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Design, Modelling and Analysis of A Solar Powered Egg Incubator

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ABSTRACT
A Solar-Powered Egg Incubator is a sustainable, off-grid solution for poultry incubation, optimized through detailed thermal analysis and energy efficiency design. The designed incubator system integrates a solar collector achieving an efficiency of 56.55%, alongside a thermal storage unit using wet sand to retain heat during low-sunlight hours, ensuring consistent incubation conditions. The incubator requires a total heat input of 72.38 kJ to maintain optimal hatching temperatures of 36–39°C for up to 30 eggs, facilitated by natural convection air circulation. Through strategic material choices, including sawdust insulation and a plywood frame, heat loss is minimized, enhancing the incubator's energy retention. This innovative design is especially suited for remote areas with limited electricity access, reducing reliance on conventional energy sources and lowering operational costs, making it a valuable asset for both small-scale and commercial poultry operations.

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I. INTRODUCTION

Study Background

Poultry products have become a significant source of protein in the United States, driven by a growing population of over 331 million people with an annual growth rate of 0.57%. Agriculture plays a critical role in the country's economy, contributing 5.6% to the Gross Domestic Product (GDP) and employing 10.4% of the workforce, particularly in rural areas, where 19% of the population resides. The agricultural sector consists of crop farming, focused on staples like corn and soybeans, and livestock farming, which includes poultry, cattle, and swine. Poultry farming has emerged as a major industry, combining the efforts of small family-owned farms and large commercial enterprises. Southeastern states lead in poultry production, balancing small-scale operations with large-scale commercial ventures to meet the increasing demand for protein-rich food.

Meeting this demand has prompted the need for innovations in poultry farming practices. Traditional rural poultry production, which relies on scavenging feed resources, struggles to satisfy growing consumption requirements. Artificial incubation methods present an alternative, offering the ability to hatch large numbers of chicks on demand while ensuring controlled conditions for temperature and humidity. However, rural poultry farmers face significant challenges, including limited access to electricity for powering modern incubators. Renewable energy sources, particularly solar power, offer potential solutions. Solar-thermal systems, which can be manufactured locally and installed affordably, are particularly suited to supporting artificial incubation in remote areas, bridging the gap left by traditional methods.

The integration of renewable energy into agricultural practices highlights the importance of sustainable innovations for improving productivity. Solar-electric energy, while promising, remains costly and space-intensive, making it less accessible for small-scale poultry farmers. In contrast, solar-thermal energy provides a viable and cost- effective alternative, particularly in areas with limited infrastructure. These advancements address the inefficiencies of natural broody hen incubation, which limits production quantity and depends on genetic and environmental factors. By embracing artificial incubation technologies and renewable energy solutions, poultry farming can better meet the protein demands of a growing population while promoting environmental sustainability and economic resilience in rural communities.

II. METHODOLY

2.1 Basic Theory

2.1.1 Solar Radiation.

The sun is a G-type, main sequence star, classified as a yellow dwarf of the fifth magnitude. The sun has a mass of approximately 10^{24} tons, a diameter of 865,000 miles, and radiates energy at a rate of 3.8×10^{24} Megawatts[13]. Present theories predict that this output will continue, essentially unchanged, for several billion years. It is necessary to say essentially, because the sun's energy output may fluctuate by a few percent from time to time.
For our purposes, we will consider the solar energy output to be a constant[13].

Between the sun and the Earth, there exists a hard vacuum and a distance that varies from 92 to 95 million miles. This distance variation implies, using the inverse square law, that the light energy reaching the earth in June (when the Earth is at maximum distance from the sun) is approximately 94% of the light energy reaching the Earth in December as illustrated in figure 2.1 below.

