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RESEARCH ARTICLE

PERFORMANCE STUDY OF MIXED MODE SOLAR KILN WITH PARAFFIN AS STORAGE MEDIUM

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ABSTRACT

In this study, the performance of a mixed mode solar kiln was carried out. The kiln was incorporated with double glazed flat plate solar heat collector with built in paraffin as a heat storage medium. The off-load site study of the kiln during sun shine and no-sun shine periods of the day were carried out in Nsukka (Latitude 7° N), Nigeria. The range of ambient temperatures during the study period was between 18.3–33.2°C. Equally, the daily radiation ranged between 11.8–20.9 MJ m^{-2}. The results obtained showed a maximum cumulative efficiency of 40.7% for the kiln. In addition to this, an average efficiency of 38.8% was obtained in the system. The result of a timber drying operation carried out with the kiln showed an improvement over a similar kiln but with pebble stone as storage medium in the literature. 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. Equally, a development of a mathematical model to simulate the solar kiln is strongly recommended.

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INTRODUCTION

It is now an establish fact that the convectional sources of energy available for human utilization especially for agricultural processing activities is limited (Towler *et al*., 2004). It is therefore necessary that alternative resources are sourced for modern agricultural advancement and for sustainability of existence on earth. Among the alternative sources, the cheapest and most accessible source is the solar energy (Phillips, 2020). Several uses of solar energy in agricultural sector of human development apart from photosynthesis in plants include water generation (which include water heating and cooling systems), drying of agricultural produce etc (Leon and Kumar, 2006). The most common of these processes is the drying process which is usually carried out in the open space by displaying the materials in an uncovered area for direct sunshine to fall on them. This however, has a lot of disadvantages which include disease infestation/contamination, sudden rainfall on them etc (Belessiotis and Delyannis, 2011; Pirasteh *et al*., 2014). To mitigate this, several solar kilns have been developed (Srivastava and Rai, 2017; Phillips, 2020). Solar kilns with natural convection circulation have been found very fit to rural areas of developing and under developed nations where certainty of electricity is unpredictable and where most agricultural activities are carried out. However, the major obstacle to its use is low or zero production of energy at sun sets (Hayder *et al.,* 2017). This obstacle can easily be overcome by the incorporation of heat energy storage systems to the solar kilns (Saxena and Goel, 2013). Materials such as pebble stone bed have been used as thermal storage medium in solar kiln as studied by Azad (2008). The use of liquid thermal storage medium in solar kilns has equally been carried out in the literature (Ugwu *et al*., 2015). However, in the studies it was rightly observed that these liquid heat storage systems are very expensive and beyond the reach of rural farmers. Among the heat storage media, current studies have proven paraffin to be the most suitable medium for low temperature applications especially in agro-activities such as crop drying, egg incubation etc (Enibe, 2003; Hayder *et al.,* 2017; Srivastava and Rai, 2017; Ojike and Okonkwo, 2019). Several works and studies have been done on the different models of solar kilns with thermal storage systems independently (Enibe, 2003; Saxena and Goel, 2013). However, little attention has been paid to the use of paraffin as a storage medium in the design of solar kiln for timber seasoning. This present study is an attempt to fill this gap. Among the various models of solar kilns are distributed, integral and mixed mode solar kilns (Ekechukwu and Norton, 1999). In distributed model, heated air is generated in the solar collector and then moved into the working chamber where it is used for desired operation.

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In integral solar kiln, the solar energy radiation falls directly on the farm produce to be dried through the transparent covers. Both the heating and drying chambers are together. The heat reduces the humidity of the air, thereby creating room for moisture vapour from the drying material to be absorbed by the heated air. The heated air been less dense continues to rise in the chamber until it exits from outlet at the topmost parts of the dryers. Some varieties of 'grapes' and 'dates' need direct sunshine for expected colouration of the dried product. Mixed mode solar kiln is simply a hybrid of distributed and integral type solar kilns. In Mixed mode model operation, solar radiation falls both on the solar collector and on the working chamber. A development of this model of solar kiln for wood seasoning using stone as a heat storage medium to avert reversal of humid air in off sunshine periods was done by Ugwu *et al.* (2015). Abubakar (2019) discussed and evaluated the results by various studies on solar kiln technology. This includes kilns with and without heat storage medium, with varying heat absorbing surface. Agrawa *et al.* (2017) evaluated solar absorber plate and reviewed the use of solar kilns on large scale and commercial purposes. Tvagi *et al.* (2012) reviewed behaviors of solar kiln thermally using either heat energy storage or none.

