Study of Thermal Storage Ability of Some Selected Pebbles (Marble and Granite) For Solar Incubation

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***Abstract*—The challenge of having cheap and available storage material that can store and sustain sufficient solar energy for artificial egg incubation during off sunshine hours necessitated this study. In this study, the heat absorption and retention of some selected stone pebbles (granite and marble) of sizes (D< 10 mm and 10 mm ≤ D ≤20 mm) were carried out using a designed thermal storage system (Test rig). The size and type of stone pebble that best sustain heat within optimum temperature range of 36-39 ^{o}C required to maintain egg incubation during off sunshine hours were chosen. Based on the designed Test rig, 16.32 kg of pebble, solar collector area of 0.5452 m^2, air ventilation diameter of 2.5cm, inlet and outlet air velocity of 0.97m/s and 0.01176 m^3 of air chamber above the solar collector were used. Result revealed that marble of size less than 10 mm recorded the highest amount of heat gain of 3.55W as against granite with 2.01 W. The temperature rise of marble and granite during 8h of sunshine were 0.875^{o}C/h and 0.593 ^{o}C/h; and the temperature loss at 16h of off sunshine was 0.181 ^{o}C/h and 0.281 ^{o}C/h respectively. The mean temperature of collector and mean ambient temperature of the Test rig were 38.5 ^{o}C and 32 ^{o}C respectively. The useful heat gain or absorbed by the collector and air leaving the air chamber were 285.377 W/m2 and 0.1556 kW respectively. The results obtained signify the possibility of using marble as heat storage material to achieve high hatchability of eggs in a well-designed solar egg incubator.**

Keywords—heat; storage; marble; sunshine; hatchability

I. INTRODUCTION

Thermal energy storage (TES) is achieved with greatly differing technologies that collectively accommodate a wide range of needs. It allows excess thermal energy to be collected for later use, hours, days or many months later, at individual building, multiuser building, district, town or even regional scale depending on the specific technology. As examples: energy demand can be balanced between day time and night time; summer heat from solar collectors can be stored inter seasonally for use in winter; and cold obtained from winter air can be provided for summer air conditioning. Storage mediums include: water or ice-slush tanks ranging from small to massive, masses of native earth or bedrock accessed with heat exchangers in clusters of small-diameter boreholes (sometimes quite deep); deep aquifers contained between impermeable strata; shallow, lined pits filled with gravel and water and top-insulated; and eutectic, phase-change materials. Other sources of thermal energy for storage include heat or cold produced with heat pumps from off-peak, lower cost electric power, a practice called peak shaving; heat from combined heat and power (CHP) power plants; heat produced by renewable electrical energy that exceeds grid demand and waste heat from industrial processes.

Reference [1] incubated eggs using kerosene lamp, to achieve efficiency of 55%. Reference [2] constructed a solar photovoltaic incubator using battery to sustain heat; but had short lifespan life. Reference [3] designed a solar incubator with solar water heater as the heat source and the efficiency was 60%. The major challenges in the artificial incubation were temperature regulation and heat storage that will meet higher efficiency of egg incubation using locally available materials. Reference [4] performed experimental study on the effect of different energy storage materials in solar still having an effective area of 0.5 m2. The materials used were black granites, pebbles blue metal stones. Paraffin was also used as latent heat storage. Result showed that the best sensible heat storage material was black granite because it had more productivity during the night. In a related study, Reference [5] designed and constructed a forced/natural convection mode for drying tomato, onion, pepper, okra and spinach, using gravel as heat storage for drying during off sunshine hours. The heat absorbed by the collector was 60.62 W/m2K. This heat was then absorbed by the heat storage system. The heat utilized during night hours was 48.9 W/m2K. To regulate solar incubation conditions, material of low heat conductivity such as wood was required. Table 1 presents the thermal conductivity of some materials [6].

