CHEMICAL ENGINEERING TRANSACTIONS
VOL. 89, 2021

A publication of
AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-87-7; **ISSN** 2283-9216

DOI: 10.3303/CET2189109

Study of Performance: an Improved Distillation using Thermoelectric Modules

Setia Budi Sasongko*, Gelbert Jethro Sanyoto, Luqman Buchori

Chemical Engineering Department, Faculty of Engineering, Diponegoro University, Jl. Prof. Soedarto S.H., Tembalang, Semarang, Indonesia
sbudisas@live.undip.ac.id

An integrated distillation system has been designed and assembled involving a thermoelectric module. This design utilizes both the hot side and cold side simultaneously, thus improving the overall distillation process. This research aims to study this thermoelectric distillation design and then proceeds to study the performance of yield and efficiency systems. Using sets of sensors and Arduino® microcontroller, changes in water sample height can be easily monitored and recorded. Experimental results showed that there were distinctions in temperature over time in various power usage with the minimum power, 18 watts, reached up to 60 °C for hot side and 50 °C for cold side and with the maximum power, 40.5 watts, reached up to 70 °C for hot side and 60 °C for the cold side. Regression by curve fitting found the data follow the 5th polynomial model.

1. Introduction

Even though about 71% of the Earth is covered by water, but only 2.5% is freshwater, Even more, clean freshwater makes up only a tiny fraction of all the water on the planet compared to its huge demand in various fields. Therefore, water purification is one of the most important which sustains the survivability and quality of civilized human life. Various efforts have been made in performing this process (Jiang et al., 2019; Taghipour et al., 2019; Chandrakumar and Pamela, 2021). The most common separation process in Industry is distillation (Chandrakumar and Pamela, 2021). However, considering heat is used as its driving force, this method consumes energy, thus needs to be enhanced to increase its efficiency. The heat provided to encourage evaporation is merely released to the condenser, thus discharged as waste heat (Rahbar and Esfahani, 2012).

Recently, a unique high-efficiency distillation method by integrating thermoelectric technology has been reported and is receiving increasing attention (Rahbar and Esfahani, 2012; Al-Madhhachi and Min, 2017; Al-Nimr et al., 2018). Utilizing the “Peltier Effect”, a single thermoelectric module can facilitate heating using its hot side for evaporation while using its cold side to induce condensation of water. Therefore, this system can improve the energy efficiency of distillation by reducing the theoretical waste heat emission. However, some of the previous studies only exploit the cold side of the module with heat from the hot side released to the environment (Vián et al., 2002; Rahbar and Esfahani, 2012). A study conducted by Al-Madhhachi and Min (2017) designed a water circulation system that is recycled between two containers. One container is exposed to the hot side of the thermoelectric module to heat the sample water with the other exposed to the cold side to induce condensation. The average water production value was 28.5 ml/hour with a specific energy consumption of 0.00114 kW hour/ml.

This study aims to redesign this portable distillation system, by utilizing thermoelectric modules, both their heat and cold sides. Then, proceeds to study the performance of the system’s yield and efficiency using sets of Arduino® sensors and microcontroller to easily monitor and record data in real-time with higher accuracy and precision. Thus, this design creates a unique and novel feature of a thermoelectric distillation design which facilitates both sides of the thermoelectric module without any need for circulation in the system. As a result, the power is solely used for water distillation and the overall efficiency can be significantly improved.

