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High productivity thermoelectric based distiller

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ABSTRACT

In this work, a thermoelectric water distiller is designed and constructed. The proposed design uses the hot side of the thermoelectric module for heating saline water up to its boiling point and the cold side of the thermoelectric module to condensate purified water drops. To study the effectiveness and productivity of the proposed distiller, an experimental study is conducted. The experimental results indicate that the system produces 216 mL/h purified water, where the input power is 127 Watts. A mathematical thermal model for this system is derived and simulations are implemented based on the derived model. Correspondingly, the simulated and experimental production rate values are compared. It is found that the difference between the experimental and the simulation results is around 20%.

Keywords: Thermoelectric; Water distiller; Mathematical model

1. Introduction

The supply of clean water is a basic human necessity along with air and food. Drinkable water is a valuable source that is rapidly becoming rare in many parts of the world. The challenge is obtaining high efficiency and less power consumption water sources. Water distillation methods are one of the most reliable water sources. Researchers studied many devices for obtaining energy-effective, low-cost and high productive distillers.

Water distillation methods vary in productivity, power consumption, availability, cost, quality, sustainability and maintenance. For example, solar distillers, in general, can be considered as a low cost, sustainable and easy maintenance method; however, it depends on the sunlight availability and the climate [1]. Using fossil fuel for distillation is an expensive method and has a side-effect on the environment due to carbon dioxide emissions to the atmosphere. The challenge is still open to provide a low-power consumption and high-water productivity distillation water methods. Thermoelectric distiller that will be proposed in this paper can provide high water production with low power consumption as it recovers some of the generated heat.

The thermoelectric module (TEM) is a significant technology since it is used in many applications and fields. For example, TEMs have several applications in water distillation and can act as a core or an auxiliary element. TEMs have been used in many solar distillation systems as an auxiliary element for increasing water vapor condensation [2–7]. In such applications, the cold side of TEM is placed near the condensation region, which results in increased water production. On the other hand, the hot side of the thermoelectric device can be attached to a fan and a heat sink, this will cause more heat losses. However, this method is not energy efficient.

Thermoelectric modules were used as a core element for heating and condensation in many previous distillers; a multistage design [8], and a concentric design of the thermoelectric distiller [9,10], and the usage of the thermoelectric distiller in urine-water recovery system are used in space-crafts [11,12].

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Another recent research proposed a design that uses the heat from the hot side of the thermoelectric to increase the saline water evaporation [13]. This method used a pump for recirculating the saline water between the water basin and the heat exchanger attached to the hot side of the thermoelectric device. The cold side of the thermoelectric device was used for water vapor condensation. This method shows a better energy saving; although, using a pump will add more operation power.

All of the already existing work doesn't propose a mathematical model for the thermoelectric distillers. Such a model is needed to help better understand the thermal dynamics of these types of distillers. This in turn will lead to more robust and optimal design and control strategies. Accordingly, in this work, a model representing a basic thermoelectric distiller unit is proposed and compared with the experimental results.

2. System description

In this section, the system core element (TEM) working principle is illustrated. Then, the proposed system components and working principles are described. Finally, the mathematical model derivations with simplifying assumptions are stated.

2.1. Thermoelectric modules

A TEM is a solid-state heat pump. Its working principle is simply the inverted version of the thermocouple temperature sensor, which means that the thermocouple generates a voltage signal from the temperature difference between the hot and the cold junctions. On the other hand, the thermoelectric module generates a heat flux and temperature difference based on a driving voltage signal. The thermocouple working principle is called the Seebeck effect and the thermoelectric working principle is called the Peltier effect [14].

In general, the TEM consists of an array of semiconductor legs which are the basic elements of the TEM. These legs are either P or N-type semiconductor material connected electrically in series and thermally in parallel as shown in Fig. 1 [15].