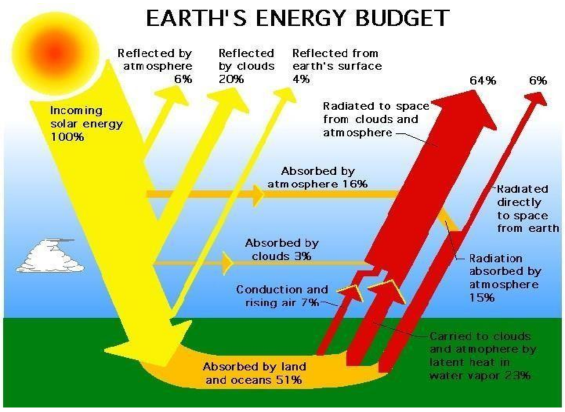


Figure 1:Illustration of various components of radiation received on the earth's surface. Atmospheric scattering gives rise to diffuse component [13]

30% (atmosphere (6%) + clouds (20%) + earth's surface (4%)) of the incoming solar radiation is reflected into space before it is converted to heat. After entering the earth's atmosphere, the remaining 70% of this solar radiation is absorbed (and converted into heat) by the land and oceans (51%) the atmosphere (16%), and clouds (3%). After the conversion to heat, all of this heat (which is the entire product of the conversion of 70% of incoming solar radiation) radiates back to space through several pathways[14].

The earth's orientation at the equatorial plane, tipped at 23.45˚ from the ecliptic plane, produces a varying solar declination as it revolves around the sun. According to the inverse square law, solar irradiance, solar power per unit area, reduces in proportion to the inverse square of the distance from the source. The mean distance of the sun from the Earth is nearly 149.6 million kilometers with sunlight covering the distance in about 8 minutes and nineteen seconds. The distance changes across the year ranging from a minimum of 147.1 million kilometers on the perihelion to a maximum of 152.1 million kilometers on the aphelion[13], [14].

2.1.2 Solar Collectors

Solar collectors are the key component of active solar heating systems. They gather the sun's energy, transform its radiation into heat, and then transfer that heat to a fluid (usually water or air). Solar thermal energy can be used in solar water-heating systems, solar pool heaters, and solar space-heating systems.

There are a large number of solar collector designs that are functional. These designs are classified into two general types of solar collectors:

i. **Flat-plate collector**s – the absorbing surface is approximately as large as the overall collector area that intercepts the sun's rays.

ii. **Concentrating collectors** – large areas of mirrors or lenses focus the sunlight onto a smaller absorber.

2.1.2.1 Flat Plate Solar Air Collectors

A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark-colored absorber plate. A part of the radiation is reflected back to the sky, another component is absorbed by the glazing and the rest is transmitted through the glazing and reaches the absorber plate as short-wave radiation as shown in Figure 2.2[15].

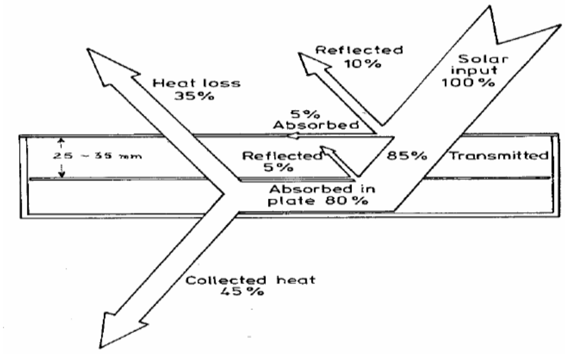


Figure 2: Heat flow through a flat plate collector

The glazing then traps the heat within the box which is then absorbed through a dark- colored metal absorption plate. This plate transfers heat to tubes in the box that contain air. The air circulates through convection warming as it passes around the absorber as shown in Figure 2.3[15].

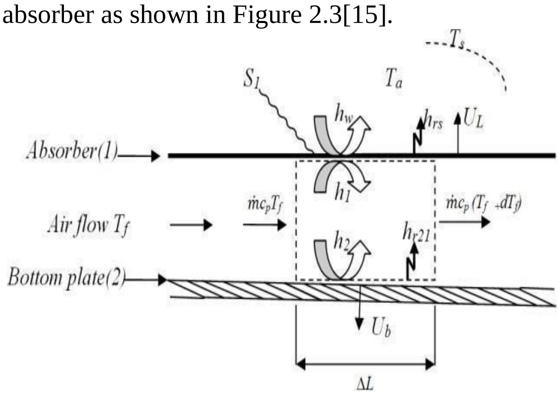


Figure 3:Heat flow through a solar collector

The hot air is then transferred by a fan to help heat water or warm the house or to the incubator as in the case of a solar thermal powered egg incubator as some transferred to the thermal storage.

2.1.2.2 Flat plate solar air collector analysis

The design analysis and energy equations for the different elements of the solar air collectors in conservation form on this project are formulated by making the following assumptions:

2.1.2.2.1 The system operates under steady- state conditions;

2.1.2.2.2 Air, absorber, and bottom plate temperatures change only in the direction of the airflow. Temperature drops between the top and the bottom of the absorber plate and the glazing is negligible.

