Adaptive PD Controller Performance for Direct Cooling of Thermoelectric Refrigerator

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Abstract. Refrigerator is the key component to keep the medicine and biological sample in the hospital. The domestic refrigerator has the problem of larger size and heavier weight since to the compact system like condenser, compressor, evaporator and expansion valve are assemble and using in the refrigerator. This project focused on design of temperature control of the portable thermoelectric refrigerator for medical purpose. Thermoelectric refrigerator is using the direct cooling method through thermoelectric module. Thermoelectric refrigerator has several advantages such as smaller size, lighter and silent when operated. Since maintain a constant temperature for the storage of medical product is important, a specific refrigerator is needed to ensure the medicine is stored in desired temperature. This project is to design and develop an adaptive control system which can perform a good temperature control for the thermoelectric refrigerator. The second order model is applied to design adaptive Proportional-Derivative (PD) controller. The selected controller is the adaptive PD controller because the performance of response shows 0.42°C of less steady state error and 0.21°C of lower undershoot. The adaptive PD control system designed able to let the refrigerator operate in different operating condition without influence the performance of the refrigerator.

1. Introduction
Thermoelectric refrigeration is using thermoelectric module to operate and it has advantages of high reliability, small size, light weight, and no working fluid [1] [2]. Thermoelectric module is a solid state energy converter that consists of a bunch of thermocouples and the thermocouples are made of two different semiconducting thermoelements [1][3].

In 2015, a thermoelectric refrigerator system was developed and the on-off control method was chosen [4]. The authors claimed that the on-off control method able to control the refrigerator to reach the desired temperature and this method was easy to use. However, the authors stated that this method was not a good method and a improved control system can be implemented in order to give a better system response.

On the third previous studies, the researchers focus on using the Fuzzy Logic control on controlling the inner temperature of the refrigerator [5]. There are some fuzzy sets of input and output parameter that has to determine such as inside temperature of the cooler (SIC), outside temperature of the cooler
(SDIS), PWM reference, and the voltage. From the experimental result, the controller able to activate immediately after the temperature inside the cooler is over the desired temperature in order to maintain the inner temperature within the desired temperature. The researchers have made a conclusion that the cooler with fuzzy control is more reliable for blood, vaccine, serum or other medical supplies.

According to [6], the studies focus on performance of proportional integral derivatives (PID) in the simulation and real hardware. The authors claim that using a black box model of a system does not need any particular prior knowledge of the character or physic and it is tested by using a set of ordinary differential equation (ODE) to get it coefficient and fitting. In the studies, the authors using only the first order and general second order model to simplify the process in obtaining the PID coefficient, \((Kp)\), \((Kd)\) and \((Ki)\). The developed system able to cool down the temperature to 15°C at the settling time of 642 second and the steady state error is ±1°C. The author conclude that although many tuning laws were introduced by other researchers for tuning PID, but unexpected problem can occurs in the real practice and this can affect the performance of the controller.

The proposed refrigerator is in a 12 litre portable refrigerator and the dimension is 41cm x 28cm x 29cm. The mass of this refrigerator is 5.3kg. This refrigerator has a transformer and full bridge rectifier to change the AC power source, 240VAC and 50Hz to a 24VDC power source to operate the thermoelectric devices. Other than that, this thermoelectric refrigerator can also operate by using the 24VDC power source such battery. Two thermoelectric devices are used in the refrigerator in order to improve the performance of the refrigerator. The desired temperature of the system is 4°C and the ambient temperature of the system operated is 20°C.

2. Adaptive Controller Design of Direct Cooling System

This project is conducted on a portable thermoelectric refrigerator. A desired temperature range of 2°C to 8°C will able to control and maintain by the refrigerator for biomedical purposes like medical storage. There are few components used to develop this refrigerator. The main components in this project are a thermoelectric refrigerator, RTD sensor, RTD amplifier, microcontroller and MOSFETs. The original electric circuit of the thermoelectric refrigerator is modified into a new circuit in order to allow the temperature of the refrigerator able to control and maintain. In this project, a commercial thermoelectric refrigerator is modified.

