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Design and Development of a Smart Incubator for Bee Queens Based on IoT Technology

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Abstract—**Successful queen bee incubation requires stringent environmental regulation to ensure consistent and reliable developmental outcomes. This paper presents the design and development of a novel smart queen bee incubator to maintain optimal environmental conditions throughout the incubation. The system provides fine-grained, gradual control of temperature and humidity across a wide operational range, and a controlled air ventilation system, thereby improving larval viability and developmental stability. Finite element analysis (FEA) and computational fluid dynamic (CFD) tools are used to simulate and study the heat distribution and airflow of the proposed incubator, where the FEA studies identify the parameters and locations of the actuators. The FEA and CFD results show the thermal distribution achieved with respect to the requirement operations of bee incubation. A control unit governs all sensing and actuation processes, enabling high-precision maintenance of environmental parameters. Additionally, Internet of Things (IoT) technology is integrated, so the beekeepers can monitor and control the proposed incubator through a mobile application and Wi-Fi connectivity. The IoT system enables the beekeepers to stream and access the collected data, which enhances apiculture and queen bee rearing process. The proposed incubator is tested using queen cells, the experimental results shows that the smart electromechanical system successfully maintains the temperature and humidity within error of <1%, where the actuators operate at 56.5 % of the system operation. The experimental test and verification demonstrate larval survival and the effectiveness in maintaining a controlled incubation environment.**

Keywords—Smart Incubator; Internet of Things; Queen Bee Rearing; Environmental Control; Finite Element Analysis

I. INTRODUCTION

The productivity and survival rate of honey bee (*Apis mellifera L.*) colonies largely depend on the successful development and performance of the queen bee, which is the only reproductive female and the main regulator of colony cohesion. Consequently, successful queen rearing has a direct influence on hive productivity, colony health, and genetic quality. As global apiculture increasingly faces challenges such as climate variability, pests, pathogens, and rising queen failure rates, controlled queen rearing has become essential for maintaining resilient colonies [1-2]. Traditionally, queen bee development relies on colony-based incubation, where nurse bees regulate temperature and humidity with remarkable biological precision. However, the bee incubation process is highly sensitive to external environmental fluctuations and colony strength, which can result in inconsistent queen quality and limited scalability for commercial breeders [3-4]. The success of queen pupal development is strongly dependent on maintaining a precise and stable environment/microclimate. Several studies have demonstrated that brood development requires temperatures narrowly maintained between approximately 34 °C and 35 °C, with fluctuations not exceeding ±1 °C, as deviations can affect emergence rate, adult morphology, and reproductive performance [5-6]. In addition to the temperature requirements, appropriate relative humidity (RH), typically between 50% and 75%, is required to prevent desiccation or excessive moisture accumulation within sealed queen cells [7-8]. In natural colonies, honey bees employ behavioral mechanisms such as fanning, evaporative cooling, clustering, and controlled ventilation to maintain a stable brood-nest microclimate, even under extreme external conditions [9-10]. Replicating these conditions artificially in a consistent and reliable manner remains challenging but is critical for successful queen rearing. Due to increasing commercial demand, modern queen bee incubators have been developed to overcome the limitations of natural incubation by providing controlled temperature, humidity, and airflow. Commercial and research-grade incubators have demonstrated improvements in queen emergence consistency and physiological quality, particularly in large-scale queen production systems [4, 11]. Nevertheless, many

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existing incubators still rely on simple on–off thermostatic control, lack adaptive environmental feedback, or exhibit slow responses to changes in ambient conditions, which may compromise environment stability [8]. Moreover, high energy consumption, limited airflow precision, and insufficient real-time monitoring further restrict the reliability and efficiency of current incubators [12-15]. To address these limitations, this work integrates smart electromechanical systems with real-time environmental sensing and adaptive control algorithms. Finite element analysis (FEA) and computational fluid dynamic (CFD) tools are used to study thermal distribution and airflow patterns within the incubator. The proposed system aims to replicate natural brood conditions with high precision while maintaining low power consumption and improved operational efficiency. A key advancement of this design is the integration of Internet of Things (IoT) technology, enabling continuous remote monitoring, automated data logging, and early detection of environmental deviations that may threaten queen viability. The real-time measurements of temperature gradients, RH, and airflow cycles are transmitted to a user dashboard, allowing beekeepers to supervise the incubator remotely. Fig. 1 presents an overview of the proposed smart electromechanical bee incubator system that contains control unit, sensors, actuators, user interface, and mobile application. The control unit acquires sensing data and control the actuators to meet the queen bee rearing environment. This includes monitoring and controlling the incubator remotely through the mobile application that is based on IoT technology.

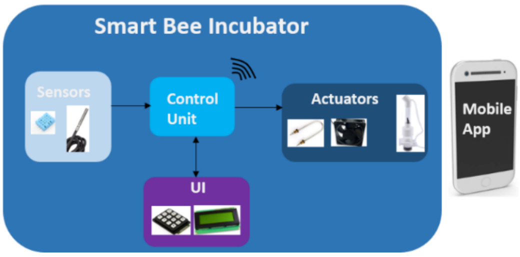


Fig. 1. System overview of smart bee incubator

This paper is organized as follows. Section I explains the goals and benefits of the smart queen bee incubator. Section II presents a comprehensive survey of existing incubator technologies in both academic research and industry, highlighting current capabilities and limitations. Section III introduces the proposed smart incubator architecture, detailing the system requirements, electronics, firmware, IoT integration, and the overall theory of operation. Section IV describes the mechanical design and FEA of the incubator, including thermal and airflow simulations under various operating conditions. Section V outlines the physical implementation, material selection, subsystem placement, and experimental evaluation of the incubator. Finally, Section VI concludes the paper by summarizing the system's performance and discussing potential future enhancements.