Solar Kiln Description: The Mixed mode model solar kiln used for the study is shown in Fig. 1. It is made up of two sections: the air heating and the working sections. The air heating section is a double glazed solar collector which houses the heat storage medium. The details of the air heating section have been given in Ojike and Okonkwo (2019). Paraffin was used as the medium for heat storage with known heat and physical characteristics (Enibe, 2003; Ojike and Okonkwo, 2019). The top surface of a box made of steel filled with 11.5kg of the storage medium served as the absorber plate while its bottom and sides were properly insulated to reduce heat loss. As can be observed in Fig 1 air flowing between the inner glazing and the absorber plate is heated by the absorber plate and then flows into the working section which is then discharged through the outlet vents. Considering the experimental site latitude, the inclination of the collector is 17^0 S (Fagbenle, 1990; Adegoke and Bolaji, 2000). The solar kiln air heating section is $0.022m^3$ while the working section is $0.08m^3$ in volume. The top of the working section of the kiln is glazed as shown in Fig 1.

MATERIALS AND METHODS

The evaluation involved the no-load performance and the actual wood drying. The no-load study involved the monitoring of the temperature of the kiln in order to ascertain its suitability to dry woods. This was done over a three month (November, 2019 to January, 2020) time. The actual drying was done between February 7 and 26, 2020 by loading the system with wood, stacked horizontally on perforated trays with 0.25m spacing for smooth flow of heated air round the drying chamber and subsequently observed till the equilibrium moisture content was reached. Fresh wood were procured from Enugu, cut into 0.4m by 0.4m by 0.03m timber sizes and weighed using digital balance. Each set comprising of 3 timber pieces was for the solar drying and open sun drying (that is, keeping the timber pieces in an open space with unshielded sun shine for drying) respectively. The weight loss in the timber pieces was taken to be as sole result of moisture loss. This weight loss in the samples was then measured at intervals until there was no more reduction in the weight.

Temperatures readings of thirty minutes interval over the period was recorded using a MTM-380SD thermometer monitor manufactured in Taiwan with k-type thermocouples wires fixed at various parts of the kilns. The temperature-meter's uncertainty value is ±0.5. The solar mean days (14th November, 10th December and 17th January) for the months selected were used for the evaluation study (Duffie and Beckman, 1991). 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 cumulative efficiency of the kiln (C_{eff}) is given as:

$$C_{eff} = \frac{\int_0^t \dot{H}_u dt}{A_c \int_0^t R_T dt} \quad (1)$$

Ac is the solar collector area for the kiln; it is the area of the solar collector in addition to the area of the top glazing cover of the working section (Fig.1). $\dot{H}_u$ is the gain in thermal energy of the working air given as:

$$\dot{H}_u = \dot{ka}_{am} s_{am}(T_{wa} - T_{am}) \quad (2)$$

T_{am} *and* T_{wa} are the ambient and working section inlet air temperatures respectively; s_{am} is the specific capacity of the air while the air mass flow rate ($\dot{ka}_{am}$) is given as:

$$\dot{ka}_{am} = d_{am} V_{inlet} A_{am} \quad (3)$$

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

RESULTS AND DISCUSSION

It can be seen from Table 1 that the ambient temperature within the evaluation period ranged from 18.3–33.2^{0}C with solar radiation ranging from 11.8 – 20.9 MJ m^{-2}. From the Table, it can equally be seen that for all through the period of study, the average heated air generated from the solar kiln were by more than 5^{0}C greater than average ambient temperatures at both the sunset (between 6:30pm and 6:30am) and during day time periods (between 6:30am and 6:00pm). The ambient, working section air inlet and outlets temperature flow for the solar kiln in addition to the daily solar radiation for the test period is graphically displayed in Figs. 3-5 where *Tam, Twam* and *Tolm* are the ambient, the working section air inlet and outlets temperature of the kiln respectively. It is observed that, all the temperatures vary in line with the solar radiation. Generally, the ambient temperatures were least in all cases while the working section air inlet had the maximum temperatures. This is in line with other related studies on solar drying systems (Enibe, 2003; Ugwu *et al*., 2015; Ojike and Okonkwo, 2019). A close look at the graph reveals that, when the solar radiation is rising to its maximum values between the 7:30 am and 3:300pm that the inlet temperatures of the kiln rise at the highest rate than others. This rise is as a result of additional solar radiation coming from the top glazing of the working section of the solar kiln. However this gain in thermal energy is not sustained as the sun begins to set, it can easily be noticed that this temperature falls at the highest rate when compare to other parametric temperatures. This is as a result of the fact that much heat is lost through the same top glazing of the mixed mode kiln (Duffie and Beckman, 1991).

