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Performance assessment of a solar powered egg incubator with a backup heater

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ABSTRACT

This study presents the performance of a novel solar-powered incubator which uses water as thermal mass. Energy absorbed by the water is transferred to the incubator chamber by a fan powered with a 12 V battery. To enable adequate control of chamber temperature and humidity, a ProNem Mini sensor and controller (ESM-3723) were incorporated into the design. The thermal mass was sized adequately to supply energy for night operations as well as periods of inclement weather. The incubator was tested with and without load. Field measurements were obtained using UT330A USB datalogger. Tests under no load conditions gave an average temperature range of 36 to 42.9°C and relative humidity of 53 % to 70.5 %. Incubation tests showed average chamber temperature and relative humidity ranges of 35 °C to 41 °C and 45 % to 61 %. Candling test gave percentage fertility and hatchability of 60% and 56%. A cost-benefit analysis gave a capital cost of 617.32 USD, incubation cost of 69 cents per chick and simple payback period of 15 months. The performance indices obtained make the proposed design a suitable architecture to build upon in order to accelerate the promotion of livelihood empowerment through poultry farming in Ghana.

1. Introduction

1.1. Background

Egg hatcheries are a viable alternative to old-fashioned or traditional backyard chicken production since they come in larger capacities fit for commercial-scale production. It not only improves chicken output greatly, but also provides a consistent source of revenue, making rural poultry farming a sustainable rural enterprise [1]. Poultry farmers in the remote rural areas of Ghana utilize hatcheries that rely on kerosene or liquefied petroleum gas (LPG), the national grid, or a mix of these as energy sources. These energy sources have high potential to cause fires and also emit exhaust gases that are poisonous to eggs, poultry, and poultry farmers alike [2]. In the case of farmers who utilize diesel-fired incubators, the cost involved is quite high due to the relatively longer distances over which the diesel fuel has to be transported as well as the bad nature of the roads. Therefore, the need to adopt a more sustainable energy supply, which is cost-effective and environmentally friendly for efficient performance and productivity is very important. Aside ensuring sustainability of energy supply, it is also important to develop an incubator that supplies the optimum chamber conditions required for efficient operation, resulting in an output that yields high returns. Incubator chamber temperature and

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Nomenclature:

Q_q	total quantity of heat transmitted (J)
A_g	glass surface area (m^2)
I_g	total solar irradiance on the glass(kW/m^2)
t	time (s)
C_p	specific heat capacity of water (kJ/kg °C)
ΔT	temperature difference (°C)
Q_{lsc}	heat loss through the walls (J)
R_T	total resistance (m^2. K/W)
x_w	thickness of alucobond (m)
k_f	thermal conductivity of polystyrene (W/m. K)
h_{ic}	radiation heat transfer coefficient (W/m^2. K)
T_{itm}	inner surface temperature of thermal mass (°C)
T_{ic}	incubating chamber temperature (°C)
A_{tm}	area of thermal mass (m^2)
Q_{ui}	useful energy delivered to the incubating chamber (J)
Q_a	quantity of heat in air (J)
m_a	mass flow rate of air (kg/hr)
C_{pa}	specific heat capacity of air (J/kg. °C)
ρ_a	density of air (kg/m^3)
A_{pvc}	cross sectional area of copper pipe trough (m^2)
D_v	depth of inlet opening to incubating area (m^2)
F_r	Froude number
T_a	ambient temperature (°C)
T_c	collector temperature (°C)
I_t	solar irradiance (W/m^2)
U_t	overall heat loss coefficient (W/m^2. K)
Q_e	heat requirement of egg (J)
m_e	mass of air (kg)
c_e	specific heat capacity of egg (J/kg. °C)
k_1	thermal conductivity of alucobond (W/m. K)
k_2	thermal conductivity of polystyrene (W/m. K)
h_i	inner fluid convective heat transfer coefficient (W/m^2. K)
h_o	outer fluid convective heat transfer coefficient (W/m^2. K)

Greek symbols

τ	transmissivity of glass
α	absorptance of solar collector

Subscripts

g	glass
w	water
ic	incubating chamber
Itm	inner thermal mass
e	egg
f	fan

humidity are known to have a strong influence on the effectiveness of incubation. During the incubation process, eggshell temperature has been shown to be the result of the balance between (a) the transfer of heat to and from the embryo, and (b) embryo heat production. It has been reported that when either heat transfer or heat production is altered, embryo temperature changes [3]. Heat transfer has been shown to be mainly determined by the temperature difference between the egg and its environment and air velocity across the egg, and to a lesser extent by humidity of the air [4, 5, 6]. As a result of the effects of temperature and humidity fluctuations on the efficacy of hatching, the incubator hardware must be designed giving utmost care to the balance between the heat and humidity supply rates that will guarantee optimum performance.

The general goal of this study is to design and construct a solar-powered guinea fowl egg incubator out of readily available local materials and to assess its performance and suitability for use by small-holder rural poultry farmers in Ghana. Most significantly, the study seeks to optimize the process of hatching eggs by storing surplus solar energy collected during the day for use at night, as well as creating a pollution-free atmosphere conducive to egg incubation. The outcome of the study will aid in addressing the country's protein requirements more quickly. It will also encourage young people to get involved in small-scale and large-scale poultry farming.

1.2 Related L\literature

In recent years, several attempts have been made to improve the design of the poultry egg incubator in order to make it less expensive, efficient and environmentally friendly because of high demand and global awareness on issues pertaining to the environment. Electro-mechanical improvements permitted the progress from natural breeding to enormous hatching machines and incubators, which resulted in high-capacity incubators suitable for industrial grade production. On the other hand, this hatching shift resulted in increased expenses including energy and water cost [7]. Temperature, humidity, and ventilation are key factors in artificial egg incubation. Temperature control is critical during incubation with the acceptable range being 35 °C and 39 °C. At extreme temperatures beyond this range, the eggs rarely hatch. If the incubator operates at 40℃ for 15 minutes, the embryos are seriously affected whereas operating at 35℃ for about 4 hours will slow the metabolic rate of the chicks [8].

