Development and Analysis of Hybrid Thermoelectric Refrigerator Systems

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Abstract. Thermoelectric module (TEM) is a type of solid-state devices which has the capability to maintain the accuracy of small temperature variation application. In this study, a hybrid thermoelectric refrigerator system is introduced by utilizing TEMs; direct and air to air thermoelectric heat pump to cool down and maintain low temperature for vaccines storage. Two different materials which are aluminum and stainless steel are used as container in hybrid thermoelectric refrigerator (HTER) configuration to investigate the response of every system in transient and steady state mode. A proper temperature sensor calibration technique is implemented to make certain real time data acquisition of the systems are not affected very much from the noise generated. From step response analysis, it is indicated that HTER I (aluminum) has rapid settling time from transient to steady state than HTER II (stainless steel) since aluminum has better thermal conductivity as compared to stainless steel. It is found that HTER I is better in cooling capability with the same input current instead of HTER II which required a longer time to achieve steady state mode. Besides, in Pseudo Random Binary Sequence (PRBS) response analysis injected to both systems shows HTER I is very sensitive to current input as the sequence length of HTER I is shorter than HTER II. However both systems depict the varying temperature in the range of 4 oC due to differences in thermal conductivity of container.
1. Introduction

Thermoelectric module (TEM) is a type of solid-state devices. It functions to cool and heat without any movement of mechanical parts. The combination ability to cool down and heat up, TEM is used for heating and cooling on a small-scale application and electric saving. The performance of thermoelectric cooling rely on a variety of variables, such as operating temperature, voltage or current supplies[1]. The efficiency of a heat sink on the hot side will help to heat pumped on the cold side surface. Normally, a thermoelectric cooling system does not operate at a same condition level. It is affected by the ambient environment that probably changing and the power dispersed at different level[2]. The capabilities of a thermoelectric cooling can be analyzed by referring to the transient and steady state condition. The transient condition is affected by thermal capacitance and thermal time constant. At the time of surface being cooled down isothermally, the temperature gradient of the cooling area becomes importance for designing a controller.

A single thermoelectric cooler will not be able to reach its optimum performance in all conditions [1]. Therefore, in order to suit with the desired condition, it is necessary to know the specific application. In normal cases, the most adequate model for large and complex analysis of thermoelectric systems is to choose a lumped model [3], whereas a distributed model is used for detailed description in order to determine the optimum number of thermocouples for the TEM, or when analyzing the performance of heat sinks. In this chapter, development of a prototype hybrid thermoelectric refrigerator using TEMs as plant is presented. The behavior of the system is also discussed in this chapter.

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2. Hybrid thermoelectric refrigerator system

Developing and designing a proper controller of a thermoelectric refrigerator is the main focus of this work, which will help to keep at least 50 ml of vaccines in the indispensable temperature (from 2°C to 8°C) with ambient temperature of 30°C [4]. The Hybrid Thermoelectric Refrigerator systems (H-TER) is designed and developed based on the two parts; namely mechanical and electrical part as shown in Figure 1. The assembly technique adopted in the thermoelectric heat pump is crucial to minimize the thermal resistance which will cause a significant improvement in its performance.

![Figure 1. Hybrid Thermoelectric Refrigerator (H-TER) control system configuration](image-url)
The primary structure of the proposed system consists of an aluminium/stainless steel container (12 cm width x 12 cm length x 9 cm height with thickness of 3.5 mm) and an insulated box with an isothermal material (polystyrene) to minimize loss of heat to the ambient. The insulation material also separates the container and acrylic casing as shown in Figure 2. Two thermoelectric heat pumps are utilized in this method, namely; direct and air-to-air thermoelectric heat pumps. Both thermoelectric heat pumps are connected in parallel configuration with 44 Watt input power at maximum input condition. The cold side heat exchanger will absorb the heat and the TEM immediately pump out. Whereas, air-to-air thermoelectric heat pump installation engages by cooling objects through convection. This is done via the hot side of the heat exchanger which is equipped with fans to dissipate the heat to its surrounding. Meanwhile, the cold surface of air-to-air thermoelectric heat pump is fixed to another heat sink, which is used to bring out the cold air and a compulsion of air convection through the length of the heat sink. In order to obtain better performance of cooling in the container, a fan is used. Furthermore, the internal air circulation will assist to maintain and keep the temperature gradient within the enclosure to a minimum level. Direct thermoelectric heat pump offer performance by cooling an object via conduction. A space block is also put to the direct thermoelectric heat pump which yields to a maximum heat transfer to the container.

