

Investigation of the Effect of the Thermal Wall Thickness on its Back Surface Temperature for a Poultry Brooding Pen Heated by Trombe Wall

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Abstract

This study was undertaken to use computer simulation to determine the effect of the thermal wall thickness on the hourly temperature variation in the wall back surface of a large scale poultry brooding pen heated solely by the Trombe wall system. Trombe walls of thicknesses 20cm, 25cm, 30cm, 35cm, 40cm, and 45cm were investigated in this work. It was found that the back surface of the 20cm thick wall had the highest average temperature of 45.13.00ºC while the back surface of the 45cm thick wall gave the lowest average temperature of 34.58ºC. These values show that, in all cases, the optimum brooding temperature requirement could be obtained easily. From these results, it was concluded that the thickness of the wall has significant effect on the temperature of back surface .

Keywords: Trombe wall, compter simulation, thermal wall back surface temperature, hourly temperature variation, poultry brooding pen

1. Introduction

There is a growing need for protein to feed the rapidly expanding population in developing countries. This has caused farmers and scientists to pay more attention to poultry production, particularly chickens which are raised for both meat and eggs (Olaniyan, 2004a; Agbo, 2004; Olaniyan, 2004b). But, the current trend in the prices of the two products – chicken and eggs – indicates that there is a widening gap between demand and supply. This is attributed to such factors as high-energy consumption cost as well as inefficient and inappropriate production technology employed by the farmers. This technology includes the use of conventional sources of energy for the brooding of the chicks. The sources are electricity and fossil fuels, both of which are not only non-renewable sources of energy, but also pollute the environment in which the birds are brooded (Okonkwo, 1993; Okonkwo and Aguwamba, 1997).

A very good 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.

The sun is an inexhaustible source of energy having at present enough capacity to continue to emit into space 3.86 x 10^{23}J of energy every second for the next four to five billion years (Morrison et al.,1995; Nichelson, 1999; Morgan, 1962). Of this total, only a tiny fraction, 1.7 x 10^{17} J/s, is received by the Earth and its atmosphere. A world population of 10 billion with a total power need per person of 10KW would require about 10^{14}W. It is thus apparent 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..

However, large-scale utilization of solar energy is fraught with problems due to 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 cycle, a regular annual cycle and is unavailable during period 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 Berg (1976) and Iqball (1983).

These problems are solved by the use of a passive solar energy system, the Trombe wall system, to heat poultry brooding pen. When applied to poultry brooding, the special merits of the passive solar energy include the fact that(Okpani, 2009)

(1) it is not affected by non-availability of electricity or frequent power failures (which are very common feature in developing countries);

(2) it creates a pollution-free environment conducive for poultry brooding,

(3) it is free from fire hazards,

(4) it produces birds of highly improved biological performance, and

(5) the cost of energy for brooding is zero. Installed passive solar system can last for decades without supplementary energy supply and with little maintenance cost.

The rational design of a solar thermal system requires a 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 modeling is computer simulation. Results from computer simulation of solar systems are very helpful for system design since they allow one to learn about a complex interactions of a large number of variables in a short time whereas experiments are time consuming and costly(Kreith and Kreider,1978).

The purpose of this work was to use computer simulation to determine for a whole year the hour by hour temperature of the back surface of a Trombe wall heated poultry brooding pen of thermal wall thicknesses 20cm, 25cm, 30cm, 35cm, 40cm, and 45cm. The range 20cm to 45cm is the normal range of thickness of the Trombe wall (Okpani, 2009). The thermal wall back surface temperature is of utmost importance because it has great effect on the brooding room temperature.

Since only monthly mean daily values of meteorological data are available calculations are performed for an average day (called characteristic day) each month.

2. Materials and Methods

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 (2005), Okpani et al, 2008; Zrikem and Bilgen (1987), Bansal and Gour (1997), Knowles(1983), Duffin and Knowles(1981), Balcomb et al (1977) and Bilgen and Chaaban(1982), Duffin and Knowles(1985).

The modelling equations were derived from consideration of heat and mass balances for each component element of the system as depicted in Fig. 1 (Shtrakov and Stoilov, 2005).

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 (Shtrakov and Stoilov, 2005).

2. The heat transfer through the glass cover is at steady state whereas that through the wall is time dependent(Sehold and Clinton,1979).

3. Material thermophysical properties are independent of temperature because of the small temperature variation involved (Zrikem and Bilgen, 1987).

4. All surfaces are considered as grey bodies with diffuse reflection and emission (Shtrakov and Stoilov, 2005).

5. Air is considered as a nonparticipating medium in radiation heat exchange (Kreith and Kreider,1978).

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.

Figure 1shows the Trombe wall system heat transfer parameters. The energy balance equations for the components and parts are obtained as follows.

