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A Low-Cost IoT Based Neonatal Incubator for Resource Poor Settings

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Abstract: *Preterm births in resource poor countries are characterised by high infant mortality. The high cost and non-availability of conventional neonatal incubators are considered to significantly affect efforts aimed at mitigating this problem. In this paper, a low-cost Internet of Things (IoT) based neonatal incubator with phototherapy blanket is presented. The device was constructed using a wooden box with a dimension of 33 × 20 × 18 inches, a heating element, a relay, a liquid crystal display (LCD) module, an l2C module, control buttons, a light emitting diode (LED), 220 Ω resistors, 5 volts' power supply, transparent 2 mm thick acrylic sheet, a mattress, Wi-Fi module and LED based phototherapy blanket. An IoT platform was developed for real-time monitoring of temperature and humidity of the incubator which can be accessed by a password protected graphical user interface (GUI) application developed using C programing language. Modelling and simulation of the incubator environment based on standard thermodynamic principles were performed using Python programming language. A relatively stable temperature and humidity suitable for an infant was observed in the developed device. The IoT platform was effective in monitoring the temperature and humidity of the device. Incubator temperature attained steady state in 200 seconds. The environmental conditions were found to be suitable for a neonate. The device was effective for real-time monitoring of environmental conditions in the incubator.*

Keywords: *Internet of Things, Humidity, Neonatal Incubator, Phototherapy Blanket, Smart Medical Devices*

1. Introduction

Preterm births account for a significant proportion of child births globally. According to the World Health Organisation (WHO), about 15 million babies born yearly are preterm (WHO, 2018). Complications from preterm births are mostly responsible for high infant mortality and morbidity especially in low income countries. Majority of preterm deaths are caused by lack of simple essential care and poor thermoregulation (Pandya et al., 2017). Thermoregulation, a mechanism that regulates body temperature plays a unique and crucial role in the nurturing and development of a baby (Shelke et al., 2017). However, the absence of thermoregulation in preterm babies leads to hypothermia, and other health complications or even death if not adequately handled. Neonatal incubators are essentially designed to improve their chances of survival. Accordingly, neonatal incubators provide a controlled environment for neonates by regulating environmental conditions such as temperature, humidity and ventilation. This system mimics the mother's womb where complete embryonic development should take place. Incubators are made of a rigid box-like enclosure that provides a closed and controlled environment for the sustenance of premature babies (Sowmiya et al., 2018). Amongst the important benefits of a neonatal incubator is the early detection of potential life-threatening events (I-smac, 2017). The average normal axillary temperature of an incubator is 37°C while a temperature of 38°C (100°F) or greater, as measured by a rectal thermometer, represents a fever (Mackowiak, 1992). Normal axillary temperature is between 36.5°C and 37.5°C (WHO, 1997).

The origin of incubators is linked to Stephen Tarnier, a French obstetrician who designed the first neonatal incubators in a form similar to chicken incubators housing several infants (Baker, 2000). However, Tarnier's incubator had no temperature and ventilation control system. Alexander Lion, in the 1890s developed a large metal apparatus equipped with a thermostat and an independent forced ventilation system, the Lion incubator was designed to compensate for less than optimal nursing or environment (Baker, 2000). Alexander Lion's incubator includes a large metal apparatus, a thermostat regulated heater and an independent forced ventilation system (Ann, 2004). Several other types of incubators have evolved over the years with a variety of innovations recorded.

A number of innovations have been introduced to enhance the effectiveness and efficiency of an incubator. Bouattoura et al. (1998) proposed an active humidification system and developed an algorithm using a combination of optimal control theory and dynamic programming approach. Furthermore, an enhanced temperature control system was designed, using thermistors and incorporating a combination of Pulse Width Modulation (PWM) and simple ON-OFF control system. Incubators have become more sophisticated since late 20th century with the use of microprocessors. Amadi et al., (2007) developed a recycled incubator technique (RIT). Tisa et al. (2012) designed an enhanced temperature control system incorporating a combination of Pulse Width Modulation (PWM) and simple ON-OFF control system, using thermistors as temperature sensors. These developments in the 21st century generally improved the focus on better designs for neonatal incubators. Also, Sun (2015) designed and implemented an infant incubator intelligent control to address the problem of cost and lack of spares for incubators in resource poor settings. Recent innovations in the design of incubators include the incorporation of IoT systems for direct communication of the doctor and mother with the incubator (Huang et al., 2015).

The current method for monitoring the baby's temperature is with a thermistor and a controlled heating unit, but it cannot account for the water lost through the skin, which is critical to maintain the neonate for the first 7 to 10 days after birth to prevent dehydration. In preterm infants, hypothermia increases morbidity and mortality. It is therefore necessary to maintain an appropriate environmental temperature in the delivery room (Robert et al., 2018). Humidity is one of the four primary variables which must be controlled during incubation - the others being temperature, ventilation and movement (or turning). In addition, Jaundice is a common disease that affects preterm infants. Approximately 80% of infants become jaundiced during the first week of life (Woodgate and Jardine, 2011). Jaundice is due to excessive accumulation of bilirubin known as Hyperbilirubinemia, a product of the degradation of red blood cells, in the blood. Hyperbilirubinemia, may also indicate liver or gall bladder disease (Kelnar et al., 1995).

