ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 6, June 2016

Design of a Microcontroller Based Temperature Measurement and Control System using PWM Technology

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ABSTRACT: In this paper a thorough and detailed design is presented where a system uses a microcontroller and a digital IC temperature sensor TMP275 to measure ambient temperature. In addition, a PID controller is implemented in the firmware and PWM signals with appropriate duty cycle are generated by the microcontroller that is used to maintain and control the temperature in a ventilated chamber. The PID controller that is implemented in the microcontroller firmware ensures to get the finest response in terms of settling time and least variation from the set point. An application is developed in LABVIEW to acquire the temperature data graphically in real time. This graphical user interface (GUI) system running in the PC allows the user to set the set-point (Temperature that is to be maintained in the chamber). The Temperature Sensor TMP275 is capable to measure the temperature with a resolution of 0.0625°C (typical value) and provides accuracy of 0.5°C (typical value) and 1°C (maximum) over a range of -40°C till +125°C. The experimental results show consistently same results and shows that the system has higher reliability and precision.

KEYWORDS: Embedded System, Freescale MC9S08JM60 microcontroller, Graphical user interface(GUI), LabVIEW(Laboratory Virtual Instruments Engineering Workbench), TMP275, PWM (Pulse Width Modulation).

I. INTRODUCTION

Temperature sensing and precise control forms an integral part of any industrial monitoring and control system. It is becoming more prevalent in the food industry, medicines, catering and supermarkets. It is a widely used parameter in any given process controlled environment. Earlier many attempts were made to develop a temperature monitoring system based on analog temperature sensors, thermocouples, resistance temperature detectors (RTD), thermistors, but the timing, response time and accuracy were insufficient. In case of industrial applications where very high sensitivity sensing and control of temperature is required we require a precise temperature monitoring and control system which can detect a small change in temperature and can maintain the same within the set-point with least variation with reasonably short response time. In the proposed temperature monitoring and control system a digital temperature sensor TMP275 of Texas Instruments is used to sense the ambient temperature that gives out the digital value of the temperature with a resolution of 0.0625°C. It is interfaced to an 8-bit Freescale Semiconductor Microcontroller MC9S08JM60 via an I2C bus. The control system part comprises the PID controller implemented in the microcontroller firmware and the PWM signal generator built-in the microcontroller. In the hardware front, two power MOSFETs are used as the switching elements, one drives the heating element and the other drives the cooling element. The MOSFETs are controlled by separate PWM signals that are generated by the PWM signal generators that is built-in the microcontroller. The duty cycle of the respective PWM signals are calculated by the microcontroller depending upon the PID error to maintain the temperature within the set-point with minimum variation. The temperature data is displayed real time graphically on the PC monitor. An application in LABVIEW is developed that is used to display the data on the PC's monitor. The microcontroller firmware was created in Freescale CodeWarrior Studio integrated development environment in C. A graphical user interface(GUI) is implemented in LabVIEW(Laboratory Virtual

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ISSN (Online): 2278 – 8875

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Instrument Engineering Workbench) where the user can set the temperature threshold value and other data acquisition parameters.

A. Literature Survey

In 2013 [1], a paper was published that described a design of temperature controller that drives the relays for switching the system ON/OFF for controlling the temperature. In 1959[2], Some improvements were proposed to a simple temperature controller using a Pt resistance thermometer as one arm of an ac resistance bridge that was published by Wilson and has been operating in many laboratories[3]. Here a transistor preamplifier is used to activate a relay that turns ON/OFF the system. In March 2010 [4], in an IEEE publication, another intelligent temperature control system based on Microcontroller AT89S51 was proposed where the temperature measurement device used consists of the 1-Wire bus digital temperature sensor DS18B20 and the temperature monitoring over a certain range could be achieved. Here in this paper a I2C based Digital Temperature sensor IC is used to measure the temperature that measures with a much higher resolution and accuracy. For the control of temperature with better precision a PWM signal is used to drive a MOSFET that in turn controls the current that drives the heating element.