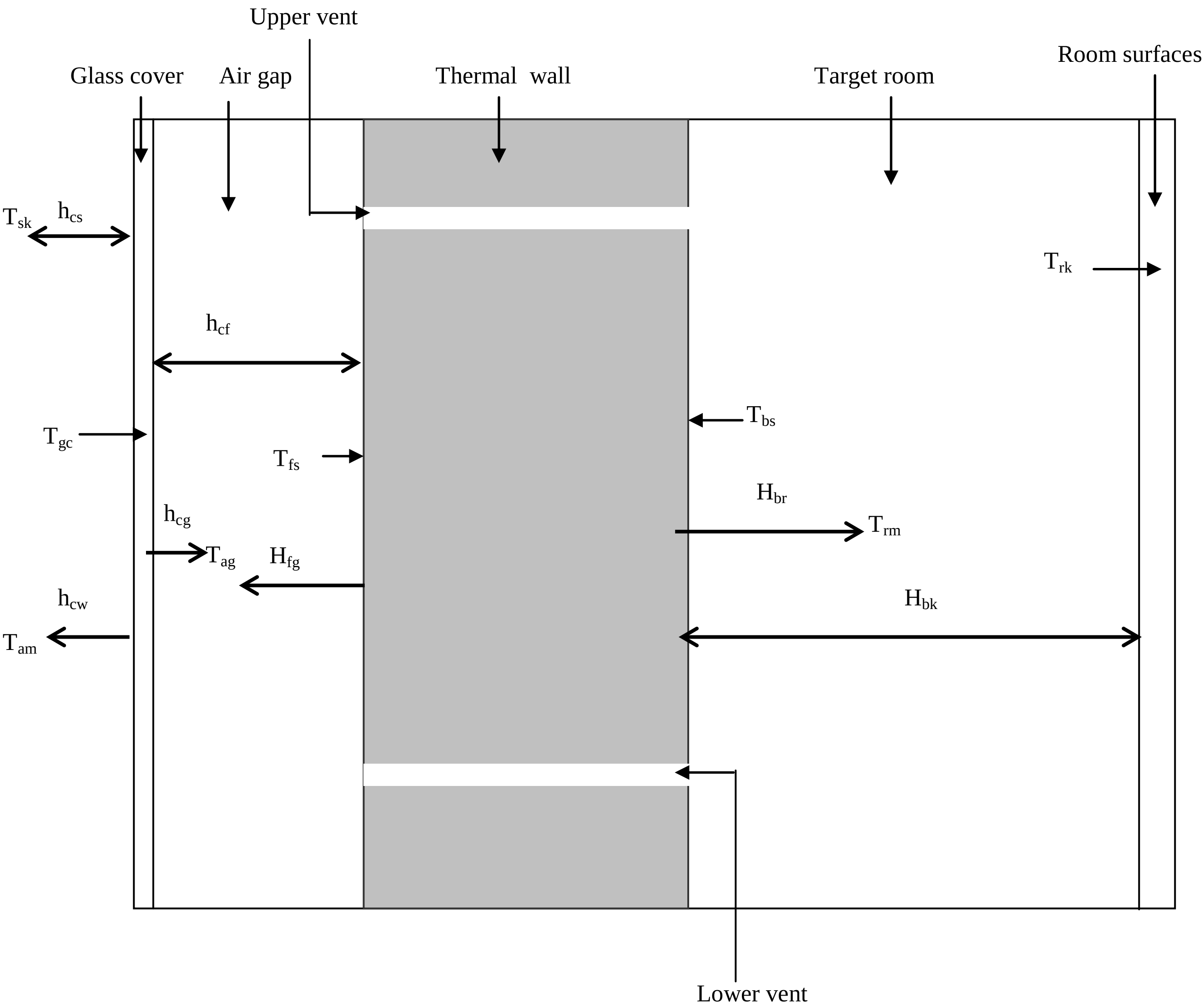

Fig. 1: Trombe wall system heat transfer parameters

2.1 The Glass Cover

The glass cover gains heat by absorption of some of the incident solar radiation and through radiation from the Trombe wall front surface. It loses heat through radiation to the sky and convection to ambient and the air gap. The energy balance equations is given by (Shtrakov and Stoilov, 2005; Ong ,1995a; Ong, 1995b):

$$\alpha_g I_{gc} + h_{cf}\left(T_{fs} - T_{gc}\right) = h_{cw}\left(T_{gc} - T_{am}\right) + h_{cg}\left(T_{gc} - T_{ag}\right) + h_{cs}\left(T_{gc} - T_{sk}\right) \quad (1)$$

where α_g is the absorbance of the glass cover I_{gc} is the hourly total radiation on the glass cover, h_{cf} is the radiation heat transfer coefficient between the glass cover and the Trombe wall front surface, h_{cw} is the wind convection heat transfer coefficient from the glass cover, h_{cg} is the convection heat transfer coefficient from the glass cover to the air gap, h_{cs} is the radiation heat transfer coefficient between the glass cover and the sky, T_{fs} is the Trombe wall front surface temperature, T_{gc} is the glass cover temperature, T_{am} is the ambient temperature T_{ag} is the air gap average temperature and. T_{sk} is the sky temperature.

2.2 Air Gap Thermo Circulation

The air gap gains heat through convection from the glass cover and the Trombe wall front surface. It loses heat by exchanging hot air with cold air from the room. The energy balance equation is given by (Bansal and Gour, 1997; Bilgen and Chaaban,1982)

$$\frac{\dot{m}c_{pa}T_{ag}-T_{rm}}{A_{tw}}=h_{cg}\left(T_{gc}-T_{ag}\right)+h_{fg}\left(T_{fs}-T_{ag}\right) \quad (2)$$

where $\dot{m}$ is the mass flow rate of the air in the air gap, c_{pa} is the specific heat capacity of air at constant pressure, h_{fg} is the convection heat transfer coefficient from the Trombe wall outer surface to the air in the air gap, T_{rm} is the brooder room temperature and A_{tw} is the surface area of the Trombe wall.

2.3 Trombe wall bulk material

At any point x from the Trombe wall front surface heat transfer is by conduction according to Fourier's law. This is given by (Shtrakov and Stoilov, 2005; Zrikem and Bilgen, 1987):

$$\alpha\frac{\partial^2 T_w}{\partial x^2}=\frac{\partial T_w}{\partial t} \quad (3)$$

where $\alpha = k_w/\rho_w c_w$ is the thermal diffusivity, T_w is the temperature of the Trombe wall at a point x from the outer surface and at the time t, k_w, ρ_w and c_w are respectively the thermal conductivity, density, and specific heat capacity of the Trombe wall material.

2.4 Trombe wall front surface

The Trombe wall front surface gains heat by absorption of the incident solar radiation. It loses heat through conduction into the bulk material, radiation to the glass cover and convection to the air gap. The energy balance equation is given by (Shtrakov and Stoilov, 2005; Rogers and Mayhew, 1980):

$$-k_w\left(\frac{\partial T_w}{\partial x}\right)_{x=1}=I_w+h_{cf}\left(T_{gc}-T_{fs}\right)+h_{fg}\left(T_{ag}-T_{fs}\right) \quad (4)$$

where I_w is the solar radiation absorbed by the Trombe wall

2.5 Trombe wall back surface

The Trombe wall back surface gains heat by conduction from the bulk material. It loses heat though convection to the room and radiation to the surfaces of the room. The energy balance equation is given by (Shtrakov and Stoilov, 2005; Rogers and Mayhew, 1980):

$$-k_w \left(\frac{\partial T_w}{\partial x} \right)_{x=L} = h_{br} \left(T_{rm} - T_{bs} \right) + h_{bk} \left(T_{rk} - T_{bs} \right) \quad (5)$$

where h_{br} is the radiation heat transfer coefficient from the back surface of the wall to the brooder room, h_{bk} is the radiation heat transfer coefficient between the Trombe wall back surface and the surfaces of the room, T_{bs} is the Trombe wall back surface temperature, T_{rm} is the brooder room temperature, T_{rk} is the average temperature of the room's surfaces.

2.6 Target room

The total energy input to the room is the sum of the energy conducted through the wall , Q_{tw} and that transferred into the room through the upper vent by natural convection of air in the air gap, Q_{ag}. The heat losses consist of the transmission heat loss, Q_{tl} and the ventilation loss, Q_{vl} The energy balance equation is given by ((Bansal and Gour, 1997) :

$$Q_{tw} + Q_{ag} = Q_{tl} + Q_{vl} \quad (6)$$

Q_{tw}, Q_{ag}, Q_{tl}, and Q_{vl} are given respectively by

$$Q_{tw} = h_{cr} A_{tw} \left(T_{bs} - T_{rm} \right) \quad (7)$$

$$Q_{ag} = 2\dot{m} c_{pa} \left(T_{ag} - T_{rm} \right) \quad (8)$$

$$Q_{tl} = \sum U_i A_i \left(T_{rk} - T_{am} \right) \quad (9)$$

$$Q_{vl} = V_x \rho_a c_{pa} \left(T_{rm} - T_{am} \right) \quad (10)$$

where U_i is the U.value of the room surface i and A_i is the corresponding area, V_{xr} is the volumetric exchange rate of the air flow, ρ_a is the density of air and c_{pa} is the specific heat capacity of air. The air exchange rate between the room and the environment include that which occurs actively through opened windows and doors and passively by infiltration through pores and cracks.