Fig. 1 also shows the heat fluxes through the thermoelectric module. The derived heat equations for the TEM module are:

$$Q_h = \alpha I T_h - k\Delta T + \frac{1}{2}I^2 R \tag{1}$$

$$Q_c = \alpha I T_c - k\Delta T - \frac{1}{2}I^2 R \tag{2}$$

$$V = IR + \alpha\Delta T \tag{3}$$

where Q_h and Q_c are respectively the heat flow rate to the hot side and the heat flow rate entering from the cold side of the thermoelectric. α is the Seebeck coefficient and R is the electric resistance, k is the thermal conductance of the thermoelectric module, and $\Delta T = T_h - T_c$. These parameters are taken from the module datasheet with number TEC1-19908 and then validated experimentally by applying a simple least square fitting procedure for collected voltage, current and temperature readings and using the voltage loop in equation 3. The results are $\alpha \cong 0.088$ V/K, $R \cong 2.38\ \Omega$ and $K \cong 0.8889$ W/K.

The TEM is used in two different ways (1) for harvesting energy and (2) for producing heat flux and temperature difference. In this work, it has been used to produce the heat flux from the cold side to the hot side acting as a thermal pump.

2.2. Proposed thermoelectric distiller design

The proposed design of the thermoelectric module distiller (TEMD) uses the hot side of the TEM to heat the water to the boiling point and the cold side to condensate part of the vapor and to recover its latent heat to the hot side. Fig. 2 shows the main parts of the TEMD which have two separate tanks (hot and cold), a cover and two TEMs modules. The right tank contains the hot water (saline water) and the left tank is for condensation (distilled water). The two TEMs are sandwiched between these two tanks in parallel. The condensate vapor in the cold tank leaves its latent heat to be almost recovered to the hot tank using the TEM. The TEM pumps the majority of the latent heat back as Q_c to heat the water in the hot tank, as a result, the power loss will be minimized. The produced vapor is larger than the condensate because Q_h is greater than Q_c due to ($Q_h = P_{in} + Q_c$). Some thermal losses occur in the hot and cold tanks to the surrounding, and also, part of the vapor escapes to avoid the pressure rise in the tank. Consequently, not all the latent heat of the vaporized water will be recovered.

Fig. 3 shows a diagram of the TEMD including energy and mass transfer. In addition, the saline water tank is connected with the hot tank from both tank bottoms. This connection reduces the heat losses since the hot water has a lower density than the cold water. As a result, the hot water will rise and not return to the saline tank. On the other hand, controlling the water level in the hot tank will be easily achieved by controlling the water level in the saline tank.

On the cold side, the water level in the cold tank is assumed to be almost zero due to the drain at the bottom of this tank. The cold tank is connected to a *U* shape pipe for preventing the vapor to escape from the tank while allowing only the distilled water to escape. A small vent through the distiller cover is important to keep the inside pressure near to the atmospheric pressure and to prevent vapor accumulation.

2.3. Mathematical modeling of the system

In this section, a mathematical model of the proposed system will be derived. This model represents energy balance, mass balance and heat transfer equations. The thermal model can be simplified into three main parts; the hot tank model, the cold tank model, and the TEM model as shown in Fig. 4. First, the TEM model is similar to Eqs. (1)–(3) but since we have n number of the TEM connected electrically in series and thermally in parallel, the equations will be as follows:

$$Q_h = n\left[\alpha I T_h - k\Delta T + \frac{1}{2}I^2 R\right] \tag{4}$$

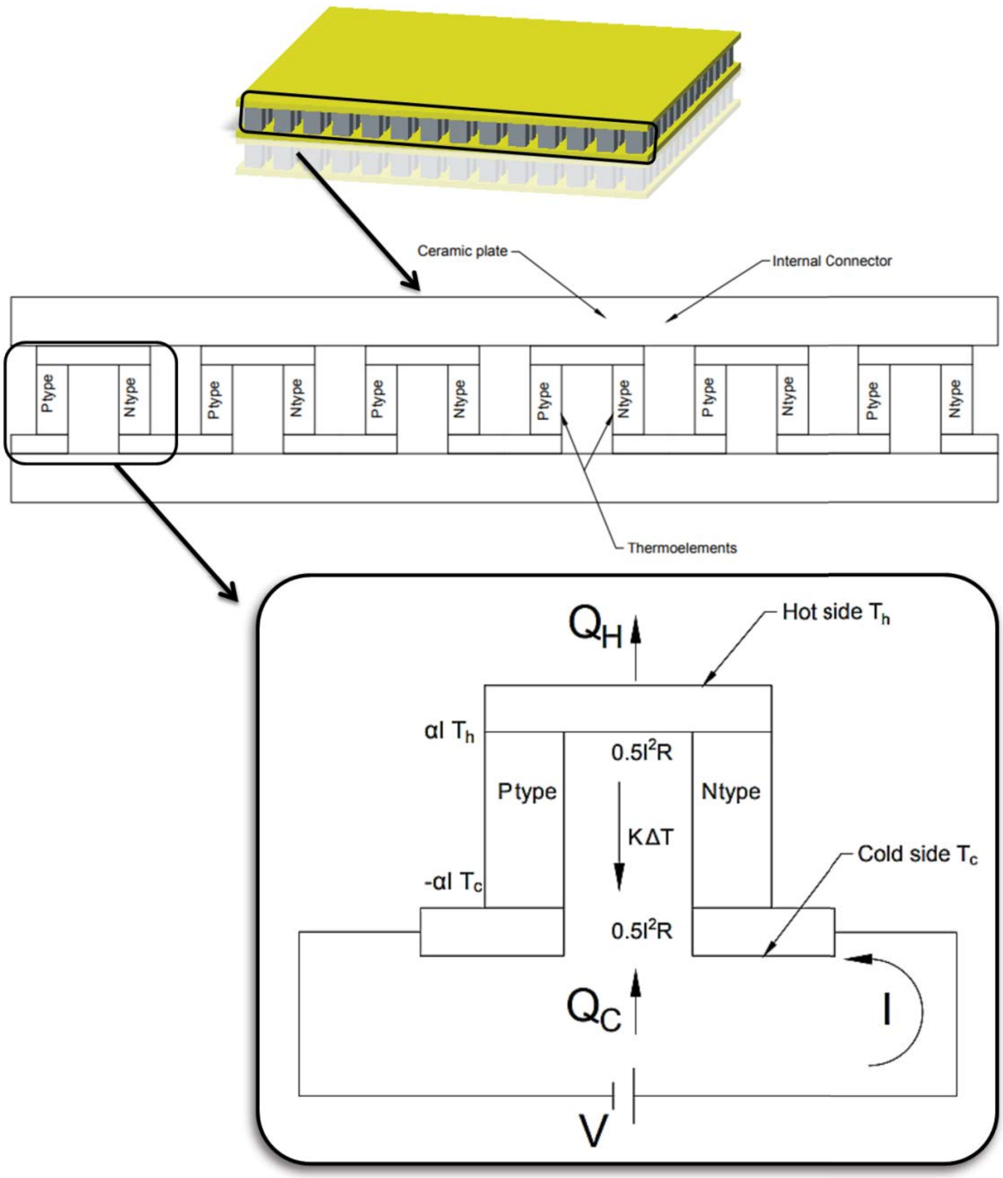

Fig. 1. Thermoelectric module.

$$Q_c = n\left[\alpha I T_c - k\Delta T - \frac{1}{2}I^2 R\right] \quad (5)$$

$$V = \frac{IR}{n} + \alpha\Delta T \quad (6)$$

The second model is the thermal model for the hot tank. The convection heat transfer from the hot side of the TEM to the water inside the hot tank is found using Eq. (7), and the heat losses from the water in the hot tank to the surrounding is calculated using Eq. (8):

$$Q_h = \frac{T_h - T_{\text{wh}}}{R_h} \quad (7)$$

$$Q_{\text{loss}} = \frac{T_{\text{wh}} - T_{\text{amp}}}{R_{\text{out}}} \quad (8)$$