Paper Received: 12 September 2021; Revised: 9 October 2021; Accepted: 15 November 2021
Please cite this article as: Sasongko S.B., Sanyoto G.J., Buchori L., 2021, Study of Performance: an Improved Distillation using Thermoelectric Modules, Chemical Engineering Transactions, 89, 649-654 DOI:10.3303/CET2189109

2. Engineering design and system description

The principle of water purification by distillation is vapor-liquid equilibrium. The vapor is generated from heating water and the liquid (condensate) is produced from cooling vapor. The heating and cooling process can be done from the thermoelectric modules. The main concept of this design is creating a simple single-stage distillation with minimizing the electric component using the thermoelectric modules. The equipment consists of two stainless steel containers that are cylindrical and cubic. The dimension of the cubic container is 8 x 8 x 8 cm^3 which is installed in the middle cylindrical container which has 10 cm height and 15 cm diameter respectively. The thermoelectric modules are installed in the cubic container which is the hot side inside the container. A schematic diagram of the thermoelectric integration distillation vessel can be seen in Figure 1.

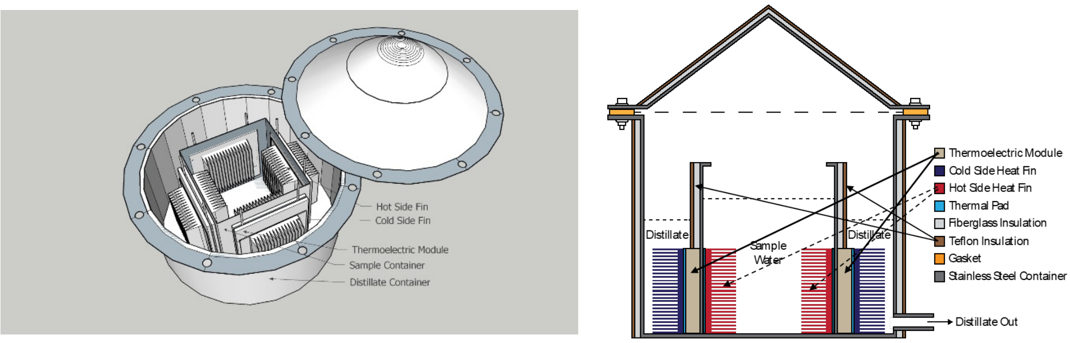


Figure 1: A schematic diagram of a simple integrated distillation vessel using thermoelectric modules

The cubic container is filled with sample water, meanwhile, the condensate droplets will fall on the cylinder part. The conical-shaped lid is chosen due to its ability to direct the flow of water vapor to the condenser fins and to spread condensed water droplets from the lid to the distiller container, refraining the droplets back to the sample water container. Thermoelectric modules are installed on four outer sides of the cubic container with the hot sides facing the cubic wall and the cold sides facing the cylindrical wall. Aluminum heat sinks with fins are connected using thermal pads both to the hot side to enhance water evaporation and the cold side to enhance water vapor condensation. Insulating layers are applied to prevent heat loss from the containers, which insulation contains polytetrafluoroethylene (Teflon®) tape 3J760.

3. Theoretical model

Theoretical modeling of the system is used to describe the heat transfer and phase change throughout the distillation process. A set of equations follow these formed assumptions:

- The properties of sample water are that of pure water and ideal gas behavior,
- The thermal conductivity of aluminium fins is a constant value.
- The convection heat transfer coefficient of water and vapor is constant.
- Heat loss from heat conductivity between containers is neglected.

Equation (1) is the energy balance between the electric power supply and heat generated from the thermoelectric modules.

$$Q_s = P \cdot t = m \cdot c_p \cdot \Delta T \tag{1}$$

where: P (watt) is power supplied to the thermoelectric modules over time, t (s), which can increase a mass m (kg) of a substance's temperature by ΔT (K), according to its specific heat capacity, c_p (J/kg.K) resulting Q_s (Joule). According to previous research (Sasongko et al., 2021), distillation using thermoelectric in the open vessel could not be enough to achieve water's boiling point at atmospheric pressure. However, evaporation could occur in an enclosed area. The energy evaporation can be estimated based on the equation (2) and (3).

