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IMPROVING THE CONTROL OF PRETERM INFANT MASS SKIN TEMPERATURE USING ADAPTIVE NEURO FUZZY INFERENCE SYSTEM

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Abstract
This paper presents a system for controlling an infant skin temperature using ArtificialNeuro-Fuzzy Inference System (ANFIS). Mathematical and Simulink models of the infant and the incubator system were developed. The ANFIS model integrates both the Fuzzy Logic Control (FLC) rules and the Artificial Neural Network (ANN) to produce optimum control for the variation of the skin temperature of the preterm infant inside the incubator. Simulation was carried out using the ANFIS model, open loop incubator and FLC in two instances. A0.9kg and 2.5kg infant masses and postnatal ages of 5 days were used in the first and second instances. Result showedthat in the first instance, the ANFIS model made a 2.2% and 0.82% improvement over the open loop incubator and the FLC respectively. While a 6.5% and 2.3% improvementwere also made by the ANFIS model over the open loop incubator and the FLC in the second instance.
Keyword: ANFIS, Fuzzy logic, incubator, Preterm, Temperature

1.0 Introduction

In developing countries, thousands of infants die due to prematurity complications (World Health Report, 1998).Premature infants are babies born prior to the normal 36 or 37 weeks of gestation and their Physiological systems are immature, consequently incapable to control their body temperature and making the infant vulnerable to a number of health complications (Michael, 1991).The net body areas of some newborn babies with growth deficiency are greater than normal babies from the same age. Moreover, their net mass is less than the normal babies and makes them unable to keep their body temperature to the required level; consequently the infants are at risk of developing hypoxia, hypothermia and many other associated improper thermoregulation conditions. These will eventually lead to death caused by an immature response of the nervous system to cold and over heat stress. A baby loses heat through four different ways namely; Evaporation, Conduction, Convection and Radiation.

During birth, the inside temperature of the mother's womb is about 38^{0}C (100.4^{0}F), the newborn finds itself in a much colder surrounding and immediately starts losing heat. Radiant warmers use infrared radiation to control the temperature of infants, while incubators use the convection of warm and humidified air. Both of these warming devices are feedback systems. The radiant warmer uses only the skin servo control, while the incubator has two modes; skin and air servo control.The use of these two devices has considerably reduced the rate of infant mortality and morbidity.

Neuro-fuzzy controllers are one of the recent controllers, that combine the advantages of fuzzy inference systems and artificial neural networks for the modelling ofuncertainties and non-linear complicated systems (Timothy, 2004).Yasser and Ahmed, (2006), proposed a comprehensive simulation model for the infant-incubator system to investigate effects on the general thermo-neutrality of the environment using a PID controller. The result under skin

mode showed that the body temperature of a 900gm infant with an initial body temperature of 35.5 °C, in two hours reached 36.87 °C and 36.5 °Cfor both the core and skin temperature respectively. But the PID controller performed poorly on air mode.
Garima, (2006), proposed a fuzzy logic control for infant incubator systemwhichincorporates both incubator air temperature and infant's skin temperature in the control action. Results revealed that fuzzy logic system incorporates both skin and air temperatures to provide a better and smooth control when compared with On-off air servo control and Proportional control for different selected conditions.Barry, Simon, Narender and Anand, (1994), proposed and designed a spatially lumped mathematical model for a computer simulation of infant incubator system for parametric assessment of the factors that affects neonatal thermoregulation. The result met requirements specified but the system was a complex one.

2.0 Theory

Many findings have confirmed that the survival rate of low birth-weight infants cared for in incubators or under radiant warmers increases when warmer environment conditions are provided (Michael, 1991). This is particularly vital in the first week of life. Neutral thermal environment is vital for premature babies throughout the first month of life, due to exceedingly high evaporative losses resulting from large skin surface area and this can only be achieved at a very small range of temperatures usually in a margin of +1 °C when the admission temperature to the incubator is greater than 36 °C (Michael, 1991; CMNRP, 2013; Ghada and Kasim, 2005).

