Experimental study on thermoelectric module’s heating and cooling performance

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Abstract. Experimental study and investigation on heating and cooling performance of a thermoelectric module have been conducted. A thermoelectric heating and cooling device, also known as Peltier, presented itself as a potential alternative of commercial distillation system by exploiting its unique nature of generating “hot-side” and “cold-side” similar to a heat pump. Looking at the fact that distillation utilizes heat to vaporize specific compounds and turns it back into a liquid by condensation, Peltier may provide both of these processes, using only a single thermoelectric unit. This simplicity and efficiency make a strong ground for further study and practical application of the thermoelectric module, especially in a distillation system. One problem is that previous studies on thermoelectric module application are not sufficient and need more analysis regarding the performance of individual module. Therefore, this research aims to study the application of thermoelectric module in order to obtain experimental and performance data. Several electrical control and Arduino® sensors are applied in this study for real-time data collection with a variation of supplied voltage and current in an adiabatic closed system. Experimental results showed that there were distinctions of module’s performances at different current and temperature difference over time with the maximum power, 10V, 5A, reached up to 80 °C for hot side and 50 °C for cold side. This data then was further analyzed by curve fitting to perceive the specific statistical model which was found to be the rational model.

1. Introduction

The need for clean water in recent years has increased significantly compared to the past few years. Looking at the fact that water is one of the essential parts in human’s life, shortage of clean water poses as a serious problem for the survival and quality of life of mankind. Clean water makes up only a tiny fraction of all the water on the planet. The oceans contain about 97% of the Earth's available water and about 2% of the remaining water is reserved as ice in the polar regions. So, only about 1% of the water on earth is clean water that can be used in everyday life [1]. One solution to dealing with the lack of water resources is through desalination of seawater [2]. The number of desalination systems has been increasing steadily in recent years with total daily production of 66.4 million m³ worldwide in 2010, 71.9 million m³ in 2011 and 81 million m³ in the first quarter of 2014 [3].

Much effort has been made to fulfil clean water demand with the aim to increase water productivity and energy efficiency with various methods. Dates back to the eighteenth century, the slow sand filtration (SSF) [4], followed by rapid sand filtration (RSF) [5], distillation [6], ultrafiltration [7], and
as the most recent breakthrough, by reverse osmosis (RO) [8]. There are also some alternatives in water treatment process using naturally available materials, such as natural coagulant [9] or activated carbon [10]. Since they require steady material consumption in every process, it is recommended to utilize this method in a large scale industrial water treatment process [11]. One of the major disadvantages of RO systems is that by removing most of the minerals from the water, it is possible to produce acidic water which may possess health problem or damage the equipment itself [12]. Also, it requires abundant amount water for every gallon of filtered water due to the need to backwash and maintain the filter as long as possible [13]. Another disadvantage is that they take high amount of time and energy because it runs in a high pressure system (up to 80 bar) [14]. Thus, while high price does speed up the water filtration process, the amount of water wasted is abundant.

One suggested alternative in water desalination method is through the utilization of thermoelectric module or Peltier. There also exists possibility that the Peltier module may be used in distillation systems to produce clean water by utilizing its design which facilitates heating on the hot side to increase water evaporation, while simultaneously using the cold side to lower the condenser temperature to increase water condensation. As a result, this system can increase water productivity and water distillation efficiency can be significantly improved. Another advantages of thermoelectric modules are having no moving parts and a relatively longer life [15]. They are silent, easy to control, and small in size, consuming less energy and resulting in less pollution [16]. Some principles regarding thermoelectric module are based on either Peltier, Seebeck or Thomson effect [17]. The thermoelectric module can either be used as cooling medium (Peltier), power generation (Seebeck), or temperature sensors (Thomson). It’s the basic concept of the thermoelectric module which is to convert thermal energy directly into electrical energy or vice versa. When a temperature gradient is set in the thermoelectric module, a voltage difference is generated and a DC current will be created (Seebeck effect). On the other hand, by applying DC current to the thermoelectric module, a temperature difference occurs between the hot and cold sides of the module (Peltier effect).