It is important to maintain a steady metabolic rate. This means that humidity outside of a very limited range has the potential to alter the number of hatched eggs. For effective and efficient hatching, the ideal humidity range is 50 to 70% [9]. Embryos acquire oxygen from the environment and produce greenhouse gases as they develop, hence incubators must have ventilation capabilities. Incubators with large quantities of eggs and older embryos require a greater amount of air to keep the eggs alive [10].

Incubators that operate on grid electricity are very efficient. However, most poultry farmers are located in remote rural communities which have no access to the national electricity grid and operate their farms with bush lamps for heat, which leads to health and environmental hazards characterized by infections and high mortality rates. This results in low productivity in the poultry industry. To remedy the situation, there is the need for other alternative sources of energy. Solar energy has become favorable due to its low GHG emission potential coupled with the fact that it is cheap and readily available. This energy can be harnessed using solar panels placed on rooftops, solar farms, and other land areas [11].

Some research studies have been carried out to improve poultry production using solar irradiance as the source of energy. Mansaray and Yansaneh [12] designed, fabricated and tested a solar photovoltaic powered chicken egg incubator. They obtained fertility rate and hatchability of 43.3% and 23.1%, respectively. Uzodinma et al. [13] used a phase change material as heat storage in a hybrid solar poultry egg incubator. The average rate of hatched eggs observed was about 63%. Ahiaba et al [14] worked on passive solar for incubating poultry chicks. The results of their research showed that poultry production is sustainable with the application of solar energy.

This study focuses on the design, construction and testing of a novel solar-powered guinea fowl incubator for subsequent development for commercial purposes. The design uses water as a heat storage medium, incorporates a backup heater and a feedback control system to achieve the right conditions needed for effective hatching.

2. Materials and methods

2.1. Development of prototype

The fabrication and testing of the incubator studied in this work was done at the laboratory of the department of Mechanical Engineering at the Kwame Nkrumah University of Science and Technology, Kumasi (6.673175, -1.565423).

Figures 1a and 1b show the isometric and exploded views of the proposed design, respectively. The incubator body unit was constructed with a bonded (alucobond) material made of aluminum and plastic. A polystyrene (foam) material was used as an insulating material and placed between the two alucobond to reduce heat loss by conduction. The incubation chamber was further galvanized with thin aluminum foil to reduce heat losses across the wall. The incubator size was largely influenced by the size of the egg trays which were the frame on which the eggs due for incubation are mounted. There were two trays with a capacity of 30 eggs each. These egg trays are held by a frame that allows 45-degree rotation in both clockwise and anticlockwise directions. This rotation is made manually possible or by a motor that is coupled to the lower rotating shaft of the frame using a belt and pulley/ chain and sprocket system. The water storage tank is made from a galvanized plate which serves as heat storage or sink for the incubating system both during the day and night. It also served as the storage for the heating medium through which solar energy is harnessed.

The solar collector consists of an outer casing made of thick plywood (at the base and sides) covered with transparent glass on top and a copper pipe coiled to form a channel through which the water is held. There exists a circulating fan to draw heat from the collector unit and circulate it through the incubation chamber as well as expelling excessive warm air out.

The ProNem Mini PMI-P digital temperature and humidity controller was used to control the heater and fan to ensure that the right conditions of temperature, humidity, and ventilation are maintained in the system. The fan is also turned on or off by the controller to draw in fresh air to ensure proper ventilation and humidification.

A bowl filled with 1.5 liters of water was placed in the incubator on day one and 0.2 or 0.25 liters of water was added as needed depending on the temperature of the day. Adding the 1.5 liters on the first day and the rest of the 25 days with an average of 0.2 liters or 0.25 liters results in 7.1 liters for the entire duration of the test.

