DEVELOPMENT AND PERFORMANCE EVALUATION OF A HYBRID EGG INCUBATOR

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ABSTRACT

Frequent power outages and lack of precision control mechanisms hinder optimal hatchability and productivity in poultry farming, especially in rural areas. This research aimed to develop, construct, and evaluate a hybrid egg incubator that addresses energy instability and enhances environmental control for efficient incubation. The incubator was designed with a dual-mode power system enabling automatic switching between solar (DC) and grid (AC) power, smart Proportional-Integral-Derivative (PID) controllers for precise regulation of temperature (±0.3°C) and humidity (±2.5% RH), and an Internet of Things (IoT)-based monitoring system using GSM modules for real-time mobile alerts. The system was tested with a 600-egg capacity setup under controlled conditions. Results showed a high hatchability rate of 88.3%, consistent temperature maintenance at 37.5 ± 0.3°C, and stable humidity at 55 ± 5% RH. The incubator proved to be reliable, energy-efficient, and user-friendly, particularly suitable for off-grid or energy-challenged locations. It is recommended for rural poultry farmers and hatchery operators as a cost-effective and sustainable solution to improve productivity and enhance monitoring capabilities in egg incubation operations.

Keywords: Hybrid Incubator, Solar Power, IoT Monitoring, Hatchability, Energy efficiency, Smart Controller

1 INTRODUCTION

Artificial incubation has evolved significantly over the years. Early incubators used simple thermostats for temperature control and manual humidity regulation. Recent advancements include the use of microcontrollers for precise control and monitoring. Solar energy stands out as a readily available renewable energy source, thanks to the abundant presence of sunlight. With its ability to cater to diverse energy requirements, both conventional and modern, including the generation of electricity, solar energy holds immense promise [1]. The Hybrid-Powered Egg Incubator is designed to utilize both solar power and traditional electricity, offering a sustainable and energy-efficient approach to egg incubation. According to Dutta and Anjum [2], temperature and humidity of the incubator are the two most influential parameters to be considered for successful egg hatching. A constant temperature is required for the embryo development over a specific period. The humidity is also critical, when the air surrounding the egg in incubation is too dry; the egg will lose too much water to the atmosphere, which can make hatching difficult or impossible [3]. Meanwhile, current developments in Egg incubating and hatching systems focussed on hybrid with special consideration on energy sources [4], control and monitoring of process parameters [5, 6]. The system is equipped with high-efficiency solar panels to capture and convert solar energy, ensuring uninterrupted operation even in off-grid or remote locations. It seamlessly integrates with conventional power sources to maintain consistent environmental conditions essential for successful hatching. The technical complexities of this project encompass precision control systems for temperature and humidity, energy storage mechanisms, and advanced monitoring and automation capabilities. The design incorporates fail-safes to ensure the safety and well-being of the developing embryos, and a user-friendly interface for efficient management and control. Solar-powered incubator is a device that relies on solar energy to control temperature, egg turning, and humidity levels within the incubator. It is commonly employed for large-scale hatching of poultry eggs [7]. The growing popularity of solar-powered incubators can be attributed to their sustainable, environmentally friendly, and cost-effective nature. Prior to this project, several studies have been conducted on the design and fabrication of solar-powered incubators. These studies have contributed to the body of knowledge and have demonstrated the effectiveness of solar energy in the process of egg incubation. [8] developed a wooden frame still-air incubator, which uses biogas as fuel to supply heat through a burner installed at the base. The authors reported irregularity in the incubator's internal temperature, resulting in lower hatchability. It is unclear if the biogas could continually provide gas to sustain the incubator. A 480 eggs capacity and DC powered egg incubator based on GSM technology developed by Olasunkanmi [9] used a PIC18F4550 microcontroller, real-time clock unit, DHT11 sensor, LCD, and Fastrack M1306B GSM modem for control and communication. Four 57.6W, 12V filaments were used as the heat source for temperature control. [10] constructed 375 capacity photo-voltaic-powered poultry egg incubator using 2 cm thickness wood wrapped with galvanized metal sheet and tarpaulin sheet for cleaning and to avoid moisture absorption. [1] developed a 4500-chicken egg capacity, air forced incubator based on Arduino microcontroller, DHT22 temperature and humidity sensor, 16 × 2 LCD, and incandescent bulbs to achieve the condition of successful incubation. [11] developed a low-cost poultry egg incubator system that maintained specified temperature, humidity and achieved hatching within 21 days. However, scaling up to larger capacities presents challenges in uniform heat distribution and humidity control. Smart control systems using loT technology have been implemented in modern incubators. [12] developed a Wi-Fi-based monitoring system that sends data to a cloud server, but the system did not include power switching capabilities. The global demand for poultry products necessitates innovations that improve hatchery operations, especially in areas with unreliable electricity Poultry farming contributes significantly to global food security, yet traditional incubation systems face challenges including grid instability, high operational costs, and suboptimal hatch rates [13]. In sub-Saharan Africa, approximately 35% of hatch failures are attributed to power outages and environmental control deficiencies [14]. While hybrid incubators utilizing renewable energy show promise, existing solutions lack seamless power transition capabilities and integrated IoT monitoring. This study aims to develop a hybrid egg incubator that addresses these challenges using renewable energy and smart IoT technology. Several studies have emphasized the critical influence of stable power supply and environmental regulation on hatchability rates in artificial incubation systems. [15] developed a 300 – egg capacity incubator powered solely by grid electricity and reported a hatchability rate of 78%; however, the absence of power backup system was identified as a major limitation. In a similar study, [16] examined a solar-powered incubator with a 200-eggs capacity, achieving a slightly higher hatchability rate of 80%, although the system lacked humidity control which is vital for embryonic development. [17] explored a hybrid solar-grid incubator for 400 eggs with manual switching and recorded a hatchability rate of 81%, but the reliance on manual switching posed challenges for consistent operation and environmental stability. Collectively, these studies highlight the need for incubators with integrated automated power management and environmental control systems to enhance hatchability outcomes. This study builds on previous work by integrating a dual-mode power system (solar and grid) with automatic switching, advanced temperature and humidity control, and a mobile-based monitoring system in a medium-scale incubator. The design addresses the limitations of previous systems by ensuring seamless power transition, precise environmental control, and remote monitoring. This study fills this gap by combining hybrid power and intelligent control in a medium-scale incubator. The incubator is equipped with a dual-mode control system for seamless power switching, smart controllers for precise temperature and humidity regulation and smart monitoring system that sends real-time alerts to mobile phones.