Recently, a large number of studies have used thermoelectric technology to increase water production rates and consequently improve system performance [2,8,18–21]. However, from the description of these researches, only one side of the Peltier module was utilized, usually the cold side, with the generated heat energy from the hot side of the module was mostly wasted and released to the environment. Therefore, the previous thermoelectric distillation system was not comprehensive enough to properly analyze the evaporation and condensation processes simultaneously in a distillation system.

One problem is that previous studies on thermoelectric module application are not sufficient and need more analysis regarding the performance of individual module. Therefore, this research aims to study the application of thermoelectric module in order to obtain experimental and performance data, such as temperature of module fins and contained liquid in a batch system of two-chambered vessel. It is expected to determine whether thermoelectric module is applicable to be used as the driving force of distillation system from the results of this preliminary research.

2. Thermoelectric Distillation
Thermoelectric module (TE), or a Peltier, is a semiconductor-based electronic component that acts similar to a small heat pump, transferring heat from one side to the other side of its device. By applying low voltage DC power to the module, heat will be transferred, creating different temperature level between each side. One side of the module will be cooled while the opposite side is heated simultaneously. One interesting fact of this process is that this phenomenon can be reversed where a change in polarity (plus and minus) of the applied DC voltage will cause heat to be transferred in the opposite direction. As a result, the thermoelectric module can be used for heating and cooling making it particularly suitable for precise temperature control applications [22]. Thermoelectric modules can also be used for power generation by taking advantage of the temperature difference between the two sides of the module with a concept called “thermoelectric generator” utilizing Seebeck effect. In this mode, the temperature difference applied across the module will produce a current [15].
Generally, thermoelectric module consists of two ceramic materials clamping together multiple pairs, or “pairs” of Bismuth Telluride. One pair of these units is connected electrically in series, and thermally in parallel, between the two sides of the ceramic. One of these tiles will be the “hot side” and the other, the “cold side”. Alumina ceramic is generally used in manufacturing TE modules since it is an electrically conductive and conductive insulator. Apart from providing a solid foundation, ceramics protect the electrical elements inside the module from cooling on the hot side of the module, and objects being cooled on the cold side. The substrate holds the entire structure together mechanically and electrically protecting the individual elements from each other and from external mounting surfaces. Most thermoelectric modules range in size from about 2.5-50 mm (0.1 to 2.0 inch) square and 2.5-5mm (0.1 to 0.2 inch) in height [double]. Various shapes, substrate materials, metallization patterns and different mounting options are available. Single unit of a standard thermoelectric module can be seen in Figure 1.

![Thermoelectric module](image)

**Figure 1.** Thermoelectric module.

Meanwhile, distillation is the process of separating components or substances from a liquid mixture using selective evaporation and condensation. This process can result in total separation with nearly pure distillate components, or as a partial separation that increases the concentration of the selected component in the mixture. In both cases, distillation is conducted by taking advantage of the difference in relative volatility of individual components inside a mixture. It is a practical and universally important unit of operation in most industrial chemistry, but it should be noted that it is a physical separation process, instead of a chemical reaction. Distillation may also be used to separate solutions with two or more liquids or soluble liquids which possess different boiling points, for example, ethanol and water separated from fermented products. When the mixture is heated until reaches more than 80 °C (ethanol boiling point is 79 °C), ethanol will evaporate and condense to be collected in a beaker.

In simple distillation, heat is provided to a mixture influencing the vapor-liquid equilibrium. Vaporous distillate is collected and cooled using condenser to obtain its liquid form. This pair of heat providing and heat dissipation system is harmonious to the behavior of a thermoelectric module. Thus, there is a possibility to apply this thermoelectric module in a distillation system with fewer moving parts, lower electric usage, and in a smaller apparatus compared to conventional steam and refrigeration system.
3. Materials and Methods

3.1. Materials
Materials needed in this study consists of several components and electronic parts for constructing the insulated vessel and Arduino® temperature sensor. Insulated vessel made from commercially available tinplate which is steel that has been coated with a thin layer of tin by electroplating. Insulation is done by ASTM F683 heat-insulating tape around the vessel and between both chambers. Single unit of thermoelectric module, TEC-12706, 12V, 6A is affixed using double side thermal pad 3M Thermal Adhesive Tape 3M Double Side 9448A assisted with two 40mm x 40mm x 11mm aluminum heat sinks to increase its heat conduction area. Arduino® temperature sensor consists of a single Arduino® UNO R3 module connected with LCD display, 10kΩ potentiometer, 220Ω and 10kΩ resistors, along with 4 sets of NTC thermistor probes 10k 1% 3950.

