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Evaluation studies of a mixed mode solar kiln with phase change material and distributed-type solar kiln

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HIGHLIGHTS

- Comparatively, efficiency of mixed-mode solar kiln is lower than distributed type.
- Kiln with PCM as storage medium showed all-time higher temperatures than ambient.
- Mixed-mode and distributed kiln performs better in the day and night respectively.

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ABSTRACT

The passive thermal performance of a distributed and mixed-mode model solar kiln was compared in the present study. The two kilns were made of double glazed flat plate thermal collector in which paraffin was used as the thermal storage medium. The range of ambient temperatures and daily radiation during the period when the study was carried out were 18.3–33.2 °C and 11.8–20.9 MJ m^{-2} respectively. The study revealed a peak cumulative efficiency of 44.3% and 40.7% for distributed kiln and 40.7% for mixed mode type. An average efficiency of 38.8% was obtained in the mixed-mode and 43.0% in the distributed type. The results show that low temperature operations such as drying of agricultural produce can conveniently be carried out with these solar kilns. The use of paraffin in the study ensured that the temperatures of the system were all time higher than the ambient temperature. Hence, when mixed-mode type is intended to be used at sun-sets, it is suggested that the top glazing of the working section should be covered with opaque materials to reduce the thermal loss as a result of the glazing to enhance efficient heat utilization.

1. Introduction

It is now an establish fact that the convectional sources of energy available for human utilization is limited [1]. It is therefore necessary that alternative resources are sourced for sustainability of existence on earth. In this respect, solar energy is the readily available resource of which generation of heated air in solar kilns is its major usage [2,3]. Hence, passive solar kilns have been found very fit to rural dwellers of non-fully developed nations where certainty of electricity is unpredictable. However, the major obstacle to its use is low or zero production of energy at sun sets [4]. This obstacle can easily be overcome by the incorporation of heat energy storage systems to the solar kilns [5]. Among the heat storage media, current studies have proven phase change materials (PCM) and in particular paraffin to be the most suitable material especially for agro-activities and other low temperature operations [1,3,4,6]. In

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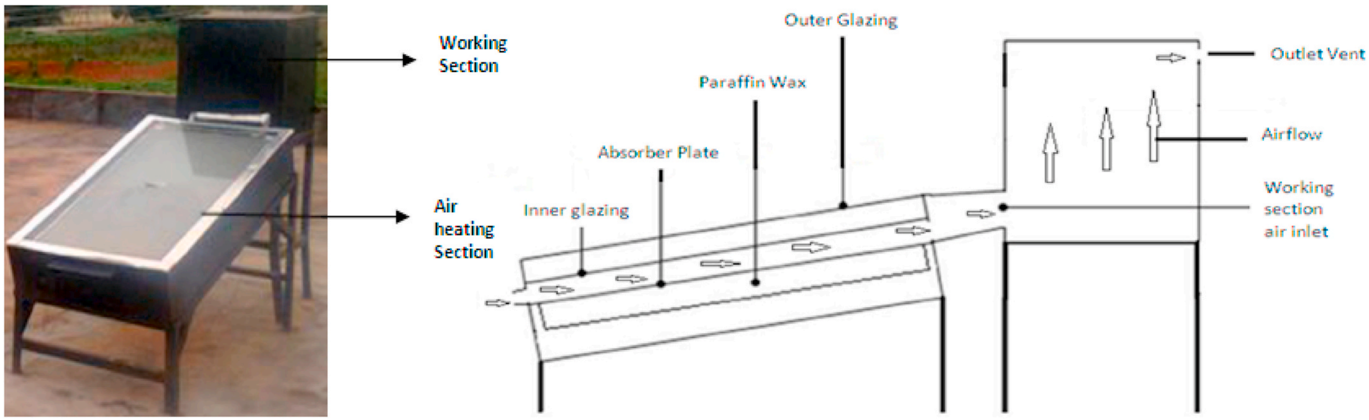


Fig. 1. Distributed model of the solar kiln used.

