Design, Control, and Simulation of a Neonatal Incubator

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Abstract— **In this project, a fully functional incubator with precise control with respect to temperature, humidity, and airflow was developed and assessed. In parallel with the development of the incubator, a heuristic simulation was created to test and tune the Mamdani fuzzy logic controller. The controller was then applied to the incubator prototype.**

Clinical relevance— **This study proposes a unique and efficient method for testing and tuning a neonatal incubator controller.**

I. INTRODUCTION

Incubators are a device by which an infant's body temperature can be regulated and monitored as needed. Incubators provide a protected environment for infants of low birth weight who are naturally sensitive to the exposure of thermal stress. The first incubator is credited to French Obstetrician by Stéphane 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 neonatal incubator. Dr. Tarnier's incubator housed multiple infants in the same enclosure and with this prototype, the mortality rate fell by nearly half. This resulted in the significance of the incubator to be recognized worldwide. [1]

The modern incubator design first appeared after World War 2; 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 to an accuracy of $1°C$ and possessed a humidistat. The humidistat had the ability to control relative humidity (RH) up to 100%. [2] The control of humidity is extremely important to thermal comfort and in the case of the neonatal incubator survivability. [3] An incubator study on 20 infants was conducted in January 2008 and March 2009. It was found that due to the poorly developed epidermis in the preterm neonate, fluid loss was a major concern often leading to death. One of the main features that led to a decrease in mortality beyond temperature control is the complete control of the RH. [4]

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Control systems have been around for thousands of years; purely physical systems such as water clocks and speed regulators are prime examples of this. However, the modern control system became prevalent 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]

In the 1970s a new type of control system was proposed using Fuzzy Logic and Fuzzy Math, and thus was called Fuzzy Control. Two types of Fuzzy Control have been developed; first is Mamdani control in which the designer assigns input values at certain ranges (membership functions). These values are then processed using a linguistic rule base, based on the location and value of the corresponding membership function triggered. This is then correlated to an output membership function and defuzzified. The defuzzification process has several methods, most of which are methods of taking the average, maximum, or minimum value of the fired membership functions. For Mamdani the corresponding defuzzified value is the control the gain.[6], [7]

The second type of Fuzzy Control is Takagi Sugeno (TS). This type of control system is developed off a math model using membership functions to process the inputs of the system to piece together several linearized math models to create an accurate and less computationally complex math model than the original. In TS Fuzzy Control, the linearized math model is calculated by taking the nonlinear math model and calculating the Jacobian matrix of this model and then inputting the values assigned for each of the membership functions. This is then defuzzified and the corresponding value is used to generate a math model. [6]-[8]

A thermal regulatory controller such as an incubator is an ideal application of Mamdani control. The simplicity of the controller and the complexity of the system allows for a simple and stable controller to be developed in a short period of time. For this reason, several Mamdani controllers have been developed for incubators, as well as, similar systems such as greenhouses and poultry incubators. [9]-[12]

II. METHODS

A. Calculation

Calculations were necessary for both the design and tuning of the simulation and the physical incubator. Heat transfer throughout the incubator was calculated using the dimensions of the incubator design and the corresponding thermal properties from Cengel et al. [13]. First of which, the mass flow rate dm in Eq. (3), is calculated from the volumetric

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flow rate VF as in Eq. (2), and the density at the operational temperature ρ.

$$A_{pipe} = \pi r^2 \tag{1}$$

$$VF = VA_{pipe} \tag{2}$$

$$dm = \rho VF \tag{3}$$

Another key calculation is that of the convection coefficient h and with it the heat transfer through convection is calculated using Eqs. (4)-(11). This is done through the interpolation of the thermal properties, kinematic viscosity ν, of the air for the setpoint temperature, which is followed by the calculation of the Reynolds Re, Rayleigh Ra, Grashof Gr, and Prandtl Pr numbers. For natural convection the Grashof number, Rayleigh number, Prandtl number, and gravity g were used to calculate the Nusselt number Nu for natural convection of a horizontal cylinder.

$$Gr = \frac{g(T_s - T_\infty)D^3}{\nu^2 T_f} \tag{4}$$

$$Ra = GrPr \tag{5}$$

$$Nu_n = \left(0.6 + \frac{0.387Ra^{1/6}}{[1+(0.559/Pr)^{9/16}]^{8/27}}\right)^2 \tag{6}$$

For forced convection, the Reynolds number and Prandtl number are used to calculate the Nusselt number for a horizontal ellipse. Assuming the Reynold values fall in the acceptable range of (1400-8200).

