Numerical modeling of Trombe wall solar chick brooder for optimal poultry production

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Abstract: Poultry brooding requires optimal provision of heat, medication, water and feed on abuilt environment deep litter for day-old chick. This built environment (Trombe wall solar chick brooder) has been developed but has not been numerically modeled and validated. Therefore, numerical modeling, simulation and validation are carried out on Trombe wall solar chick brooder. Predictive linear differential equations based on physical, mathematical principles and relationships governing thermo-physical properties of the components of the brooder are formulated, discretized and expressed in their finite different forms using SCILAB 5.5.2. Predicted data is gotten from the simulation thereafter validated with the measured data. The temperature varied with definite pattern (sinusoidal) for both measured and predicted for the six days simulation with average temperature variation of 3^oC -5^oC.T-test statistics is carried out on predicted and measured mean data: temperature of Trombe wall glaze (T_{G1}), temperature of pebble glaze (T_{G2}), temperature of the pebble bed bin (T_p), temperature of the brooding room (T_{Br}), and temperature of the Trombe wall outer surface ($T_{w\ (outer\ surface)}$)then separated using Levene test for equality. The model adequately predicted the measured temperature of the brooder at 5% probability level. This model serves as a tradeoff platform between physical and modeled system.

Keywords: numerical modeling, simulation, validation, Trombe wall solar chick brooder, poultry production.

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1 Introduction

Chicks at day-old have no feathers/cover and as such require optimal heat supply in proper quantities during chick brooding to maintain the body-mass temperature of the birds for metabolic processes to take place. Inadequate heat supply is one of the predisposing factors that lead to high bird mortality at infancy (Okonkwo and Akubuo, 2001). However, limited energy sources and unsustainable energy utilization efficiency are major problems bedeviling brooding operations in developing countries.

The overall effects of these are low production, high mortality rate, low income, and cold stroke. Thus to increase the level of poultry production in developing countries above the present position requires concerted efforts, these issues are surmountable (Okonkwo and Akubuo, 2001). Energy (heat) supply for brooding is a problem in poultry production. For optimal performance,

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appropriate heat supply technologies that are user friendly, sustainable, low cost and affordable are imperative. Meanwhile, Okonkwo and Akubuo (2007), and Okonkwo (2000) studied the Trombe wall system as a heat source for passive solar energy poultry chick brooder. The results showed that the system supported poultry brooding of day-old chicks. Odo (2016) also work on Trombe wall solar chick brooding, thus established a relatively cheap passive solar energy heated chick brooder using locally available materials. Khedari et al (1999) discussed the possibilities of using Trombe wall to ventilate houses within Bangkok ambient conditions. The effects of air gap and wall height on the induced passive ventilation were studied experimentally. Ohagwu et.al. (2019) studied the stability analysis of equilibrium for Trombe wall solar chick brooder; the result showed the system is locally stable. Meanwhile, the success and efficiency of poultry production are highly dependent on brooding techniques adopted by farmer (Okonkwo and Agunwamba, 1997). Recently, heating, ventilating and air conditioning technological research (HVACT) is growing. It is imperative to harness the use of the renewable energy to provide space heating (energy) for building with simple configuration, high efficiency and minimum running cost (Wei et al., 2015).Burek and Habeb (2007) conducted an experiment of heat transfer and mass flow in Trombe wall and the result showed that the mass flow rate through the channel was a function of both the heat input and the channel depth. Fawaz et al (2014) investigated design to provide the required heating and ventilation for chicken broilers in their six week brooding cycle. Ohagwu (2017) also developed mathematical model of computing the heat and ventilation requirement of Trombe wall solar chick brooder for optimal poultry production. Oluyemi and Roberts(1979) also studied numerical 3-D simulations in order to model the heated space where a convective unit is employed to deliver the heating needs as well as fresh air requirement that maintain Ammonia (NH_3) and Carbon (VI) oxide (CO_2) concentrations at the micro environment of the chicken below 25 ppm and 2500 ppm, respectively.

The objectives of this work are to develop a numerical model of Trombe wall solar chick brooder, simulate and validated the model using measured data for optimal poultry production. It involves formulating mathematical model equation of the Trombe wall solar brooder and then performed thermal simulation of brooding operation using the developed model as well as validates the model using experimental data and tested weather data, then test for significance over the measured and predicted parameters using t-test statistics. The numerical model will serve as a modeling platform for further studies vis a vis the physical model futuristic expensive research study.

2 Material and method

2.1 Material description and physical process

The developed Trombe wall solar chick brooder was dimensioned 3m × 2.2m × 3m (Okonkwo and Akubuo, 2007). The building materials used for the construction were material accessed locally in the tropics namely: solid cement blocks, acrylic transparent glazing, ceiling board, zinc, pebble stone (limestone chippings), black paint and wooden door. Brooding process provided enabling environment (deep litter system) for the chicks to survive as day old chicks. The recommended brooding room/ space of 0.04m^2 per chick plus 10% of the brooding space for drinker and feeding troughs for deep litter system (Oluyemi and Roberts, 1979) were adopted in Trombe wall solar chick brooder. The building elements includes: the glass cover, the air gap, the Trombe wall surfaces, the brooder room, and the room surfaces. The east, west, north and south walls of the brooder were constructed with solid blocks except for the south wall made of Trombe wall (the wall was painted black, and glazed, lower and upper vents which aided thermo circulation of the heat to the brooding room). The foot of the Trombe wall was also filled with pebble rock painted black with a glazing and vented to empty its heat to the brooding floor (Ohagwu et al., 2019). The roof of the brooder was made of conventional roofing sheets (zinc) and sealed with asbestos ceiling board.