The active air exchange is used to manually regulate the temperature of the brooder room by opening the window for a period of time so that some of the hot air inside can be exchanged for cooler air from outside . The time t the window is left open is derived from a consideration heat balance between the exchanging fluids and is given by

$$t = \frac{V_{rm} \left(T_{ra} - T_{rd} \right)}{V_w A_{wd} \left(T_{rd} - T_{am} \right)} \quad (11)$$

where V_{rm} is the volume of air in the room, V_w is the velocity the air entering the room, A_{wd} is the area of the window, T_{ra} is the actual room temperature and T_{rd} is the desired room temperature.

For passive air exchange because of infiltration the American Society of Heating Refrigeration and Air conditioning Engineers(ASHARE) shows that the volume exchange rate in m^3s^{-1} for a second level fitting is given by (Igbal, 1983)

$$V_{xr} = \frac{(2L_{cd} + L_{cw})(a_{wd} + b_{wd}\rho_a V_w / 4)}{3600} \qquad (12)$$

where L_{cd} is the door crack length , L_{cw} is the window crack length ,ρ_a is the density of air, V_w is the velocity of wind and the infiltration function constants a_{wd} and b_{wd} are respectively 1.3 $m^2 s^{-1}$ and 0.049 m^4skg^{-1}.

The design parameters and the meteorological data used are shown in Tables 1 and 2, respectively

A computer program is drawn to read the meteorological data for the representative day of the month and calculate for each wall thickness the hourly temperature of the thermal wall back surface using the design parameters and the modeling equations. The flow chart for the computer program is shown above in Figure 2

3. Results

Figures 3 to 14 show the hourly temperature of the thermal wall back surface for Trombe wall thicknesses of 20cm, 25cm, 30cm, 35cm, 40cm and 45cm for the characteristic day in the months of January to December respectively. The hourly variation of the ambient temperature is included in each case for comparison. Table 3 shows the average hourly temperature of the thermal wall back surface for Trombe wall thicknesses of 20cm, 25cm, 30cm, 35cm, 40cm and 45cm for the characteristic day in the months of January to December. The average hourly ambient temperature is also included for comparison.

4. Discussion

From Figures 3 to 14, we see that, for all the thermal wall thicknesses the Trombe wall back surface temperature and hence the brooder room temperature are always higher than the ambient temperature. They also have comparatively very small daily swings.

A careful examination of the graphs shows that the daily swing of the hourly temperature decreases as the wall thickness increases from 20cm to 45cm for all the months of the year.

From Table 3, it can be observed that the Trombe wall back surface hourly temperature has the lowest average value of 34.58ºC in August for the 45 cm thick wall and the highest average value of 45.13ºC in February for the 20 cm thick wall. The lowest and highest values of the ambient temperature occur in the same months and they are 27.30 ºC and 31.80 ºC respectively.

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. (Okpani, 2009; Okpani and Nnabuchi, 2009)

Hence these findings show that the optimum brooding temperature requirement can be met. This is achieved by opening the window for a period of time so that the hot air inside can be exchanged with the cooler air outside. This time is a function of the actual room temperature, the desired room temperature, the ambient temperature and area of the window The values obtained here are close to those obtained by Echiegu(1986) and Okonkwo(1993a).

Table 1 : Design parameters

Description	Value
Room floor area, Afl	11.925 m^2
Room walls area, Awl	23.520 m^2
Room roof area, Arf	11.925 m^2
Room total surface area, Arm	47.370 m^2
Floor U-value, Ufl	0.72 $Wm^{-2}K^{-1}$
Wall U-value, Uwl	2.92 $Wm^{-2}K^{-1}$
Roof U-value, Urf	0.115 $Wm^{-2}K^{-1}$
Room mean U-value, Urm	1.660 $Wm^{-2}K^{-1}$
Door crack length, Lcd	4.50 m
Window crack length, Lcw	2.70 m
Door area, Adr	1.190 m^2
Window area, Awd	0.455 m^2
Trombe wall surface area, Atw	6.30 m^2
Trombe wall height, Htw	1.40 m
Trombe wall thickness, Dtw	Variable: 0.20m, 0.25m, 0.30m, 0.35m, 0.40m, 0.45m
Trombe wall specific heat capacity, c_w	880 $Jkg^{-1}K^{-1}$
Trombe wall density, ρ_w	2720 kg m^{-3}
Trombe wall thermal conductivity, κ_w	1.41 $Wm^{-1}K^{-1}$

Trombe wall surface coating absorbance, α_{ss}	0.87
Trombe wall outer surface IR emittance, ε_{fs}	0.09
Trombe wall inner surface IR emittance, ε_{bs}	0.88
Trombe wall upper vent area, Auv	0.096 m^2
Distance between upper and lower vents, Dv	1.155 m
Air gap width, Wag	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	1.983×10^{-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, κ_a	0.0262 $Wm^{-1}K^{-1}$
Space interval, Δx	0.02 m
Time interval, Δt	3600 s
Tilt angle, β	90º ($\pi/2$ rads)
Latitude(Enugu), ϕ	6.47 º N

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Table 2 : Meteorological data

Month	[a] Monthly mean daily solar radiation on a horizontal surface (MJ m^{-2} day^{-1})	[a]Monthly mean wind velocity (ms^{-1})	[b]Monthly mean daily maximum temperatures (° C)	[b]Monthly mean daily minimum temperatures (° C)	[b]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

[a] From *Renewable Energy for Rural Industrialization and Development in Nigeria,* Abuja: UNIDO (Dec. 2003).

[b] From the records of the Nigerian Meteorological Agency, South Eastern Zone, Akanu Ibiam International Airport, Enugu.