2.1.2.2.3 The outside convective heat transfer coefficient is constant along the length of the solar air heater.

2.1.2.2.4 Air temperature is assumed uniform through the cross-section.

2.1.2.2.5 Heat conduction is considered negligible

2.1.2.3 Solar incidence on collector

The solar declination (δ) represents the angular distance of the sun's rays north or south of the equator and can be calculated using a standard equation based on the day of the year. Solar radiation intensity (I) on a plane normal to the sun is determined by considering atmospheric and solar altitude parameters. The solar altitude angle (α), a key factor, varies throughout the day and affects the intensity of solar radiation. Equations are used to calculate direct and diffuse radiation on horizontal and tilted surfaces, which, when combined, give the total solar radiation.

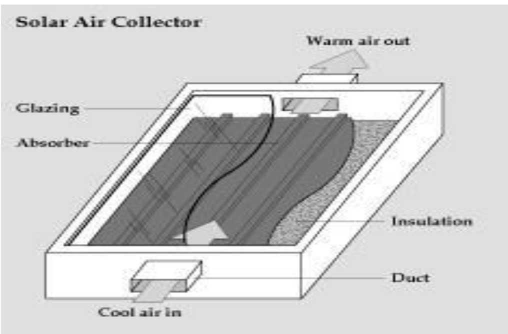


Figure 4: Flat plate solar air collector

Solar collectors capture and utilize this energy, with their performance heavily influenced by the design and orientation.

The energy gain by a solar collector depends on the intensity of radiation (Iδ), collector area (A), and material properties such as transmission (τ) and absorption (α) rates. Heat losses occur due to convection and radiation, described by an overall heat transfer coefficient (UL). The useful energy extracted (Qu) is calculated as the difference between absorbed energy and losses. Efficiency (η) is expressed as the ratio of useful energy gained to incident solar energy. Key factors include mass flow rate, specific heat capacity of air, and the collector heat removal factor, which relates the actual energy gained to theoretical potential.

2.2.3 Main Components of Incubation. Incubation involves maintaining controlled conditions of temperature and humidity to support the development of eggs, with chicken eggs typically requiring 21 days to hatch, similar to natural hatching. Unlike natural incubation, where the parent warms the eggs through physical contact, artificial incubation creates an optimal environment through mechanical means. Successful incubation requires maintaining precise temperature and humidity levels to regulate the embryo's metabolic processes, periodic turning of eggs to prevent the embryo from adhering to the membrane (which can lower hatchability and chick quality by 20%-30%), and ensuring constant airflow to provide oxygen while removing carbon dioxide. A clean and disinfected environment is crucial to prevent infections. Additionally, ventilation systems, particularly in solar-thermal incubators, are vital for maintaining fresh air circulation and managing moisture, ensuring healthy chick development.

2.2.4 Factors necessary for the hatching process

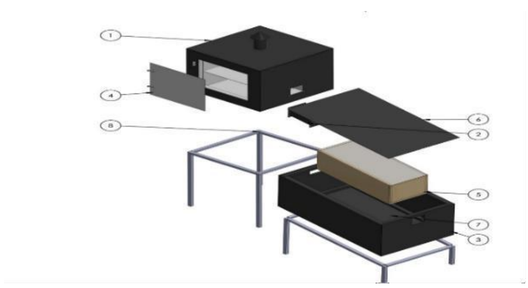
Successful egg hatching relies on maintaining optimal conditions for temperature, humidity, and ventilation. Temperature is critical, with an ideal range of 36˚C-39˚C to support embryo development; overheating can cause embryo mortality, while underheating slows development. Relative humidity should be maintained at 60% during most of the incubation period, increasing to 65%-70% in the final days to prevent evaporation issues that could hinder hatching or cause chicks to hatch deformed. Proper ventilation ensures a steady oxygen supply (21%) and the removal of carbon dioxide (up to 5%) without disrupting the incubator's temperature and humidity levels. Imbalances in any of these factors can significantly compromise hatch rates and chick quality.