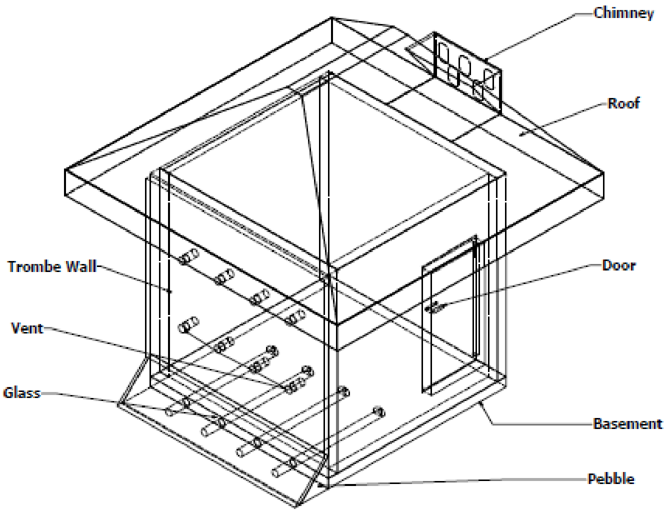
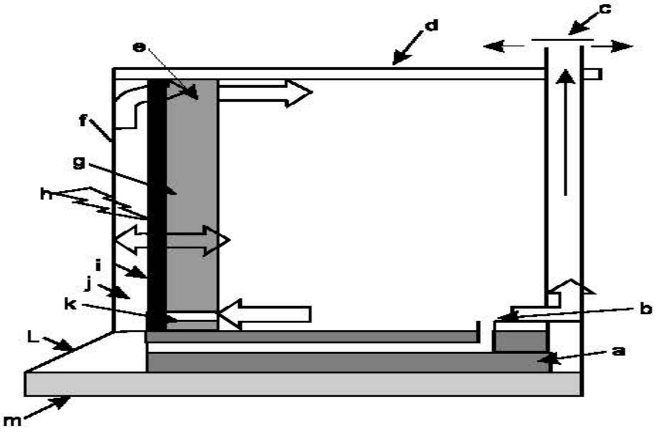


Figure 1 Three dimensional sketch of Trombe wall solar chick brooder



(a) pebble bed storage (b) heat exchanger (c) air chimney (d) roof (e) upper air vent (f) glass cover (g) Trombe wall heat storage system (h) solar radiation (i) solar collector (j) sunspace (k) lower air vent (l) pebble bin glass cover (m) basement

Figure 2 Cross sectional view of the Trombe wall solar chick brooder.

For the distribution of temperature and evacuation of humid/dense air from the room, an air chimney was centrally located at the roof to allow the exhaust gases to exit from the brooding room. The chimney dimension was 0.3m × 0.3m × 3.3m and was extended above the roof of the brooder. The chimney usually creates natural draft for natural air circulation and this allowed ventilation and environmental control within the brooding room. The total heat load came from solar energy (Okonkwo and Akubuo, 2001). In between roof and ceiling board was usually the insulating mass of air which does not allow heat losses across the roof. The physical component models with vents of the Trombe wall solar Chick brooder under studied were presented in Figure 1, as well as the cross-sectional view shown in Figure 2. Descriptively, the cross-sectional view of the Trombe wall solar chick brooder is shown in Figure 2. The component parts were labeled and named accordingly.

2.2 Design assumptions of Trombe wall solar chick brooder.

General assumptions adopted for design assumptions were as follows:

(a) Heat transferred to the collector was uni-direction (in the x-direction).

(b) there were no heat gains through any openings except through collector (Trombe wall); the roof was also insulated.

(c) The system had a single glass cover.

(d) Energy was stored on the Trombe wall at uniform temperature.

(e) Solar energy collector and glazing radiated heat as gray bodies, glazing does not store energy rather exchanges heat by convection and radiation.

(f) Air circulation rate and temperature over the surface of the collector were uniform and at normal atomspheric pressure and relative humidity.

(g) Thermophysical properties of the Trombe wall were assumed to be the same.

2.3 Themophyscial properties and dimensions of Trombe walled solar chick brooder.

The system's thermophyscial properties and dimensions with material properties provided the aggregate précised heat requirement for the brooding of day old chicks. The details of the physical design component parts and dimensions are shown in Table 1.