supporting this, Sajawal et al. [7] did a heat performance study of finned tube with and without thermal storage system (TSM) using a double pass solar air heater and concluded that the overall average thermal efficiency of tube with TSM (paraffin wax) is almost 15% higher than the ones without TSM. Loem et al. [8] studied the heat behaviors of melting/solidification of low temperature PCM using paraffin wax balls packed bed which led to the development of correlations that was used in determining at a given time and paraffin thickness the temperature of air leaving the bed. In a study by Hlimi et al. [9] on the impact of Rayleigh number during a passive melting process of PCM inside a horizontal cylinder, it was discovered that even though heat conduction in the initial stages of the process is very pronounce, the final shape and temperature of melts show the significance of passive thermal transfer at the melt region. One hindrance to the effective use of PCM is low thermal conductivity; however this can be overcome by the use of fins [10]. Hence, Abdulateef et al. [11] worked on enhancing fin parameters for improved melting/solidification of PCM in a heat exchanger unit. Equally, the use nano-additives have shown to improve the thermophysical properties PCM [12,13].

Distributed and mixed-mode solar kilns are part of different types of solar kilns [14]. Heated air produced in the thermal collector flows into the working section of the distributed solar kiln. The working section is where the thermal energy is utilized for drying activities and receives no direct solar radiation, while in mixed-mode system, solar radiation falls on both the thermal collector and the working section. A development of this model of solar dryer for wood drying using stone as TSM to improve the drying efficiency during sunsets was done by Ugwu et al. [14]. Abubakar [15] reviewed several works on the utilization of solar kiln technology. Agrawa et al. [16] evaluated different materials for solar absorption. Tvagi et al. [17] studied the thermal behaviors of solar dryers using either TSM or none. Various evaluation studies of different types of kilns with TSM have independently been carried out. On the other hand, side-by-side study evaluation of different models of solar kilns is rarely done [1,5]. This study is an effort to carry out side-by-side comparative study of two different modes of solar kiln.

2. Solar kiln description

Fig. 1 shows the distributed type solar kiln composed of two chambers: the air-heating and the working sections. The solar thermal collection and TSM are carried out in the first section. The details of the air heating section have been given in Ojike and Okonkwo [1]. Paraffin was used as the medium for heat storage with known heat and physical characteristics (Table 1). The top surface of a box made of steel filled with 11.5 kg of the paraffin served as the absorber plate while its bottom and sides were properly insulated with fibre glass of thickness 0.06 m to reduce heat loss. As can be observed in Fig. 1 air flowing between the inner glazing and the absorber plate by natural convection is heated by the absorber plate and then to the working-section where it is then discharged through the outlet vents. In-line with [18], the collector is incline 17° S to reflect the latitude of the site [18]. The solar kiln air heating section is 0.022 m^3 while the working section is 0.08 m^3 in volume.

Fig. 2 shows the mixed-mode model which is of the size and characteristics as Fig. 1 apart from the glazed top of the working-section. The inclination of this glazed top is 22° to the horizontal as shown. This is to reduce the dust effect on the glazing [18].

3. Experimental procedure

The study was done at the University of Nigeria, Nsukka. 24-hour temperature readings of 30 min interval over a three month (November 2019 to January 2020) time was recorded using a MTM-380SD thermometer monitor manufactured in Taiwan with k-type thermocouples wires fixed at mid position of various parts of the kilns (Fig. 3) where T_{ab}, T_{ig}, T_{og}, T_{hf}, T_{pa} and T_{op} represent the absorber plate, inner glazing, outer glazing, collector air column, paraffin and working chamber temperature respectively. The temperature-meter's uncertainty value is ±0.5 with a temperature range of 0–200 °C.

The solar mean days (14th November, 10th December and 17th January) for the months selected were used for the evaluation study [19]. The solar radiation (R_T) was measured with Kimo-solarimeter, model SAM 20, made in France. AM-4822 anemometer with model number giving as N296898 was used to measure the inlet air velocity (V_{inlet}). The instantaneous and cumulative efficiencies of the kilns (C_{eff}) are given as eqs. (1) and (2) respectively.

$$C_{eff} = \frac{\dot{H}_{out}}{\dot{H}_{in}} \tag{1}$$

Table 1
Paraffin wax (RT60) heat and physical characteristics at room temperature [1].

