IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 7 December 2023, accepted 29 December 2023, date of publication 3 January 2024,
date of current version 16 January 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3349426

RESEARCH ARTICLE

Design of Multivariable PID Control Scheme for Humidity and Temperature Control of Neonatal Incubator

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ABSTRACT A preterm baby requires an environment identical to that of the womb. Therefore, a neonatal incubator can be used to provide an environment comparable to that of neonates in women. In this study, the overall system was designed using mathematical analysis. The neonate is shown as a single lump with two layers: core and skin. The model included all components of the neonatal incubator system. The neonatal incubator system was simulated using the MATLAB/Simulink software. Both the skin and air modes have a closed-loop simulation model controlled by a multivariable PID controller. In fact, we performed tuning using the sequential loop-closing tuning method. The simulation results show that for the skin temperature (T_s), the overshoot is reduced from 23.1096% to 6.117% and the settling time is also reduced from 4066.8 seconds to 755.8 seconds using decoupling and sequential loop closing tuning method with PID controller. Similarly, for air temperature (T_a), the overshoot was reduced from 59.65% to 7.2456%, and the settling time was also reduced from 2302.1 seconds to 530.48 seconds. For both skin mode and air mode operation, using decoupling and sequential loop closing tuning method with PID controller, the relative humidity has an improved settling time with an overshoot of 8.559% and 9.43%, respectively. In general, a PID controller improves the overall system performance. The PID controller accelerated the system by reducing the time constant.

INDEX TERMS Humidity, multivariable PID controller, neonatal incubator, temperature.

I. INTRODUCTION

For approximately 160 years, incubators have been used to produce and maintain a safe and comfortable hydrothermal atmosphere for low-birth weight, sick, or preterm newborns. The concept of these devices has evolved over time. Currently, most of them have to maintain the humidity and temperature in optimal ranges set by the medical staff [1], [2], [3].

Neonatal nursing in carefully air-controlled incubators was found to reduce mortality rates by at least 22%. Determining which variables or stimuli can be used to influence the generation of heat is an intriguing topic for research when researching a control system. In contrast to the absolute values of either deep body temperature or surface temperature, Adamsons, Gandy, and James found that the rate of oxygen consumption of neonates is primarily a function of the temperature gradient between the body surface and the surroundings. A flow sensor is required to assess the temperature difference between the skin and surroundings if heat generation is controlled by heat flow [4], [5], [6].

Professor Mildred Stahlman founded the first recognized neonatal intensive care unit (NICU) at Vanderbilt University in 1961. Premature or exceptionally small babies are placed in an incubator to provide a regulated and protected environment for care [7], [8].

In the developing world, more than 1 million neonates die due to heat loss and dehydration, which could have been prevented with the use of a neonatal incubator. Thus, Incubators provide a comfortable environment for neonates, which

The associate editor coordinating the review of this manuscript and approving it for publication was Min Wang.

aids in regulating temperature and humidity. The incubator is a specially designed air-conditioned room in which the condition of the baby can be monitored. Incubators are specially developed to provide the best possible environment for newborns with growth issues or illnesses [9], [10].

The incubator is a dust- and bacteria-free environment with the ability to maintain optimum levels of humidity, oxygen, and temperature by regulating them. Heat loss from newborns should be reduced by temperature and humidity management. Temperature, humidity, oxygen saturation, and light are key physical elements that determine the incubator environment [11], [12].

In this study, a mathematical model was designed for the overall system of a neonatal incubator. Using the mathematical model, it is possible to use a variety of design strategies to choose controller parameters that satisfy the transient and steady-state requirements of the plant [13], [14].

Controller tuning is the process of choosing controller parameters to satisfy the stated performance requirements. In order to select values for K_p, T_i, and T_d based on experimental step responses, Ziegler and Nichols proposed certain guidelines for tuning PID controllers. Instead of providing the final settings all at once, Ziegler- Nichols tuning rules offer an appropriate prediction that serves as an initial point for fine tuning [13], [15].

The sequential loop closing (SLC) method is a well-known method for tuning multi-loop control systems for multivariable processes. In this method, each controller is designed sequentially with single-input single-output methods by finding the transfer function for the paired input and output, while the former loops are closed. The relative humidity and temperature coupling system is based on the strong coupling qualities between temperature and humidity management processes. Without decoupling, each loop in such systems interferes with the others during operation, making it challenging to obtain the best possible control effect. The decoupler is compensated and positioned in front of the control object or on the feedback channel to eliminate the coupling between temperature and relative humidity. In this study, the feedforward compensation decoupling approach, which is based on the feedforward compensation principle, was used. The coupling channel is considered as the disturbance signal of the control object to perform the feedforward compensatory decoupling of the disturbance signal [24].

A paper entitled "Temperature and Humidity Controlling System for Baby Incubator" was published by Abdul Latif et al. in 2021. The incubator in this study had a length of 60 cm, a width of 40 cm, and a height of 30 cm. The fan and/or heating in the baby incubator will automatically turn on or off based on the typical incubator temperature and humidity ranges. Temperatures ranging from 33°C to 35°C are commonly used. While the normal range for air humidity in the incubator is 40 to 60%, The data collection system includes a temperature and humidity sensor, an ATmega8535 microprocessor, a fan, a heater, and an LCD to manage the temperature in the incubator [18].

In 2019, "a review of industrial MIMO decoupling control" was published by Liu et al. Multi-input and multi-output systems are becoming increasingly popular in industrial applications. Various decoupling control techniques have been investigated. The scattered coupling interaction analysis and decoupling algorithms were gathered in this work and split into distinct groups, each with its own set of characteristics, application fields, and helpful comments for selection. Furthermore, some of the most commonly discussed decoupling control issues have been highlighted [27].

This research mainly focuses on designing a neonatal incubator system using a multivariable PID controller to monitor and adjust temperature and humidity. Proportional, Integral, and Derivative (PID) is a method for automatically regulating a plant. This is one of the most well-known and widely used techniques. In this work control scheme for a non-linear multivariable neonatal incubator system is designed. A multivariable controller is designed using model-based design method and sequential loop closing methods are employed. A two-stage design procedure is proposed. First decouplers are designed using model-based methods. Second the closed loop controllers are designed using the sequential loop closing methods. Further the performance of the proposed design method is compared with the multi-loop control scheme.

Mathematical modeling of neonatal incubator is presented in section II. Design of proposed multivariable PID controller design method is presented in section III. The simulation and comparison results are presented in section IV followed by concluding remarks in section V.

II. MATHEMATICAL MODELING OF NEONATAL INCUBATOR

Providing suitable thermo-neutral conditions for newborn neonates, particularly preterm neonates, while feeding them shortly after birth, is a crucial concern. This allows neonates to have a standard temperature between 36.5 and 37.5 °C [9], [17].

A. NEONATAL INCUBATOR COMPONENTS

The neonatal incubator consists of many components, such as the core layer, skin layer, air inside the incubator, walls, mattress, heater, and fan. These components exhibit their own heat interactions, as shown in Fig. 1. Radiation, conduction, evaporation, and convection are the four ways in which a baby loses heat [18].

To simplify the modelling, appropriate assumptions were made where necessary. Various empirical relationships were implemented during the modelling process to further simplify the equations [16], [19].

The type of incubator model selected for this study was the ATOM V-850. This type of neonatal incubator is most commonly used [16]. The heat flow between the components of the neonatal incubator is illustrated in Fig. 1.

