IJCSE International Journal of Computer Sciences and Engineering Open Access
Survey Paper Volume-4, Special Issue-7, Dec 2016 ISSN: 2347-2693

Study on Accurate Temperature Measurement Using Different Sensors and Microcontroller Based System

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Available online at: www.ijcseonline.org

***Abstract*—Much of technology advances in the field of temperature measurement have led to a huge variety of sensors and measuring instruments now being available for making accurate measurements at relatively low costs. This paper makes an attempt to do a study on improving the accuracy of temperature measurement using most popular temperature measurement sensors and implementing in a microcontroller based measurement system, that will help to choose the correct method and sensor for specific application of temperature measurement.**

Keywords—RTD(Resistance Temperature Detector), ADC(Analog to Digital Converter), CJC(cold junction compensation), I2C(Inter Integrated Circuit), PWM(Pulse Width Modulation), PRT(Platinum Resistance Thermometer),

I. INTRODUCTION

Measurement and monitoring temperature is a widespread and common engineering task. Whether in a factory, laboratory, performing accurate, high resolution temperature measurement is essential but may become difficult and expensive. Most commonly, a simple thermocouple is used along with a data acquisition device and some kind of signal conditioning hardware. Highly accurate temperature measuring equipment is now widely available at very reasonable costs but, whilst this should be making the task of making temperature measurement easy, there are errors either in using the sensor or making a correct choice of the sensor for a particular application of temperature measurement. Purchasing the highest specification, most expensive sensor and measuring instrument that one can afford is not always the right way to set about making accurate measurements. Some processes do not require high level of temperature measurement accuracy, and others do. When considering technology for a given application, it is important to understand the accuracy requirement.

There are three groups into which temperature measurement can be categorized:

a) Those that do not require accuracy

b) Those that do require accuracy

c) Those where there is uncertainty about the accuracy requirement.

While performing a temperature measurement following must be ensured for correct measurement:

a) select the best sensor for the application

b) Reduce errors caused by external environment

c) Reduce errors caused by lead wires

d) Reduce measurement errors.

II. LITERATURE SURVEY

In September, 2015, [1] National Instruments published an article on how to perform high accuracy temperature measurement using thermocouples and RTD. In July, 2015, [2] Garry Prentice of Moore Industries published an article in Flow Control Magazine some guidelines on making accurate temperature measurements. The issues that are required to be taken care while performing temperature measurements for a specific applications were discussed.

III. TEMPERATURE MEASUREMENT SENSORS

The three sensors most commonly used in research and industry are: Thermocouple, Resistance Temperature Detector (RTD and the Thermistor.

A. *Thermocouples*

Although almost any two types of metal can be used to make a thermocouple, a number of standard types are used because they possess predictable output voltages and large temperature gradients. For example, a K type thermocouple (the most popular Chromel/Alumel) at 300 °C will produce 12.2mV. As mentioned, different choices of metals for the thermocouple's two conductors produce sensors with different characteristics. Thermocouples are made of thin wire to minimize thermal shunting and increase response times. This thin wire causes the thermocouple to have a high resistance that can cause errors due to the input impedance of the measuring instrument. A typical exposed junction thermocouple with 32 AWG wire (0.25 mm diameter) will have a resistance of about 15 Ohm/m. If thermocouples with thin leads or long cables are needed, it is worth keeping the thermocouple leads short and then using thermocouple extension wire (which is much thicker and has a lower resistance) to run between the thermocouple and measuring instrument.

To reduce the error induced by the leads connecting the thermocouple to the measuring instrument a technology called cold junction compensation (CJC) is required to be used. The accuracy of thermocouples can be improved by using thermocouples constructed with special tolerance(also called premium grade) wire. The reduced error is achieved by using higher purity alloys. Changing from a standard thermocouple to a premium grade thermocouple cuts the error to half.

B. Resistance Temperature Detector (RTD)

Another common type of temperature measuring device is the resistance temperature detector — the most stable and accurate (although expensive and fragile) of the three sensor types discussed in this article. It has a positive temperature coefficient. Perhaps the most common type of RTD is the platinum resistance thermometer (PRT), the practical operating range of which is -250 to 850 °C. Depending on type, RTDs have an accuracy of between 0.03 and 0.3 °C. The most frequently used PRT is the Pt100 — so called because it has a resistance of 100 ohm at 0 °C. PRTs are either wire–wound or metal film resistors. Of these, the latter exhibits the faster response time. As a Pt100 sensor is basically a resistor, its value can be measured with an Ohmmeter as per figure 4. However, the low resistance of the sensor and its low sensitivity (0.385 Ohm/°C) make accurate measurements difficult due to lead resistance. A 1 Ohm resistance in each lead connecting the Pt100 to the meter will cause an error of more than 5 °C.

