

Validation of Vapour / Water Production in a Thermoelectric Distillation System

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Abstract - In this study, mathematical calculations developed through water-vapour phase-change theory is used to interpret the processes involved in the fresh water production of a thermoelectric distillation system. The rate of water production depends on various parameters of vaporization phenomena such as water and vapour temperatures, pressure, specific volume, heat capacity and water-vapour surface area. The water-vapour surface area is constant $10 \times 10 \text{ cm}^2$, the initial depth of the sample water is 3 cm and the air occupies the 500 cm^3 volume inside the chamber. The volume and the mass of vapour and water at water-vapour interface are calculated through one hour of the system operation. The temperatures of the system components, humidity and water production of the thermoelectric distillation system are measured. As a result, an increase in the temperature of water and hot side of the thermoelectric module leads to an increase in the water production by increasing the vapour formation at atmospheric pressure. After one hour of system operation, the water production reaches 34.5 mL and the humidity inside the chamber increases from 51 % to 74 %. The results also show the distillation ratio is 11.5%. The mathematical calculations validate the experimental data with reasonable agreement.

Keywords: Phase-change phenomena, thermoelectric system, thermal distillation process, water production

1. Introduction

Liquid-vapour phase change processes play a key role in many technological systems. The heat transfer associated with evaporation and condensation has made the use of these processes increasingly attractive in the thermal control of distillation systems [1]. To find out the energy needed in the distillation process, it is necessary to have reasonable predictive models for the evaporation and production rates as a function of various system parameters [2]. Thermal distillation uses evaporation and condensation processes to operate on the principle of vapour-liquid equilibrium as a basis for molecule separation [3]. In a phase – change phenomenon, each of these phases have different thermodynamic properties such as mass, volume, specific volume, heat capacity, temperature, and humidity. As the water temperature increases, a larger fraction of water molecules will be able to escape as a vapour from the interface surface [4]. Identifying and calculating these properties will make the implementation of renewable energy sources for distillation technologies much easier, with locations close to the sea or with high solar intensity favourable [5]. Thermoelectric modules consists of n-type and p-type semiconductor materials joined electrically in series. A temperature difference occurs on the hot and cold sides of the thermoelectric module due to Peltier effect when DC electric current is supplied. A thermoelectric module doesn't need to use any refrigerant gases and have no moving parts. Because of these advantages, thermoelectric modules are used in many heating and cooling systems [6]. There are a few investigations and analyses into the parameters that influence the evaporation and condensation processes in water distillation systems. J. P. Schwartz and S. Bröcker [7] carried out some investigations on the evaporation of water at different air temperatures and humidities. P. K. Abdenacer and S. Nafila [8] set up a model to simulate the performance of a solar still using a simplified greenhouse effect. They proposed that the temperature difference between the cooling cover and water will improve the evaporation rate since large temperature differences are a driving force for the distillation process and will increase fresh water production. Increasing

the evaporative area and/or condensing surfaces have been observed to enhance the performance of water distillation [9] and increasing the water temperature also leads to a greater production rate for distillation systems [10]. In the present study, mathematical calculations based on the phase-change phenomena are employed in a thermoelectric distillation system to identify and validate the fresh water and vapour production after one hour of system operation.

2. System Description

Vaporization occurs at the water–vapour interface inside the system. Once the temperature of the water increases, vapour is then driven spontaneously to the aluminium heat sink, and condenses at the cooled fins and flows down under the influence of gravity to the collector. Fig.1 shows the main components of the water distillation system which includes a thermoelectric module with a heat exchangers on each side. The core of the thermoelectric distillation system is the thermoelectric module, which uses the Peltier effect to create a temperature difference between both sides. The hot side is attached to a water heat exchanger and the cold side is attached to the aluminium heat sink. When an electrical DC current is supplied to the thermoelectric module, the hot side of the module is used to heat the sample water and the cold side is used to cool the aluminium fins (condenser). A centrifugal pump is used to circulate the sample water through the top heat exchanger for heating.