Equipping the incubator with a phototherapy blanket could be useful in the treatment of jaundice in preterm infants (Rose, 2000). With the phototherapy blanket, there would not be a need to attach a phototherapy light to the incubator. Phototherapy blankets perform a better function than phototherapy lights because they cover larger surface areas. Phototherapy breaks down bilirubin to a water-soluble form that could be excreted in the urine (Vreman, 2004). Prior to phototherapy, sunlight was used to treat jaundice. However, long exposure to sunlight is associated with various levels of risks to the newborn. Phototherapy blankets are more effective because they can be used both indoors and at night (Aeroflow, 2011). Potentially harmful ultraviolet and infrared energy are filtered out in a phototherapy blanket.

Traditional incubators lack real-time remote monitoring features which make them very difficult for busy parents and care givers to monitor the health condition of their babies. However, modern incubators could be optimised with the Internet of Things (IoT) technology. The IoT is a network-based system that enables machine to machine (M2M) communication between various devices (Sarmah et al., 2017). Automatic identification of devices within the network and information sharing are achieved by the use of the IoT (Sun, 2015). Physical and virtual objects are linked by an internet-built network with various sensors and devices on the basis of exploiting data with advanced communication (Verdouw and Beulens, 2013). The IoT obtains the object’s information using cloud computing and intelligent computing technique (Wang, 2011).

This paper focuses on the design of a low cost smart neonatal incubator for monitoring parameters like temperature, humidity, amount of gas, bilirubin level in the baby, pulse rate of the baby and light inside the incubator. The device also sends these details to an online information storage platform where any mobile phone that can provide security information for the website can easily access. This study improves existing designs with the incorporation of an IoT system with a LED designed phototherapy blanket.

2. Materials and Method

2.1 Materials

The device consists of a wooden box, a heating element, a relay channel, an LCD module, an l2C module, control buttons, a female header, a 5 mm LED and a neonatal incubator. Table 1 shows the materials and reasons for their selection. Cost, availability and safety

Table 1. Materials Selection

S/N	Part	Material Description	Reason for choice of material
1.	Incubator top	4 × 8 feet transparent glass, 2 mm thick acrylic sheet, and wood	Cheap and readily available
2.	Angle Brackets	Aluminum	Aluminum is strong and durable
3.	Table stand	Wood and Aluminum	Cheap and readily available
4.	Table top	18 mm medium density fiber sheet	Strong, cheap and readily available
5.	Mattress	Foam	Biocompatibility
6.	Blanket	Cotton Towel fabric	Towels are soft and furry

Table 2. Design Requirements

S/N	Characteristics	Description
1.	Power	• The device requires a 220 V, 50 Hz clean and stable AC power supply.
2.	Temperature	• The device needs to operate at a suitable temperature range of between 30°C and 35 °C ambient temperature.
3.	Humidity	• The relative humidity of the incubator should be between 40 % and 75%.
4.	Safety	• The incubator will not expose the baby to any form of electrical shock. • The device will be properly ventilated. • Biocompatibility of the materials that make contact with the baby. The materials should not cause injury or any form of harm to the baby.
5.	Cost	• The device should be affordable to majority of hospitals/users in resource poor settings. • Maintenance costs should be affordable.
6	Maintainability	• The incubator should be easy to maintain.

considerations were the main criteria for material selection. The design requirements of the device are depicted in Table 2.

The incubator is made of rectangular box with a glass cover at the top and circular openings at the sides of the boxes with a communication system incorporated. It is to provide information to the medical personnel and caregivers. The hardware and software modules of the device are discussed.

2.3 Device Design and Implementation

2.3.1 Hardware Design and Implementation

The 3D CAD design of the device is presented in Figure 1. All dimensions of the CAD design are in millimeters. The device was designed with a dimension of 830 × 450 × 500 mm with a circular space with a diameter of 100 mm and a top cover of 774 x 250 mm. Figure 2 shows a picture of the prototype device. The incubator was designed using a rectangular box made of glass and wood of 33 × 20 × 18 inches. With a door at the top made of an acrylic material, the incubator also has an access port of 3.5 inches diameter enclosed by an elastic leather band. The hardware is supported by a wooden stand, and two pairs of wheels for easy transportation of the device. A mattress was placed inside the incubator.

