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Advancements and Innovations in Thermodynamics for Infant Incubators: A Review

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ABSTRACT

An infant incubator, a critical piece of biomedical equipment, provides a regulated environment tailored to a newborn's needs, including temperature, humidity, and oxygen levels. This controlled environment ensures fresh air, cleanliness, and sanitary conditions for newborns. Moreover, the incubator maintains a consistent temperature, relative humidity (RH), and oxygen gas concentration, all crucial for early newborn care. Given the shared constraints with other medical devices, it is essential to employ the most effective methods to measure and improve humidity in these vital devices. This study offers a comprehensive overview of recent advances in infant incubator research, with a particular focus on experimental and numerical studies related to energy storage. An in-depth evaluation of design enhancements in infant incubators, particularly those employing phase change materials (PCMs) for thermal energy storage, is presented. The review highlights the ability of PCMs to maintain a temperature exceeding 32℃ for over 8 hours in neonatal incubators, underscoring their significance. Furthermore, the review explores the latest design advancements in high-temperature neonatal incubators, including an audible temperature alarm circuit that alerts healthcare professionals when temperatures exceed a predefined acceptable range of 26 to 38℃, thereby ensuring infant safety. The study concludes with recommendations for future research, derived from the insights gained from existing studies.

1. INTRODUCTION

For nearly 160 years, incubators have been instrumental in cultivating a beneficial hydrothermal environment for newborn infants, particularly those born prematurely, underweight, or with pre-existing health conditions [1-3]. The concept and functionality of these devices have evolved over time, with a consistent emphasis on maintaining humidity and temperature within medically recommended optimal ranges [4-6].

Despite possessing the same homoeothermic capabilities as an adult, a newborn's range of ambient temperatures for functioning effectively remains relatively narrow. Several inherent limitations contribute to a newborn's heightened vulnerability to thermal stress. These include a significant surface area in relation to their mass, insufficient thermal insulation, and limited heat sink capacity. Furthermore, a newborn's capacity to preserve heat by changing position is minimal, and their ability to adjust clothing as a response to thermal stress is non-existent [7]. Adverse conditions such as disease or hypoxia (below normal levels of oxygen) may further compromise their thermal responses [8]. Research has highlighted the critical role of an optimal temperature environment in reducing morbidity and mortality rates among preterm newborns. Studies have shown that when newborn care is administered in incubators with carefully regulated temperature and airflow, mortality rates can decrease by at least 22% [9].

An infant incubator serves as a temporary dwelling for preterm infants, offering adjustable temperature settings to cater to the specific needs of the child. Traditionally, these devices depend on an external electrical energy source for operation. With a standard operating temperature set at an average of 37℃ [10], equivalent to a newborn's body temperature post-delivery, the reliability of the incubator becomes compromised in regions with unstable electrical supply.

Alternative energy sources have been explored to mitigate this challenge, with phase change materials (PCMs) emerging as a promising solution [11]. PCMs store energy through a material phase shift, releasing it as latent heat [12]. They offer substantial heat storage per unit volume, and the heat extraction occurs at a uniform temperature. Functionally, latent heat outperforms sensible heat due to its lower temperature fluctuation, smaller size, and reduced weight per unit capacity [13]. However, a key drawback of PCMs is their poor thermal conductivity, resulting in a swift heat absorption process and limited heat release [14].

Extensive research has been conducted on the application of PCMs in water heaters and infant incubators. A notable study by Mettawee and Assassa [15] presented the development of an infant incubator powered by an electric motor, utilizing organic PCM and lithium batteries. Independent of the local electricity supply, this incubator effectively functioned using a microcontroller and temperature sensor for monitoring operations.

To the authors' knowledge, a comprehensive examination of the state-of-the-art technology in infant incubators is of paramount importance. It symbolizes not only the pinnacle of medical innovation but also our commitment to ensuring the safety, health, and comprehensive development of vulnerable infants. Therefore, the primary objective of this study is to investigate advancements in the design of non-electrical incubators for newborns. This involves detailing the design specifications and reviewing seminal studies on the topic. Such an approach will facilitate an in-depth analysis of the progress made in the design of infant incubators that utilize phase change thermal energy storage, and an evaluation of their thermal insulation capabilities.

2. DESIGN OF NON ELECTRIC INCUBATOR

Temperature and humidity are two extremely critical characteristics that need to be maintained and supervised continually in the infant incubator chamber. This is done in order to provide an environment for pre-term infants or newborn babies that is comparable to their mother's womb. Because of the high rate of heat loss and immature or nonexistent thermoregulatory systems, the preterm newborn is more susceptible to hypothermia [16]. Even with today's sophisticated systems for controlling temperature, the increased metabolic demands that are brought on by thermal stress might result in a lack of energy that is left over for healthy development. The body works hard to keep its core temperature at a consistent level while staying within certain parameters. In order to do this, there has to be a harmony between the generation of heat and the transfer of heat into and out of the environment. This interaction with the surrounding environment may take place by a combination of conduction, convection, radiation, and evaporation. The significance of high-humidity to avoid evaporative heat losses and, as a result, maintain the required body temperature of infants is discussed by Shin et al. [17]. The impact of these four modes will vary based on factors such as gestation, postnatal age, and environmental conditions like temperature and humidity.