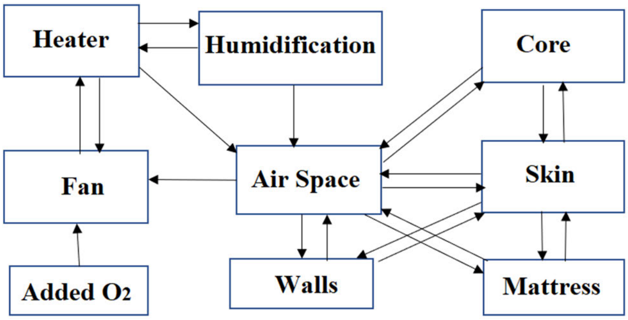

FIGURE 1. Neonatal incubator component interactions.

B. NEONATE MODELING

The neonate can be modeled by considering the neonate as one or four lumps. For the four lumped together, the parts of the neonates were considered as limbs (upper and lower), head, and trunk. The neonate was divided into core and skin layers in each of the formulated models, as shown in Fig. 2 [16], [20].

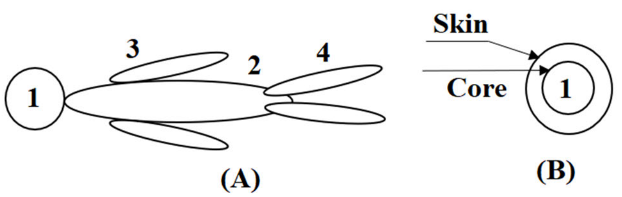

FIGURE 2. (A) Neonate modelling, (B) Layers of the neonate.

In this study, the neonate was considered to have one lump. Many assumptions were made to simplify the neonatal model. For instance, the neonate is modelled as a black cylinder, the neonate is considered at rest, and the incubator is placed in a room with air that has a minimum velocity.

The components of the neonatal incubator exhibited temperature changes over time. This change in temperature is called the instantaneous temperature. The first law of thermodynamics is applicable for modeling each component using mathematical analysis. The heat storage (Q_{str}) is the difference between the heat in (Q_{in}) and heat out (Q_{out}), and can be computed using the energy conversion law of the heat balance in a period dt as follows [21]:

$$Q_{str} = [Q_{in} - Q_{out}]\, dt \tag{1}$$

1) MODELING OF THE CORE LAYER

When the core layer is modelled, mathematical equation (2) can be used by considering the neonate mass as one lump. Therefore, the heat balance over a period of time was calculated as [18]:

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

where: Q_{met} denotes the neonate's core ability to generate heat, Q_{sen} denotes sensible heat, Q_{lat} denotes latent heat, Q_{cd} stands for skin layer conduction, Q_{bc} is Convection skin-blood, m_c is the neonate's core mass, C_{pc} is Core specific heat, T_c is Core temperature.

2) MODELING OF THE SKIN LAYER

When the skin layer is modelled, mathematical equation (3) can be used by considering the neonate mass as one lump. Therefore, the heat balance over a period of time was calculated as [21].

$$dT_s m_s C_{psk} = \left[Q_{bc} + Q_{cd} - Q_{sr} - Q_{se} - Q_{scv} - Q_{mc}\right] dt \tag{3}$$

where: Q_{scv} is skin-incubator airspace convection, Q_{mc} is skin-mattress conduction, Q_{se} stands for skin evaporative loss, Q_{sr} stands for skin-wall radiation, Q_{cd} is Skin layer conduction, Q_{bc} is Convection skin-blood, m_s is neonatal skin mass, C_{psk} is skin specific heat, T_s is skin temperature.

C. MODELING OF THE INCUBATOR

1) MODELING OF THE AIR SPACE

The neonatal incubator system facilitates heat transfer with the incubator air space, mostly by convection. The processes of evaporation and respiration also include mass and heat transfer.

The air temperature in the incubator (T_a) was calculated as follows:

$$dT_a C_{pa} M_a = [Q_{acv} + Q_{se} + Q_{scv} + Q_{sen} + Q_{ht} + Q_{lat} - Q_{mat}]dt \tag{4}$$

2) MODELING OF THE INCUBATOR WALLS

Plexiglass was used to construct the walls of the incubator. The walls had a thickness of 6 mm. The wall temperature (T_w) was calculated using the heat balance equation.

$$dT_w C_{pw} M_w = \left[Q_{sr} + Q_{acv} - Q_{ro} - Q_{cvo}\right] dt \tag{5}$$

3) MODELING OF THE MATTRESS

The neonatal skin conducts heat through the mattress, and the incubator airspace convection heats the mattress. The mattress temperature (T_m) was computed using the heat balance equation.

$$dT_m C_{pm} M_m = [Q_{mat} + Q_{mc} - Q_{ic}]dt \tag{6}$$

D. MODELING OF THE HEATING ELEMENT

The temperature of the mixed air was determined using the heat balance equation.

$$T_{mx} C_{p_{mx}} \dot{m}_{mx} = \dot{m}_a C_{p_a} T_a + \dot{m}_{O_2} C_{p_{O_2}} T_{O_2} \tag{7}$$

where: $\dot{m}_{mx}$ is the mass flow rate of the mixed air, $\dot{m}_{O_2}$ is added oxygen mass flow rate, $\dot{m}_a$ is incubator mass flow rate.

The mixed air temperature can be modified using the volumetric air and oxygen flow rates, as follows:

$$T_{mx} = \frac{T_a q_{air} C_{p_a} \rho_a + T_{O_2} q_{O_2} C_{pO_2} \rho_{O_2}}{C_{p_{mx}}(q_{air}\rho_a + q_{O_2}\rho_{O_2})} \tag{8}$$

where: C_{pmx} is considered to be equal to C_{Pa} (1007 J/kg.°C) [21].

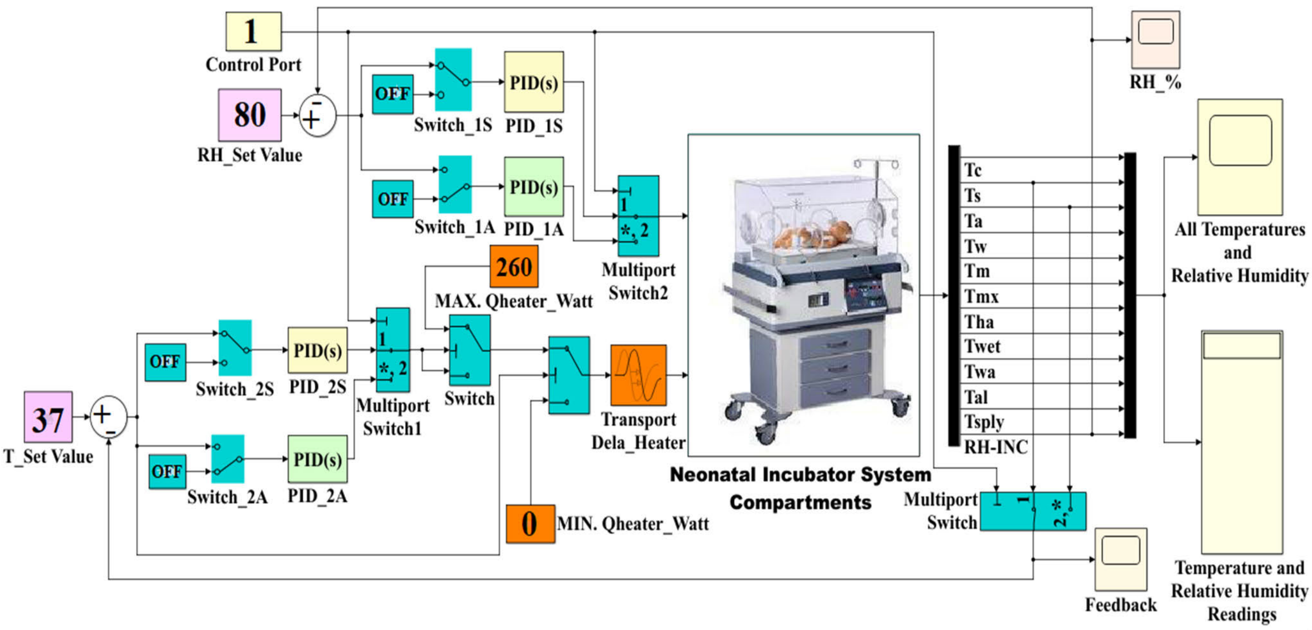

FIGURE 3. Overall simulation model.