II. LITERATURE SURVEY

This section presents an expanded survey of the literature on temperature and humidity regulation for honey bee (*Apis mellifera*) brood and queen development, with a focus on incubator-based systems and the biological constraints that inform their design. The reviewed studies provide important insights for optimizing environmental control in artificial bee incubators and highlight the sensitivity of honey bee brood to small deviations from optimal microclimate conditions. Kaftanoglu *et al.*, developed and tested controlled in vitro rearing protocols by analyzing larval survival and development under fixed temperature and humidity conditions. Maintaining brood at 34 °C and 90% RH enabled successful progression from larval to adult stages. Inadequate humidity caused rapid thickening of royal jelly, preventing larval feeding and leading to starvation. Larvae reared without appropriate environmental control failed to complete metamorphosis, highlighting the necessity of high humidity and stable temperature during early developmental stages [14]. A comprehensive review of environmental effects was conducted on bee behavior and brood development, emphasizing the importance of thermoregulation in functional colonies. The authors reported that brood temperatures should be maintained within a narrow range of 33–36 °C and egg hatching is optimized at 90–95% RH. This was achieved through behavioral mechanisms such as wing fanning, clustering, water collection, and evaporative cooling. Hatching failure occurred below 50% RH and short-term temperature disruptions were shown to negatively affect growth rate, wing development, and adult survival [8]. Ex situ queen rearing was investigated under artificially controlled temperature and humidity conditions. At 35–36 °C and 75% RH, a dry film formed on the larval diet, limiting ingestion and significantly reducing survival. Increasing RH to 85% improved larval development, with 20–25% successfully emerging as mature queens. These findings demonstrated that humidity was a dominant limiting factor in artificial rearing environments. Unlike natural colonies, incubators lack nurse bees to replenish royal jelly, requiring higher RH levels to prevent diet desiccation [15]. Sealed queen cells (transferred directly into incubators) were evaluated and compared with colony-based controls. Operating the incubator at 33 °C and 70% RH resulted in wax accumulation over the queen emergence slot due to the absence of natural grooming behavior, necessitating manual removal. However, the study demonstrated that incubator-based rearing enabled the simultaneous production of multiple queen batches, effectively doubling production capacity compared with traditional hive-based methods [16]. The influence of stable incubator conditions was assessed on queen weight that is strongly correlated with reproductive success and colony performance. Queens reared in incubators at 34.7 °C and 80% RH exhibited higher emergence weights than those reared in queen-right or queen-less colonies, indicating superior physiological quality under controlled environmental conditions [13]. The effects of rapid heat hardening during the larval stage was investigated on queen progeny. Controlled pre-exposure to elevated temperatures enhanced antioxidant gene expression in worker offspring, improving thermotolerance during subsequent heat stress. These findings demonstrated that even minor variations in developmental temperature can induce long-term physiological changes, reinforcing the importance of strict thermal stability in incubator design [17].

Collectively, the literature indicates that honey bee brood development requires highly stable thermal conditions, typically around 34–35 °C, and consistently high RH, particularly above 85% during larval stages. Deviations from these conditions can result in reduced survival, impaired morphology, or increased manual intervention. These findings highlight the need for an automated incubator system capable of replicating natural hive microclimates, maintaining high humidity, preventing larval diet dehydration, and ensuring uniform heat distribution. This paper presents the design and development of a smart electromechanical bee incubator that addresses the limitations of existing systems through integrated electronic, mechanical, and control solutions, as described in the following sections.

III. SYSTEM ARCHITECTURE OF SMART INCUBATOR

This section outlines the design and development of the smart queen bee incubator system, highlighting the smart electromechanical design. The primary objective is to achieve precise and adaptable control of temperature, humidity, and ventilation to ensure an optimal incubation climate. The incubator is required to maintain a temperature of 34–35 °C and consistently high humidity, particularly above 85% RH. This is accomplished through achieving air circulation while keeping airflow gentle and heat distribution uniformly. The electromechanical system architecture integrates several subsystems, including temperature regulation, humidity control, ventilation management, sensing and feedback, airflow handling, and a user interface (UI) linked to the IoT platform. The architecture is developed with modularity, energy efficiency, and biological compatibility in mind. The control system contains an ESP32 microcontroller (MCU) and interface circuits, which achieves closed-loop control systems for the temperature and humidity. The ESP32 MCU collects real-time environmental data, processes sensor feedback, and adjusts actuators to maintain the required conditions. The electronic circuits consist of subsystems based on their functions, which are control, sensing, interface, and actuator circuits. The sensing circuit contains the environmental sensors and their power circuitry, while the actuator circuit interfaces with the heater, humidifier, fan, pumps, and UV (ultra violet) disinfection components. The interface circuit is based on a customized transistor drive circuit, which isolates the low-voltage and control signals from the actuator components and ensures proper power delivery. The electronic circuits operate on a 12 V_{DC} supply that is regulated to provide the required 5 V and 3.3 V rails for logic circuits and peripheral devices. Environmental monitoring is achieved using a high-accuracy temperature and humidity sensor, which supplies continuous data to the controller. The ESP32 MCU executes the control algorithms automatically and also supports manual adjustments through the UI. The ESP32 MCU is selected for its dual-core architecture, built-in communication capabilities, and flexible I/O support, allowing it to multitask efficiently within a compact system. Temperature regulation uses two heaters driven through power transistors and controlled based on feedback from the temperature sensor. The control algorithm compares the measured temperature to the target range and activates the heaters adaptively to minimize overshoot and energy consumption. Humidity is maintained using an ultrasonic humidifier module controlled by the MCU, ensuring that the humidity setpoint is achieved. The firmware (FW) is structured in a modular format, with dedicated functions for sensing, control logic, actuator management, and communication. This approach improves readability, maintainability, and scalability. The settings of the incubator are configured through either offline or online schemes. The UI operates on two levels that are local LCD in the device and the mobile application. The local interface uses an LCD and keypad for configuration and offline control, while a cloud-based monitoring interface displays real-time system data through a mobile application. The LCD displays the settings and parameters of the incubator and communicates with the MCU via the I^2C protocol, while the user interaction is provided through the keypad interface. In addition to the LCD, a visual indicator based on LEDs is included for operational status, along with a tactile reset switch for system re-initialization. Core control functions remain local for safety, while remote monitoring enhances accessibility.