2.2 System Description

The system design integrates two primary components: the incubating unit and the solar air collector, both engineered to optimize hatching conditions through effective thermal management. The incubating unit is designed with a wooden chimney that facilitates proper ventilation while preserving the necessary humidity levels for successful egg incubation. Wood is utilized as a structural material due to its insulating properties, minimizing heat loss. The space between the inner and outer walls of the incubator is filled with 40mm thick foam material, reducing thermal conductivity to $0.043Wm^{-1}K^{-1}$. Inside, the compartment features an egg tray and a water pan that maintains the required relative humidity. The inner surfaces are painted white to reflect heat and further reduce thermal loss, ensuring stable and optimal incubation conditions.

The solar air collector consists of a flat plate system with a cover plate, absorber plate, and casing, designed to harness and store solar energy. The transparent glass cover plate permits short-wave radiation, which the black absorber plate converts into heat energy. This heat is retained as the glazing prevents long-wave radiation escape, leading to efficient thermal build-up. Beneath the absorber plate is a thermal storage unit filled with moist sand that stores and releases heat. During sunshine hours, the sand absorbs heat, which is released during off-sunshine periods to maintain airflow. Air circulates naturally through the collector due to buoyancy forces created by density gradients, a phenomenon known as thermosiphon flow, which ensures consistent heat transfer to the incubating chamber without mechanical pumps.

2.2.1 Conceptual system design layouts



ITEM NO.	PART NAME	QTY.
1	Incubator	1
2	Duct	1
3	Solar Collector	1
4	Door	1
5	Sand compartment	1
6	Top Plate	1
7	Stand1	1
8	Stand 2	1

Figure 5: Exploded view of solar powered egg incubator

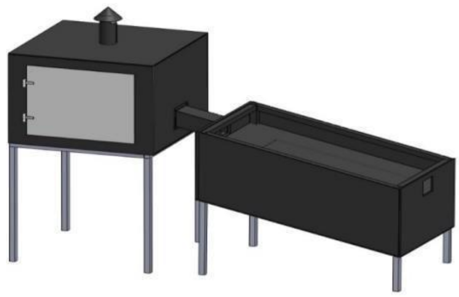


Figure 6: Isometric view of the system

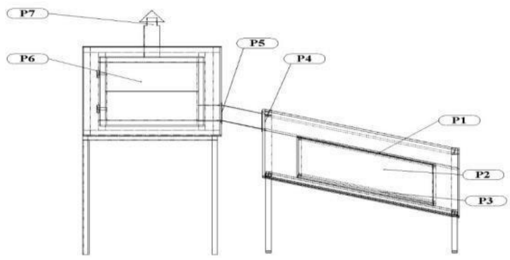


Figure 7:2D-Dimensional view

Where;
P1-Temperature at the absorber plate;
P2- Temperature at the middle part of the wet sand in the solar collector;
P3-Temperature at the bottom part of the wet sand in the solar collector;
P4- Temperature of air leaving the solar collector and entering the incubator;
P5-Temperature of air from the duct as it enters the incubator;
P6- Temperature of air in the incubator;
P7- Temperature of air as it leaves the incubator through the chimney.

2.3 Material Selection

The materials used in the system are selected for their availability and cost-effectiveness, with specific considerations for thermal efficiency and durability. The thermal storage unit employs a mild steel absorber plate for its excellent conductivity and affordability. The plate is painted black to enhance its absorptivity, capturing 90% of incident rays and emitting them as long-wave radiation. Heat is transferred to both the air flowing through the collector and the wet sand in the thermal storage unit, which acts as a heat reservoir. The collector casing, made of wood, provides insulation, while a glass glazing minimizes heat losses through convection and radiation, outperforming plastic alternatives due to its resistance to UV corrosion. The wet sand in the thermal storage unit adds additional thermal capacity, utilizing the heat of condensation to sustain the system's efficiency.

The incubator box is constructed from plywood, chosen for its cost-efficiency, availability, and high thermal resistance, which reduces heat conduction losses. Humidity within the incubator is maintained using a water-filled pan, ensuring proper conditions for egg incubation. Optimal relative humidity is achieved through wet and dry bulb thermometers or a hygrometer, maintaining 55–60% during early incubation and increasing to 70% in the final days before hatching. This careful regulation of humidity ensures the eggs are in a controlled environment conducive to successful hatching, supported by the materials and design of the system.