The heat sink disperses heat from both pumps which are generated by the TEM as a result from the Joule effect. This indicates that the lower the thermal resistance of the heat sink, the better indication of performance of the TEM. The heat sink attached to a fan will change the performance of the heat sink by decreasing the thermal resistivity of dissipating heat via forced convection. The fans are operated at a constant speed with 12V direct current (DC) and 0.18A input.

![Figure 2. Hybrid Thermoelectric Refrigerator with insulation assembled and integrated with air-to-air and direct thermoelectric heat pumps](image)

3. Experimental setup

3.1 Temperature measurement

In order to accomplish a successful system identification procedure and the implementation of on-line control strategies, a suitable computer program and interfacing device is very important. The system interface should be able to handle the implementation of real-time measurement capabilities as shown in Fig. 3. It is not only the ability to read and send data between computer and the plant, the computer memory and data acquisition (DAQ) should be adequately realized the online system
identification and control strategies.

The setup and installation of the interfacing system should be easy in a very simple procedure. Both hardware and software fitted with the system is reliable in handling long-run experiment and analysis. The data collected by this system is useful and easily processed and retrieved without any issues or problems. Moreover, the input-output programming should be easy and simple by adopting reliable programming software. The following measurement instruments in Fig. 3 are used in the identification and control of H-TER systems.

![Temperature measurement instrumentation of H-TER systems using RTD sensor and DAQ](image)

**Figure 3.** Temperature measurement instrumentation of H-TER systems using RTD sensor and DAQ

NI-9219 is plugged to NI-9174 as a USB modular instrument chassis. Such connection will allow synchronization and triggering capabilities as well as flexibility that will help to obtain a proper measurement. Fig. 4 described the connection of 4-Wire Resistance and 4-Wire resistance temperature detector (RTD) sensor, where the NI 9219 is generating current that depends on the load of resistance between the EX+ and EX– terminals. The measured resistance is computed by NI-9219 from voltage reading of the sensor. However, the wire resistance is not affecting this sensor since high input impedances of analog-to-digital converter (ADC) allow a slight amount of current flows across the HI and LO terminals.

![Connection in 4-wire resistance and 4-wire RTD sensor circuit to measurement DAQ instrument](image)

**Figure 4.** Connection in 4-wire resistance and 4-wire RTD sensor circuit to measurement DAQ instrument

The RTD is known as precision sensor and being used in industrial and laboratory’s applications for low temperature measurement. The RTD element is more repeatable and accurate than the thermocouple. In fact, the RTD sensor produces stable readings longer than thermocouple. RTD also characterizes as more repeatable readings sensor, which is the same temperature readings produce same results over multiple trial. RTD sensor employs the property that the electrical resistance of metal varies with temperature. The resistance of the sensor is changed linearly according to the temperature change. This resistance is measured by DAQ and later converts into a temperature reading. The resistance reading can be carried out by passing a small current through RTD’s element.
NI-6008 digital analog input-output (IO) data acquisition (DAQ) is a control unit that interfaces computer and H-TER systems. This DAQ supplies digital analog channel that allows for closed loop control through connections to solid-state relay (SSR) in order to control the input actuator that is, the thermoelectric heat pumps. The NI USB-6008 DAQ is a USB supported as a standard control device using analog as well digital IO. Pulse width modulation (PWM) is generated by digitally controlling current using NI-6008 DAQ by digital encoding analog signal levels. The duty cycle is able to encode a specific signal of current level by modulating the square wave. However, the signals of PWM are always in digital form since the supply of DC is either fully on/off, or intermediate. The current output is applied to the H-TER systems through series of recurring of on and off pulses.

The thermoelectric heat pump is used for refrigerator application that will function directly from DC power. The input current will be controlled by a digital computer programming, interfaced to NI-6008 DAQ output to maintain temperature inside the container that produces by SSR. It automatically corrects the temperature using a feedback loop. The MOSFET transistor junction in SSR is a component to control the current input through photodiodes that generates electric insulation. This technology allows NI-6008 DAQ devices to control the flow of PWM input current of thermoelectric heat pumps in H-TER systems applications. In addition, the SSR enables for a lower current controlling signal like NI-6008 DAQ. The SSR is connected in series to 12V DC power supply, thermoelectric heat pumps and DAQ digital output. The SSR is also wired with digital input DAQ to generate PWM input current from power supply to control the inner temperature of H-TER systems as shown in Fig. 5.

