and flows into the working column, from where it is exited through air outlets. In the system, the flow of air is by naturally driven convection. Considering the experimental site latitude, the collector is inclined 17^0 S towards equator [13]. The system air heating column and working column are 0.022 m^3 and 0.08 m^3 respectively. System 'b' is a replication of System 'a' except that the storage medium in system 'b' is palm oil. For fair comparison between the two storage media they must be subjected to the same condition, in this case exposure to equal amount of solar radiation (i.e. the same absorber plate surface area).

To determine the equivalent quantity of palm oil to be used the following calculations were done. Total heat, Q_p needed to raise the paraffin in melting point temperature:

$$Q_p = m_p\,[C_p\,(T_p\text{-}T_{amb})] \tag{1}$$

In Ojike [12], the storage medium was designed not to exceed the melting point temperature, hence the use of equation (1). The mass of palm oil, m_{po}, to store the same quantity of heat needed for the system and assuming it is sustained at the melting point temperature of paraffin T_p (that is, $T_p = T_{po}$) is

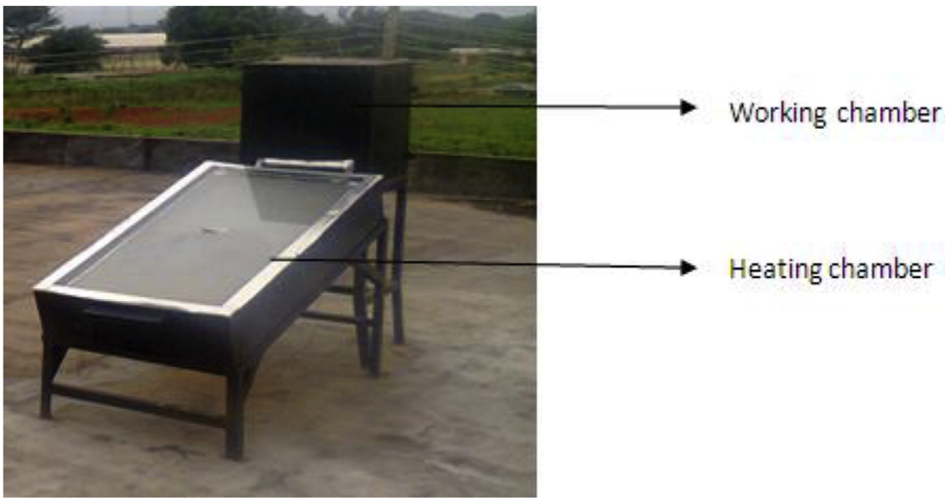

Fig. 1. Solar air heater photograph.

Table 1
Thermo physical properties of paraffin wax (RT60) and palm oil at ambient temperature [5,9and12].

Property	Paraffin Palm Oil
Specific heat J (kg K) $^{-1}$	900 1900
Melting temperature °C	59[a] -
Heat conductivity W (m K) $^{-1}$	0.2 0.17
Enthalpy/heat of Fusion kJ kg^{-1}	214.4 -
Solid state density kg m^{-3}	850 -
Liquid state density kg m^{-3}	775 877
Viscosity kg (m s) $^{-1}$	1.07×10^{-6} 16.93×10^{-3}

[a] From laboratory result.

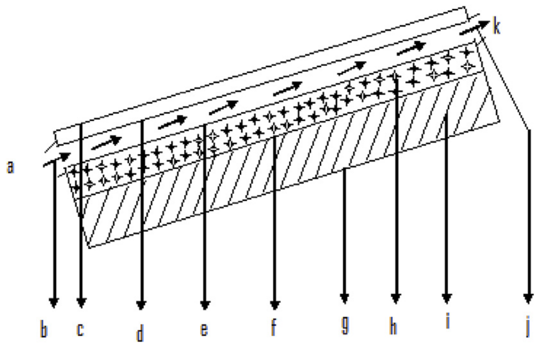

Fig. 2. Schematic diagram of the heating chamber.