TABLE 1: THERMAL CONDUCTIVITIES OF SOME MATERIALS

Material	Granite	Marble	Gravel	Sand
Thermal conductivity (W/m2K)	1.7-4.0	2.08-2.94	0.7	0.33-1.4

Usually, in egg incubation air vent is created to allow exchange of gas, since the embryo gives off CO_2 and takes up O_2 [7]. The required ventilation at chick emergence is 0.0275 m3/min [8]; and the recommended humidity for egg incubation is 60-55%; but in the last three days it may require a rise to near 70 % for chicks. Normally, so, solar energy is cheap, clean and abundance in Nigeria; hence, necessary to be exploited for effective storage using material that would retain heat from the sun for higher efficiency of incubation. In this study, selected pebbles of high thermal conductivity were tested for heat retention capacity that would likely sustain egg incubation during off sunshine hours.

II. THEORY

A. The amount of heat stored by heat storage material (marble and granite pebbles) is given [9] as:

$$Q_s = M_s C_{ps} T_2 \qquad (1)$$

and the amount of heat gain $\hat{Q}_s$ by the pebble is:

$$\hat{Q}_s = M_s C_{ps}(T_2 - T_1) \qquad (2)$$

Where M_s = mass of heat storage material (pebbles); C_{ps} = specific heat capacity of heat storage material (pebbles) (0.88 KJ/Kg^{o}C and 0.79KJ/Kg^{o}C for marble and granite respectively) [6]; T_2 and T_1 are respectively the average ambient temperature and average temperature of heat storage material (marble) directly behind the absorber plate (Temperature of heat storage material (pebbles) = collector temperature).

The heat gain per second (Q_s^*) is given as:

$$(Q_s^*) = \frac{Q_s}{[\text{average sunshine time (8h=2800s)used}]} \qquad (3)$$

Q_s^* is in KJ/s or W and $\hat{Q}_s$ is in KJ

B. The rate of heat stored by air Q_u flowing through solar collector was estimated using the relationship [10] as:

$$Q_u = C_{pa}\dot{M}_{pa}T_a \qquad (4)$$

and the rate of heat gained Q^*_u by air is given as:

$$Q^*_u = C_{pa}\dot{M}_{pa}(T_a - T_1) \qquad (5)$$

Where, C_{pa} =specific heat capacity of air above solar collector.

$\dot{M}_{pa}$ = mass flow rate of air and T_a is average temperature of air chamber.

The maximum heat stored by air is therefore:

$$Q_s = Q_u \times t \qquad (6)$$

Hence, $Q_s^* = Q_u$

Where t = the hour(s) for which the marble is exposed to sunshine.

C. The power generated q_u (useful energy gain) by solar collector is estimated [3] as:

$$\frac{Q_u}{A_c} = q_u = I_o(\alpha\tau) - U_c(T_2 - T_1) \qquad (7)$$

Where I_o = global insolation on plane of collector;

A_c = area or size of collector

$\alpha\tau$ = transmittance-absorptivity index of collector;

U_c = overall heat loss

T_2 = average collector surface temperature; T_1 = ambient temperature

D. The incidence solar radiation I_o is given by [11] for Uyo meteorological area. It is computed as an average for the twelve months. Average measured monthly mean global radiation is 1492 MJ/m2day (360.4 W/m2) transmittance-absorptivity factor of collector ($\alpha\tau$) is 0.83 and for Uyo meteorological area the latitudinal angle of inclination of solar collector is 5.04^o.