Table 1 Physical properties, materials and dimensional parts of Trombe wall solar brooder

Trombe wall glaze (perplex)	Values
Thickness(m)	0.003
Height (m)	3
Width (mm)	3
Trombe wall (Masonry wall)	
Thickness (m)	0.40
Radius of vents(mm)	0.015
width of the air gap(m)	3
Sunspace width (D_{gap}) (m)	0.003
Height (m) and height of the air gap (m)	3
Pebble bed bin	
Height between inlet and outlet (m)	0.5
Brooder (Deep litter)	
Width (m)	2.2
Length of door (m)	1.83
Width of door (m)	0.3
Door thickness (m)	0.15
Area of the brooding room(m)	A_{Tw} x (4)
Area of the chimney outlet vent (m)	0.0009

Note: Source from Ohagwu, et.al. (2019)

These dimensions, design and material properties were synergistically contributing to the effectiveness of the system. The required thermodynamic parameters that governed and passively directed the heat from the sun to be harnessed in the deep litter brooder were shown in Table 2. Meanwhile, measuring instruments to determine the temperatures of the contributing components like the outer Trombe wall surface facing the sun, inner Trombe wall surface, temperature of the airgap, brooding room temperatures and similar temperatures for the pebble bed bin were thermometric sensors and anemometric sensors connected to a data logger, also solarimeter was used to record daily insolation during the study. 200 Day-old chicks, feeder, drinker, sawdust, water and feed were deployed for the experiments.

Table 2 Heat transfer properties and materials parts of Trombe wall solar brooder

Trombe wall glaze (perplex)	Units
Emissivity	1180
Absorptivity	0.05
Specific heat capacity ($Jkg^{-1}K^{-1}$)	1470
Transmissivity	0.75
Trombe wall (Masonry wall)	
Emissivity	0.86
Absorptivity	0.95
Thermal diffusivity	$K_{TW}/(\rho_{TW}Cp_{TW}T)$
Thermal Conductivity (K) (Wm^{-2})	0.1
Specific heat capacity ($JKg^{-1o}C$)	920
Density (Kgm^{-3})	2240
Pebble bed bin	
Emissivity	0.88
Absorptivity	0.95
Brooder (Deep litter)	
Overall heat loss (JKg^{-2})	30
Thermal conductivity of door	0.16
Area of the chimney outlet vent	0.0009
Discharge	0.62
Air	
Specific heat capacity (KKg^{-2})	1005
Viscosity (Kgm^{-3})	1.857
Density (Kgm^{-3})	1.177
Prandtl Number	0.713
Thermal conductivity ($Wm^{-1}K^{-1}$)	0.02544
Thermal diffusivity (m^2s^{-1})	2.213 x10^{-5}

The heat transfer properties of the Trombe walled solar brooder were presented. Since, the system operated in a passive manner, air flow properties were also presented as the convective mode of transport during the brooding operation as well as thermo circulating medium. Furthermore, air flow current drawn from the chimney created draft used to evacuate respired, odorous moist gases from the brooding room during brooding operation. Therefore, the system was locally stable (Ohagwu et al., 2019).

2.4 Mathematical modeling

2.4.1 Theory/development of the mathematical model

A set of predictive mathematical equations were developed based on physical and mathematical principles and relationships governing thermo-physical properties of the components of the Trombe wall system and the heat and mass transfer between the thermal storage wall and the brooding room. The developed mathematical models were discretized and expressed in their finite difference forms. Scilab 5.5.2 codes for these mathematical expressions were used to simulate the system using the input measured parameters namely: Ambient Temperature of Nsukka, air properties, solar radiation data of Nsukka at 6.8^0N, 7.37^0E. Measured temperatures of Trombe wall glaze, pebble bed bin glaze, Trombe wall outer surface facing the glaze, pebble bed, and Trombe wall inner surface facing the brooding room were used to validate the model. Based on the finite forward discretization of the model equations, expressions for discrete transient temperature of the components of the Trombe wall system were determined. For the Trombe wall glazing, transient temperatures are given as:

$$T_{G1}{}^{t+\Delta t} = T_{G1}{}^{t} + [\Delta t / (\rho_G d_G C_{p_G})][\alpha_{G1} I_T - h_{C,G1A1}(T_{G1}{}^{t} - T_{A1}) \\ -h_{r,G1W}(T_{G1}{}^{t} - T_{W,1}{}^{t}) - h_{r,G1S}(T_{G1}{}^{t} - T_S^t)] \tag{1}$$

Heat transfer across the Trombe wall thickness in discretized form was shown in Figure 3.

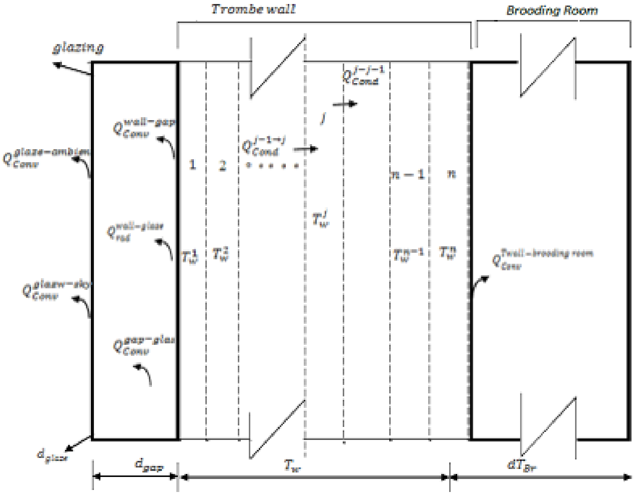


Figure 3 Discretization of the Trombe wall showing thermal energy transfers

For intermediate nodes in the Trombe wall, it is given as:

$$T^{t+\Delta t}{}_{TW,1} = T^{t}{}_{TW,1} + \frac{[(\alpha_{TW}\frac{\Delta t}{\Delta x})(\tau_G \alpha_W I_T)]}{K_{TW}} + \frac{h_{C,W1A1}(T_{A1} - T_{TW,i}{}^{t})}{K_{TW}} + \frac{h_{r,G1W}(T_{G1,i}{}^{t} - T_{TW,i}{}^{t})}{K_{TW}} + \frac{(T_{TW,i}{}^{t+\Delta t} - T_{TW,i}{}^{t})}{\Delta x} \tag{2}$$

Equations 1 and 2 defined Heat stored in the $i^{th}T_W$ node which was equal to conductive heat transfer from the i^{th}+1node+conductive heat transfer from the i^{th}-1 node. For n^{th}-1 node, we had heat stored in the last Trombe wall node equal to convective heat transfer from brooding room plus conductive heat transfer from the n^{th}-1 node. This was expressed as:

$$\frac{T^{t+\Delta t}{}_{TW,n} - T^{t}{}_{TW,n}}{\Delta t}\left(\frac{\rho_{TW} C_{PTW} \Delta x A_{TW}}{K_{TW}}\right) = \\ \frac{h_{c,W1B1} A_{TW}(T_B{}^{t} - T_{TW,n}{}^{t})}{K_{TW}} + \frac{A_{TW}(T^{t}{}_{TW,n-1} - T^{t}{}_{TW,n})}{\Delta x} \tag{3}$$

For the pebble bed bin, the temperature of the pebble bin at any given time was expressed as:

$$T_{pb}{}^{t+\Delta t} = T_{pb}{}^{t} + [\Delta t / (\rho_{pb} C_{p_{pb}} V_{pb})](\tau_G \alpha_{pb} A_{pb} I_T) - \\ h_{r,G2P} A_{pb}(T_{pb}{}^{t} - T_{G2}) - h_{C,P1A2} A_{pb}(T_{pb} - T_{G2}) + Q_p \tag{4}$$

But, the Convective heat transfer coefficient for pebble bed bin glazing to air gap/sunspace was expressed as:

$$T^{t+\Delta t}{}_{G2} = T_{G2}{}^{t} + [\Delta t / (\rho_{G2} d_{G2} C_{PG2})][\alpha_{G2} I_T - \\ h_{C,G2A2}(T_{G2}{}^{t} - T_{A2}) - \\ h_{r,G2P}(T_{G2}{}^{t} - T_P{}^{t}) - h_{r,G2S}(T_{G2}{}^{t} - T_S{}^{t})] \tag{5}$$

It was assumed that temperature of air gap of the pebble bed bin was the average of the temperature of pebble bed bin glaze and temperature of the pebble bed bin:

$$T_{a,pebble} = \frac{(T_{C2}{}^{t} - T_p{}^{t})}{2} T_{a,pebble} = T_{A2} = \left(\frac{T_{C,pebble} - T_{pebble}}{2}\right)$$

The time-varying of temperatures of the brooding room was expressed as :

$$\frac{T^{t+\Delta t}-T^{t}{}_{B}}{\Delta t}(\rho_{air}C_{p_{air}}A_{TW}W_{B})=h_{c,W1B1}A_{TW}(T_{TW}{}^{t}-T_{B}{}^{t})+h_{C,W1A1}A_{TW}(T_{TW1}{}^{t}-T_{A1}{}^{t})-M_{A2}C_{Pair}(T_{B}{}^{t}-T_{p}{}^{t})+G_{chi}+U_{B1s}A_{B}(T_{B}{}^{t}-T_{a})-\dot{Q}_{v}-\dot{Q}_{p}-\dot{Q}_{ch} \tag{6}$$

3 Results and discussion

The model equations formulated of the Trombe wall solar energy chick brooder predicted the following results: that the daily unidirectional quantities of heat stored and transferred by Trombe wall to the brooding room are shown in Figure 4.

