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Design and Simulation of Infant Incubator with Temperature Control

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ABSTRACT: This paper presents a concept of mathematical model of premature infants placed in an infant incubator, it is developed to investigate all heat exchange relationships, variables and factors that have an influence on the overall thermoneutrality of the environment. An incubator is a device made of a box like structure in which a premature baby kept in a controlled environment for medical care. An infant incubator provides stable temperature. The model consists of the infant incubator system which include incubator air space, incubator wall, infant core. Results of the simulation are in form of the temperature variation vs time, of the following parts of the system: infant temperatures and incubator air space temperature. The model of this simulation is a closed-loop system with a PID controller for each mode. The controller parameters are virtually calculated by the Zeigler-Nichols Method. The overall stability of the system has been achieved by applying a step input which was verified by the Root Locus Method. These simulations provide a useful basic information to prepare a real validation in future.

Keywords—Infant incubator, PID controller, Zeigler-Nichols

1. INTRODUCTION

Incubators are a device by which a premature baby(infant) body temperature can be regulated and monitored as needed. Incubators provide protected environment for infants of low birth weight who are naturally sensitive to outside temperature. The first incubator is credited to French physician by Stephane Tarnier, who was looking for a way to warm infants who commonly died of hypothermia with a visit to the Paris Zoo's chicken incubator display, Dr.Tarnier was inspired to develop the first incubator for infant his incubator housed multiple infants and with this prototype, the mortality rate fell by nearly half. This resulted in the significance of the incubator to be accepted worldwide [1].

The modern incubator first design after WW2; it was known as the Air Shields C33. Dr. Charles Chappell was credited with the invention. The Air Shields temperature control was capable of maintaining temperature accurately [2]. The control of temperature is extremely important in the case of the neonatal incubator survivability. The temperature inside the mother's womb is 37.6° C. Leaving the womb at birth, the wet new born finds itself in a much colder environment and starts losing heat. The first 10-20 minutes the infant is not thermally protected may start to lose heat from body and temperature may fall by 2-4° C, with even greater falls if appropriate care is not given [3, 4].

Control systems is purely physical systems such as speed regulators are prime examples of this. The modern control system became frequent around the 1940-1950s. This was supported by the rapid development of technology and computer systems. Over the course of the next few decades, the scope and complexity of control system engineering expanded greatly, seeing applications from general industry to aerospace [5]. To overcome this, we need a technique to control the temperature in order to further conserve power, which is in this paper we use Proportional Integral Derivative (PID) control. PID control technique is likely to get a response that has high degree of stability so that it can more accurately control the temperature and save energy compared to using the on off control [6].

As part of a proposed design of the incubator controller, we have developed a thermodynamic model which is mathematically expressed the complex interaction between a premature infant and an incubator. Model requires the infant gestational age, post pregnancy age, weight, and room temperature and humidity. The output is a minute-by-minute prediction of the infant temperatures and of the incubator's temperatures.

2. MODELLING DESIGN

This One of the major concerns of new born infants particularly preterm infants soon after birth, is providing them with appropriate thermo neutral environments. This can maintain their body's temperature at the normal level of 36.5-37.5 °C. This can only be implemented by placing the infants inside thermo regulating devices, which are also called 'infants warmers' [7,8]. Each body compartment is characterized by a temperature, volume, surface area, density, specific heat, thermal conductivity, and metabolic rate. Each compartment of the model is subjected to the 1st law of thermodynamics (law of energy conservation), namely that in a period of dt, heat balance results in [9,10]:

(Heat in – Heat out) dt = Heat Storage. 1

1. Infant core

Heat produced by infant core (T_c)in a period of time, dt, the heat balance of the core layer can be written as:

$$[Q_{met} - Q_{sen} - Q_{lat} - Q_{cd} - Q_{bc}]dt = M_c C_{Pc} dT_c \tag{2}$$

The instantaneous temperature of core can be written as:

$$\frac{dT_c}{dt} = \frac{Q_{met} - Q_{sen} - Q_{lat} - Q_{cd} - Q_{bc}}{M_c C_{Pc}} \tag{3}$$

Using the differential operator $D = d/dt$ allows equation (1) to be written as:

$$T_c = \frac{Q_{met} - Q_{sen} - Q_{lat} - Q_{cd} - Q_{bc}}{M_c C_{Pc} D} \tag{4}$$

Where, M_c is mass of core it is determined as the difference between infant mass and mass of infant skin and C_{Pc} specific heat of core.

