ISSN 2229-5518

Poultry Brooding Pen Heated by the Trombe Wall System - Investigating the Effect of the Wall Bulk Material on the Collection Efficiency

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Abstract— A large-scale poultry chick brooding pen heated solely with the Trombe wall system was designed to make use of locally available building and energy storage materials. This study was undertaken to use computer simulation to determine the effect of the wall bulk material on the hourly variation of its efficiency. Trombe wall bulk materials investigated in this work include granite, concrete, brick, adobe and Abakaliki quarry dust. It was found that the granite wall gave the highest average efficiency of 87.02 % in the month of June while the adobe wall gave the lowest average efficiency of 10.94 % in the month of February. From these results, it was concluded that the wall bulk materials has significant effect on the collection efficiency of the Trombe wall system

Index Terms— collection efficiency, computer simulation, poultry brooding, Trombe wall bulk material.

1 INTRODUCTION

For successful poultry production in developing countries such as Nigeria, alternative methods of meeting the energy needs in the poultry industry have to be evolved [1], [2].

Poultry is an essential component of the agricultural sector in that it is a major source of protein of high biological value needed for optimum health of the citizenry. It also provides raw materials for some industries and promotes crop agriculture through provision of manure [3], [4].

But, there is a widening gap between demand and supply of poultry products. This is attributed to such factors as high-energy consumption cost as well as inefficient and inappropriate production technology employed the farmers.

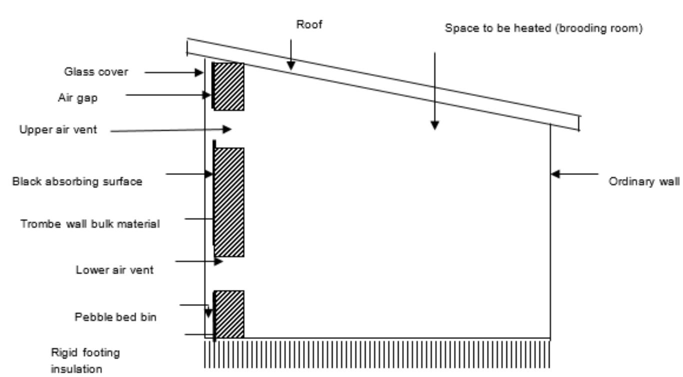
The technology includes the use of conventional sources of energy for the brooding of chicks. Common sources of electricity and fossil fuels used are not only non-renewable but also pollute the environment in which the birds are brooded [5], [6].

The solution to this problem is to use a source of energy that is renewable, affordable, and environmentally friendly for poultry chick brooding, which is the most delicate period in poultry production. The energy from the Sun meets these requirements. It has been found that if the irradiance on only 1 percent of the Earth's surface could be converted into useful energy with 10 percent efficiency, solar energy could provide the energy needs of all the people on Earth[1].

However, large-scale utilization of solar energy is fraught with problems due to the two main limitations of solar energy. The first limitation is the low flux density of solar radiation. This necessitates the use of large surfaces to collect solar energy. The second limitation is its intermittency. Solar energy has a regular daily and regular annual cycle, and is unavailable during periods of bad weather. These daily and seasonal variations in irradiance, exacerbated by variations due to weather, introduce special problems in storage and distribution of this energy which are entirely different from problems involved in the utilization of conventional energy sources as mentioned by [7] and [8]. These problems are solved by the use of a passive solar energy system, the Trombe wall system, to heat poultry brooding pens [9],[10],[11],[12].

The passive solar thermal storage (Trombe) wall system was invented and patented by Edward L. S. Morse in the USA in 1881(US Patent 246626), but it was ignored for decades. In the 1960's the idea was revived, developed and popularized by Engineer Felix Trombe of France in collaboration with Architect Jacques Michael following the construction of a passive solar house using the principle in Odeilo, France [13],[14], [15],[16].

A typical Trombe wall consists basically of a south facing 20 – 45 cm thick wall coated with a dark heat absorbing material and faced with a single or double layer of glass placed 20 to 50 mm from the wall to create a small sunspace. The basic structure is shown in fig. 1.



The brooding room is heated by solar energy incident on the south facing wall through the processes of convection, conduction and radiation.

Solar radiation passing through the glass cover is converted into heat when it strikes the wall's outer surface. Part of the heat generated (35 – 40%) is used to warm the air in the air gap. The heated air rises and as it flows into the brooder room through the upper vent in the wall cold air from the room flows through the lower vent into the air gap. In this way a natural convection current is set up.

The remaining heat generated (55 – 60%) at the outer surface of the wall is transferred by conduction to the inner surface, being driven by the temperature difference between the two surfaces. The heat transmitted to the inner surface of the wall is released by radiation to heat the brooder room.