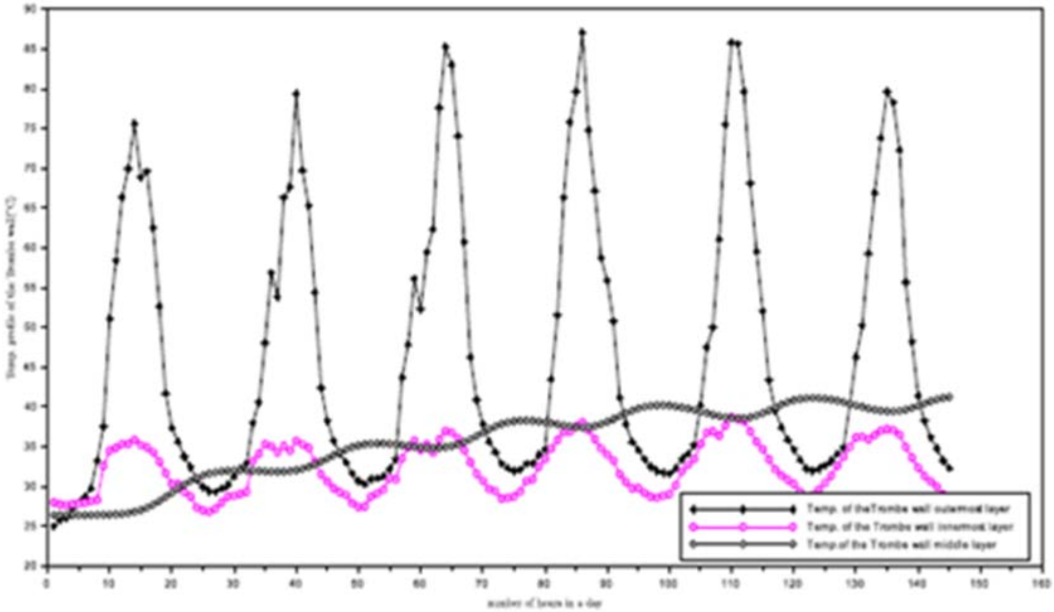


Figure 4 Layers of Temperature profile across Trombe wall (Outermost, middle and innermost) per time (hr)

These represented the thermal transport of energy across structural material by conduction from the sunspace by convection to the inner Trombe wall surface for hourly solar radiation for Nsukka location. Furthermore, the temperature profile in Figure 4 were further delineated to show the finite temperature profile for the outermost layer of the Trombe wall facing the glaze to sun, the middle layer/grid transferring the heat by conduction and innermost layer facing the brooding room where brooding took place. These temperature profiles are expressed as horizontal discretized 30 nodes + 1 of the one x-directional heat transfer mode across the Trombe wall. It is similar to the thermal performance influence of the massive wall material, thickness and ventilation system on the Trombe wall analysed based on an analytical methodology (Briga Sá et al., 2018).

The graph (Figure 4) showed the transient heat transfer across interactions between outermost (surface facing the sun), innermost (surface facing brooding room) and middle (interface) the layer to elucidate the thermal behavior of the Trombe wall thickness and material properties that supported the brooding process as seen in Figure 5.

For outermost layer, the minimum temperatures were 30°C and maximum temperatures were 76°C -88°C for 28 days simulation periods. Similarly, for innermost layer, the minimum temperatures were 26°C and maximum temperatures were 37°C for 28 days simulation period. Furthermore, the addictive energy source for the system was the pebble bed bin; Figure 6 showed the transient temperature of the pebble bed bin that assisted in providing heat requirement of brooding process. For 28 (twenty-eight) days of brooding simulation, the minimum temperatures predicted in a day around 6.00am was 24°C and maximum temperature profiles of 37°C -38°C as shown in the deep litter system constructed supported by the Trombe wall (Okonkwo and Akubuo, 2001).