1.1. Heat production of infant Q_{met}

$$Q_{met} = M_{rst} \times S_a \tag{5}$$

Where, M_{rst} is resting metabolic rate and S_a is surface area of infant

1.2. Heat losses of infant core

Convective heat losses during breathing

$$Q_{sen} = IV \times m \times C_{pa} \times \rho_a \times (T_c - T_a) \tag{6}$$

Difference between in haled air and exhaled air

$$Q_{let} = IV \times m \times hfg \times \rho_a \times (W_{ex} - W_a) \tag{7}$$

Where, IV is inspired air volume, m is mass of infant, C_{pa} is specific heat of air, ρ_a is air density, hfg is latent heat of water, humidity ratio of exhailed air is determined by W_{ex} and inhailed air is W_a

$W_{ex} = W_a = 0.622\frac{P_{H_2O}}{P_t - P_{H_2O}}$ and $P_{H_2O} = P_{\mathrm{sat}} \times RH\%$ Where, P_{t} is atmospheric pressure and P_{sat} is saturation pressure 2.234T-18.104

The loss of heat due to conduction through skin layer Q_{cd} is determined by

$$Q_{cd} = \frac{(T_c - T_i)K_c S_a}{m/\rho_c \times S_a} \tag{8}$$

Where, T_s is skin temperature. K_c is thermal conductivity and ρ_c is core density

The blood of core constitutes a medium for convective heat loss is given by

$$Q_{bc} = V_{cb} \times bf \times C_{pb} \times \rho_{bl} \times (T_c - T_s) \tag{9}$$

Where C_{pb} is specific heat of blood, ρ_{bl} is blood density V_{cb} is blood volume and bf is blood flow rate.

The total heat produced by infant core is difference heat produced and losses. The Simulink subsystem module of infant core in subsystem is given below. There are three input one is fed from other compartment and two are constant skin temperature and relative humidity.

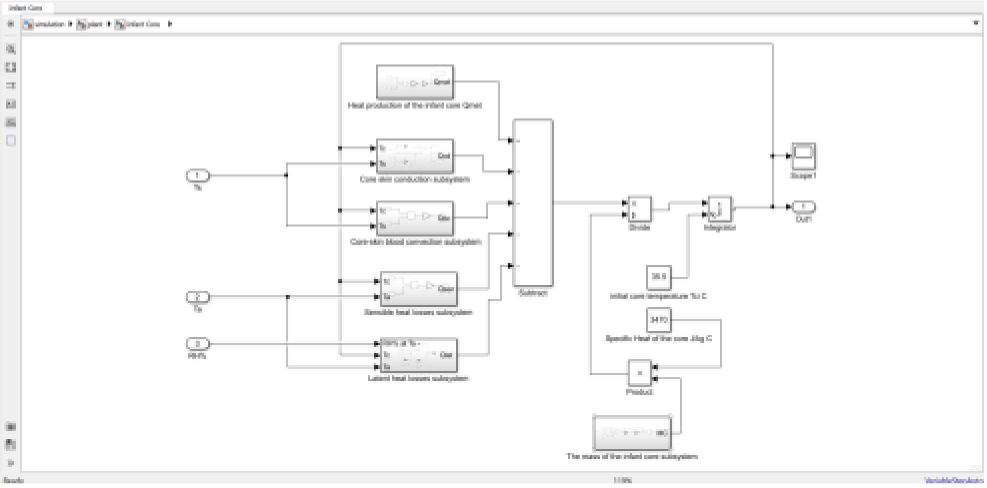

Fig. 1 Simulink subsystem module of infant core compartment.

2. Air space of compartment

The air space module exchanges heat with infant core as well as with wall of incubator by convection and with respiration. Temperature of air space is represented as T_a. Heat balance equation for air space of incubator is given as

$$[Q_{scv} + Q_{se} + Q_{ht} + Q_{sen} + Q_{lat} - Q_{acv}]dt = M_c C_{Pc} dT_a \qquad 10$$

Temperature of air space using D-operator can be written as:

$$T_a = \frac{Q_{scv} + Q_{se} + Q_{ht} + Q_{sen} + Q_{lat} - Q_{acv}}{M_a C_{Pa} D} \qquad 11$$

Where, M_a is mass of air space, C_{Pa} specific heat of air

2.1 Convection from infant skin

Skin undergoes convection of heat losses due to difference in temperature of skin and air space. This determined by the equation as:

$$Q_{scv} = h_{scv} \times A_{cv} \times (T_s - T_a) \qquad 12$$

where, h_{scv} is heat transfer coefficient it is depend on geometry of incubator hood also it the function of the Nusselt and Reynolds numbers [9] and A_{cv} is surface are exposed to air since 90% skin area is exposed to air A_{cv} is give as 0.9× S_a where S_a is total surface area.