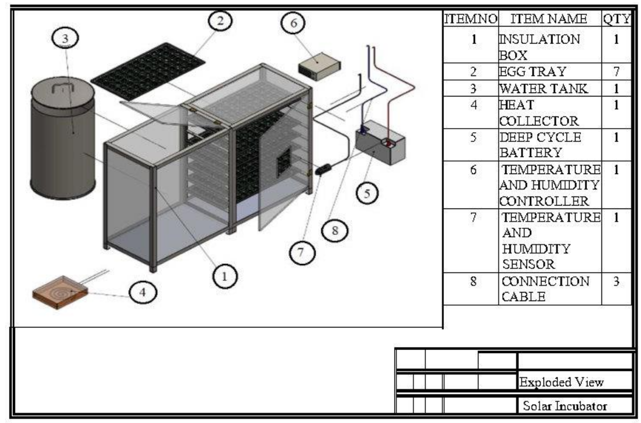

Figure 1a. Isometric view of the selected concept

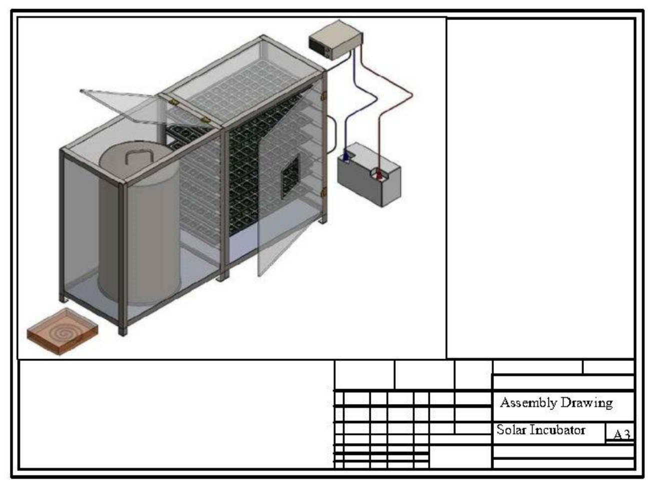

Figure 1b. Isometric view of the selected concept

2.1.1 Description of incubator heating cycle

Solar radiation absorbed by the thermal mass (i.e., water) is the primary source of energy to the incubator. A fan installed in the wall that separates the collector chamber and the incubator chamber draws air over the thermal mass and causes the warm air to flow through the incubator chamber, providing the desired chamber temperature for hatching. A close-loop temperature and humidity sensor installed in the incubator chamber ensures that the chamber temperature and humidity are kept within the desired ranges of 35 to 39 °C and 50% and 70%, respectively. In the case of undesirable temperature drops in the night as a result of depleting thermal energy reserves a halogen lamp integrated into the incubator design serves as a backup heater to restore chamber temperatures to desired values (see Figure 2 for details).

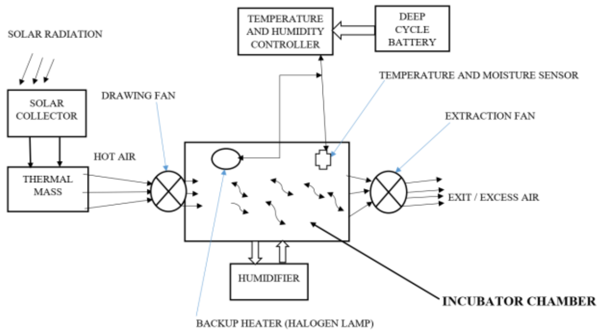

Figure 2. Heating cycle of incubator

2.2. System design

The total quantity of heat transmitted to the water in the collector tubes over a period of time, t, is given by

$$Q_g = A_g \times I_g \times t \times \tau \quad (1)$$

Where:

A_g = Glass surface area (m^2), (0.4 ×0.4 = 0.16 m^2)

I_g = Total solar irradiance on the glass, (5.1 kW/m^2-day for the location under study) being the average solar irradiance in Accra

τ = the transmissivity of glass (i.e., 0.89, this case).

The Heat collected by water in the storage tank is given by.

$$Q_w = V_w \times \rho_w \times C_p \times \Delta T \quad (2)$$

Where:

Q_w = Heat accumulated by water

V_w = Volume of water used in the tank ($\pi \times r^2 \times h$ = $3.142 \times 0.19^2 \times 0.72 = 0.0817$ m^3)

ρ_w = Density of water (1000 kg/m^3)

C_p = Specific heat capacity of water (4.18 kJ/kg °C)

ΔT = Temperature difference between the heat collector and the ambient (i.e., about 42 – 32 °C)

Hence, the total useful energy delivered to the incubating chamber from the heat storage medium,

$$Q_{us} = Q_g - Q_{lsc} \quad (3)$$

Where:

Q_g = Total energy absorbed by collector.

Q_{lsc}= heat loss through the walls of the storage chamber.

$$Q_{lsc} = \frac{\Delta T}{R_T} \quad (4)$$

and

$$R_T = \frac{1}{A}\left(\frac{x_w}{k_w} + \frac{x_f}{k_f}\right) \quad (5)$$

Where:

R_T= the total resistance (R-value) of alucobond and polystyrene (insulating material) that made up the wall system.

x_w = thickness of the alucobond (0.004 m)

x_f = thickness of the polystyrene (0.05 m)

k_w = thermal conductivity of the alucobond (0.29 W/mK)

k_f = thermal conductivity of the polystyrene (0.043 W/mK)

Useful energy delivered to the incubating chamber is determined by:

$$Q_{ui} = Q_w + Q_a \quad (6)$$

$$Q_w = (h_{ic} \times A_{tm}(T_{itm} - T_{ic})) \quad (7)$$

Where:

Q_w = Direct heat dissipation from the thermal mass (water);

h_{ic}= Radiation heat transfer coefficient from the inner surface of the thermal mass to the incubating chamber.

A_{tm} = Area covered by the thermal mass; T_{itm} = Inner surface temperature of the thermal mass; T_{ic}= Incubating chamber temperature.

$$Q_a = 2\acute{m}C_{pa}(T_{hac} - T_{ic}) \quad (8)$$

Where:

ḿa = mass flow rate of air (kg/hr)

C_{pa}= specific heat capacity of air (kJ/kg.°C);

But,

$$\dot{m}_a = \rho_a \times A_{pvc} Fr \times \sqrt{\frac{g \times D_v \times (T_{ha} - T_{ic})}{T_{hac} + T_{ic}}} \quad (9)$$

Where, ρ_a = Density of air, kg m^{-3} ; A_{pvc}= cross sectional area of the copper pipe trough, m^2; D_v= depth of inlet opening to incubating chamber; Fr = Froude number

Equations (8 and 9) are as provided by [15] and [16] respectively. The collector heat removal factor which relates the actual useful energy gained by the collector to the useful energy gained by the air is given by,

$$F = \frac{\dot{m}_a C_{pa}(T_c - T_a)}{A_c[\propto \times \tau \times I_t - U_t(T_c - T_a)]} \quad (10)$$

Where:

T_c = Collector temperature; T_a = Ambient temperature; A_c = Area of collector, α = Absorptance of solar collector; I_t= Solar irradiance; U_t= Overall heat loss coefficient. The heat absorbed by the air within the incubator to ascend from ambient temperature of 32 °C (as measured), to the incubating temperature of 39 °C was estimated as follows.

$$Q_a = \acute{m}a \times Cp_a \times \Delta T \quad (11)$$

The heat requirement of eggs is calculated using the equation,

$$Q_e = m_e \times C_e \times \Delta T \quad (12)$$

Where:
m_e = mass of egg (kg/hr)
C_e = specific heat capacity of egg (kJ/kg. °C)
ΔT = Average temperature difference for eggs, °C .