3.2. Equipment Design
In order to study the characteristic of thermoelectric module, a simple vessel with two chambers is designed with heat insulation around each chamber to simulate two stages of distillation column. A thermoelectric module is affixed using adhesive double side thermal pad to the bottom of the upper chamber and heat sinks to increase its heat providing and dissipation area. A simple thermometer using probes are provided to obtain water and fins temperature data inside both chambers. Voltage and current (power) provided are varied to determine the performance of thermoelectric module in different level of power supply. This variation will be analysed from the temperature response from each probe. Overall design and vessel configuration can be seen in Figure 2.

![Figure 2. Design of simple two-chambered insulated vessel.](image)

3.3. Data Extraction
Arduino® circuit was designed to extract water temperature data with the schematic shown in Figure 3. Sensors used are NTC 10k thermistors which generate analog signal to be extracted with Arduino® UNO R3 board.
To obtain temperature data, the analog signal is converted using the Arduino® code to digital data. This practical design was applied in order to extract data in real time, thus enabling high accuracy and precision. Brief summary of data extraction steps is shown in Figure 4.

**Figure 3.** Multi-NTC thermistor Arduino® schematic

**Figure 4.** Steps of data extraction.
4. Results and Discussion

4.1. Temperature effects from varied power supply

Analysis was conducted using the specified equipment with voltage and current variation. The results are shown in Figure 5 to Figure 9.

Usage of thermoelectric module using 3V with 1.5A showed some changes of water and heat sink fins’ temperature as shown in Figure 5. It seems that water temperature (Wh) and fin temperature (Fh) in the hot chamber are increasing throughout the time with water (Wc) and fin temperature (Fc) of the cold chamber decreasing compared to initial water and fin temperature at 25 °C. This proves the utilization of thermoelectric module may create two different operating conditions within the vessel. However, with 3V and 1.5 A (9 Watt) maximum hot temperature only reached 30 °C and minimum cold temperature 22 °C. There’s also stable temperature difference between the hot and cold side of water (Delta Tw) and fins (Delta Tf) at 7-10 °C around 10 minutes after equipment starting and remains stable to next 30 minutes. While cold temperature is applicable as condenser, generated heat from thermoelectric module is not enough by itself to create significant change upon vapor-liquid equilibrium. Thus, it is required to increase the power supplied to the module.

Something interesting happened when the power supply is ramped to 5V and 3.5A (17.5 Watt). Generated heat increased water and fin temperature to around 45 °C after 30 minutes and from the plot of Figure 6., it is to be expected that the temperature still may rise to higher degree. However, while the temperature of hot chamber is higher and more applicable compared to 9 Watt variation, temperature of the cold side decreased in the first 10 minutes, but increased in the remaining time. Temperature difference between hot and cold side also increases to 15-17 °C.
Increase of cold temperature showed more significant changes when the power supply is ramped up to higher level at 7V, 3.5A (24.5 Watt). Now, this phenomenon also affects the stability of temperature difference as seen in Figure 7. Fortunately, hot temperature may rise and reached 55 °C with higher temperature difference at 24 °C, but increased in the first 10 minutes and decreased afterwards. Cold temperature also showed similar phenomenon, decreased, but in smaller period at around 5 minutes, and increased afterwards.

This phenomenon keeps occurring at higher power supply, both 9V, 4.5A and 10V, 5A variations as shown in Figure 8, and Figure 9. with higher hot side, 70 °C and 80 °C, also higher cold side, 40 °C and 55 °C. Temperature difference also showed more extreme reduction in smaller period starting from 35 °C to 20 or 15 °C.
Possible explanation of this phenomenon is due to heat accumulation and the design of the insulated vessel itself which entraps heat, ultimately preventing heat from exiting the system. On the other hand, energy supply to the thermoelectric module keeps providing the system with external energy source. While thermoelectric module itself acts as heat pump to drive heat energy from one chamber (cold chamber) to the other (hot chamber), excess accumulation of heat made it to work harder and rendering the module incapable of delivering more energy. In the end, flow of heat from the cold chamber to hot chamber inverted to the usual phenomenon, from hot chamber to cold chamber, following the laws of thermodynamics [23].