2.2 Evaporation losses from the skin Q_{se}

The water losses from skin to air space through evaporation is inversely proportional to the ambient partial pressure of water vapor.

$$Q_{se} = \frac{m \times hfg \times E_{vap} \times P_{H_2O}}{864000} \qquad 13$$

where, E_{vap} is evaporation loss from skin of infant to environment it is the function of gestation age (week age) and postnatal age

$$E\_vap = [6.5 \exp(168/(age + 11.8))(\exp(-5.2GA/(age + 12.2))) + 4.8] + [2(P_{H_2O}/23)] \qquad 14$$

P_{H_2O} is particle pressure of water vapor

2.3 Heat supply subsystem Q_{ht}

Heat energy supplied to incubator air space can be determined as

$$Q_{ht} = \dot{m_a} \times C_{pa} \times (T_{sply} - T_a) \qquad 15$$

where, $\dot{m_a}$ is mass of flow rate incubator air.

2.4 Mass of incubator air M_a

The mass of incubator M_a can be determined by equation below

$$M_a = [[= [Y_{N_2\%} \times P_t/R_{N_2}] + [Y_{O_2\%} \times P_t/R_{O_2}] \times [V_{\text{inv}} / T_a] \qquad 16$$

Where, density of nitrogen $Y_{N_2\%} = 0.79 - O_2\%$ and density of oxygen $Y_{O_2\%} = 0.21 - O_2\%$ as $O_2\%$ is added oxygen which is considered to be zero, V_{inv} is a volume of incubator air space, R_{gas} gas constant for oxygen and nitrogen.

2.5 Incubator air wall convection Q_{acv}

The inner wall of incubator gain heat by convection from the incubator air space as it is considered as the loss fron incubator air space compartment.

$$Q_{acv} = h_{acv} A_{wi} Q_{cvo} \qquad 17$$

where, A_{wi} is surface area of wall and h_{acv} is depends on the geometry of the incubator hood and the regime of the airflow inside the hood. It is also a function of the Nusselt and Reynolds numbers [9]. $h_{acv} = NU\ (\frac{k_a}{Dh})$

NUNusselt number for the incubator inside, ka thermal conductivity of the incubator air space and Dh is friction factor for internal forced convection

The Simulink subsystem module of air space is show below. There are five input three is fed from other compartment and two are constant skin temperature and relative humidity.Q_{sen} and Q_{lat} are defined in equation (6) (7) respectively.

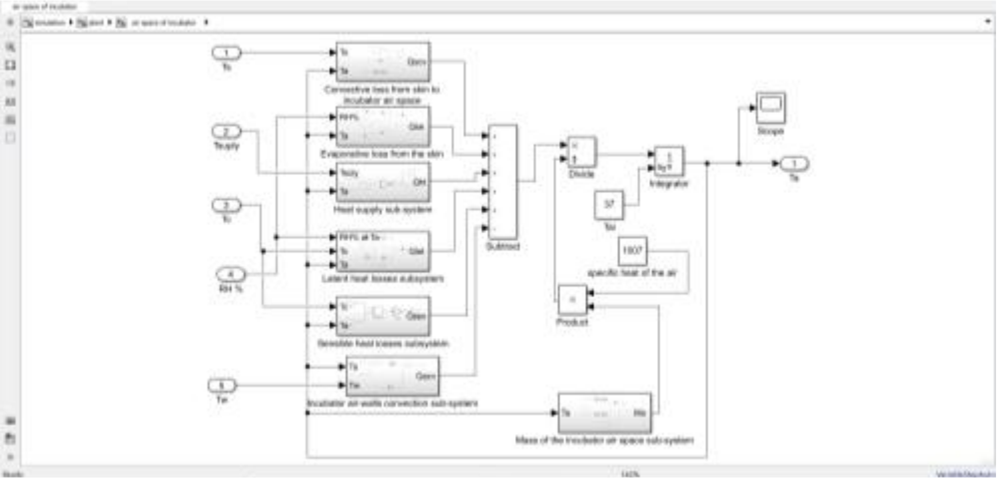

Fig. 2 Simulink subsystem module of air space compartment.