![Figure 5. Control circuit of SSR configuration for controlling input and generate current output signal for system load](image-url)

However, the SSR performance to generate the output current is depending on the ambient operating temperature of the device as shown in Fig. 3.9. The H-TER systems data is recorded by a DAQ for every single second. It is very useful in closed loop feedback application to control and correct any temperature variation. Fig. 6 shows configuration components within the system that dynamically do not intervene and affect its performance. There is an aluminium block spacer that connects the direct thermoelectric heat pump cold side to the aluminium/stainless steel vaccine’s container.
This includes the material use in insulation, which made of polystyrene with thermal conductivity of 0.033 W/(m·K). The container is placed in acrylic casing as a holder. The vaccines will be kept and stored in a container and insulated by the polystyrene to avoid ambient or any other heat source affecting the inner temperature.

3.2 Sensor Calibration

The aim of performing sensor calibration is to make certain on the consistency aspect in measuring a temperature range under specified environmental condition. In this work, the sensor calibrated online to reduce the effect of noise and bias, which is affected by the instrument and transmission cables from the data logging devices and plant as well. The main aspect of calibration is to determine the relationship between the measured variables with the electrical signal such as resistance, voltage, and current. Platinum RTD is used with a typical resistance of 100Ω at 0°C. In addition, the calibration is done to get accuracy measurement for other than 0°C and 100°C, and able to measure up to 200°C. RTD can determine its resistance and hence the temperature by measuring the voltage across the element. The resistance and temperature have a linear relationship. The RTD is categorized at nominal resistance of 0°C with the sensor of 100Ω. The following Equation (1) describes linear relationship between resistance and temperature:

\[ R_T = R_0 + aT + bT^2 \]  

(1)

\( R_T \) is resistance at temperature of \( T \); \( R_0 \) is nominal resistance; \( a \) and \( b \) are constant that applied in scaling the RTD. The calibration test of temperature in a specific range is very important to perform accuracy measurement. In this work, the sensor will be calibrated at 0°C to 8°C as this temperature range is considered safe storage for vaccine. The average resistance or temperature curve for this 100Ω pure platinum RTD is shown in Fig. 7. A specific calibration technique, i.e. in-situ technique is implemented for this work in order to obtain its accuracy. The calibration is conducted at Calibration and Measurement Laboratory of SIRIM Sdn. Bhd. at Penang, Malaysia. RTD sensor is calibrated using...
water bath at 28°C -30°C ambient condition to determine scaling parameter by direct measurement.

![Graph](image)

Figure 7. The average resistance/temperature curve for RTD sensor calibration graph using ice water bath

The relationship between resistance and temperature is found to be relatively linear. The fitted curve is used to ensure an accurate RTD measurement. The constant values of a and b are extracted as and respectively by the curve fitting.

### 3.3 Filtering Operating Data

A first order low-pass filter is designed for noise minimization of the sensor. The transfer function for the filter can be written in as:

$$\frac{Y(s)}{U(s)} = \frac{1}{T_c s + 1}$$  \hspace{1cm} (2)

where $T_c$ is the time constant, $U(s)$ is the input and $Y(s)$ is the output. The above equation is discretized Euler Backward finite difference method as:

$$y(k) = \frac{T_e}{T_e + Ts} y(k-1) + \frac{T_s}{T_e + T_s} u(k)$$  \hspace{1cm} (3)

$$y(k) = \frac{T_e}{T_e + Ts} y(k-1) + \frac{T_s}{T_e + T_s} u(k)$$  \hspace{1cm} (4)

where $Ts$ is sampling time of the system. From the Equation (5), $F_a$ is defined as filter parameter:

$$F_a = \frac{T_s}{T_e + T_s}$$  \hspace{1cm} (5)

Haugen suggested the following rules, which is the sampling time should be smaller than time constant of the system to avoid elimination of system dynamic information [5]:

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The filter is fitted into the H-TER systems with appropriate specification and significant frequency range. Signal output temperature that has been measured to be filtered using a computer program such as the equations above to remove noise. This is important in order to obtain better parameter estimation.