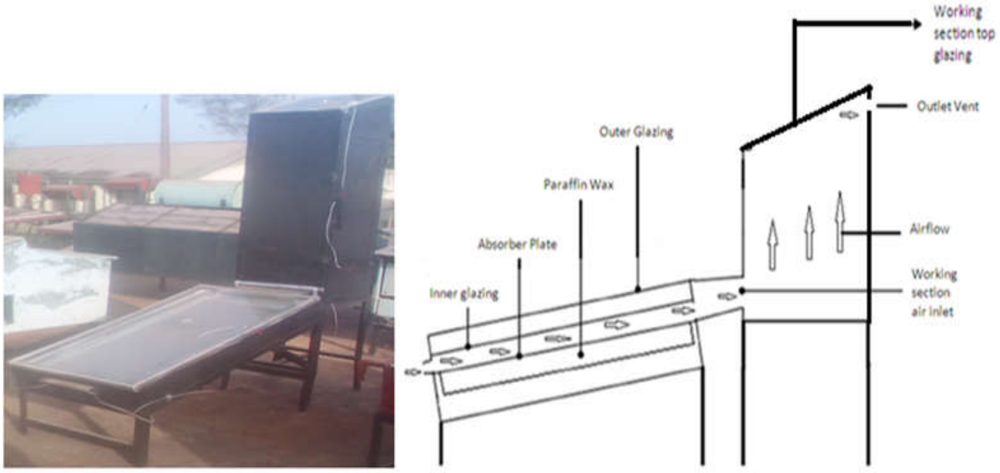

Fig. 1. Mixed mode type solar kiln used for the study

Table 1. Daily Solar Radiation and Temperature Characteristics

Date	Total Solar Radiation	Ambient Temperature (^{0}C)			Mean kiln Heated Air Temperature (^{0}C)		Mixed mode Model (%)
	(MJ m^{-2})	Min.	Mean	Max.	Day time	Sunset	
14 November	11.8	18.8	26.6	30.0	53.7	28.3	40.7
10 December	15.6	21.5	29.1	31.1	53.6	33.7	38.3
17 January	20.9	18.3	25.8	33.2	51.0	36.5	37.4
Mean			27.2		52.8	32.8	38.8

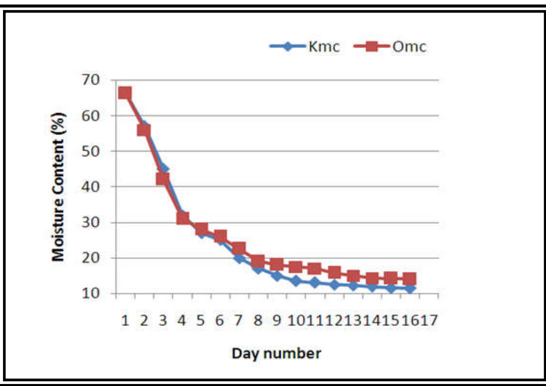

Fig. 2. Comparative moisture content of timber during drying

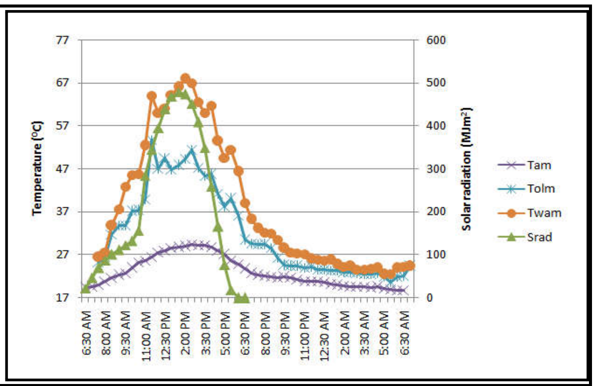

Fig. 3. Daily irradiance and temperature profiles of absorber plate, ambient and air outlet (November 14)