And the related energy balance equation is:

$$Q_h - Q_{\text{loss}} - \dot{m}_{v,\text{loss}} h_v + \dot{m}_{\text{win}} h_{\text{win}} - \dot{m}_v h_v = 0 \quad (9)$$

The vapor losses due to the vent and the corresponding vapor energy losses are given in the following equation:

$$\dot{m}_{v,\text{loss}} = \dot{m}_v - \dot{m}_{\text{cond}} \quad (10)$$

The third thermal model is related to the cold tank, Eq. (11) gives the convection heat transfer from the cold side of the TEM to the vapor inside the cold tank:

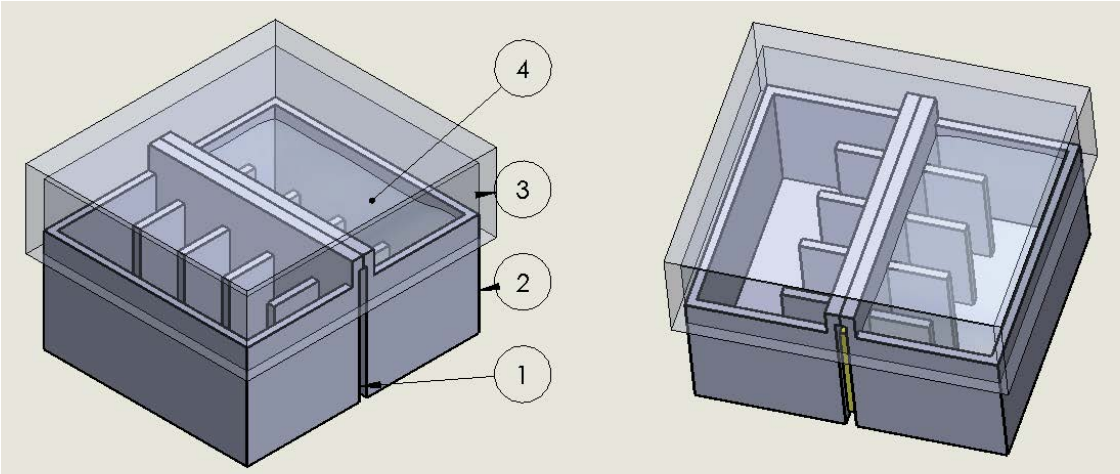

Fig. 2. TEMD structure; (1) is the TEM; (2) is the hot tank; (3) is the cover part; (4) the hot water in the hot tank.

$$Q_c = \frac{T_v - T_c}{R_c} \tag{11}$$

Eq. (12) is the heat balance in the cold tank, which can be used to find the condensation mass flow rate.

$$\dot{m}_{\text{cond}} h_v - Q_c - Q_{\text{loss}} - \dot{m}_{\text{cond}} h_{\text{cond}} = 0 \tag{12}$$

To simplify the model some assumptions were suggested:

- $T_v = T_{\text{wh}} = 98°\text{C}$ while boiling;
- $\dot{m}_v = \dot{m}_{\text{win}}$ in the hot tank;
- Pressure inside the tanks is the atmospheric pressure due to a small vent in the design as shown in Fig. 3;
- Thermal resistances R_c, R_h and R_{out} are constants;
- Vapor losses can be calculated by $\dot{m}_{v,\text{losses}} = \dot{m}_v - \dot{m}_{\text{cond}}$, and it was found experimentally to equal $\dot{m}_{v,\text{losses}} = 55\%\ \dot{m}_v$.