$$m_{po} = \frac{Q_p}{[C_{po}(T_{po} - T_{amb})]} \tag{2}$$

The volume, V_{po} the palm oil occupies is

$$v_{po} = \frac{M_{po}}{\rho_{po}} \tag{3}$$

The depth of the storage tank H_c, is as given in equation (4) where A_c is the area (m^2) of the solar collector which is the surface area of the storage tank.

$$\mathrm{H_c} = \frac{\mathrm{V_{po}}}{\mathrm{A_c}} \tag{4}$$

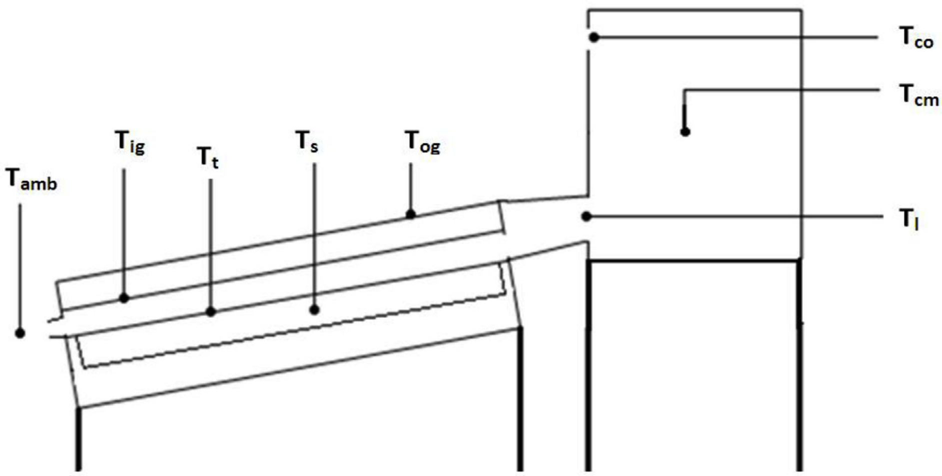

Fig. 3. Locations of Temperature Monitoring Instruments in the Solar air heater.

A high quality palm oil was bought from Nsukka palm oil market, Nigeria.

3. Materials and methods

The performance evaluation of the systems was carried out in University of Nigeria, Nsukka. Temperatures readings were done with MTM-380SD thermometer monitor made in Taiwan using k type thermocouples wires. The instrument has an uncertainty value of ± 0.5. Thermal glue, 'modified acrylic adhesive' was used to fix hot point junctions of the thermocouple wires at the components of the systems shown in Fig. 3. Temperature readings of 30 min interval between 6:30 a.m. and 6:30 a.m. local time of the following day over a three month period were used to compare thermal performance evaluation of the systems and the cumulative efficiencies of the systems (η_{nc}) determined. The months were September to November, 2017. For effective evaluation, three days were chosen within this period.

These days were 10th November, 3rd October and 18th November representing the highest solar radiation day, intermediate solar radiation day and lowest solar radiation day for the period respectively. Kimo-solarimeter, model SAM 20, made in France was used to measure instantaneous solar irradiance at 5 min intervals. Collector inlet air velocity, V_{Amb} was measured with a digital meter, AM-4822 Anemometer, model no. N296898. $\dot{m}_{amb}$ is the mass rate of air flow given as in equation (5) where density, ρ_{amb}, was evaluated assuming air to be a perfect gas with definite pressure.

$$\dot{m}_{amb} = \rho_{amb} v_{amb} A_{amb} \tag{5}$$

A_{amb} is the air inlet cross-sectional area. Equation (6) showed the thermal gain rate $\dot{Q}_u$, of heated air.

$$\dot{Q}_u = \dot{m}_{amb} c_{amb} (T_l - T_{amb}) \tag{6}$$

Equation (7) gives the cumulative efficiency η, at any time as

$$\eta = \frac{\int_0^t \dot{Q}_u dt}{A_c \int_0^t G dt} \tag{7}$$

4. Experimental results

Table 2 shows a three-day evaluation data of the systems for the total solar radiation and ambient temperature with 10th November having the highest solar radiation as well as the maximum ambient temperature.