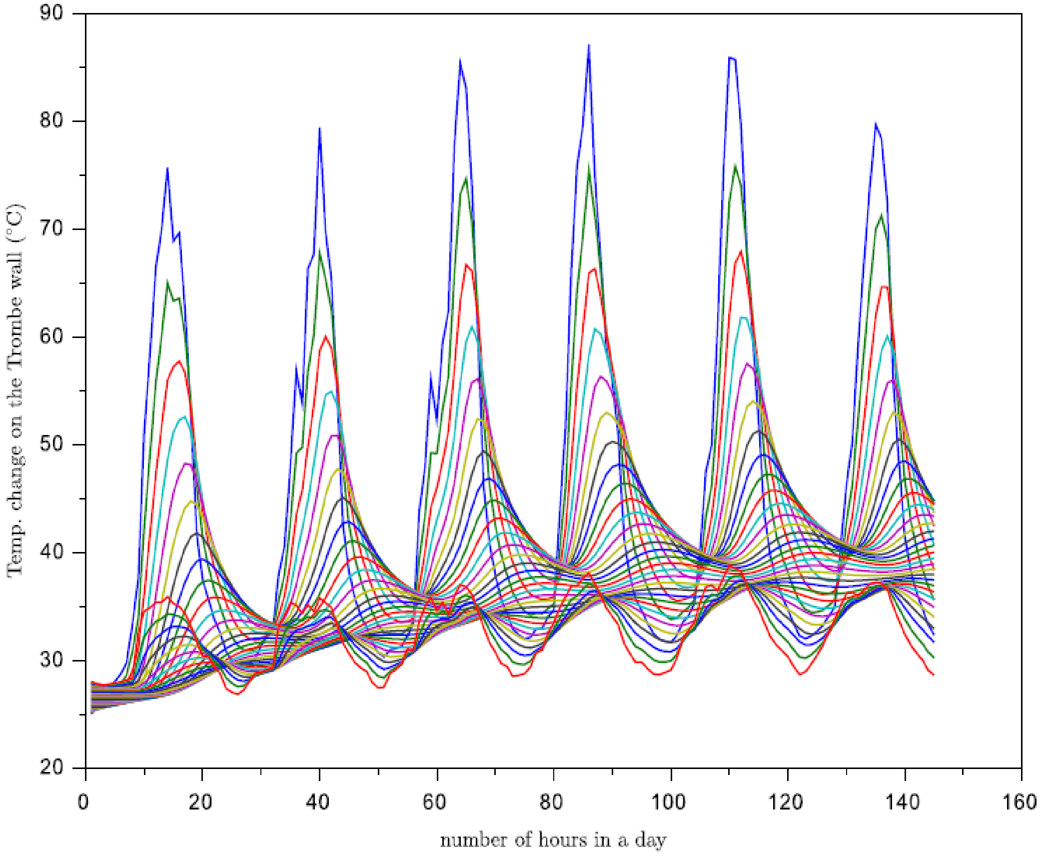


Figure 5 The temperature profile across the Trombe wall as delineated above

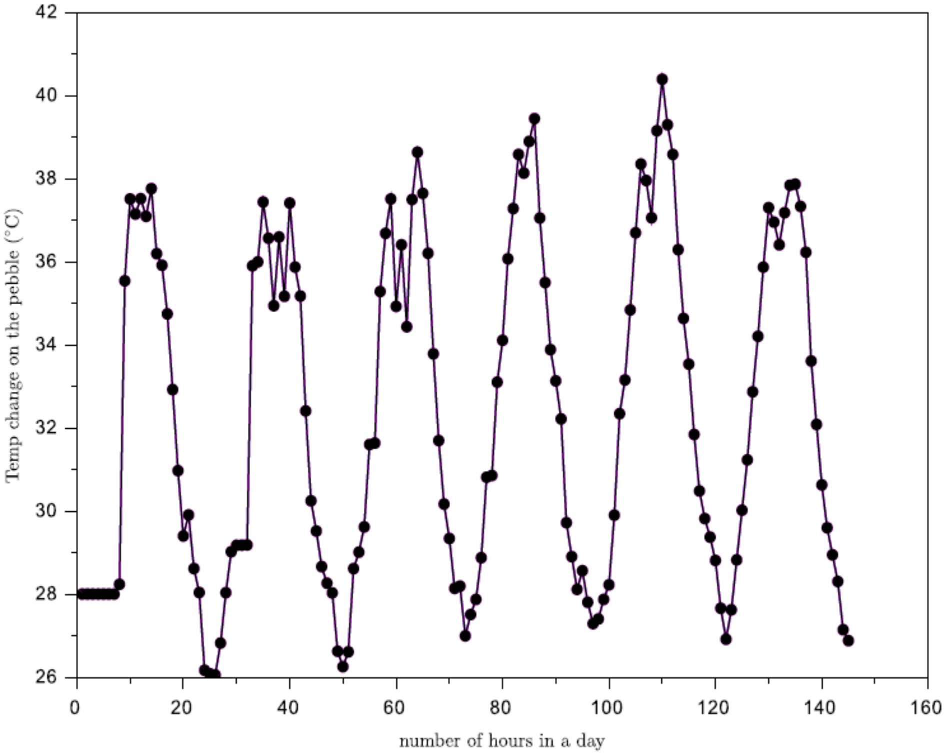


Figure 6 Temperature regime of the Pebble bed bin with time (hr)

3.1 Validation of the system model

Predicted and measured for the distinct model components were compared as shown in Figure 7. The graph showed close relationship between measured and predicted temperatures of the Trombe wall inner brooding room surface with respect to time (hour in a day). The temperature varied with definite pattern (sinusoidal) for both measured and predicted for the six days simulation with average temperature variation of 3°C -5°C.

Similarly, Figure 8 showed measured and predicted temperatures for the pebble bed bin with respect to time (hour in a day). The temperature varied with definite pattern (sinusoidal) for both measured and predicted for the six days simulation with minimum average temperatures difference of less than 3°C -5°C.