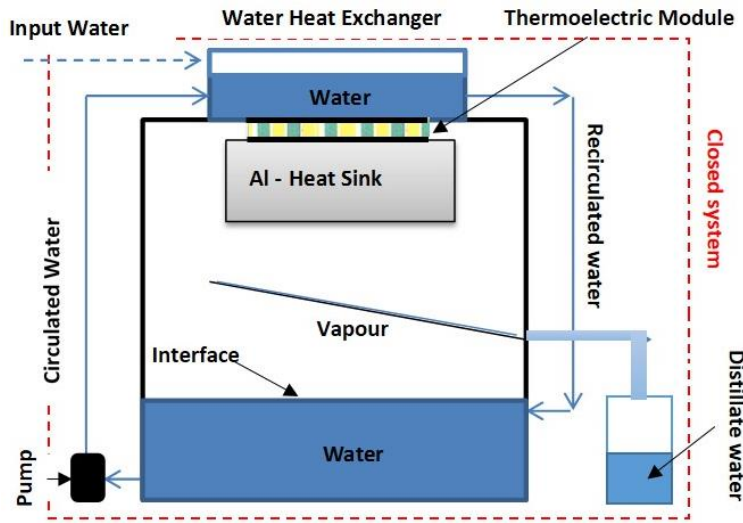


Fig.1: A schematic diagram of the main components of the thermoelectric distillation system.

3. Mathematical Formulations

Two mathematical formulations based on the specific volume of a two phase system and the measured humidity inside the system were applied to estimate the mass of the vapour and water produced at the water-vapour interface are outlined in the next two sections.

3.1. Specific Volume of water in contact with its vapour

To identify the thermodynamic properties of each phase (water and vapour), the quality mass fraction x is required to be calculated at a specific water temperature. The quality defines the proportions of each phase of the mixture [11]. The thermodynamic properties of water including vapour, liquid and solid phases can be represented using steam tables values which have been determined elsewhere [12]. There is direct relationship between water temperature and fluid specific volume at the atmospheric pressure. Specific volume v is the volume V per unit mass m of the phase in (m^3/kg) given by:

$$v = V/m \quad (1)$$

At a specific water temperature, v_f is the specific volume of the water, v_g is the specific volume of the vapour and v_{gf} is the difference between the specific volume of the vapour and the water ($v_{gf} = v_g - v_f$). Fig.2 shows the initial

mass of sample water and initial vapour volume (which is initially air at a temperature T_{ambient}) in the distillation chamber. The initial volumes of the sample water and vapour are 300 ml and $5 \times 10^{-4} \text{ m}^3$ respectively. The surface area of the water-vapour interface is 0.01 m^2 . The system is assumed to be closed to the surroundings and the amount of the fluid will always be the same. In evaporation – condensation processes, the pressure increases due to evaporation while the condensation pressure decreases [13]. Useful results are obtained by making three assumptions: 1) the pressure inside the chamber is at atmospheric pressure, 2) the gas is assumed to be a pure vapour with no air present and 3) there is a saturation region for the water/vapour interface at thermal equilibrium. The general specific volume of a two phase system is defined by the total mass and volume of the water and vapour mixture, which are constant in the equilibrium state:

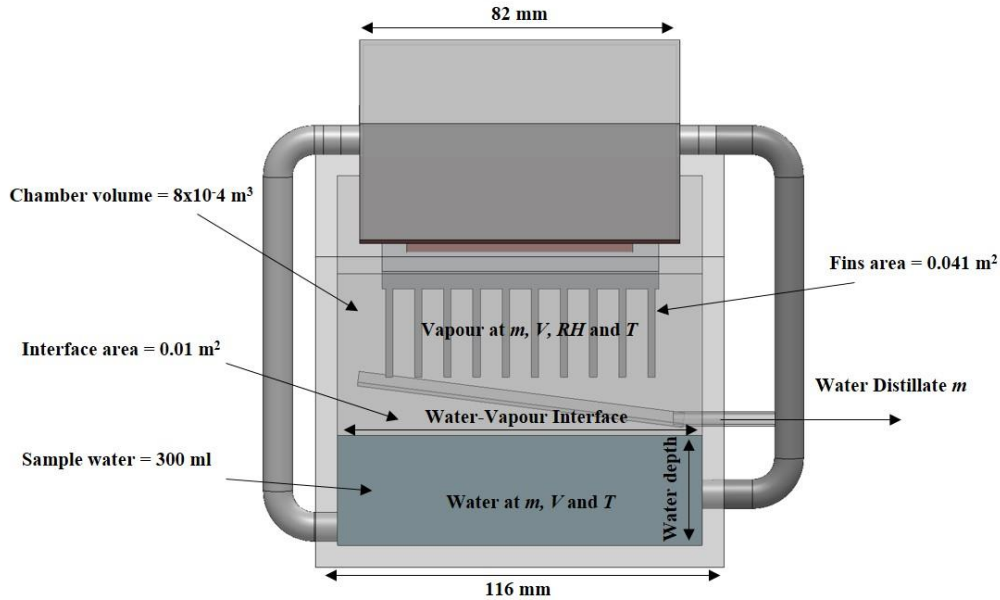


Fig. 2: The initial properties of water and vapour inside the distillation chamber.

$$m_{total} = m_f + m_g \quad (2)$$

$$V_{total} = V_f + V_g \quad (3)$$

$$v_{total} = (V_f + V_g)/(m_f + m_g) \quad (4)$$

The quality of the vapour x is the vapour mass fraction, which is the ratio of the vapour mass to the total mass:

$$x = m_g/m_{total} \quad (5)$$

Substituting Equation 1 into Equation 3 and divided by m_{total} and then substituting in Equation 5, v_{total} can be written as:

$$v_{total} = v_f + x(v_g - v_f) \quad (6)$$

With x written as;

$$x = v_{total} - v_f/(v_g - v_f) \quad (7)$$

Equation 7 is used to calculate the vapour mass fraction x . The water, vapour and water-vapour specific volumes can be obtained at a given water temperature using Steam Tables at atmospheric pressure. Then at any mass fraction, the mass of the vapour can be estimated using equation 5. To calculate the mass of water remain in the chamber (not evaporated) after the distillation process, it can be use the following expression:

$$m_{remain} + m_{distillate} = m_{total} \quad (8)$$

$$m_{remain} = m_{total} - m_{distillate} = m_{not\ evaporated} + m_{not\ collected} \quad (9)$$

Where $m_{distillate}$ is the mass of fresh water produced after system operation in (ml) and can be measured experimentally. The distillation ratio is the mass of water distillate and collected to the initial water mass $m_{initial}$ filled in the basin and equal to:

$$Distillation\ ratio = m_{distillate} / m_{initial} \quad (10)$$

3.2. Humidity inside the System

The relative humidity RH of the system is the ratio of the actual density ρ_{actual} in (kg/m^3) to the saturation density $\rho_{saturation}$ of the vapour in (kg/m^3) at a given vapour temperature. The saturation density of the vapour can be obtained from steam tables at the atmospheric pressure [12]. So, the mass of the vapour can be estimate related to the RH and vapour temperature measurements:

$$RH = \rho_{actual\ vapour} / \rho_{saturation\ vapour} \quad (11)$$

$$V_{actual\ vapour} = V_{total} - V_{water\ remaining\ in\ the\ chamber} \quad (12)$$