3. Wall of incubator

The wall of incubator represents variations of an incubator wall temperature over time. This system reflects the relationship between infant skin and internal and external wall of incubator in terms of convection and radiation.

$$[Q_{acv} + Q_{sr} - Q_{cvo} - Q_{ro}]dt = M_w C_{Pw} dT_w \qquad 18$$

Temperature of wall using D-operator can be written as:

$$T_w = \frac{Q_{acv} + Q_{sr} - Q_{cvo} - Q_{ro}}{M_w C_{Pw} D} \qquad 19$$

The inner surface of the incubator wall gains heat by convection from the incubator air space, Q_{acv} which is determined using equation (17).

3.1 Skin wall radiation Q_{sr}

The wall gain heat from the skin of infant by radiation the rate of radiative heat transfer Q_{sr} given as:

$$Q_{sr} = A_r \times \varepsilon_s \times \sigma \times [(T_s + 273.15)^4 + (T_w + 273.15)^4] \qquad 20$$

where, A_rThe surface area of the infant normal to the walls of the incubator,ε_s is Radiant emissivity of the skin, assumed to be 1.0 and σ is Stefan-Boltzmann constant, 5.64×10-8 W/m2.K4

3.2 convective heat transfer wall to environment

The rate of convective heat transfer is determined by Q_{cvo} is

$$Q_{cvo} = h_{cvo} A_{wi} (T_w - T_e) \qquad 21$$

where, A_{wi} is Surface area of the incubator walls and h_{cvo}heat transfer coefficient for free convection.

3.3 walls-room environment radiation

The rate of radiation heat transfer from wall to environment is determined by Q_{ro} .

$$Q_{ro} = A_w \times \varepsilon_w \times \sigma \times [(T_w + 273.15)^4 - (T_e + 273.15)^4] \qquad 22$$

where, A_wNormal surface area of the incubator,ε_w is Radiant emissivity of the wall, assumed to be 0.86 and σ is Stefan-Boltzmann constant, 5.64×10-8 W/m2.K4.

3.4 The mass of incubator wall

The mass of the incubator walls, M_w , is determined using:

$$M_w = \rho_w th_w A_{wi} \tag{23}$$

where, ρ_w is wall material density, th_w is wall thikness and A_{wi} surface area of the incubator

The Simulink subsystem module of wall of incubator is show below. There are two input one is fed from other compartment and one are constant skin temperature.

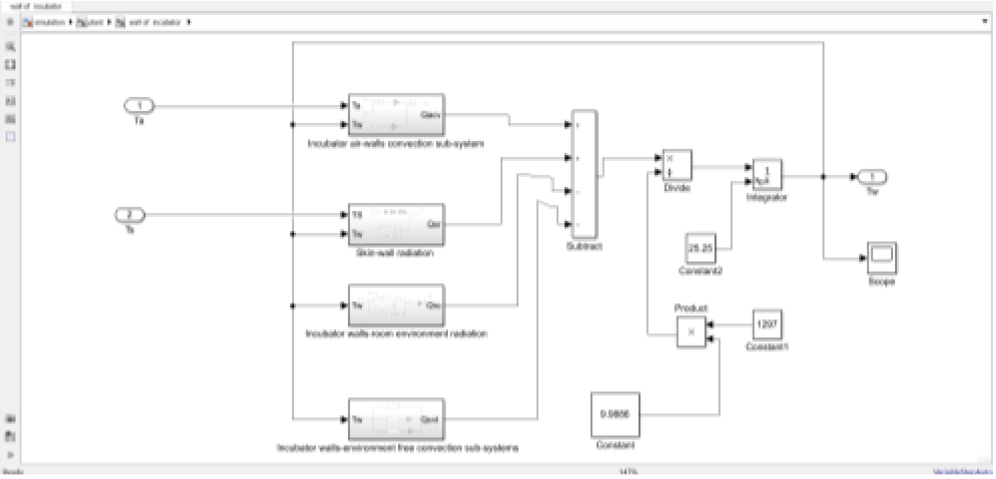

Fig. 3 Simulink subsystem module of wall compartment.