$$Re = (VF\ D)/\nu \tag{7}$$

$$Nu_f = 0.197Re^{0.612}Pr^{1/3} \tag{8}$$

The dominant type of convection is determined to be natural by the equation convection type where natural convection is much larger than 1, mixed convection is around 1, and forced convection is much less than 1.

$$convection\ type = \frac{gr}{Re^2} \tag{9}$$

$$Nu_{mix} = (Nu_f^{3.8} - Nu_n^{3.8})^{1/3.8} \tag{10}$$

Finally, the convection coefficient for both internal and external flow is calculated through the Nusselt number of the selected type with the following equation.

$$h = \frac{Nu\ k}{D} \tag{11}$$

For internal convection constant surface temperature, laminar flow, and spherical shape where assumed giving a Nusselt number of 3.66.

B. Simulation

During the construction of the incubator a simulation was developed in parallel in order to test and tune controllers. The development of this simulation also provided many of the background calculations that supported design decisions. The equations below serve as the core of this simulation. The heating and humidification process was simulated using the equations of heat transfer Eq. (12) through Eq. (14) which were taken from Cengel et al [13].

$$\dot{Q}_{cond} = -k\ A\frac{\Delta T}{\Delta x} \tag{12}$$

$$\dot{Q}_{conv} = h\ A_s(T_s - T_\infty) \tag{13}$$

The convective heat transfer coefficient was calculated for the airflow on both sides of the plexiglass using the airflow rate from a commercial variant on the inside of the plexiglass dome of 0.3 m/s. [14] While building codes for a neonatal ward were used to estimate the air flow outside the plexiglass.

$$\dot{Q}_{flow} = dm\ C_p \Delta T \tag{14}$$

The simulation relies on several assumptions first of which is that the heat loss through the body of the incubator is negligible compared to that lost through the plexiglass and convection throughout. Secondly that the heat transfer due to radiation is negligible, verified by a calculation done at steady-state and standard conditions. Finally, fan curves and interpolations around the setpoint are accurate enough for operation within the range of operating conditions. From these calculations and assumptions, a simulation of the heat and humidity transfer to the intake air is formed for each cycle. The intake and recirculated air is heated and humidified to bring the dome to the setpoint. From this, the air is moved into the incubator using the volumetric flow rate calculated from the fan curve. This then displaces the same amount of air at the temperature and humidity of the previous step, and the resulting balance is then recalculated for the current step using thermal mass and the total amount of water vapor in the air.

$$T_{heater}(n+1) = \frac{T_{inc}(n) + T_{amb}}{2} + \frac{\dot{Q}_{heater}U_T}{dmC_p} \tag{15}$$

$$T_{inc}(n+1) = \frac{\rho VOL_{air}C_pT_{inc} + dmC_pT_{heater}(n+1) - dmC_pT_{inc} - \dot{Q}_L}{\rho VOL_{air}C_p} \tag{16}$$

Eqs. (15) and Eq. (16) are the core equations used to track the heat transfer throughout the incubator. Eq. (15) is the temperature of the 50% outside air, 50% recirculated air plus the change in temperature the air goes through across the heating element. This is variable with the control input, and the mass flow rate which is varied through the control input for the fan applied to the fan curve. From Eq. (15) the air then flows into Eq. (16) which in the numerator sums the thermal energy stored in the incubator from the previous step, the heat transfer from the heater, the heat loss due to exhaust air, and the heat loss through the dome. The sum of the heat energy is then divided by the thermal mass of the incubator this then results in the temperature of the incubator at this step.

$$RH_{hum}(n+1) = \frac{RH_{inc} + RH_{amb}}{2} + \frac{\dot{RH}_{hum} U_H}{H_{sat} V F} \tag{17}$$

$$RH_{inc}(n+1) = \frac{H_{sat} VOL_{air} RH_{inc} + H_{sat} V F \ RH_{hum}(n+1) - H_{sat} V F \ RH_{inc}(n)}{H_{sat} VOL_{air}} \tag{18}$$

Similar to the heat transfer equations, Eq. (17) and Eq. (18) models the humidity. It does this by modeling the humidity at the humidifier with the same 50% ambient, 50% recirculated air assumption. The mixed air is then adjusted by multiplying the humidification rate by the control input, all divided by the volumetric flow rate and the saturation density. To rephrase this, Eq. (17) calculates the percent change of the relative humidity and adds it to the intake humidity. From the intake the air then flows into the incubator simulated by Eq. (18). This equation calculates the sum of the mass of the water vapor in the incubator. First by calculating the grams of water in the incubator at the previous step. The next part of the numerator is the grams of water having just flowed in to the incubator from the humidifier. Finally, the amount of humidity exhausted from the previous step is then subtracted from the total. This is then divided by the total volume of air to convert the units back to relative humidity.