Characteristics	RT60
Specific heat capacity	900 J $(kg\ K)^{-1}$
Melting temperature	≈59 °C
Heat conductivity	0.2 W $(m\ K)^{-1}$
Enthalpy	214.4 kJ kg^{-1}
Solid state density	850 kg m^{-3}
Liquid state density	775 kgm^{-3}
Viscosity	1.07×10^{-6} kg $(m\ s)^{-1}$

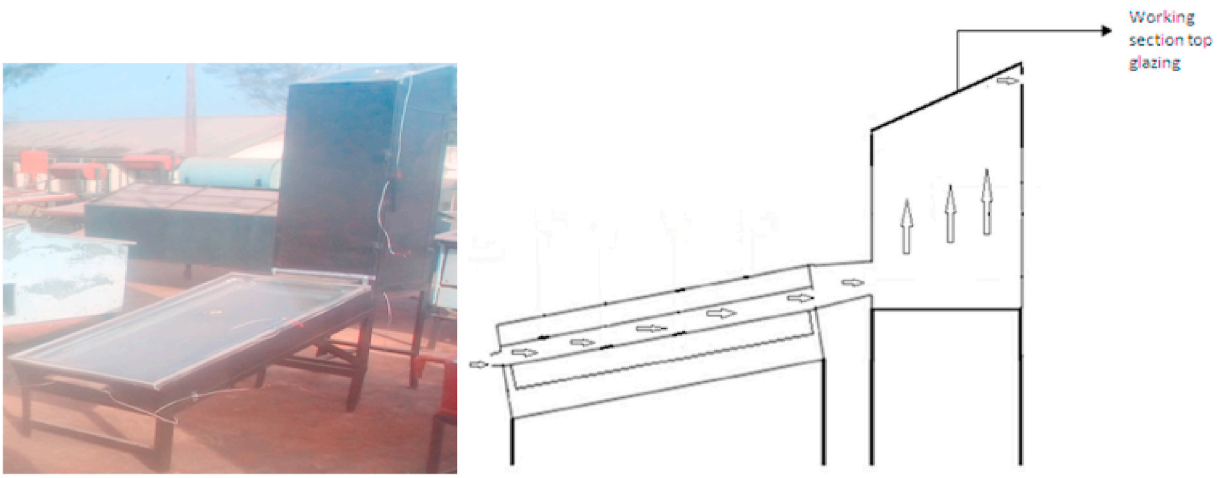


Fig. 2. Mixed mode model.

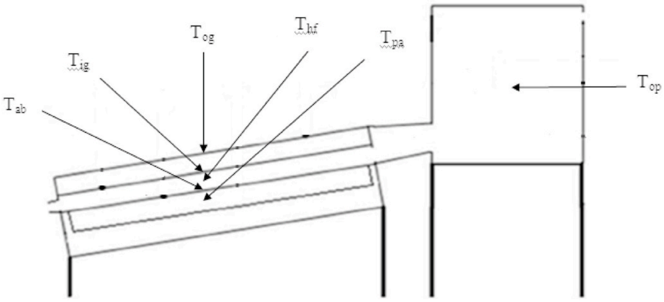


Fig. 3. Schematic position of thermocouples on the kiln.

$$C_{eff} = \frac{\int_0^t \dot{H}_{out} dt}{\int_0^t \dot{H}_{in} dt} \tag{2}$$

where

$$\dot{H}_{in} = A_c R_T - \dot{H}_{st} \tag{3}$$

A_c is the solar collector area for the distributed type; for mixed-mode, it is the area of the solar collector in addition to the area of the top glazing cover of the working section (Fig. 2). R_T is the solar radiations intensity at the plane of the collector given as

$$R_T = R_b R a_b + R_d[(1 + cos\beta) / 2] + R\rho_g[(1 - cos\beta) / 2] \tag{4}$$

where the components of Equation (4) are as defined in Ref. [19].