II. HARDWARE ARCHITECTURE

A. System Block Diagram

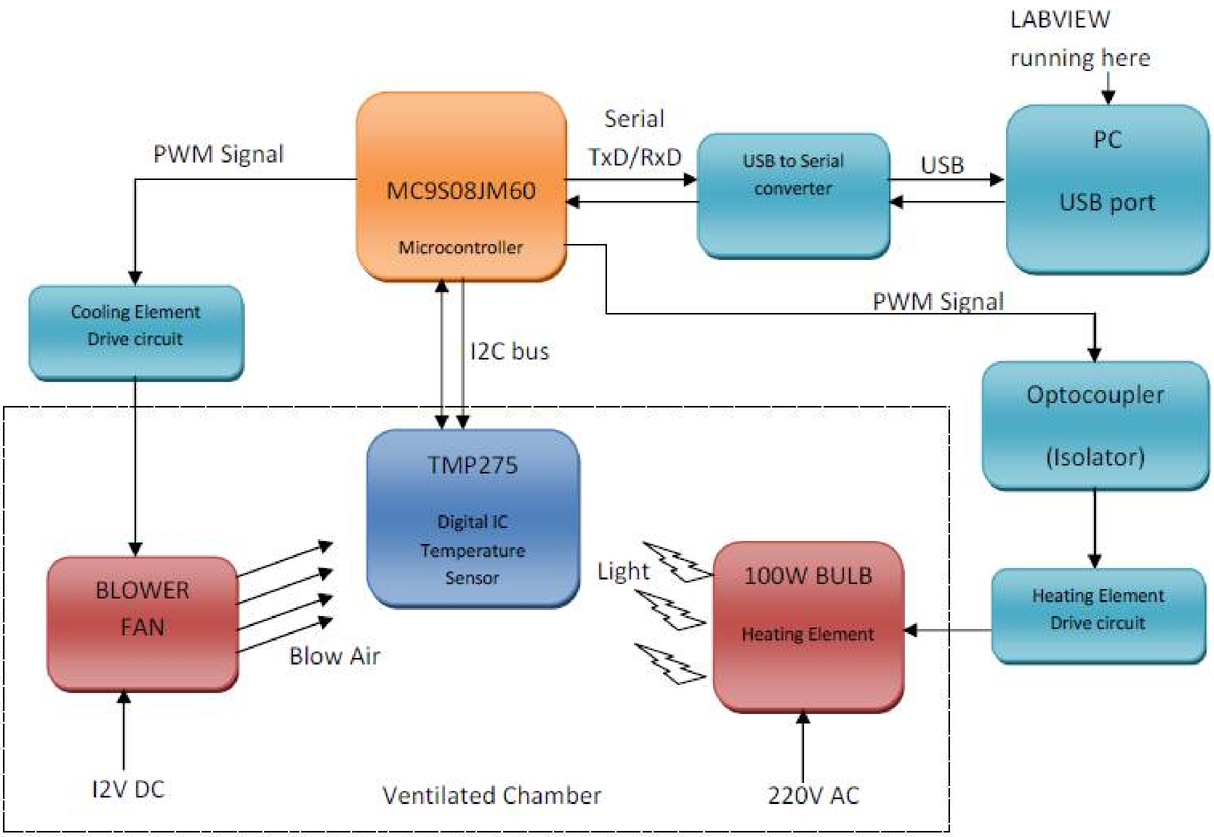

Figure 1: System Block Diagram

Figure 1 shows the building blocks of the system that comprise the digital temperature sensor, microcontroller, USB-to-Serial converter, PC, driver circuit for driving the DC blower FAN (cooling element), driver circuit for driving the 100W incandescent bulb (Heating element), Optocoupler (isolator) and the ventilated chamber.

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B. Temperature Measurement

For sensing the temperature a I2C digital temperature sensor TMP275 is used that is 0.5°C accurate and available in a tiny 8-pin SOIC surface mount device package. It is capable of reading temperature with a resolution of 0.0625°C. It is specified to operate over a range of -40°C till +125°C. The microcontroller reads the digital value of the temperature measured via its two wire serial interface. The I2C slave address pins A2, A1 and A0 of the sensor is connected to ground in the hardware design so that it has a slave address of 0x90 for write and 0x91 for read. The temperature register reserves 12 bit for the temperature value. Most significant bit is used for sign and 11 bits are used for magnitude. On the positive side, the 11 bits being all ones represent 127.9375°C. Therefore one LSBit represent 0.0625°C. On the negative side the sensor can measure a maximum negative value of -40°C. The device takes a time interval of 220ms (typical) for converting into 12 bit digital value of the temperature. The I2C slave interface of TMP275 uses standard I2C protocol to communicate with the I2C master interface of the microcontroller. All bytes are transmitted MSB first. It is operated at fast mode at a frequency of 100 kHz. The sensing of TMP275 is the chip itself. Thermal paths run through the package leads as well as the plastic package. The lower thermal resistance of the metal causes the leads to provide the primary thermal path. If it is used for surface temperature measurement then a thermally conductive adhesive should be used between the IC package and the surface of which the temperature is to be measured. This will help in achieving better accuracy. IC temperature sensor have the advantages of low cost, small size and high linearity. However it has certain disadvantages: limited operating temperature range (-40°C till +125°C), self heating error, and poor thermal coupling with the environment. The sensor detects the ambient temperature and upon being initialised by the microcontroller converts the temperature into digital value and stores in the internal register of the sensor. The microcontroller reads the internal temperature register and sends it to the PC via the serial port. A LABVIEW application running in the PC displays the temperature graphically in real time.

C. Temperature Control

An incandescent bulb of 100W is used as the heating element to heat the air within a chamber of volume 27000 cubic centimeter. A PWM signal whose duty cycle is controlled automatically by the microcontroller is used to turn ON the bulb. Therefore the average DC current passing through the bulb is controlled by the duty cycle of the PWM signal thereby controlling the intensity with which the bulb glows and hence the heat generated. If the measured temperature rises above the temperature that is to be maintained inside the chamber, a 12V DC blower fan is switched ON to cool down the ambient air temperature. The speed with which the DC blower fan turns ON is also controlled by a PWM signal whose duty cycle is controlled by the microcontroller. Once the current temperature rises up to the set value of the temperature, the FAN blowing the air at an appropriate rate helps to maintain the temperature with the least variation. A PID controller is implemented in the microcontroller firmware to get the finest response in terms of settling time and least variation.

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D. Schematic Diagram and Working