The wall is made south facing in the Northern Hemisphere for maximum solar energy collection all the year round. For Ikwo (Lat. 6.18^{O} N, Long. 8.13^{O} E) the sun is northwards only between the second week of April and first week of September, when solar declination is higher than the latitude. This is the period of the year when diffuse radiation predominates because of cloud cover. For the rest of the year the sun is southwards and direct radiation on the wall is the main contributor.

The wall is made unusually thick so that it takes some time for the heat received at the outer surface to reach the inner surface. Depending on the thickness and the material of which the wall is made the time lag is 8 to 10 hours. This means that the brooder room continues to receive slow even heating many hours even after sunset, in fact until the next sunrise. To augment the heat supply a pebble bed bin may be incorporated into the Trombe wall system for additional solar collection and storage .

The outside surface of the wall is coated with a dark spectrally selective material. A spectrally selective surface combines a high absorbance for solar radiation with a low emittance in the infrared range. This combination of surface characteristics is possible because 98% of the energy in the incoming solar radiation is contained within wavelengths below 3000nm, whereas 99 percent of the radiation emitted by the black surface is at wavelengths longer than 3000nm.

The wall is covered with one or two sheets of glass. This reduces significantly the convective and radiative heat losses of the absorber surface due to the selective transmittance of glass. It is highly transparent to the incoming short wave solar radiation but virtually opaque to the long wave infrared radiation emitted by the absorber surface.

From the foregoing it can be seen that the effectiveness of the Trombe wall system, like any other flat plate collector, depends on the special materials used for its construction namely transparent materials, selective surfaces and thermal storage materials.

When applied to poultry brooding, the special merits of passive solar energy include the fact that (a) it is not affected by non-availability of electricity or frequent power failures (which are a very common feature in developing countries), (b) it creates a pollution-free environment conducive for poultry brooding, (c) it is free from fire hazards, (d) it produces birds of highly improved biological performance and (e) the cost of energy for brooding is zero (beyond the capital cost of the system). Installed passive solar systems can last for decades without supplementary energy supply and with little operations or maintenance cost [6],[17].

2 MATERIALS AND METHODS

2.1 Computer Simulation

The rational design of a solar thermal system requires knowledge of the dynamic interaction of all solar system components, namely solar collection, thermal storage fluid circulation, energy distribution, and controls. Although essential and valuable experience can be gained by testing solar systems in the field, the generalization of experimental results and their applications in other locations can best be handled by a modeling approach. A very useful and accurate type of modeling is computer simulation. Results from computer simulation of solar systems are very helpful for system design since they allow one to learn about complex interactions of a large number of variables in a short time whereas experiments are time consuming and costly. Also, the simulation results and the measured values have been compared and it is seen that they are in good agreement as testified by Koyunbaba et al [18], Liu et al [19], and Ma et al[20].

The purpose of this paper is to use computer simulation to determine, for a whole year, the effect of the thermal wall bulk material on the hour-by-hour efficiency of the designed poultry brooder pen heated by the Trombe wall system. But since only monthly mean daily values of meteorological data are available, calculations are performed for the representative or characteristic day of each month. Trombe wall materials investigated in this work include granite, concrete, brick, adobe and Abakaliki quarry dust. The relevant properties of these materials are shown in table 1[21].

TABLE 1
TROMBE WALL BULK MATERIAL THERMAL PROPERTIES

MATERIAL	MASS DENSITY KGm^{-3}	SPECIFIC HEAT CAPACITY $Jkg^{-1}k^{-1}$	THERMAL CONDUCTIVITY $Wm^{-1}k^{-1}$
GRANITE	2720	880	**2..85**
CONCRETE	2360	880	**1.30**
BRICK	1840	840	**0.75**
ADOBE	1700	1000	**0.52**
ABAKALIKI QUARRY DUST	**2300**	**570**	**0.60**

For the purpose carrying out the thermal analysis of the Trombe wall system, various models have been used to represent the system. Examples include those of Shtrakov and Stoilov [22], Okpani et al [23], Zrikem and Bilgen [24], Bansal and Gour [25], Knowles[26], Balcomb et al [27] and Bilgen and Chaaban[28].

The modeling equations were derived from consideration of heat and mass balances for each component element of the system as depicted in Fig. 2 [22]