$$ln\left(\frac{P_2}{P_1}\right) = -\frac{\Delta H_{vap}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{2}$$

$$Q_{vap} = m \cdot \Delta H_{vap} \tag{3}$$

P_1 and P_2 (atm) are the vapor pressures at temperatures T_1, T_2 (K) respectively, while ΔH_{vap} (J/kg) is the enthalpy of vaporization, and R (0.082 L.atm/mol.K) is the universal gas constant. The Antoine parameters (Guo et al., 2016) are applied to determine the water vapor pressure for the calculation of heat of vaporation based on equation (3). Since the vapor is condensed using the thermoelectric module's cold side, and then released in its liquid form, the concentration of the evaporated substance in the vessel can remain constant, allowing the sample water to evaporate at a constant rate. Given that sample water's surface area remains constant as container's base area, A, in cm^2, the volume of the water, V (ml), can be calculated by only obtaining the depth/height, h (cm), of the remaining water as shown in the equation (4).

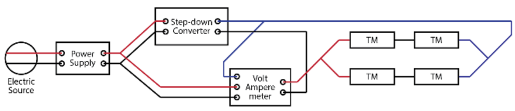
$$V = A \cdot h \tag{4}$$

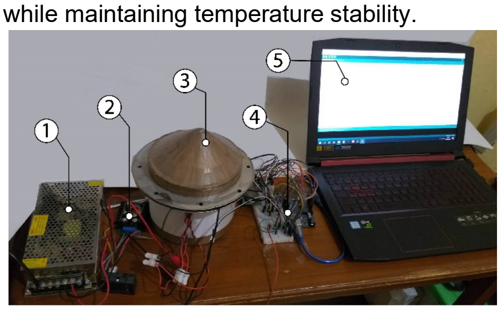
Equation (5) shows the evaporation rate of water distillate.

$$E = \frac{\Delta T}{t} = A\frac{\Delta h}{t} \tag{5}$$

4. Experimental setup

The temperature and water volume in real-time are measured using sets of Arduino® module, temperature probes, and HC-SR04 ultrasonic sensor. The wiring diagram of the thermoelectric module and experimental setup can be seen in Figure 2. The electrical component properties of the experimental setup can be found in Table 1. The experiment was conducted in laboratory condition with an initial temperature of sample water at 30 °C, ambient temperature at 31 °C, and humidity of 74%. Distillation was carried out for 200 minutes with 200 ml tap water by varying its power, 18 watts, 28.125 watts, and 40.5 watts. These variables are chosen due to the specification of the thermoelectric module, which in the previous studies (Sasongko et al., 2021), 9V, 4.5A (40.5 watts) provided the highest maximum temperature. However, temperature difference instability was observed when high power was supplied, thus, it's necessary to vary the power supply (lower values) to study how much power is needed to operate the equipment while maintaining temperature stability.





1. Adaptor
2. Electrical Components and Regulators
3. Distilation Vessel
4. Arduino Measuring Instruments
5. PC for Data Collection

a. Wiring diagram of the thermoelectric module

b. Experimental setup

Figure 2: Wiring diagram (a) and experimental setups for investigating integrated thermoelectric distillation system (b)

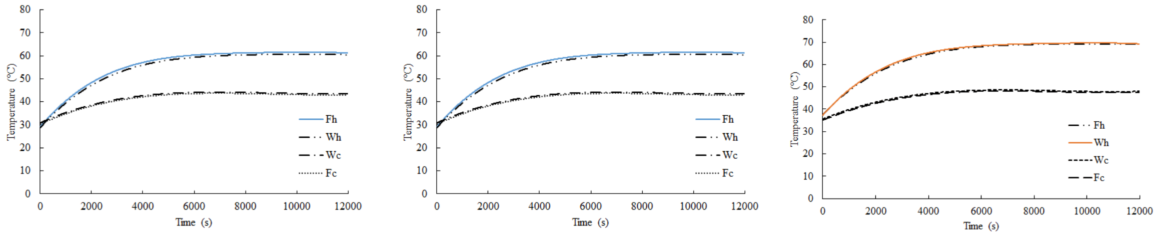
Table 1: Properties of electrical components in the system