2.1. Recursive Least Square Method

Parameter estimation is the process to determine the value of parameter conduct to dynamics behaviour of a system. Dynamic behaviour of the refrigerator system has a few parameters that represent the structure of a system. The parameter estimation in adaptive control should be continual to allow the system or controller parameter to be updated as if the estimated parameter was correct. The output and input will update at each sample interval of the system. RLS method is introduced in that refer to the principle of certainty equivalence. Figure 1 shows the representation of RLS method that used in this study.
Figure 1. Recursive least square method schematic diagram

ARMAX structure is selected to develop the modelling scheme for the refrigerator system. It generates together with system disturbance and measured noise. The parameter ARMAX will predicted based on recursive least square method. The ARMAX model is developed by Equation 1:

\[ y(t) + a_1 y(t-1) + \ldots + a_n y(t-n_a) = b_0 u(t-d) + \ldots + b_m u(t-d-n_b) + e(t) + c_1 e(t-1) + \ldots + c_e e \]  

(1)

ARMAX model can give accurate model in areas of control, process and econometrics for both systems modelling and design of controller. There are three type of polynomials orders used in analysing ARMAX models. Equation 2 is represent the parameter structure of \( n_a = 2, n_b = 1, n_c = 1 \).

\[ \theta = [a_1, a_2, b_1, c_1] \]  

(2)

Where, \( a_1, a_2, b_1, c_1 \) is a parameter coefficient. The adjustable parameter of ARMAX structure is expressed as below:

\[ A(q^{-1}) = 1 + a_1 q^{-1} + \ldots + a_m q^{-m} \]  

(3)

\[ B(q^{-1}) = b_0 + b_1 q^{-1} + \ldots + b_n q^{-n} \]  

(4)

\[ C(q^{-1}) = 1 + c_1 q^{-1} + \ldots + c_n q^{-n} \]

Equation 3 is rearrange and perform Equation 4 and 5, that introduced mathematical structure of ARMAX model system;

\[ A(q^{-1}) y(t) = B(q^{-1}) u(t) + C(q^{-1}) e(t) \]  

(4)

\[ y(t) = \frac{B(q^{-1})}{A(q^{-1})} u(t) + \frac{C(q^{-1})}{A(q^{-1})} e(t) \]  

(5)
Each parameter is analysed in order to discuss the effect of parameter introduced in ARMAX model. The parameter is representing the best model that contain lower time taken of convergence data (time taken of steady state) and smaller steady state value. The model of ARX structure and ARMAX structure will compare and analyse with performance of vapour compression refrigeration structure. The output error method is used to compare the most exact model to represent the behaviour of refrigerator system.

2.2. Adaptive PD Controller Design

Proportional controller is a basic controller setting of refrigerator control system. It is also known as proportional gain to the system. Proportional gain is a very important parameter in PID controller design. It is a tuning method that can change the steady state error of a system. The manipulation of proportional gain of controller system is done to achieve the desired output. If the proportional gain value higher, the steady state value for the systems will increase. Figure 2 shows the adaptive controller system with proportional gain. The value of $K_p$ is introduced as state in Ziegler-Nichols procedure method. The value of $K_p$ is only to make sure that the refrigerator system performance in range to achieve the desired output.

![Figure 2. Adaptive control system with proportional derivative gain](image)

The transient response of refrigerator system is can be manipulated by introduced the derivative gain to the control system. Derivative gain can operate the controller system manage the derivative error. The PD controller design in order to improve the transient response of the system while meet the stability requirement of the refrigerator system. Figure 2 shows the block diagram of Adaptive Proportional Derivative (PD) control. The adaptive control system will be tuning the proportional and derivative gain to maintain the desired output of refrigerator system.

