Automated Humidity Control System for Neonatal Incubator

S Alduwaish1*, O Alshakri1, R Alamri1, R Alfarieh1, S Alqahtani1, K Hameed1 and A Alomari1

1Biomedical Engineering Department, Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia

*saraluwaish@gmail.com

Abstract. Premature neonates are nursed in closed incubators to prevent transcutaneous water loss, dehydration, and excessive body cooling. These issues have serious risks that need to be eliminated by controlling the air’s relative humidity (RH) in the incubator. This paper aims to implement a closed-loop control system that maintains desired RH levels inside the incubator with an acceptable settling time and percentage. Designing the prototype is actuator-process-sensor based, and the implementation was in two main phases. First, building the incubator, which involved assembling the incubation space and the humidifier using a readily available ultrasonic piezoelectric transducer. Second, designing the control algorithm which is based on the ON/OFF algorithm with four levels of ON Humidification power. Finally, the results taken are the control system responses to a step input of desired values of relative humidity based on clinical guidance. Response results showed a maximum steady-state error of 2.5 and a minimum settling time of 0.8 min. The results indicate that the control system is fast and stable which meets the desired requirements. The designed control system is beneficial in reducing power usage and creating a safe humidification method for the infant.

1. Introduction

It is undeniable that the environment in which a premature infant develops should closely be similar to that of the mother’s womb so that the baby can develop into a mature healthy baby. Thus, this project focuses on developing a control system to maintain high humidity levels in neonatal incubators. This study’s work scope is limited to the design and creation of a neonatal incubator humidity controller based on a microcontroller. The prototype design has several features that enhance its work such as the use of an ultrasonic atomizer to generate humidity, and the ability to adjust the desired humidity level as an operator.

The study made in 1957 by William A. Silverman and William A. Blanc [1], had a clinical trial studying the effects of several aspects regarding premature infants. The aspects were: humidity conditions against respiratory issues, death rate, and necropsy findings. The infants were placed in two environments of different humidity levels, 80 – 90 % RH, and 30 – 60 % RH. Infants that were nursed in the first environment had faster respiratory rates and a higher degree of temperature in their bodies, and reduced death rates. This clinical trial helped to give an idea of which humidity levels are to be tested in the control system for this project. One of the main factors of heat and evaporative loss is the skin surface of the infant. Infants have more skin surface per pound of body weight than adults or older children. When there is more skin, it means more radiant heat and more loss in water [2]. Moreover,
Infants have fewer glycogen stores and brown fat. In addition, less ability in maintaining flexion. All these elements are the main factors affecting infants’ thermal and hydro regulations.

In this research paper [3] the automated controller calculates the value of the regulated variable, compares it to the desired value means by the reference input, calculates the deviation, and generates the smallest value possible by feedback signal to reduces the deviation to zero. The mode of controller is the mechanism by which the automatic controller generates the control signal. The control action may be mechanical, hydraulic, pneumatic, electromechanical depending on the controller type [3]. An amplifier and error detector are composing the controller. The measurement element is a mechanism that transforms the output variable to another appropriate variable, such as displacement, pressure, or electrical signals so that the output can be compared to the reference input signal [3]. ON/OFF control is considered the simplest form of the feedback control system. There are only two positions for the control element: completely closed or fully open, this control factor is inactive, and it means the control element does not operate at any intermediate position, transmits only two output signals, OFF is 0 % and ON is 100 % powered value. In this project, on the other hand, the controller levels were increased to four levels above zero instead of one.

2. Materials and methods

The control system in this project uses the negative feedback mechanism [4] alongside four levels of ON/OFF controller to drive the incubator. The system, see Figure 1, consists of the main aspects of any control system, a controller, an actuator, a process, a sensor, and a user input method.

![Figure 1. Humidity closed-loop system block diagram](image)

2.1. Incubator design

To simulate a neonatal incubator, we built a small incubator using acrylic sheets for the infant unit and balsa sheets for the storage cabinet which contained the circuit of the incubator, see Figure 2. The incubator has a user interface where the user can input the desired relative humidity level and observe the changes in the humidity and the control system state, see Figure 3.

![Figure 2. Neonatal incubator device](image)  ![Figure 3. Neonatal incubator device user interface](image)

The project used the Arduino Uno board to run the neonatal incubator prototype. For the controller of the control system, a program code was written using the C++ language. The sensor used to feedback the level of the humidity is a DHT22 type humidity sensor. The actuator of the control system is a
significant part of the control system which is an ultrasonic piezoelectric humidifier. It consists mainly of two functional parts: the ultrasonic piezoelectric transducer that converts water into steam, and the fan that blows the steam into the incubation unit.

Water atomizer is a comprehensive term used to refer to both the ultrasonic piezoelectric and its driving circuit. This project uses water atomization module BMZ00040 to generate the steam that will increase and maintain the humidity level inside the incubation unit. The module can generate different power levels for the piezoelectric which contribute to different amounts of steam using four different values of resistors. As the resistor value gets higher the atomization power gets higher. The power levels generated are 10 W, 7.5 W, 4.7 W, and 2.7 W.