A block diagram of the incubator is shown in Figure 3. The incubator is powered by 240 V mains electricity supply and regulated by a 5V switching power supply. The heating element made of a metallic plate with a dimension of 8 cm × 1.8 cm is heated once the device is powered on. Heat generated by the heating element keeps the surface temperature warm. Temperature and humidity control are necessary in a neonatal incubator to provide a safe and conducive environment for the infants. DHT11, a simple, low-cost digital temperature and humidity sensor was used for this purpose. Operating within a voltage range of between 3V and 5V, the sensor is capable of measuring temperature of (0ºC - 50ºC) and humidity (20% - 90%). The sensor transmits its signals to an 8-bit microcontroller (PIC 18F4520). The microcontroller consists of an on-chip eight channel, 10-bit Analog-to-Digital Converter (ADC) which converts the analog signal to digital. The amplified and conditioned sensor signals are fed to the microcontroller. The temperature and humidity values are displayed on a liquid crystal display (LCD) module capable of showing 16 characters in 6 lines.

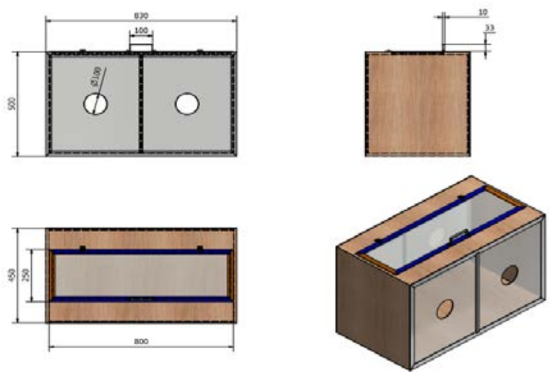

Figure 1. 3D CAD Design of the incubator

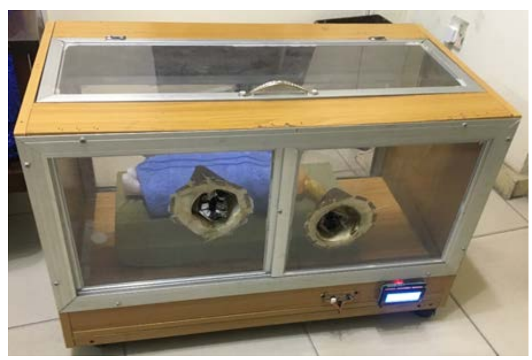

Figure 2. A Picture of the Prototype

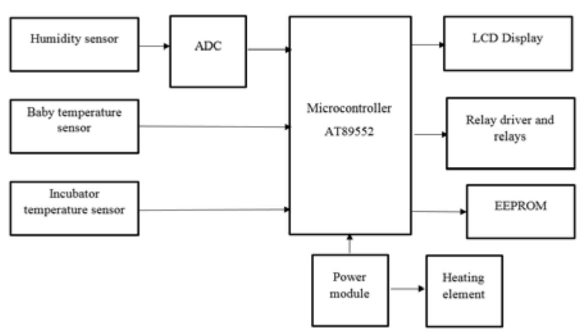

Figure 3. Block Diagram of the Incubator

The surface temperature is measured with a surface mounted thermistor (NTC temperature sensor) and relative humidity is measured with the help of a moisture holding component between two electrodes through the measurement electrical resistance between the two electrodes in order to detect the water vapour content. For temperature regulation, a precision integrated circuit temperature sensor, LM35 was used to measure temperature in the range of -40ºC to +125ºC which is sufficient for the targeted body temperature range and provides an analogue output with a linear transfer function given by:

$$V_{out} = 10mV/oC \text{ X } T \quad (1)$$

where, V_{out} = Output voltage; T = the Temperature in °C

Temperature is controlled by turning on an alarm whenever the temperature exceeds the prescribed temperature. Consequently, the heater gets turned off through the mobile app. The app also helps to continuously monitor the temperature in order to notify the care giver in case of an emergency (Sowmiya et al., 2018). The IoT system works with sophisticated microprocessor that regulates temperature and humidity of the incubator. It also sends the information from the incubator to a web platform in periods almost in real time. A circuit diagram for detection and monitoring of the incubator is shown in Figure 4.

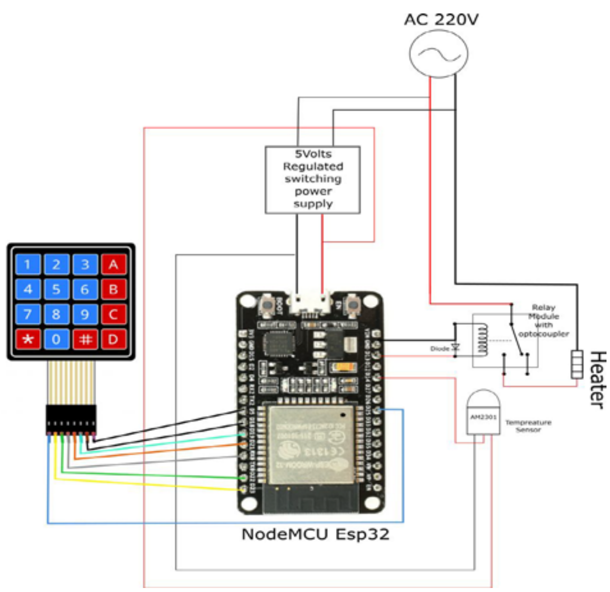

Figure 4. Circuit Diagram for the Detection and Monitoring of the Incubator

2.3.2 Control Logic of the Incubator

The system is a closed loop system controlled by the NodeMCU and powered by a 220 V AC supply which is supplied to the heater once the switch is closed. Conversely, the relay is fed with a 5V DC supply. The temperature sensor (DHT11) senses the temperature within the device and as soon as it detects a temperature beyond the set point, the relay cuts off to disconnect the heater with minor temperature fluctuations which can only be detected by smart sensors. The control system of the incubator is illustrated in Figure 5.