E. The overall heat loss U_c due to radiation between the absorber plate and glass cover is given [12] as:

$$U_c = \frac{\sigma(T_{plate} + T_{glass})(T^2{}_{plate} + T^2{}_{glass})}{\frac{1}{\varepsilon_{plate}} + \frac{1}{\varepsilon_{glass}} - 1}$$

(8)

Where T_{plate} = temperature of aluminum plate; T_{glass}= temperature of glass σ= Stephan Boltzmann constant; ε_{plate}= emissivity of aluminum plate ε_{glass}= emissivity of glass; T_{plate}= mean collector temperature; T_{glass} = mean ambient temp. $\sigma = 5.6697 \times 10^{-8}$ W/m2K^{-4}; ε_{plate}= 0.3; ε_{glass} = 0.94

F. Diameter of hole for the required ventilation is given [3] as:

$$Q = A_v V_{eh} \quad (9)$$

Where Q = volumetric flow rate of air [ventilation at chick emergence is 0.0275 m^3/min (4.58x10^{-4}m^3/s)] [8]; A_v = ventilation area; and V_{eh} = wind velocity

$$A_v = \pi d^2 / 4 \quad (10)$$

Where, d = ventilation diameter

$$d = [4Q/\pi V_{eh}]^{1/2} \quad (11)$$

G. Volume of a given air in solar collector chamber V_a is given by:

$$V_a = \left[\frac{A_c{}^2 \times \dot{M}_{pa}}{V_{eh} \times \rho_a}\right]^{1/2}$$

(12)

ρ_a is the density of air.

III. MATERIALS AND METHOD

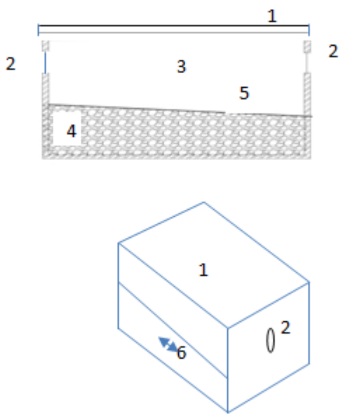
A. Materials

The following materials were used for this study:

- wood as a material of low thermal conductivity to design a chamber to accommodate a maximum of 16.32kg of heat storage material (stone pebbles),
- marble and granite as heat storage materials based on Table 1,
- aluminum plate as heat absorber plate,
- a tray made of steel was used for placing stone pebbles,
- hammer mass of 7kg was used to break the stone pebbles into smaller sizes,
- sieves were employed to sort the broken stone pebbles into various size ranges, and
- a weighing balance was used in measuring the weight of the stone pebbles.

B. Equipment Description

In this study, the Test rig (thermal storage unit) used is shown in Fig. 1. It has ventilated hole of 2.5 cm. The thermal storage unit frame include: doors, walls and bottom plate. They were fabricated using plywood material. The inlet and outlet holes for air passage were bored based on the designed ventilation diameter required for egg incubation. The door handle was then fixed. The inside of the cabinet was painted black. An absorber plate (Aluminum sheet) also was painted black and placed inside the heat collector chamber. The collector was inclined at the latitudinal angle of 5.04^{o}for Uyo meteorological area. A glass support was placed on top of the collector chamber and sealed with silicone. The outside frame was painted grey.



1	Glass
2	Air Vent
3	Collector Chamber
4	Pebble Bed
5	Collector
6	Door Handle

Fig.1. Thermal storage unit (Test Rig)

C. Experimental Procedure

Based on Table 1, marble and granite had high thermal conductivity and were selected to test for size (D) that would absorb and retain much heat. Granite and marble were broken and sieved into two size ranges of dimensions D<10 mm and 10≤ D ≤20 mm. For each size range the weight of the stone pebbles was measured and recorded. The rate of heat absorption and retention was tested for a particular size range when placed in the incubator heat storage chamber and exposed to sunshine from 9 am to 4 pm daily for ten days.

For each experimental run, the final temperature of the stones before off sunshine and inception of sunshine were recorded. The average temperature loss in ten days was evaluated for each size range. Three replicates were carried out. The size and type of stone pebble found as the best for heat sustenance off sunshine was chosen.

IV. RESULTS AND DISCUSSION

The size range of pebbles (marble) that was remarkable is D<10 mm as it holds temperature up for off sunshine hours as shown in Table II.