E. MODELING OF THE HUMIDIFICATION SYSTEM

The humidifier adds water vapor to the humidification system. This system is composed of plastic containers and finned aluminum blocks. Air exchange was conducted using 80 mm × 50 mm openings.

The airflow rate through these openings can be calculated as follows:

$$Q_{ah} = A_{op} \times V_a \tag{9}$$

where: $V_a = 0.1$ m/sec and $A_{op} = 0.004$ m^2. Hence, the air flow rate is 0.0004 m^3/sec.

The heat was stored in an aluminum block. The stored heat is exchanged between the water and air by convection. Through conduction, some heat was transferred to the unshielded components of the aluminum block.

The water tank air temperature was calculated using the heat balance equation as expressed below [16].

$$\begin{aligned} dT_{wet} C_{p_a} M_{ah} &= \left[\dot{m}_a C_{p_a} T_{ha}\right] dt + \left[A_{wa} \frac{h_{wa}}{C_{pm}} \left(W_{wet} - W_{ha}\right) hfg_1\right] dt \\ &\quad - \left[A_{wa} h_{wa} \left(T_{wet} - T_{wa}\right)\right] dt \\ &\quad - \left[h_{al1} A_{al1} \left(T_{wet} - T_{al}\right)\right] dt - \left[\dot{m}_a C_{p_a} T_{wet}\right] dt \end{aligned} \tag{10}$$

The water mass temperature (T_{wa}) was calculated using the heat balance equation as follows:

$$\begin{aligned} dT_{wa} C_{P_{wa}} M_{wa} &= \left[A_{wa} h_{wa} \left(T_{wet} - T_{wa}\right)\right] dt \\ &\quad + \left[A_{al_2} h_{al_2} \left(T_{al} - T_{wa}\right)\right] dt \\ &\quad - \left[A_{wa} \frac{h_{wa}}{C_{pm}} hfg_1 \left(W_{wet} - W_{ha}\right)\right] dt \end{aligned} \tag{11}$$

The aluminium block temperature (T_{al}) is also derived from the heat balance equation as follows:

$$\begin{aligned} dT_{al} C_{p_{al}} M_{al} &= \left[A_{al_1} h_{al_1} (T_{wet} - T_{al})\right] dt + \left[A_{al_2} h_{al_2} \left(T_{wa} - T_{al}\right)\right] dt \end{aligned} \tag{12}$$

The temperature of the supplied air (T_{sply}) was calculated as follows.

$$T_{sply} \left(\dot{m}_{wet} + \dot{m}_{dry}\right) C_{p_a} = T_{wet} \dot{m}_{wet} C_{p_a} + T_{ha} \dot{m}_{dry} C_{p_a} \tag{13}$$

The relative humidity (RH) can be determined using the dew point temperature (t_d) and air temperature (t) as follows [22] and [23]:

$$RH = 100 - 5 \times (t - t_d) \tag{14}$$

III. MULTIVARIABLE PID CONTROLLER DESIGN USING MATLAB/SIMULINK

The neonatal incubator system model, which was mathematically modelled in Section II, was transformed into a computer simulation for each component. A model was constructed for each component of the plant using the MATLAB/Simulink software. Then, in a single block known as the Plant, these Simulink models are linked via internal loops. In other words, the input to one component serves as the output to the other.

The temperature and relative humidity levels are essentially the two variable inputs of the plant. The plant is then connected to a multivariable PID controller. The general concept of the simulation model is illustrated in Figs. 3 and 4.

The neonatal incubator system consisted of 12 components. These components were divided into two parts. These

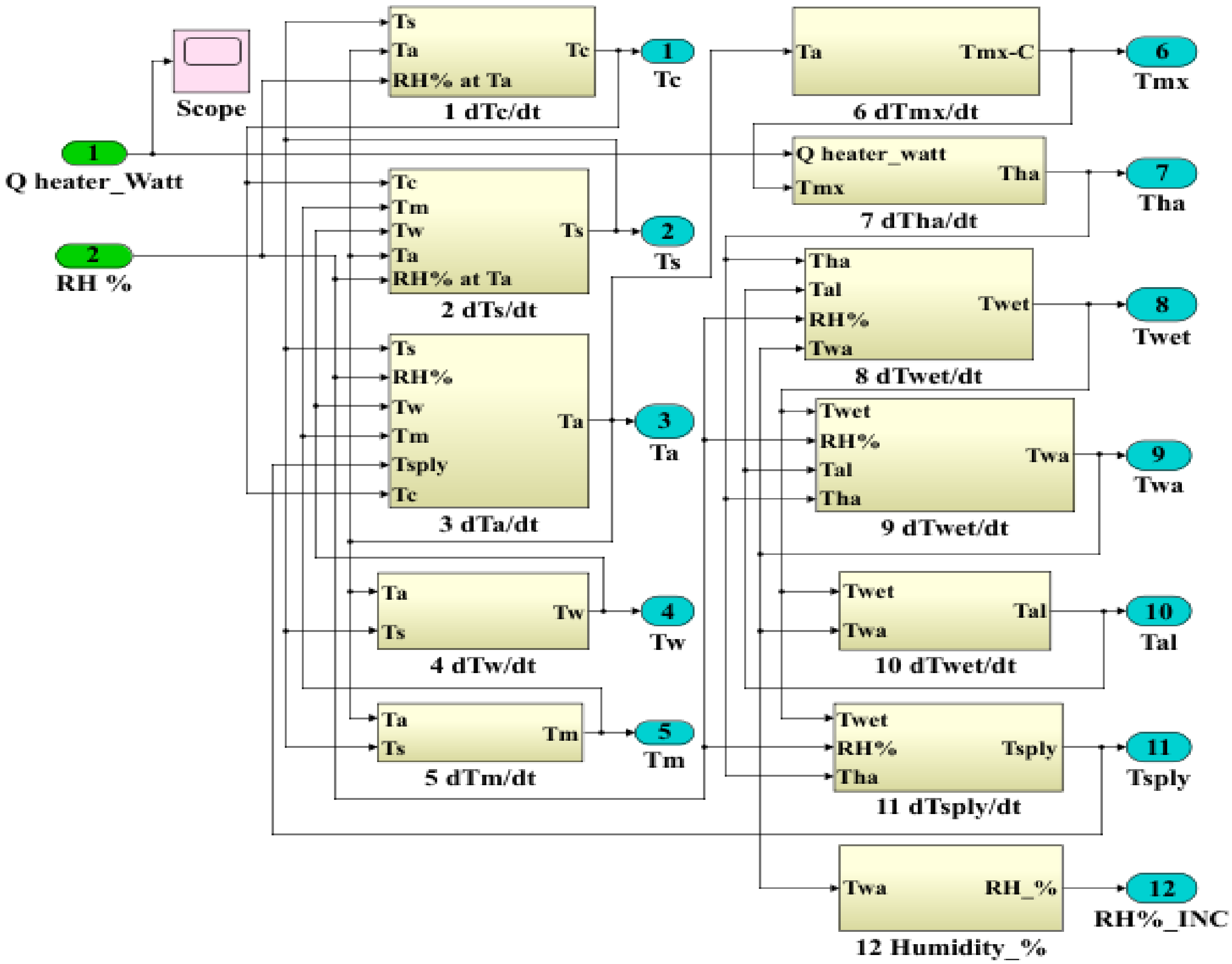

FIGURE 4. Overall system components.

are the neonate and incubator parts, respectively. The neonate parts were the skin and core layers, while the incubator parts were the mattress, heater, walls, blowing fan, air space inside the incubator, air space (above the water surface), heat sink (aluminum), supplied air temperature, water surface, and relative humidity.