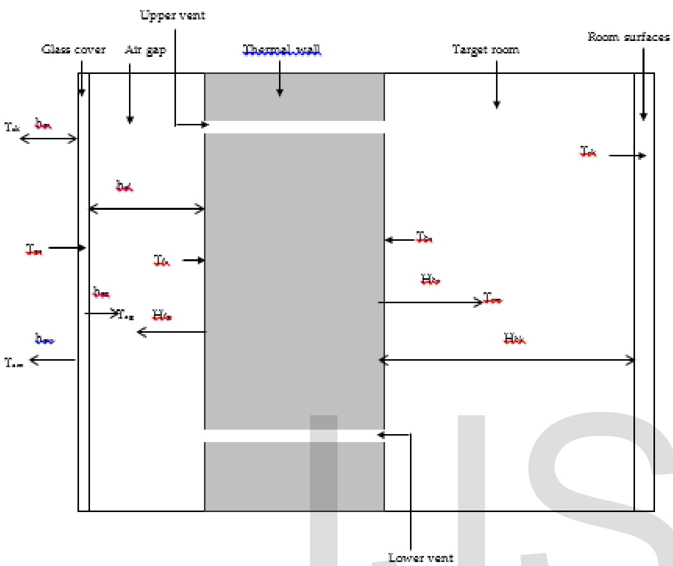


Fig. 2: Trombe wall system heat transfer parameters

In forming the equations, the following assumptions were made

1. The heat transfer in the massive wall is one dimensional. This is justified by the fact that there is very little vertical temperature variation in the wall [22].
2. The heat transfer through the glass cover is at steady state whereas that through the wall is time dependent [29].
3. Material thermophysical properties are independent of temperature because of the small temperature variation involved[24].
4. .All surfaces are considered as grey bodies with diffuse reflection and emission [22]
5. Air is considered as a nonparticipating medium in radiation heat exchange. [30].
6. Heat gain by the brooder room is only through the outer surface of the Trombe wall but heat loss is through all the surfaces of the room – floor, ceiling, walls, doors and windows. This results in a slight under simplification of the heat gain since there are actual heat gains through the building walls and windows and internal heat generation. But these are negligible compared to heat gain through the outer surface of the thermal wall [2].

The temperatures designated in fig. 2 are sky (T_{sk}), ambient (T_{am}), glass cover (T_{gc}), air gap (T_{ag}), Trombe wall front surface (T_{fs}), Trombe wall back surface(T_{bs}), brooding room(T_{rm}) and brooding room surfaces (T_{rs}).

The heat transfer coefficients designated are the radiation heat transfer coefficient between the glass cover and the Trombe wall front surface, h_{cf}; the wind convection heat transfer coefficient from the glass cover, h_{cr}; the convection heat transfer coefficient from the glass cover to the air gap, h_{cg}; the radiation heat transfer coefficient between the glass cover and the sky, h_{cs}; the convection heat transfer coefficient from the Trombe wall outer surface to the air in the air gap , h_{fg}; the radiation heat transfer coefficient from the back surface of the Trombe wall to the brooder room, h_{br}; the radiation heat transfer coefficient between the Trombe wall back surface and the surfaces of the room, h_{bk}; the radiation heat transfer coefficient from the back surface of the Trombe wall to the brooder room, h_{br}; the radiation heat transfer coefficient between the Trombe wall back surface and the surfaces of the room, h_{bk}.

The hourly efficiency η_H of the Trombe wall system is given by [25],[26]

$$\eta_H = \frac{Q_{ud}}{Q_{gc}} \tag{1}$$

where Q_{ud} is the total useful energy delivered into the room during the hour and Q_{gc} is the solar energy incident on the glass cover during the same hour. The total energy delivered to the room is given by

$$Q_{ud} = Q_{ag} + Q_{tr} \tag{2}$$

where Q_{ag} is the heat transferred into the room by the heated air in the air gap and Q_{tr} is the heat transferred to the room by conduction through the Trombe wall. The heat transferred into the room by the thermo circulation of the heated air in the air gap is given by

$$Q_{ag} = 2\dot{m}c_{pa}\left(T_{ag} - T_{rm}\right) \tag{3}$$

where c_{pa} is the specific heat capacity of the air and $\dot{m}$ **is the** mass flow rate given by [24], [25].

$$\dot{m} = \rho_a A_v F_r \sqrt{\frac{g D_v \left(T_{ag} - T_{rm}\right)}{T_{ag}}} \quad \textbf{(4)}$$

where ρ_a is the density of air, A_v is the upper vent area, F_r is Froude number ($0.6 \le F_r \le 0.8$) and D_v is the vertical distance between the upper and the lower vents.
The solar energy incident on the glass cover during any hour is given by

$$Q_{gc} = A_{gc} I_{gc} \quad (5)$$

where A_{gc} is the glass cover surface area and I_{gc} is the total solar radiation on the glass cover during the hour. The hourly total radiation on the glass cover I_{gc} is composed of beam I_{bm}, sky diffused I_{sd} and ground reflected I_{gr} components. Hence

$$I_{gc} = I_{bm} + I_{sd} + I_{gr} \quad (6)$$

In terms of monthly mean hourly values, these components are given respectively by

$$I_{bm} = \dot{I}_b \overline{r}_b \quad (7)$$

$$I_{sd} = \dot{I}_d \overline{r}_{sd} \quad (8)$$

$$I_{gr} = \dot{I} \overline{r}_{gr} \quad (9)$$

where $\dot{I}_b$ is the monthly mean hourly beam radiation on a horizontal surface, $\dot{I}_d$ is the monthly mean hourly diffuse radiation on a horizontal surface, $\dot{I}$ is the monthly mean hourly global radiation on a horizontal surface, $\overline{r}_b$ is the monthly mean hourly beam radiation tilt factor, $\overline{r}_{sd}$ the monthly mean hourly sky diffuse radiation view factor, and $\overline{r}_{gr}$ is the monthly mean hourly ground reflected radiation view factor.