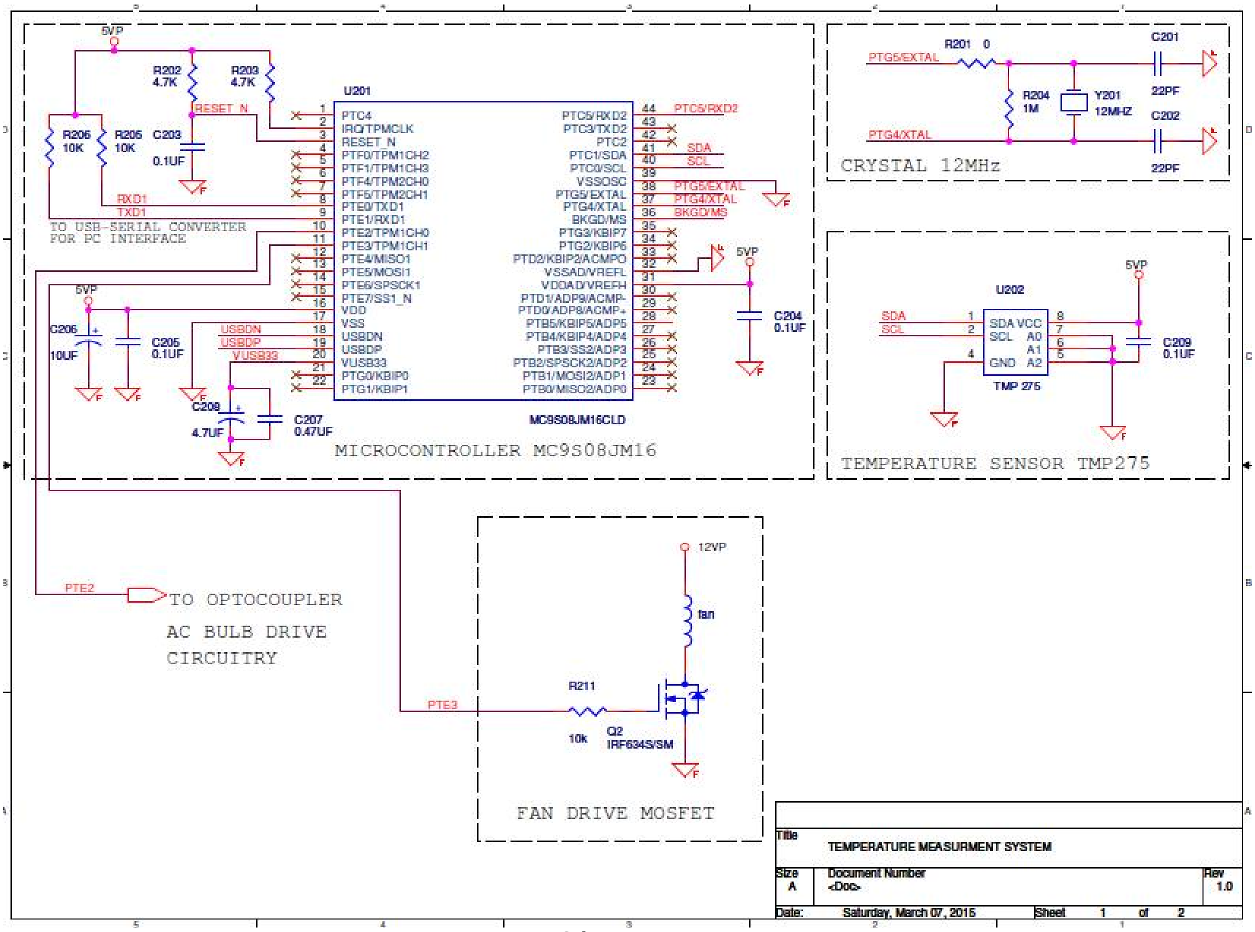

Figure 2: Schematic Diagram-1

Figure 2 shows the first part of the schematic of the design showing the Microcontroller, Sensor and the cooling device (fan) drive circuitry.

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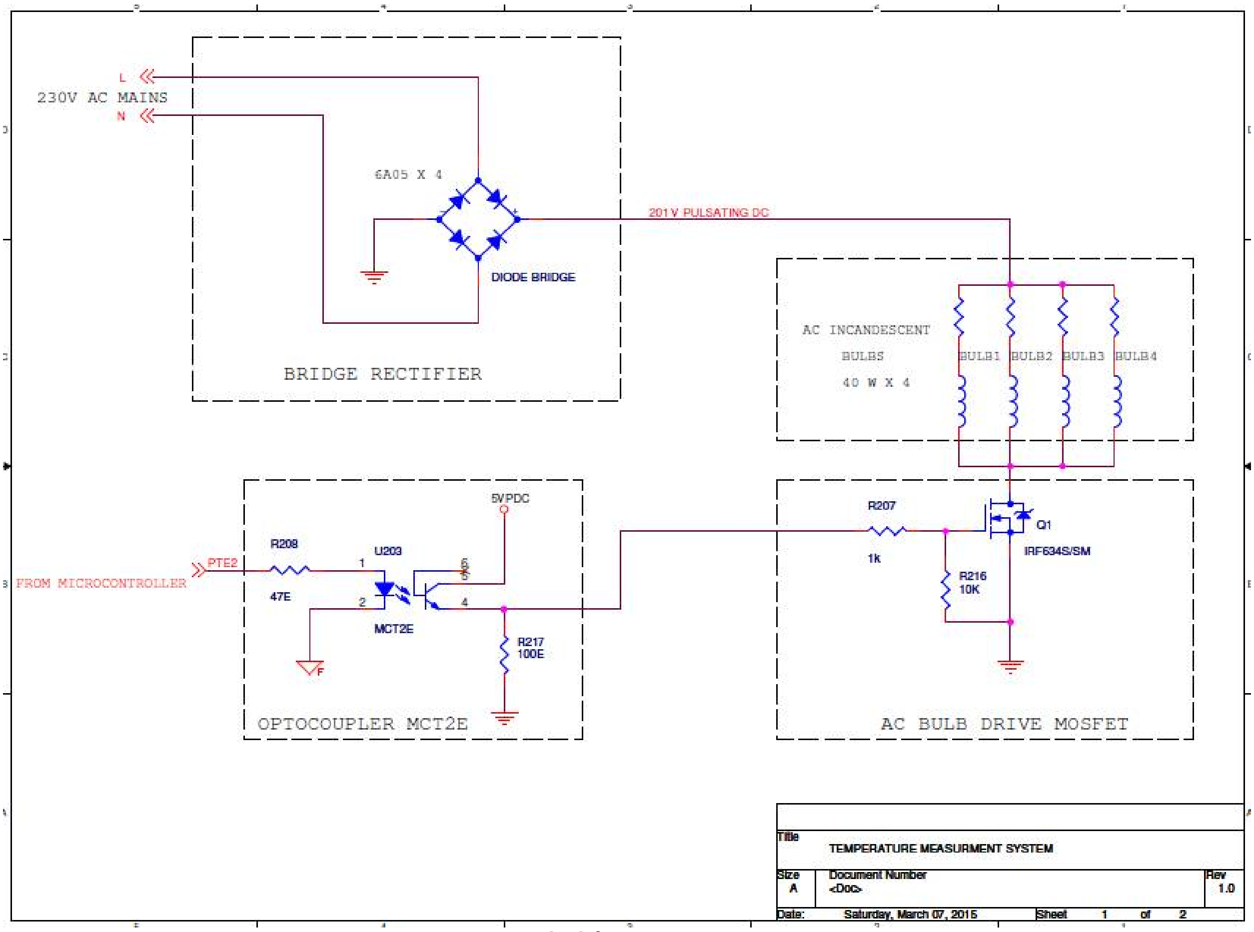