4. Mixed air compartment

T_{mx} is the response to variation in the concentration of added oxygen as well as variation in the densities of N_2 and O_2 in incubator air space as temperature is changes. These N_2 and O_2 concentration in incubator air remains normal at 79% and 21%. Some assumptions are made such that material is homogeneous and distribution of temperature is uniform.

$$T_{mx} = \frac{\dot{m_a} C_{pa} T_a + \dot{m_{O_2}} C_{PO_2} T_{O_2}}{\dot{m_{mx}} C_{Pmx}} \tag{24}$$

where, $\dot{m_{mx}}$ mass flow rate of mixed air, $\dot{m_a}$ mass flow rate of incubator air, $\dot{m_{O_2}}$ is mass flow rate of oxygen, specific heat of mixed air is same as incubator air $C_{Pmx} = C_{pa}$. The final density of the incubator air depends on N2 and O2 gases. The Simulink subsystem module of mixed air compartment is shown below.

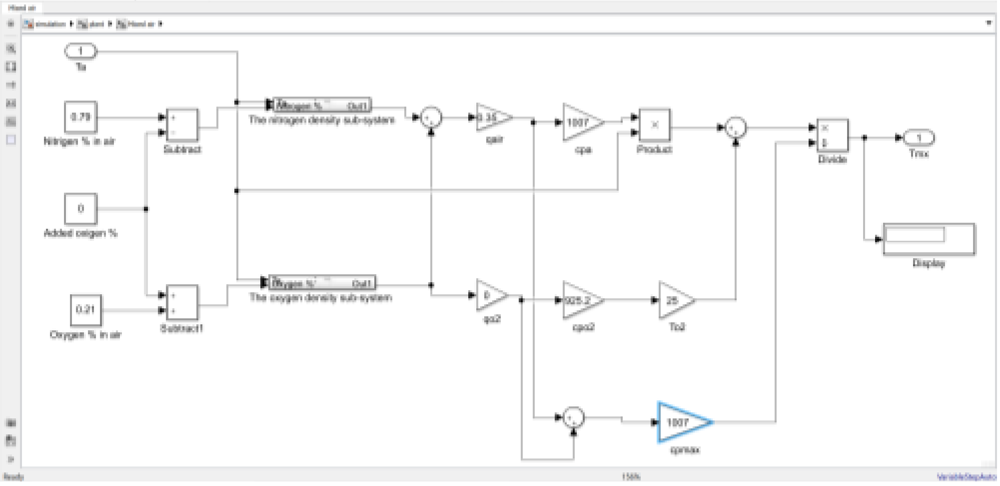

Fig. 4 Simulink subsystem module of mixed air compartment.

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5. Heated air compartment

Simulink model the heated air temperature varies as the variation of T_{mx}, the percentage of the added oxygen which varies the density of N2 and O2 and thus the density of the circulated air. It also adjusts the power rating of the heater element.

$$T_{ha} = T_{mx} + \frac{Q_{heater}}{\dot{m_a} C_{pa}} \qquad 25$$

where, Q_{heater} is reference temperatature given to the system.

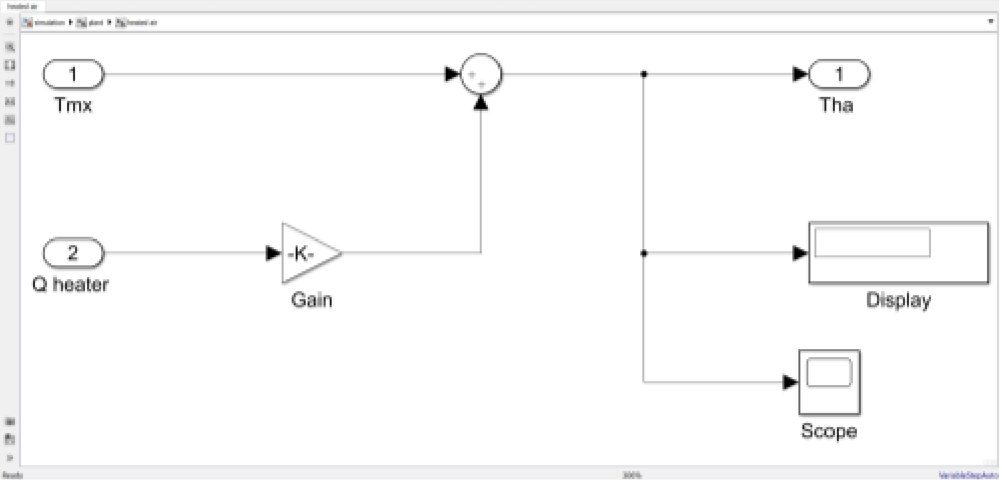

Fig. 5 Simulink subsystem module of heated air compartment.