Lokuge et al. [18] demonstrated the full design of low cost incubator that run independent of electricity. To fulfill its function as an incubator for infants, the device's design must meet the following standards:

- A heat source and a heat sink in order to keep the room temperature in the range of 34℃ to 37℃ for as long as feasible, preferably for 24 hours, with little temperature monitoring required.
- A relative humidity that is more than 70 percent RH. High humidity levels in incubators aid in preventing dehydration, maintaining the moisture content of the baby's skin, and fostering healthy growth of the lungs. Early children, in particular, have sensitive skin and developing lungs, making them particularly prone to dehydration and respiratory problems. Therefore, it is essential to keep the environment humid for their wellbeing and general health [19].
- An efficient mechanism for cleaning the air that will provide the child with the necessary amount of oxygen circulation. Air purification lowers the risk of infection by assisting in the removal of airborne germs. Infants born early have weakened immune systems, making infections a serious threat to them [20]. The danger is reduced by an environment with clean air, which aids in faster healing.
- A powerful air filtration system that can eliminate germs and other airborne particle matter from the environment.
- A straightforward design for the incubator that allows for uncomplicated removal of the baby should it become necessary.

The design specifications of the incubator presented by Lokuge et al. [18] are identified in the following.

The incubators id designed as a small tent-like incubator. The tent is easy to clean, carry, and recreate with its basic design. Lowest-material dome tent with square base and self-tensioning. A nurse or doctor may fit within the 15" square base, which can hold a 1.2-kilogram baby. One sewed piece of cloth contains two semicircular arcs of spring steel, aluminum, hot-pulled carbon fiber, or pre-tensed wooden dowels. Fabric pockets at the four corners secure the arcs. Low-radiative, convective, and conductive heat insulation blanket. Urban building projects commonly use mylar-coated spun cotton or fiberglass insulation blankets.

The tent has a double-insulated floor. This will allow the phase change heated mattress to slip in. The mattress and dome panels are connected by a tight mesh to filter airborne particulate matter and microorganisms. The filter and air supply are driven by the difference in hot air density at the bottom and top (like a fireplace), with an exit hole at the dome's top. Four primary pathways allow preterm babies to exchange heat with their environment: (1) convection, (2) conduction, (3) radiation, (4) evaporation. Heat transmission between the infant and the atmosphere is convection. Contact between objects causes heat transmission, which is conduction. Conduction heats the infant on the PCM mattress. Radiative exchanges occur when a subject emits or receives energy at a fixed temperature. Evaporative heat losses occur when water evaporates through a preterm infant's thin skin. To avoid infection, preterm babies should be maintained in sterile environments due to their immature immune systems. Air filtration prevents most germs and other airborne pollutants from entering the incubator. Physician surgical masks made of non-woven, spun bond polypropylene are being investigated.

This choice is light, hypo-allergic, and has 0.5micron filtering effectiveness over 95%, whereas microorganisms average 1-2 microns.

3. IMPROVEMENT DETAILS OF INFANT INCUBATOR

Incubators for newborn babies have been the subject of intensive research and development efforts by scientists for a very long time. In recent years, a great number of new designs for infant incubators have been developed [21], including the Grashof, the open-box, the closed-box, the double-wall, the servo-control, and the transport incubator. The following demonstrates a number of successful studies that present innovative designs of phase change thermal energy storage infant incubator.

In 2002, Kim et al. [22] used computational fluid dynamics (CFD), hot-wire velocity measurements, and flow visualizations to mimic the airflow within a newborn incubator. A three-dimensional laser scanning technology and rapid prototyping device were used to create an anatomically accurate neonate model. Large-scale rotating airflow was created within the chamber, as shown by flow visualizations, and a number of tiny, stationary eddies are located in the areas between the air input and the neonate. Hot-wire measurements revealed that the lengthy inlets' air velocities are not constant. The neonate's front aspect is pretty uniformly heated to roughly 34℃ according to CFD, with the right armpit and crotch reaching the greatest temperature of 36.1℃. Hot-wire measurements, airflow visualizations, and computational fluid simulations all produced flow fields that are extremely comparable in both quality and quantity. Convective and evaporative heat transfers from the newborn can be hindered by the minor eddies created between the infant and the mattress.

In 2005, Amer and Al-Aubidy [23] developed a unique way for simulating the control system of the incubator for preterm infants using the back propagation method. Sensors were utilised to measure the oxygen content, humidity, and temperature within the incubator. The sensors' output is sent into the artificial neural network (ANN), which recognises the relevant situation and selects the appropriate response based on prior training. The suggested ANN preterm incubator control system was the best choice in all scenarios that may arise in an early newborn incubator.

In 2007, the main physical processes occurring within a newborn incubator were examined by Ginalski et al. [24] both before and after alterations made to the chamber's interior. To reduce radiation heat losses from the baby put inside the incubator, an overhead screen was added as a modification. Ginalski et al. [24] examined the impact of these adjustments on the convective heat flow from the baby's body to the incubator's surroundings. To determine the temperature and velocity within the incubator before and after the design adjustment, a specific study of airflow and heat transfer owing to conduction, convection, radiation, and evaporation was carried out. The commercial CFD program FLUENT was utilised for all numerical computations, together with internal routines for management and user-defined functions (UDFs), which enhance the capabilities of the basic solver. Three alternative air inlet temperatures were considered in the numerical calculations: 32, 34, and 36℃. According to this research, the presence of an overhead screen reduces heat losses by convection and radiation.

An Oxygen Air Servo Baby Incubator's digital control unit was constructed by Zahran et al. [25]. It was designed to monitor, adjust and show the three primary temperatures including the set point temperature, the temperature of a baby's skin, and the temperature of the air. Specific tests were conducted on the implemented control unit both in the lab and outside. A change of 0.1℃ would affect the control unit significantly. Depending on a special control method, the incubator took roughly 14 minutes to achieve its steady state after launch.

Using a model of heat exchange between the baby and its surroundings as well as a strong fuzzy control system, Ele et al. [26] demonstrated the findings of digital simulation for the created system that has a high level of output accuracy despite the high level of dynamic in the input range. In addition, a hardware architecture for hosting the system as well as prospective applications in the real world were described. Because the calculations capabilities that are accessible lead to robust fuzzy control, one may anticipate a greater level of precision for the values of the targeted parameters.