Component	Properties	Model
Thermoelectric Module	Area: 40 x 40 mm2 Thickness: 3.8 mm Max current = 6A Max voltage = 12V	TEC-12706
Power Supply	Input: AC 110-245V, 50/60Hz Output: DC 12V, 10A	S-120-12 Switch Mode Power Adaptor (SMPS)

5. Results and Discussion

5.1 Temperature effects from the varied power supply

The principle of thermoelectric is the formation of a hot side and a cold side. Therefore, the thermoelectric performance can be indicated based on the temperature difference. Figure 3 shows the temperature achieved for the sample-water (Wh), distillate (Wc), Fin hot-side (Fh), and Fin cold-side (Fc). Table 2 indicates the temperature difference.



18 watts 28.125 watts 40.5 watts

Figure 3: Temperature as a function of time and power supply

Table 2: Achieved temperature and temperature difference using specified power supply

Power supply	T_o (°C)	Wh (°C)	Wc (°C)	∆TW (°C)	Fh (°C)	Fc (°C)	∆TF (°C)
18 watts	31.9	60.48	43.54	16.94	61.14	43.52	17.62
28.125 watts	31.9	64.61	47.31	17.3	64.8	46.86	17.94
40.5 watts	31.9	68.76	48.31	20.45	69.4	47.48	21.92

From Table 2, it can be seen that with a higher power, a higher temperature difference could be achieved with the value remaining constant throughout the stationary phase. Assuming the power supplied to the system does not fluctuate, this constant value means that the energy released from the system was equal to the energy supplied. Several studies also found similar results (Hájovský et al., 2016; Al-Madhhachi and Min, 2017). However, compared to previous studies, heat accumulation on the thermoelectric module cold side prevented the cold side from reaching lower temperature, if not equal to, the ambient temperature. Nevertheless, the thermoelectric module showed capability in maintaining the temperature difference between the two sides, preventing both sides from having the same temperature. Another comparable study also found out that using a different type of thermoelectric module may provide different temperature differences (Al-Maddhachi and Min, 2017). Still, since the TEC-12706 module itself is widely used in Indonesia for hot-cold water dispensers, the price is relatively cheaper and commercially available compared to the other thermoelectric module types.

5.2 Evaporation rate

Changes in height on the water surface or distance rate were measured using an ultrasonic sensor and recorded by utilizing the Arduino® module. Distance rate can be seen in Figure 4a at the various power supply. Assuming that the surface area of the cubic container is constant, then the rate of evaporation can be calculated as shown in Figure 4b at the various power supply. All curves in Figure 4b show a similar trend of evaporation rate at the various power supply. Therefore, the relation between evaporation rate E_v versus time can be made an equation based on the least-square curve fitting. The fifth-order polynomial equation was found as shown in equation (6) with a summary of the parameters that can be seen in Table 3. Similar studies also show some similarities of this phenomenon especially in the relationship between evaporation rate and time (Johnson et al., 2019).

$$Ev = a.t^5 + b.t^4 + c.t^3 + d.t^2 + e.t \quad (6)$$

a b

Figure 4: Distance rate at various power supply (a) and evaporation rate at various power supply (b)

Table 3: Parameters of polynomial model evaporation rate as a function of time (s)

Power supply (watts)	a	b	c	d	e	R^2
18	8E-23	-3E-18	3E-14	-1E-10	2E-07	0.9874
28.125	8E-23	-3E-18	3E-14	-9E-11	2E-07	0.9841
40.5	-2E-25	1E-19	-4E-15	3E-11	1E-07	0.9910

Figure 5 is similar to the evaporation rate from Figure 4b, however, there are some differences to be noted. Each graph forms five similar areas, but with points that have different coordinates, namely initial values, transient threshold, straight linear, transient shoulder, stationary, and decline. Using 18 watts, the transient region occurred with a longer period compared to the others, on the other hand, 40.5 watts was the fastest and 40.5 watts reached the stationary region faster. In the stationary phase, the evaporation rate reached a constant value, hence the evaporation of water occurred in a steady state. Previous studies showed some similarities especially in the transient threshold and straight linear phases (Al-Madhhachi and Min, 2017) with the stationary phase observed in the final stage of system operation (Canbazoglu et al., 2018). These two results can be correlated with each other in a bigger picture, forming a complete graph as shown in Figure 5.