The NodeMCU is the IoT platform programmed in C programming language. When a targeted temperature is set from the keypad the microcontroller switches on the heater by sending 5 volts to pin 13 which triggers the relay. The program monitors the temperature reading from the temperature and humidity sensor every 0.5 seconds. Once the temperature exceeds the targeted temperature by 0.5 degrees the program switches pin 13 off thereby turning off the heater. Besides, once the temperature drops by 0.5 degrees, the program switches on the heater again and the cycle goes on. The NodeMCU is connected to a webserver via the Wi-Fi to update its own data, and to check for remote commands sent to it. A website was designed using HTML5, which displays the status of the status of the incubator, by connecting to a remote webserver and retrieving the latest report left there by the incubator.

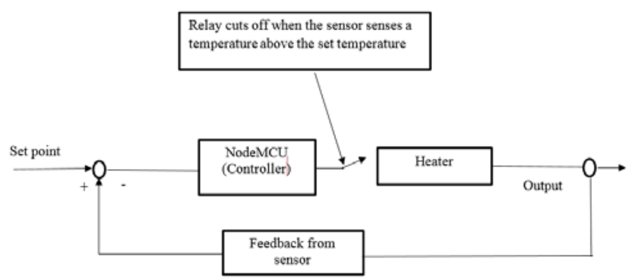

Figure 5. Control system of the incubator

2.3.3 Phototherapy Blanket

The incubator is equipped with a phototherapy blanket, for the treatment of neonatal jaundice. The phototherapy blanket is a covered pad consisting of flexible LEDs light strip which are considered suitable and comparable to conventional phototherapy lamps for the treatment of neonatal jaundice (Kumar et al., 2010). The LED light strips were attached to the cotton fabric material. When powered, the UV LEDs will emit light of between 395 - 405 nm wavelengths. The UV LEDs are powered by a built in 5V DC supply adapter. The phototherapy blanket is shown in Figure 6.

Figure 6. The phototherapy blanket under construction

2.3.3 The IoT System Implementation

The device was designed with an open source IoT platform, NodeMCU which is considerably preferred over other boards because of its low cost, low power consumption, reduced size and integrated support of Wi-Fi. The NodeMCU is from the ESP8266 family (Bento, 2018). Ubidots cloud is an easy and affordable means of IoT data analytics, which changes the sensor data into information. This storage platform also provides access to shared pools of data, which is often accessible only over the internet. A block diagram of the IoT system is shown in Figure 7.

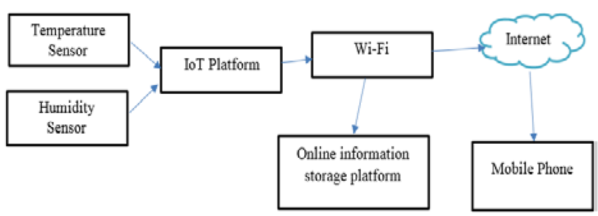

Figure 7. Block diagram of the IoT system

2.3 Device Testing and Validation

Testing of the device was performed after the integration of the incubating system, IoT system and the Phototherapy blanket: Voltages and other electrical signals were measured and were absent in all contact areas of the human subject. The device was tested on plastic dummies with the temperature set to a target temperature of $24^{o}C$. The time it takes to reach the targeted temperature depends on the voltage supply which is proportional to the targeted temperature. The LCD displays the temperature as shown in Figure 8.

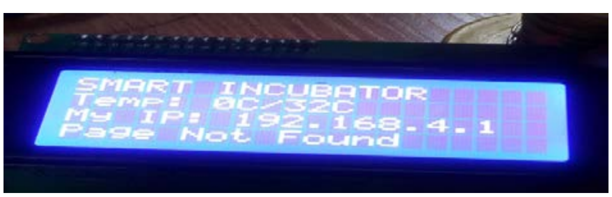

Figure 8. Real-time display of parameters on LCD

The SSID and IP address of the Wi-Fi is displayed on the LCD as indicated in Figure 8. An administrator or user can access information to determine the status of the device logging on to the device as shown in Figure 9 with the target temperature is set. User authentication is through the use of username and encrypted passwords either as admin or guest as indicated in Figure 10. The IoT device renews the information sent from the incubator to the phone every minute. The IoT platform was effective in monitoring the conditions in the incubator.