Heat Loss through the walls of the incubating chamber,

$$Q_s = \frac{\Delta T}{R_T} \quad (13)$$

$$R_T = \frac{1}{A}\left(\frac{1}{h_i} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{1}{h_o}\right) \quad (14)$$

Where:

k_1 = thermal conductivity of alucobond (W/mk)
k_2 = thermal conductivity of polystyrene (W/mk)
h_i = inner convective heat transfer coefficient (inside air)
h_o = outer convective heat transfer coefficient (outside air)
x_1 = thickness of the alucobond (mm)
x_2 = thickness of the polystyrene (mm)

The rate at which air is circulated in the incubation chamber is given as;

$$F_f = A_f \times N_f(2 \times \pi \times r) \quad (15)$$

A_f = area of fan ($0.055^2 \times 3.142 = 0.0059$ m^2)
N_f = speed of fan (1400 rev/min)
r = radius of fan blade (0.055 m)

Therefore,

$$F_f = 0.055^2 \times 3.142 \times 1400 \times 2 \times 3.142 \times 0.055 = 4.59 \text{ m}^3/\text{min}$$

The selected Proportional-Integral-Derivative (PID) controller was used since it is the most widely used temperature control system in the egg incubation industry. The block diagram of the PID controller is shown in Figure 3, where K_p is the proportional gain, T_i is the integral time constant, and T_d is the derivative time constant. The transfer function of the standard PID algorithm is:

$$U_{(t)} = K_p e^{(t)} + \frac{K_p}{T_i}\int_0^t e(t)dt + \frac{de(t)}{dt} K_p T_d \quad (16)$$

In the s-domain, the PID controller can be written as:

$$U_{(s)} = K_p[1 + \frac{1}{T_{i.s}} + T_{d.s}]E_{(s)} \quad (17)$$

The discrete form of the PID controller can be achieved by finding the Z – transform of equation (17) as:

$$U_{(z)} = E_{(z)}K_p[1 + \frac{T}{T_i(1-Z^{-1})} + T_d\frac{(1-Z^{-1})}{T} \quad (18)$$

Equation (18) can also be written as:

$$\frac{U(z)}{E(z)} = a + \frac{b}{1-z^{-1}} + c(1 - z^{-1}) \quad (19)$$

Where:

$a = K_p$, $b = \frac{K_p T}{T_i}$, $c = \frac{K_p T_d}{T}$

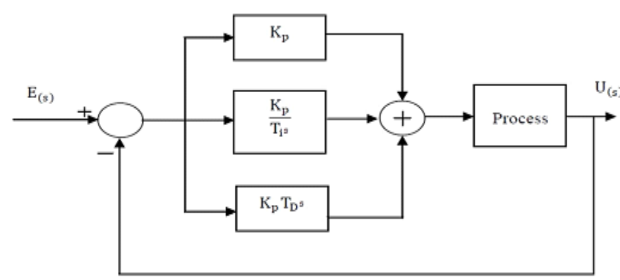

Figure 3a. Block diagram of a PID controller

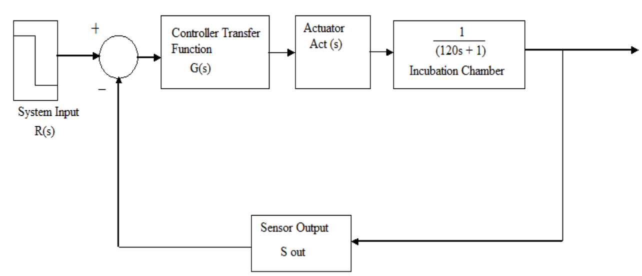

Figure 3b. Block diagram of the Closed Loop Incubation Temperature Control System

2.3. Test description

The solar incubator was constructed and assembled with all other attachments in place. The data on temperature and humidity were monitored and collected with the aid of a data logger and a controller. The data logger was placed inside the incubating chamber closer to the egg trays to monitor and record the incubator chamber temperature and humidity. for the daytime tests conducted, the incident solar radiation intensity was found to be between 680 W/m^2 and 870 W/m^2 over the test period.
The incubator was first tested for three (3) days without load to establish the no-load performance characteristics of the incubator. The incubator was thereafter loaded to a capacity of 30 with guinea fowl eggs. Turning of the eggs was carried out at an interval of four (4) hours (four times a day starting from the 2nd day through to the 15th day of incubation test). Candling test was also used to check the percentage of fertile eggs and the

development of the embryo on the 7th day and 14th days of incubation, respectively.

3. Results and discussion

Figure 4 shows the data obtained from the 72 hours (3 days) of no-load test (i.e., the preliminary test). During the busiest hours of the day, the findings of the performance evaluation done on the incubator in comparison to the benchmark values exhibited some minor deviations. However, the periods in question indicated that as the ambient temperature rises during high solar irradiance hours of the day, the incubator cabinet temperature increased. This temperature disturbance was slightly more than what the controller feed-forward mechanism could handle, which is in the range of plus one (+1 °C) and minus (-1 °C) degrees Celsius. This observed anomaly has the capacity to cause irregularities in the incubation rate during peak incubation hours in case the incubator is run with eggs loaded in it. However, amid the observed fluctuations in temperature outside the benchmark range of 35 to 39ºC, the rate of incubation would have remained fairly steady. It must be mentioned that the fluctuations in temperature would have been far worse without the use of the automatic control system incorporated into the incubator for regulating incubator cabinet temperature within the required tolerance range. Details of temperature and relative humidity variations over the first three days can be seen in Figure 4.