Figure 3: Schematic Diagram-2

Figure 3 shows the second part of the schematic diagram of the above mentioned proposed scheme. Average voltage of the pulsating DC given out from the bridge rectifier is applied to the incandescent bulb is 198 V. Power MOSFET IRF634 is used to switch this voltage across the bulb. The MOSFET is driven by the PWM signal generated by the microcontroller. The light intensity of the bulb can be controlled smoothly to minimise the deviation of the actual temperature from the set-point by controlling the pulse-width that in turn control the current through the bulb. MOSFET device is voltage controlled in contrast to the bipolar transistor device that is current controlled. It has high input impedance and being a majority carrier device they do not suffer from minority carrier storage time effect, thermal runaway or second breakdown. Major advantage of the power MOSFET is its fast switching speed. Drain current is strictly proportional to the gate voltage. Being a majority carrier device its turn-off time is not delayed by the minority carrier storage time in the base as in the case of bipolar transistor. A MOSFET device begins to turn off as soon as the gate voltage begins to drop down below the threshold voltage. If on-state power losses due to Rds(on) will predominate then there is little point in designing a costly drive circuit. The conduction power loss is independent of the gate drive voltage as long as the gate source voltage exceeds the gate threshold voltage by several volts. In contrast if the MOSFET is switching at a frequency of 200 KHz or more, then the switching loss will be a significant portion of the total power loss. Therefore the frequency of the PWM signal is generated to be a very low frequency of 200 Hz. Therefore the switching loss can be neglected and the total power dissipation in the MOSFET is equal to the conduction loss. Since the MOSFET is a voltage controlled device, the only gate current required is to turn on the MOSFET is to charge the input capacitance. MOSFET IRF634 is triggered by the PWM signal generated by the microcontroller. To provide electrical isolation between the microcontroller and the incandescent bulb that operates on AC mains, an opto-coupler is used between the microcontroller and the MOSFET. A DC voltage of 12V is used to drive the fan. Power MOSFET IRF540 is used to switch the voltage across the fan. The MOSFET is driven by the

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PWM signal generated by the microcontroller. The speed of the fan can be controlled precisely to maintain the temperature within the set-point with as much less variation as possible.

III. MICROCONTROLLER FIRMWARE ARCHITECTURE

A. *Small Embedded Operating System*

The microcontroller has two built-in 16-bit timers. One of the timer is configured to generate an interrupt(a 'tick') to the processor at regular and precise interval of 5ms. The interrupt service routine is used as the scheduler. The simple operating system architecture used in designing the software has two key features: A time-triggered architecture and a co-operative scheduling algorithm. The time-triggered approach has an advantage that it results in a system that has a predictable behaviour. A pre-emptive or time sliced approach is used so that from the perspective of the user, the OS appears to be running multiple tasks at the same time.

B. *Serial Port Driver*

A memory buffer is implemented to hold the data that needs to be transmitted via the UART. The serial port functions are executed on a periodic basis by the OS. This approach is advantageous in case of transmission of longer strings which might take longer time than the tick interval and stall the execution of other tasks. On a periodic basis the serial port functions are executed by the scheduler that checks the buffer and if there are any characters in the buffer ready to be send then the same are transmitted. The code has been designed to read the sensor and transmit the temperature value on receiving a read temperature command from the PC to which the microcontroller is connected through the serial port. The speed of transmission via the serial port is 9600 bps.

C. *Flowchart*

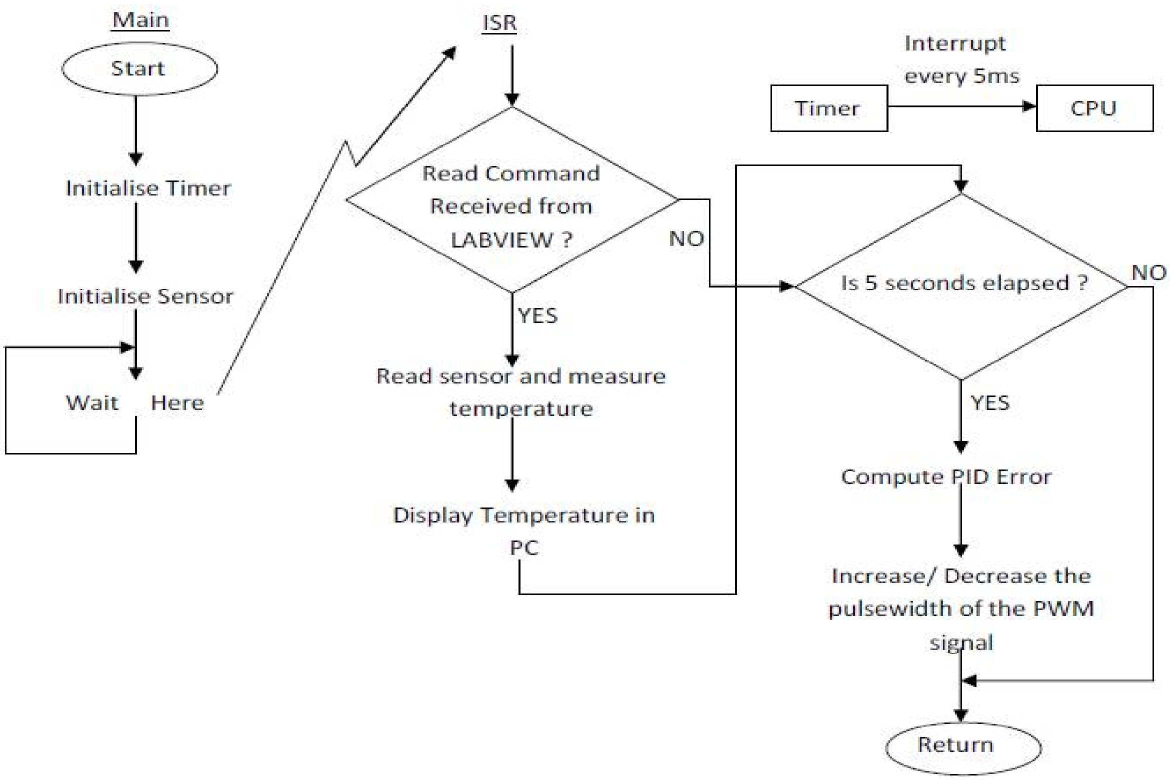

Figure 4: Flowchart

Figure 4 shows the flowchart of the firmware that is run by the microcontroller.

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IV. DATA ACQUISITION AND GRAPHICAL USER INTERFACE USING LABVIEW

The LABVIEW application is used to build a graphical user interface with the microcontroller based temperature measurement and control system. The PC is connected to the system through a USB interface via a USB-serial converter. The LABVIEW application issues a read temperature command through the virtual serial port to the temperature measurement and control system. The microcontroller on receiving this command reads the sensor and transmits the temperature to the PC through the serial port. The temperature data is received by the LABVIEW application and displays the same graphically in real time. The interval after which the application issues a temperature read command can be altered with the help of a sampling control knob designed on the LABVIEW frontpanel.