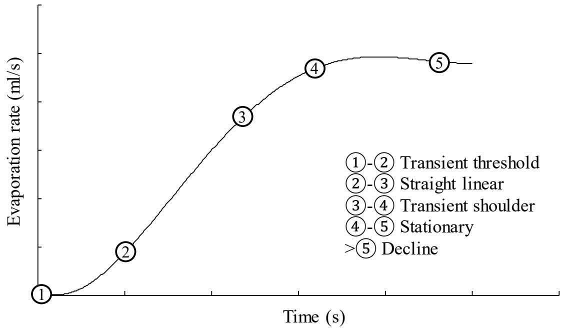


Figure 5: Regions of evaporation rate

5.3 Yield and efficiency

Table 4 shows distillate volume product as energy supplied. The increase in the amount of energy is proportional to the amount of distillate obtained.

Table 4: Relation between power supply, distillate volume, power/volume, and energy/volume

Power supply (watts)	Total energy (J)	Distillate volume (ml)	Power/volume (watts/ml)	Energy/volume (J/ml)
18	216,000	19.6	0.918	11,020.4
28.125	337,500	29.4	0.957	11,479.6
40.5	486,000	41.8	0.969	11,626.8

Table 5 shows the computation of the total heat of water distillate. The Antoine parameters (Guo et al., 2016) were applied to determine water vapor pressure for the calculation of heat of vaporation based on equation (3).

Yield (in volume percentage) can be calculated by dividing the volume of the distillate by the volume of the initial sample. COP can be calculated using the COP equation for the heat pump seeing that this distillation system uses a thermoelectric module as a heat pump to transfer heat from the cold side to the hot side while supplying heat from outside the system (Zhang, 2017). Table 6 shows the yield and COP of thermoelectric distillation based on the total heat usage as indicated in Table 5.

Table 5: Calculation of Total Heat usage

Power supply (watts)	T_o (°C)	T_{max} (°C)	ΔT (°C)	Sensible Heat Q_s (J)	Heat of Vap Q_{vap} (J)	Total Heat (J)
18	31.9	61.3	17.0	23,879	44,637	68,516
28.125	31.9	64.8	17.8	27,330	66,891	94,221
40.5	31.9	69.4	20.9	30,797	94,986	125,783

Table 6: Calculation of Yield and COP of thermoelectric distillation

Power supply (watts)	$Q_{supplied}$ (J)	Q_{usage} (J)	Yield (%)	COP (%)	Yield: COP
18	216,000	68,516	9.8	31.7	0.31
28.125	337,500	94,221	14.7	27.9	0.53
40.5	486,000	125,783	20.9	25.9	0.81

Final calculation results show that the use of 18, 28.125, and 40.5 watts tend to result in lower efficiency with increased power. However, higher power usage resulted in higher yields, but with lower efficiency (COP). In general, this is due to lower water heat of vaporization which causes more molecules to leave the sample, resulting in an increase in yield, as well as reducing the burden of energy required for evaporation by the thermoelectric module. A decrease in efficiency with increasing power is due to the performance of the thermoelectric module itself where the increase in energy used is not significantly proportional to the maximum hot side temperature that can be achieved, instead, it creates heat accumulation on the module’s cold side which hinders condensation. Therefore, less power usage may provide higher efficiency, but with lower yields.