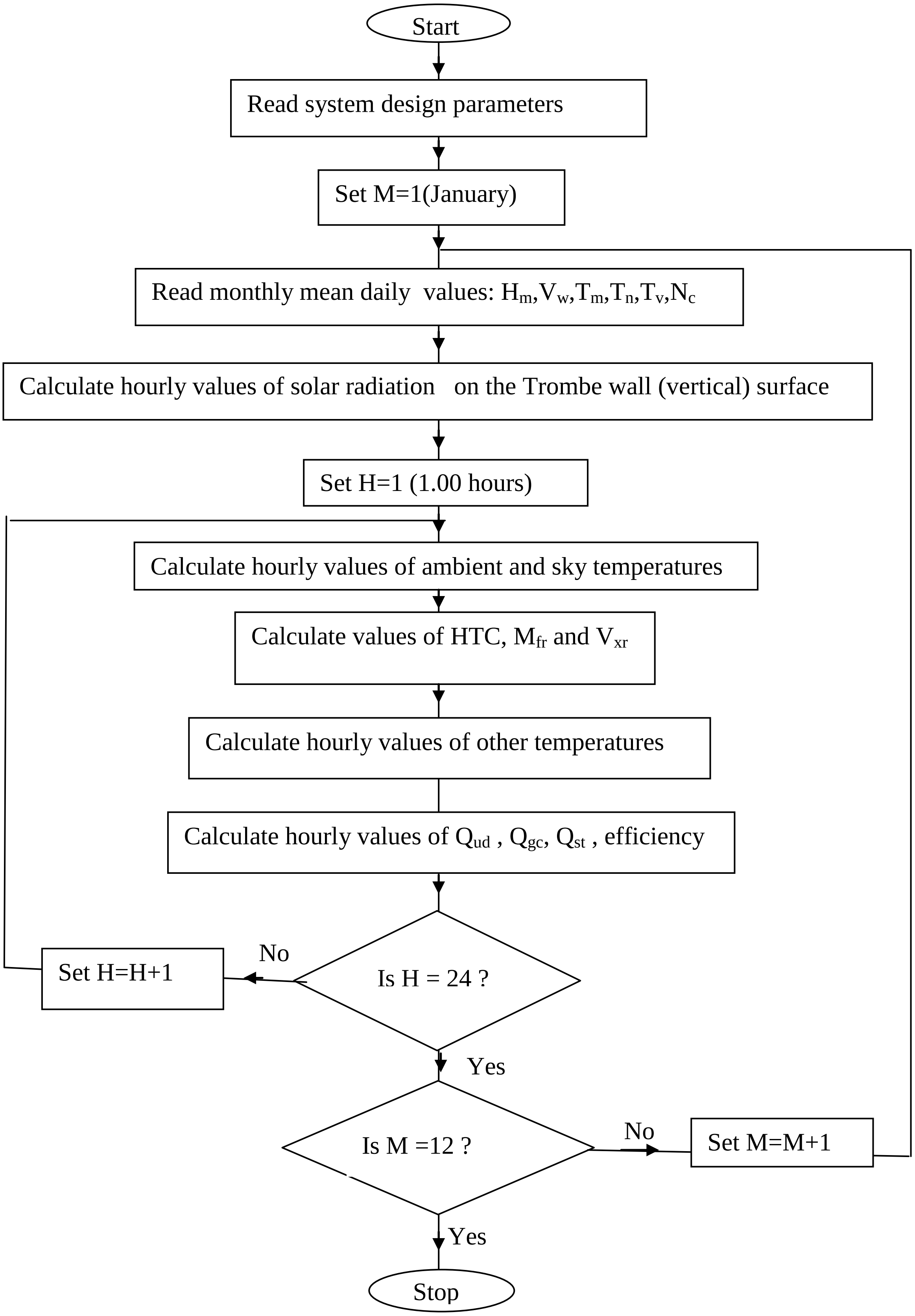

Fig. 2: Flow Chart for the Computer Program

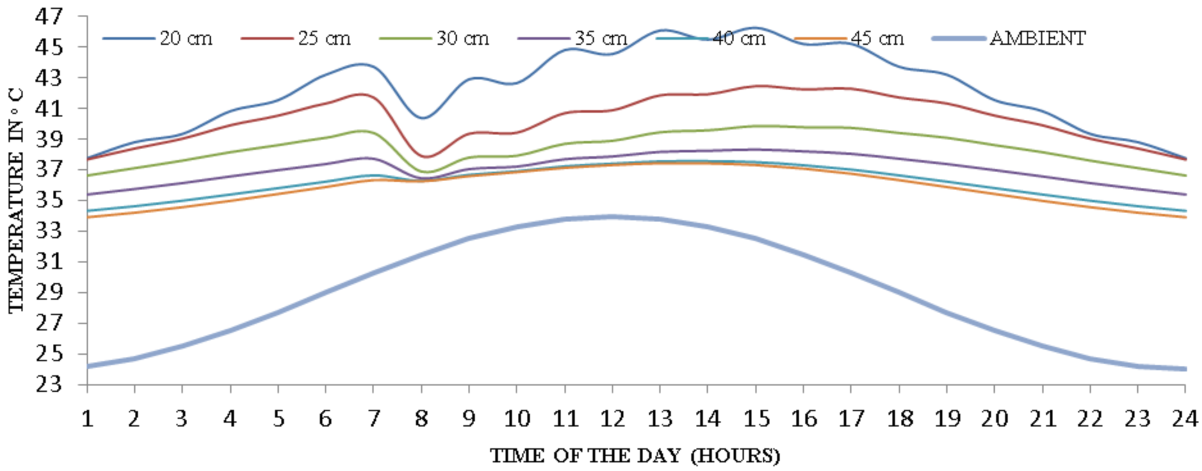

Fig. 3:Hourly variation of the Trombe wall back surface temperature for the month of January