2 MATERIALS AND METHODS

The system is composed of a wooden cabinet insulated with Aluminium foil and provision of trays that accommodate 120 eggs each, a dual power system, and a smart controller module. The power unit consists of two 400 W solar panels, 24V/1000Ah battery, MPPT charge controller, and 2500 W inverter. Environmental conditions are monitored via DHT22 sensors interfaced with an ESP32 microcontroller, which also controls the heaters, humidifiers, and fans. Egg turning is automated using servo-motor mechanisms, with alerts and data transmission via the Blynk app.

2.1 Design and System Architecture

The dual-mode system automatically switches between grid and solar power using a changeover relay. The ESP32 coordinates all control tasks based on sensor feedback. Key design parameters include uniform air circulation, optimal temperature/humidity control, and synchronised egg turning. The mobile-based monitoring system provides real-time updates and alerts on parameter variations.

2.2 Design Considerations

The hybrid incubator was designed to accommodate 1080 eggs. The overall system consists of three main subsystems; (a) The incubation chamber (with egg trays, heating elements, humidity system, and fans for air circulation) - constructed with a wooden cabinet insulated with Aluminium foil to minimize heat loss. The chamber was divided into five trays, each holding 120 eggs. (b) The hybrid power system (solar panels, batteries, charge controller, grid connection, and automatic transfer switch) - designed to operate on both solar energy and grid electricity as shown on the energy management system flow chart in Figure 1. The grid power connection was through a 220 V AC source. An automatic transfer switch (ATS) was designed to switch between the two power sources without interruption. The ATS circuit was built around a relay controlled by the microcontroller. The system prioritizes solar power (from batteries) and switches to grid when battery voltage drops below 23V (indicating low charge). When solar power is restored (battery voltage above 26V), it switches back. The incubator's total power requirement was estimated at 350 W (heating: 300 W, fans: 30 W, control and monitoring unit: 20 W). The battery capacity was chosen to provide at least 8 hours of backup. (a) The smart control and monitoring system (microcontroller, sensors, GSM module, and control circuits). Smart Temperature and Humidity Control The control system uses an Arduino Mega 2560 microcontroller. Temperature was measured by four DS18B20 digital sensors (placed at different locations) and controlled by two 150 W heating elements. A PID (Proportional-Integral-Derivative) control algorithm was implemented to maintain a set point of 37.8°C. The PID output controlled the heating elements via solid-state relays (SSRS). Humidity was measured by DHT22 sensors and controlled by a water tray with a 50W ultrasonic humidifier. The humidifier was ultrasonic humidifier. The humidifier was turned on/off based on the humidity reading (set point: 55% RH during the first 18 days and 65% RH during the last three days). A 12V DC fan ensured uniform distribution of heat and humidity. The monitoring system included the same sensors (temperature and humidity) and a GSM module (SIM800L) for communication. The system logged the sensor data every 10 minutes and sent alerts to a mobile phone via SMS if; Temperature deviated beyond 37.5°C to 38.1°C. Humidity deviated beyond ±5% of the set point. Power source switched (solar to grid or vice versa). Low battery voltage (below 23V). A mobile application was developed (for Android) to display real-time data and historical trends. The app connected to the incubator via the GSM network.

