Thermoelectric-based temperature control for rapid heating and cooling

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Abstract. Temperature control is one of the important factors in chemical sensor using Quartz Crystal Microbalance (QCM). The QCM sensor has been known to be sensitive to deposited mass and also the mechanical property of the sensitive coating layer. The mechanical property of the coating layer and also the interaction between the coating layer and the target molecules also depend on the temperature. Therefore it is important to maintain the temperature of the reaction chamber of the chemical sensor. This paper presents the development of a temperature control system using thermoelectric modules. The system was developed such that the temperature of the target can be heated or cooled with a simple system and consumed little energy. The surface temperature of the thermoelectric was measured using a thermistor. The microcontroller (Arduino module) acts as the heart of the control system. The heating and cooling of the thermoelectric were altered using the H-bridge circuit which able to switch the current direction flowing into the thermoelectric element. A simple pulse width modulation was used to deliver the current to the thermoelectric element to control the heating or cooling speed. The result showed that the system could maintain the target temperature at a given set value.

Keywords: temperature control; thermoelectric; H-bridge; thermistor; microcontroller

1. Introduction

Temperature is a fundamental quantity which is involved in many mechanisms. Many processes, material property, and interaction be influenced by temperature. The temperature needs to be controlled during many measurements and controlling process. Sensor detection also depends on the temperature during the sensing process [1]. Some sensor, for example, metal oxide gas sensor, works only at elevated temperatures such as 300°C or 350°C, depending on the oxide property [2].

Quartz Crystal Microbalance (QCM) sensor is one sensor where its work is also temperature dependent, not because of the sensor property but the property of material and reaction being detected is temperature dependent. When the QCM sensor works as a gas sensor, the reaction between the gas molecule and the sensor sensitive layer depend on the temperature. In its operation in liquid, the liquid viscosity and density in contact with the sensor lead to a sensor responds [3]. Therefore controlling the temperature stability during the detection process is needed. The temperature should be precisely and continuously controlled and monitored in order to get the sensor to respond correctly [4].

However, the temperature tends to have rapid changes and high sensitivity towards the surroundings that even the slightest disturbance could affect the temperature. It is a natural process that the object will
release or absorb heat to decrease or increase its temperature to reach the equilibrium temperature with
the surroundings. The object temperature can decrease or increase depending on the temperature
difference between the object and its surroundings. Therefore it is required that in the QCM sensor
detection system, the temperature of the object being detected should be constant. When the temperature
of the object decreased, an action to increase the temperature is required and vice versa. Temperature
control is aimed to set a given point throughout the system and its ability to maintain the temperature.

Temperature control can be performed by using many devices. Controlling object temperature higher
or lower compared to the surroundings requires heater and cooler. Instead of using a separate heating
and cooling devices, the thermoelectric element can be used for both. By altering the electrical current
direction to the thermoelectric module, the working side of the thermoelectric can behave as cooler or
heater [5,6]. This work presents the use of the thermoelectric element as heater or cooler which will be
targeted as heating and cooling of the object being detected using the QCM sensor. This paper shows
that the response time for heating and cooling of the thermoelectric in open air depend on the duty cycle
of the pulse width current injected to the thermoelectric.

2. Materials and method

2.1. Materials
In the experiment, we used a signed TEC1-12706 (TEC) thermoelectric module as the cooler and heating
element. The module was made of Bismuth Telluride (Bi₂Te₃) semiconductor placed in two parallel plat
of alumina (Al₂O₃) substrate. The dimension of the module was 40×40×3.8 mm with a weight of 27 g.
The maximum temperature difference between the two plats of the TEC is 70°C. The maximum
temperature of the hot side is 138°C. The TEC has a maximum current of 6A. The module was attached
to a fan cooling to speed up the heat transfer from the module surface to the air.

Temperature measurement of the TEC surface temperature was done using a negative temperature
coefficient (NTC) thermistor. Two NTC B3950 thermistors with a resistance of 10KΩ and tolerance of
1% were used to measure the TEC surface temperature and the ambient temperature. In order to measure
the temperature, the Steinhart-Hart equation is used to calculate the temperature based on the measured
thermistor resistance as described in equation (1).

\[ T = \left( \frac{1}{A + B \ln(R+C) + \ln(R)} \right) - 273.15 \] °C \hspace{1cm} (1)

where the given coefficient values are \( A = 1.009249522 \times 10^{-3} \), \( B = 2.378405444 \times 10^{-4} \), \( A = 2.019202697 \times 10^{-7} \) and \( R = 10000 \). Steinhart-Hart equation has errors of less than 0.1°C, making it
very accurate and efficient [7].

Resistance measurement was done using a simple voltage divider and directly read by a
microcontroller to be converted as a temperature value. The microcontroller module Arduino Mega 2560
was used as the core of the measurement and control system. Arduino Mega 2560 has a total of 54 digital
I/O pins, 16 analog inputs, four hardware serial ports, a 16 MHz oscillator, a USB connection, and a
larger space, making it convenient for a big and complex project.

An L298N H-Bridge controller was used to switch the current direction to the thermoelectric. The
thermoelectric The current direction Therefore changing both heating and cooling automatically without
having to switch the wires manually. The H-bridge delivered the current from a 12VDC source to the
thermoelectric module.