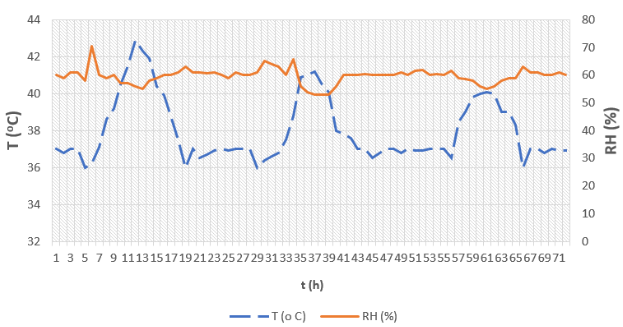

Figure 4. The temperature and humidity variation for no-load test

On day one of the test with 30 guinea fowl eggs, the incubation chamber temperature remained within the temperature tolerance range of 4 °C (i.e., 35 to 39 °C) within the first 10 hours and the last 7 hours (i.e., from 17:00 GMT to 24:00 GMT hours from the start of incubation). The deviation outside the temperature tolerance range occurred between the 10th and the 17th hours with the highest deviation being 3.9 °C (i.e., 42.9 -39 = 3.9 °C) (see Figure 5). These deviations, as explained earlier, could be attributed to surges in ambient temperature during hours of significantly high solar irradiance levels. It must be pointed out that long hours of deviation in the temperature tolerance range have the potential to affect the fertility rate hence, the incubation efficiency. The lowest temperature recorded for day 1 was 36ºC, the highest was 42.9 °C and the average value for the day was 38.27 °C.

The performance of the incubator on day 2 as compared to day 1 is far better with the extent of temperature deviation outside the tolerance range being only 2.2 ºC (i.e., 41.2 – 39 = 2.2 ºC) as compared with a deviation of 3.9 ºC on the 1st day. The slight surge in temperature on day 2 occurred for just 3.5 hours (i.e., between the 12th and 15.5th hours from the start of incubation). The cabinet temperatures were within the required tolerance range between the first 12 hours and the last 8 and half hours. The trial period for day 2 gave the minimum, average, and maximum temperature values of 36 ºC, 37.78 ºC, and 41.2 ºC, respectively. The 3rd day of incubator testing showed incubator cabinet temperatures remaining within the required temperature range of 35 to 39 ºC within the first 10 hours of testing and the last 8 hours of testing. The increase in incubator chamber temperature above the upper limit of temperature value (i.e.,39 ºC) was only 1.1 ºC, which is an appreciable improvement in performance relative to the deviations noted on the first two day of the trial. Although the deviation lasted for 5 hours, the marginal nature of the deviation makes the 3rd day of testing the most efficient trial set in terms of incubator cabinet temperature variation. The trial period for day 3 gave the minimum, average, and maximum temperature values of 36 ºC, 37.70 ºC, and 40.1 ºC, respectively.

Figure 6 shows the variation in relative humidity in the incubator cabinet with respect to time for the three days of testing. The trend of results show that the RH value was within the recommended range of between 50% and 70%. Except that the RH variation for day one reached a maximum value of 70.5% after 6 hours of testing. However, RH values normalized afterward and remained within the tolerance range. The minimum and average RH values observed for day 1 were 55% and 59.73% respectively. For day 2 (see Figure 6), incubator cabinet relative humidity values remained within the required tolerance range that promotes adequate fertility for incubation. However, the variation in RH values within the range indicated for day 2 was random between the 6th and the 17th hours of testing. But effectively, the RH values remained within the required tolerance range which reveals the effectiveness of the current design in maintaining the required humidity levels for adequate fertility and a high incubation rate. The minimum, maximum, and average values of 53%, 65.8%, and 59.10%, respectively. The variation in relative humidity values for day 3 as indicated in Figure 6, also exhibits a relatively linear trend as compared with the variations for days 1 and 2, with the minimum and maximum RH values being 55% and 63% and an average value of 59.44% The average RH values of 59.73%, 59.10%, and 59.44% recorded for days 1, 2, and 3 show that the proposed incubator design can effectively maintain the right moisture levels for efficient incubation.

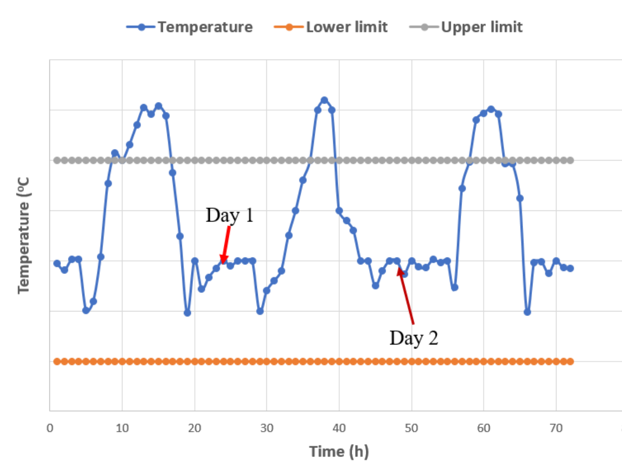

Figure 5. Variation of incubator chamber temperature when loaded with eggs

The results obtained during the test show that out of 30 eggs set in the incubator, 18 were fertile (Table 2), yielding a percentage fertility of 60%. Also, out of 18 fertile eggs, 10 were hatched, giving a percentage hatchability of 56%. The complete system, which consists of the incubation chamber, a temperature controller (PID), a solar collector, an air circulating fan, and a backup heat source, was simulated using MATLAB/Simulink.