The meteorological data that are usually available in this part of the world are monthly mean daily global solar radiations on a horizontal surface, $\overline{H}_m$. Given these data, a formulation, which is used for computer modelling, is obtained by assuming that the instantaneous radiation on a tilted surface is sinusoidal peaking at noon and with zero at sunrise and sunset which are taken to be 6.00 and 18.00 hours respectively.

The instantaneous insolation is given by [31]

$$\mathrm{I}(\mathrm{t}) = -\mathrm{I}_{\max} \cos\left(\frac{\pi t}{12}\right) \quad \text{for } 6 \le t \le 18 \quad (10)$$

and zero otherwise. The maximum insolation, $\mathrm{I}_{\max}$ is given by [31]

$$\mathrm{I}_{\max} = \frac{\pi}{24} \mathrm{H}_t \quad (11)$$

where H_t is the total daily insolation on a tilted surface. This is given by [31]

$$H_t = \overline{H}_m \dot{r}_{gr} + \overline{H}_b \dot{r}_b + \overline{H}_d \dot{r}_{sd} \quad (12)$$

where $\overline{H}_m$ is the monthly mean daily global solar radiations on a horizontal surface. $\overline{H}_b$ and $\overline{H}_d$ are its beam and diffuse components respectively. The expressions for $\overline{r}_{gr}$, $\overline{r}_b$ and $\overline{r}_{sd}$ are respectively as follows [31];

$$\overline{r}_{gr} = \frac{\rho(1-\cos\beta)}{2} \quad \textbf{(13)}$$

$$\overline{r}_b = \frac{\omega_{sv} \sin(\phi-\beta)\sin\delta_c + \cos(\phi-\beta)\cos\delta_c \sin\omega_{sv}}{\omega_{sh} \sin(\phi)\sin\delta_c + \cos(\phi)\cos\delta_c \sin\omega_{sh}} \quad \textbf{(14)}$$

$$\overline{r}_{sd} = \frac{1+\cos\beta}{2} \quad \textbf{(15)}$$

where ρ is the ground albedo, β is the tilt angle, ω_{sv} is the sunset hour angle for a vertical surface, ω_{sv} is the sunset hour angle for a horizontal vertical surface and δ_c is the solar declination. The sunset hour angle for a vertical surface and the sunset hour angle for a horizontal vertical surface are respectively given by [31]

$$\omega_{sh} = \cos^{-1}\left(-\tan\delta_c \tan\phi\right) \quad (16)$$

$$\omega_{sv} = \cos^{-1}\left(-\tan\delta_c \tan(\phi-\beta)\right) \quad (17)$$

The design parameters and the meteorological data used are shown in Tables 2 and 3, respectively.
A computer program in Mathcad 15 is drawn to use the design parameters (including the data of the wall bulk materials in table 1) and meteorological data for the representative day of the month as inputs, and calculate, using (1) to (17), the hourly values of solar radiation on the Trombe wall surface , the hourly values of ambient and sky temperatures, the heat transfer coefficients, the hourly values of other temperatures (T_{gc}, T_{ag}, T_{fs}, T_{bs},T_{rk}), the hourly values of Q_{ud} , Q_{gc}, Q_{st} , and finally the hourly efficiencies of the system for each of the

Trombe wall bulk materials . The flow chart for the computer program is shown in Figure 3.

TABLE 2
DESIGN PARAMETERS

Description	Value
Room floor area, A_{rf}	11.925 m^2
Room walls area, A_{rwl}	23.520 m^2
Room roof area, A_{rr}	11.925 m^2
Room total surface area, A_{rts}	47.370 m^2
Floor U-value, U_f	0.72 $Wm^{-2}K^{-1}$
Wall U-value, U_{rw}	2.92 $Wm^{-2}K^{-1}$
Roof U-value, U_{rr}	0.115 $Wm^{-2}K^{-1}$
Room mean U-value, U_{rm}	1.660 $Wm^{-2}K^{-1}$
Door crack length, L_{cd}	4.50 m
Window crack length, L_{cw}	2.70 m
Door area, A_{dr}	1.190 m^2
Window area, A_{wd}	0.455 m^2
Trombe wall surface area, A_{tw}	6.30 m^2
Trombe wall height, H_{tw}	1.40 m
Trombe wall thickness, D_{tw}	0.30m,
Trombe wall surface coating absorbance, α_{tw}	0.87
Trombe wall outer surface IR emittance, ε_{to}	0.09
Trombe wall inner surface IR emittance, ε_{ti}	0.88
Trombe wall upper vent area, A_{uv}	0.096 m^2
Distance between upper and lower vents, D_v	1.155 m
Air gap width, W_{ag}	0.050 m
Glass cover short wave absorbance, α_{gc}	0.065
Glass cover IR emittance, ε_{gc}	0.941
Glass cover short wave transmittance, τ_{gc}	0.896
Ground reflectance, ρ_{gr}	0.35
Air viscosity at 300K, μ_a	1.983 x 10^{-5} kgm^{-1}
Air density at 300K, ρ_a	1.7774 kg^{-3}
Air specific heat capacity at constant pressure, c_{pa}	1005.7 $Jkg^{-1}K^{-1}$
Air conductivity, k_a	0.0262 $Wm^{-1}K^{-1}$
Space interval, Δx	0.02 m
Time interval, Δt	3600 s
Tilt angle, β	90° (π/2 rads)