The actual environmental temperature required to achieve thermo-neutrality for a premature infant with very low birth weight during the first day of life is around 39 °C (Michael, 1991). This temperature is significantly influenced by insensible water losses of premature infants. Also it is worth noting that babies under radiant warmer have a higher metabolic rate than those that are cared for in incubators. This may be attributed to the inconsistency of radiated energy distributed over the exposed surface area of the baby's body in which some sections of the body receive more heat than other parts while the vertical parts might remain cold (no heat received) (Rojer,1993; Michael, 1982).

Generally, optimal thermal conditions are achieved when baby's temperature remains in the range between 36.8°C - 37.2 °C (Miller and T.K.O, 1966; Phillippe Chessex and Jean, 1988) and both oxygen consumption (heat production) and insensible water losses (heat loss) are at minimum levels (Tisa, Nisha and Kiber, 2012; Hey and Katz, 1970). The radiant warmers and incubators are used to maintain optimal temperature of preterm babies. The radiant warmer allows immediate contact with the infant and provides skin servo controlled heating through radiation. For those infant lying in open bed, there is an excess volume of humidity loss and the infant is more prone to infection.

In addition, infants have considerable quantity of heat loss through convection and evaporation.Eventually,infants have to be transferred to incubators due to limitations of radiant warmers, (Lyon, Pikaar, Badger and McIntosh, 1997).The infant incubator is considered as an air conditioned room with distinct specification which can be controlled with respect to the health condition of the infant. Incubators are created to give an ideal environment for newborn babies with development problems or with infections. The incubator has the capacity to regulate and maintain temperature, relative humidityand concentration of oxygento acceptable levels of 36.5°C-37.5°C, 40% - 90% and 25%-60% respectively(Lyon, Pikaar, Badger and McIntosh, 1997; Garima, 2006)

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Thermo regulation inside the incubator relies on several factors. These factors may depend on infant related parameters or incubator related parameters (Thomas and Burr, 1999).Infant related parameters include variables such as size, maturity level, gestational age, metabolic factor, maturity of skin and body development etc. The incubator related parameters include incubator size, geometry, and thickness of walls, materials of the incubator, mattress, incubator-heating type and control mechanisms. Majority of incubators warm the infant by a forced or usual flow of heated air in to the incubator compartment. Many incubators are furnished with relative heating controls that give electrical power to the heating coil in response to the variation between the actual temperature and the desired temperature. In skin temperature, an automatic or servo control mode is employed, a sensor is taped to the infant's skin and the heater reacts to variations in the sensor to keep the skin temperature at the pre-set level.

3.0 Methodology

The mathematical models of the infant and the incubator system were developed. The developed models were used in building the Simulink model. Simulations were carried out in two instances using open loop incubator system, fuzzy logic controller and the proposed ANFIS model.

Infant Modeling: in modeling an infant, one lumped model isused (Barry, 1994). The one lumped model considers the infant with two layers; the core and the skin layers (Rojas, Bell and Dove, 1996).The one lumped infant model is shown in figure 1 whilefigure 2 illustrates the heat exchange between the core and skin layers within an infant's body.

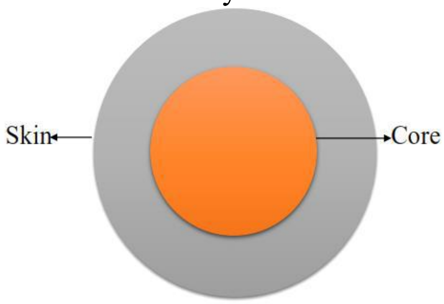

Figure1: One Lumped Infant Model (Rojas, Bell and Dove, 1996)