In 2009, Enilson et al. [27] developed a humidity control system, software, and a micro-controlled system specifically for the newborn incubator to monitor the temperature and relative humidity conditions inside the incubator. For the purpose of carrying out the measurements, two identical micro-processed newborn incubators were employed, one of which included distilled water and the other did not. Over the course of 96 hours, the measurements were taken every 2 minutes. The relative humidity within the neonatal incubator deviates from the acceptable range set by standards when there is no water present and when there is water present but no humidity control. If it stayed within the predetermined range of comfort per standard, water and humidity management would help. The authors verified that, when considering the requirements of the standard NBR IEC 601-2-19, the newborn incubator employed in this investigation did not completely care for the preterm neonates.

In 2012, an improved temperature management system was created and developed by Tisa et al. [28] using thermistors as temperature sensors in conjunction with a combination of Pulse Width Modulation (PWM) and a straightforward ON-OFF control mechanism. The range of temperature change in relation to the target temperature (37℃) was determined to be 1℃, which is sufficient. Through the use of a thermistor in a circuit network, a temperature monitor has been created where the voltage output is linearly connected to the temperature. This enabled the direct display of the temperature using a basic milli-voltmeter with the necessary scale. An alarm circuit was also formed to safeguard the baby's safety. If the temperature rises over a predetermined safe range - 26℃ to 38℃ - it will emit an alert to draw staff attention.

It is crucial to offer a favorable environment (especially temperature regulation) for prematurely born newborns in order to reduce the number of fatalities that occur in neonates. Warmth can be provided to newborns via the use of solar thermal energy. In 2013, Satyanarayana and Rao [29] designed a solar thermal incubator system that incorporates a solar water heating unit and a water-air heat exchanger for housing five infants. In this regard, babies that weighed less than 1500 g at birth were divided into three groups according to their rectal temperature: 36℃, 36℃ to 36.5℃, and more than 36.5℃. In a solar-heated incubator with a temperature range of 33.5 to 34℃, 85 newborns with birth weights ranging from 1000 to

1250 g each were successfully cared for. It was observed that out of a total of 5050 rectal temperature readings, 86.8% were higher than 36.5℃; 10.2% were in the range of 36 to 36.5℃; and the remaining 3% were lower than 36℃. During the testing period of three years, the system did not experience any malfunctions.

In 2014, Tran et al. [30] have developed an innovative and cost-effective incubator specifically designed for use in resource-constrained environments. Three cutting-edge features are incorporated into the design: (1) the use of a disposable baby chamber to reduce infant mortality brought on by hospital-acquired infections; (2) a passive cooling system that makes use of inexpensive heat pipes and evaporation from locally accessible clay pots; and (3) insulated panels and a thermal bank of water to effectively retain and store heat in a hospital environment. Figure 1 shows how using the clay pot with the integrated heat pipe allowed for a successful 3.5℃ temperature reduction in the incubator. This drop is less than what the clay pot could conceivably give as a result of the temperature gradient that exists inside the incubator as well as the constraints that exist in the heat transfer that occurs between the incubator and the clay pot. Accordingly, increasing the efficiency of the heat transmission between the pot and the incubator would result in an increase in the overall effectiveness of the cooling system.

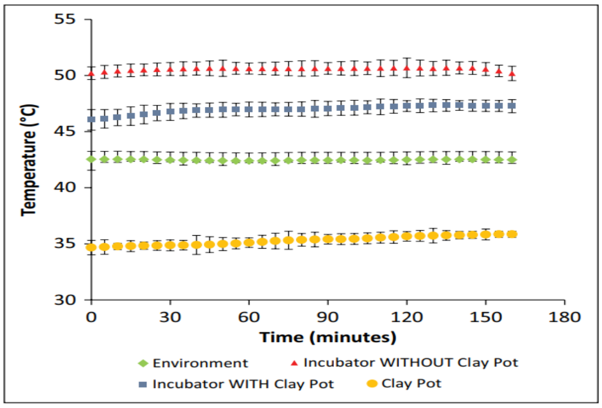

Figure 1. Temperature against operational time of a passive cooling mechanism made of a clay pot coupled with a heat pipe [30]

In 2015, a closed loop control system was created and put into use by Bansal et al. [31] to manage the humidity and temperature within a newborn incubator. Additionally, it was utilised to keep an eye on and regulate the incubator's lighting and oxygen levels. To create the hardware, a microcontroller and PID controller were utilised. The incubator's temperature environment was maintained by the closed loop control system, which consists of synchronously operating sensors and actuators. The authors discovered that the DS18B20's time reaction is very quick, at only one second. If the temperature rises over the assigned limit, the fan turns on to keep the device's temperature. If the temperature falls below the assigned limit, the bulb turns on to generate heat until the temperature rises above the threshold level once again. The potentiometer was used to manually set the threshold.

In 2016, the research conducted by Sinaringati et al. [32] focuses on analysing the performance of beeswax and paraffin materials as the sources of heat energy on newborn incubator. The findings showed that the PCMs are able to keep the heat energy at a temperature of more than 32℃ for a period of more than 8 hours in the neonatal incubator environment. Nevertheless, it was discovered that beeswax achieved far better than paraffin when it came to the storage of heat energy. This research recommended the use of beeswax as the primary component material for newborn incubators, as well as perhaps for any other practical use.