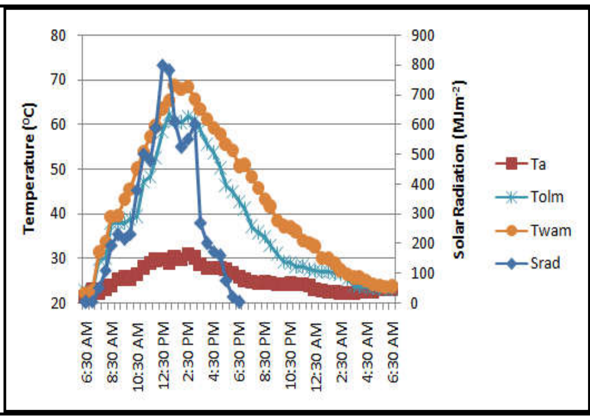

Fig. 4. Daily irradiance and temperature profiles of absorber plate, ambient and air outlet (December 10)

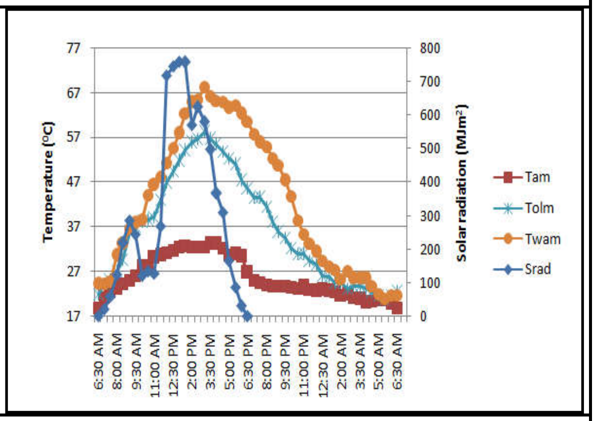

Fig. 5. Daily irradiance and temperature profiles of absorber plate, ambient and air outlet (January 17)

To reduce the rate of heat loss through the top glazing, Enibe (2002) suggested the use of opaque materials to cover the top of the working chamber during sunsets. The temperatures of the solar kilns being higher than the ambient temperatures all through the evaluation period even at sunset (especially between 6:30 pm and 6:30am) gives credence to the use of the heat storage medium in the study. The last column of Table 1 showed the cumulative efficiencies of the solar kiln. The day with low solar radiation showed better efficiencies with maximum cumulative efficiency as 40.7%. The low efficiencies was as a result of the fact that only a fraction of the solar radiation falling on the absorber plate was immediately converted to useful energy of the outlet air temperature, the rest were absorbed by the storage medium and then gradually released the absorbed energy to the flowing air all through the heating period (Enibe, 2003; Ojike and Okonkwo, 2019). The low daily efficiencies were due, in part, to the relatively low volumetric heat capacity and low conductivity of air, as observed by Enibe (2002).

However, these peak efficiencies are welcomed development when compared to a peak efficiency of 17 – 22% for single cover systems as obtained in the literature (Enibe, 2002; Enibe, 2003). This has given credence to the use of double glazing as used in this study and as suggested by Duffie and Beckman (1991) for improved efficiencies. Fig. 2 is a graph comparing the moisture contents of the timber dried in the solar kiln and in open air drying where *Kmc* and *Omc* are for solar kiln and open air drying systems respectively. Form the graph it could easily be seen that the timber dried in the kiln had lower final moisture content of 11.5% than the one dried in the open air. These results could be regarded as an improvement to the studies by Ugwu *et al*. (2015) who reported a final moisture content of 12.9% in timber kiln drying after 15 days of drying operation. Ugwu *et al*. (2015) in conclusion of their study using pebble stones as heat storage medium had recommended a further study on their work using a phase change material as thermal storage medium.

CONCLUSION

A performance study of a passive solar kiln- mixed mode type- was carried out successfully. A 24-hour period system evaluation of the solar kilns without load were carried out experimentally in Nsukka, Enugu State, Nigeria, 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 40.7% with an average efficiency of 38.8% for the mixed mode solar kiln. The result of a timber drying operation carried out with the kiln showed an improvement over a similar kiln but with pebble stone as storage medium in the literature (Ugwu *et al*., 2015). 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. Equally, a development of a mathematical model to simulate the solar kiln is strongly recommended.

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