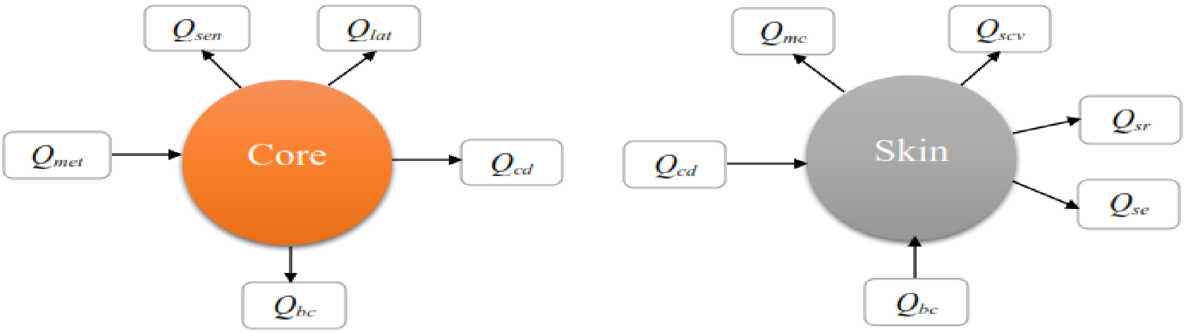

Figure 2: Heat Exchange Block Diagram for Infant's Core and Skin Compartment

Where(Rojas, Bell and Dove, 1996);
Q_{met} = Rate of metabolic heat production of the core.
Q_{bc} = Rate of convection heat transfer between core and skin via blood.
Q_{sen} = Rate of sensible heat energy due to breathing.
Q_{lat} = Rate of latent heat energy due to breathing.

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Q_{cd} = Rate of conductive heat transfer between core and skin.
Q_{mc} =Rate of conductive heat transfer between skin and mattress.
Q_{scv} = Rate of convective heat transfer between skin and incubator air.
Q_{sr} = Rate of radiation heat transfer between skin and incubator wall.
Q_{se} = Rate of evaporative heat transfer between skin and incubator air.

One lumped model is based on Rojas's model.From Figure 2 the core of an infant gains heat through:

- Metabolic rate,Q_{met} .

While the core of an infant losses heat via:

- Convection with the blood (Q_{bc})
- Respiration (i.e. sensible heat, Q_{sen} and latent heat (Q_{lat}).
- Conduction with the adjacent skin layer (Q_{cd}).

Similarly the infant skin layer gains heat via:

- Conduction with the adjacent skin layer (Q_{cd})
- Convection with the blood (Q_{bc})

And the skin of an infant losses heat via:

- Conduction with the mattress (Q_{mc})
- Convection with incubator air space (Q_{scv})
- Radiation losses to the incubator walls (Q_{sr})
- Evaporation losses through the skin, (Q_{se})

Many assumptionswere made in deriving the equation for the infant incubator model. The first law of thermodynamics (law of energy conservation) was applied to each compartment of the neonatal incubator model to obtain the variation in temperature of each compartment over time (that is instantaneous temperature).

Here, the infant body is approximated as a cylinder with air flows parallel to its axis as show in figure 3.

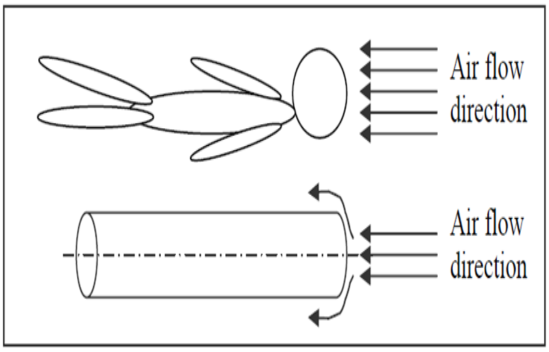

Figure 3: Infant shape approximation (Yasser and Ahmed, 2006)

Core Layer

Consider the one lumped mass model for the infant as shown in figure 1. For a given period of time the heat balance of the core layer can be written as:

$$[\, Q_{met} - Q_{sen} - Q_{lat} - Q_{cd} - Q_{bc} \,]dt = M_c C_{Pc} dT_c] \quad (1)$$

Therefore the instantaneous temperature of the core can be written as;

$$\frac{dT_c}{dt} = \frac{[\, Q_{met} - Q_{sen} - Q_{lat} - Q_{cd} - Q_{bc}}{M_c C_{Pc}} \quad (2)$$

Where,
C_{pc} = specific heat of the core
M_c = mass of infant core and can be determined by;

$$m_c = m * m_s \qquad (3)$$

m_s = mass of infant skin and m = mass of infant.