The FW leverages a modular approach with separate libraries for each subsystem. This design facilitates maintainability, code reuse, and scalability for enhancement performance. The main modular components of the FW are fan manager, humidification system, air ventilation system, temperature control system, display & door drivers, EEPROM driver, Wi-Fi manager and firebase manager, which are called through API commands. The fan manager controls one or more exhaust fans with safe, non-blocking timing. It prevents conflicts with other subsystems, supports duty-cycle scheduling, and includes failsafe stop conditions on abnormal sensor/thermal states. The humidification system enables the humidifier when the RH drops below the target and runs a short, configurable fan overrun to distribute moisture evenly. It uses a hysteresis control scheme to reduce chattering. The air ventilation system schedules full-volume air exchanges per day using incubator volume and pump/fan capacities. Maintains fresh air intake and removes excess CO_2 without disturbing thermal stability. The temperature control system reads SHT31 (and related) sensors at fixed intervals and actuates heaters to track the temperature setpoint. It implements basic feedback control and sanity checks for stuck or drifting sensors. The Display & Door Drivers include the drivers of the I^2C LCD plus keypad and sensors of the door. The display and keypad are for local UI, which present password gate, status pages, setpoint edits. The Door sensor triggers status/alerts and can pause risky actions while open. The EEPROM driver persists configuration (temp/humidity setpoints, ventilation cycles, password, flags) so the device recovers cleanly after power loss or updates. The Wi-Fi Manager & Firebase Manager include AP (access point) and STA (station mode) provisioning for Wi-Fi credentials and robust reconnect logic. It considers a real-time telemetry and config sync with Firebase Realtime Database. The system follows an event-driven architecture where the main loop monitors sensor inputs and triggers subsystem actions, as shown in Fig. 2. Each module exposes well-defined interfaces to the main application, minimizing interdependencies. The FW employs a state-machine-based approach to manage incubator operation modes, whereas the states include idle, humidifying, ventilation, and alert that are configured in cases of the FEA studies as well, as described in Section IV. Timers and thresholds govern transitions between the states, where the flowchart of the proposed incubator is illustrated in Fig. 3. Critical operations such as humidifier activation and ventilation are scheduled using non-blocking delays (milliseconds-based timers). This ensures concurrent handling of multiple tasks without interrupt conflicts. Sensor readings are updated at fixed intervals to maintain consistent feedback control. FreeRTOS Tasking includes two cooperative tasks provide deterministic real-time behavior, which are display task (priority 1.50 milliseconds delay) refreshes LCD and reads keypad, and system update task (priority 2.50 milliseconds delay) handles sensor sampling, actuator control, and cloud sync. This separation keeps the UI responsive while maintaining reliable control loops. The pin assignments are centralized in the "app_config.h" for portability. This allows easy reconfiguration for different hardware revisions without modifying core logic. The FW includes safety checks such as watchdog monitoring, error handling for sensor read failures, and failsafe shutdowns for actuators when thresholds are exceeded, which guarantees the robustness of the operation of the incubator.

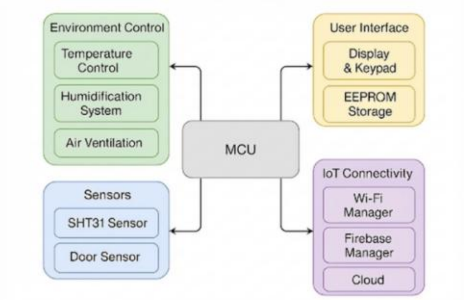


Fig. 2. System architecture of the FW & IoT of the incubator.

The IoT system connects the incubator to a cloud backend through Wi-Fi protocol, so the users can control and acquire the parameters of the incubator remotely. The system employs Firebase real-time database for data logging and remote configuration. Each sensor reading is timestamped and pushed to the cloud, allowing historical analysis and visualization. The communication follows a request-response model for configuration updates and a push model for sensor telemetry. JSON payloads are transmitted via HTTP or MQTT depending on network conditions, as shown in Fig. 4. The mobile app-based dashboard is developed using Flutter, which provides real-time monitoring of temperature, humidity, and ventilation cycles. Alerts are displayed when parameters exceed safe ranges, whereas this interface supports remote parameter tuning, enabling adaptive control. In the AP mode, the ESP32 MCU creates its own Wi-Fi hotspot, allowing a phone or laptop to connect directly without needing a router. This mode is typically used for initial configuration, where the user opens the mobile app to enter the local Wi-Fi credentials.

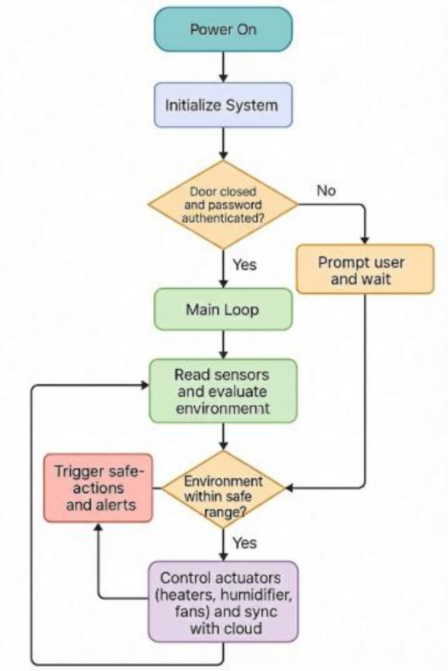


Fig. 3. Flowchart of smart bee incubator.