The simulink module of all subsystem is shown below where T_{heat} is input to the plant from controller and air space temperature considered T_a is consideed as the ot of the plant.

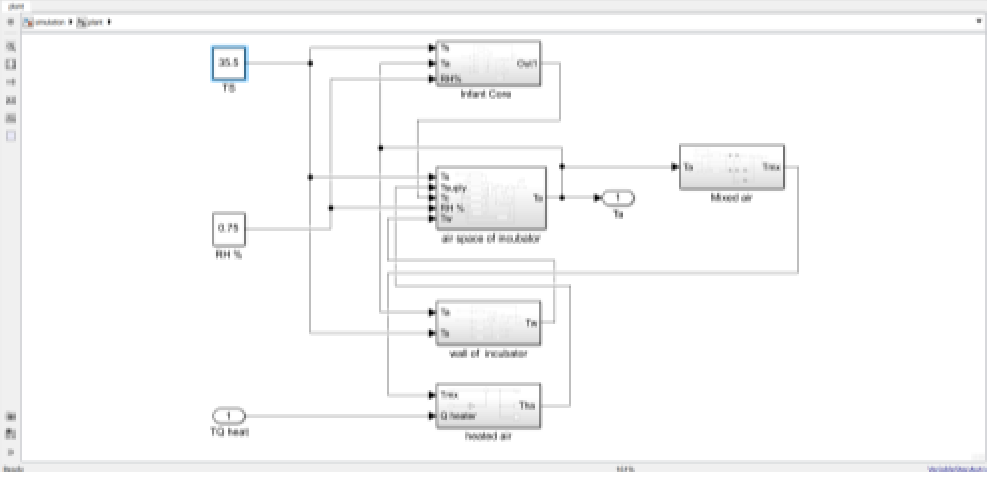

Fig. 6 Simulink module of plant.

3. CONTROLLER DESIGN

PID controller provides a more convinient improved response compared to other controller in termes of rise time, minimised stability time and reduced oscillation. The parameters of the PID system are selected using continuous cycling Ziegler-Nichola method availabele in several controller engineering books. Increase gain Kc slowly and monitor y(t) whether it shows oscillating response. If y(t) does not respond to Kc change apply a short period of small pulse input on r(t) input. Increase Kc until y(t) shows continuous cycling. Let Ku be Kc at this condition. Tu is period of oscillation under this condition [11].

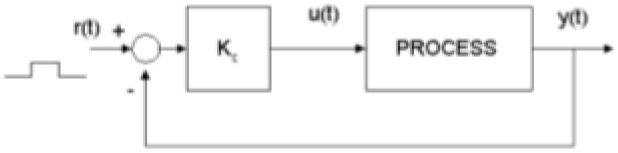

Fig. 7 Simulink module of plant.

Controller	Kc	Ti	Td
P	0.5Ku	-	-
PI	0.45Ku	Tu/1.2	-
PID	0.6Ku	Tu/2	Tu/8

Table 1. Ziegler-Nichols Controller Settings

We call Ku ultimate gain, Tu ultimate period ($w_{co} = 2\pi/T_u$ critical frequency)

4. SYSTEM STABILITY

The system stability is verified sing MATLAB function, in terms of response of input and output to step input applied on to a feedback system. MATLAB function linearize the Simulink module and convert it into state space module, which consist of A, B, C and D matrices of appropriate dimension. Using function in MATLAB we get transfer function tf. The stability of the system has been examined with help of root locus method it shown in below figure. It found that system is stable for all values of gain k [12,13].

$$tf = \frac{0.006385\, s^2 + 26.145\, s + 0.1455}{s^3 + 8.27e^{04} s^2 + 1.547e^{06} s + 8602}$$