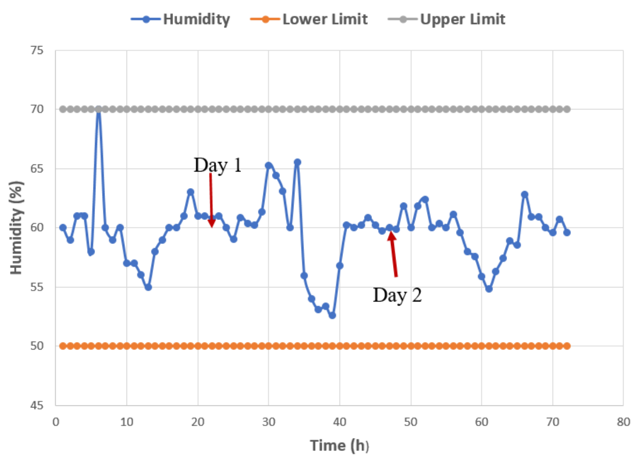

Figure 6. Variation of incubation chamber humidity with time when loaded with eggs

The incubation system with partial and full control from the PID temperature controller was tuned using the Ziegler Nichol tuning technique during the simulation to determine the values of the parameters that provided the system the specified transient response when subjected to a unit step input. The system control outcomes with PID tuning were simulated and studied. The incubation system is depicted in Simulink block diagrams 7a and 7b.

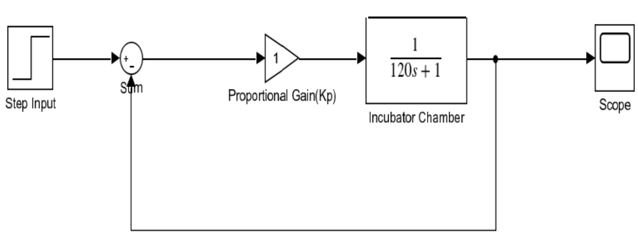

Figure 7a. Simulink Block Diagram of the partial incubation temperature control

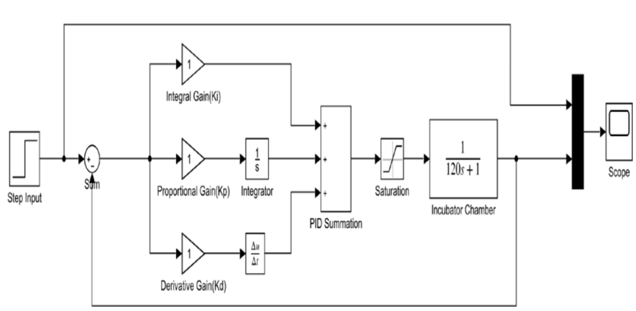

Figure 7b. Simulink Block Diagram of the full incubation temperature control

Table 1 shows the hypothetical values considered for the PID controller parameters and the response of the system to these values.

Figure 7c is the response of partial PID or P control. From the response, it is obvious that the system was not properly controlled looking at the lack of correlation between the block-response and the tuned-response. This outcome goes to explain why solar irradiation should not be solely relied on during the day, which is likely to under-heat or overheat the system.

The graph shown in Figure 7d illustrates that the system has improved with complete control of the system by the PID during incubation. This is a speedier reaction than the one depicted in Figure 7c. Mp, or Maximum Overshoot, climbed to around 22%. This is still acceptable because it is within the allowed overrun of 25%. The settling time (ts), Peak Time (tp), and delay time do not change. The new PID/tuned parameters obtained are: K_p =1.338, K_i =0.02228, and K_d = -5.829.

Table 1. Values of the PID temperature control parameters

Test	Parameter	Kp (sec)	K_i (sec)	K_d (sec)
Test 1	Values	1	0	0
Test 2	Values	1	0	0
	New values	1.338	0.02228	-5.829

Figure 7e response shows that the system has improved comparatively, compared to the situations depicted in Figures 7a to 7d. Hence, it can be seen that the final parameters are superior to the earlier two responses. However, the setback is the M_p, which is the same as the M_p of the response in Figure 7d. Nevertheless, the final response M_p is still within the 25% maximum overshoot allowable.

Candling test was used to track the progress of incubation during the test. This was done by shining a light with intensity of between 400 to 520 W/m^2 on an egg in a dark room so that one is able to see what is going on inside the egg. This observation was done throughout the entire duration of the test.

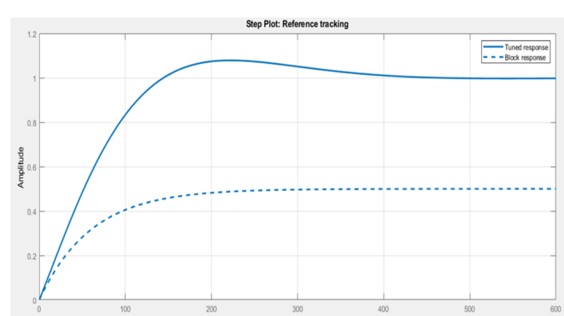

Figure 7c. Unit step response of the system for test 1

In this study, candling was carried out on the 30 loaded eggs on the first (1st), fourth (4th) and seventh (7th) days of incubation. In the end, eighteen (18) eggs were fertile per the test, as indicated in Table 2. Fertile eggs were identified upon seeing web-like lines and rings running across the egg.

The percent fertility and hatchability of the eggs estimated were 50% and 56%, respectively. Figure 8a shows an egg placed on a Candler before the start of the incubation test. The picture shows a clear and spot-free egg, which is an indication that no embryonic development has begun.