$$m_{actual\ vapour} = \rho_{actual\ vapour} V_{actual\ vapour} \quad (13)$$

4. Experimental Setup

A thermal distillation system using a thermoelectric unit for both evaporation and condensation was constructed. A more detailed description of the design can be found elsewhere [14]. Fig. 3 shows the experimental setup including the power supplies, the multi-meters and the digital scale connected to the thermoelectric distillation system. The thermoelectric unit was designed to accommodate one thermoelectric module (62 mm x 62 mm) sandwiched between two heat exchangers. The top heat exchanger (copper) was mounted on the hot side of the thermoelectric module and the bottom one (Aluminium) was attached to the cold side of the thermoelectric module. To evaluate the thermal performance of the thermoelectric distillation system (temperatures of the system components, humidity, pressure and water productivity), the setup was tested under standard laboratory conditions (initial sample water temperatures and air humidity). The experiments were carried out for 60 minutes and the basin was filled with 300 mL of tap water. Once the system was isolated, water is pumped between the basin and the hot side heat exchanger with a constant flow rate of 0.2 L/min. During the experiments the hot side heat exchanger, vapour and basin water temperatures were recorded using a data logger (Pico logger TC-08) along with the external laboratory temperature. The distillate water due to the condensation process was collected and measured. The pressure inside the system was measured to be around 101.3 kPa.

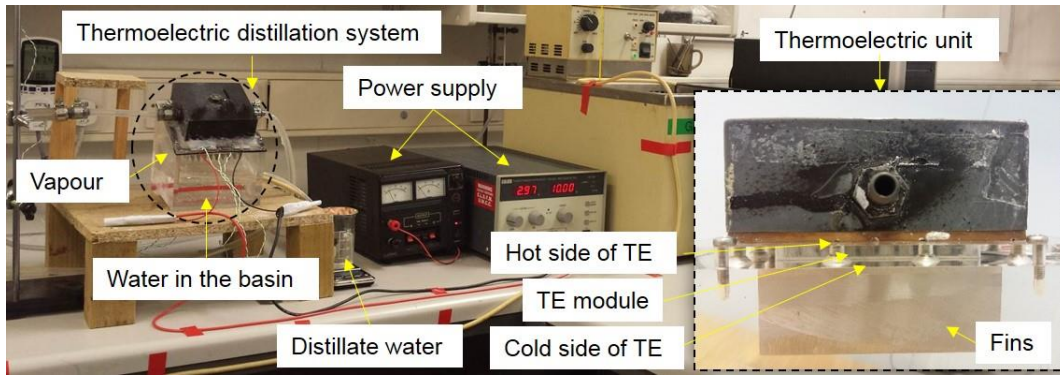


Fig. 3: The experimental setup of the thermoelectric distillation system.

5. Results and Discussions

Heating water causes the molecules within to speed up and spread slightly further apart and this results in a decrease in the density and an increase in the specific volume. There is also an increase in the vapour density (adding mass to a fixed volume due to the evaporation process) and this leads to a decrease in the specific volume of the vapour. The result is a decrease in the specific volume difference between the water and the vapour, as well as an increase in the vapour mass fraction. During experimental operation, the thermoelectric unit and pump were run for one hour, increasing the water temperature due to the heat transferred from the hot side of the thermoelectric module to the water, leading to an increase in the basin water temperature and increased distillate production (See Fig.4). It is observed that the change in water temperature (from 21.9 °C to 25.2 °C) is particularly great within the first 10 minutes of thermoelectric operation. The amount of distillate water during one hour system operation was 34.5 ml (water temperature of 42.7 °C) with an 11.5% distillation ratio. Fig. 5 shows a comparison of the relative humidity RH with the vapour temperature. Although there is an initial decrease in RH from 55% to 51%, this subsequently increases to 74% after one hour of operation. The result shows the relative humidity increases with increasing vapour temperature. Fig. 6 shows the vapour mass calculated using Equation 13 based on the experimentally obtained relative humidity values and is compared with the theoretical calculations of Equation 5 using Steam Table values. Fig. 7 shows a plot of water remaining in the system (experimentally determined using Equation 9) which has not been distilled by the thermoelectric unit at different water temperatures represented by red crosses. The theoretical value was calculated from $m_{total}(1-x)$ and is shown as a solid black line on the graph. This corresponds to a theoretical distillation ratio of 17.5% for a water temperature of 42.7 °C and is in reasonable agreement with the 11.5% experimental value obtained. There is a slight difference between the experimental and calculated theoretical values and this is due to losses during the condensation process.

