

High Performance Temperature Controller For Infant Incubators

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Abstract— Temperature is one of the most important parameters that need to be maintained to provide suitable environment for infants especially premature born infants. It is important that the temperature that is set by the doctor is maintained with out significant variation over time.

The product that has been developed here uses proportional and integral controllers together with pulse width modulation and switching to provide accurate temperature maintenance with reference to the input temperature.

This paper provides an overview of the temperature control system developed and explains the techniques used in the optimization of the temperature regulation within $\pm 0.1^{\circ}\text{C}$. It further discusses the safety methods used and the sensor that is used in order to get the required temperature feedback for the control.

Keywords—Bilinear transformation, Pulse width modulation, Proportional constant, Integral constant

I. INTRODUCTION

The premature infant care is one of the most sensitive and delicate areas in bio medical field. Premature infant exposed to the unprotected environment outside the womb has to be provided with a similar environment until the infant is able to cope with the changes in the environment with out external help.

The infants have very low thermal regulation and it is not possible for the feeble body to cope with the thermal loss. This requires the body of the infant to be in a moist heated environment [1]. Therefore temperature is one of the most important factors that need to be maintained with minimum variations. The value of the temperature once set by the attending physician should be maintained constantly in order to protect the body of the infant form harm.

The main aim of this project was to develop a control system that can be used with existing units which are outdated and have large variations. As the survey done in Colombo South hospital (Kalubovila) and Lady Ridgeway hospital Colombo-8, the poor conditions for infants in pediatric units were observed. The infant mortality rate in Sri Lanka is about 16 deaths for every 1000 live births [2]. According to chief

engineer of Biomedical Division of Sri Lanka, even though there exist imported machinery, maintenance and high replacement cost of sensors and calibration instruments have forced many incubator units to be in not good condition. Therefore the need for an improved control system that provides stable temperature level was needed.

The following pages cover the details of the product that was developed, with Section II covering the overview of the product, Section III the temperature regulation methodology, Section IV the control system used and the results obtained covered in Section V.

II. FUNCTIONALITY OF THE SYSTEM

A. Block Diagram

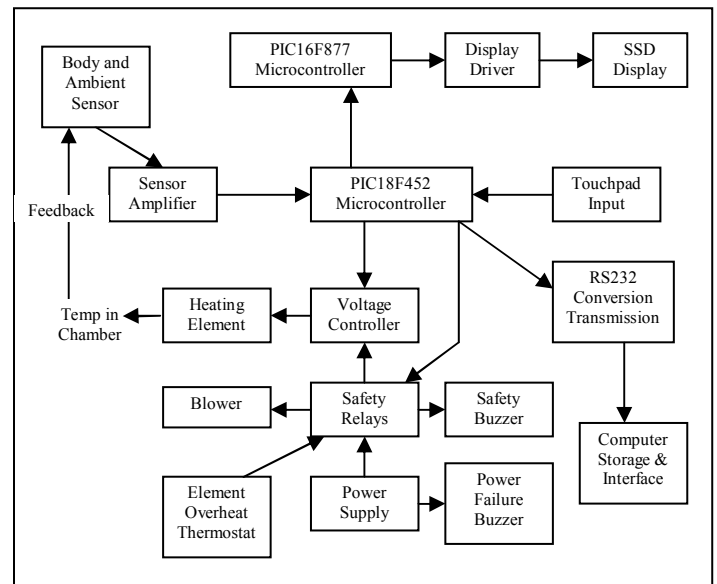


Figure 1. Block Diagram of the System Used

The above diagram can be used to explain the system used in the incubator. Two temperature inputs are taken in to the system. Namely the body temperature of the infant and the ambient of the chamber. Both sensors have resistance

variation according to the temperature and this is converted to voltage and supplied to the microcontroller.

The set temperature that can be set using a keypad on the front panel is also taken into the microcontroller and this is taken as a reference. The microcontroller compares the two temperature values produce a PWM (pulse width modulation) output according to error value. This signal is then sent to a voltage control circuit which set the voltage level as required to the heating element reducing or increasing the heat output as necessary.

The front panel also contains three temperature indicators which show the current set temperature, ambient temperature and skin temperature. A RS232 link is used to communicate with a computer. Software has been developed to use this data and provide storage of temperature variation history. This also analyses data graphically and provide information using a simple and understandable format. This software also provides the ability to monitor the temperature live from the nurses' station of the premature baby ward rather than having to visit each incubator [3]. The different levels of voltage required for the controller circuits is provided through a voltage regulator circuit.