$\dot{H}_{st}$ is the stored energy as a result of the storage medium given as:

$$\dot{H}_{st} = \dot{H}_{paraffin} + \dot{H}_{mild \quad steel} \tag{5}$$

$\dot{H}_{paraffin}$is energy in the paraffin expressed as

$$\dot{H}_{paraffin} = m_{paraffin} c_{paraffin} \Delta T_{paraffin} \Big/ \Delta t \tag{6}$$

$\dot{H}_{mild \quad steel}$, energy in the absorber plate housing the paraffin given as:

$$\dot{H}_{mild \quad steel} = m_{mild \quad steel} c_{mild \quad steel} \Delta T_{mild \quad steel} \Big/ \Delta t \tag{7}$$

$\Delta T_{paraffin}$ is the temperature difference in paraffin, $\Delta T_{mild \quad steel}$ is that of absorber plate. $\dot{H}_{out}$ is the gain in thermal energy of the working chamber air given as:

$$\dot{H}_{out} = \dot{m}_{air} c_{air} (T_{wa} - T_{am}) \tag{8}$$

T_{am} *and* T_{wa} are the ambient and working-section inlet air temperatures respectively; the air mass flow rate ($\dot{m}_{air}$) is given as:

$$\dot{m}_{air} = d_{air} V_{inlet} A_{am} \tag{9}$$

d_{air} is the density of air while area of inlet air vent for the heating-section is A_{am}.

4. Uncertainty analysis of the study

Uncertainty analysis was carried out as a result of measurements done using the thermocouples, solarimeter and air flow meter by following the method outlined in Ref. [7,20]. The Fractional uncertainty in the efficiency is given as:

$$\frac{\partial C_{eff}}{C_{eff}} = \sqrt{\left(\frac{\partial \dot{H}_{out}}{\dot{H}_{out}}\right)^2 + \left(\frac{\partial \dot{H}_{in}}{\dot{H}_{in}}\right)^2} \tag{10}$$

Considering the fact that $\dot{H}_{out} = f(\dot{ka}_{am}, T_{wa}, T_{am})$, the fractional uncertainty for the gain in thermal energy is then given as:

$$\frac{\partial \dot{H}_{out}}{\dot{H}_{out}} = \sqrt{\left(X_{\dot{ka}_{am}} \partial X_{\dot{ka}_{am}}\right)^2 + \left(X_{T_{wa}} \partial X_{T_{wa}}\right)^2 + \left(X_{am} \partial X_{am}\right)^2} \tag{11}$$

The fractional uncertainty for the input energy is expressed as:

$$\frac{\partial \dot{H}_{in}}{\dot{H}_{in}} = \sqrt{\left(\frac{\partial [A_c R_T]}{[A_c R_T]}\right)^2 + \left(\frac{\partial \dot{H}_{pa}}{\dot{H}_{pa}}\right)^2} \tag{12}$$

Solving eq. (10)-(12) leads to fractional efficiency of 3.87% and 4.54% for the distributed and mixed-mode type kilns respectively. The higher value in the mixed –mode was as a result of the uncertainity in the solar radiations which is more in this type of the solar kiln.

5. Experimental results

Table 2 shows that the ambient temperature and solar radiation during the study is between 18.3 and 33.2 °C; and between 11.8 and 20.9 MJ m^{-2} respectively. The ambient (*Tamb*), working-section (*Top*) and air-heating section (*Thf*) temperature flow for the kilns-distributed (*d*) and mixed-mode (*m*) including the solar radiation (*RT*) for the study period is graphically displayed in Fig. 4 while the temperatures of the absorber plates (*Tab*) and paraffin (*Tpa*) are in Fig. 5. It is noticed that, all the temperatures flow in pattern with the solar radiation. In all, *Tamb* were least while *Thf* had the maximum temperatures. When solar radiation falls on the collector, the absorber plate absorbs solar radiation and converts it to heat energy. Since the absorber plate is in thermal contact with both the thermal storage medium and the working fluid, the absorbed energy is shared between the two components apart from the loss due to radiation from absorber plate to the glazing. The proportion of energy received by each depends on its thermal properties. Hence, paraffin with higher thermal conductivity (0.2 W/mK) and lower specific heat capacity (0.9 kJ/kgK) gave higher temperature values at any given time than air, the working fluid with thermal conductivity and specific heat capacity of 0.026 w/mK and 1.012 kJ/kgC respectively. Equally, during sunsets when the heat energy need is purely released by the thermal storage medium, the temperature values of paraffin were still higher than that of heated air. This is because of the fact that the rate of heat flow from the thermal storage medium to the working fluid via absorber plate is drastically affected by the low thermal conductivity and higher heat capacity of air. As solar irradiance starts reducing from the peak period less heat energy is available for storage medium and increasing quantity of stored energy is conveyed by the moving air into the working section. This continues till the minimum value is attained around 6:30a. m when solar radiation starts heating up the system again.