4. H-TER Systems Response Performance

4.1 Step Response Analysis

The objective of this section is to analyze the dynamic behavior of thermoelectric refrigerator under the effect of heat conduction and convection. In practical sense, this refrigerator always work under transient operating conditions due to the time change in the current and voltage supply, hot and cold side of TEM surface temperatures, and electronic devices performance. A study of transient behavior of the thermoelectric refrigerator rather than the steady state behavior is very important for two reasons: (a) to investigate the H-TER behavior during the startup and shutdown period and (b) to understand the system behavior when all or some of the operating condition are varying with time. Examples of these operating conditions are the cold temperature, hot temperature, and the imposed electric field. The transient behavior of the open loop H-TER systems due to a sudden imposed electric current is illustrated in Fig 8. Initially, the input current is set to 85% duty cycle, which is the current input varies linearly with duty cycle. By using this input current, the air temperature of refrigerator is 8.4°C and 8.7°C for H-TER I and H-TER II systems respectively. At 1000 seconds, a constant 90% duty cycle of input current is imposed suddenly, in the form of a unit step function, on the system causing the air temperature inside the both containers stainless steel and aluminum are decreased drastically and maintained at around 3.93°C and 4.19°C for H-TER I and H-TER II systems respectively. After 2000 seconds, the temperature continues to decrease at a slower rate response.

The response for both H-TER I and H-TER II is given in Fig. 8. It shows the response towards the experiment data is recorded at 20 second sampling time. It also indicates that the H-TER systems have slow settling time of transient response with time delay performance. However, the system did not provide any overshoot performance. The H-TER II system take longer time to reach steady state condition than H-TER I system because of thermal resistance of stainless steel container is higher than aluminium container.

\[
T_o \leq \frac{T_c}{5}
\]  

(6)

\[T_o \leq \frac{T_c}{5}\]
Table 1 shows the characteristics step response performance for H-TER I and H-TER II systems. It shows that H-TER I transient response is faster than H-TER II system. The H-TER I found to be better in cooling efficient with the same step input current. It can be deduced that any increase of thermal resistance of the container will cause air temperature respond more slowly and increase the time required to reach steady state condition.

**Table 1.** Characteristics measured step response performance of H-TER I and H-TER II

| System performance | H-TER I system | H-TER II system |
|--------------------|---------------|-----------------|
| Time constant [s]   | 660           | 710             |
| Settling time [s]   | 2490          | 2960            |
| Time delay [s]      | 20            | 40              |

The generated step response data of the experiment in Fig. 8 is compared with simulated data that is generated by transfer function in Equation 7 and Equation 8. The transfer functions are developed based on characteristic of H-TER systems in Table 1. The validation of a simulated first order model with a measured step response of H-TER I and H-TER II systems are shown in Fig. 9 and 10 respectively. The estimation model of the system is digitized by implementing zero order hold method. Based on the converted model to digital form in Fig. 9 and 10, it indicates that the simulated first order model provides a close transient and steady state characteristics as compare to the measured data of H-TER systems. It can modeled in the discrete time transfer function of H-TER I and H-TER II as Equation (7) and Equation (8) respectively,

\[
\frac{T_{H-TERI}(z)}{U_{H-TERI}(z)} = z^{-1} \frac{0.1334z^{-1}}{1 - 0.9702z^{-1}} \tag{7}
\]

\[
\frac{Y_{H-TERII}(z)}{U_{H-TERII}(z)} = z^{-2} \frac{0.1217z^{-1}}{1 - 0.9722z^{-1}} \tag{8}
\]

**Figure 9.** Step response of measured and simulated first order model for H-TER I system
Another way to understand about system’s properties is by referring to the poles and zeros in z-plane plot of the system in Fig. 11. The pole-zero diagrams are generated based on Equation 7 and Equation 8 discrete transfer function. Particularly, the poles area has a direct effect upon the properties of a dynamic system which is noted its stability. The Fig. 11 also indicates that the system is found to be stable as the pole located within the unit circle of z-plane.

The location of the poles is relatively near to the unit circle’s circumference of z-plane. The transient properties will depict an oscillatory response. Thus, a first order model is maybe not adequate representation of the H-TER systems due to oscillatory characteristic of step response in Fig. 11. This called for higher order model to represent the H-TER systems. A second order system may be appropriate since the response of the first order model indicates poor relative stability as a result from the pole location. This supports the second approach of modeling by which it is required to optimize the identification with the model.