3 RESULTS

Figs. 5 to 16 show the hourly efficiency of the system for different Trombe wall bulk materials for the characteristic day in the months of January to December respectively. Table 4 shows the daily average hourly efficiency of the system for different Trombe wall bulk materials for the characteristic day in the months of January to December.

TABLE 3
METEOROLOGICAL DATA

Month	Monthly mean daily solar radiation on a horizontal surface (MJ m^{-2} day^{-1})	Monthly mean wind velocity (ms^{-1})	Monthly mean daily maximum temperatures (°C)	Monthly mean daily minimum temperatures (°C)	Monthly mean daily average temperatures (°C)	Characteristic day number for the month
JAN	16.0992	2.81	34.5	24.6	29.0	17
FEB	17.6508	3.03	36.7	28.8	31.8	45
MAR	18.0468	3.37	35.1	26.6	31.7	74
APR	18.9316	3.37	34.6	27.2	30.9	105
MAY	17.9316	3.05	33.8	25.9	29.6	135
JUN	15.5952	2.95	32.7	25.3	29.0	161
JUL	14.2344	3.12	30.9	24.9	27.8	199
AUG	14.3748	3.28	30.0	24.4	27.3	239
SEP	15.2424	3.75	31.3	24.4	27.9	261
OCT	14.5800	2.50	31.8	24.6	28.3	292
NOV	17.2980	2.39	33.8	26.0	29.8	322
DEC	16.4556	2.87	34.0	25.3	29.6	347

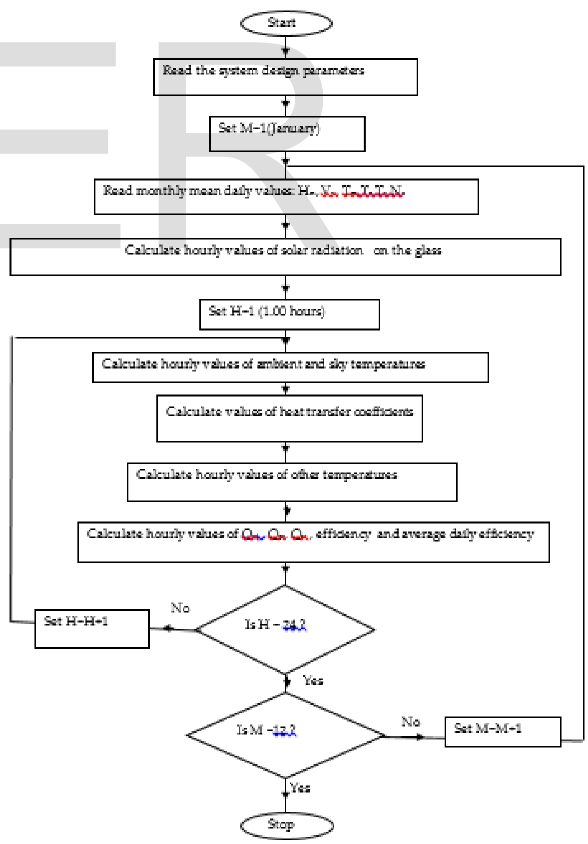


Fig.3: Flow Chart for the Computer Program

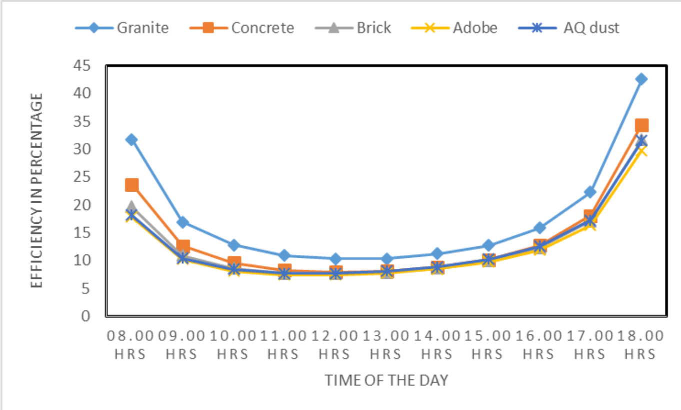


Fig. 5. Hourly efficiency graph for the characteristic day in the month of January