A. SYSTEM DESIGN WITH MULTIVARIABLE PID CONTROLLER

Fig. 5 shows a system that illustrates a centralized control organization. More transfer function blocks (decouplers) can be added between the controller loop and the process. The primary goal of decoupling is to compensate for the loop interactions caused by cross-couplings of the process variables [25], [26]. Interactions between system variables cannot be entirely removed, even if decouplers are used. In this case, a sequential tuning approach that considers relations is used. The fundamental concept is to use a single loop to analyze a series of control loops using decouplers. This sequential tuning process can be continued until all controller parameters have converged. It should be noted that the system acted as a single loop for each tuning stage. Thus, any single-loop tuning method can be used to tune numerous control loops sequentially and iteratively [25].

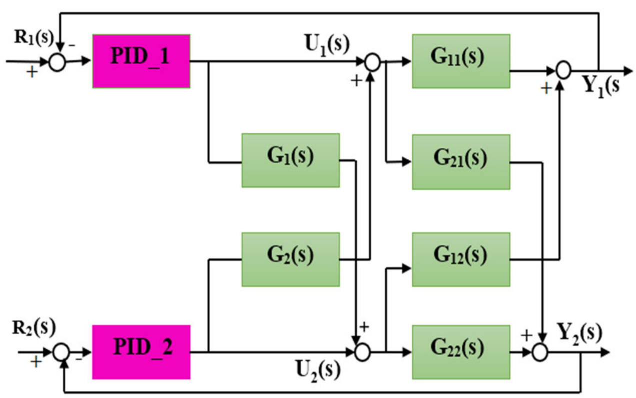

FIGURE 5. Feedforward decoupling with multivariable PID controller.

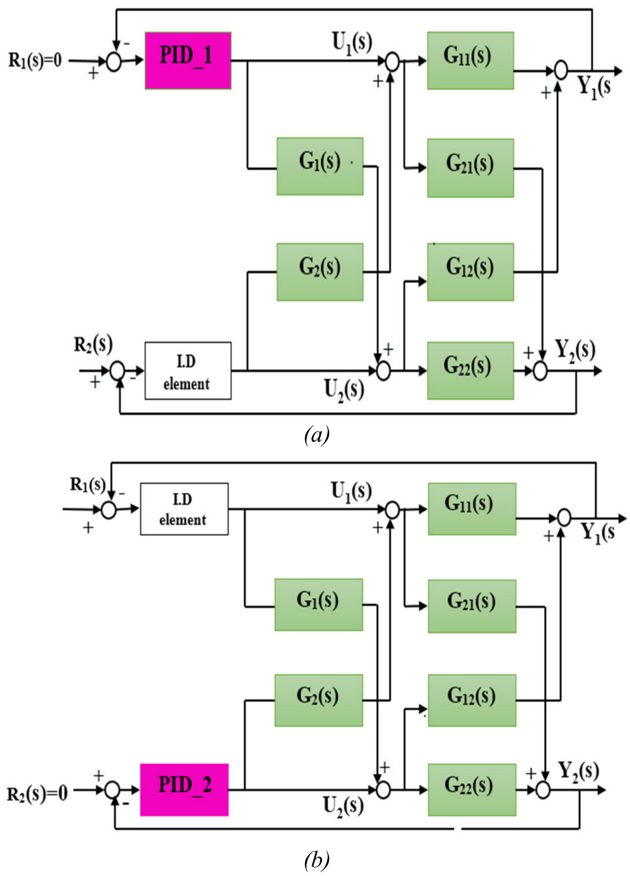

FIGURE 6. **Procedures of the sequential tuning method.**

The method of feedforward compensation decoupling principle can be stated using the mathematical expression as follows.

$$\frac{Y_2(s)}{U_1(s)} = G_{21}(s) + G_1(s)\, G_{22}(s) = 0 \tag{15}$$

$$\frac{Y_1(s)}{U_2(s)} = G_{12}(s) + G_2(s)\, G_{11}(s) = 0 \tag{16}$$

From equations (15) and (16), the feedforward decouplers $G_1(s)$ and $G_2(s)$ can be determined as:

$$G_1(s) = -\frac{G_{21}(s)}{G_{22}(s)} \tag{17}$$

$$G_2(s) = -\frac{G_{12}(s)}{G_{11}(s)} \tag{18}$$

Fig. 6 depicts the procedure of the sequential loop closing (SLC) tuning method using two control loops. As shown in Fig. 6 (a), the tuning process started at loop 1 by applying a closed-loop identification test. Subsequently, the controller settings were fixed. Similar tasks are continued for loop 2, as shown in Fig. 6 (b). The sequential tuning procedure is continued until convergence of all controller parameters is achieved. This procedure is continued by alternatively using Fig. 6 (a) and (b) and considering the system as a single loop.

The SLC method is well suited for designing control systems and identifying process models. The classical SLC method, applied to tune multiloop control systems in the field, identifies a transfer function between the paired input and output at each step. However, outputs other than the paired output are also excited, whereas the paired output is excited for identification. Hence, if these signals are analyzed appropriately, all the transfer functions can be obtained.

In this study, for the skin mode operation, the system without decoupling is shown in Fig. 7 and the simulation result is shown in Fig. 8. This system should be decoupled to eliminate interaction between skin temperature and relative humidity using feedforward decoupling method. Therefore, the MATALB model, which simulates the working of a neonatal incubator with a PID controller in skin mode, is shown in Fig. 9 and its simulation result is shown in Fig. 10. The skin temperature is set to 36.5 degrees Celsius, with an additional humidity of 80 % [28], [29].

Similarly, for air mode operation, Fig. 11 shows the system without decoupling and the simulation result is shown in Fig. 12. This system should be decoupled to eliminate interaction between temperature of air and humidity using the feedforward decoupling method. Therefore, the MATALB model, which simulates the working of a neonatal incubator with a PID controller in air mode, is illustrated in Fig. 13 and its simulation result is shown in Fig. 14. The temperature of air is set to 37 degrees Celsius with an additional humidity of 80% [28], [29].

For both skin and air mode operations, the multivariable PID controller parameters values when the SLC tuning method is applied are listed in Tables 1 and 2.