The full system is implemented on 5 modularized circuit boards. These are the power supply and voltage controller, control circuit, display driver, sensor input circuit and the interface circuit.

B. Sensors

The sensors used in this unit are manufactured by Exacon[®]. These are specifically made for bio medical applications and have an accuracy of $\pm 0.1^{\circ}\text{C}$ [4] of in the required range of 20°C to 40°C as the set temperature varies from about 30°C to 37°C [7]. The sensor resistance value is converted to a voltage signal and amplified to suit the AD (analog to digital) conversion.

It is necessary to measure temperature with an accuracy of up to a decimal of a degree. Thus 10 bit conversion is used. This gives a voltage resolution of 4.88mV (for a 0 to 5 volt variation of input)

The sensor voltage variation over the range of 20°C to 40°C is 1.5V to 4.5V therefore 1 degree Celsius is represented by 150mV therefore a resolution of 4.8mV detects a minimum variation of 0.0325°C .

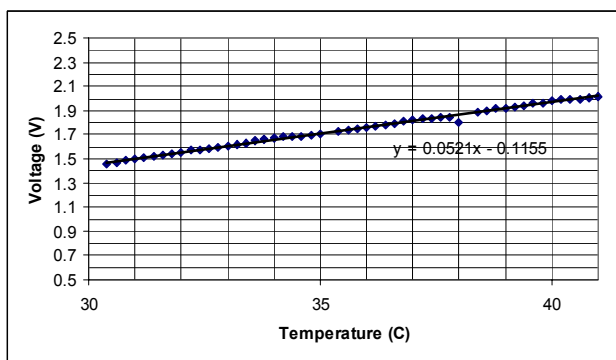


Figure 2. Test Data, voltage output variation with temperature from the sensor circuit

The linearity of the variation of voltage with the difference in temperature is given from the graph in fig. 2. The Voltage values were taken at the output of the pre amplifier. The linearity of the sensor can be illustrated from this graph.

The ambient temperature value measured and used for control purposes should be 10cm above the mattress level [2]. However the temperature sensor cannot be located at this exact position. Therefore the sensor is calibrated with a sensor located at this level to map the temperature at this position to the temperature value measured by the sensor.

C. Safety

Safety is an important consideration in the incubator. The normal safety procedures such as earthing as well as having the baby isolated from any metal parts have to be considered. The 230V circuits are located inside the side panel of the incubator where there is little chance of contact with water incase of any water being spilled on the equipment.

Further the supply to the heater and blower is provided through a relay. This relay coil is supplied with 9V safety circuit. Therefore safety equipment can be connected in series with this line. Incase of one of the safety devices tripping the heater supply will be cut off and a buzzer will sound notifying the user of a malfunction [7]. Similar buzzer is used to inform of power failure or the loss of power to the unit. Both these buzzers can be silenced once the problem is noted.

The safety relay is signaled by the microcontroller as well. This can be used to cut off the unit in instances such as overheating sensor failure etc.

When considering overheating the equipment should not heat up more than 39°C [7]. If either of the sensors shows a temperature more than this value the microcontroller will cut off the safety circuit through a transistor switch. Other malfunctions such as sensor failure are discussed later under further improvements in Section VI. The circuit is also connected in series with a thermostat which monitors the heat of the heating element. Incase of overheating the thermostat will cut the safety loop causing the relay to trip.

III. METHOD OF VOLTAGE CONTROL

The heater output needs to be controlled in order to control the temperature of the system. This is done through the control of the voltage given to the heater there by controlling the dissipated power output of the heater [5]. This can be illustrated from the graph shown in Figure 3.

In this unit the heater is supplied with a regulated DC supply. The DC supply was used in order to simplify the circuitry of the controller and also to extract more than the rated output from the heater element. This is especially advantages in the warm-up where more than 100% power output is used to reduce warm-up time.

The controller is a simple switching circuit which chops the current to the heating element. A MOSFET is driven by a pulse train which will switch on and off the current through the heater. The system is supplied with rectified and smoothed

DC voltage. It is possible to use the same switching method in AC using a MOSFET driver to supply the gate bias voltage to the required level to the gate of the MOSFET with reference to the source however this will not enable the use of extra power output at warm-up.