The system coefficient of performance can be calculated using the following equations:

$$\text{COP}_h = \frac{Q_h}{P_{\text{in}}} = \text{COP}_c + 1 \tag{13}$$

$$\text{COP}_c = \frac{Q_c}{P_{\text{in}}} \tag{14}$$

$$P_{\text{in}} = I \times V \tag{15}$$

3. Experimentation and simulation

In this section, the simulation and the experimental results are discussed. The simulation considers the steady-state case.

3.1. Steady-state analysis

By solving the previous equations with different input current values, the expected water production was obtained.

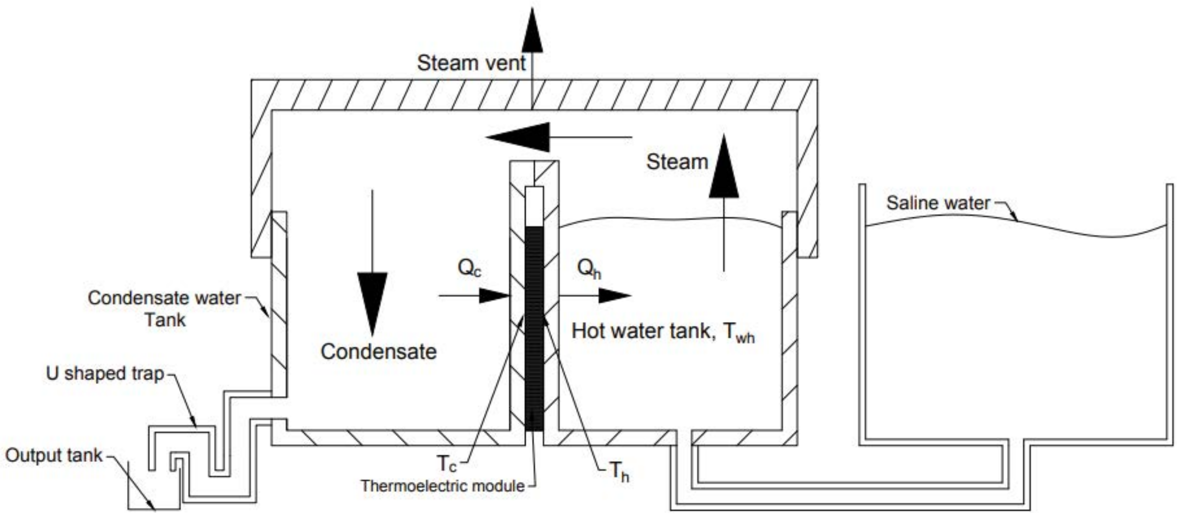

Fig. 3. TEMD diagram.