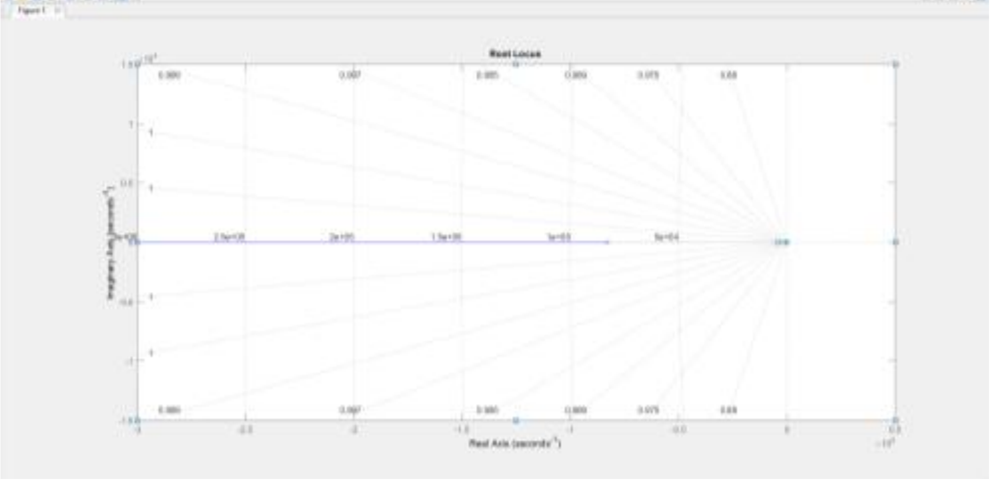

Fig. 8 Root locus of system

5. SIMULATION RESULTS

The simulation model of the infant-incubator system developed in the MATLAB® which provides numerous quantitative results such as the final temperatures for each compartment, as well as other results for each subsystem blocks of each compartment. Skin temperature of infant is considered as 36.5° C and relative humidity of incubator is considered as 70%. Step input which acts as the input the system is set as 37.2℃ as determined by LeBlanc [14]. The outside environment temperature is considered as 25° to 38° C.