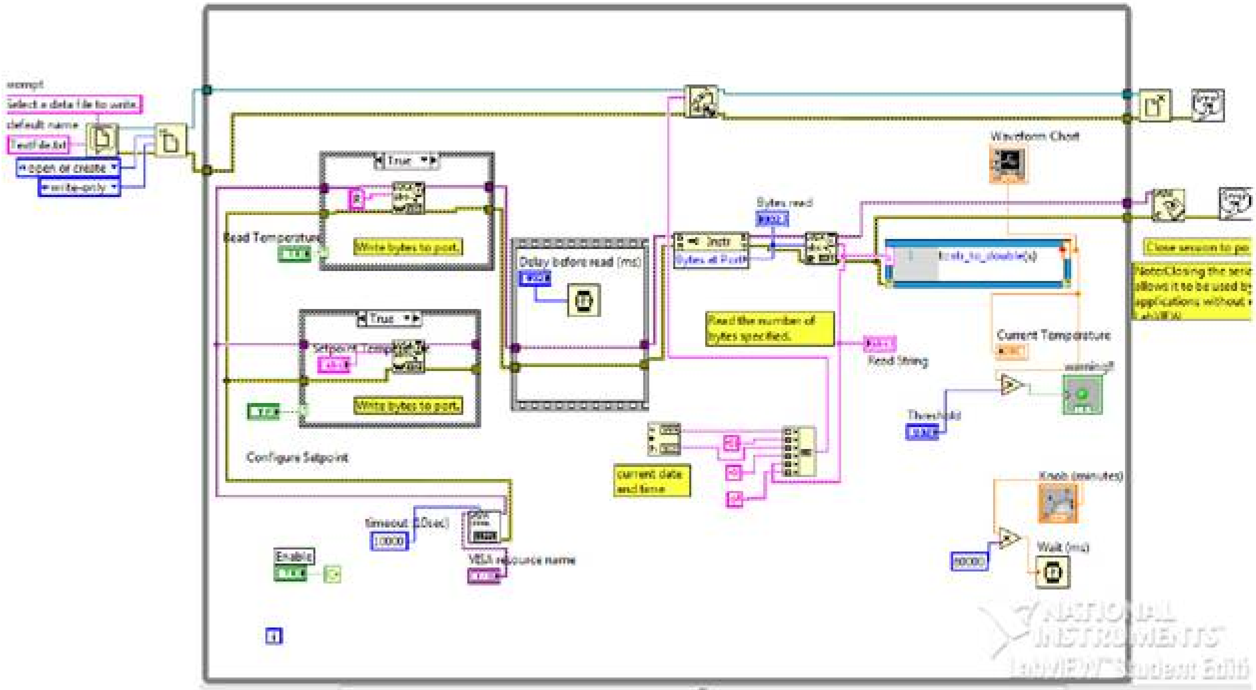

Figure 5: LABVIEW block diagram

Figure 5 shows the block diagram of the LABVIEW application for data acquisition. Following features are incorporated into the LABVIEW application for better data acquisition:

- Real time capture of temperature graphically.
- The set-point temperature can be configured from LABVIEW front panel.
- The data is logged into a file in the hard-drive with current date and time.
- The sampling interval of temperature can be configured by a control knob in the LABVIEW front panel.

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V. EXPERIMENTAL RESULTS

A. *Ambient Temperature measurement*

Figure 6 and 7 shows temperature measurement graphical display during entire day and night respectively. The values of the temperature are also logged into the hard-disk of PC for offline analysis.

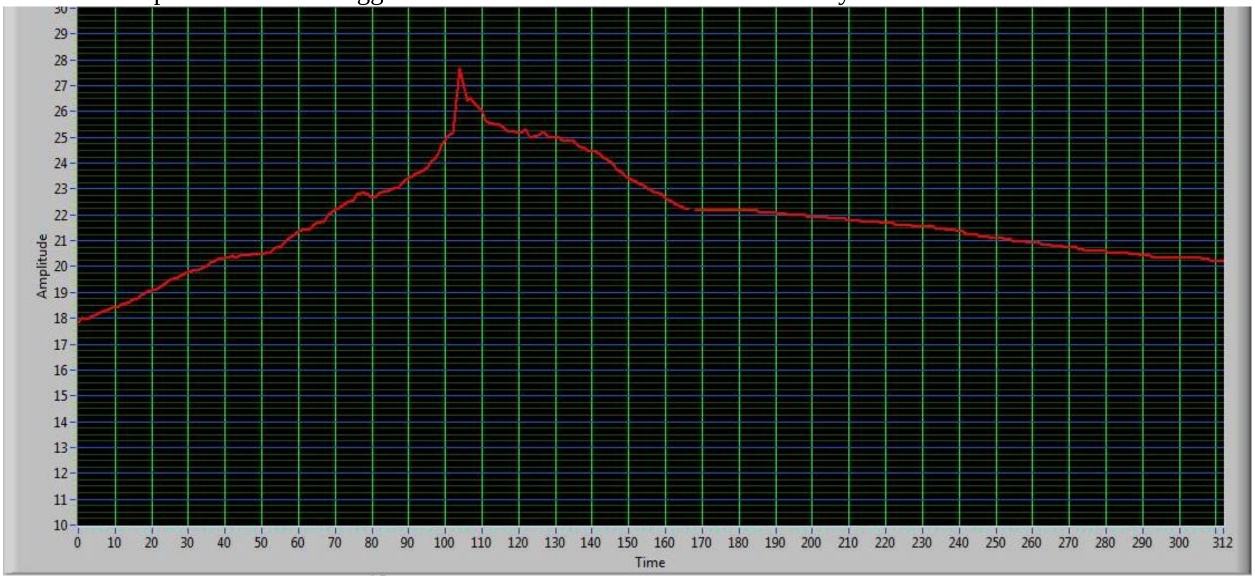

Figure 6: Graphical representation of temperature variation during day time in winter season

Figure 6 shows the temperature measured during day time in a winter season over a span of 12 hours. Y-axis shows the temperature in degree celcius and X-axis the different samples at an interval of time. The real-time of the samples are logged into the hard-disk.