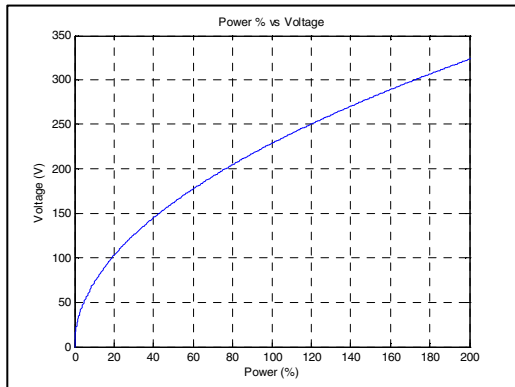


Figure 3. The voltage that is required to be applied to achieve a required power level for a heater rated at 230V

The MOSFET is driven by a PWM signal generated from the microcontroller. The duty of the signal will decide the voltage level of the heater. The variation of voltage with the heater was calculated and is shown in Figure 4.

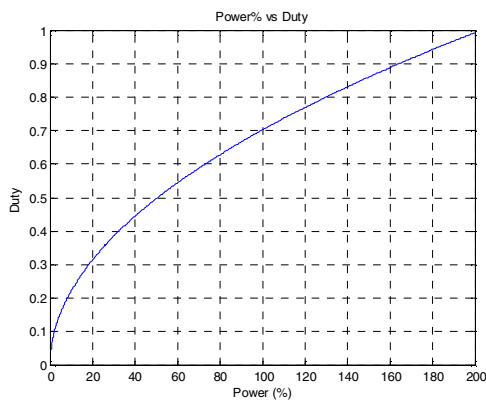


Figure 4. The duty level that needs to be set to achieve a required level of power

IV. CONTROL LOOP

A. System Used

The control loop in the system can be illustrated from the diagram in fig. 5. The chamber temperature is sensed from the temperature sensor and is then converted to digital form and compared with the set temperature entered by the user in the interface which is already in digital form the error is fed into the controller which adjusts the PWM duty cycle according to the error value and send to the voltage controller which converts the PWM signal to a voltage level which will control the output heat.

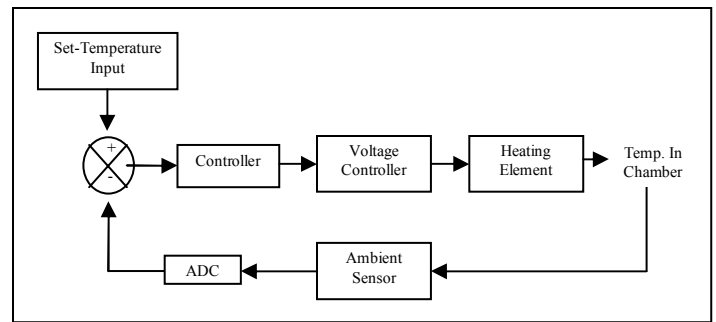


Figure 5. Block diagram of the control loop

B. Proportional Controller

The controller used initially was a P controller. The results obtained can be seen in Figure 6.

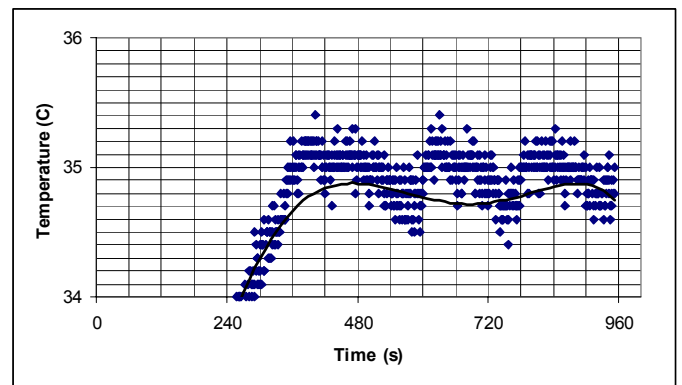


Figure 6. Test data, temperature variation with time where set temperature =35C and $K_p = 7$

The variation of the temperature was rather high as can be seen from the graph above with values ranging form $\pm 0.5C$. This variation is unacceptable.

Therefore it was necessary to incorporate an integrative controller to the proportional controller to reduce the steady state error

C. PI Controller

The PI controller can be represented in Laplace in Equation 1.

$$M_t = \left(K_p + \frac{1}{s} \times K_i \right) E_t \tag{1}$$

- K_p – Proportional Constant
- K_i – Integral Constant
- M_t – Output
- E_t - Error

However as the controller is digital therefore it is necessary to consider the sampled values. For this an approximation method needed to be considered to convert Laplace domain to Z domain.