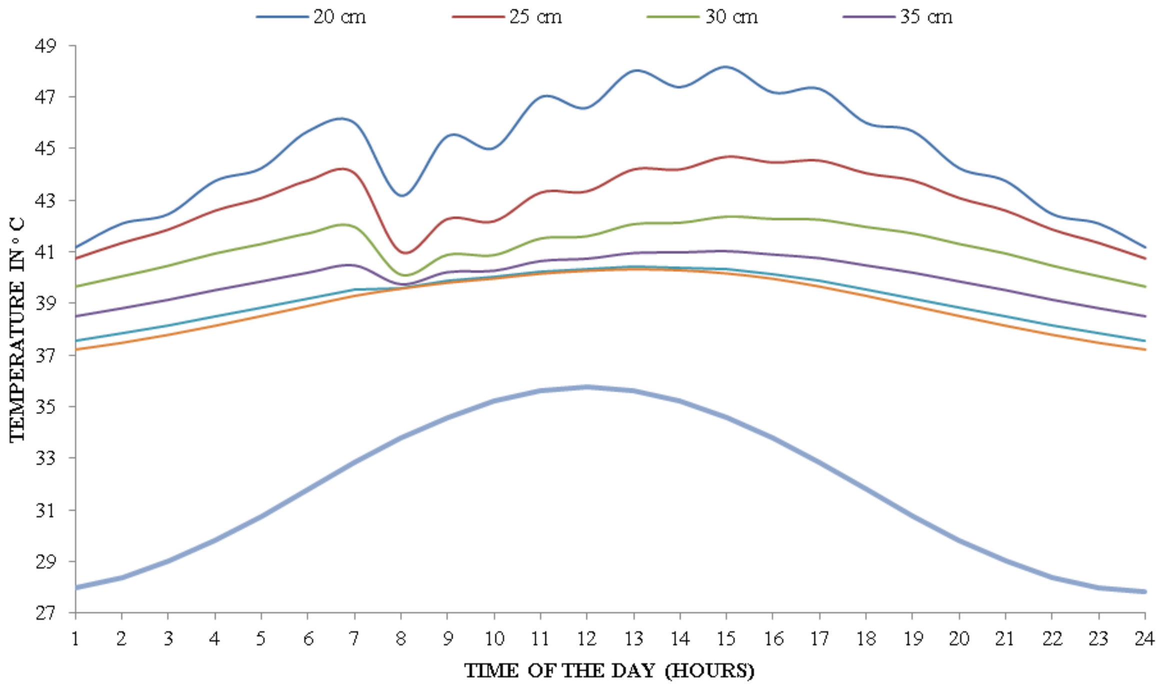

Fig. 4:Hourly variation of the Trombe wall back surface temperature for the month of February

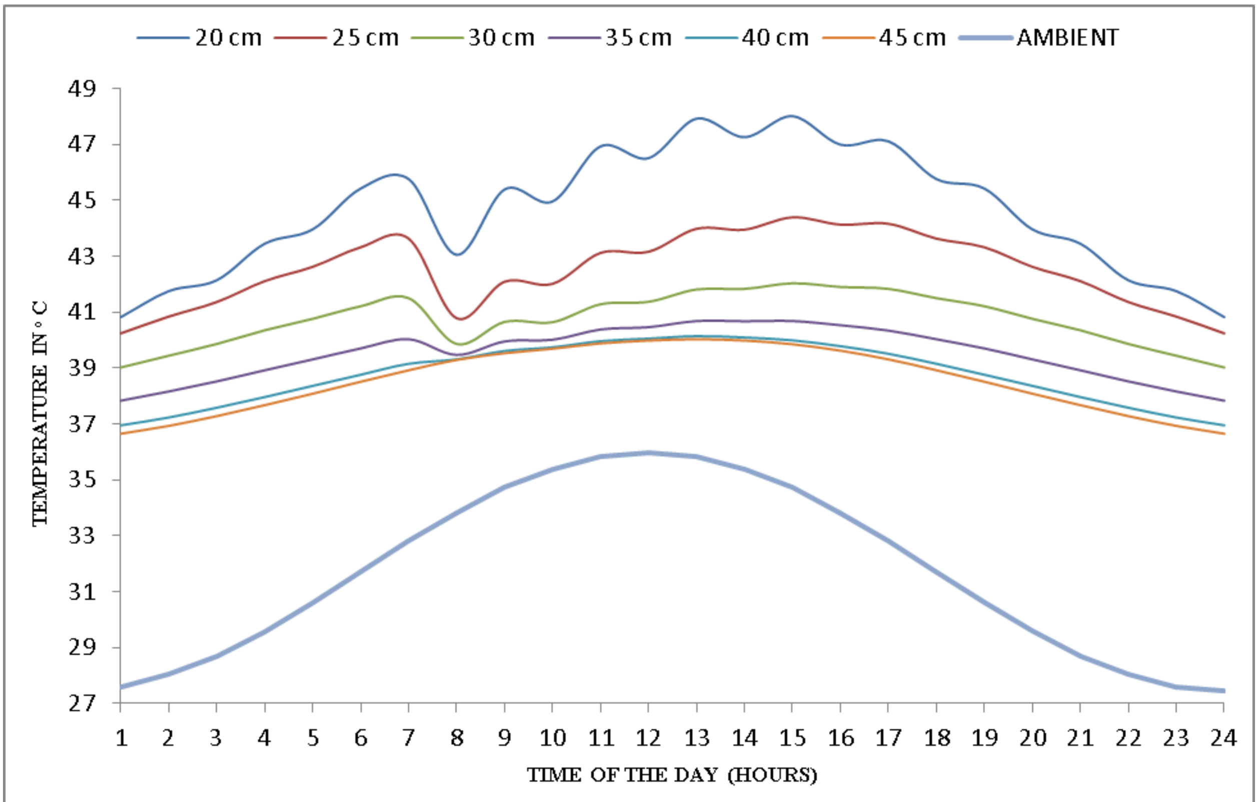

Fig. 5: Hourly variation of the Trombe wall back surface temperature for the month of March

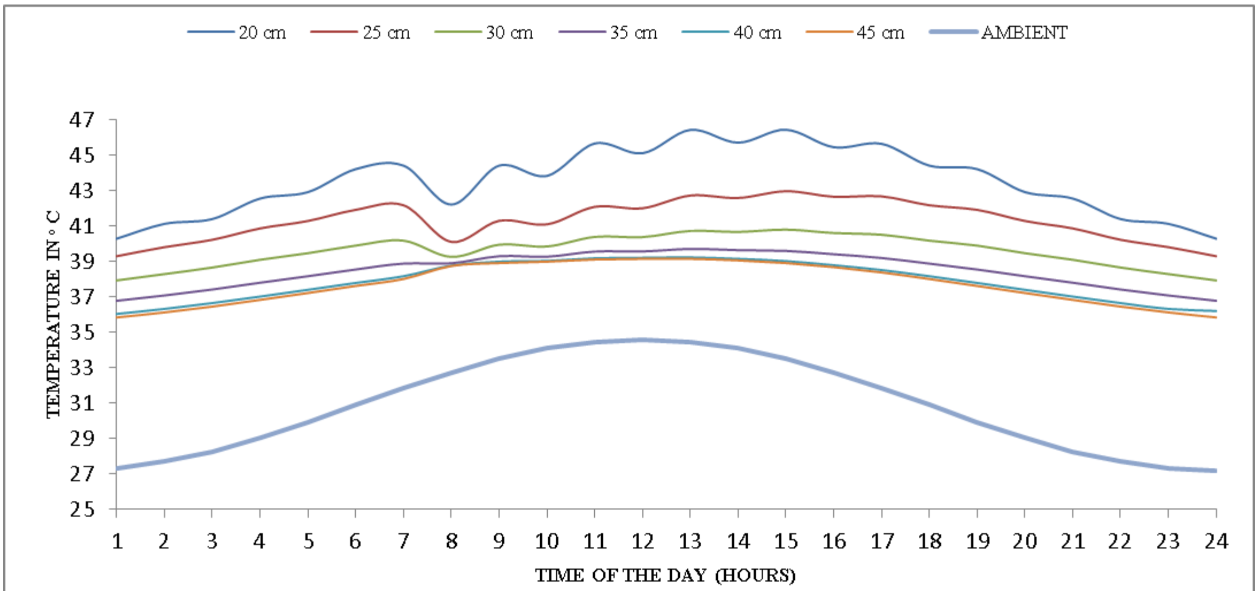

Fig. 6: Hourly variation of the Trombe wall back surface temperature for the month of April