Equation 2 describes all heat flow rates, which manipulate the heat transfer relationships associated with the infant body. Each one of the terms in this equation is determine as follows:

Heat Production of infant core (Q_{met})

The heat production of the infant core of the infant body can be written as;

$$Q_{met} = M_{rst} * S_a \qquad (4)$$

Where M_{rst} is the resting metabolic rate and S_a is the surface area of the infant, this is a function of infant weight and was determined using equation 4.

$$S_a = \frac{mass}{10.85}^{0.75} \qquad (5)$$

Heat losses of infant core

The infant core loses heat during breathing process in the form of convective heat which takes the form of Q_{sen} and Q_{lat} caused by the difference between water-vapour pressure of the inhaled and exhaled air, in terms of respiratory rate and tidal volume (Barry, Simon, Narender and Anand, 1994).Q_{sen} andQ_{lat} are given as;

$$Q_{sen} = IV * m * C_{pa} * \rho_a * (T_{ex} - T_a) \qquad (6)$$

$$Q_{lat} = IV * m * hfg * \rho_a * (W_{ex} - W_a) (7)$$

Where,

IV =inspired air volume and is equal to 3.33mL/Kg/sec.T_{ex} = Exhaled air temperature, T_a = Air temperature/Inhaled air temperature. Q_{cpa} = Specific heat of air, ρ_a= Air density, hfg = Latent heat of water at 350C. W_{ex} =Humidity ratio of the exhaled air, W_a =Humidity ratio of the inhaled air. For more precise results, T_{ex} is assumed to be equal to T_c (Yasser, and Ahmed, 2006). The humidity ratio of the exhaled air is determined by;

$$W_{ex} = 0.622 \frac{P_{H_2O}}{P_t - P_{H_2O}} \text{(Michael, 1987)} (8)$$

And the inhaled air also given by;

$$W_a = 0.622 \frac{P_{H_2O}}{P_t - P_{H_2O}} \qquad (9)$$

Where

P_{H_2O} = Partial pressure of water-vapour at T_a and T_{ex} and is determined by;

$$P_{H_2O} = P_{sat} * RH\% \text{ (Wilbert and Jerold, 1983)} \qquad (10)$$

P_t= Atmospheric pressure and P_{sat} =Saturation pressure for air, retrieved from (Yunus, 2003). The Infant core also loses heat through conduction and convective heat loses as given below.

$$Q_{cd} = \frac{(T_{ex} - T_a) * K_c * S_a}{\frac{m}{\rho_c} * S_a} \text{(Yasser, and Ahmed, 2006)} \qquad (11)$$

$$Q_{bc} = (T_c - T_s) * \rho_{bl} * bf * C_{pb} * V_{cb} (12)$$

Where,

T_c = Core temperature, T_s = Skin temperature, K_c= thermal conductivity of the core. P_c = core Density, P_{bl} = Blood density, *bf* = blood flow rate parameter

C_{pb} = specific heat of the blood,V_{cb} = blood volume, which is given as:

$$V_{cb}(mL) = 80\left(\frac{mL}{kg}\right) * m(kg) \qquad (13)$$

Skin Layer: Consider the skin layer shown in figure 2 in a period of time *dt*, the heat balance equation for the skin layer can be written as;

$$[\, Q_{cd} + Q_{bc} - Q_{scv} - Q_{mc} - Q_{se} - Q_{sr}\,]dt = m_s C_{Ps} dT_s \quad (14)$$

Therefore, the instantaneous temperature of skin can be written as:

$$\frac{dT_s}{dt} = \frac{Q_{cd} + Q_{bc} - Q_{scv} - Q_{mc} - Q_{se} - Q_{sr}}{m_s C_{Ps}} \quad (15)$$

Where,

C_{Ps} = specific heat of the skin

$$m_s = th_s * \rho_s * S_a \quad (16)$$

The rate of conductive heat loss from the skin in contact with the mattress can be determined by:

$$Q_{mc} = \frac{A_s * K_{mat} * (T_s - T_m)}{th_m} \text{(Yasser, and Ahmed, 2006)} \quad (17)$$

t_{hs} = skin thickness and t_{hm} = mattress thickness

$$A_s = 0.1 * S_a \quad (18)$$

K_{mat} = thermal conductivity of the mattress, and T_m = mattress Temperature.