Close looks at the graphs reveal that, as *RT* increases in the morning hours to its peak from 7:30 a.m. to around 3:300pm that the mixed-mode temperatures rise more than the distributed type. This is because of the additional solar radiation coming from the top glazing of the working-section of the mixed-mode kiln. However this gain in thermal energy especially in the PCM is not retained as the sun sets, it can easily be noticed that the temperatures of the mixed-mode fall below that of the distributed kiln. This is as a result of the fact that much heat is lost through the same top glazing of the mixed mode kiln [19]. In all cases the difference between the inlet and

Table 2
Daily solar radiation and temperature characteristics.

Date	Total Solar Radiation (MJ m^{-2})	Ambient Temperature (^{0}C)		
		Min.	Mean	Max.
14 November	11.8	18.8	26.57	30.0
10 December	15.6	21.5	29.06	31.1
17 January	20.9	18.3	25.76	33.2

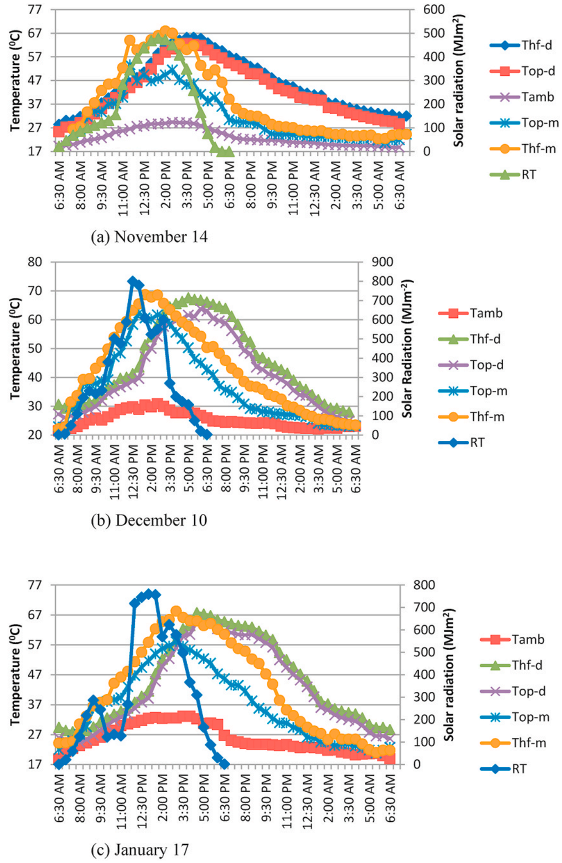


Fig. 4. Daily irradiance and temperature profiles of ambient, air-heating and working chamber respectively.

outlet temperatures in distributed model is lower than that of the mixed-mode model. This is because of the absence of the top glazing in the distributed type thereby reducing the top heat lost to the possible minimum.

The temperatures of the solar kilns being higher than the ambient temperatures all through the evaluation period even at sunset (especially between 6:30 p.m. and 6:30am) gives credence to the use of the heat storage medium in the study.

Table 3 shows the mean air temperature for the solar air heaters. From the Table, it can be seen that for all through the period of study, the average heated air generated from the solar kilns irrespective of the model were by more than 5 °C greater than average ambient temperatures.