In 2016, an incubator method was developed by Biswas et al. [33] and customized by dust and air particle masks, put at the windows of the incubator, to eliminate dust and air particulates. Biswas et al. [33] showed that a market-available 12v 100 Ah standard battery can power sensors and a fan motor system for 20 days. By employing materials that were readily accessible nearby, the authors attempted to keep the cost of the incubator low. The authors claimed that the suggested non-electric newborn incubator will drastically lower the death of preterm infants in Bangladesh's rural areas, where accessibility, cost, and electricity are the key issues.

In 2017, to avoid the mortality of newborn newborns, Shelke et al. [34] developed and constructed a baby incubator based on a microcontroller. The solar-powered microcontroller-based infant incubator assists all parents in protecting their children from the detrimental effects of environment. Comparing the price of this technology to other infant incubators used in super-specialty hospitals, it is much less expensive. The system can be used to monitoring and regulating temperature besides regulating weights of newborns.

In 2017, a generalized predictive control (GPC) that considers both the newborn preterm model and the closed incubator model was created and verified by Feki et al. [35]. Using a microcontroller card, the authors applied this control rule to a DRAGER neonatal incubator with and without a neonate. A prediction model served as the foundation for the creation of the predictive control legislation. This enabled to account for all thermal exchanges - radioactive, conductive, convective, and evaporative - as well as the different interactions between the incubator's environment and the preterm baby, thanks to the established model. It was also possible to assess the effectiveness of the method of controlling the air temperature to which newborns should be elevated. In comparison to a proportional-integral-derivative controller (PID controller) and based on the Figure 2, the outcomes of the simulation and application of the air temperature within the incubator (both with and without a newborn) confirmed the feasibility and efficacy of the suggested GPC controller.

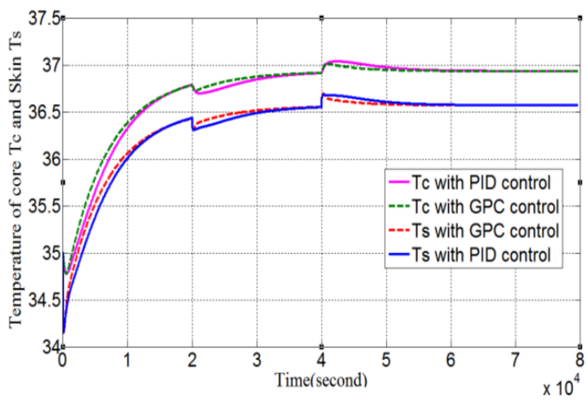

Figure 2. Skin temperature of infant against operational time with utilising GPC and PID control [35]

In 2018, Yadav [36] constructed a cost effective and portable baby incubator to help newborns survive in harsh environmental circumstances, particularly in tribal parts of India where medical assistance, hospitals, and other health care services are not readily accessible. PCMs, thermal energy storage devices, and thermal insulators were used together to achieve the goal of creating a microclimate for infants. As a consequence of this, the evolution of PCM into nano-HVAC (heating ventilation air conditioning) components led to the creation of a phase change thermal energy storage infant incubator. In the regulation of thermal applications in spacecraft, solar engineering, and heat pumps, PCMs have special uses that include the storage of thermal latent heat systems. The temperature at which the phase transition occurs drops to a lower level if there is a rise in the concentration of the mixture (hexadecane - tetradecane) contained inside the walls of the incubator (Figure 3). This is because the mixture has not enough energy to be compressed.

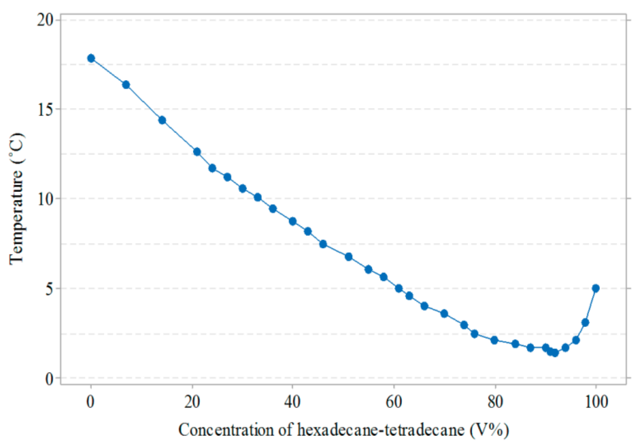

Figure 3. Freezing temperature against concentration of hexadecane - tetradecane mixture [36]

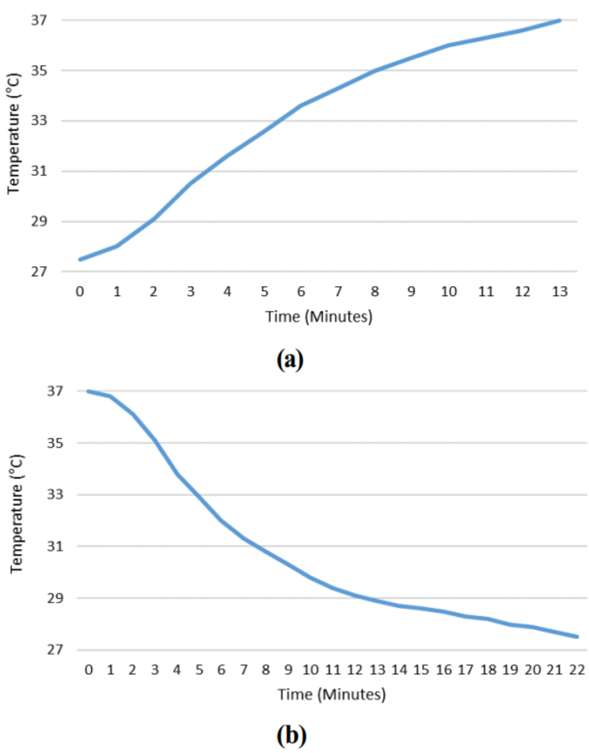

Figure 4. Testing results, (a) heating, and (b) cooling [37]