![Figure 10. Step response of measured and simulated first order model for H-TER II system](image1)

**Figure 10.** Step response of measured and simulated first order model for H-TER II system

![Figure 11. First order model Pole-zero diagrams of (a) H-TER 1 and (a) H-TER II systems showing the poles located relatively near the unit circle onto z-plane](image2)

**Figure 11.** First order model Pole-zero diagrams of (a) H-TER 1 and (a) H-TER II systems showing the poles located relatively near the unit circle onto z-plane
4.2 PRBS Response Analysis

Pseudo Random Binary Sequence (PRBS) signal is injected to the H-TER systems interfaced with computer. During the data collection, the noise is filtered using a low pass filter of 200 seconds time constant. Starting from steady state condition, a sequence of input signal is injected to excite the H-TER systems. Two sets of real-time data are collected from the H-TER systems having different container material. Each set of measurement consists of 250 output discrete data with 20 seconds sampling time. PRBS sequence length and magnitude are required and have to be selected carefully especially in real-time parameter estimation. In parameter estimation the choice of input magnitude is critical in the sense that if the magnitude input is too small, the system cannot be simulated enough dynamic then the response to be improperly represented. However, if the magnitude is too large, then the system will have nonlinearity characteristics and the stability will be affected.

A PRBS is a periodic, deterministic signal, which approximate a discrete-time white noise-like properties may switch between two constant levels only at certain equally spaced time intervals, at time $t=0, \Delta t, 2\Delta t, 3\Delta t, \ldots$, where $\Delta t$ is clock period. In this experiment, the useful rule of thumb is used to calculate clock period according to [3] in Equation (9):

$$cT_{tot} = \frac{5}{2.0}$$

(9)

where $T_C$ is time constant of the system.

Furthermore, since there is a time delay in the H-TER systems response, the time period chosen in designing the PRBS is then become:

$$\Delta t = (0.2 \text{ to } 0.5) \times T_c + \text{time delay}$$

(10)

In order to identify correctly sequence of length of PRBS input, the total duration time of the signal to exhibit a complete the steady state gain of the plant dynamic model should be considered. Therefore, the settling time of the H-TER systems is approximated equal to the sequence period $T$ of the PRBS signal, the minimum PRBS sequence length can be determined by:

$$T = \Delta t \times N \approx T_c$$

(11)

where $T_s$ is settling time and $N$ is sequence length. The time constant, settling time and time delay is referred to Table 1 to calculate sequence length and clock period. The maximum of sequence length in which $n$ is the number of cells of the shift register as in following equation:

$$N = 2^n - 1$$

(12)

where $n$ is the number of registers. The input signal sequence repeats itself every $2^n - 1$ bit interval for a $n$-bit shift register. A PRBS signal with maximum length sequence of 6 to 16 is used during data collection for H-TER systems. However, the sequence length form did not produce significant changing on output of H-TER systems, which is not varying at 4°C. By using trial and error procedure, a PRBS signal input with maximum length sequence of 3 and 7 are used during data collection for H-TER I and H-TER II respectively. The sequence length of H-TER I is smaller than H-TER II is maybe due to H-TER I is sensitive to changing input current compared to H-TER II. The input
magnitude of the PRBS signal is chosen to be ±5% of steady state value of the H-TER systems temperature, which is 85% to 90% duty cycle of current input switching up and down continuously. Fig. 12 and Fig. 13 are the measured temperature response of H-TER systems for filtered and unfiltered condition. The result shows that the temperature responses of H-TER I and H-TER II systems slightly vary in the range of 4°C as optimum operating point. It may be due to differences in conduction heat transfer rate and thermal conductivity of container material.

Figure 12. Filtered and unfiltered of measured temperature response of H-TER I system (a) PRBS input to SSR, (b) output

Figure 13. Filtered and unfiltered of measured temperature response of H-TER II system (a) PRBS input to SSR, (b) output
5. Conclusion

In this work, development of a refrigerator system called H-TER systems based on thermoelectric cooling technology is presented. The experimental setup is designed for modeling and controlling the system in real-time application. In addition, the importance of calibration and data conditioning process using first order low pass filter in work activities is implemented. This is crucial to confirm on the accuracy aspect of low temperature measurements for critical application, which are always influenced the dynamic ambient condition. As the nature of thermoelectric devices is nonlinear, therefore, the selection of optimum operating point for a thermoelectric refrigerator in given application requires an iterative process. The operating point of this work application is 85% to 90% duty cycle input current to achieve temperature range of vaccines storage. A step and PRBS input response experiments are conducted to analyze the dynamic characteristics of H-TER systems. The system is sensitive to the varied and fluctuation of current input especially the aluminium container material properties. A first order dynamic model of H-TER systems has been developed, to validate the system and to work the system properties based on pole and zero plots.

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