The temperature flow of the ambient, absorber plates and outlet air for the two systems and daily irradiance for the test period is shown in Fig. 4 where *Tamb, Tta* and *Tla* are the ambient, absorber plate and air outlet temperatures for system 'a' while *Ttb* and *Tlb* are the absorber plate and air outlet temperature for system 'b' respectively. As sun began to rise, radiation value started increasing till it reached its peak period. After this, radiation decreased till sunset at about 06:30 PM h. The minute's fluctuations of the daily irradiance were as a result of several factors such as inconsistent cloud cover and fluctuating ambient humidity [14]. All the temperatures vary in line with the solar radiation. Generally, the absorber plate had the highest temperature while the ambient was the least for all points. The outlet air temperatures of the system 'b' were higher than that of system 'a'. In all cases, the generated heated air, that is the outlet air temperatures were greater than the ambient temperatures. The higher temperatures of the systems above ambient when the solar radiation is already zero shows the impact of using storage systems.

Table 3 shows the mean air temperature for the solar air heaters. For all days, generated mean air temperatures were more than mean ambient temperatures by more than 10 °C.

The temperature flow of the storage media and the glass covers of the air heaters is shown in Fig. 5 where *Tsa, Tiga* and *Toga* are the storage, inner and outer glass temperature for system 'a' respectively and *Tsb, Tigb* and *Togb* are the storage, inner and outer glass temperature for system 'b' respectively. It may be seen in comparison to Fig. 4 that as the solar radiation rises to the peak that the storage medium temperatures of the system 'a' rise higher than that of system 'b'. Then gradually as the sun is setting, the paraffin temperature drops to that of system 'b'. This fall continues until the early morning hours when it visibly drops below palm oil temperatures. This can be explained by considering the fact that paraffin has higher thermal conductivity (Table 1) than palm oil. Hence, with increasing solar radiation paraffin absorbs heat faster than palm oil and rises higher in temperature while as the radiation falls, paraffin losses heat faster and drops faster than palm oil in temperature. Similarly, the inner and outer glass cover temperatures for the systems at all periods run in line with the storage temperatures (Fig. 5).

Table 2
Daily solar radiation and temperature characteristics.

Date	Total Solar (± 0.8)	Ambient Temperature (°C) (± 0.5)		
	Radiation (MJ m^{-2})	Min.	Mean	Max.
3 October	14.7	24	26.9	31.1
10 November	21.1	24.2	27.6	32.4
18 November	11.6	23.6	26	30.4