Q_{scv} is given as:

$$Q_{scv} = h_{scv} * A_{cv}(T_s - T_a) (19)$$

A_{cv} = infant surface area exposed to air

h_{scv} = the convective heat transfer coefficient for forced convection. Since the surface area in contact with the mattress is 10% of the total surface area exposed to the air. Then A_{cv} is given as;

$$A_{cv} = 0.9 * S_a \quad (20)$$

The evaporation heat rate Q_{se} (in watts) can be determined by:

$$Q_{se} = \frac{hfg * m * Evap. * Ph_2o}{86400} \text{ (Yasser, and Ahmed, 2006)} \quad (21)$$

Where Evap. is the evaporation loss from the skin of the infant to the environment (mL/kg/day), which is a function of gestational age (GA) and postnatal age (age), which can be determined from the equation as follows:

$$Evap. = \left[6.5 \exp\left(\frac{168}{age + 11.8}\right) * \exp\left(-\frac{5.2GA}{age + 12.2}\right) + 4.8\right] * [2 - \left[\frac{P_{H_2o}}{23}\right]]$$ (Yasser, and Ahmed, 2006; Michael, 1987) (22)

The skin of an infant also loses heat to the walls of the incubator by radiation. The rate of radiant heat losses can be determined by:

$$Q_{sr} = A_r * \sigma * \varepsilon_s * [((T_s + 273.15)^4) - ((T_w + 273.15)^4]$$ (Yasser, and Ahmed, 2006) (23)

Where,

A_r = The surface area of the neonate body normal to the walls of the incubator

Σ =stephan-boltzmann constant, ε_s = emissivity of the skin

Incubator modeling: The incubator was modeled in terms ofAir space, Wall (hood) and Mattress. The incubator air space exchanges heat with all compartments of the incubator system, mainly due to convection and also, due to heat and mass transfer via respiration and evaporation. The heat balance equation for the incubator air space given a period *dt*, is given as:

$$[\, Q_{scv} + Q_{se} + Q_{ht} + Q_{sen} + Q_{lat} - Q_{acv} - Q_{mat}\,]dt = M_a C_{Pa} dT_a (24)$$

Some of assumptions are made to simplify the modeling of the incubator wall: The material of the wall is homogenous and uniform and that there is a uniform temperature distribution

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across the internal and external surfaces of the wall (Kieth, Marks, John, and Jeffrey, 1980). The heat balance equation for the incubator walls at time *(dt)* is given as:

$$[Q_{acv} + Q_{sr} - Q_{cvo} - Q_{ro}]dt = M_w C_{pw} dTw] \qquad (25)$$

The mattress gains heat by conduction with the skin of the infant, and is convectively heated by the incubator air space.In a period of *dt*, the heat balance equation for mattress can be written as follows:

$$[Q_{mc} + Q_{mat} - Q_{ic}]dt = M_m C_{pm}\ dT_m (26)$$

The Design of the ANFIS model follows a number of systemic procedures. The mathematical models developed were used in building the Simulink model of the various components that made up the entire system. The data sets used for the ANFIS network was generated from the developed system. A total of 153 data sets were collected,70% of this data was used for training(107),15% of the data set was used for testing(23) and checking(23).

4.0Simulation and Results

Simulation in Simulink usingthe open loop controller, the ANFIS controller and the FLC were carried out for 10sec in two instances;

1. 0.9kg infant mass and postnatal –age of 5days and
2. 2.5kg infant mass and postnatal –age of 5 days.