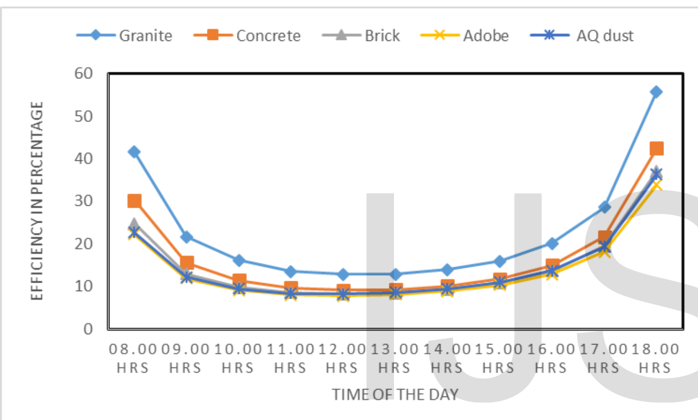


Fig. 6. Hourly efficiency graph for the characteristic day in the month of February

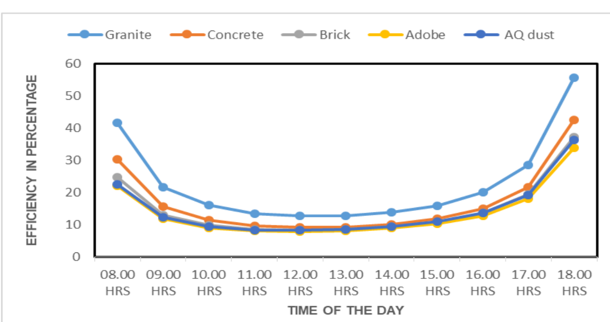


Fig. 7. Hourly efficiency graph for the characteristic day in the month of March

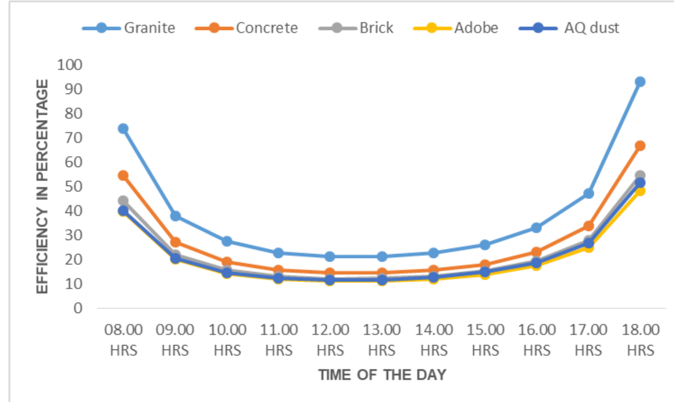


Fig. 8. Hourly efficiency graph for the characteristic day in the month of April

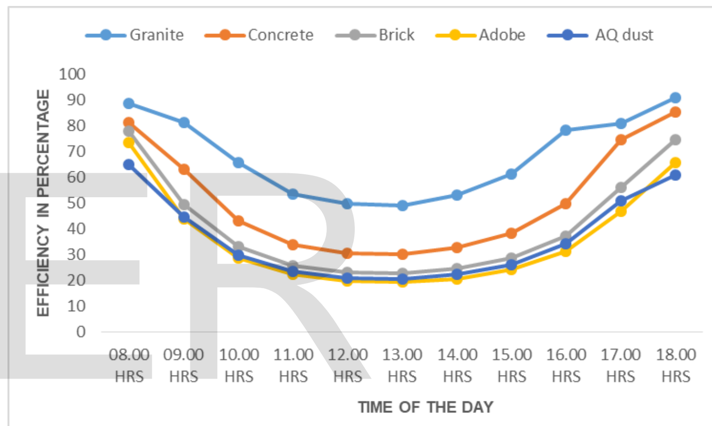


Fig. 9. Hourly efficiency graph for the characteristic day in the month of May

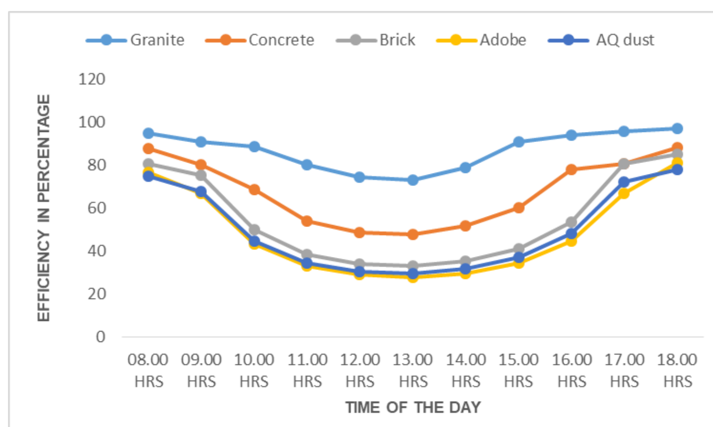


Fig. 10. Hourly efficiency graph for the characteristic day in the month of June