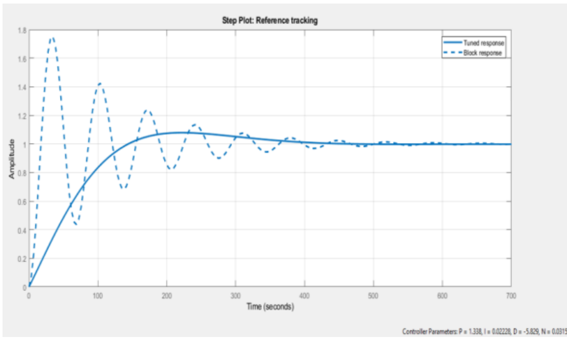

Figure 7d. Unit step response of the system for test 2

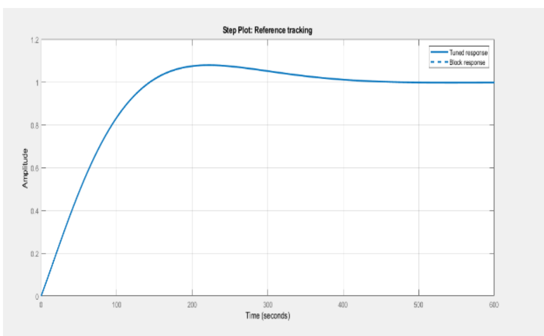

Figure 7e. Unit step of an improved response of the system for test 2

Table 2. Candling Test on the 7th day

Group	Number of Eggs	Development	Observation	Remark
1	7	Not visible	Clear	Infertile
2	5	Not visible	Large air space (bad eggs)	Infertile
3	3	Visible at the centre	Visible patches of red strains	Fertile
4	15	Visible at one end	Lines running across (rings)	Fertile

A blood spot was seen in some of the eggs on the fourth (4th) day of incubation when the candling was done. This blood spot is an indication of fertility as well as embryonic development in eggs as shown in Figure 8b. Nonetheless, studies such as [17] believe that overheating the eggs is more important than under heating since it accelerates the rate of development, producing aberrant embryo development in the early stages and reducing the hatchability %. Meanwhile, running the incubator for at least 15 minutes at 40.5°C is lethal and will severely harm or destroy the embryos [17]. The temperature of the incubator should be kept between 35 and 39 degrees Celsius.

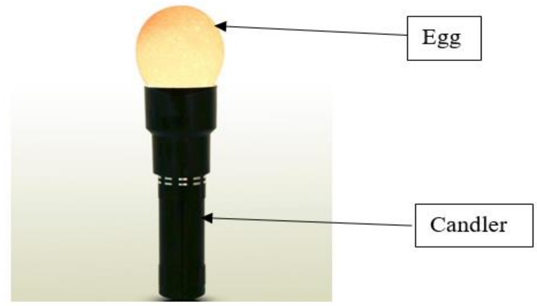

Figure 8a. Egg positioned on lamp in preparation for candling test (day one)

If the temperature dips below 35 ºC or climbs above 39 ºC for several hours, death occurs. Hence, it is evident per experimental observations in this study that the 30 eggs used for the testing experienced some overheating during the peak hours of the day.

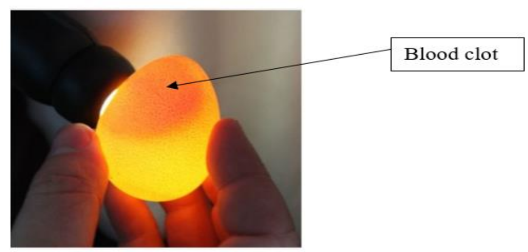

Figure 8b. Candled egg on day four

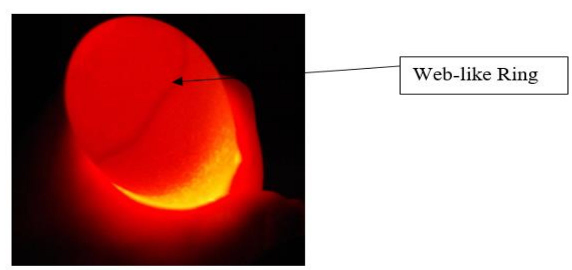

Figure 8c. Candled egg on day seven

In machine design, the principal aim is to design a unit that is adequately functional and economically viable. The machine should be standard, safe, and affordable. It is very important to take into consideration existing machines in the market to form a basis for estimation. The materials/instruments, their brief description, their size/capacity, and their cost, and the total price were recorded for the purpose of assessing the economic feasibility of the solar-powered incubator. These include the handling and transportation cost and the labor cost. The total estimated cost of the project is 474.90 USD (at the prevailing bank rate of GHC 7.37 =1 USD as of April 2022).

The selling price was determined by putting into consideration the production cost, tax, and suitable profit margin. Assuming a profit of 30% of the total production cost, the selling price was determined to be 617.32 USD. Assuming that the Solar Hybrid Incubator hatches fifty (50) eggs out of sixty on the average per month; then the benefit for a year on saving for sale of week-old chicks (Total Revenue) is 976.93 USD. If the expenses per year are assumed to be GHC 488.47, the net profit per year (total revenue – total cost (Expenses) will work out to 488.47 USD. Hence the Payback Period will be 1.26 years.