C. Controller Design

Using MATLAB [15] and the previous calculations to gauge performance characteristics the system was modeled, and a controller was developed to achieve the desired conditions. First using the Fuzzy Logic Toolbox a 2 input 3 output Mamdani controller was developed. As seen in Fig. 1, the inputs are temperature and humidity. The outputs of the controller actuate the temperature, humidity, and fan.

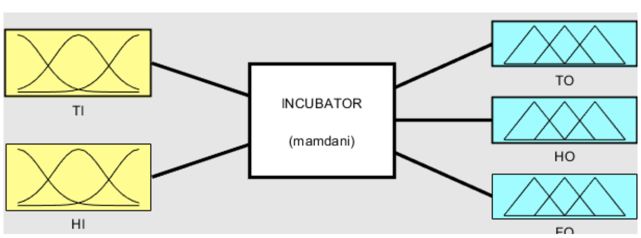

Fig. 1. flowchart of the design process

Each input and output has 5 corresponding membership functions as seen in Fig. 2 This controller was applied to the simulation and actuator inputs were estimated using supporting calculations.

D. Simulation Results

The results of the simulation depicted in Fig. 3 and Fig. 4 show that for the Mamdani controller it takes approximately 28 cycles to reach the temperature setpoint and 38 cycles to reach the humidity setpoint.

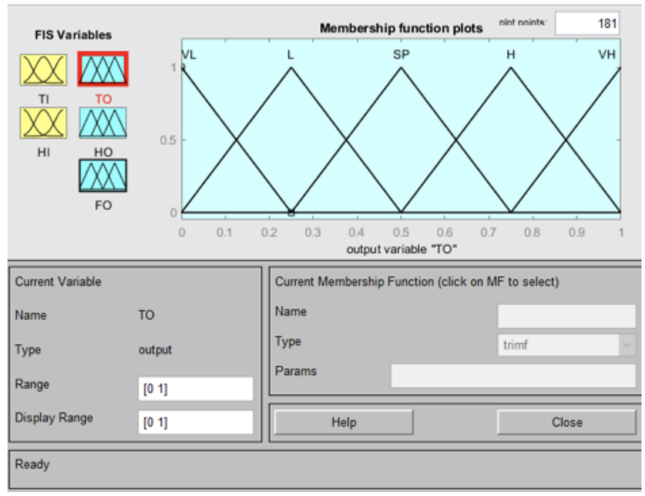

Fig. 2. Fuzzy membership rules

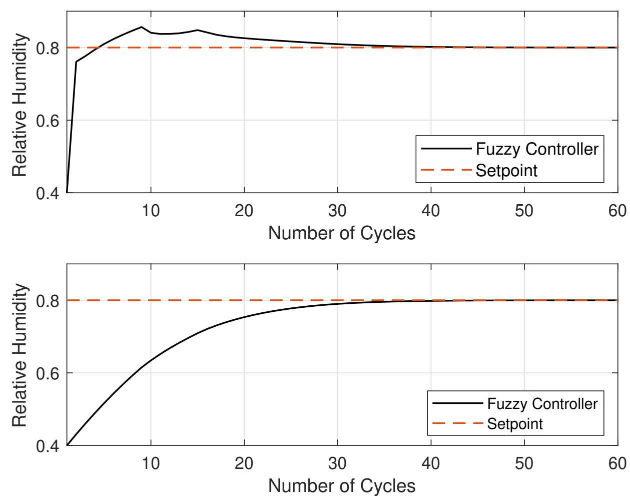

Fig. 3. The simulated temperature at the heating coil (top) and in the incubator (bottom).

E. Physical Model

The body Fig. 5 consists of a foam box covered in fiberglass; piping was made of PVC, while the dome is constructed of acrylic glass.

The heating coil is a nichrome heating element, and a heat shield made of steel pipe and exhaust wrap. The fan was an insignia case cooling fan controlled through pulse width modulation. Instrumentation was purchased through

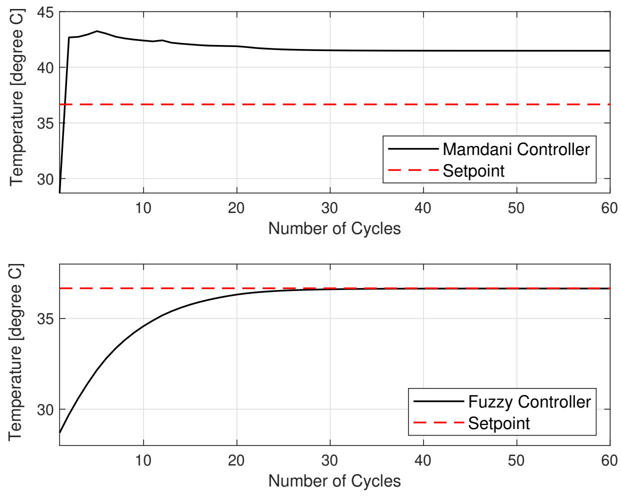

Fig. 4. The simulated humidity at the humidifier (top) and in the incubator (bottom).