The ultrasonic piezoelectric transducer is a ceramic crystal that needs a high frequency (in the range of 100 – 3 MHz) oscillating AC signal with no DC shift (voltage is based on the driving circuit, but mostly in the range of 3 – 24 V). While the crystal is immersed in water, this signal causes it to deform, thus, generating kinetic energy and vibrations in the water. These vibrations cause the water to be separated into fine droplets which are practically considered steam, see Figure 4.

![Piezoelectric effect](image)

**Figure 4.** Piezoelectric effect [5]. Changes in oscillation amplitudes create a vacuum on top of the crystal which then turns into implosion and thus tiny droplets are formed

Each crystal needs specific conditions to generate mist based on its manufacturing features. For example, crystals with higher frequency generate finer water droplets, however, work best on lower water volumes than lower frequency crystals do. So, there is a limit of water level to which a crystal can handle before stopping mist generation [6]. Moreover, the shape of the water tank where the crystal is placed affects its operation, which was experienced when the humidifier was being built. The crystal needs to be placed in a cone-shaped or sphere-shaped base for it to work.

It is worth mentioning that the steam does not possess a high-temperature degree or increase in temperature for that matter, which makes this steam generation method a safe option for infant incubators. Another feature that makes the use of the ultrasonic humidification method better than using heating elements is less usage of power.

Safety of infants has been considered by ensuring the incubator’s electrical safety where the water was isolated from electrical equipment by adding silicone to the tank. Also, the water used is purified water to preserve the incubator from precipitates that could occur through the steam process.

The fan is the main auxiliary component in the distribution of air movement inside the incubator, which is regularly used to circulate moist air. The speed of the fan can be controlled by Pulse Width Modulation [7]. This technique is used to change the value of the voltage in between the high or low value of the fan speed. So, to get the highest, mid-high, mid-low, and lowest speed, the percentages of the duty cycle are 37%, 29%, 25%, 22% respectively.
2.2. Control algorithm

The controller is based on four levels of humidification power to choose the suitable amount of humidity to be delivered to the incubation unit Figure 5.

*Figure 5. Four-level ON/OFF controller block diagram*

The equation used to obtain the error that is shown in equation 1:

\[
\text{Error}(t) = \text{Desired RH} - \text{Measured RH}
\]  

Where RH is the ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water and is known as relative humidity [8]. The desired RH represents the input RH, where the measured RH represents the output RH that is measured by the sensor. The controller, as seen in Figure 6, has two outputs. So, it has two input-output responses [9] of power level and voltage level as shown in the two figures below (Figure 6 and Figure 7).

*Figure 6. Controller input-output response (power level)*  
*Figure 7. Controller input-output response (voltage level)*

The flowchart of the control algorithm is shown in Figure 8. The control system loop repeats every 0.5 seconds. It starts with the user inputting the desired value of RH. Then the sensor measures the current value of RH to be used in calculating the error that is inputted in the controller. After that, the controller uses a comparison algorithm to decide on the values of the output. The controller generates two outputs for the humidifier, one for the power level of the ultrasonic piezoelectric and the other is for the voltage level for the fan. The determining of the four ranges of error (difference between desired RH and measured RH), and what value of power and voltage for each condition was based on experimenting with several trials to reach the best system response.
2.3. Process mathematical modeling

After implementing the humidifier, it is time to test the RH response inside the incubator. Testing the response can be done using the open-loop system as shown in the figure below (Figure 9). The procedure steps are [10]:

1. Run the humidifier on the maximum power and voltage.
2. Measure the relative humidity percentage inside the incubator.
3. Plot the response against time.
4. Calculate the transfer function of the incubator process.

\[ G(s) = \frac{9.61 \times 10^3}{42.2s+1} e^{-11.5s} \]  

(2)

\[ 42.2 \frac{dy}{dt} + y(t) = 9.61 \times 10^3 x(t - 11.5) \]  

(3)

Figure 8. Control system flowchart

Figure 9. Open-loop incubator system.

The equations below (2 and 3) are the transfer function and differential equation of the open-loop system respectively which are the results of the procedure described.

3. Results

The results taken for this project is the control system response to a step input of the desired value of relative humidity. The desired values were chosen based on clinical guidance of the relative humidity level needed for the incubation duration of the infant [11]. Figure 10 shows the open-loop system result. It was taken at a different setting with an ambient temperature of 21 °C.
In Figure 11 and Figure 12 a simple type of disturbance was introduced to the system to test its performance in such conditions. The disturbance was created by opening the door of the incubator for a short amount of time (25 – 30 sec). The disturbance was tested while the control system was in the transient state to reach a steady-state value of 50 %. Also, in Figure 14 and Figure 15 the maximum desired RH 80% value was tested.
4. Discussion

4.1. Open-loop

In Figure 10 the response easily and quickly reaches the highest value of the relative humidity, and it is one of the characteristics of the open-loop system. Also, because there was no effect on the output to the controller, the system runs continuously, and the humidifier keeps working. Furthermore, since the size of the incubator is small, the system reaches a high value of humidity in a short time and then the value remains relatively constant or increases in a very small amount since there were no external disturbances. The shape of the response indicates a first-order system, which can be easily controlled.