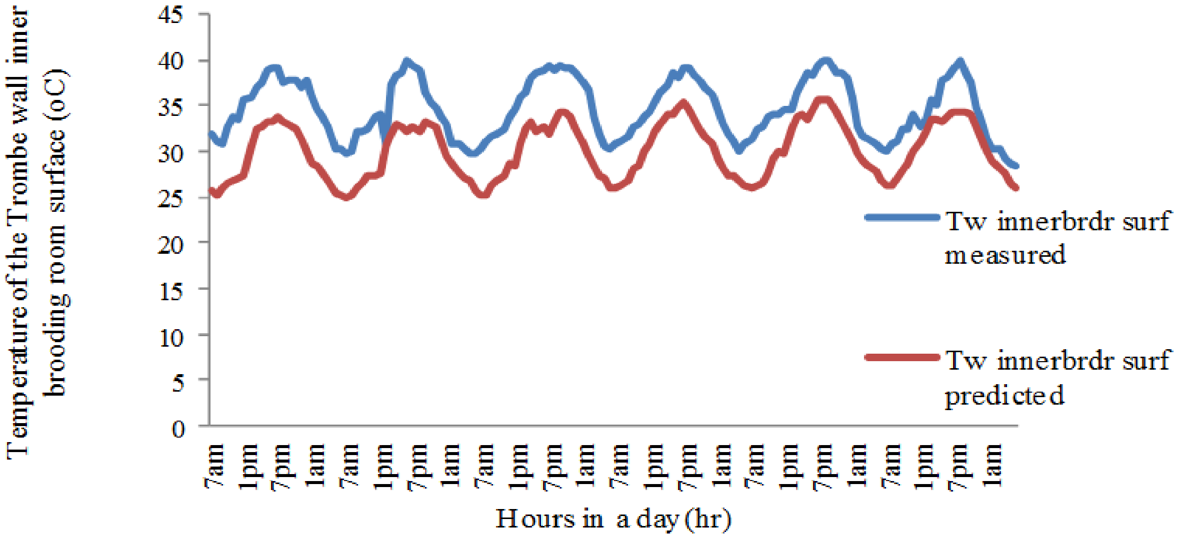


Figure 7 Measured and predicted Trombe wall inner brooding room surface temperature.

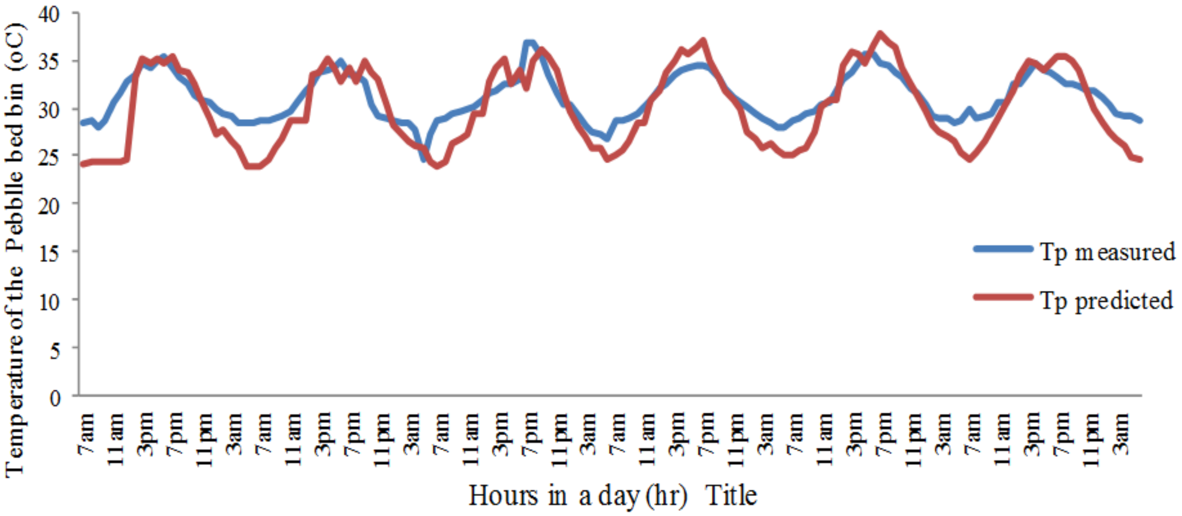


Figure 8 Measured and predicted pebble bed bin temperatures.

Furthermore, Figure 9 showed the measured and predicted temperatures of the brooding room, and Trombe wall inner brooding surface with respect to time (hour in a day). The graph showed that the temperatures varied with definite pattern (sinusoidal) for both measured and predicted for the six days simulation with minimum average temperature difference of less than 3°C.

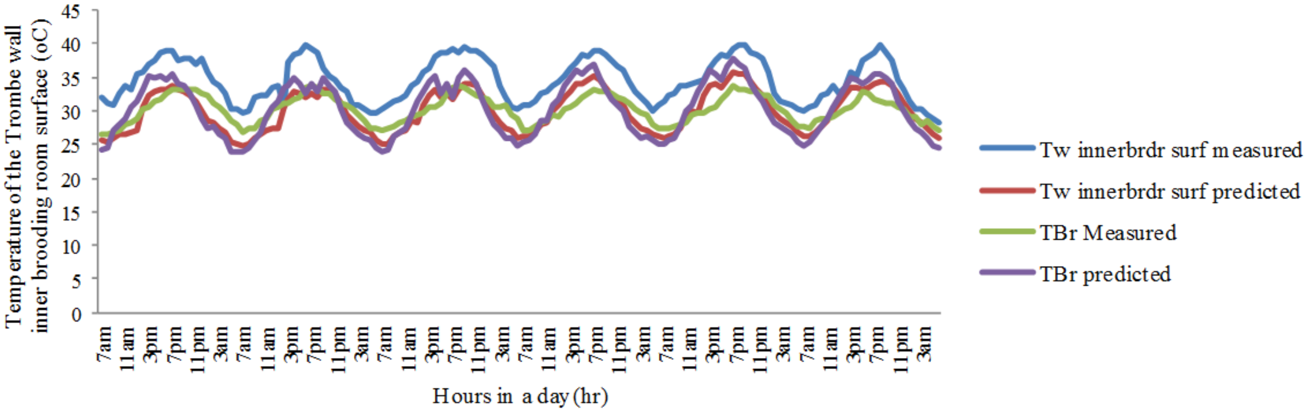


Figure 9 Measured and predicted temperature of the brooding room and Trombe wall inner brooding surface Temperature.

Table 3 Analysis of variance for measured and predicted temperatures of the Trombe wall solar chick brooder.