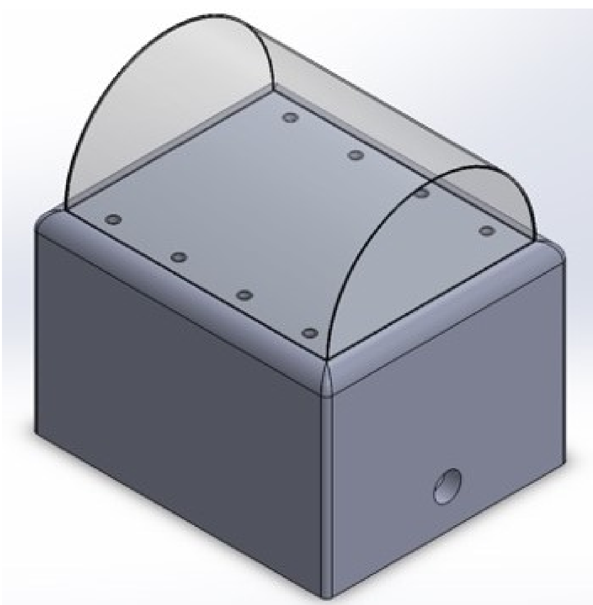

Fig. 5. Incubator assembly drawing.

Adafruit and communicated through I2C before being run to the Arduino. The Adafruit MCP9808, SHT31-D, and BMP388 sensors were used for the temperature, humidity, and barometric pressure respectively. The main power supply to the heating coil was run through a dimmer switch before a solid-state relay controlled the input by the Arduino.

As seen in Fig. 6 the air intake is through the pipe at the bottom of the figure while the exhaust is through the pipe at the top. Air supply to the inside of the incubator is supplied by the right vents and exhausted through the left vents. In the bottom right corner is the humidifier. The T in the piping is the connection between intake and recirculating air, the foam box just above this is the fan box, above the fan box, in black, is the heating coil and heat shield. To the left of the heating coil is the breadboard and the solid-state relay, above these, is the Arduino.

Fig. 6. Internal layout of the incubator.

F. Integration and Experiment

The instrumentation consists of temperature, pressure, and humidity sensors. These are monitored using an Arduino Mega which passes the sensor reading on to MATLAB via a serial communication line as seen in Fig. 7. The control system processes the readings through the fuzzy inference system and sends the corresponding inputs back to the Arduino to control the heating coil, the humidifier, and the fan.

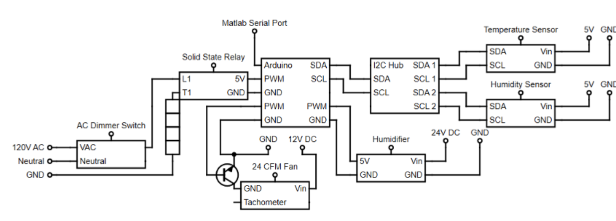

Fig. 7. Wiring diagram.

The instrumentation was integrated into a functioning control system. Through trial and error, the system was debugged, and the controller was optimized by further adjustment of actuator inputs and membership functions. The end result is a hybrid system through which the fuzzy logic controller is run on MATLAB, and the sensors and actuators are run on an Arduino Mega. These two platforms communicate through a serial USB connection. The main power for the actuators was connected using DIN mount terminal blocks. Plugs were wired up for AC/DC converters to connect to the main power. The three voltages required, $5V$, $12V$, and $24V$, were provided to their respective instruments using wall adapters. The multiplexer was plugged into a breadboard which served as a hub for all of the Arduino controlled devices. The Arduino was connected to and powered by a laptop running $MATLABR2019B$.

Once the controller was applied to the system, several adjustments were made to the system in order to optimize performance. First of which was the positioning of the dimmer switch controlling the amount of AC current supplied to the heating coil. Secondly, the cycle time of the controller and the pulse width modulation controllers was adjusted. Finally, the location of membership functions was changed in order to adequately control temperature without reaching temperatures at which there was a risk of melting certain components of the incubator.