The bright side is, utilization of thermoelectric module reached 70 °C and 80 °C, which are applicable to generate most compound vapors through vapor-liquid equilibrium (i.e. ethanol). And also the cold side at 40°C is lower than distillate’s vapor point, and barely applicable as condenser. However, it should be noted that there is still a problem lies in the heat accumulation of cold side and lower cold side temperature is preferred and even better if it has lower than water at room temperature (25 °C).

Some suggested solutions of this problem is either by increasing the performance of the thermoelectric module itself, by increasing its heat transferring stages, or by removing excess heat from the system, by creating mass and energy flow. Thus, creating steady state system is better compared to this batch system. These solutions may be conducted in the next researches and the results can be compared as further characterization study of thermoelectric module.

4.2. Fitting and modelling

Curve fitting analysis was done using CurveExpert 2.1.0 software to some of the variables, which are the water temperature and temperature difference using lowest, 3V, 1.5A, and highest, 10V, 5A power supply. These data showed possibility of fitting with the results as shown in Figure 10.
Figure 10. Curve fitting results of hot water temperature 3V, 1.5A (a), cold water temperature 3V, 1.5A (b), hot water temperature 10V, 5A (c), cold water temperature 10V, 5A (d), water temperature difference 3V, 1.5A (e), water temperature difference 10V, 5A (f).

It seems that the highest coefficient of determination ($R^2$) is achieved by regression using rational model compared to other possible models. Rational model, as ratio of two polynomial functions [24], which for this data, can be written as:

$$ temperature = \frac{a + b \cdot time}{1 + c \cdot time + d \cdot (time)^2} \quad (1) $$

Interestingly, this model is applicable throughout all the plots shown in Figure 10 which is due to its ability to compute starting values using a linear least squares fit. However, there are some parameter differences (a, b, c, d) for each plot and coefficient of determination that contribute to the distinctions between each plot. Summary of these parameters can be seen in Table 1.
Table 1. Summary of rational model parameters.

| Figure | a     | b     | c     | d     | R²  |
|--------|-------|-------|-------|-------|-----|
| (a)    | 25.06 | 0.104 | 0.003 | 5.6x10⁻⁸ | 0.927 |
| (b)    | 26.10 | 0.042 | 0.002 | -2.2x10⁻⁷ | 0.907 |
| (c)    | 19.64 | 0.265 | 0.003 | 9.6x10⁻⁸ | 0.996 |
| (d)    | 22.37 | 0.004 | -0.0007 | 2.2x10⁻⁷ | 0.994 |
| (e)    | -2.8 x10⁻⁸ | 1.2 x10⁻⁷ | 9788 | 1089 | 0.831 |
| (f)    | -45.19 | 1.888 | -0.080 | 0.002 | 0.694 |

Application of these parameters should correspond to the specific figures. Nevertheless, application of rational plot may be possible for all of the data reported in this study and may assist the prediction of resulting temperature from specific power supply to the module.

5. Conclusion

Utilization of thermoelectric module as alternative for distillation system has been conducted and shows fair potential and possibility for application in the future. From the heat side, generated heat is enough to change vapour-liquid equilibrium of most compound, encouraging the formation of vapour distillate. However, the problem lies within the cold side, which is due to the heat accumulation in the system, temperature of the cold chamber increasing overtime instead of decreasing or maintaining at lower temperature. Some suggested solutions of this problem is either by increasing the performance of the thermoelectric module itself or by removing excess heat from the system, by creating mass and energy flow. Thus, creating steady state system is better compared to this batch system and may be conducted in the next researches as further study of thermoelectric module. Moreover, from curve fitting analysis, overall data of thermoelectric module performance showed high coefficient of determination from regression using rational model. This model may assist the prediction of resulting temperature from specific power supply to the module.

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