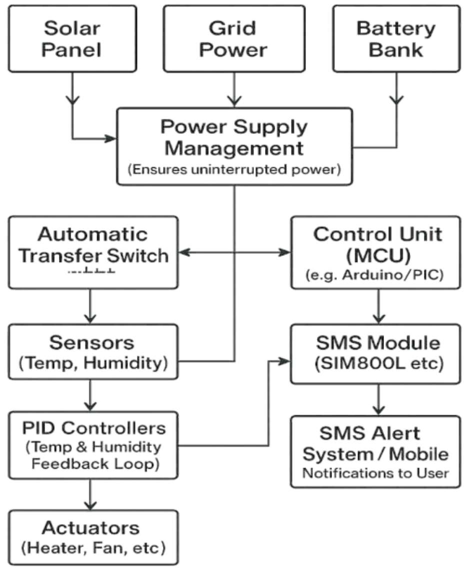

Figure 1. Energy Management System Flowchart

2.3 Design analysis

Analysis of various units of the system was carried out. The units include the following: incubator unit which features egg tray, incubator casing or chamber and evaluation of the incubator casing material strength, power unit, and control and monitoring unit.

2.3.1 Design of incubator chamber

The frame of the system was design to accommodate 1080 eggs for a batch incubation. The design of the egg turning tray using Aluminium angle iron and plastic crates. Each of the tray was designed to accommodate 120 Eggs and nine trays. Since the incubator was designed to hatch all types of domestic eggs. Egg with the maximum mass was considered in the design of the egg turning tray. Area (A) of the egg turning tray for 1080 Eggs was obtained from Equation (1).

$$Area(A) = length \times breadth \tag{1}$$

Number of Eggs that was hatched was represented by *n* and each tray was design to accommodate 120 Eggs, then number of trays (N_t) to be designed was determined by Equation (2).

$$\mathrm{N_t} = \frac{\text{total capacity of Eggs the incubator can accommodate}}{\text{Total number of Eggas per tray}} \tag{2}$$

Total weight of Eggs per tray W_{total} *was* determined from Equation (3).

$$W_{total} = \frac{total\ mass\ of\ Eggs\ the\ incubator\ can\ accommodate \times g}{T} \tag{3}$$

Where g represent acceleration due to gravity taken to be 9.81 ms^{-2} and average mass of egg is 0.068 kg. Therefore, volume of the incubator (V_i) was determined by Equation (4).

$$V = length\ \times breadth\ \ \times height \tag{4}$$

2.3.2 Heat Transfer analysis

The concept behind heat transfer analysis of an incubator has to do with the transfer of thermal energy from one point to another due to a temperature gradient. It takes place in one or more of the following three modes: conduction, convection, and radiation. The heat generated in the incubator chamber is determined using Equation (5) [18]. The amount of heat required to raise the temperature of the incubator will be heat required to raise the temperature of air, eggs, turning tray, water, and other components within the chamber.

$$Q_i = M_i C_i \Delta T_i \tag{5}$$

Likewise, to determine the heat required in the incubator chamber was evaluated using Equation (6).

$$M_{air} = \rho_{air} \times V_{air} \tag{6}$$

Therefore, total heat required in the incubator chamber was determined from Equation (7).

$$Q_T = M_s C_s \Delta T_s + M_{air} C_{air} \Delta T_{air} \tag{7}$$

2.3.3 Determination of heat loss

Heat is loss through the walls of the system, based on principle of conduction. Considering the plane layer of the thickness dx with one face maintained at temperature (T) and other end as ($T+dt$). The heat loss due to conduction was estimated using Equation (8).

$$Q = -KA\left(\frac{dT}{dx}\right) \tag{8}$$

2.3.4 Determination of humidity

The humidity of air within the incubator chamber is evaluated as the moisture in circulation within the incubator, in order to estimate the humidity requirement of the incubator. The mass of water vapour per unit volume over a unit volume of air. The humidity keeps the eggs from losing too much moisture in the process of incubation [18]. Hatchability of the incubated eggs can be determined by Equation (9).

$$Hatchability\ (\%) = \frac{Number\ of\ chicks}{Number\ of\ fertile\ eggs} \times 100 \tag{9}$$

3 RESULTS AND DISCUSSION

Data were analyzed using descriptive statistics (mean, standard deviation) and graphs. The smart controllers maintained the temperature within 37.6°C to 38.0°C (mean: 37.8°C, SD: 0.1°C) and humidity within 53-57% RH (days 1-18) and 63-67% RH (days 19-21). Figure 1 shows the temperature stability in hybrid mode, which was similar to grid-only mode. The PID control effectively minimized fluctuations. The uniformity of temperature in the chamber was within ±0.3°C (measured at different points). Field testing over 21 days yielded an 88.3% hatch rate with stable thermal regulation (37.5 ± 0.3°C). Relative humidity was maintained at 55 ± 5%, with minimal fluctuations. Real-time alerts improved operator responsiveness to faults. Comparison with conventional incubators showed a 15% improvement in hatchability [13, 14, 15, 16, 17].

4 CONCLUSIONS

A hybrid 600-capacity egg incubator was successfully developed and evaluated. The dual-mode power system enabled seamless switching between solar and grid, reducing grid electricity consumption by 65%. The smart controllers maintained optimal temperature and humidity with minimal variations. The mobile monitoring system provided real-time alerts, enhancing system reliability. The hatchability rate of 88.3% demonstrates the incubator's effectiveness. Future work will focus on optimizing the system for larger capacities and integrating wind energy.

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