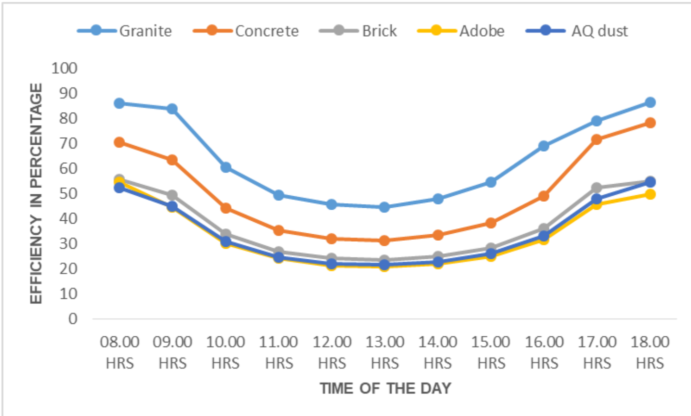


Fig. 11. Hourly efficiency graph for the characteristic day in the month of July

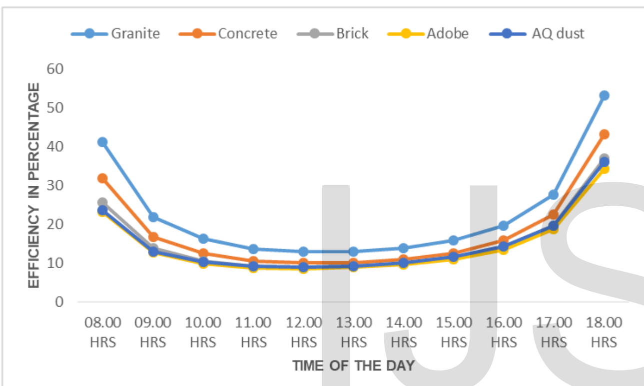
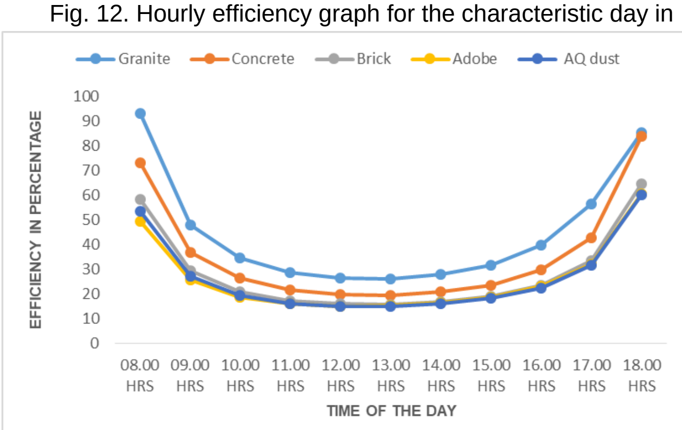


Fig. 12. Hourly efficiency graph for the characteristic day in



the month of August

Fig. 13. Hourly efficiency graph for the characteristic day in the month of September

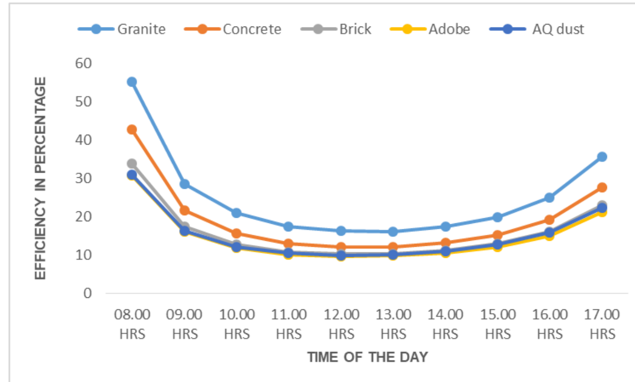
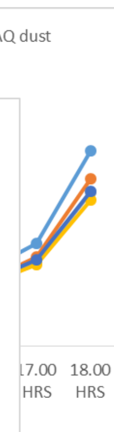


Fig. 14. Hourly efficiency graph for the characteristic day in the month of October