TABLE 1. **The multivariable PID controller values for loop 1.**

S/N	PID Controller Values	Skin Temperature (T_s)	Relative Humidity (RH)
1.	Proportional (P)	105.061	46.945
2.	Integral (I)	0.2968	2.097
3.	Derivative (D)	37.12	29.678

TABLE 2. **The multivariable PID controller values for loop 2.**

S/N	PID Controller Values	Air Temperature (T_a)	Relative Humidity (RH)
1.	Proportional (P)	5.193	52.538
2.	Integral (I)	0.034	2.946
3.	Derivative (D)	97.274	31.556

The open loop system for both air mode and skin mode are non-linear systems as shown in Fig. 4. Therefore, these systems should be linearized using the MATLAB *Linear Analysis Tool*. The linear analysis tool is applied so as to drive the transfer function of the system. MATLAB uses Taylor series approximation. As it is observed from simulation results using *controlSystemDesigner tool*, the system is stable for both air mode and skin operations.

Simulink Control Design linearizes models using a block-by-block approach. This block-by-block approach individually linearizes each block in the Simulink model and

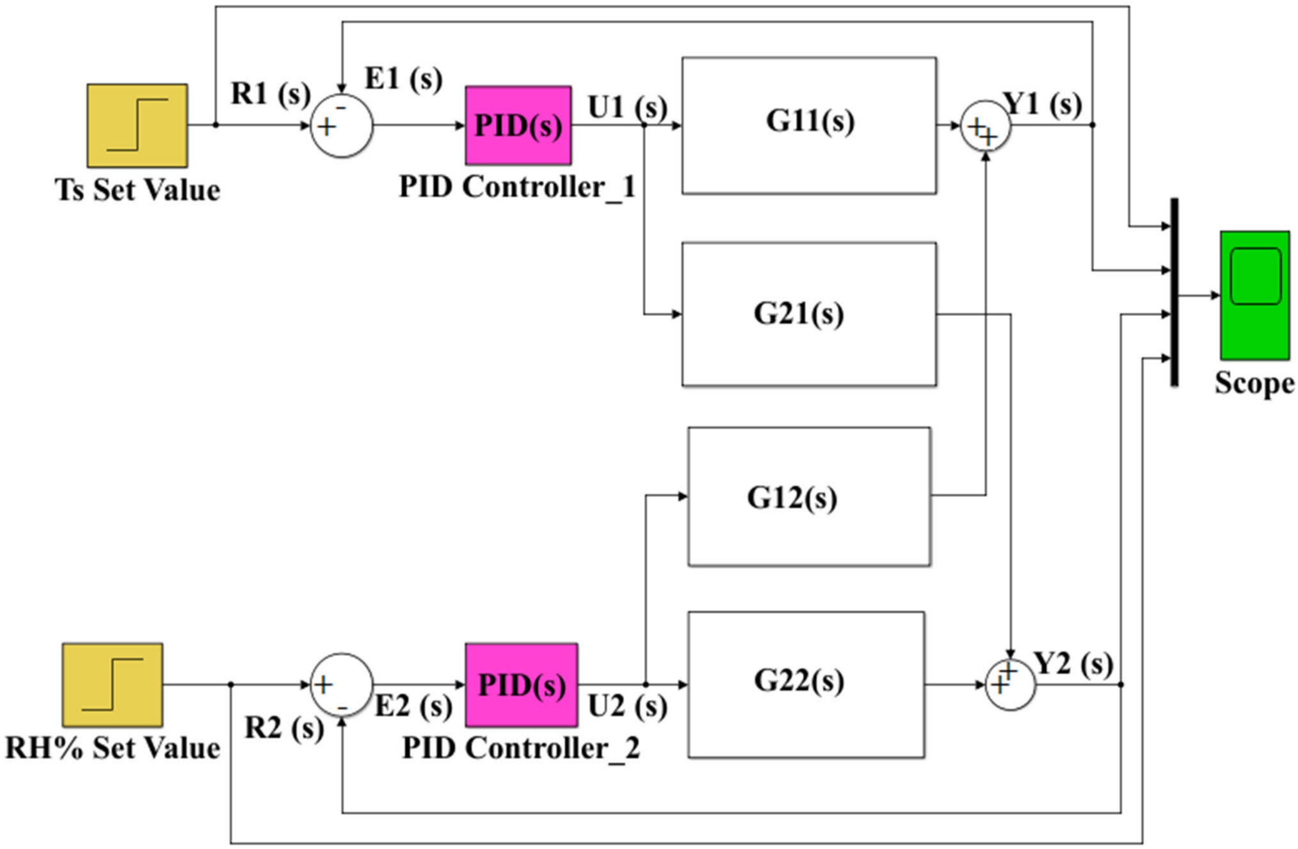

FIGURE 7. Multiloop PID controller for skin mode operation.

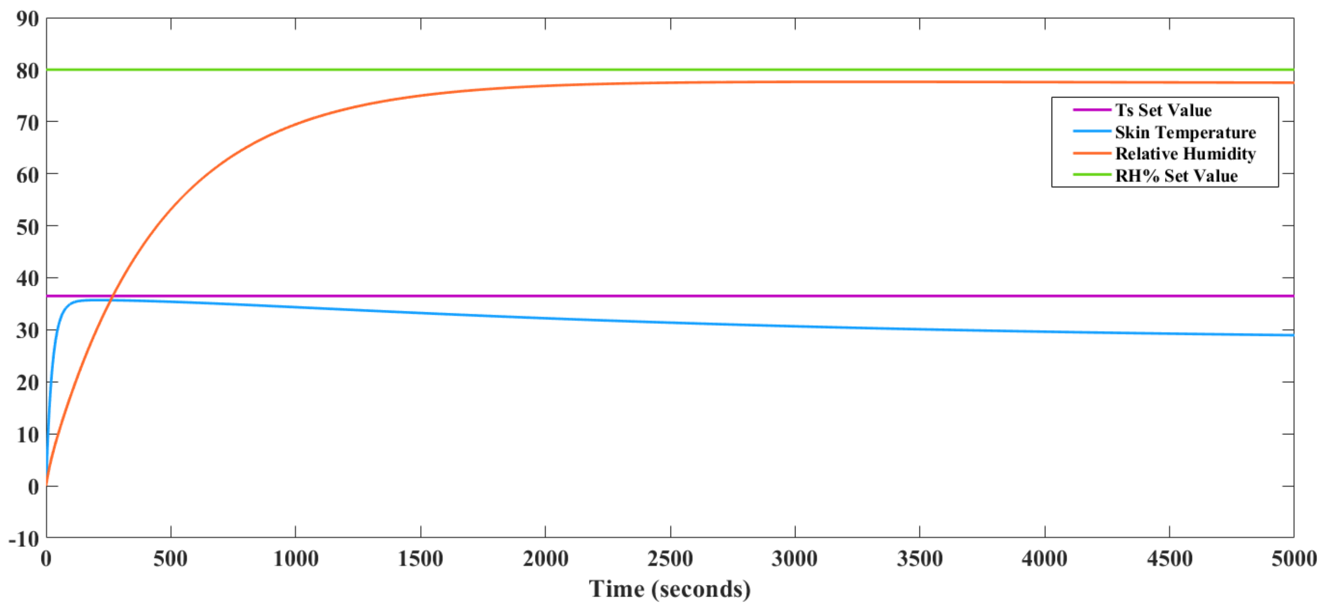

FIGURE 8. Step response of multiloop PID controller for skin mode operation.

combines the results to produce the linearization of the specified system. and also linearize the system using full-model numerical perturbation, where the software computes the linearization of the full model by perturbing the values of the root-level inputs and states. For each input and state, the software perturbs the model by a small amount and