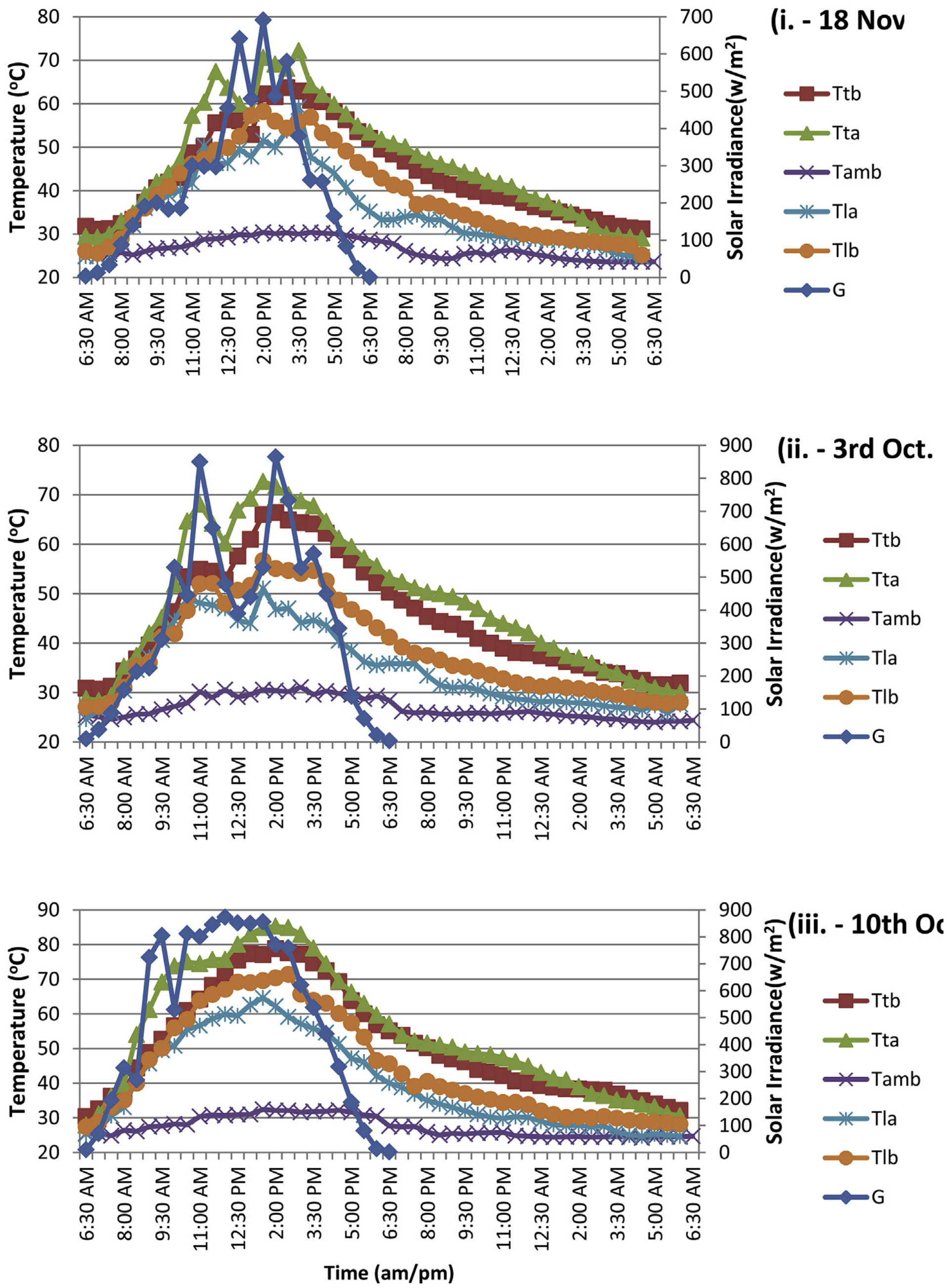

Fig. 4. Daily irradiance and temperature profiles of absorber plate, ambient and air outlet.

Table 3
Daily mean heated air temperature characteristics.

Date	Ambient (°C) (± 0.5)	System 'a' (± 0.5)	System 'b' (± 0.5)
3 October	26.9	37.66	39.62
10 November	27.6	43.69	42.41
18 November	26	38.64	39.58

Table 4 shows the cumulative efficiencies of the systems. System 'b' showed higher mean efficiency than system 'a'. However, on 10th November, system 'a' had better efficiency. This could be explained by considering Table 2 that showed that 10th November had extremely high solar radiation, hence, paraffin of system 'a' with higher thermal conductivity gave higher rate of heat transfer to the