To complete the tuning of the incubator, it took several runs to make the necessary adjustments. Starting at room temperature, the controller ran until the temperature came to a steady-state value. The system was then allowed to cool. After several trials, it was identified that the system response was the same for a temperature of $33.5°C$ as it was for lower temperatures. With subsequent trials, adjustments to current to the heating coil, cycle timing, and membership functions were made through trial and error by bringing the temperature below $33.5°C$ before adjusting the tuning variables and running the incubator to inspect the results. The tuning variables were adjusted to achieve a steady-state temperature and humidity closer to the desired setpoints of $36.67°C$ and 80% relative humidity. This was repeated until both setpoints consistently came within an acceptable margin of the desired setpoint values.

G. Experimental Results

Despite the development of the controller with the simulation, the final controller still needed additional tuning before reaching the optimal setpoint and rise time. To do this, the dimmer was adjusted to 80% of the maximum heating coil power. At this power the temperature measured at the output of the heating coil was $60.44°C$. The membership functions were constrained to values very close to the setpoint values in order to maximize the output during the warm-up phase. Additionally, the ruleset was changed so the fan was only correlated with the temperature. The incubator was then run for one hour and Fig. 8 and Fig. 9 were generated.

It can be seen from Figure 5 that the temperature reached a steady-state value of $36.82°C$, for a 0.4% error from the desired setpoint of $36.67°C$. While the relative humidity reached a steady-state value of 77% for a 0.3% error from the desired setpoint as seen in Fig. 9.

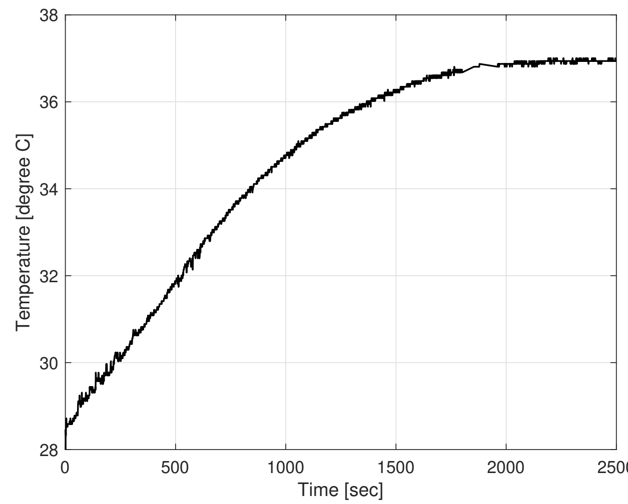

Fig. 8. The temperature of the incubator.

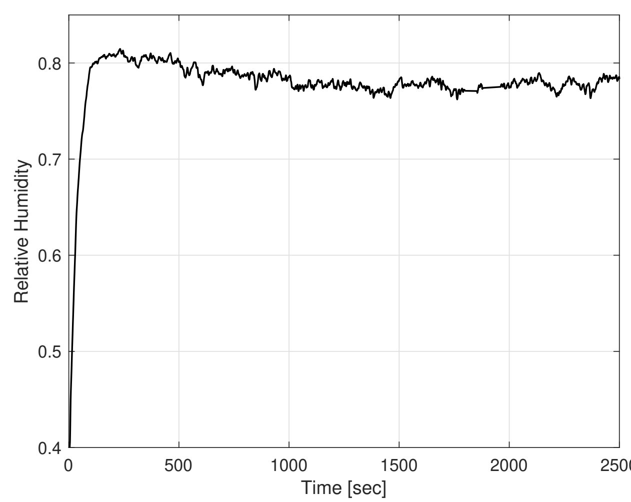

Fig. 9. The humidity of the incubator.

III. Discussion

There are several limitations to the simulation. Since the simulation is not time-variant, rise time was not accurately predicted. Additionally, the model is not in state-space thus many controllers cannot be developed off of this. While the simulation aided in the controller design and control inputs, the tuning of the controller still required a fair amount of effort. A method of editing the membership functions and other control parameters so that the controller has a non-zero steady-state error may provide a way to account for disturbances such as changes in ambient temperature and is worth investigating in future experiments.

IV. Conclusion

For the simulation; a steady-state error of 0.038% and 0.014% was achieved with a rise time of 28 cycles and 38 cycles for temperature and humidity respectively. With further tuning the temperature of the incubator was successfully brought to within 0.4% of the setpoint value and the humidity to within 0.3% of the setpoint value. From these results it can be concluded that this method of simulation can verify the operation and provide a starting point for the tuning of a Mamdani controller.

Fig. 10. Final product.

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