Simulation in the first instance.

In order to attain the thermo-neutral environment for the preterm infant, the standard clinically suggested incubator infant skin Temperatures for 0.9 kg infant mass and postnatal age of 5 days is between 35°CC and 36.6°C respectively. Figure 4 illustrates the variations in the skin temperature of the infant mass for the three models. Temperature of 37.5°C was recorded at the start of the simulation for the open loop controller, and steadily decreases to 36.53°C at 10secs. The preterm infant temperature observed for the FLC model at the start was 37.26°C which is high for the infant mass; a control by the FLC model was enforced to reduce the temperature to 36°C at 8secs and finally maintained the temperature within the standard limit to the end of the simulation.

The proposed ANFIS model recorded a maximum temperature of 35.5°C and maintained slow decrease in the temperature of the infant mass as its incubator heat energy changes thereby introducing adaptive control to the preterm infant temperature. At 10secs the infant skin temperature was at 34.18°C thus, readings of the skin temperature for the proposed model conformedto the clinical empirical findings reported in (Rojer, 1993; Kieth, Marks, John, and Jeffrey, 1980).

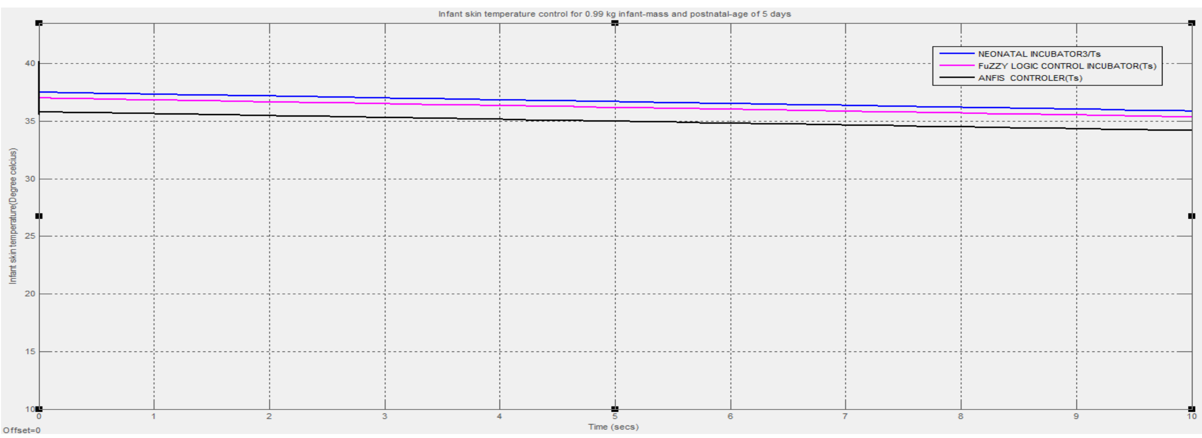

Figure 4: Infant skin temperature control for 0.9kg infant mass and postnatal-age of 5days

The ANFIS model shows a better performance when compared with the other models in terms of maintaining a maximum temperature not greater than 36.6°Cfor the preterm infant mass. The percentage deviation observed by the other two models in terms of sensitivity and control is given in equations 27 and 28.The open loop incubator controller Mean value =37.4°C, FLC Mean value =36.9°C and the Standard Maximum reading=36.6°C. Percentage improvement was deduced using:

$$Percentage = \frac{Icmr - smr * 100}{smr} \quad (27)$$

(((37.4 -36.6)*100)/36.6) = 2.2%

and

$$percentage = \frac{Icmr - smr * 100}{smr} \quad (28)$$

((36.9 -36.6)*100)/36.6) = 0.82%

From equations 27 and 28, it can be stated that the proposed model has a 2.2% improvement when compared with the open loop infant incubator model and a 0.82% improvement when compared with the Fuzzy logic control model.

Simulation in the second instance.

Considering a clinically suggested incubator infant skin temperature for a 2kg infant mass and postnatal age of 5 days, the standard temperature range in is between 32°C and 36°C respectively (Rojer, 1993).