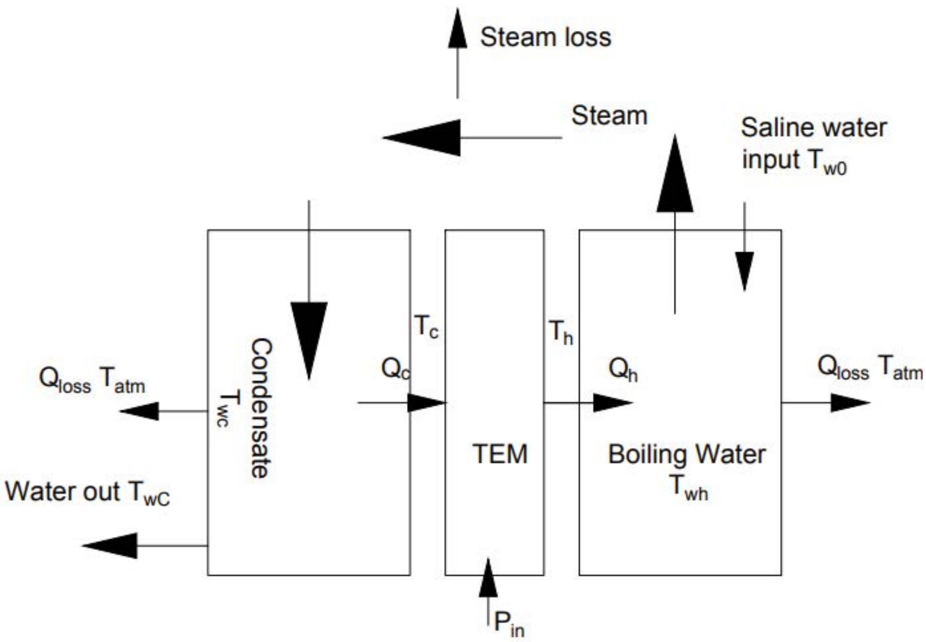

Fig. 4. Thermal model diagram.

The steady-state system response can be shown in Fig. 5. The nominal production of the purified water is 281 mL/h where the input current is 8 A, and the input power is found by Eq. (15) to equal 131 W.

3.2. Experiment description and results

The experimental setup is shown in Fig. 6. The main body consists of the hot tank, cold tank and the cover, where all of them are made of casted aluminum since aluminum has high thermal conductivity. The saline tank is made of a 1.0 mm galvanized steel sheet.

After reaching the steady-state, the condensate water is collected in a small beaker. After 15 min, the results were recorded to start another trial.

3.3. Experimental results

As shown in Table 1, the experimental results show that productivity increases when the input power increases.

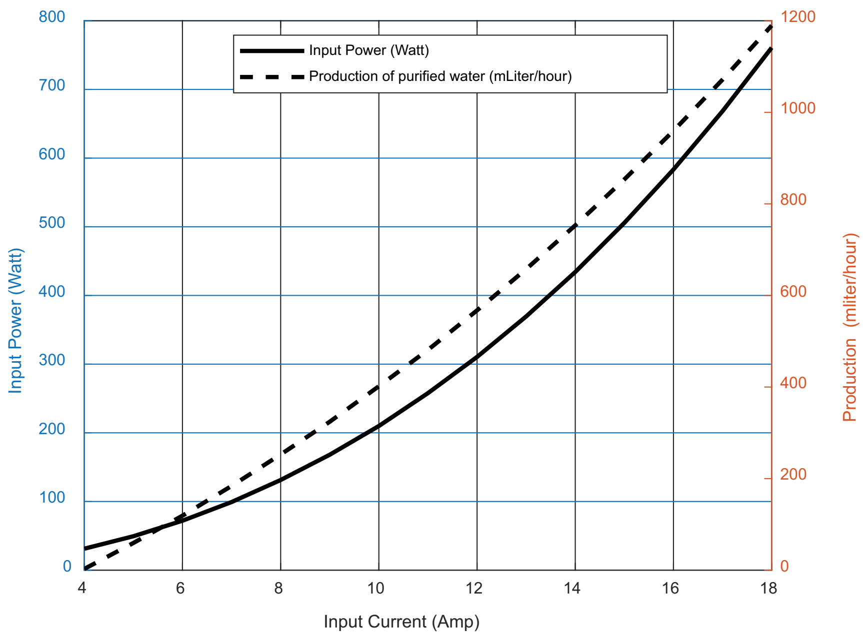

Fig. 5. Steady-state results for TEMD production and input power vs. different input current values.