Treatment	Group	N	Mean	Std. Deviation	Std. Error Mean
Tg	measured	144	29.3093056	4.27400431	0.35616703
	predicted	144	45.2000989	17.45148332	1.45429028
Tpg	measured	144	28.2622222	2.68162524	0.22346877
	predicted	144	64.1203577	16.66140228	1.38845019
Tp	measured	144	31.0861111	2.40233776	0.20019481
	predicted	144	30.0854969	4.09168572	0.34097381
TBr	measured	144	30.2658333	2.04527889	0.17043991
	predicted	144	30.3093409	3.97167688	0.33097307
Tw_inner	measured	144	34.5547222	3.25945015	0.27162085
	predicted	144	30.0104301	3.10124441	0.25843703
Tw_outer	measured	144	33.6312500	6.57762714	0.54813560
	predicted	144	44.3809858	16.74044710	1.39503726

Analysis of variances of the measured and predicted temperature of the Trombe wall solar chick brooder was evaluated using T-test as shown in Table 3. It showed the sample size, mean, standard deviation, and standard error for both measured and predicted temperature data. The measured T_{G1}, T_{G2}, T_{Br}, and $T_{w\ (inner)}$ were greater than predicted values by about 15°C, 35°C, 0.04°C, and 4°C respectively. But, 0.04°C is not significant for brooding operation. On the other hand, the measured T_p and $T_{w\ (outer)}$ were both lower than predicted values by about 1°C and 10°C respectively. Table 3 also showed that the predicted temperatures generally varied more around their means than the measured temperatures. Analysis of variances of the measured and predicted temperature of the Trombe wall solar chick brooder was evaluated using T-test as shown in Table 3.

Table 4 The independent sample T- test of measured and predicted temperature data of the Trombe wall solar chick Brooder

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	T	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
T_{G1}	Equal variances	236.195	.000	-10.613	286	.000	-15.891	1.497	-18.838	-12.944
	Unequal variances			-10.613	160.093	.000	-15.891	1.497	-18.848	-12.934
T_{G2}	Equal variances	226.239	.000	-25.498	286	.000	-35.858	1.406	-38.626	-33.090
	Unequal variances			-25.498	150.404	.000	-35.858	1.406	-38.637	-33.079
Tp	Equal variances	82.589	.000	2.531	286	.012	1.001	.395	.222	1.779
	Unequal variances			2.531	231.118	.012	1.001	.395	.223	1.780

TBr	Equal variances	111.700	.000	-.117	286	.907	-.044	.372	-.776	0.689
	Unequal variances			-.117	213.861	.907	-.044	.372	-.777	0.690
Tw inner	Equal variances	0.349	.555	12.121	286	.000	4.544	.375	3.806	5.282
Tw outer	Equal variances	138.083	.000	-7.172	286	.000	-10.750	1.500	-13.700	-7.780
	Unequal variances			-7.172	186.126	.000	-10.750	1.500	-13.707	-7.793

It showed the sample size, mean, standard deviation, and standard error for both measured and predicted temperature data. The measured T_{G1}, T_{G2}, T_{Br}, and $T_{w\ (inner)}$ were greater than predicted values by about 15^{o}C, 35^{o}C, 0.04^{o}C, and 4^{o}C respectively. But, 0.04^{o}C is not significant for brooding operation. On the other hand, the measured T_p and $T_{w\ (outer)}$ were both lower than predicted values by about 1^{o}C and 10^{o}C respectively. Table 3 also showed that the predicted temperatures generally varied more around their means than the measured temperatures. The independent sample T- test for measured and predicted temperature data of the Trombe wall solar chick Brooder was shown in Table 4. The significance values of the levene test for equality of variance statistic for T_{G1}, T_{G2}, T_p, T_{Br}, and $T_{w\ (outer\ surface)}$ were each 0.000 < 0.10. Because these values were each less than 0.10, the assumption that the groups have equal variances were rejected and moved to the second test which assumed variances are not equal. However, the significance value of the levene statistic for $T_{w\ (inner\ surface)}$ was 0.55. Because this value was greater than 0.10, we accepted the assumption that the groups have equal variances and ignored the second assumption that the variances of the group are unequal. Since the significance values of the T-test for T_{G1}, T_{G2}, T_p, $T_{w\ (inner\ srface)}$ and $T_{w\ (outer\ surface)}$ were less than 0.05, we therefore conclude that the average temperatures more or less as indicated in this groups either by the measured/predicted was not due to chance alone. Contrary to these observations, the significance value of the T- test for T_{Br} group was 0.907 > 0.05 indicating that there were no significant differences between the measured temperature and the model predicted temperature for the Brooding room. We therefore conclude that the developed model adequately predicted the measured temperature of the brooding room at 5% probability level.

4 Conclusions

From the result of this study, the following conclusions were drawn: numerical model was developed to describe and predict the Trombe wall solar chick brooder, the simulation and validated results of the model were in good agreement with the experiment data. Therefore, the model serves as a tradeoff between physical model and numerical model and as such can stand as modeling platform for further study on Trombe wall solar chick brooder for optimal chick brooding operation against physical model structure.

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