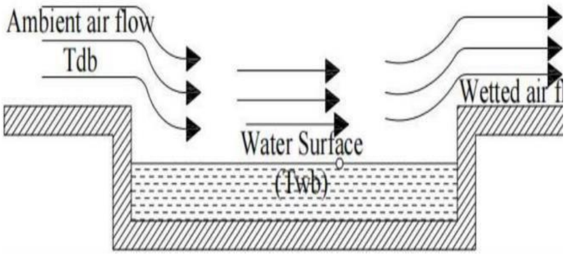


Figure 8:Pan carrying water for humidifying the chamber

2.3.3 The chimney

It is located to the top center of the incubating unit. It is constructed from galvanized iron sheets. It is also covered by a wire net to prevent entrance of rodents and insects.

III. RESULTS AND DISCUSSIONS

In this chapter, the data collected is analyzed and an energy balance of the system components is also analyzed.

3.1 Data Collection

Climate and average weather year-round in Shelton, Connecticut in the United States was obtained for the analysis of this design. The data shows that in Shelton, the summers are warm, humid, and wet while the winters are very cold and snowy and it is partly cloudy year-round. Over the course of the year, the temperature typically varies from -5°C to 27°C and is rarely below -13°C or above 31°C. The following graphs show the various climatic and weather conditions[17].