Figure 7: Graphical representation of temperature variation during night time in winter season

Figure 7 shows the temperature measured during day time in a winter season over a span of 12 hours. Y-axis shows the temperature in degree celcius and X-axis the different samples at an interval of time. The real-time of the samples are logged into the hard-disk.

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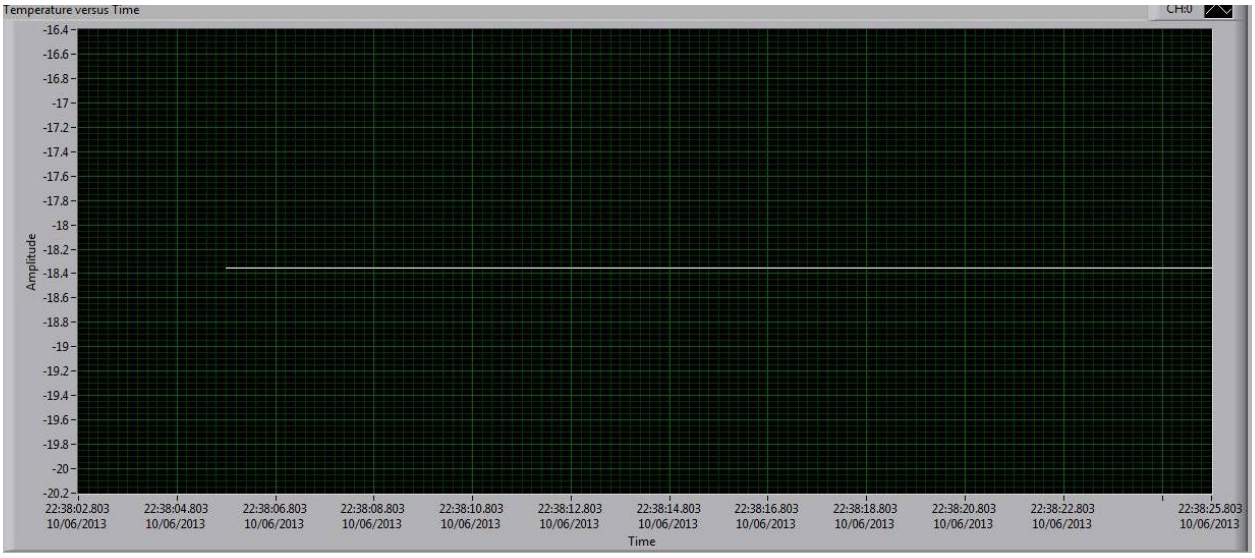

Figure 8: Graphical representation of low temperature measurement

Figure 8 shows the measurement of a low temperature as low as -18 degree celcius. X-axis shows the real time stamp at which the measurement is done.

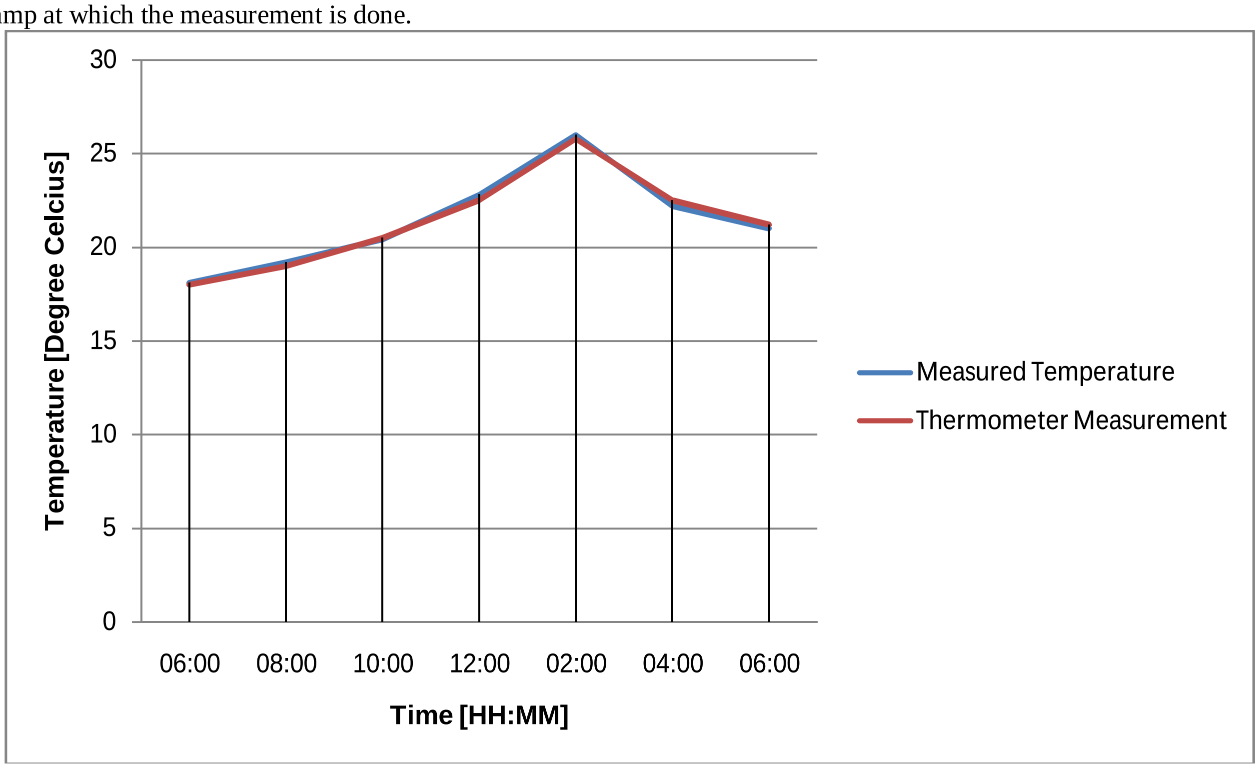

Figure 9: Comparison between the temperature measured by the system and standard mercury wall thermometer temperature during daytime

Figure 9 shows graphically the comparison between temperature measured by the system and a standard mercury wall thermometer for a period of 12 hours.