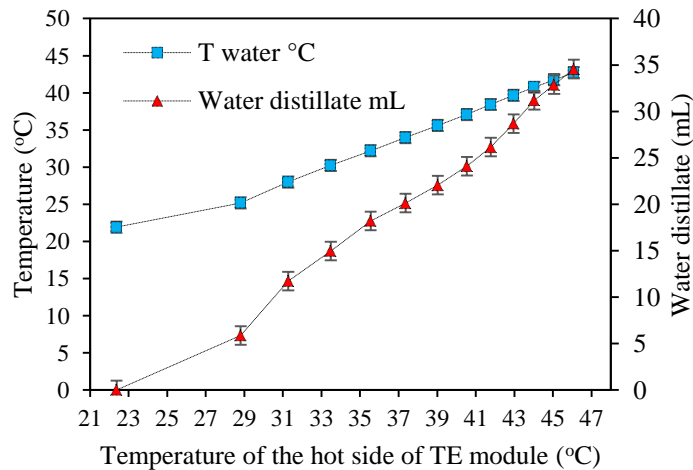


Fig. 4: The water temperature against hot side of TE temperature.

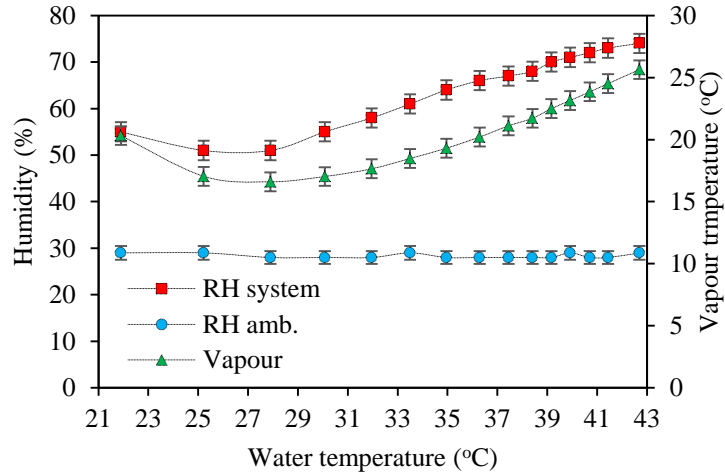


Fig. 5: The experimental data of vapour temperature and humidity.

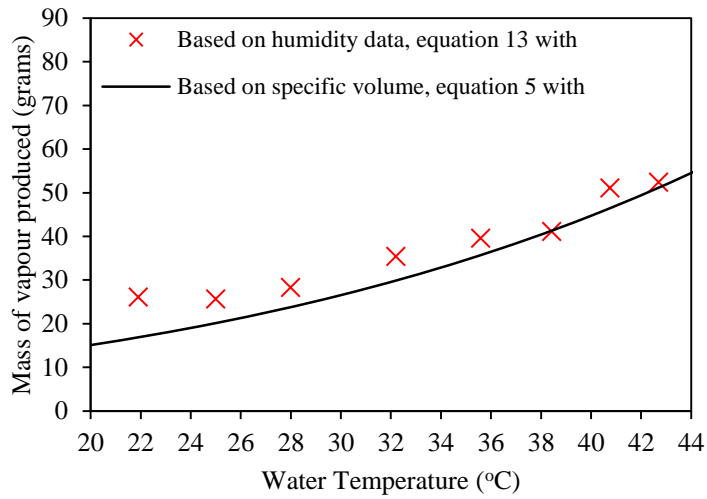


Fig. 6: The validation of the vapour mass produced.