In 2019, the creation and system validation of a portable incubator were conducted by Eizad et al. [37]. The system's foldable infant cage can be kept inside the system base when not in use. Because it is made of acrylic, the enclosure is easy to clean, allows for unlimited observation of the occupant, and is robust enough to withstand transportation circumstances. Either a 12-VDC automotive power source can power the system. It also features an inbuilt battery to provide a constant supply while traveling. No matter the outside temperature, a Peltier plate controlled by a microprocessor maintains the required temperature of incubator. The infant's skin temperature, heart rate, blood oxygenation level, and ECG can all be measured by built-in sensor probes, and those results may be shown on the system screen. The environment control system's heating and cooling capabilities, as well as the system's peak power usage, are tested to verify its proper operation. Figure 4 depicts the incubator's sensors for measuring the most important indicators of the infant.

In 2019, the idea for the grashof incubator was created by Koestoer et al. [38] to meet the demands of Indonesian residents. The name "Twin Baby Incubator" refers to an existing grashof incubator with a larger capacity that can accommodate two infants at once. The twin grashof baby incubator's design development primarily employs 3D modeling software to adapt the existing features of the original grashof incubator, such as maintaining the infants' cabin temperature between 33°C and 35°C by enabling natural convection and circulation to take place. In addition to the primary functions, the design emphasizes ergonomics and material consideration as a way to increase its performance. In addition, a study was conducted to ensure that the temperature between 33°C and 35°C could be maintained despite the larger capacity of the baby cabin. The essential parts of the design, which is based on the idea of the grashof incubator, are light bulbs acting as the primary heater and a digital thermostat controlling the temperature. At ten separate measurement locations, a DHT22 sensor was used to record the humidity and DS18B20 sensors were utilised to record the temperature. The twin incubator that has been designed can touch the mandatory temperature within the cabin utilising four 15 W light bulbs as a heater.

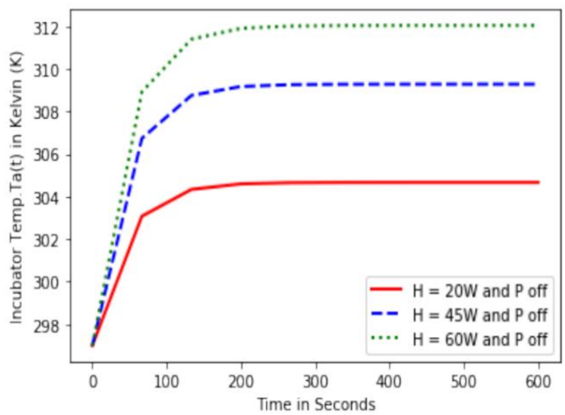

Figure 5. The plot of Incubator temperature against time [39]

In 2020, a low-cost Internet of Things (IoT)-based newborn incubator with a phototherapy blanket was demonstrated by Nwaneri et al. [39]. To track the temperature and humidity of the incubator in real-time, an IoT platform was created. Python programming was also used to model and simulate the incubator environment using conventional thermodynamic concepts. The produced device was found to have a generally steady temperature and humidity that is adequate for a child, as illustrated in Figures 5 and 6, respectively. The IoT platform keeps track of the humidity and temperature of the device. The temperature reached stable state after 200 seconds.

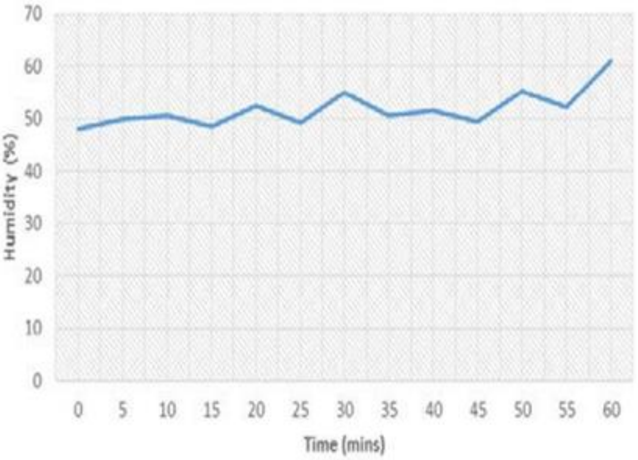

Figure 6. Humidity against time [39]

In 2021, Casado et al. [40] constructed and tested a thermo-electric conditioning system that was intended to be installed in a neonatal incubator. The purpose was to improve the precision of the interior air temperature and reducing noise and interior vibration, and therefore to improve the life of the neonate. A one-dimensional thermal model was established. This model comprises the resistances and thermal capacities, simulates the thermal behavior of all the system's components. It was feasible to identify the mathematical connection between the input and the output by using a nodal technique to extract the model's correlations. The utilised enables to enhance temperature management, eliminating the errors that happen in the conventional model, which is regulated by sensors. Figure 7 shows that the computational model enables the prediction of the fluctuation of temperatures in both the permanent and transient regimes. The results demonstrated a coefficient of operation (COP) of 1.38, obtaining a greater level of performance than the conventional electrical resistance system that is in use today (COP=1). In addition, the CFD analysis has been conducted in order to examine the flow of air inside the incubator, examine the temperature distribution, and calculate the HVAC system's number of air exchanges each hour.