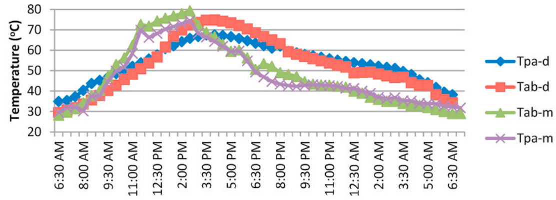
Table 4 shows the cumulative efficiencies of the systems. In all cases for the days tested, mixed-mode model showed lower efficiency than the distributed model. The day with low solar radiation showed better efficiencies with maximum cumulative efficiency as 40.7% and 44.3% for mixed mode and distributed model models respectively. Paraffin's low thermal conductivity (Table 1) prevents it from absorbing most of the energy generated during the high irradiance period. This leads to lower efficiency during high solar radiation days.

The lower efficiencies during the day was as a result of the fact that only a fraction of the solar radiation falling on the absorber plate was immediately transferred to the working medium (air), the rest were absorbed by the storage medium and then gradually released to the flowing air all through the heating period [1].

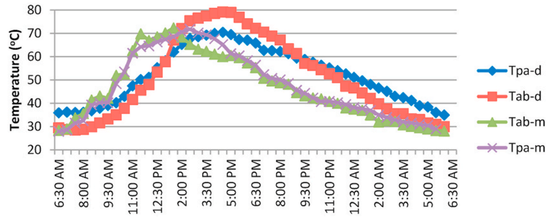
6. Conclusion

The thermal performance study of two passive solar kilns-mixed mode and distributed models-was carried out successfully within the weather temperature and daily radiation of 18.3–33.2 °C and 11.8–20.9 MJ m^{-2} respectively. The results obtained showed a maximum cumulative efficiency of 44.3% and 40.7% for distributed and mixed mode models respectively. In addition to this, an average efficiency of 38.8% was obtained in the mixed mode model while the distributed model gave an average of 43.0%. The use of paraffin in the study ensured that the temperatures of the system were all time higher than the ambient temperature. The results show that low temperature operations can conveniently be carried out with these solar kilns.

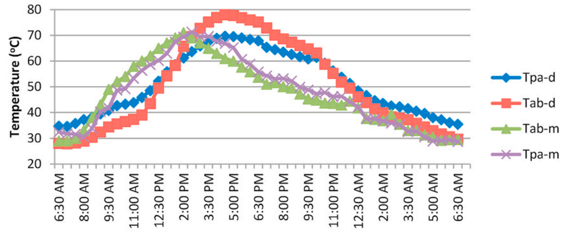
It is therefore recommended that for optimum thermal energy utilization while using mixed mode model during the sunset periods, the top glazing of the working section should be covered to reduce the top heat loss since it is no longer receiving any solar radiation during these periods.



(a) November 14



(b) December 10



(c) January 17

Fig. 5. Temperature profiles of absorber plate and paraffin.

Table 3
Daily solar radiation and mean heated air temperature characteristics.

Date	Total Solar Radiation (MJ m^{-2})	Ambient (^{o}C)	Mixed-mode (Daytime: 6:30am-6:00pm)	Distributed (Daytime: 6:30am-6:00pm)	Mixed mode (Sunset: 6:30pm-6:30am)	Distributed (Sunset: 6:30pm-6:30am)
14 November	11.8	23.0	53.7	49.0	28.3	43.01
10 December	15.6	25.3	53.6	47.41	33.7	44.9
17 January	20.9	25.7	51.0	46.58	36.5	46.7

Table 4
Cumulative efficiency.

Date	Mixed mode Model (%)	Distributed model (%)
14 November	40.7	44.3
10 December	38.3	43.1
17 January	37.4	41.5
Mean Efficiency	38.8	43.0

CRediT authorship contribution statement

S.N. Ugwu: Conceptualization, Writing - review & editing, Funding acquisition, Resources. **O. Ojike:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing - original draft, Writing - review & editing. **W.I. Okonkwo:** Supervision, Validation. **E. Okafor:** Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Visualization. **B.O. Ugwuishiwu:** Funding acquisition, Resources, Writing - review & editing. **E.A. Echiegu:** Funding acquisition, Resources, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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