Once the credentials are saved, the ESP32 MCU can switch to the STA mode and connect to the configured network automatically. Fig. 5(a) shows the UI for the user when the Wi-Fi network is configured, the beekeepers can monitor and control the temperature and humidity measurements through the app, as illustrated in Fig. 6(b). All communication is secured with API keys and encrypted channels (HTTPS). Reconnect logic ensures the device automatically resumes operation after temporary Wi-Fi outage, which are device power state, ventilation cycles, humidity and temperature setpoints, where the device power state turns the device on or off remotely. The humidity and temperature setpoints define the target humidity level and desired operating temperature, respectively. The mobile app notifies the beekeepers of the status of the door or the Wi-Fi connection through activating the icons and displaying message over the mobile app. The control features are Wi-Fi connectivity, ventilation & door status, and streaming temperature & humidity live, whereas the Wi-Fi connectivity status shows whether the ESP32 MCU is connected to the internet or not. The ventilation and door status illustrate whether the ventilation system is currently running and the device door is open or closed, respectively. Built-in AP provisioning allows sending SSID and password from the app to the ESP MCU, so it joins the specified Wi-Fi network without manual serial configuration, as illustrated in Fig. 5(b). Combining remote control, real-time monitoring, and easy Wi-Fi setup makes the app a practical and user-friendly tool for managing the device. It enables flexibility, situational awareness, and reliable connectivity.

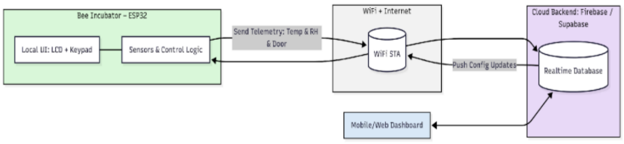
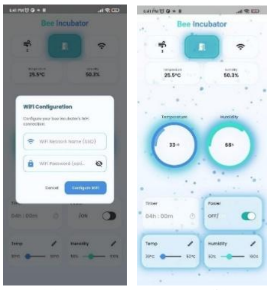


Fig. 4. Communication flow of proposed IoT system.

The incubator is mechanically organized into three vertically stacked chambers: the queen cell chamber, the mixing chamber, and the lower drawer. Each section performs a specific function within the environmental control process. The queen cell chamber is the primary incubation zone and is designed with very low airflow to prevent mechanical stress on larvae. The mixing chamber contains the main circulation fan, which gently mixes warm, moist air before it rises into the cell chamber. The lower drawer holds the humidification system, water reservoir, and optional storage space. This geometry creates a pressure buffer at the upper chamber, keeping airflow slow around the queen cells while enabling overall thermal mixing. Some airflow recirculates toward the heaters to dissipate excess heat before rising again, promoting gradual thermal uniformity. The heat redistributes passively within the sealed chamber, leading to natural equilibrium over time when the fan is off. The system is modeled and analyzed to study airflow and thermal distribution using FEA and CFD studies, as described in the following Section.



(a) (b)

Fig. 5. IoT UI; (a) AP configuration and (b) UI of mobile app.

IV. FEA AND CFD STUDIES

This section highlights the mechanical design aspect of the incubator, including FEA and CFD studies. The queen bee incubator is designed to provide a controlled, biologically stable environment that ensures optimal conditions for larval development. The system's goal is to regulate critical environmental parameters, including a target temperature range of approximately 35°C to 39°C, a RH of about 65%, controlled ventilation, and an internal airflow velocity of roughly 0.2 m/s. The incubator can be divided into three vertically stacked chambers, each with a distinct function. First, the main section of the incubator (upper section), is the queen cell chamber where the bees are residing. The lower section is the water and storage drawer and contains a humidification system, a water reservoir where a humidifier is mounted, and space for optional component storage. The mixing chamber, is separated from the queen cell chamber by a wooden divider, with four well-placed air circulation vents that work to diffuse the heat to the upper section. This middle section is equipped with two heaters placed diagonally from each other, and 40W axial fan operating at 2600 RPM is located at the center to draw in warm, moist air from the lower section, mixing it and then gently pushing it upward to the queen cell chamber. The humidifier is mounted in the middle of the divider between the mixing chamber and the drawer. The geometry of the system is specifically designed to create a pressure buffer at the queen cell chamber, where the air layer counteracts the upward flow generated by the fan. This configuration redirects a portion of the airflow back toward the heating zone, where excess heat is dissipated before recirculating. Consequently, the airflow velocity in the vicinity of the queen cell cages remains minimal, protecting the larvae from mechanical stress while maintaining overall thermal mixing. Although minor temperature variations may temporarily arise in these low-velocity regions, thermal uniformity is ultimately achieved through natural convection and molecular diffusion, consistent with the second law of thermodynamics and the ideal gas law. In the absence of active fan operation, the sealed environment facilitates passive heat redistribution, ensuring equilibrium throughout the incubation chamber. The goal is to study the system's behavior under several operating scenarios, starting with active heating with a circulation fan, then active heating with a circulation fan plus ventilation, circulation fan and finally shutdown mode. The transient FEA study is split into four different operating cases that are alternated in between for a specific time duration. The first case is active heating with circulation fan, whereas, both heaters, rated at 40W, are turned on and actively heat up the internal temperature to the optimal range. The circulation fan works at the same time to distribute the air uniformly throughout the queen cell chamber. Only internal airflow is considered in this scenario; it is created by the internal circulation fan, and the air pumps aren't activated. The second case is active heating, circulation fans, and air pump ventilation, where the heaters and the fan are operating at the same. The exhaust air pump is enabled, where it introduces external ventilation of fresh air, at a rate of 6 L/min, into the system to prevent carbon dioxide buildup. The third case is circulation fan, which is the same as the first case, but the heaters are turned off because the optimal temperature required should be achieved right before. The fourth case is shutdown mode that simulates the system after it has reached its optimal temperature, and then all its active components are turned off (being decelerated) to study how it will cool down over time with no heat addition or ventilation [17-19]. The According to the Ideal Gas Lap and the Second Law of thermodynamics, the heat will distribute uniformly over the incubator with time, as described in detail in this section. Steady and transient states are performed using ANSYS Meshing and Fluent. Table I illustrates the geometric details as well as the specs of the heater and fan and the number of iterations and time steps used by Fluent Ansys to calculate the results. The total time studied is 1140 seconds, divided into time intervals where the four cases are alternated, whereas Table II summarizes the time used for each case.