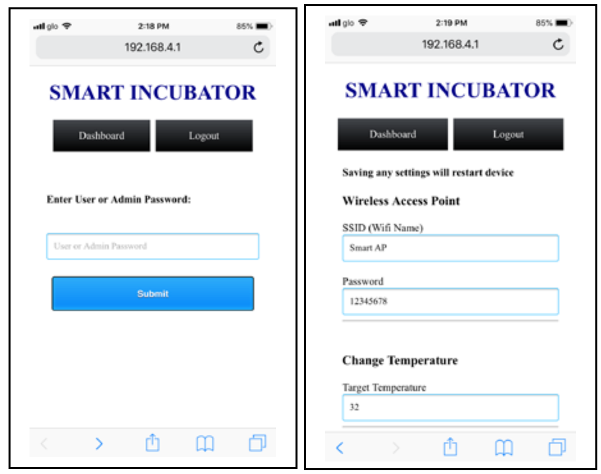

Figure 9. Login Page of the IoT system

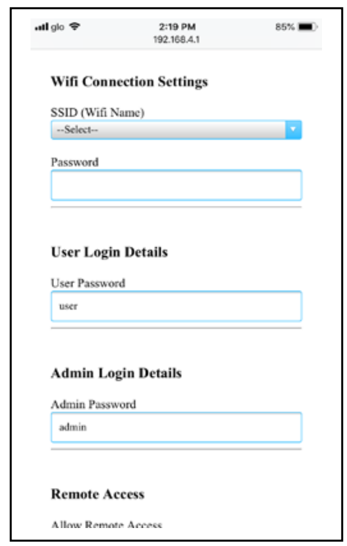

Figure 10. Wi-Fi connection settings on the website

In accordance with the Failure Modes and Effects Analysis (FMEA) we determined the risks associated with the use of the device. Probable risks and their severity were calculated in accordance with FMEA. Risk Priority Number (RPN) for each risk was obtained by the multiplication of the probability of failure (PF), severity of effect (S) and probability of detection of an existing defect (D) (Abike et al., 2010) as shown in Equation (2):

$$RPN = S \times P \times D \quad (2)$$

The evaluation metrics used in this study is presented in Table 3. The FMEA was calculated in Table 4 which also includes preventive measures included in the design to mitigate the effects of the failure modes and risks associated with the use of the device.

2.3 Device Modelling and Simulation

Temperature and heat loss calculations are important because the incubator's internal environment temperature must be warmer than the external

Table 3: Probability-Severity-Detection Matrix

Variable	**Severity**	**Probability of Occurrence**	**Detection**
Very high	Death (10)	Very High: Failure is inevitable (10)	Impossible to be detected (10)
High	Severe injury (8)	High: Failure is Possible to repeat (8)	Difficult to be detected (8)
Moderate	Moderate injury (5)	Moderate: Failure occurs occasionally (5)	Detected occasionally (5)
Low	Minor injury (3)	Low: Relatively few failures (3)	Easy to be detected (3)
Very Low	Very minor injury (1) No injury (0)	Very /low: Less likely to occur (1) unlikely to occur (0)	Almost certain to be detected (1)

Table 4: Failure Mode Effects Analysis for Incubator

S/N	**Risks**	**Detection (D)**	**Severity (S)**	**Probability of occurrence (P)**	**RPN**	**Preventive Measures Taken**
1.	Over or under-heating of the infant due to thermostat failure, dehydration	3	8	3	72	Temperature sensors/other components operate with low DC voltages (3V – 5V)
2.	Electric Shock to the infant	10	10	1	100	Components operate with low voltages (3V – 5V)
3.	Failure of alarm in the event of deviation of temperature from set values	1	5	3	15	Frequent monitoring of device
4.	Hypothermia of infant due to low temperatures	3	8	3	72	Remote monitoring capability of device will help address this. Regular
5.	Device falls unexpectedly causing trauma to infant	1	8	1	8	Device is very balanced and unlikely to fall. Instructions to ensure it is properly placed.
6.	Doors unable to open easily causing the infant to be trapped inside the device	1	6	1	6	Door at the top freely opens. Hinges can easily be dismantled in the event of any failure.
7.	Air ceases to flow through the device due to mechanical failure	1	6	1	6	Adequate provision of hole with diameter 3.5 inches and enclosed by an elastic leather band.
8	Inadequate humidity in the system	1	6	3	6	Regular monitoring needed.

environment. The body temperature of the baby should also be higher than the incubator's internal environment. Heat losses through various forms including conduction, convection and radiation are minimal. Conductive heat loss between the infant and foam is minimal as the foam is made of an insulator. Equations (3), (4) and (5) show temperature and heat calculations for the device. The equations reveal that heat entering the incubator and heat generated by the incubator are equivalent to heat consumed by the incubator with the baby and heat lost by the incubator to the environment. This obeys the first law of thermodynamics which states that:

The change in the internal energy of a system, ΔU *is equal to the heat added to the system,* Q *minus the work done by the system,* W *as shown in Equation (3):*

$$\Delta U = Q - W \tag{3}$$

Notations:

$\Delta\theta_{incubator}$ = change in temperature inside the incubator
$\Delta\theta_{heater}$ = change in temperature outside the incubator
$\Delta\theta_{baby}$ = change in temperature of the baby
$m_{incubator}$ = mass of the incubator
m_{baby} = mass of the baby
m_{heater} = mass of the heater
c = hear capacity
$heat_{in}$ = heat entering the incubator
$heat_{gen}$ = heat generated by the incubator
$heat_{consumed}$ = heat consumed or absorbed by the incubator
$heat_{lost}$ = heat lost by the incubator to the environment

Equation (3) is further simplified into equations (4) – (6). Total heat energy is conserved. Therefore, regulation of the heat generated by the incubator is necessary to ensure the infant within the device does not have too much heat or lose too much heat.

$$heat_{in} + heat_{gen} = heat_{consumed} + heat_{lost} \tag{4}$$

$$mc\Delta\theta_{entering} + mc\Delta\theta_{heater} = mc\Delta\theta_{baby} + mc\Delta\theta_{incubator} + mc\Delta\theta_{out} \tag{5}$$

$$\Delta\theta_{incubator} = \frac{mc\Delta\theta_{entering} + mc\Delta\theta_{heater} - mc\Delta\theta_{baby} - mc\Delta\theta_{out}}{(mc)_{incubator}} \tag{6}$$

The temperature inside the neonatal incubator depends on both physiological and environmental variables. Simulation is based on the equilibrium of metabolic heat generation in the body (M) and the various methods of heat transfer including conduction, convection, evaporation and radiation between the skin, phototherapy blanket and the environment. Figure 11 shows the block diagram of the heat exchange model which is similar to previous study. The major difference is the inclusion of the phototherapy blanket (Delanaud et al., 2019). The model was partitioned into four homogenous sections including the incubator airspace, incubator wall, the phototherapy blanket and the mattress.

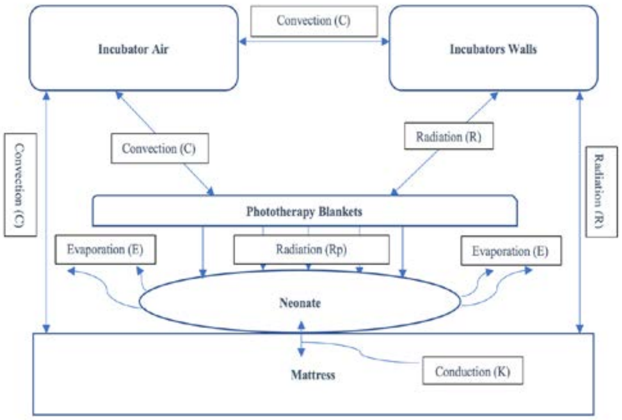

Figure 11: A block diagram of the heat exchange in the incubator
Source: Abstracted from Delanaud et al., (2019)

Heat exchange models well reported in literature were adopted for this work (Delanaud et al., 2019; Decima et al., 2012). The governing differential equation for heat exchange in incubator is given as:

$$P * V * C_v * dT_a/dt = M + H_{heater} + H_{RP} - H_{str} \quad (7)$$

Where ρ (Kgm^{-3}) is the density of the air, V(m^3) is the volume of the incubator and Cv($JKg^{-1}K^{-1}$), T_a(K) the temperature of the incubator, H_{heater} is the electrical power of heating element, H_{RP} is the heat energy supplied by LED phototherapy blanket, H_{str} is the heat energy loss from the incubator structure to the environment and M is the metabolic heat generated by the infant's body. Metabolic heat in neonate body can be partitioned as shown in equation (8)

$$M = H_c + H_k + H_E + H_{CR} + H_{EB} + H_R \quad (8)$$

Here H_c is the convective heat transfer from the skin surface to the moving air in the incubator, H_R is the radiant heat between the infant's skin to distant cold objects, H_E is the skin evaporative heat loss, H_k is the heat conducted from the skin to the mattress, H_{EB} is the evaporative heat loss that is due to breathing and H_{CR} is the convective heat loss through the respiratory tract. Metabolic heat production can also be calculated using Equation (9)

$$M = m_{inf}(0.052P_{inf} + 1.64)/V_{inf} \quad (9)$$

Here, m_{inf} (Low Birth Weight (LBW) < 2.5Kg) is the mass of the infant, P_{inf} is the baby' age (days) and V_{inf} is the volume of the infant's body. Equation (10) is the compartmentalised equation for heat loss to the incubator structure.

$$H_{str} = H_{wood} + H_{glass} + H_{aluminum} + H_{rubber} \quad (10)$$

Where H_{wood} , H_{glass} , $H_{aluminum}$ and H_{rubber} are the heat lost in the incubator to wood, glass, aluminum and rubber respectively.

$$H_{wood} = A_w U_w (T_a - T_o) \quad (11)$$

Here A_w is the net area of the wooden structure, U_w is the heat transfer coefficient of the wood, T_a is the inside design temperature and T_o is outside temperature. Similarly, the heat lost in H_{grass}, H_{rubber} and $H_{aluminum}$ takes the form of Equation (11) but with different values of areas and heat transfer coefficients. Heat loss due to infiltration and ventilation is not considered. H_{RP} is the radiant heat energy supplied by the phototherapy blanket. Simulation was performed in Python programming language based on the following parameter values indicated in Table 5.