The value of $K_p$ and $K_D$ is calculated based on Ziegler Nichols method. The gain value will analyse and adjust to achieve the desired output. The formulation that describe the PD controller at Figure 2 is shown in Equation 5. The formulation that describe the PD controller at Figure 2 is shown below, where $T$ is sampling time.

$$U(z) = \left( K_p + \frac{1}{T_D} \frac{z-1}{z} \right) E(z)$$

Equation 5
3. Result and Discussions
The performance of the controllers for the refrigerator system is tested in a room with the ambient temperature is 20°C and the refrigerator is in no load condition. The temperature is recorded every 2 seconds for controllers performance test. The controllers are feeds 100% duty cycle due to 255 binary input of the PWM signal to the refrigerator. When the temperature of the refrigerator is approximately near to 4°C, the controllers adjusted the duty cycle feeds to the system. The lower limit of the duty cycle for the controllers is 39.2% which the binary input is 100.

3.1. Step Response Analysis
Adaptive PD controller performance shows the system settles approximately at 1552 seconds where the system is 4.48°C as shown in Figure 3. The peak time is at 2944 seconds when the temperature is 4.21°C and the system has an undershoot problem which is 0.21°C.

The adaptive PD controller is able to maintain the temperature at 4.2°C to 4.3°C which is suitable to store the blood. Figure 3(a) shows the control effort of controller adaptively inject the current to maintain the temperature response. The inner temperature of the system is able to maintain in a temperature range that suitable to store the medical entities even the system is in the transient response.

![Control Effort](image1.png)

![Temperature Response](image2.png)

Figure 3. Step response of PD controller of thermoelectric refrigerator (a) control effort, (b) temperature response

3.2. Load Test of PD Controller Performance
There are 2 different conditions are tested for the thermoelectric refrigerator to learn about the performance. The first condition is added two different volumes of load into the refrigerator and study about the temperature response of the refrigerator.
In order to test the performance of refrigerator with load, there are two different volume loads are tested, which are 250ml and 500ml mineral water to represent the blood bag. The settling time of the system for each experiment are recorded. After the system is settled, the system is continued running for about 5000 seconds to observe the refrigerator steady state temperature response. Figure 4 shows the performance of the refrigerator with 250ml mineral water.

The settling time of the system is 2658 seconds when 250ml load is insert into the system as shown in Figure 4. The temperature of the system is maintains in the range of 4.2°C to 4.3°C.
Meanwhile, the settling time of the system is 3945 seconds when 500ml load is insert into the system, which is the settling time for 500 ml load is longer than 250 ml load. As shown in Figure 5, the controller able to maintain at desired temperature with ±0.4°C steady state error, where is control effort of the controller crucially controlling the current.

3.3. Step Disturbance Test to PD Controller Performance
The second condition is open the thermoelectric refrigerator lids for a certain amount of time. The purpose of running disturbance test is to ensure that the controller able to perform well in the real life application.

Figure 6. Disturbance test at 2116 seconds and 3112 seconds by opening the door during 2 seconds and 5 seconds respectively.
In this experiment, the lid of the thermoelectric refrigerator is opened twice, for 2 seconds and 5 seconds and when only the system is at the steady state. The temperature responses of refrigerator when the lid is opened are shown in Figure 6. When the lid is opened for 2 seconds at the $t = 2116$ seconds, the temperature is rise from 4.2°C to 4.7°C. At $t = 3112$ seconds and the system is steady again, the lid is opened for 5 seconds. The temperature is rise from 4.2°C to 5.1°C after the lid is opened. From the experiment, the system is able to cool down the temperature quickly after the lid is closed again. The control effort of the controller also quickly react at maximum input to maintain temperature response.

4. Conclusions
The adaptive PD controller show as good controller for the thermoelectric refrigerator system. The adaptive PD controller is also able to perform well in maintaining the temperature when 250ml and 500ml loads are added into the refrigerator system. To understand the performance of adaptive PD controller more detailed, the disturbance is added during the system is operated under no load condition. The disturbance is done by opened the lid of the refrigerator for a certain amount of time. When the disturbance is occurred, the temperature of the refrigerator is increased and exceeded the set point of the system. When this occurred, the controller able to response quickly and maintained the temperature after the lid is close. As a conclusion, the adaptive PD controller can reacted well in maintaining the temperature when load or disturbance is occurred on the system.

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