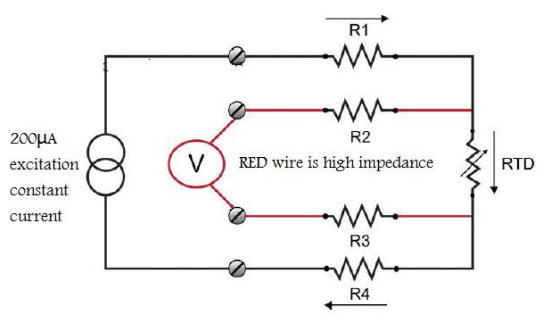

Fig. 1. 4-wire RTD diagram

To avoid the problem of lead resistance errors, most Pt100 measurements are made using a 4-wire configuration as shown in figure 1. Here, two of the wires are used to provide an excitation current and the other two connect a voltmeter over the PRT. Provided the impedance of the voltmeter is high then a few Ohms of resistance in the cables will not cause an error. The 4-wire configuration affords the best accuracy, but low resistance and low sensitivity of the RTD place considerable demands on the measuring instrument and a compromise has to be made between excitation current, noise and resolution. Excitation current should be as low as possible (< 1 mA) in order to minimise self–heating of the sensor. This reduces the sensor's output voltage, the signal to noise ratio (through increased noise pickup) and resolution of the instrument. At this point use of microcontrollers with built-in analog to digital converters (ADC) can increase the resolution to large extent. Use of a 24 bit analog to digital converter — still provides 0.001 °C resolution. However for high accuracy measurement, self-heating errors should always be taken into account. The small signals from a Pt100 sensor lead to noise pickup problems similar to those encountered for thermocouples and the same precautions against pickup should be used.

C. Thermistor

For extreme accuracy the RTD is still the best choice, but modern thermistors can also provide a much higher accuracy. Thermistors with 0.1 °C accuracy are now widely available and at very reasonable costs. They have a fast response time and a greater output per °C than RTDs. As with RTDs, thermistors also exploit the fact that a material's resistance changes with temperature. However, the majority of thermistors employ a metallic oxide and have a negative temperature coefficient (NTC). Thermistors provide relatively high accuracy (0.1 to 1.5 °C) but only operate over a limited temperature range: –100 to +300 °C. The thermistor's response is non-linear and, as with RTDs, providing too large an excitation current through the thermistor should be avoided because of self-heating. Connection to instruments is a simple 2-wire configuration, as — unlike RTDs — we do not need to compensate for lead resistances: this is small compared to the thermistor's resistance (typically between 1 and 100 kO). Thermistors, because of their high sensitivity, are ideal for detecting small changes in temperature — especially when it is the change and not the absolute value that is important. When using thermistors, implementing the same using a microcontroller based system will solve the problem of non-linearity of thermistor since look-up table can be implemented in the software.

IV. COMPARISON OF SENSORS

Table 1 compares various parameters and contrasts the three sensors. IC sensors that are both analog and digital are also being frequently used in microcontroller based temperature measurement systems. These IC sensors are used in application where the temperature range is generally limited to a smaller range typically -25°C to 125°C.

TABLE I.

	Temperature Measurement Sensors		
	Thermocouple	***RTD (Resistance Temperature Detector)***	***Thermistor***
Operating Range	-200°C to 2000°C	-250°C to 850°C	-100°C to 300°C
Accuracy	Low 1°C	Very High 0.03°C	High 0.1°C
Linearity	Medium	High	Low
Thermal response	Fast	Slow	Medium
Cost	Low	High	Low to Moderate
Noise Problem	High	Medium	Low
Long term stability	Low	High	Medium
Cost of instrument	Medium	High	Low

RTD is the most accurate sensor to use when the process temperature that is to be measured is within its range. But sometimes less accurate thermocouples need to be used when the temperature is hotter than the RTDs upper limit.

V. MICROCONTROLLER BASED SCHEME

A simple scheme of using a microcontroller MC9S08JM60 to measure and control the temperature is outlined below.

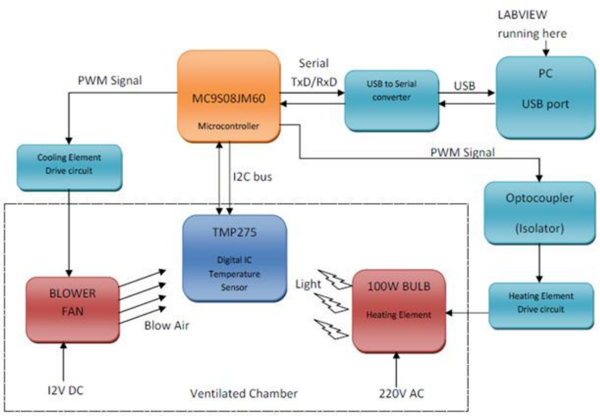

Fig. 2. Microcontroller Based Temperature Measurement and Control

For reference, a I2C based digital IC sensor TMP275 is used to sense the temperature. It is a digital sensor that communicates to the microcontroller via the I2C bus. The temperature sensed by the sensor is available to the microcontroller in a 12-bit digital format. The ADC is built inside the IC sensor. No signal conditioning circuitry is required because the IC sensor gives out the temperature in digital format that can be directly read by the microcontroller to measure and control. The building blocks of the system 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.

A. Temperature measurement

For sensing the temperature a I2C digital temperature sensor TMP275 is used that is 0.5°C accurate. 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 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.

B. 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.

With the use of microcontrollers, look-up table can be implemented to overcome the problem of non-linearity of thermistors. If IC based sensors are used then digital sensors are better than analog sensors as it simplifies the circuitry involved and reduce errors that might creep into while digitizing the analog data.

CONCLUSION

Summarizing the points altogether for performing a high accuracy temperature measurement following need to be ensured: a) Four-wire RTDs eliminate the errors caused by copper wire leads. b) Use Class A RTDs that have been aged through temperature cycling. c) Use premium-grade thermocouples and premium-grade extension wires if the temperature is required to be measured with thermocouples. For accurate measurements, calibration is a must and where possible instrument and sensor(s) should be calibrated together as a system. High precision temperature measurement is possible through the use of well-specified and suitably calibrated sensors and instrumentation. However, the accuracy of these measurements will be meaningless unless the equipment and sensors are used correctly.

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