TABLE II. TEMPERATURES OF D<10 MM AND 10≤D≤20 MM SIZE RANGES FOR MARBLE AND GRANITE

Size Range (mm)	Granite			Marble		
	Average temperature throughout the sunshine hours (^oC)	Average temperature at the end of the off sunshine hours (^oC)	Temperature loss during off sunshine hours (^oC)	Average temperature throughout the sunshine hours (^oC)	Average temperature at the end of the off sunshine hours (^oC)	Temperature loss during off sunshine hours (^oC)
D<10	36.74	32.24	4.5	39.12	36.22	2.9
10≤D≤20	36.20	30.82	5.32	39.25	34.85	4.4

The 16.32 kg mass of pebbles used was based on (1), (4) and (6). The size ranges used showed that for granite of size range D< 10 mm, the heat retention average temperature of 36.74 ^oC was achieved as against size of 10 mm ≤D≤ 20 mm with average temperature of 36.2 ^oC. For marble the average temperature of heat retained during sunshine hours for sizes D< 10 mm and 10 mm ≤D≤ 20 mm were 39.12 ^oC and 39.25 ^oC respectively. The temperature retained at the end of off sunshine hours showed that for granite of sizes D< 10 mm and 10 mm ≤D≤ 20 mm the temperature losses were 5.38 ^oC and 4.5 ^oC respectively. For marble, the temperature losses for sizes D< 10 mm and 10 mm ≤D≤ 20 mm were 2.9 ^oC and 4.4 ^oC within a period of 16 h [5 pm-9 am] of off sunshine hours. It is suggested that since void between the particles are expected to be smaller than larger sizes, there would be less air flow circulation through the internal bed of the marble to cause less reduction in heat loss to the surrounding. Hence, higher retention of heat for the small size ranges.

Marble was chosen as heat storage medium suitable for egg incubation. The three best off sunshine heat retention was observed for marble (D< 10 mm); (10 mm ≤D≤ 20 mm) and granite (D< 10 mm) as their heat loss were 2.9 ^oC, 4.4 ^oC and 4.5 ^oC respectively within the period of 16 h of the off sunshine. The amount of heat loss over 16 h was 0.722 W and 1.01 W for marble and granite respectively. More so temperature rise of 0.875 ^oC/h and 0.593 ^oC/h were recorded during sunshine hours while 0.181 ^oC/h and 0.281 ^oC/h were temperature losses for marble and granite respectively.

The area of the collector was 0.5452 m2 and the volume of air chamber above solar collector was 0.01176 m3. The collector area was calculated based on average daylight time of 8 h of which the thermal storage unit was exposed. The air ventilation diameter of 2.5 cm in the thermal storage unit is required for effective air flow to meet the recommended volumetric flow rate of 0.0275 m3/min necessary for chick emergence; while air velocity was 0.97 m/s. Using (1), (2) and (3) and temperature T_2 = 39.12 ^oC and T_1 = 32 ^oC, obtained from this study, Q^*_s and Q_s for marble were 3.55 W and 155.4 W while that of granite were 2.01 W and 138.7 W respectively. These results further indicate that the highest amount of heat is stored in marble. The mean marble temperature, mean collector temperature and mean ambient temperature obtain during the experiment were 39.12 ^oC (312.12 ^oK), 38.5 ^oC (311.5^{o}K) and 32 ^oC (305^{o}K) respectively. The calculated U_c was 1.965 W/m2K and q_u evaluated to be 285.377 W/m2. The Q_u was obtained as 0.1556 kW.

V. CONCLUSION

Marble of size range D< 10 mm and mass 16.32 kg sustained temperature range of 39.12 to 36.22 ^{o}C. This temperature range is good enough to maintain egg incubation off sunshine hours. The temperature rise of marble when exposed to eight hours of sunshine is 0.875 ^{o} C/h while it losses temperature during off sunshine at the rate of 0.181 ^{o}C/h.

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