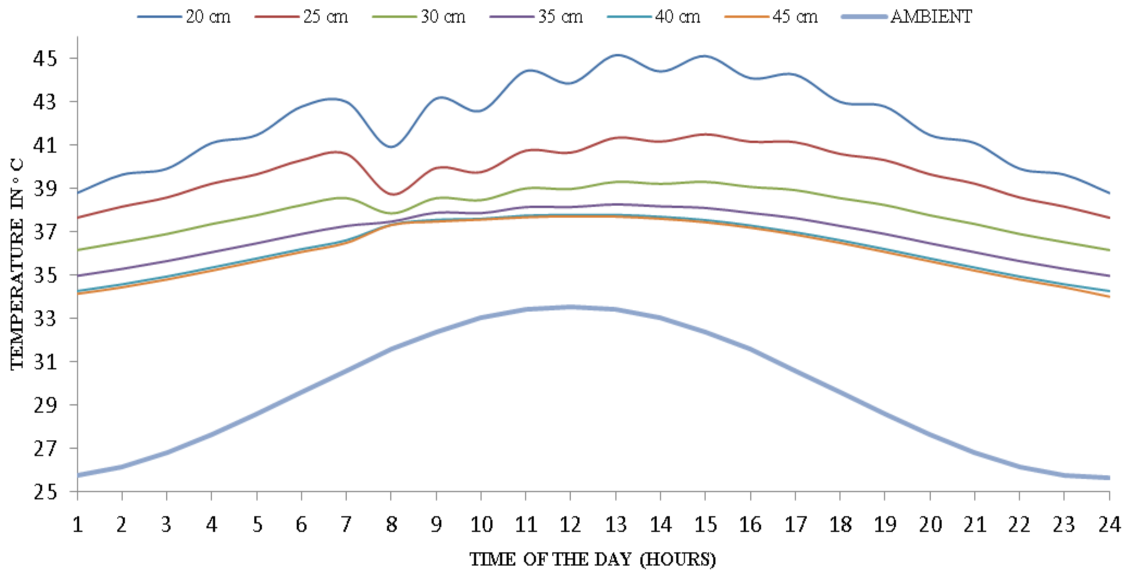

Fig. 7:Hourly variation of the Trombe wall back surface temperature for the month of May

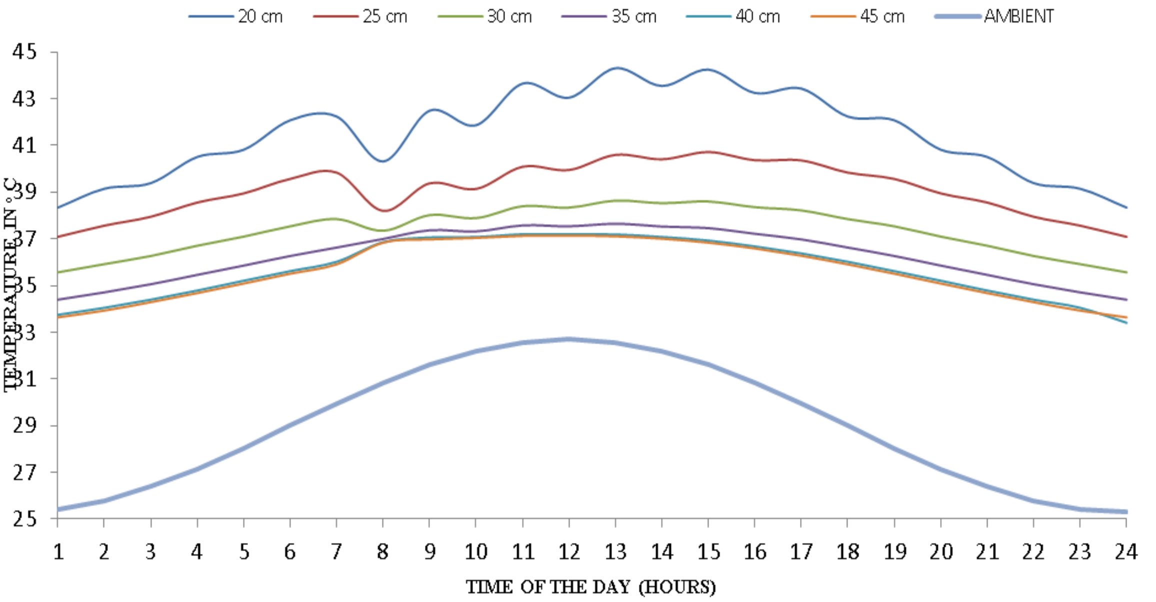

Fig. 8:Hourly variation of the Trombe wall back surface temperature for the month of June

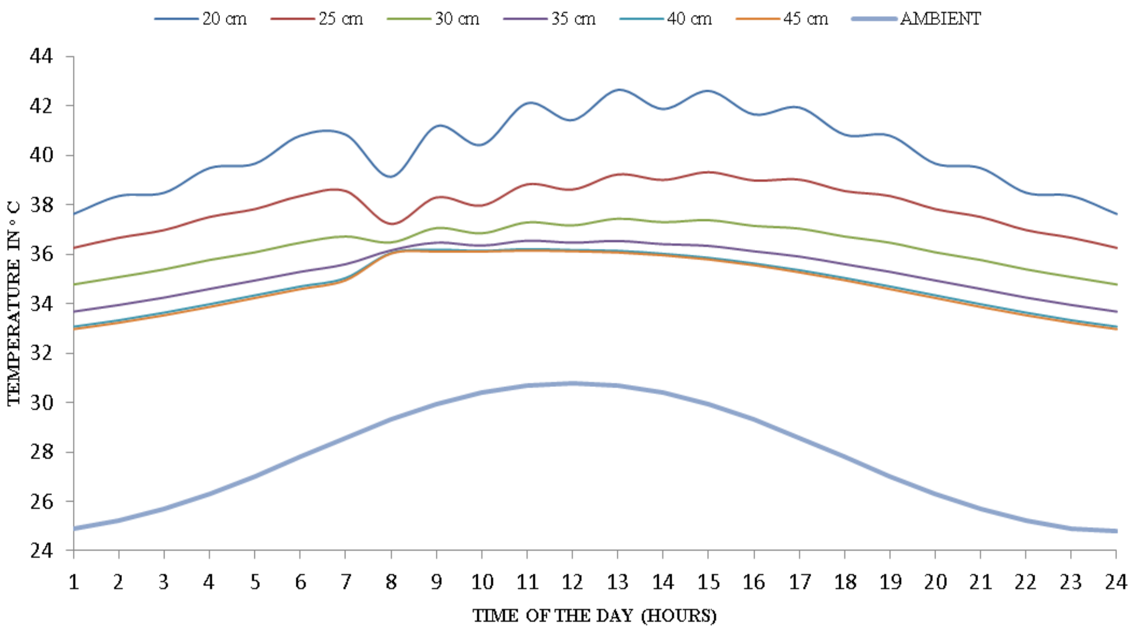

Fig. 9:Hourly variation of the Trombe wall back surface temperature for the month of July