2.2. Methods
To obtain the heating and cooling performance of the TEC, the TEC was installed on a thermal block
with the cooling fan. Figure 1 shows the configuration system. One side of the TEC was thermally in
contact with the thermal block, and the other side was isolated from the air by the thermal isolator. The
temperature of the TEC surface beneath the thermal isolator was the temperature of the TEC being
controlled. The thermistor was placed in contact with the TEC surface with the thermal isolator. The
surface temperature of the TEC and the thermal block with the cooling fan was not measured.
Cooling and heating were controlled using PWM mode of the microcontroller[8-10]. Initially, a target surface temperature was set together with the PWM mode. Different PWM was used (20%, 40%, 60%, and 80%) on the Arduino Mega 2560 throughout the experiment to test out which PWM was the most effective in terms of heating and cooling on the thermoelectric.

The surface temperature of the TEC and the room temperature were monitored via the analog to the digital input of the microcontroller. When the TEC temperature higher than the target temperature, the microcontroller set the working mode of the TEC as a cooler. As the TEC temperature reaches the target temperature, the cooling process was terminated. In another hand, when at initially the target temperature was higher than the initial temperature of the TEC, the microcontroller set the working mode in heating state. In the cooling mode, the heat was transferred from the measured surface to the surface in contact with the thermal block and the fan. Therefore, the fan on the thermal surface was activated when the TEC work in the cooling mode only.

Figure 1. Experimental setup

3. Results and Discussion

In this experiment, different target temperature and PWM duty cycle were observed. Variety of data were recorded in a period time of one minute using different duty cycles which were 20%, 40%, 60%, and 80%. The 0% and 100% duty cycles were not used because 0% states the voltage regulated throughout is entirely off the circuit, and 100% means fully on.

Cooling and heating test were done by setting the target temperature around 2°C higher and lower than the room temperature. The room temperature of the experimental condition was at 24.5°C. Based on the measured room temperature, the target temperature for the cooling process was set to 23°C, while for the heating process, the target temperature was set to 27°C.

Figure 2 shows the temperature of the TEC surface at heating and cooling for 20% PWM duty cycle. It can be seen that the measured room temperature was varied at around 24.5°C. The small thermal mass of the thermistor could be the source of the temperature variation is measured. The thermistor quickly responded to the temperature change as the thermal mass of the thermistor is small, so that small change in the environment affects the thermistor immediately. The thermoelectric reached the target temperature within 25 seconds. However, when cooling was set to the thermoelectric, it failed to reach the temperature set at the given time. At a 20% duty cycle, the heat transfer from the surrounding to the thermoelectric was higher than the ability of the thermoelectric to transfer the heat from the cold side to the hot side. Therefore implementing 20% duty cycle on the circuit is not recommended for cooling.

The thermoelectric temperature at 40% duty cycle is presented in Figure 3. On 40% duty cycle, both functions of the thermoelectric as heating and cooling can be achieved in the given time. When heating
was set on the thermoelectric, it needed 14 seconds to reach the designated temperature. Compared to the previous duty cycle where it took 25 seconds to reach the set point temperature, the 40% duty cycle resulted in quicker response. Whereas when cooling was set on the thermoelectric, it needed 24 seconds to reach the setpoint temperature. Hence, the 40% duty cycle the thermoelectric abled to reach the given target temperature. However, the cooling process took longer time than the heating.

Figure 2. Data results of the 20% duty cycle, room temperature 24.5°C.

Figure 3. Data results of the 40% duty cycle, room temperature 24.5°C.

Figure 4 shows the 60% duty cycle. Compared to the previous duty cycles, the 60% duty cycle reached the target temperature quicker when it worked in heating process. On this duty cycle, it took around 12 seconds for the thermoelectric to reach the setpoint temperature when heating was conditioned. Whereas on the other hand, it took 24 seconds for the thermoelectric to achieve the cooling setpoint temperature. The stability of the temperatures recorded was far more stable.

Figure 4. Data results of the 60% duty cycle, room temperature 24.5°C.
Figure 5 depicts the 80% duty cycle. The thermoelectric took 10 seconds to achieve the set heating temperature as well as the set cooling temperature. The required time showed a faster response of thermoelectric to change the temperature. It also showed that the thermoelectric performed better acquisition towards the set point temperature, reaching the setpoint temperature way more effectively. The 80% duty cycle data carried out as the best-achieved data and the recommended duty cycle.

**Figure 5.** Data results of the 80% duty cycle, room temperature 24.5°C.

The fluctuations on the data achieved on every duty cycle differ from one to another. The fluctuation was due to the on-off situation that the H-bridge originally carried. Based on the data gained from the experiment, the higher the duty cycle resulted in bigger fluctuations towards the temperature. It gave better attainment to the results. The bigger the duty cycle led to a shorter time to reach the set point temperature on the thermoelectric. However, the variation of the thermoelectric temperature at the set temperature was bigger on the higher duty cycle.

4. **Conclusions**
Throughout the experiment and based on the graphs collected, it resulted that the bigger the PWM leads to better acquisition towards the setpoint temperature given. From this experiment, PWM 80% has the best results in terms of heating and cooling on the thermoelectric. When the temperature was set at either high or low, PWM 80% has the shortest time delay reaching the set point. The shorter the time delay, allows a faster rate and a better performance. Though the results in all the PWM might not be smooth, this is a typical response of an on-off control.

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