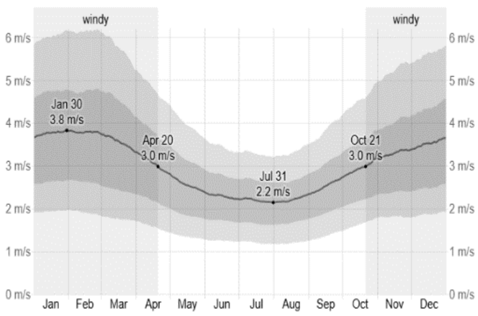


Figure 9:Average wind speed in Shelton

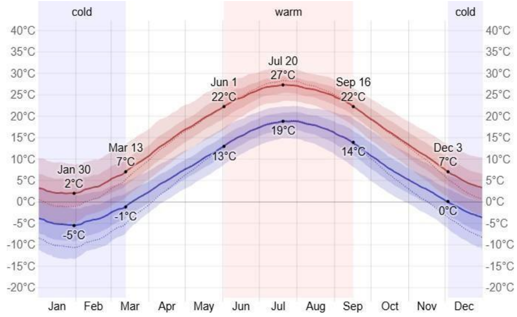


Figure 10: Average High and Low Temperature in Shelton

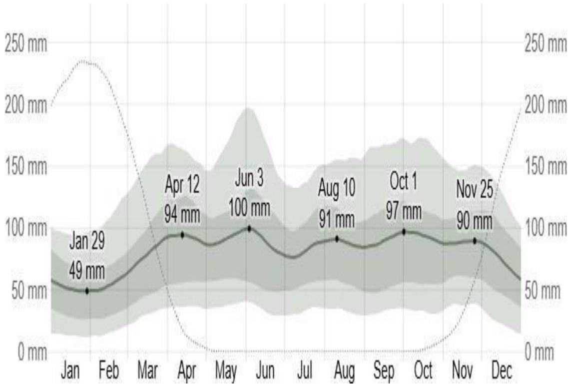


Figure 11: Average Monthly Rainfall in Shelton

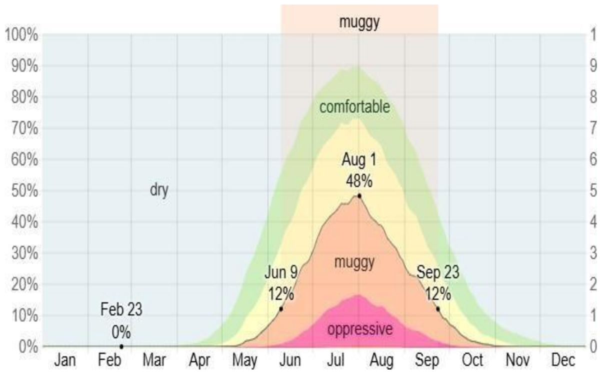


Figure 12:Humidity comfort level in Shelton

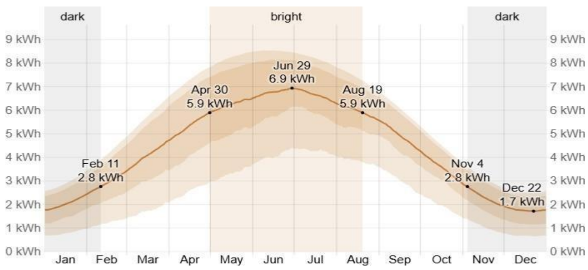


Figure 13: Average Incident Shortwave Solar Energy in Shelton

3.2 Numerical Results

3.2.1 Incubator heat load capacity

For thirty eggs, the minimum inner dimensions required at the incubator are 350mm length, 350mm width and 300mm height to comfortably fit the eggs for adequate aeration and also enough space for turning after a period of 3-4 hours. In order to achieve minimum heat loss, the incubator consists of a 12mm plywood box within another 12mm plywood box separated by a 40mm layer of sawdust insulation.

3.2.2 Rate of heat required for optimum conditions in the incubator

The rate of heat required for optimum conditions in the incubator is calculated using the formula $Qb=Mb\times Cb\times \Delta T$. The area of the walls is determined to be 0.665 m^2, and the mass of the plywood is 7.98kg, while the mass of the sawdust is 4.256kg. The total mass of the materials in the incubator is 12.236kg. For optimal conditions, the temperature difference (ΔT) is 11°C, from 27°C to 38°C. Using these values, the required heat for the incubator is calculated to be $Qb = 12.236 \times 1.5 \times 11 = 201.894kJ$

3.2.3 Rate of heat required for air in the incubator.

We obtain the rate of heat required for air in the incubator by using equation (2.22)

$$C_a = C_{air} = 1.005kJ/kgK$$

$$M_a = V_{inc} \times \rho_{\boldsymbol{air}}$$

$$V_{inc} = 0.35 \times 0.35 \times 0.3 = 0.03675m^3$$

$$density\ of\ air\ at\ 38°C\ is\ 1.13696kg/m^3$$

$$M_a = 0.03675 \times 1.13696 = 0.04178kg$$

$$\Delta T = 11°C$$

$$Q_a = 0.04178 \times 1.005 \times 11 = \mathbf{0.4619kJ}$$

3.2.4 Rate of heat required for incubated eggs

In the case of the solar-thermal egg incubator, the size of the incubator is able to incubate 30 eggs. Therefore, we use equation (2.21)

$$C_e = 3.184kJ/kgK$$

$$M_e = 0.06kg(for\ 1\ egg)$$

$$\Delta T = 11°C$$

$$Q_e = (30 \times 0.06) \times 3.182 \times 11 = \mathbf{63.0036kJ}$$

3.2.5 For the mesh egg tray,

We obtain the heat rate by using equation (2.26)

$$C_m = 0.36kJ/kgK$$

$$Q_m = 0.04557 \times 0.36 \times 11 = \mathbf{0.1805kJ}$$

According to Renema et. al., a warming rate for incubation is taken to be 0.0488kJ/min per kilogram of energy in an egg. Therefore, the time taken to raise temperature is found to be;

$$63.0036 \div 0.0488 = 1291.057minutes = \mathbf{21.5176223\ hours.}$$

3.2.6 Rate of heat lost through the incubator walls

The rate of heat loss from the incubator is determined using the overall heat transfer coefficient (U), which is the inverse of the total thermal resistance (R_T). The thermal resistance for each layer (plywood, sawdust, and plywood) is calculated by the formula $R_T = \frac{t_i}{k_i A_i}$ where t_i is the material thickness, k_i is the material's thermal conductivity, and A_i is the area of the layer.

For the incubator's walls, the resistance of the inner wall (plywood) is calculated as 5.6591 K/W, the insulating material (sawdust) resistance is 33.1701 K/W, and the outer wall (plywood) resistance is 2.73068 K/W. The total thermal resistance is 41.55988 K/W.