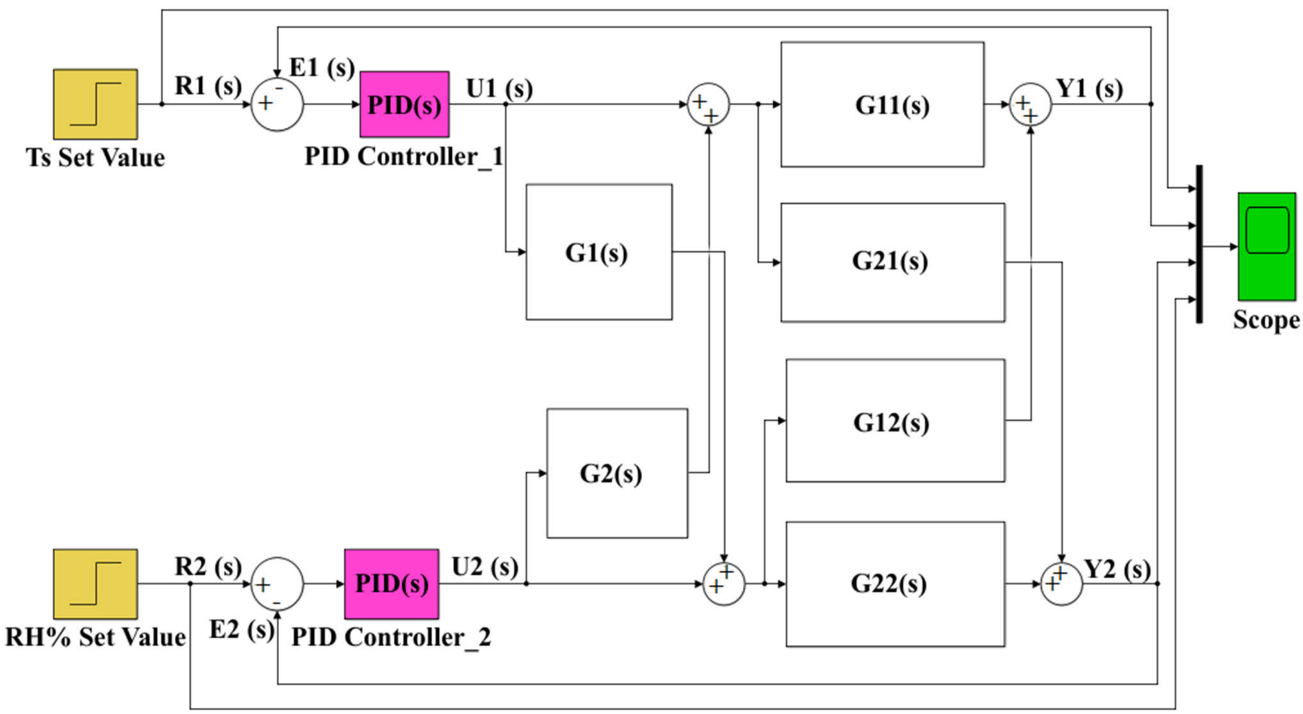

FIGURE 9. Multivariable PID controller for skin mode operation.

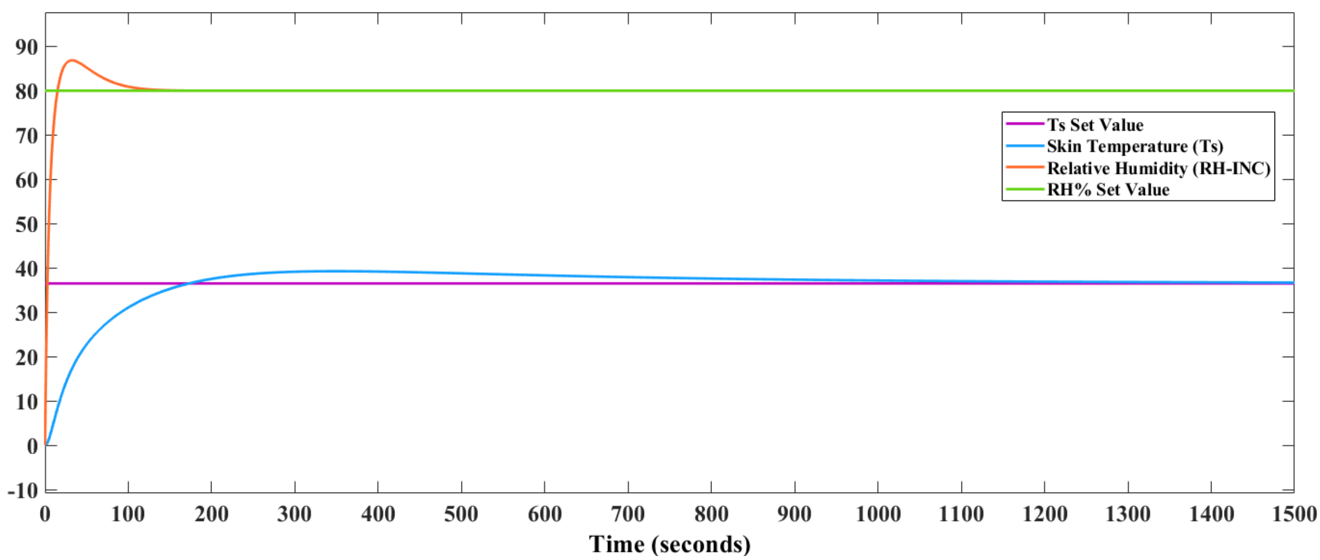

FIGURE 10. Step response of multivariable PID controller for skin mode operation.

computes a linear model based on the model's response to these perturbations.

IV. RESULTS

The air- and skin-mode simulation results are discussed in this section. This applies to a baby who was born weighing 900 g at 28 weeks of gestation on the first day of life. Both types of related initial circumstances and other information are provided. The neonatal incubator system developed numerous quantitative results using the MATLAB/Simulink software.

The skin mode results were determined using skin temperature (T_s) and relative humidity (RH) as inputs to the plant. In contrast, the air mode results were determined using the air temperature (T_a) and relative humidity (RH) as inputs to the plant.