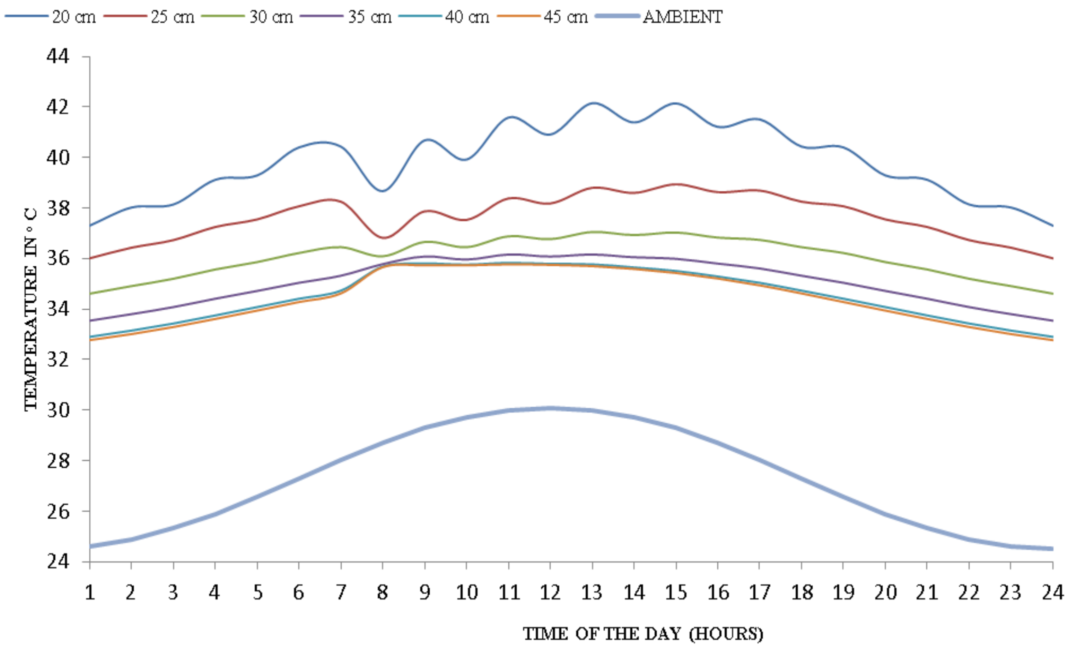

Fig. 10:Hourly variation of the Trombe wall back surface temperature for the month of August

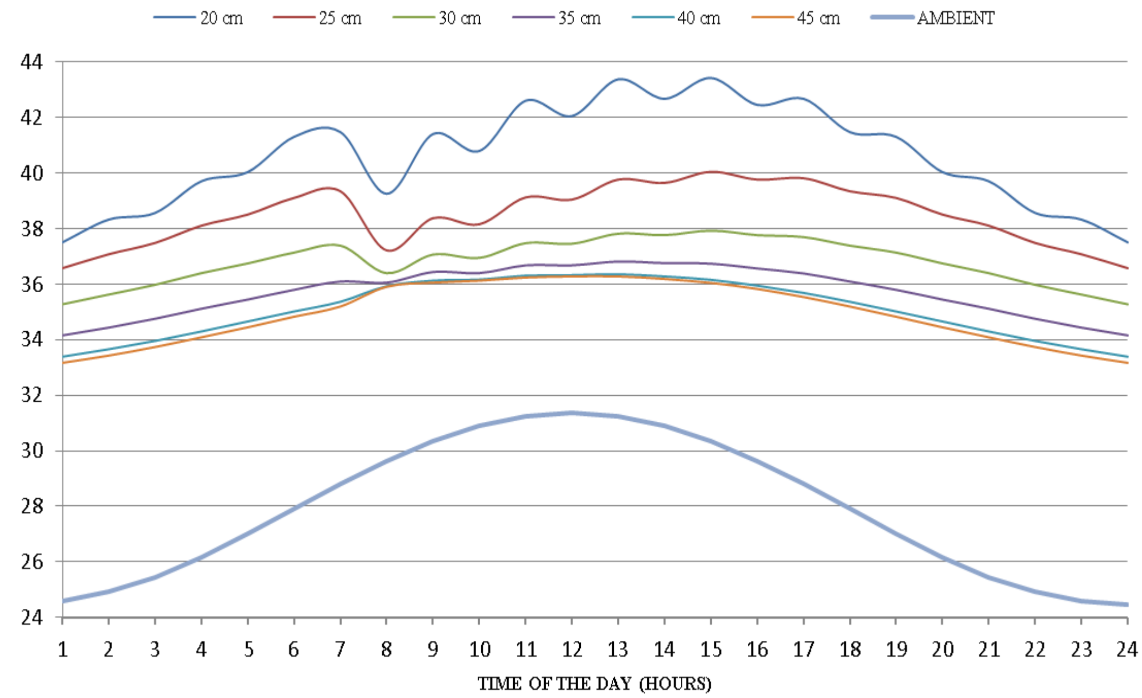

Fig. 11:Hourly variation of the Trombe wall back surface temperature for the month of September