TABLE I. ANSYS SETUP

Parameter	Value
Initial Temperature	25
Number of Mesh Elements (in one quarter)	737,729
Time Step	0.33 seconds
Iterations per Time Step	15
Fan (one)	120 mm diameter, 8.5 m/s (max speed)
Heaters (two)	40W
Inlets (two)	15 mm diameter
Outlet (one)	15 mm diameter
Bee Cages	108 pcs in 3 rows (36 pcs/row)

As seen in Fig. 6, the velocity streamlines within the incubator under steady-state conditions. The left image presents a front view, while the right image shows a side view. Local velocity peaks reaching 5.692 m/s are observed at the four inlet openings, which is consistent with Bernoulli's principle and conservation of momentum, as the reduced cross-sectional area accelerates the flow. In the central region, where the fan is located, the flow is accelerated to almost 1.4 m/s, which produces a strong upward jet that drives the overall circulation. Downstream of the inlets and the fan, the flow expands and undergoes diffuser-like spreading, leading to a gradual reduction in velocity as it distributes within the chamber. In the queen cell section, where the airflow encounters the cages, the velocity levels fall within the expected operational range of optimal operation, which is around the value of 0.2 m/s. Fig. 7 is used in the following section for better understanding of the heat distribution behavior at different points of time.

TABLE II. USED CASES

Time (S)	Case
0 – 220	Case 1: Fan + Heater
220 - 340	Case 2: Fan + Heater + Ventilation
340 - 460	Case 3: Fan
460 - 580	Case 1: Fan + Heater
580 - 700	Case 3: Fan
770 - 765	Case 1: Fan + Heater
765 - 900	Case 4: Shut down mode
900 - 1020	Case 1: Fan + Heater
1020 - 1140	Case 3: Fan

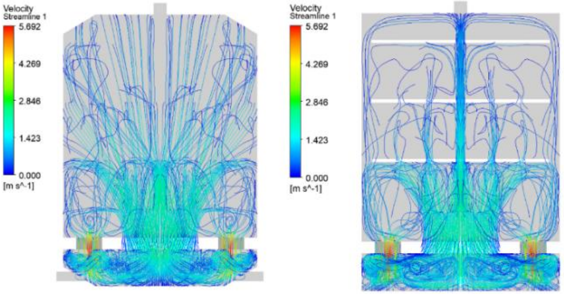


Fig. 6. Flow path and velocity inside the incubator.

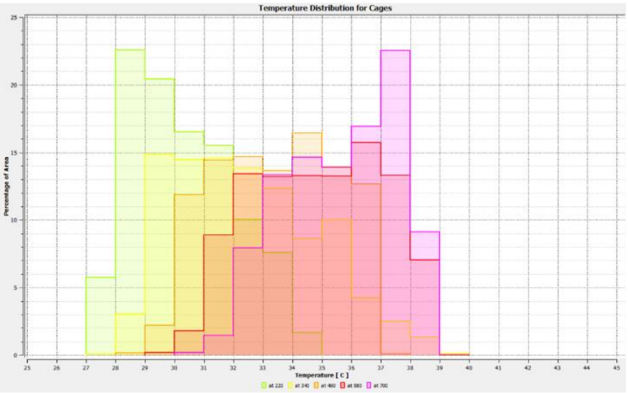


Fig. 7. Temperature distribution plot around the cages for different times

Fig. 8 shows the temperature distribution within the incubator at 220 seconds of operating the first case (only the heater and fan are on). It can be observed that the temperature around and inside the bee cages is ranging approximately between 27°C and 35°C. The results indicate that while localized heating occurs near the bottom region close to the heater, the desired optimal temperature of 35°C has been reached by only 2% of the bee cages area, while almost 22.8% of the area is between 28°C and 29°C. It is noticed that the upper layers of the bee cages remain almost 8°C cooler compared to the lower regions, showing that the temperature distribution has not yet reached uniformity and has not fully developed at this stage.

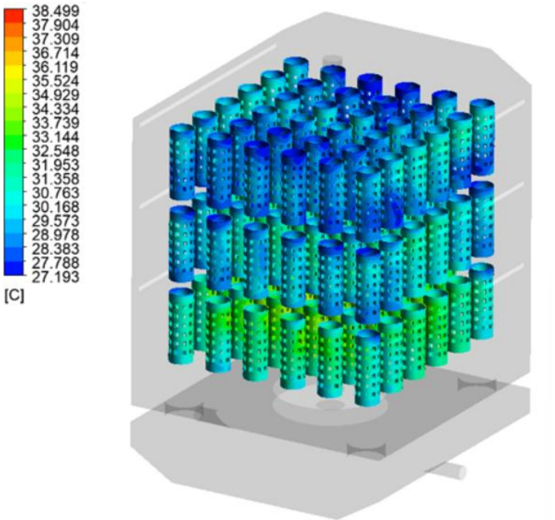


Fig. 8. Cage temperature at 220 seconds of operating first case.

Fig. 9 showcases the temperature distribution within the incubator at time 340 seconds, when the incubator has been running for 120 seconds under operating of the second case. The color scale shows that the temperature around the cages mostly ranges from approximately 28°C to 39°C, with most of the area being around to 34°C and only approximately 1.2% between 38°C and 39°C. Compared to the distribution at 220 seconds, the overall temperature has increased; however, the heat distribution remains uneven, with a temperature difference of nearly 11°C between the top and bottom shelves. Despite this non-uniformity in the heat distribution, the bee cages located in the middle of the top shelf have reached the required operational temperature range between 35°C and 39°C, indicating that localized regions of the incubator are achieving suitable conditions which is an obvious improvement, while others remain below the target. Fig. 10 illustrates the temperature distribution at 460 seconds of the third case, where the first row bee cages (at the bottom) and middle row reach to the required temperature of 35°C and 37°C. Fig. 11 illustrates the temperature distribution within the incubator at time 580 seconds, after the system has been running for 240 seconds at operating the third case, where only the fan is turned on and all the other components are deactivated, to allow the system time to cool down. From the color scale, the temperature around the cages is shown to range from approximately 29°C to 38°C, with most of the area ranging between 30°C to 37°C. The heat distribution is highly uneven, with a significant thermal gradient and a temperature difference of over 9°C between the warmest (middle lower shelve) and coolest regions (middle top shelve). Despite the difference in temperature, more cages, mainly in the lowest shelf and some regions in the middle shelf have reached the required operational temperature range between 35°C and 38°C, indicating that localized regions of the incubator are achieving suitable conditions. However, the majority of the recorded areas remain below the target range.