6. Conclusions

Utilization of thermoelectric module as an alternative for distillation system has been conducted and shows reasonable potential and possibility for application. From the heat side, the generated heat is enough to change the vapor-liquid equilibrium of most compounds, encouraging the formation of vapor distillate. Alternately, absorbed heat at the cold side creates temperature difference which enhances condensation.

References

Al-Madhhachi, H., Min, G., 2017, Effective use of thermal energy at both hot and cold side of thermoelectric module for developing efficient thermoelectric water distillation system, Energy Conversion and Management, 133, 14-19. DOI: 10.1016/j.enconman.2016.11.055

Al-Nimr, M.A., Qananba, K.S., 2018, A solar hybrid thermoelectric generator and distillation system, International Journal of Green Energy, 15, 473-488. DOI: 10.1080/15435075.2018.1479266

Canbazoglu, M.F., 2018, Interfacial Thermal Conductivity/Enhanced Solar Evaporation of Water and Ethanol-Water Mixtures from Porous Media, PhD Thesis, University of California San Diego, California, US.

Chandrakumar, A.G.S., Pamela, D., 2021, Advancements in hybrid controllers and new era models of distillation column : A review, Materials Today: Proceedings. DOI: 10.1016/j.matpr.2020.11.725

Guo, H., Ali, H.M., Hassanzadeh, A., 2016, Simulation study of flat-sheet air gap membrane distillation modules coupled with an evaporative crystallizer for zero liquid discharge water desalination, Applied Thermal Engineering, 108, 486-501. DOI: 10.1016/j.applthermaleng.2016.07.131

Hájovský, R., Pieš, M., Richtár, L., 2016, Analysis of the Appropriateness of the Use of Peltier Cells as Energy Sources, Sensors, 16(6): 760. DOI: 10.3390/s16060760

Jiang, C., Cui, S., Han, Q., Li, P., Zhang, Q., Song, J., Mingrui, L., 2019, Study on Application of Activated Carbon in Water Treatment, IOP Conference Series: Earth Environmental Science, 237(2): 022049. DOI: 10.1088/1755-1315/237/2/022049

Johnson, A., Mu, L., Park, Y.H., Valles, D.J., Wang, H., Xu, P., Kota, K., Kuravi, S., 2019, A Thermal Model for Predicting the Performance of a Solar Still with Fresnel Lens, Water, 11, 1860. DOI: 10.3390/w11091860

Rahbar, N., Esfahani, J.A., 2012, Experimental study of a novel portable solar still by utilizing the heatpipe and thermoelectric module, Desalination, 284, 55-61. DOI: 10.1016/j.desal.2011.08.036

Sasongko, S.B., Buchori, L., Sanyoto, G.J., 2021, Experimental study on thermoelectric module's heating and cooling performance, IOP Conference Series: Materials Science and Engineering, 1053 012127. DOI: 10.1088/1757-899X/1053/1/012127

Taghipour, A., Ramirez, J.A., Brown, R.J., Rainey, T.J., 2019, A review of fractional distillation to improve hydrothermal liquefaction biocrude characteristics ; future outlook and prospects, Renewable and Sustainable Energy Reviews, 115(August), 109355. DOI: 10.1016/j.rser.2019.109355

Vián, J.G., Astrain, D., Domínguez, M., 2002, Numerical modelling and a design of a thermoelectric dehumidifier, Elsevier Applied Thermal Engineering, 22(4): 407-422. DOI: 10.1016/S1359-4311(01)00102-8

Yong, C., Tu, Y., Bai, Y., Tang, M., Liu, W., Wu, H., 2016, Combined Adsorption/Ultrafiltration of Secondary Effluents Using Powdered Zeolites, Chemical Engineering & Technology, 39(2), 285-292. DOI: 10.1002/ceat.201500238

Zhang, H., 2017, Solar Energy Desalination Technology, Elsevier, Amsterdam, Netherland.