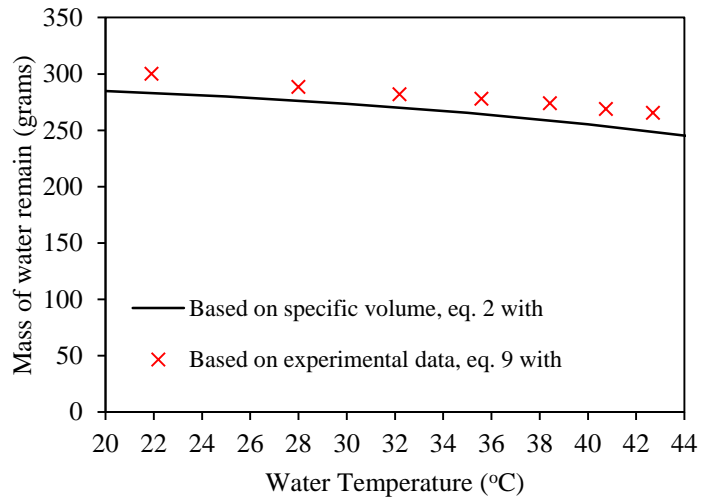


Fig. 7: The validation of the water mass remain.

6. Conclusions

An effective method for the thermal distillation of fresh water using a thermoelectric system is presented. A feedback system is used to maximise the efficiency of the system by circulating water through the hot side heat exchanger of the thermoelectric to heat the water for evaporation. Increasing the vapour produced has a direct effect on increasing the water productivity of the system. Liquid water to vapour phase change calculations were used to assess the performance of the system and to find a theoretical maximum distillation ratio of 17.5% with a water temperature of 42.7 °C. After operating the system for one hour, the distillation ratio was calculated to be 11.5% and is in reasonable agreement with the mathematically determined value.

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References

- [1] V. P. Carey, *Liquid-Vapour Phase-Change Phenomena*. LLC, 2nd Ed. USA: Taylor & Francis Group, 2008.
- [2] M. Al-Shammiri, "Evaporation rate as a function of water salinity," *Desalination*, vol. 150, no. 2, pp. 189-203, 2002.
- [3] V. G. Gude, N. Nirmalakhandan, and S. Deng, "Renewable and sustainable approaches for desalination," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 2641-2654, 2010.
- [4] Y. Nagata, K. Usui and M. Bonn, "Molecular Mechanism of Water Evaporation," *Physical review letters*, vol. 115, no. 23, pp. 236102-5, 2015.
- [5] A. Al-Karaghoul and L. L. Kazmerski, "Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes," *Renewable and Sustainable Energy Reviews*, vol. 24, pp. 343-356, 2013.
- [6] C. Yildirim, S. Soylu, I. Atmaca, I. Solmus, "Experimental investigation of a portable desalination unit configured by a thermoelectric cooler," *Energy Conversion and Management*, vol. 85, pp. 140-145, 2014.
- [7] J. P. Schwartze and S. Bröcker, "The evaporation of water into air of different humidities and the inversion temperature phenomenon," *International journal of heat and mass transfer*, vol. 43, no. 10, pp. 1791-1800, 2000.
- [8] P. K. Abdenacer and S. Nafila, "Impact of temperature difference (water-solar collector) on solar-still global efficiency," *Desalination*, vol. 209, no. 1, pp. 298-305, 2007.
- [9] A. E. Kabeel, "Performance of solar still with a concave wick evaporation surface," *Energy*, vol. 34, no. 10, pp. 1504-1509, 2009.
- [10] T. Elango and K. K. Murugavel, "The effect of the water depth on the productivity for single and double basin double slope glass solar stills," *Desalination*, vol. 359, pp.82-91, 2015.
- [11] A. Shavit and C. Gutfinger, *Thermodynamics: from concepts to applications*. CRC Press, 2nd Ed. USA: Taylor & Francis Group, 2008.
- [12] J. H. Keenan, *Steam tables: thermodynamic properties of water, including vapour, liquid, and solid phases*. (English units). New York: John Wiley, 1969.
- [13] H. K. S. Abada, M. Ghiasib, S. J. Mamouric, M. B. Shafii, "A novel integrated solar desalination system with a pulsating heat pipe," *Desalination*, vol. 311, pp. 206-210, 2013.
- [14] H. Al-Madhhachi and G. Min, "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*, vol. 133, pp.14-19, 2017.