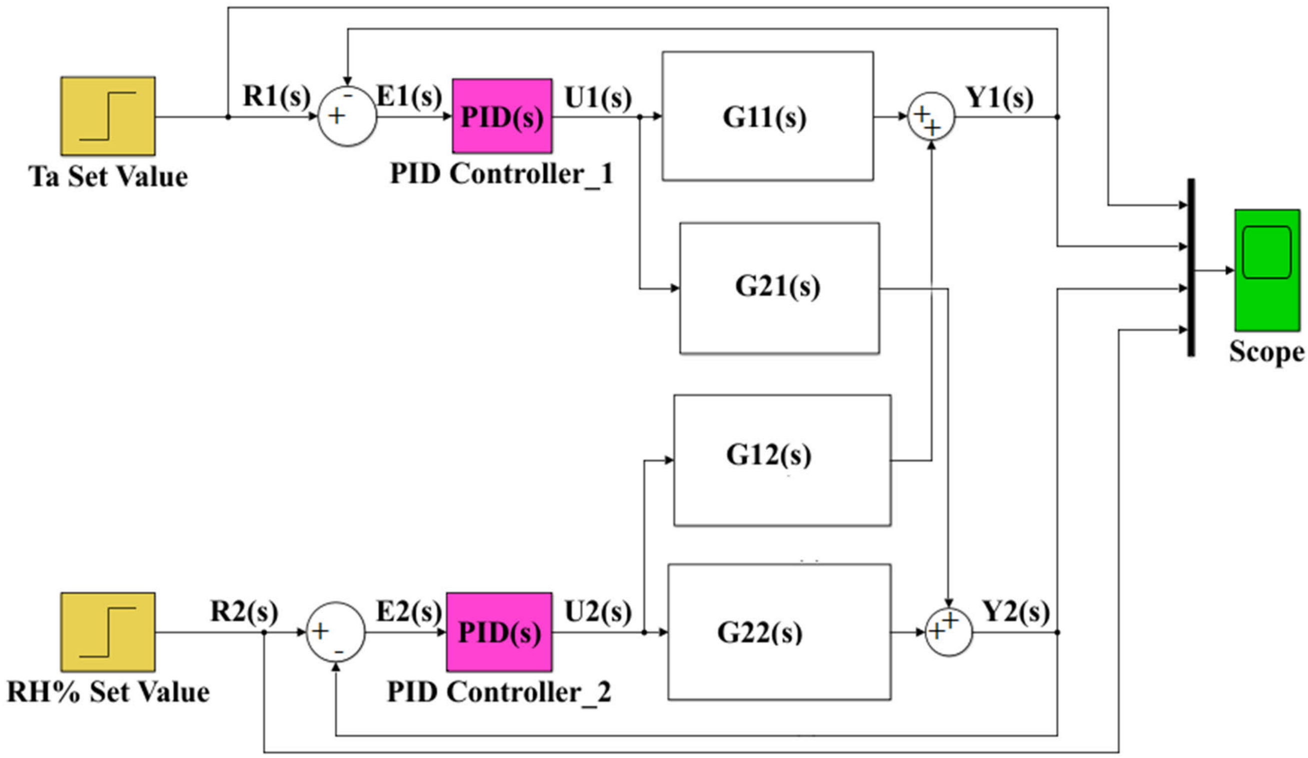

FIGURE 11. Multiloop PID controller for air mode operation.

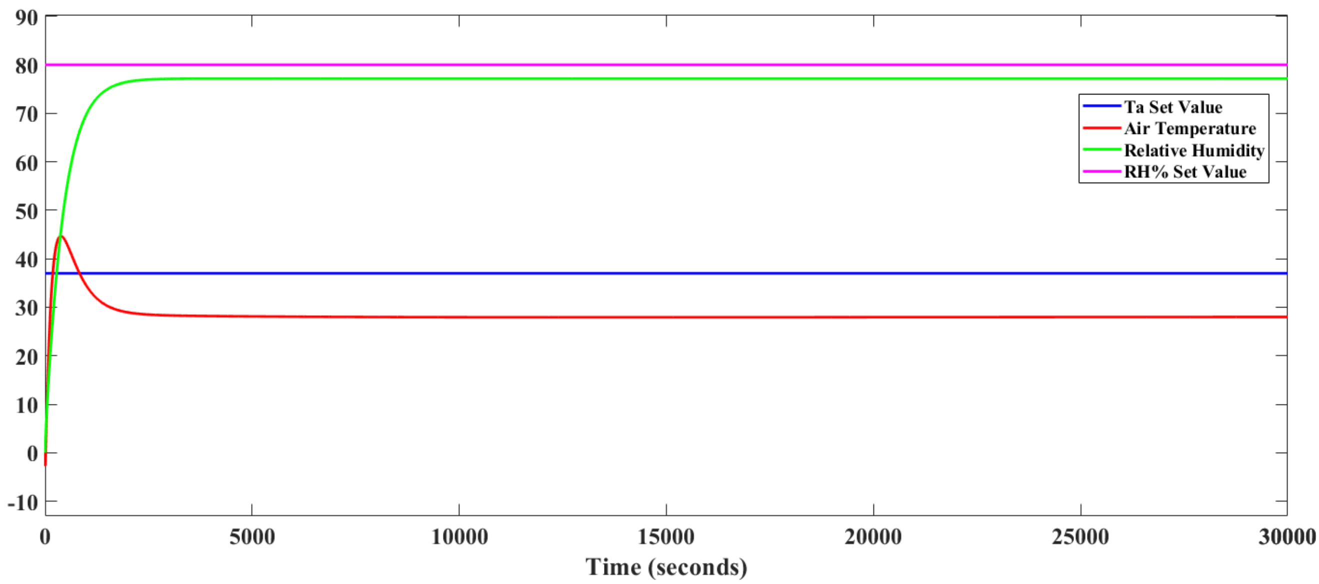

FIGURE 12. Step response of multiloop PID controller for air mode operation.

A. SKIN MODE RESULTS

The simulation results for the skin-mode operation of the neonatal incubator were obtained for the two conditions. The first condition simulates the system without using a PID controller, and the second condition simulates the use of a multivariable PID controller. Fig. 10 shows the simulation results. The performance indicators are listed in Tables 3 and 4.

B. AIR MODE RESULTS

Similar to the simulation of the skin mode operation of the neonatal incubator, simulation results for the air

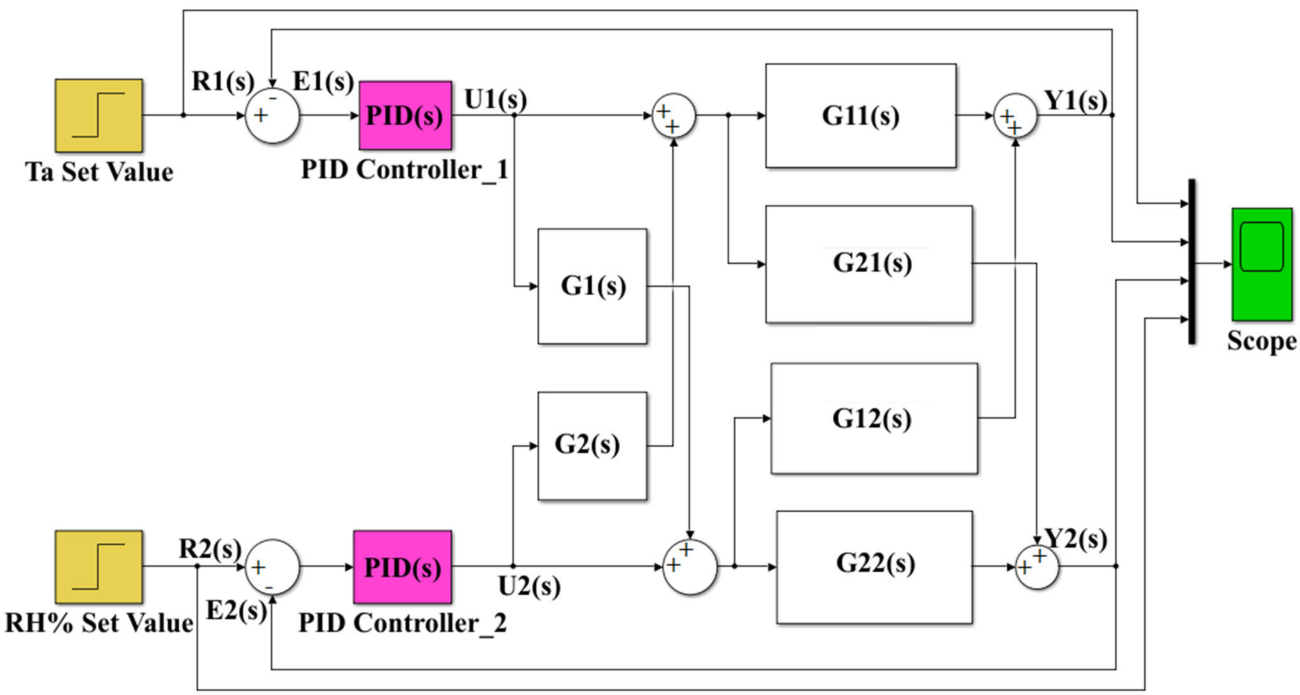

FIGURE 13. Multivariable PID controller for air mode operation.