Table 5. Parameters and Corresponding Values

Parameter	**Values**
m_{inf} , mass of infant	2,500 g
P_{inf} , the baby' age (days)	1 day
V(m^3) is the volume of the incubator	0.25
C_v , Specific heat capacity of air	1005 J/Kg K
T_a , the inside design temperature	297 K
ρ(Kgm^{-3}), the density of the air	1.225 Kg/m^3
V, Volume of incubator design	0.18675 m^3
Thermal conductivity of rubber	0.163 W/m K
H_{wood}, Heat transfer coefficient of wood	1.613 W/m^2 K
H_{glass}, Heat transfer coefficient of glass	5.28 W/m^2 K
$H_{aluminum}$, Heat transfer coefficient of aluminum	3.6 W/m^2 K
A_{wood} , Area of wood	0.511 m^2
A_{glass}, Area of glass	0.6444 m^2
A_{rubber}, Area of rubber	0.01571 m^2
UV LEDs	395 – 405 nm
Heating power of LED blanket	2(8.64)=17.28W

3. Results and Discussions

3.1 Modelling Temperature versus Time

Simulation results were obtained and briefly discussed. The relationship between incubator temperature and time is demonstrated by varying the conditions of the heater H, and the phototherapy blanket, P. The plot of incubator temperature against time of operation is shown in Figure 12. When both H = 80W (maximum value of the heating element) and P is on, the incubator temperature is greater than 37 degrees Celsius. If *H* is switched off and *P* is operating, the incubator temperature is less than 32 degree Celsius.

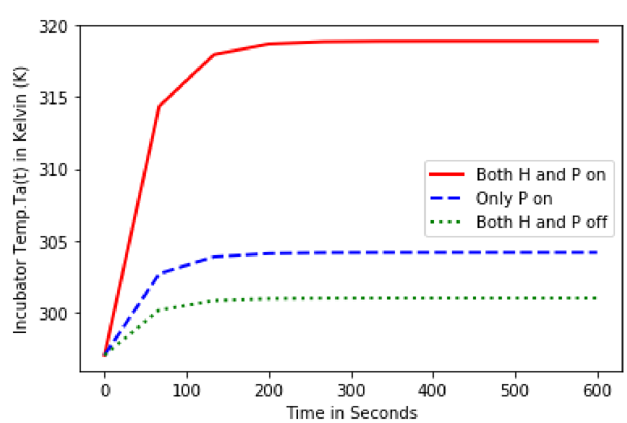

Figure 12. Temperature Versus Time (Case 1)

The most suitable temperature for full-term and preterm infants is obtained when H = 20W and P on (34.5 degree Celsius after 200 seconds) as shown in Figure 13.

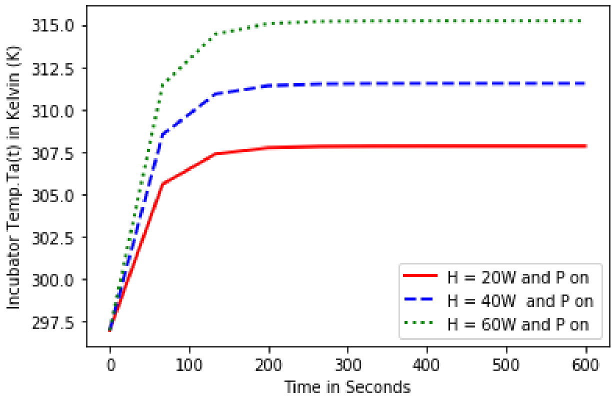

Figure 13. Temperature Versus Time (Case 2)

The behaviour of incubator temperature is examined for various H values while P is switched off. We observed in Figure 14 that at H = 45W the incubator temperature remained constant at 36 degree Celsius from time 200 seconds and above. For the three (3) cases considered, incubator temperature attained steady state in 200 seconds (less than 4 minutes).