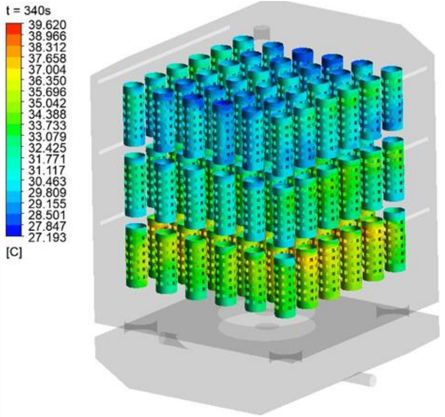


Fig. 9. Cage temperature at 340 seconds of operating second case

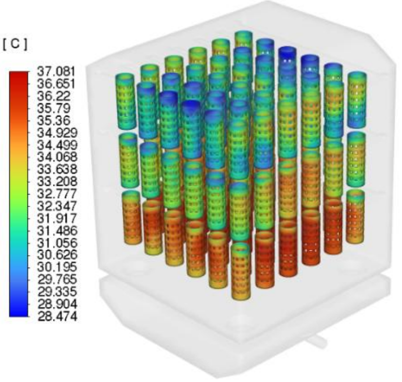


Fig. 10. Cage temperature at 460 seconds of operating third case

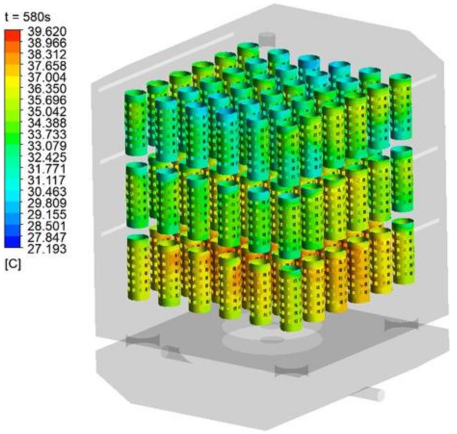


Fig. 11. Cage temperature at 580 seconds of operating first case.

The thermal distribution at 700 seconds represents a critical point of analysis, indicating a system approaching a more stable operational state after operating once again in the first case, as illustrated in Fig. 6. Fig. 12 reveals a temperature range from 31°C to 39°C, which is a total temperature differential of 7°C. While the difference still remains bigger than desired, the 700 second profile demonstrates improved thermal stability, where the heat seems to now be distributed in a more uniform and stable manner when compared to earlier temperature data, this is proven using Fig. 13 (operating first case), where almost 62% of the total area of the cages is within the 35°C to 39°C operating range. This evolution strongly indicates that the system's thermal mass has become fully saturated, and convective and conductive heat transfer processes have reached an equilibrium. The consistent repetition of the operational cycle has effectively reduced thermal "hot spots" and minimized temperature differences, leading to a smoother heat distribution throughout the incubator chamber. This suggests that repeat of operating the third case and then the first case again would further optimize the heat distribution, which should be deployed in the control system (embedded system), as shown in Section V. The described sequence cases in Table II are investigated accordingly, the fourth case (shutdown mode) and first case at 1020 seconds are illustrated in Fig. 14-15, respectively. The third case operates over 120 seconds from the 1020 seconds to the 1140 seconds, whereas the thermal stability is achieved inside the incubator, as illustrated in Fig. 16 (operating at 1140 seconds). This described (Table II) sequences is repeated to achieve the required thermal distribution with respect to the sensor readings and the status of the actuators (fan & heaters).

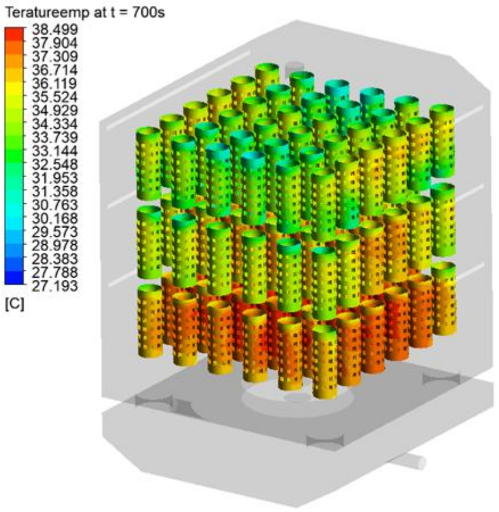


Fig. 12. Cage temperature at 700 seconds of operating third case.

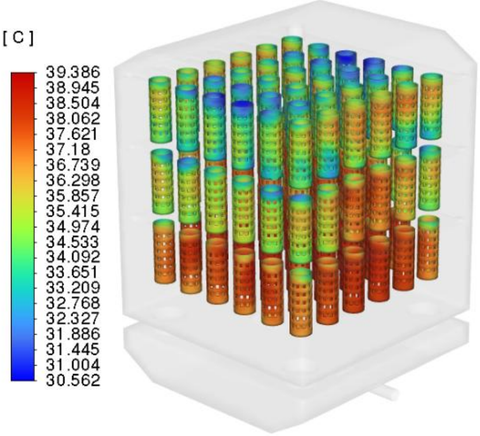


Fig. 13. Cage temperature at 765 seconds of operating first case.