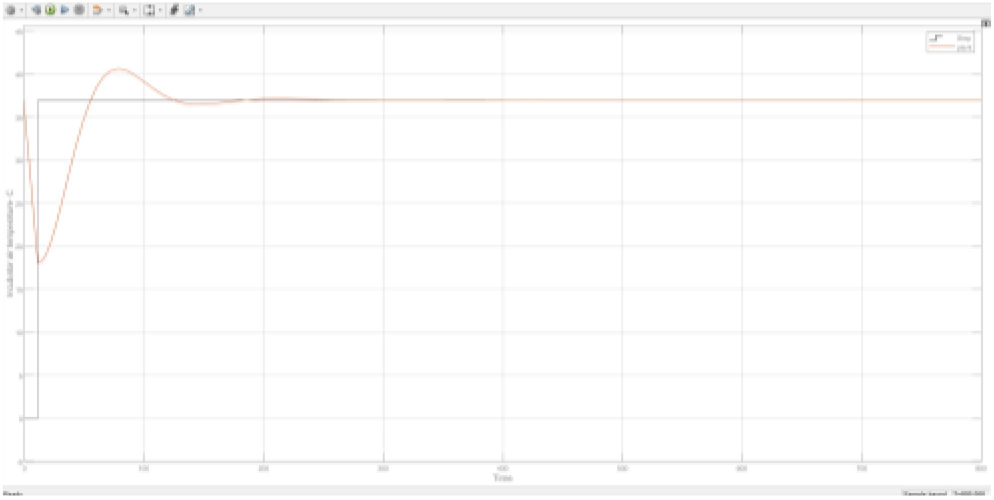

Fig. 9 Output of the system

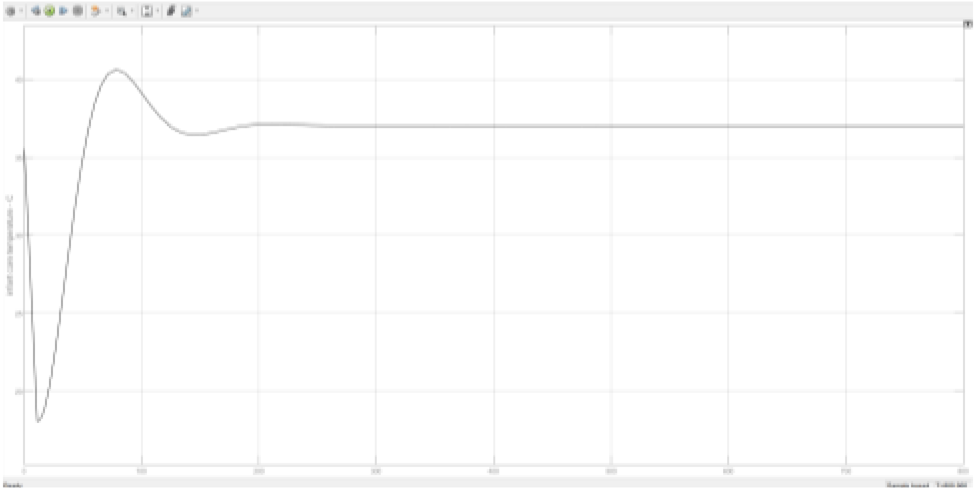

Fig. 10 Infant core temperature

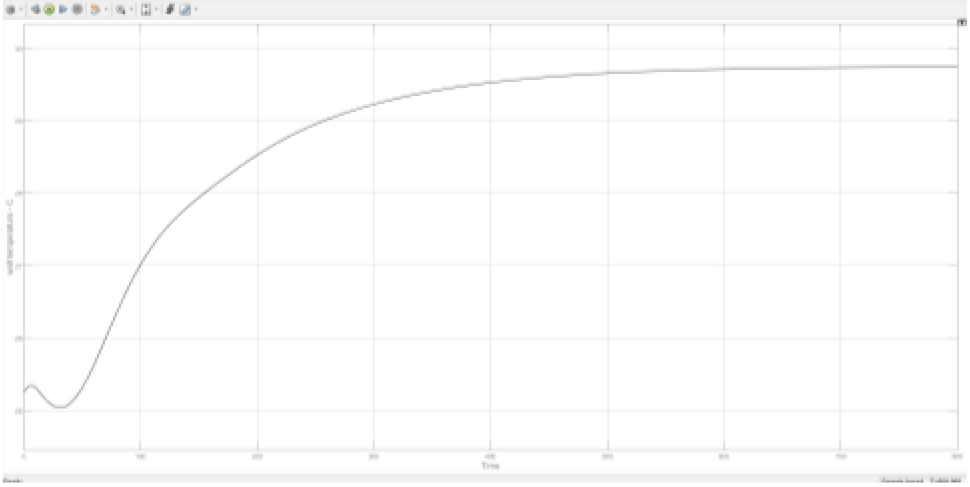

Fig. 11 Wall temperature

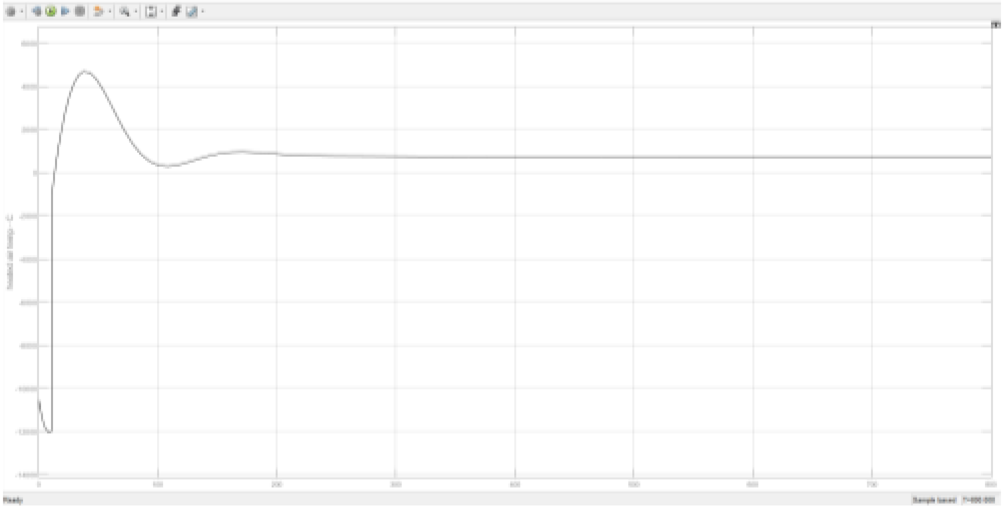

Fig. 12 Heated air temperature

CONCLUSION

The module includes the thermodynamic model of infant and thermodynamic model of an incubator. It is a complex thermodynamic interaction between infant and incubator. We have shown that model predicted temperature and heat changes in incubator. The overall model presented used for improving the performance of infant incubator.

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