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B. *Data logging*

The temperature measured can be logged on to the hard-drive of PC for further offline analysis. The data is logged with the current time-stamp as shown below:

11/14/2014	11:40 PM	25.0943
11/14/2014	11:40 PM	25.0318
11/14/2014	11:40 PM	24.9693
11/14/2014	11:40 PM	24.9693
11/14/2014	11:40 PM	24.9693
11/14/2014	11:40 PM	24.9693
11/14/2014	11:41 PM	24.9693
11/14/2014	11:41 PM	24.9693
11/14/2014	11:41 PM	24.9068
11/14/2014	11:41 PM	24.9068
11/14/2014	11:41 PM	24.8443
11/14/2014	11:41 PM	24.8443
11/14/2014	11:42 PM	24.7818
11/14/2014	11:42 PM	24.7818
11/14/2014	11:42 PM	24.7818
11/14/2014	11:42 PM	24.7193
11/14/2014	11:42 PM	24.7193
11/14/2014	11:42 PM	24.7193
11/14/2014	11:43 PM	24.7193
11/14/2014	11:43 PM	24.7193
11/14/2014	11:43 PM	24.6567

C. *Temperature Control*

TABLE I
SETTLING TIME, OVERSHOOT AND UNDERSHOOT

Set-point Temperature ^{0}C	Settling time in sec	Overshoot	Undershoot	Variation %
26	5	26.2821	26.2196	0.24
27	4	27.03	26.968	0.22
28	10	28.03	27.97	0.21
29	7	29.09	28.97	0.41

As seen from the Table I, with PID control and PWM technology the temperature variation around the set-point is very small.

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In support of table I, Figure 10, 11, 12 and 13 shows the measurement of temperature inside the chamber with different values of set-point temperature.

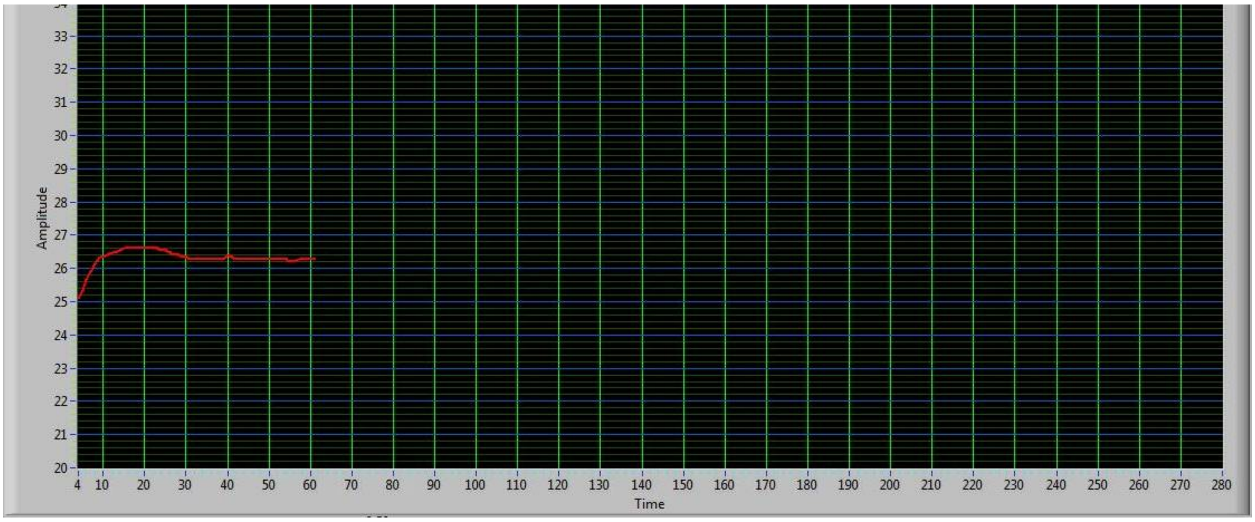

Figure 10: Set-Point Temperature 26°C

Figure 10 shows the measurement and control of the temperature inside the air chamber where the desired temperature is set to 26 degree celcius.

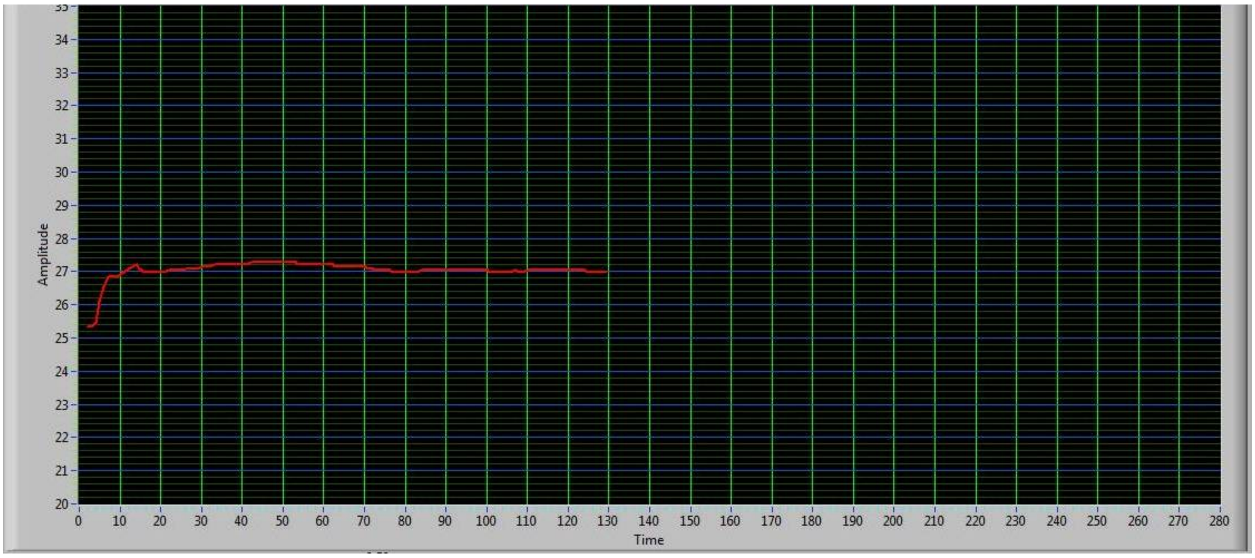

Figure 11: Set-Point Temperature 27°C

Figure 11 shows the measurement and control of the temperature inside the air chamber where the desired temperature is set to 27 degree celcius.