4.2. Closed-loop

As it can be seen from Figure 11, the system was at a value just below 50 %, then the door was open, and some amount of humidity was leaked, dropping the relative humidity level to 43 %. When the door was closed after humidity leakage, the system starts to rise again. Since there is not much difference between the initial humidity level and desired one, we can expect an overshoot in the system since the tuning of the controller is more adapted to higher humidity levels. Yet, from Table 1 the maximum overshoot for the system is 4.8 %, which is still in the acceptable range.

In 80 % RH step responses (see Figure 13), the system has an overshoot equal to 0.75 % and a settling time of 0.8 min. Furthermore, the system’s settling times for different desired RH (60% and 70 %) was a maximum of 1 min which considered fast response and shows the system robustness and how fast the system can adapt to changes. The delay times for the same different desired RH values were from 0.3 min to 0.8 min. Also, the system shows some small oscillations as a result of the ON/OFF power control, as the minimum power of the system was not small enough to provide a small power value.

| Desired RH% | Delay time, $t_d$ | Rise time, $t_r$ | Peak time, $t_p$ | Maximum overshoot, $M_p$ | Settling time, $t_s$ |
|-------------|-------------------|-----------------|-----------------|--------------------------|-------------------|
| 50%         | 0.4 min           | 2.9 min         | 4.6 min         | 4.8 %                    | 2.1 min           |
| 80%         | 0.3 min           | 0.7 min         | 3.3 min         | 0.75 %                   | 0.8 min           |

4.3. Limitation

As with every project, there will be limitations and challenges that will limit the possibilities and the ability to implement the concept in a manner that is identical to fact. Choosing the appropriate type of humidifier to generate moisture in the incubator was a very difficult step because the humidifier used in market available neonatal incubators need a high amount of voltage and produce heat which might not be safe for prototyping examination, so this is considered the first limitation. Also, because the size of the humidifier is not the same as the actual size used in the real incubator, the size of the incubator has been reduced to match the effectiveness of the humidor.

5. Conclusion

This paper implemented a closed-loop system that maintains desired relative humidity levels inside the incubator with an acceptable settling percentage and a fast rise time.

The incubator prototype incorporated one significant feature which is the ultrasonic humidifier. Assembling a piezoelectric actuator with the required specifications for the control system played a major role in the efficiency of the incubator. Also, designing the control algorithm was based on the trial-and-error method since there were no tuning techniques established in the literature for tuning 4-level controllers. The fact that humidity is a first-order system with fast dynamics has both advantages and disadvantages which the control system balanced out.
Enhancement of the control system algorithm cannot be done without having suitable hardware that can comprehend and translate the control signals. So, the recommendation includes building a power-adjustable driving circuit for the piezoelectric transducer from scratch.

References
[1] Silverman W A and Blanc W A 1957 The effect of humidity on survival of newly born premature infants. Pediatrics. 20 477–87.
[2] Visscher M O, Adam R, Brink S, and Odio M 2015 Newborn infant skin: physiology, development, and care. Clin. Dermatol. 33 271–80.
[3] Cane R F 1968 A versatile electronic on-off controller. J. Phys. E: Sci. Instrum. 1 566–8.
[4] Feedback Systems and Feedback Control Systems [Internet]. Basic Electronics Tutorials. 2013 [cited 2021 Jun 30]. Available from: https://www.electronics-tutorials.ws/systems/feedback-systems.html
[5] Ultrasonic humidifier: Principle of Operation [Internet]. CLIMATE. CUSTOMIZED. | STULZ USA. [cited 2021 Apr 16]. Available from: https://www.stulz-usa.com/en/ultrasonic-humidification/principle-of-operation/
[6] Senthil Murugan S and Vijayakumar P 2017 Identification of ultrasonic frequency for water mist generation using piezoelectric transducer. Arch. Mater. Sci. Eng. 83 74–8.
[7] Heath J. PWM: Pulse Width Modulation: What is it and how does it work? [Internet]. Analog IC Tips. 2017 [cited 2021 Apr 21]. Available from: https://www.analogictips.com/pulse-width-modulation-pwm/
[8] Greaves C 1881 Relative humidity. Q. J. R. Meteorol. Soc. 7 132–8.
[9] On-off control system [Internet]. x-engineer. [cited 2021 Jun 30]. Available from: https://x-engineer.org/graduate-engineering/signals-systems/control-systems/on-off-control-system/
[10] How to Perform a Step Test [Internet]. Control Station. 2016 [cited 2021 Jun 30]. Available from: https://controlstation.com/blog/perform-step-test/
[11] Neonatal Coordinating Group. CLINICAL GUIDELINE: Thermoregulation [Internet]. Government of Western Australia - Child and Adolescent Health Service; 2006 [cited 2020 Dec 2]. Available from: https://www.cahs.health.wa.gov.au/-/media/HSPs/CAHS/Documents/Health-Professionals/Neonatology-guidelines/Thermoregulation.pdf?thn=0