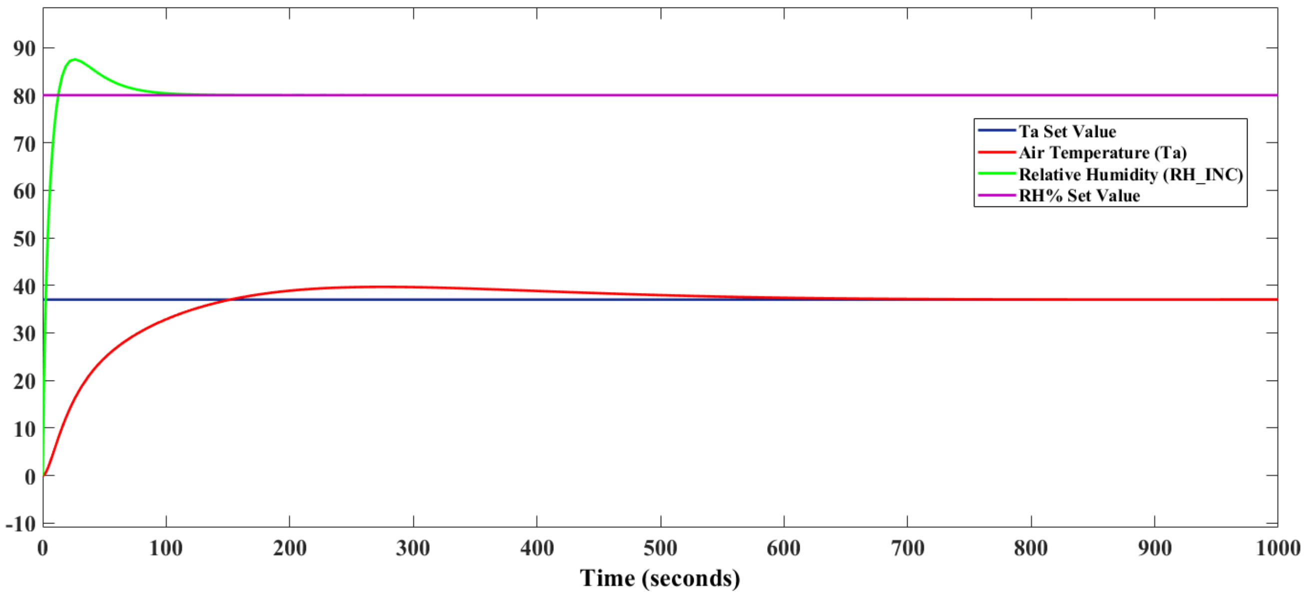

FIGURE 14. Step response of multivariable PID controller for air mode operation.

mode operation of the neonatal incubator were obtained under two different conditions. The first condition simulated the system without using a PID controller, and the second condition used a PID controller. The performance indicator parameters of the multivariable PID controller (shown in Fig. 14) such as rise time (*s*), settling time (*s*), overshoot (%), peak value, and peak time (*s*) are presented in Tables 5 and 6.

The plant was designed using a multivariable PID controller. Therefore, performance indices such as Integral Square Error (ISE), Integral of time-multiplied Absolute Error (ITAE), and Integral Absolute Error (IAE) are also

TABLE 3. Performance indicator parameters for skin mode operation without multivariable PID controller.

S/N	Performance Parameters	Skin Temperature (T_s)	Relative Humidity (RH)
1.	Rise time	30.67	1063.6
2.	Settling time	4066.8	2405.9
3.	Over shoot	23.1096	0
4.	Peak	35.7018	77.6563
5.	Peak time	205.463	3248.7

TABLE 4. Performance indicator parameters for skin mode operation with multivariable PID controller.

S/N	Performance Parameters	Skin Temperature (T_s)	Relative Humidity (RH)
1.	Rise time	114.3	9.8311
2.	Settling time	755.8	85.91
3.	Over shoot	6.117	8.559
4.	Peak	39.26	86.85
5.	Peak time	348.4	31.66

TABLE 5. Performance indicator parameters for air mode operation without multivariable PID controller.

S/N	Performance Parameters	Air Temperature (T_a)	Relative Humidity (RH)
1.	Rise time	81.3113	983.949
2.	Settling time	2302.1	1962.1
3.	Over shoot	59.65	0
4.	Peak	44.7026	77.1609
5.	Peak time	376.48	4353.3

TABLE 6. Performance indicator parameters for air mode operation with multivariable PID controller.

S/N	Performance Parameters	Air Temperature (T_a)	Relative Humidity (RH)
1.	Rise time	96.8157	8.697
2.	Settling time	530.48	69.82
3.	Over shoot	7.2456	9.43
4.	Peak	39.681	87.54
5.	Peak time	274.3	26.07

TABLE 7. Performance indicator parameters.

S/N	Performance Parameters	Results
1.	ISE	0.02335
2.	ITAE	0.01831
3.	IAE	0.07819

observed during the overall system simulation as shown in Table 7.

V. CONCLUSION

The overall system design of the neonatal incubator was determined using a mathematical analysis. The model consists of 12 components. These include the skin, air, core, walls, heater, fan, mattress, water surface air, supplied air temperature, water surface, heat sink, and relative humidity. The neonatal incubator model selected in this study was ATOM V-850.

The overall system was simulated using MATLAB software. The simulation was performed for both the air and skin modes of operation. The performance of the designed system was analyzed for each mode of operation. In this study, relative humidity and temperature were the main parameters monitored in the neonatal incubator. A proportional-integral-derivative (PID) tuner was used to tune the PID parameters automatically. Multiple loops existed in the overall system. To reduce the interaction between loops, a feedforward decoupling method was applied. In addition, the sequential loop-closing method is used for tuning the PID controller sequentially until it reaches converged values.

The simulation results show that for the temperature of skin (T_S), the overshoot is reduced from 23.1096% to 6.117% and the settling time is also reduced from 4066.8 seconds to 755.8 seconds using the decoupling and sequential loop closing tuning method with PID controller. On the other hand, using the decoupling and sequential loop closing tuning method with a PID controller for air mode operation, the simulation results show that for the temperature of air (T_a), the overshoot was reduced from 59.65% to 7.2456%, and the settling time was also reduced from 2302.1 seconds to 530.48 seconds. For both skin mode and air mode operations, using the decoupling and sequential loop closing tuning method with a PID controller, the relative humidity improved the settling time by 8.559% and 9.43%, respectively.

In general, the overall system performance was improved by the multivariable PID controller, as observed from the simulation results. The multivariable PID controller accelerates the system by reducing the time constant.

ACKNOWLEDGMENT

Lamrot Hailemichael Woldeamanuel express her deepest gratitude to his advisor Dr. Arun Ramaveerapathiran, for his critical and valuable comments, suggestions, and advice. She would like to thank the staff of Debre Berhan Referral Hospital for their valuable support. She also like to thank her husband who always helped her by providing comments, technical support, and sharing ideas.

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