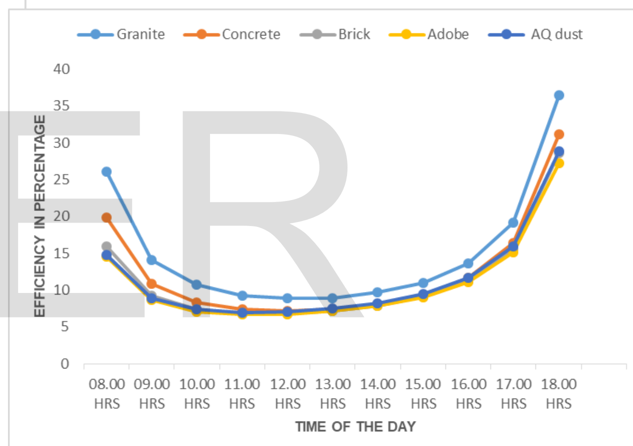


Fig. 15. Hourly efficiency graph for the characteristic day in the month of November

Fig. 17. Hourly efficiency graph for the characteristic day in the month of December

TABLE 4

DAILY AVERAGE HOURLY EFFICIENCY(%) OF THE SYSTEM FOR DIFFERENT TROMBE WALL BULK MATERIALS FOR THE CHARACTERISTIC DAY IN THE MONTHS OF JANUARY TO DECEMBER

MONTH	Granite	Concrete	Brick	Adobe	AQ dust
JANUARY	16.25	12.45	11.52	10.94	11.57
FEBRUARY	17.95	14.02	12.87	12.26	12.80
MARCH	23.02	16.98	14.87	13.79	14.51
APRIL	38.72	27.51	22.72	20.50	21.42
MAY	68.35	51.08	41.15	36.00	36.19
JUNE	87.02	67.68	55.11	48.34	49.81
JULY	64.27	49.85	37.33	33.68	34.74
AUGUST	45.19	36.10	28.63	26.36	26.78
SEPTEMBER	29.33	22.52	18.53	17.10	17.76
OCTOBER	22.62	17.90	15.38	14.47	15.04
NOVEMBER	16.02	13.26	12.13	11.71	12.19
DECEMBER	15.27	12.51	11.45	11.02	11.54

4 DISCUSSION

From Table 5, it can be observed that the system hourly efficiency has the lowest average value of 10.94% in February for adobe material and the highest average value of 87.02% in June for granite material.

These figures show clearly that it is possible to create an environment heated with solar energy but independent of fluctuations of weather. This is the ideal condition for poultry brooding. The temperature comfort zones for poultry brooding are 35^{O}C for week 1, 31 – 29^{O}C for week 2, 29 – 27^{O}C for week 3 and 25^{O}C (ambient) from week 4 onwards. [11]

Comparing the variation of efficiency with that of solar radiation (Tables) we can see that generally the months that have high solar radiation are associated with low efficiency and vice versa. This trend is the opposite of what is obtainable with ordinary solar collectors[30]. But the Trombe wall system is not an ordinary solar collector because it incorporates energy storage. Hence for the period when solar radiation (the input energy) is low the total energy transmitted to the brooder room (the output energy) a large part of which is the stored energy is relatively high. Therefore the efficiency is relatively high. . This is in harmony with the results obtained by Pine [32]. The comparatively high efficiency of the system indicates that the project is worth the effort and finance needed to construct it. Hence it is highly recommended.

This research work undertaken here is not just on the use of solar energy system but on the use of a passive solar energy system, the Trombe wall system, whose advantages include the following:

1. The system is easy to build and requires little special knowledge to construct since it relies so closely on traditional methods of building construction.
2. The initial cost is relatively low since the system is simple and the building materials are readily available.
3. The system is very reliable and easy to maintain because of the absence of complex mechanical equipment as valves, fans, pumps, electric control devices, etc.
4. The system has inherently high collection efficiency as we have seen since it normally operates with low temperature rises in the collector system.
5. It. is easy for the users of the system to understand and operate because there are no complex mechanical parts.
6. A passive solar system is, in its basic form, independent of other energy supplies in operation. This is because there are no pumps, fans etc, relying on electricity. Hence the system is not subject to energy supply disturbances

5 CONCLUSION

The major finding of this study is that the bulk material of the thermal wall has significant effect on the efficiency of the system. For a thermal wall of given material the temperature of back surface of the wall is almost constant irrespective of weather conditions. This helps to maintain the brooder room temperature at any desired value which is usually above ambient for proper chick brooding.

Hence the Trombe wall system can be used to avert the inefficient and inappropriate production technology employed by the farmers to heat the chick brooding room and to solve the problems that fraught large-scale utilization of solar energy due to its limitations.

ACKNOWLEDGEMENT

The author wishes to express his gratitude to the management and staff of the Nigerian Meteorological Agency South East Zone, Akanu Ibiam International Airport Enugu, for their cooperation in willingly giving him access to their records. The author also wishes to express his gratitude to his friend ,Chief David Ogudu, and his son , Chukwuemeka Ogudu for their willing and eagerness to pay the publication fees in foreign currencies.

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