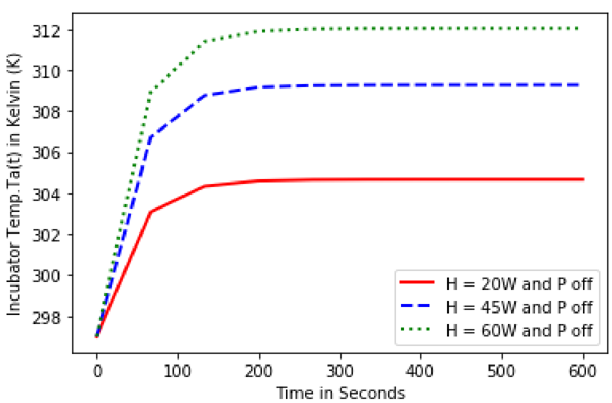

Figure 14. The plot of Incubator temperature against Time (Case 3)

3.2 Device Testing Results

Physical parameters within the infant incubator were measured by smart sensors with no infant in the device. To observe the behavior of the system, the temperature and humidity of the incubator readings were taken at every 5 minutes' interval. To begin the test, the temperature was set to 25ºC and a temperature sensor was used to observe the change in temperature. The relationship between the device temperature and time is displayed in Figure 15. The temperature is held between 24ºC and 26ºC under the control thermistor in the infant incubator that measures and regulates the temperature within the set value.

In Figure 16, the relationship between the device humidity and time is presented. The relative humidity is between 48 % and 61 %. This range of temperature and relative humidity are suitable for the baby. These data and experiment show that the intelligent infant incubator system works well based on the design.

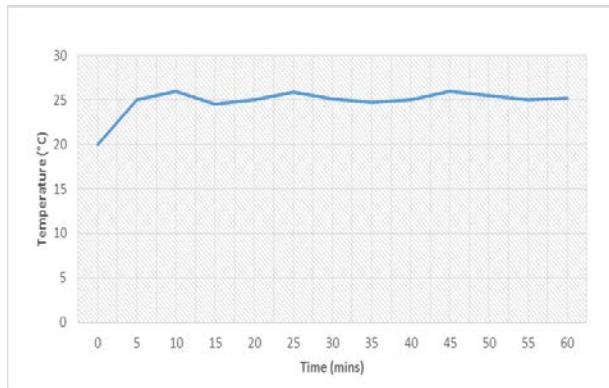

Figure 15. Temperature versus Time

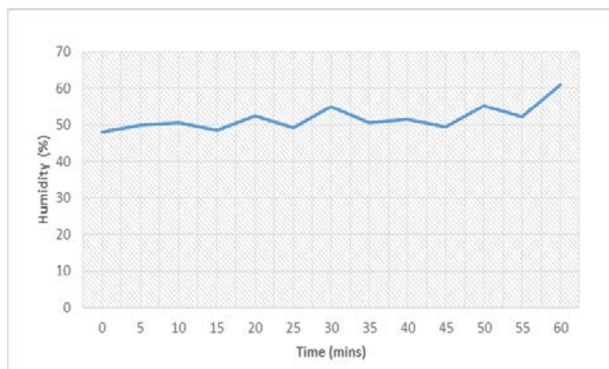

Figure 16. Humidity versus Time

3.3 Discussion

The expensive nature and limited features of conventional neonatal incubators underscores the need for a low cost, smart infant incubator which was developed in this study for resource poor settings. Several innovative features have been incorporated to the device to assist physicians and care givers in monitoring the environmental conditions within the device remotely. The effectiveness of the IoT platform in monitoring the temperature and humidity of the device was demonstrated. The IoT has been extensively applied in the interconnection of medical devices and sensors by assisting physicians in accurately monitoring the health of their patients (Dridi et al., 2017). Although security is a concern in IoT systems, the benefits far outweigh the disadvantages. A two-factor authentication system based on username and encrypted password protection which was implemented in this study will to a large extent provide basic security.

A comparison of the cost of developing the device and other related neonatal incubators shows our device to be relatively cheaper. The market prices of similar incubators are between $2,000.00 and $3,000. The device was produced at a lower cost of $390, which makes it suitable for resource poor settings. The high cost of medical devices manufactured in developed economies is often too expensive for small and medium sized hospitals in resource limited settings. Moreover, the limited resources for device training and repair make advanced equipment difficult to use (Blue, 2014).

Analysis of the results shows that the time taken for the incubator to reach the target temperature is 5 minutes with the initial temperature at 20℃. The analysis also shows a fluctuation within 24℃ to 26℃ temperature range, and the thermistor cuts off the heater once the desired temperature is exceeded. The temperature later reduces to the set temperature. This process happens continuously and causes a variation between the temperature ranges of 24℃ to 26℃. The humidity also varies between 48% and 61% due to the varying temperature. Another unique feature of the incubator is the phototherapy blanket, for the treatment of neonatal jaundice. In addition to the other benefits of a conventional neonatal incubator, this device is suitable for the treatment of neonatal jaundice in premature infants. A significant reduction in infant mortality could be achieved in developing countries with the mass production of the device. The incorporation of the phototherapy blanket to the device will no doubt reduce infant morbidity and mortality.

4. Conclusion

In this paper, an IoT based neonatal incubator was developed. This work provides solution to the challenges of untimely death of neonates and also treats jaundice at the same time at an affordable price. The system controls the temperature and humidity of the environment, and provides a means of monitoring and readjusting the values of the temperature and humidity of the environment of the baby and treating jaundice simultaneously.

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