In 2021, Sushil and Kumar [41] provided a notion of a mathematical model of preterm newborns put in an infant incubator. A box-shaped device called an incubator is used to keep a preterm newborn in a controlled environment for medical treatment. A baby incubator maintains a constant temperature. The newborn incubator system shown by the model comprises of the infant core, incubator wall, and air space. The simulation's results considered the temperature variations against time for the newborn temperatures and incubator air space temperatures. A closed-loop system with a PID controller for each mode makes up the simulation's model. The Zeigler-Nichols Method virtually calculates the controller settings. Applying a step input that was confirmed by the Root Locus Method allowed the system to stabilize overall. Infant skin temperature and incubator relative humidity were assumed to be 36.5°C, and 70%, respectively. The step input, which serves as the system's input, is set at 37.2°C. The outdoor air temperature ranges from 25 to 38°C.

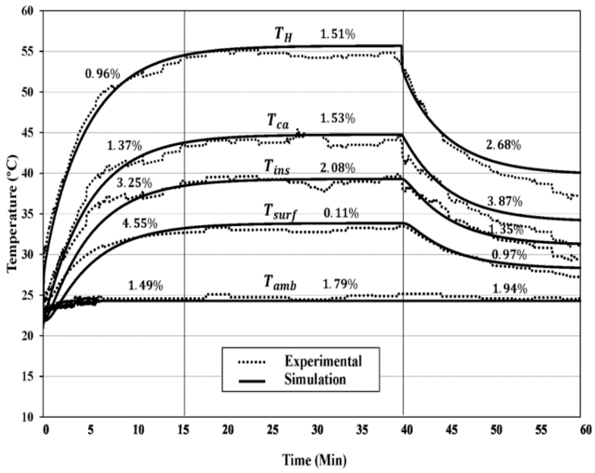

Figure 7. Comparison of temperatures between the thermal resistance system with the computational model in three stages [40]

Table 1. A summary of studies that focused on infant incubator

References	Configuration	Studied Parameters	Highlighted Results/Findings
Kim et al. (2002) [22]	The flow of air inside a neonatal incubator can be simulated through the use of flow visualizations, hot-wire velocity measurements, and CFD	Impact of small eddies produced between the neonate and the mattress	When a neonate is placed on a mattress, small eddies can form between the neonate and the mattress. These eddies have the potential to disrupt convective and evaporative heat transfer from the neonate
Amer and Al-Aubidy (2005) [23]	Control system for premature infant incubators that uses the back propagation method to control the device	The new design	The ANN premature incubator control system that was proposed was proven to be the right decision in all conditions that are capable of occurring in the environment of a premature infant incubator
Ginalski et al. (2007) [24]	Incubator for infants that has a screen above it	Impact of placing overhead screen in the infant incubator	When there is an overhead screen, the amount of heat that is lost as a result of radiative and convective processes is reduced
Zahran et al. (2008) [25]	Control panel for an Oxygenaire Servo Baby Incubator made of digital components	Impact of applying control system	The incubator, based on its one-of-a-kind control strategy, reaches its steady state in about 14 minutes after the start of operation
Ele et al. (2009) [26]	Baby and environment heat exchange, as well as a strong fuzzy control algorithm.	Design of the incubator.	The system that was designed has a high dynamic range for the input range, which results in good output accuracy

Enilson et al. (2009) [27]	Micro-controlled system devoted to the newborn incubator	Impact of using water inside newborn incubator	The relative humidity inside of the newborn incubator exceeds the band of comfort that has been established by standard both when there is no water present and when there is water present but no humidity control
Tisa et al. (2012) [28]	Enhanced system for controlling the temperature, using a combination of pulse width modulation and thermoelectric cooling	Effect of applying alarm circuit	The temperature must not exceed a predetermined safe range, which was determined to be between 26 and 38℃ when the alarm circuit was designed. If the temperature does exceed this range, personnel will be alerted through the use of audible alarms
Satyanarayana and Rao (2013) [29]	Five-baby solar thermal incubator system, including a water-air heat exchanger and solar water heater	Design of the incubator	It was observed that out of a total of 5050 rectal temperature readings, 86.8% were higher than 36.5℃; 10.2% were in the range of 36 to 36.5 °C; and the remaining 3% were lower than 36 ºC. During the testing period of three years, there was not a single instance of the system failing
Tran et al. (2014) [30]	Advanced low-cost incubator	Temperature gradient	This drop is less than what the clay pot could conceivably give as a result of the temperature gradient that exists inside the incubator as well as the constraints that exist in the heat transfer that occurs between the incubator and the clay pot. The overall effectiveness of the cooling system could be significantly boosted by enhancing the heat transfer that occurs between the pot and the incubator
Bansal et al. (2015) [31]	A temperature and humidity regulation system that uses a closed control loop and is housed inside of a neonatal incubator	Impact of closed loop control system.	The bulb will turn on to produce heat if the temperature falls below the threshold level and continue to do so until it does so once more. The fan will switch on to maintain the device's temperature if the temperature exceeds the threshold value. The fan will stop operating if the temperature drops below the threshold level
Sinaringati et al. (2016) [32]	Materials used as the incubator's heat sources include paraffin and beeswax	Impact of using paraffin and beeswax materials as the sources of heat energy on infant incubator	In the infant incubator room, the PCMs have the ability to maintain heat energy at a temperature of more than 32 degrees Celsius for more than 8 hours in the neonatal incubator. On the other hand, it was discovered that beeswax was superior than paraffin in terms of its ability to store heat energy
Biswas et al. (2016) [33]	Dust and air particulate of a unique variety generated by the incubator system	Impact of non-electrical type infant incubator	The infant incubator of the non-electrical type that is currently being proposed will be of great assistance in lowering the mortality rate of premature babies in rural areas
Shelke et al. (2017) [34]	An incubator for babies that is controlled by a microcontroller	Impact of A microcontroller based baby incubator	The design system that has been proposed is not only utilised to adjust the temperature, but it also provides a number of benefits. These advantages include controlling the temperature, monitoring the weight of the infants who are being observed, and so on
Feki et al. (2017) [35]	A form of predictive control known as generalized predicting control (GPC) that considers the closed incubator model	Impact of using newborn inside the incubator	The viability and efficiency of the suggested GPC controller are demonstrated by comparing the air temperature inside the incubator with a proportional-integral-derivative controller and the air temperature inside the incubator with and without a baby
Yadav (2018) [36]	PCM into Nano-HVAC components	Effect of concentration of the mixture inside the walls of the incubator	The temperature at which the phase transition occurs drops to a lower level if there is a rise in the concentration of the mixture contained inside the walls of the incubator. This is because the mixture lacks the energy necessary to contract
Eizad et al. (2019) [37]	The portable incubator consists of a baby enclosure that is both collapsible and able to be stored away within the system base when it is not in use	The influence of using collapsible baby enclosure	It is possible to control the temperature inside the enclosure to the desired value, which can be either higher than or lower than the ambient temperature. The infant's skin temperature, pulse, blood oxygenation level, and electrocardiogram can all be monitored with the help of the incubator's built-in sensors, which are also included
Koestoer et al. (2019) [38]	Twin Baby Incubator	Impact of using twin incubator	The capacity of the developed twin incubator to reach the required temperature inside the cabin while making use of four light bulbs each rated at 15 watts as a heater
Nwaneri et al. (2020) [39]	neonatal incubator based on the Internet of Things (IoT) that is inexpensive and includes a phototherapy blanket	The new design	In the newly developed apparatus, a temperature and humidity level that is suitable for a newborn were observed to be relatively stable
Casado et al. (2021) [40]	A neonatal incubator has a thermoelectric conditioning device installed	Impact of installing Thermo-electric conditioning device in neonatal incubator	A coefficient of operation (COP) of 1.38, which results in improved performance in comparison to the conventional electrical resistance system that is in use today (COP=1)
Sushil and Kumar (2021) [41]	infants born prematurely who are being cared for in an infant incubator	Impact of placing premature infants in an infant incubator	The newborn incubator system with a closed-loop system of a PID controller can sustain an incubator relative humidity of 70% and interior temperature of 36.5℃
Sallam and Sezdi (2022) [42]	Reliable incubator analyzer	Impact of using sound noise sensor	The sound noise sensor had an error ratio of 20 dB when it came to detecting measurements of the environment