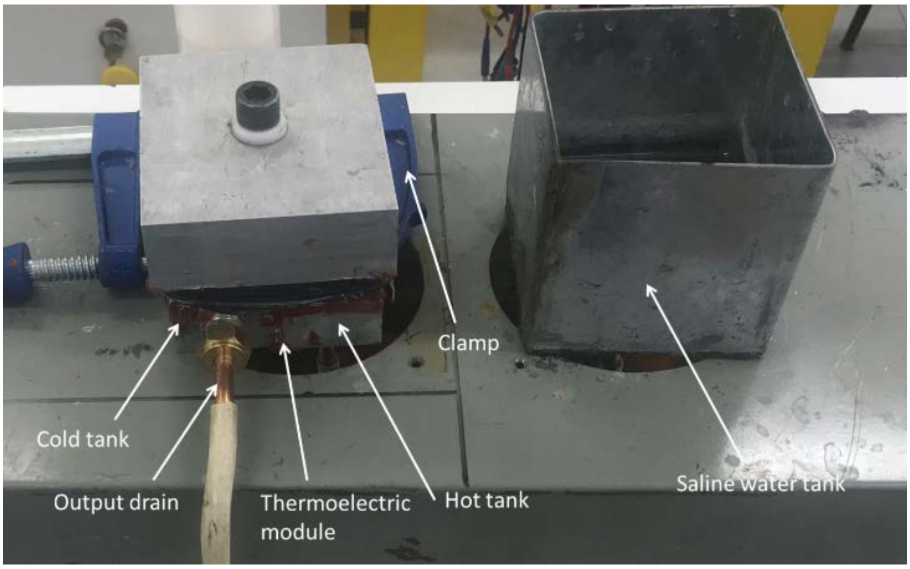

Fig. 6. Experimental setup.

Table 1
Experimental results

Exp. #	Time duration (min)	V_{in} (Volt)	I_{in} (amp.)	P_{in} (Watt)	TDS for the water source (ppm)	T_c (°C)	T_h (°C)	TDS of distilled water (ppm)	Distilled water volume (mL)	Distilled water flow rate (mL/h)	Production flow to power ratio mL/h Watt
1	15	16	8	128.0	699	77	113	173	48	192	1.5
2	16	16	8	128.0	699	79	114	136	48	180	1.4
3	16	15.8	8.05	127.2	699	82	114	108	55	206.25	1.62
4	15	15.8	8.04	127.0	699	82.5	115	105	53	212	1.67
5	15	15.8	8.03	126.9	699	84	115	93	54	216	1.70
6	15	15.7	8	125.6	671	85	115	106	49	196	1.56
7	15	14	7	98.0	671	79	112.5	159	35	140	1.43
8	15	14	7	98.0	671	79	112	90	35	140	1.43
9	15	14	7.1	99.4	671	80	112.5	93	37	148	1.49
10	15	12.6	6.11	77.0	671	70	108	93	24	96	1.25
11	20	11.2	5.18	58.0	671	65	106	111	20	60	1.03

The total dissolved solids (TDS) measurements are around 100 ppm, which shows a respectable water quality level for the condensate water. The production flow rate to power ratio is 1.73 mL/s W which is more than a 200% increase in that of a previous design which was 0.85 mL/s W [13]. This significant improvement is due to two reasons: (1) minimizing the lost power by removing the pump and (2) running the system to the boiling point which increases the system vapor production compared to running the system only using evaporation strategies.

Moreover, it was found that the proposed TEMD has better production compared to that of the solar distiller from the previous design [16]. However, it is evident that large bubbles were produced in the hot tank due to water boiling. These bubbles cause an increase in the TDS of the condensate tank since water bubbles explode and displace salt particles into the cold tank when operating at high voltage.

Fig. 7 shows a comparison between the simulated and experimental results. Due to the unpredicted losses, such as vapor losses from the vent and the variable heat transfer convection coefficients, it was found that the experimental production values are around 80% of the simulated values. Noting that the error increases when input power increases, the expectation is that the system thermal coefficients will be more unpredictable with more thermal dynamics, and the pressure inside the tanks will increase and cause more vapor losses.

4. Conclusions

Thermoelectric based water distiller was designed, constructed and experimentally tested. The productivity of purified water was 216 mL/h, where the input electrical power was 127 Watt.