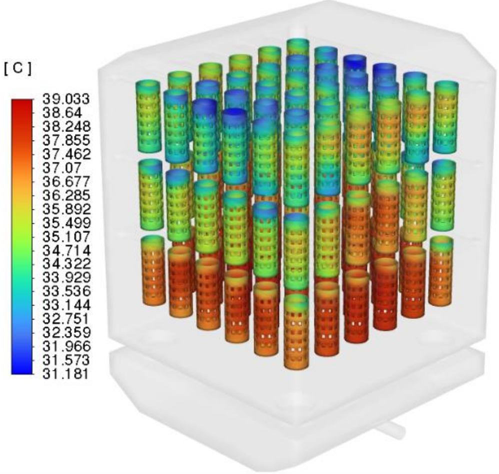


Fig. 14. Cage temperature at 900 seconds of operating fourth case.

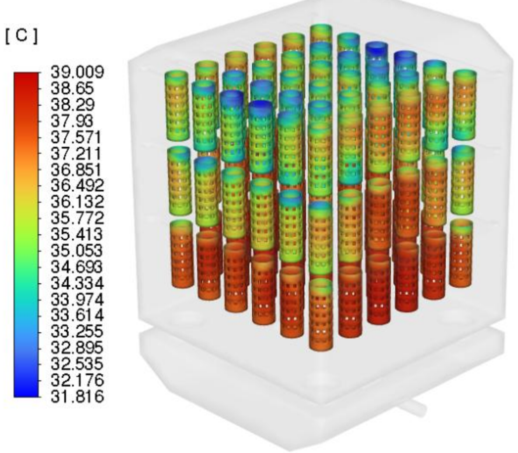


Fig. 15. Cage temperature at time 1020 seconds of operating first case.

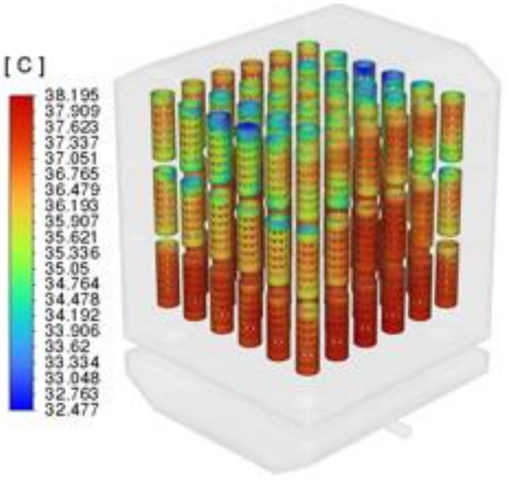


Fig. 16. Cage temperature at 1140 seconds of operating third case.

V. SYSTEM SETUP AND ANALYSIS

This section describes the manufactured smart bee incubator, including experimental setup and testing. The queen bee incubator is engineered to maintain a controlled and biologically stable environment that supports optimal conditions for larval development. The key environmental parameters regulated within the system include a target temperature of approximately 37 °C, relative humidity around 65%, controlled ventilation, and an internal airflow velocity of approximately 0.2 m/s. Fig. 17 illustrates the manufactured smart electromechanical system, highlighting the electronic circuit, actuators, bee cages, and sensors. The incubator is constructed from high-density polywood, coated with high-pressure laminate for its resistance to heat, humidity, and chemical degradation while remaining non-toxic. All internal gaps are sealed using thermal-grade silicone, while the incubator door is sealed with a thermal-grade rubber gasket, ensuring airtight insulation. The incubator is decomposed into three vertically stacked chambers that are queen cell chamber, mixing chamber, and drawer, as shown in Fig. 17. Each chamber serves a distinct function, the queen cell chamber (upper section) is the primary incubation area where the queen cells are placed, where the airflow velocity is too low, as illustrated in Fig. 6. This is due to the air resistance in the upper section, to protect the larvae from stress. The mixing chamber (middle section) is a very small chamber located directly below the cell chamber and separated by a wooden divider with strategically placed four air circulation vents that contribute to dissipating the heater's temperature. This chamber includes the 220V 40W 2600 RPM axial fan at its center, whereas the fan draws in warm, moist air from the lower section and mixes it before gently pushing it upward into the cell chamber. The humidifier is mounted in the middle of the divider between the mixing chamber and the drawer. The water and storage drawer (lower section) is the bottom compartment containing a humidification system, a water reservoir where the humidifier is mounted on. This geometry is designed to create a pressure buffer at the queen cell chamber, where the air layer resists the upward push from the fan's flow. The control unit acquires the sensing data at 1.5 milliseconds sampling to control the actuators (the heaters and fan) to guarantee the required environment and avoid any interrupted external heat or humidity. The control algorithm in the ESP MCU keeps measuring the temperature and humidity continuously to ensure the stable environment for queen pupal development. This electromechanical design feature causes a portion of the airflow to be redirected back toward the heater area, where it dissipates excess heat before recirculating again. The control system eliminates the incubation process and sends notifications to beekeepers if there are any excessive/high temperature or humidity measurements, to protect honey bee (Apis mellifera L.) colonies. As a result, airflow velocity in the region surrounding the queen cell cages remains minimal, protecting the larvae from mechanical stress while still promoting overall thermal mixing. Although slight temperature variation may temporarily occur due to the low-velocity zones, the incubator achieves thermal uniformity over time through natural convection and molecular diffusion, based on the second law of thermodynamics and the ideal gas law. When the fan is deactivated, the sealed environment promotes passive heat redistribution, which ensures thermal equilibrium across the incubation chamber.

The baseline operation represents the reference condition of the bee incubator under standard control settings and without any experimental modifications. The smart bee incubator is operated over days and hours to verify and validate the requirements operation. Fig. 18 shows the temperature and humidity profiles over 522 minutes. During this operation, the controller temperature set-point is maintained at approximately 37 °C, as shown in Fig. 18(a). The humidity set-point is set to approximately 79 % RH. At the start of the baseline period, the incubator exhibited a clear warm-up transient. The internal temperature increased rapidly from approximately 26 °C to the target set-point, after which it stabilized. Concurrently, relative humidity decreased from an initial value of approximately 92 % RH to the target level near 79 % RH, as illustrated in Fig. 18(c). Following this transient phase, the system reached steady-state operation with stable environmental conditions.