In 2022, a trustworthy incubator analyzer that guarantees incubator sustainability was created by Sallam and Sezdi [42]. Researchers provided a thorough design for an analyzer that can be used to keep an eye on the incubator's operational characteristics using three distinct sensors that controlled by a separate AVR Atmega32 microcontroller unit and interfaced to a liquid crystal display. The analyzer was designed to detect temperature, humidity, and noise. With an average error ratio of 3.54% for air temperature readings and 1.4% for humidity, the DHT11 sensor performed well. The LM35 mattress temperature sensor has a 2% error ratio. Measurements with an error ratio of 20 dB might be detected by the sound noise sensor. The suggested design is a rough prototype that has to be improved upon and put to the test.

Table 1 shows a summary of the associated studies related to infant incubator.

4. CRITICAL ANALYSIS OF THE INNOVATIVE DESIGNS OF INFANT INCUBATORS

Referring to the discussion made in the above section, this section provides a critical evaluation of the promoted and innovative designs of infant incubator.

A ground-breaking development in infant incubator design is the introduction of large-scale rotational airflow, as pioneered by Kim et al. [22] using three-dimensional laser scanning technology. The welfare of babies is of the utmost concern with this breakthrough. The design guarantees a homogeneous and controlled thermal environment for preterm babies by helping users visualize and comprehend the specifics of airflow within the incubator. This invention helps to keep temperatures steady, which is important for neonates' delicate physiology, especially preterm infants who have trouble thermo-regulating. The control of airflow patterns precisely improves thermal stability, maintains constant oxygen levels, and reduces the possibility of airborne illnesses.

Sensors were added to the incubator by Amer and Al-Aubidy [23] and used to measure the oxygen content, humidity, and temperature within the incubator. In order to provide premature infants with the best environment possible, these sensors are crucial. Healthcare professionals can prevent oxygen poisoning and inadequate oxygen supply by carefully monitoring oxygen levels and maintaining the precise oxygen concentration required for a newborn's developing respiratory system. Keeping optimum humidity levels reduces skin dryness and respiratory problems in preterm newborns, who are particularly sensitive to changes in air moisture. Monitoring humidity is essential. For premature infants who have trouble controlling their body temperature, temperature sensors ensure a uniform and controlled environment. In this regard, Zahran et al. [25] provided a digital control unit to measure and monitor the set point temperature, the temperature of a baby's skin, and the temperature of the air. Similarly, Enilson et al. [27], Tisa et al. [28] and Bansal et al. [31] developed micro-controlled system, thermistor (temperature sensor), and closed loop control system, respectively, for the newborn incubator to monitor the temperature and relative humidity inside the incubator. Interestingly, the addition of an alarm circuit to the incubator was prominent to alert workers if the temperature exceeds the acceptable range between 26 to 38℃.

Ginalski et al. [24] developed the design of infant incubators by adding an overhead screen to mitigate heat losses by convection and radiation. In other words, the overhead screen aids in keeping the incubator's temperature steady and uniform by minimising radiation heat losses. For premature babies who have trouble efficiently controlling their body temperature, this stability is essential. Indeed, a steady thermal environment is important for the growth and development of baby, since it fosters comfort and well-being. Furthermore, by limiting heat losses, the infant's safety is improved because the risk of hypothermia is considerably reduced.