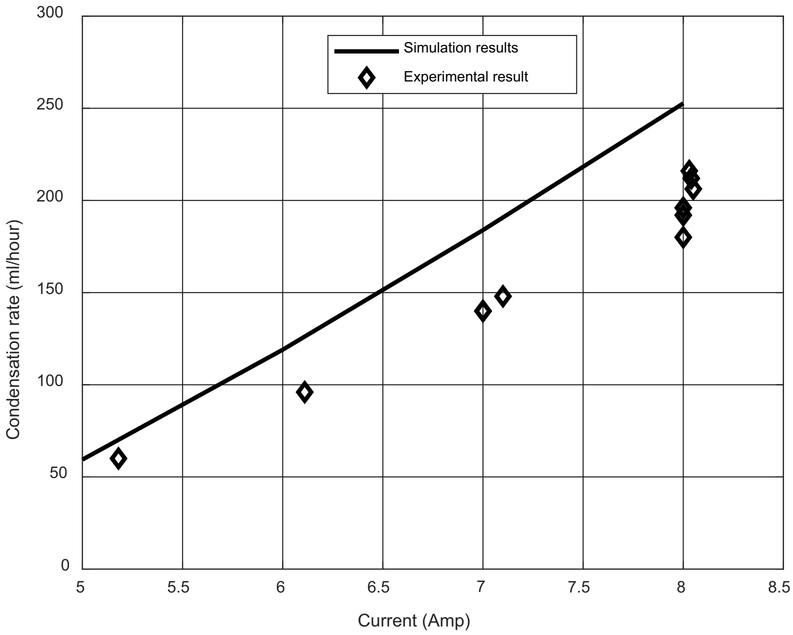

Fig. 7. Comparison between the simulation and experimental results.

The mathematical model for thermoelectric based water distiller was built, and the results of the experiments were compared with simulated values. Due to the variable vapor losses caused by the vent and the estimated thermal convection coefficients, it is found that the difference between experimental and simulation results is around 20%.

Symbols

- T_h — TEM hot side temperature, Kelvin
- T_c — TEM cold side temperature, Kelvin
- T_{wh} — Temperature of the water in the hot tank, Kelvin
- T_v — Temperature of the vapor, Kelvin
- T_{wc} — Temperature of the water in the cold tank, Kelvin
- T_{atm} — Temperature of the surrounded environment, 25°C
- k — Thermal conductivity of the TEM W/°C
- Q_c — Heat flux of the TEM cold side, Watt
- Q_h — Heat flux of the TEM hot side, Watt
- R_c — Thermal resistance between the TEM cold side and the vapor, °C/W
- R_h — Thermal resistance between the TEM hot side and the hot tank water, °C/W
- $\dot{m}_{win}$ — Mass flow rate of the inlet water, kg/sec
- h_{win} — Enthalpy of the inlet water at 25°C, kJ/kg K
- $\dot{m}_v$ — Mass flow rate of the produced vapor, kg/sec
- h_v — Enthalpy of the vapor, kJ/kg K
- h_{cond} — Enthalpy of the output water at 45°C, kJ/kg K
- I — TEM Inlet current, amp
- R — TEM electrical resistance, ohm
- h_{fg} — Latent heat of the boiled water, kJ/kg K
- α — Seebeck effect coefficient, Volt/K
- R_{out} — Thermal resistance between the system and the environment, kJ/kg K
- $\dot{m}_{cond}$ — Mass flow rate of the produced water (condensation), kg/s
- V — Voltage source value, Volt
- m_{hw} — Total water mass in the hot tank, kg
- c_p — Heat capacity of the water, kJ/kg K
- Power_{in} — Electrical power consumed by the TEMD = $I \times V$, Watt
- n — Number of TEM connected in parallel
- $\dot{m}_{v,losses}$ — Vapor losses flow rate outside the tanks from the vent, kg/s
- TDS — Total dissolved solids, ppm
- ΔT — $T_h - T_c$, Kelvin
- n — Number of the TEM
- Q_{loss} — Heat losses from the hot or the cold tank to surrounding
- COP_h — Coefficient of performance for heating process in the TEM
- COP_c — Coefficient of performance for cooling process in the TEM
- P_{in} — Electrical power input to TEMs, Watt

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