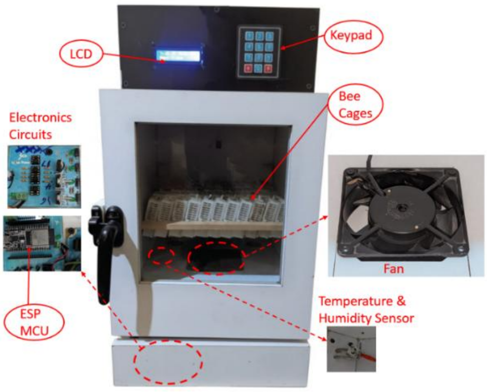
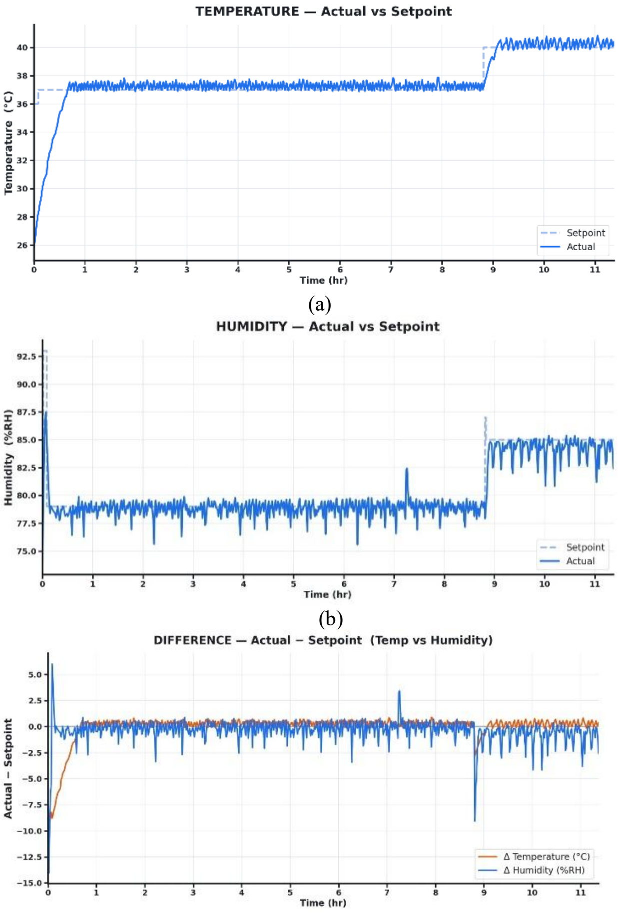


Fig. 17. Smart bee incubator build.



(a)

(b)

(c)

Fig. 18. Temperature and humidity profiles; (a) temperature, (b) humidity, and (c) difference between actual and setpoint.

Once equilibrium is achieved, temperature regulation is highly stable. The mean measured temperature during the baseline period is 36.90 °C, compared to a mean set-point of 37 °C, yielding a mean temperature deviation of −0.09 °C. The median temperature difference is approximately +0.24 °C, indicating minimal fluctuation around the target value. Humidity control exhibited similarly stable behavior, with a mean measured RH of 78.87 % against a mean set-point of 79.11 % RH, corresponding to a mean deviation of −0.24 % RH. The distribution of temperature values during normal operation is narrow and centered around 37.2 °C once steady-state conditions were reached, with a low-temperature tail attributable to the initial warm-up phase.

RH values also showed a tight distribution centered near 79 % RH, indicating low variability and consistent environmental control. Actuator activity during the baseline case reflected efficient closed-loop regulation. The circulation fan and heater are active for 56.5 % and 52.7 % of the operation time, respectively, operating in short duty cycles to maintain thermal stability. The humidifier is active for 21.3 % of the time, sufficient to sustain the humidity set-point without excessive operation. Ventilation events are infrequent, occurring only 3.1 % of the time, typically as short periodic pulses. Overall, the baseline operation demonstrates stable and effective environmental regulation under standard conditions. Following the initial warm-up transient, the incubator manages the temperature and humidity within a narrow margin of the set-points using moderate actuator duty cycles. This operating regime serves as a reliable reference case for evaluating system performance under thermal and humidity conditions in subsequent experimental scenarios.

VI. CONCLUSION AND FUTURE WORKS

This paper presented the design and development of a low-cost smart incubator for rearing bee queens through an integrated hardware–software architecture. The system incorporated an ESP32-based modular control framework that managed temperature regulation, humidity control, ventilation cycles, door-state monitoring, local user interfacing, and cloud synchronization. Sensors, actuators, and the FW modules operated cohesively to maintain the environmental conditions required for optimal queen development while enabling data logging and remote monitoring. Steady and transient CFD and FEA simulations were conducted using ANSYS software tool, which provided detailed insights into airflow circulation and thermal distribution within the chamber. The simulation results confirmed that the fan–inlet configuration generated stable mixing with low velocities around the queen cells, while the alternating heating and mixing cycles effectively reduce temperature gradients. The progressive stabilization observed in simulation validated both the mechanical design and the control strategy used in the incubator. Experimental setup further demonstrated that the system consistently maintained temperature and humidity within biologically suitable ranges, where the median temperature and RH difference are approximately +0.24 °C and −0.24 %, respectively. The performance of the incubator indicates minimal fluctuation around the target value, which confirms its reliability, energy efficiency, and suitability for small-scale or research apiculture environments.

Future enhancements can further improve the system's performance, adaptability, and biological relevance. Implementing machine-learning or model-predictive control algorithms may optimize heater, fan, and humidifier duty cycles, reduce settling time, minimize overshoot, and adapt to dynamic environmental or loading conditions. Adding multi-point temperature arrays, CO_2 sensors, or airflow measurements and applying AI-based anomaly detection could enable early detection of system failures such as fan degradation, heater malfunction, or abnormal thermal patterns.

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