Thus, the overall heat transfer coefficient is $U = \frac{1}{41.55988} = 0.024062J/K$. Therefore, heat loss due to the incubator body is, $Q_s = 0.024062 \times (32 - 29) = 0.072186J$

3.2.7 Heat loss through ventilation

In order to obtain heat loss through ventilation, we use equation (2.24)

$$V = \frac{3 \times 0.35 \times 0.35 \times 0.3}{3600} = 3.0625 \times 10^{-5} m^3/s$$

$$Q_v = \rho V C_p \Delta T$$

$$Q_v = 1.13696 \times 3.0625 \times 10^{-5} \times 1.005 \times 11 = \mathbf{0.3849J}$$

3.2.8 Total heat requirement in the incubator

The total heat required for the incubator is obtained by using equation (2.20)

$$Q_T = 0.0839778 + 17.1828 + 55.062 + 0.04922 + (0.10498 \times 10^{-3}) + (0.072186 \times 10^{-3})$$

$$Q_T = \mathbf{72.37817kJ}$$

3.2.9 Sizing of the Thermal Storage

3.2.9.1 Solar incidence radiation on the collector

The declination of the sun for October 21st is calculated using the formula $\delta = 23.45\sin\left(\frac{360}{365}(284 + N)\right)$ where N =294 results in a value of δ= $-11.754°$. The Local Solar Time (LST) is adjusted using the equation $LST = LST_i + {}^4/_{60} \times (local\ longitude - standard\ longitude\ ) + EoT$. The Equation of Time (EoT) is calculated as -6.1589 minutes, which adjusts the LST to 11.7727 hours. The hour angle is calculated as $h = 15 \times (LST - 12) = -3.4095°$ indicating the hour angle is 3.4095° West of the Local Meridian. The optimal tilt angle for the solar collector is 20.33°, giving an incidence angle of $\alpha = 74.84°$. The solar radiation intensity is calculated as $I = 1.353 \times 10^3 e^{-\frac{0.25}{0.9652}}$ =1066.1261 W/m^2, and the direct solar radiation on a horizontal surface is $I_h = 1029.0242 W/m^2$. The diffused radiation is found to be I_d= 198.5660W/m^2, leading to a total solar radiation of I_t =1066.1261+198.5660 = 1264.6921W/m^2. The solar radiation on a tilted collector surface is $\boldsymbol{I_\delta} =$ **1260. 767W/m^2.** The energy gain by the collector, considering heat losses and the solar radiation incident on the collector, is calculated to be *Q_u=708.756W/m^2*.

3.2.9 .3 Collector Thermal Efficiency η ;

Is the ratio of the useful heat energy gain Q_u carried by the working fluid to the irradiance incident on the solar collector, namely;

$$\eta = \frac{Q_u}{A_c I_t} = \frac{708.756}{1264.6921} = \mathbf{56.55\%}$$

3.3 Discussion

The project's objective was to design, model and analyze the performance of a solar thermal egg incubator. The radiation incident on the solar collector was found to be 1264.6912W/m^2. The possible energy gain by the solar collector was found to be 708.756W/m^2. The solar collector efficiency of the solar collector is estimated to be about 56.55%. Air was chosen as a heat transmission medium in the solar thermo-powered egg incubator. The solar collector at the analysis time of 12:00 noon, should be inclined at an angle of 20º to take advantage of the natural circulation of air through the collector and incubating chamber due to convection and also to prevent accumulation of condensed water droplets from settling on the absorber plate as they could roll off. This also enhances the solar collection ability of our solar collector. The total amount of heat required to raise the temperature of 30 eggs and maintain them at steady conditions is established to be 63.0036kJ.

Saw dust, a material with extremely low thermal conductivity was used to insulate the incubator and the solar collector units, considerably reducing heat losses. This design incorporates wet sand as a thermal storage material opposed to previous designs which have put into practice ballast as the storage material. The design reveals facts that would form a good guideline in rating the performance of a solar thermal egg incubator.

IV. CONCLUSION

The analytical results obtained showed a high thermal performance of the system. The energy needed for the incubator is found to be 72.37817kJ. This project design shows the possibility of a solar collector with an efficiency of 56.55%, designed to tap useful solar energy. The modification which involves the use of wet sand proves to be a good idea. The wet sand tapped into the latent heat of condensation and resulted in an increased efficiency from 36.5% of the solar thermal storage unit from the use of ballast as a thermal storage material.

V. RECOMMENDATIONS

a. The solar thermal egg incubator should be tested while there are eggs places in them. This is to practically test on whether the incubator is functional.

b. Fins can be incorporated to enhance the thermal storage efficiency by transferring excess heat to the storage material during the day and from the storage to the air chamber at night.

c. A thermostat system mechanism for airflow regulation can be installed at the entry point to the incubator chamber to open/close as per the set temperature ranges for incubation.

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