Figure 5 shows the simulation of the three models of the infant-incubator system. At the start of the simulation, the open loop controller recorded a skin temperature of 38.8°C for the preterm infant and decreased to 37.5°C at 5secs.Finally at 10sec, the skin temperature record was 36.5°C. The skin temperature for the FLC controller was 37°C at startof simulation, andmaintained a steady decrease for 5secs recording a skin temperature of 36°C at the end of the simulation.

From figure 5 the ANFIS model recorded a maximum temperature of 34.5°C and maintained slow decrease in the temperature of the infant mass as its incubator heat energy changes thereby, bringing adaptive control to the preterm infant temperature. At 10secs the temperature was 32.5°C. Thus, readings of the skin temperature for the proposed model conformedto the clinical empirical findings reported in (Kieth, Marks, John, and Jeffrey, 1980).

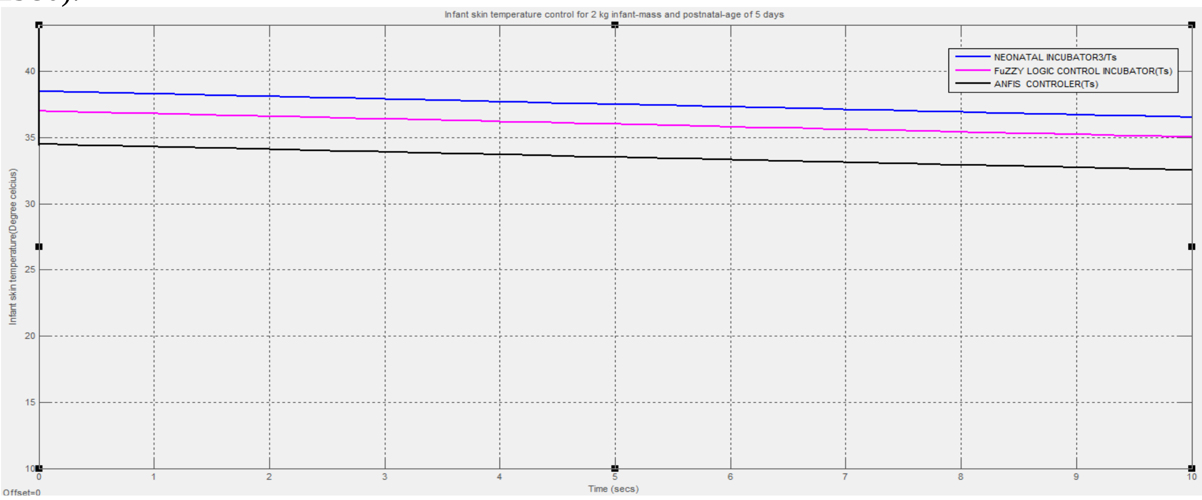

Figure 5: Infant skin temperature control for 2kg infant mass and postnatal-age of 5days

The ANFIS model shows a better performance when compared with the other models in terms of maintaining a maximum temperature not greater than 36°Cfor the preterm infant mass. The percentage deviation observed by the other two models in terms of sensitivity and control is given in equations 29 and 30.Mean of open loop incubator controller =38.34°C, mean of FLC =36.84°C and aStandard Maximum reading =36°C. The percentage improvement can also be deduced using:

$$Percentage = \frac{MIC - smr * 100}{smr} \quad (29)$$

(((38.34 -36)*100)/36) = 6.5% and $Percentage = \frac{MFLC - smr * 100}{smr}$ (30)

((36.84 -36)*100)/36) = 2.3%

From equations 29 and 30, it can be stated that the proposed model has a 6.5% improvement when compared with the open loop infant incubator and a 2.3% improvement when compared with the FLC.

Conclusion

Mathematicalmodels of the infant and the incubator system were developed.These models were used to control the skin temperature of the preterm infant mass in the Simulink. Results show that the proposed ANFIS model performed better when compared with the other models in terms of maintaining a maximum temperature not greater than 36.6°C for the preterm infant mass.

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