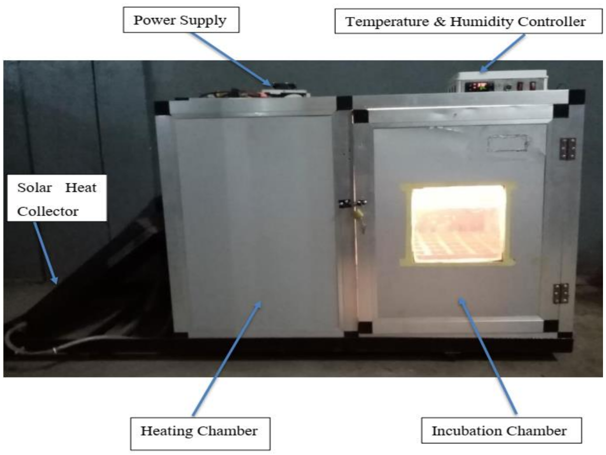

Figure 9 Picture of assembled incubator showing instrumentation

4. Conclusion

A solar-powered poultry egg incubator was conceived and built utilizing locally accessible materials in this study. The proposed incubator has a solar collector, built-in heat storage, an automated controller, and a 1,130 mm 630 mm 780 mm incubation chamber with a capacity of 60 eggs. The primary goal of this research was to compare the incubation parameters (temperature and humidity) to benchmark values based on the heating mode. This was made possible using the UT330A USB datalogger. The results obtained during the three (3) days of no-load test showed a temperature range of 36 °C to 42.9°C and relative humidity range of 53 % to 70.5 %. The incubation test gave incubation chamber temperature and relative humidity values 35 °C to 41 °C, and 45 % to 61 %, respectively. Candling tests gave percentage fertility and hatchability of 60% and 56%, respectively. A cost-benefit analysis gave a capital cost of 617.32 USD, incubation cost of 69 cents per chick and a simple payback period of 15 months. The performance of the proposed incubator shows that the proposed design has great prospects to improve poultry farming and productivity for livelihood empowerment within rural communities in Ghana so that the incidence of migration will be curbed among the poor rural communities of Ghana. Significantly, the study has provided a sound working design for effective hatching of eggs with a notable percentage fertility of 60%. This design serves as a solid basis for further development through optimization studies. It is hoped that future studies will focus on improving the percentage fertility and hatchability to much higher values through a stricter regulation of temperature and relative humidity within the ideal ranges reported in this study. Further studies will also explore harnessing excess solar energy during peak sunshine hours of the day (i.e., between 12:00 GMT and 15:00 GMT) and storing it in a Phase-Change Material (PCM) for use during the night.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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REFERENCES

[1] A.M. Kingori, Review of the Factors that Influence Egg Fertility and Hatchability in Poultry, International Journal of Poultry Science, 10 (6) (2011) 483-492.
[2] W. I. Okonkwo, O. C. Chukwuezie, Characterization of a Photovoltaic Powered Poultry Egg Incubator, International Proceedings of Chemical, Biological, and Environmental Engineering, 47 (2012) 1-18.
[3] Meijerhof, R. 2002. Design and operation of commercial incubators. Pages 41–46 in Practical Aspects of Commercial Incubation. Ratite Conference Books, Lincolnshire, UK.
[4] Kashkin, V. V. 1961. Heat exchange of bird eggs during incubation. Biophysics 6:57–63
[5] Meijerhof, R., and G. Van Beek. 1993. Mathematical modeling of temperature and moisture loss of hatching eggs. J. Theor. Biol. 165:27–41.
[6] Van Brecht, A., H. Hens, J. L. Lemaire, J. M. Aerts, P. Degraeve, and D. Berckmans. 2005. Quantification of the heat exchange of chicken eggs. Poult. Sci. 84:353–361.
[7] R.T. Wilson, Poultry production and performance in the Federal Democratic Republic of Ethiopia, World's Poultry Science Journal, 66 (3) (2010) 441-444.
[8] Okpagu P.E and Mbachu C.B, Nwosu A.W, 2015, An Improved Temperature Control System for Neonatal Incubator, European Journal of Engineering and Technology, 3 (6) 2015.
[9] Gregory S. Archer and A. Lee Cartwright. Incubating and Hatching Eggs. Texas A&M AgriLife Extension Service. (date accessed: May 02, 2022)
[10] A. Barri, Effects of Incubation Temperature and Transportation Stress on Yolk Utilization, Small Intestine Development, and Post-Hatch Performance of High-Yield Broiler Chicks. PhD. Thesis. Department of Animal and Poultry Science, Faculty of the Virginia Polytechnic Institute and State University, 2008.
[11] X. Zhan, L. Shen, S. Y. Chan, The diffusion of solar energy use in HK: What are the barriers?, Energy Policy 41 (2012) 241-249.
[12] K.G. Mansaray, O. Yansaneh, Fabrication and Performance Evaluation of a Solar Powered Chicken Egg Incubator, International Journal of Emerging Technology and Advanced Engineering, 5 (2015) 31-36.
[13] E. O. Uzodinma, O. Ojike, U. J. Etoamaihe, W. I. Okonkwo, Performance study of a solar poultry egg incubator with phase change heat storage subsystem, Case Studies in Thermal Engineering, 18 (2020), 100593.
[14] U.N. Ahiaba, U.V. Theresa, S.E. Obetta, Development and evaluation of a passive solar powered system for poultry egg incubation. International Journal of Engineering Research and General Science, 3 (2015), 748-760.
[15] N.K. Bansal, B.C. Gour, Application of U and G values for sizing Passive Heating Concepts, Solar Energy 57(5):361–373, 1996.
[16] Zriken, Z. And Bilgen, F. "Theoretical Study of a Composite Trombe'. *Michael Wall Solar Collector System*. Canada. 39(5): 409 – 419. 1987.
[17] A. Lourens, R. Meijerhof, B. Kemp, H. van den Brand. 2011. Energy partitioning during incubation and consequences for embryo temperature: A theoretical approach. Poultry Science 90 :516–523. doi: 10.3382/ps.2010-00928