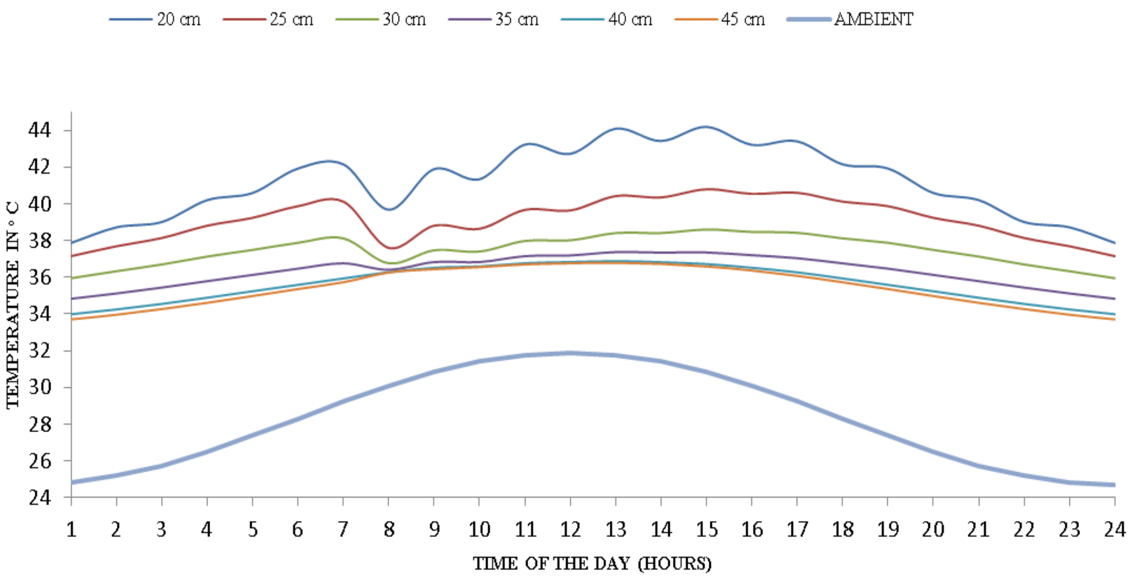

Fig. 12:Hourly variation of the Trombe wall back surface temperature for the month of October

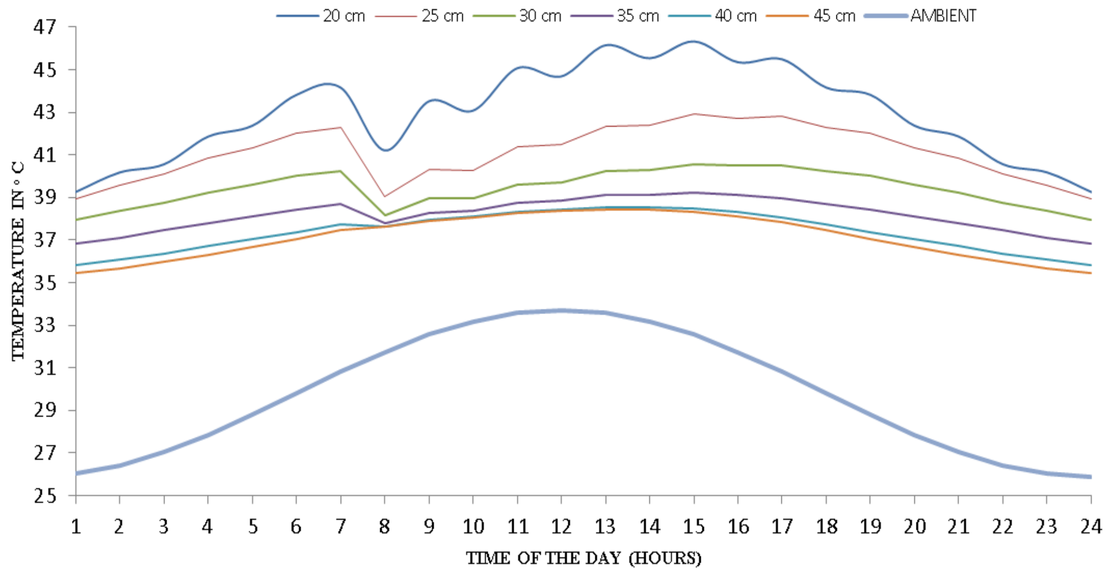

Fig. 13:Hourly variation of the Trombe wall back surface temperature for the month of November

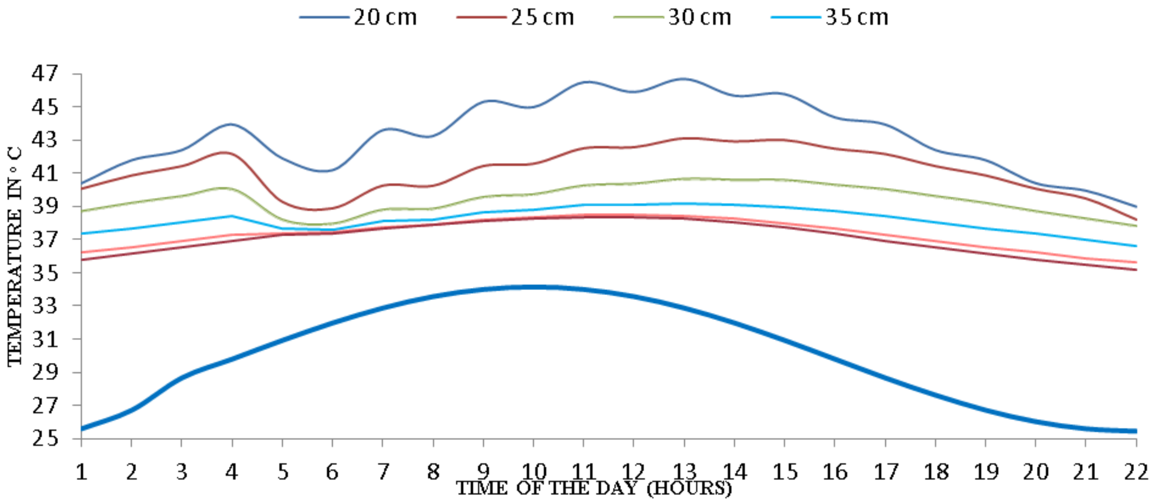

Fig. 14:Hourly variation of the Trombe wall back surface temperature for the month of December

Table 3 : Average hourly temperature of the thermal wall back surface for Trombe wall thicknesses of 20cm, 25cm, 30cm, 35cm, 40cm and 45cm for the characteristic day in the months of January to December

MONTH	20 cm	25 cm	30 cm	35 cm	40 cm	45 cm	Ambient temperature
JAN	42.59	40.45	38.54	37.17	36.29	36.02	29.00
FEB	45.13	43.05	41.30	40.09	39.32	39.10	31.80
MAR	44.92	42.68	40.86	39.64	38.91	38.71	31.70
APR	43.81	41.48	39.74	38.64	38.04	37.9	30.90
MAY	42.39	39.93	38.13	37.02	36.44	36.33	29.60
JUN	41.71	39.25	37.49	36.42	35.87	35.795	29.00
JUL	40.43	38.08	36.44	35.46	34.98	34.89	27.80
AUG	40.01	37.75	36.16	35.18	34.68	34.58	27.30
SEP	40.85	38.62	36.93	35.84	35.22	35.07	27.90
OCT	41.43	39.28	37.58	36.44	35.76	35.50	28.30
NOV	43.24	41.24	39.52	38.29	37.49	37.25	29.80
DEC	43.23	41.13	39.41	38.17	37.35	37.09	29.60

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 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 thickness of the thermal wall has significant effect on the temperature of back surface. For a thermal wall of given thickness 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.

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