Based on utilising the renewable energy, Satyanarayana and Rao [29] constructed a solar thermal incubator that assures a solar water heating unit and a water-air heat exchanger for housing five infants simultaneously. The incubator offers a constant and environmentally beneficial power source by utilizing solar energy, which also lessens dependence on traditional energy systems and lowers operating expenses. The simultaneous provision of a steady and monitored thermal environment for five infants is made possible by the combination of a water-air heat exchanger and a solar water heating unit. By lowering the carbon footprint, this strategy not only supports environmental responsibility but also increases access to newborn care.

The PCMs and thermal insulation were firstly incorporated to newborn incubators by Sinaringati et al. [32] who made possible to maintain the temperature inside incubator environment at more than 32℃ for a period of more than 8 hours. The greatest advantage of this design is that it has the ability to significantly enhance outcomes for premature infants, particularly in areas where reliable access to energy is a problem. This incubator's design lowers the danger of hypothermia, a serious problem for premature infants, by guaranteeing a steady and warm environment for a protracted length of time. Their development and survival depend on maintaining a constant temperature, which is a problem that this invention effectively addresses. In this regard, Yadav [36] utilised PCMs for the same purpose.

The design of incubator was further improved by Biswas et al. [33] by adding dust and air particle masks. This invention is significant because it can make the incubator's inside extremely hygienic and secure. Due to their immature immune systems, preterm newborns are particularly susceptible to infections and airborne contaminants. This design creates a safeguard to keep potential pollutants out of the incubator by incorporating dust and air particle masks.

Light bulbs acting as the primary heater and a digital thermostat and DHT22 sensor were added with the infant incubator to control the temperature between 33-35℃ and humidity, respectively (Koestoer et al. [38]).

The interior air temperature, noise and interior vibration inside the incubator were maintained within the standards by incorporating a thermo-electric conditioning system by Casado et al. [40]. The key merit of this design is upholding ideal conditions, guaranteeing a secure, peaceful and stable environment for the growth of babies.

Lastly, a rough prototype of three distinct accurate sensors that controlled by a microcontroller unit and interfaced to a liquid crystal display were introduced by Sallam and Sezdi [42] to measure temperature, humidity, and noise within trivial errors. This technology enables to having accurate measurements of the most important parameters of incubators as even minor deviations can influence an infant's well-being. It is also important to keep an eye on noise levels since too much noise can interfere with a baby's ability to sleep and grow.

5. CONCLUSIONS

In-depth analyses of several newborn incubator innovative designs, purposes, and configurations were conducted in this study. The conclusions that can be made are as follows:

1. Incubator design using three-dimensional laser scanning technology ensures an appropriately controlled thermal environment for premature infants by assisting users in visualizing and understanding the complex mechanics of airflow within the incubator.
2. Oxygen content, temperature, humidity sensors are cut-edge technology to provide premature infants with the best environment possible.
3. An alarm circuit was developed to inform workers if the temperature rises above a certain safe range between 26℃ to 38℃. This design ensures the baby's safety.
4. When an overhead screen is provided, heat losses by convection and radiation can be reduced.
5. Through the use of solar energy, the incubator provides a consistent and ecologically friendly power supply while reducing its reliance on conventional energy sources.
6. The PCMs can sustain heat energy at a temperature over 32℃ for more than 8 hours in the neonatal incubator.
7. The incubator with dust and air particle masks can make the incubator's inside extremely hygienic and secure.
8. The neonatal incubator system, which uses a closed-loop PID controller, can maintain an internal temperature of 36.5℃ and a relative humidity of 70%.

6. RECOMMENDATIONS FOR FUTURE WORK

The most current research literature on newborn incubators is thoroughly reviewed in this study. A table that has been created as a summary sum up the experimental, numerical, and combined experimental and numerical examinations of newborn incubators. The thermal performance analysis that was included in each study was looked into, as well as the evaluation of the data that were included in Tables 1, may lead to the following recommendations:

1. More research needs to be done on the construction of solar energy system components that are appropriate for isolated locations with limited access to typical power.
2. To improve the system's capabilities, certain functions may be introduced in the future. The system does not yet have an onboard ventilator. The inclusion of an on-board ventilator may make the transfer of newborns at danger considerably simpler, even if there is room to put ventilator tubing into the cage.
3. The incubation system may also benefit from a network connection. In order for the medical professionals to be prepared to welcome the baby or to give their opinion on the infant's health, the lively indications captured by the onboard sensors may be sent to them if a network connection is accessible.
4. Investigate the application of cutting-edge sensors and monitoring tools that can deliver quite accurate and real-time readings of incubator temperature, relative humidity, and oxygen levels. By doing this, it may be possible to increase the accuracy and dependability of environmental management in these vital medical devices.
5. Create and improve control algorithms that allow temperature, humidity, and oxygen levels inside incubators to be dynamically adjusted based on the unique needs of babies. To ensure the best settings for child growth and health, this may entail incorporating feedback loops, machine learning strategies, and predictive and complicated models.
6. In order to minimise heat loss and lower energy usage, concentrate on enhancing the thermal insulation capabilities of incubator designs. Investigate the utilisation of cutting-edge insulation materials and design principles that can keep temperatures steady with little energy input.
7. In neonatal incubator designs in the future, it is crucial to get rid of eddies surrounding the baby.

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NOMENCLATURE

PCMs	Phase change materials
RH	Relative humidity
HVAC	Heating ventilation air conditioning
COP	Coefficient of performance
CFD	Computational fluid dynamics
CAD	Computer-aided design
UDFs	User-defined functions
ANN	Artificial Neural Network
GPC	Generalized predictive control
PWM	Pulse Width Modulation
ERI	Electronics Research Institute