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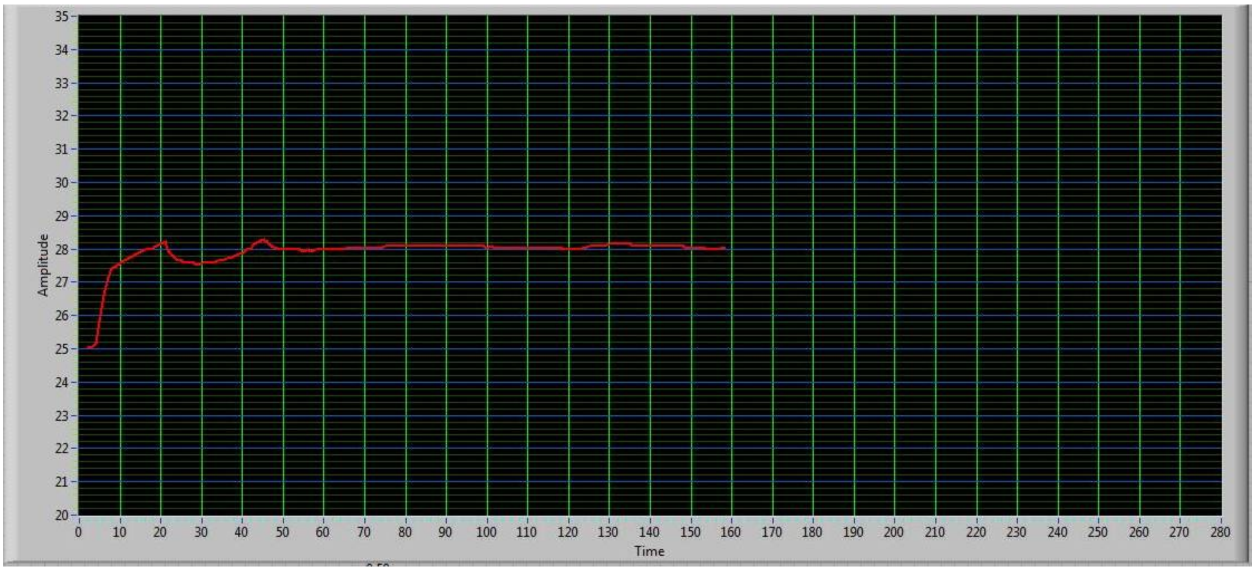

Figure 12: Set-Point Temperature 28°C

Figure 12 shows the measurement and control of the temperature inside the air chamber where the desired temperature is set to 28 degree celcius.

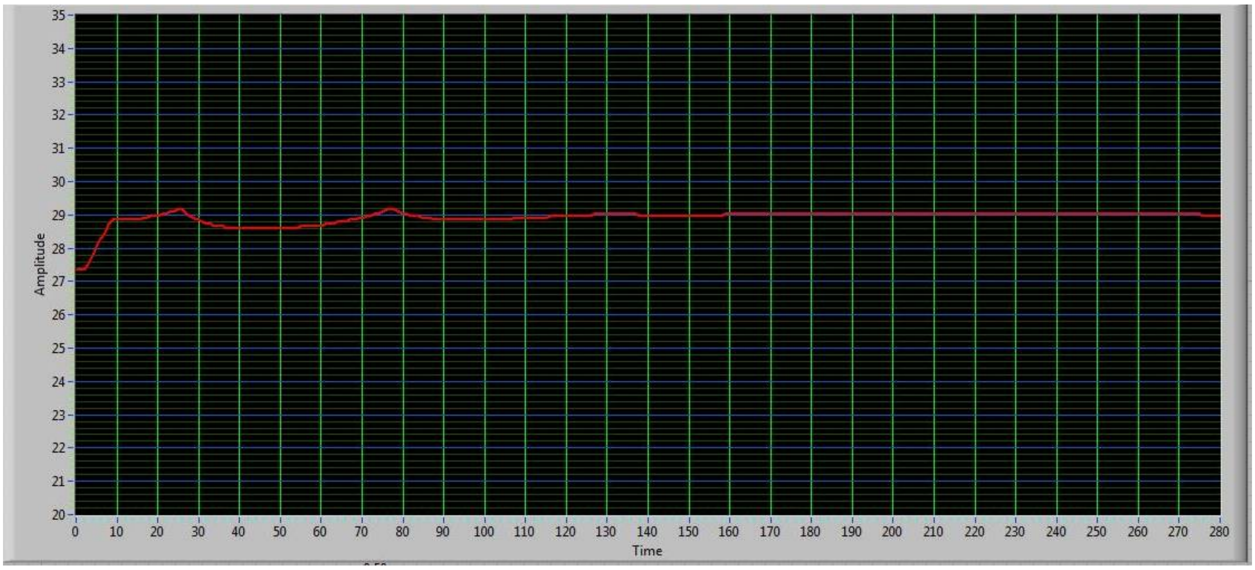

Figure 13: Set-Point Temperature 29°C

Figure 13 shows the measurement and control of the temperature inside the air chamber where the desired temperature is set to 29 degree celcius. Figure 10 till 13 evidently shows that the current temperature inside the chamber rises up to the desired temperature that is to be maintained with least overshoot and undershoot, and the same is maintained with precision and least variation as given in table I.

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VI. CONCLUSION

The proposed system is functionally tested to measure temperature between low temperature as low as -18°C till higher temperature as high as +70°C with a resolution of 0.0625°C and accuracy of 0.5°C. With PID control and PWM method the temperature can be maintained at the set-point with much less variation, better settling time, lower overshoot and undershoot. It can maintain and control the temperature within the required set temperature with least variation. Therefore this system can be used to monitor and control temperature in a ventilated chamber where precise detection of temperature change and control is required. It can be used in processing plants in the field of medicine, food, biotechnology and other sectors where it is required to maintain a constant temperature with very less variation. It is also optimal for thermal management and thermal protection applications. Microcontroller based temperature measurement system can measure the temperature with much higher accuracy and stability. The response of microcontroller based temperature measurement system utilizing a digital temperature sensor is much faster compared to a conventional mercury based thermometer. The use of digital temperature sensor has enabled to get rid of external signal conditioning circuitry resulting in much simpler and reduced hardware components thereby increasing the overall reliability of the system.

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