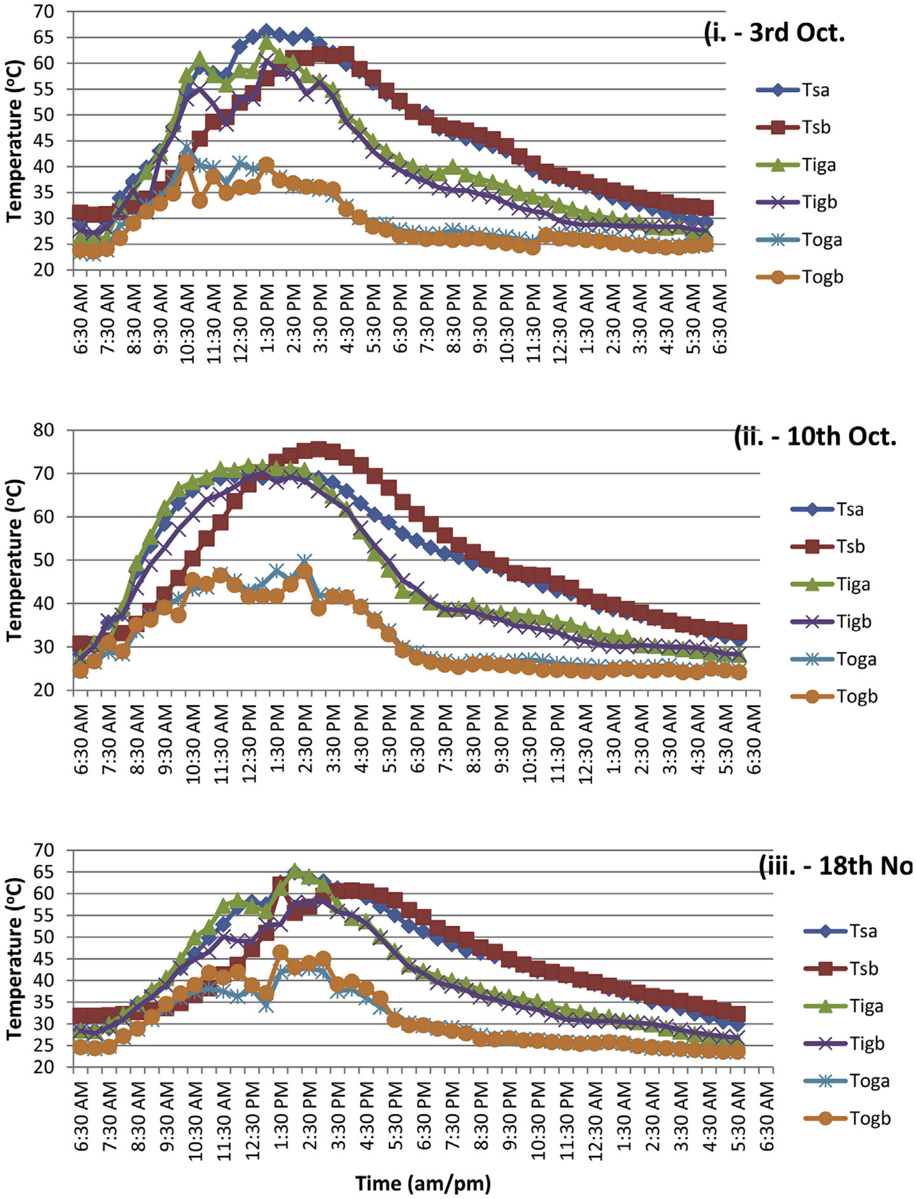

Fig. 5. The temperature profile of the storage media and glass covers.

Table 4
Cumulative efficiency.

Date	System 'a' (%)	System 'b' (%)
3rd Oct.	34.5	36.3
10th Nov.	34.5	29.5
18th Nov.	46.3	57.3
Mean Efficiency	38.4	41.0

heated air while palm oil with lower thermal conductivity could not transfer the generated heat to the heated air.

The day with low solar radiation showed better efficiencies with higher cumulative efficiency for both systems. The low daily efficiencies were due, in part, to the relatively low volumetric heat capacity and low conductivity of air, as observed by Pottler et al. [15]. These efficiencies are welcomed development when compared to an efficiency of 17–22% for single cover systems as obtained in the literature [5,9]. This has given credence to the use of double glazing as used in this study and as suggested by Duffie and Beckman [14] for improved efficiencies.

5. Conclusion

The study of two thermal storage media had shown that palm oil which had not been considered in the literature as a solar thermal storage medium had higher mean efficiency than paraffin. Equally, the two systems generated heated-air all through the off-sunshine periods of the study. Hence, for low temperature solar air heaters both systems can successfully be implored. From the study, it can be concluded that the use of palm oil as storage medium for solar air heaters is a good substitute for paraffin which is a non renewable medium with its future uncertainties due to depleting global crude oil reserves.

Declarations of interest

None.

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