Bi-Linear transformation was chosen as the method of approximation. This approximates by taking into consideration the area covered by the sampled error vs time graph and the error vs time graph. This gives the relationship between S and Z [6] as in Equation 2.

$$s = \frac{2}{T} \left[\frac{1 - Z^{-1}}{1 + Z^{-1}} \right] \quad (2)$$

T - Sampling time

By substituting this in the above given formula the output can be obtained as follows,

$$M_K = \left(K_P + \frac{T}{2} \left[\frac{1 + Z^{-1}}{1 - Z^{-1}} \right] K_I \right) E_k$$

$$2(1 - Z^{-1}) \times M_K = [2(1 - Z^{-1}) \times K_P + T(1 + Z^{-1}) \times K_I] E_k$$

$$M_k = \frac{1}{2} [(2 \times K_P + T \times K_I) E_k + (K_I - 2 \times K_P) Z^{-1} \times E_k] + Z^{-1} \times M_K$$

By using inverse Z transform;

$$M_k = \frac{1}{2} [(2 \times K_P + T \times K_I) E_k + (K_I - 2 \times K_P) E_{k-1}] + M_{k-1} \quad (3)$$

- M_k – K^{th} sample
- M_{k-1} – Sample prior to the K^{th} sample
- E_k – Error at K^{th} sample
- E_{k-1} – Error at $K-1^{\text{th}}$ Sample
- T – Sampling time
- K_P – Proportional Constant
- K_I – Integral Constant

It can be seen from the above formula, that by giving the current error, previous error and the previous output the integral can also be incorporated in the proportional controller.

Another issue with the heating system that was faced is the low response time. Even though the voltage is increased and there by the heat output is increased, for it to be transferred to the air there is a time delay. Also the heater has to increase the temperature in the volume of air that is inside the incubator chamber.

A further difficulty is once the heat increases the time taken to dissipate the heat is rather large as can be seen by the graph in Figure 6. Time taken for the temperature to reduce is much greater than the time taken to increase the temperature. Therefore it is necessary to reduce the overshoot in order to reduce the settling time. This is due to the fact that there is no method of heat absorption. The heater and the surrounding area under the mattress is heated more (especially metal parts) than the air and this causes the temperature of the air to rise

even after the heater has cut off (due to dissipation of heat absorbed by the surroundings).

Further the level of dissipation varies with the set temperature.

$$Q = kA(\theta - \theta_a) \quad (4)$$

- Q – Heat dissipated
- K – Proportional constant
- A – Surface area of dissipation
- θ – Temperature of surface
- θ_a – Ambient temperature

This means taking the ambient as 27°C the difference between 31°C and 35°C set temperature is significant. Also there are instances when monitoring equipment is plugged into the infant and thus it becomes necessary to keep access doors open. This causes the amount of heat loss due to loss of heated air to increase.

Taking these facts and the fact that it is necessary to reduce the time during warm up the PWM was set according to the PI controller using an optimizing graph. This allowed 85% duty (approx 130% power) until the error is reduced to 2°C then the PI controller reduces the heater element voltage and once the set temperature is reached the heater is cut off completely. However the minimum power reduction setting is 25% duty (approx 40% power) which is the power needed to compensate for heat dissipation when the side panel is open at 36°C .

D. Control Algorithm

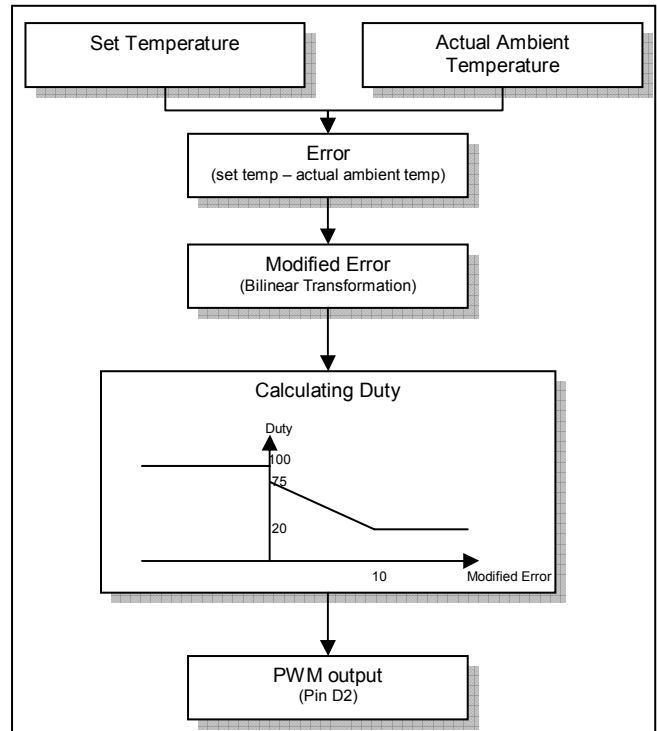


Figure 7. Flow chart of the implementation of the control algorithm in the microcontroller

