Experimental investigation of dehumidification process regulated by the photothermoelectric system

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ABSTRACT

To decrease indoor relative humidity and have relaxing environments, small dehumidifiers are widely used in tropical climatic. Due to the benefits of eco-friendly, small size and silence operation, the thermoelectric dehumidifier has gained interest but has limited practical application due to poor efficiency. Therefore, this study investigates the dehumidification characteristics of the thermoelectric module powered by a photovoltaic system for the production of fresh water under real climatic conditions. The performance of a novel prototype named as the Photo-Thermoelectric Dehumidifier (PVTE-D) was investigated both numerically and experimentally in different combinations of airflow rate and input power. The results obtained from the experiment suggested that the water condensate collection was increased by increasing the input power from a PV panel to the TE-D. In the month of May, the maximum water condensate collection of 1,852.3 mL/hr was attained at the input supply of 6 A and 5 V to the PVTE-D system. In the majority of cases, when the airflow rate is below 0.013 kg/s, maximum collections of water condensate have been achieved. This study provides a detailed understanding of the optimally suitable structural parameters of the PVTE-D under different operating conditions and reveals a novel configuration for higher water condensation capacity.

Key words: dehumidification, photovoltaic, simulation, thermoelectric module, validation

HIGHLIGHTS

- Photovoltaic powered thermoelectric dehumidification system.
- Simulation and experimental study of PVTE-D system.
- Optimum performance parameter evaluation by regulating input power and air flow rate.

INTRODUCTION

In recent decades, population and industry development have contributed to a dramatic rise in pollution from CO2 emissions and the issue of fresh water shortages (Dickens et al. 2020). There are over one billion individuals that do not have access to safe drinking water (Boretti & Rosa 2019). Nearly half of the world's people will reside in water-stressed environments by 2030 (van Vliet et al. 2021). Nearly all tropical countries have high relative humidity, average annual rainfall, ambient temperature and solar irradiance and are classified as humid countries (Han et al. 2020). One of these tropical countries is Malaysia, which is in South-East Asia. Malaysia climatic condition having daily average relative humidity values from 84% during the dry season to 95% during the rainy season, with varying annual average air temperature rates from 23 to 37 °C, with approximately 21 g of water vapor holding in 1.0 m3 of its atmosphere (Tuck et al. 2020). The most popular form of dehumidification of an airstream that exists in Malaysia or related countries is the cooling coil-based air-conditioning system (Yusliza et al. 2020). The humidity level inside the test room was maintained at the prescribed level by condensing the airstream moisture on the cool surfaces of fin and coil of the traditional air-conditioning systems (Khorram et al. 2020). However, these conventional air-conditioning systems consume substantial amounts of electrical energy, causing a peak load on the electric grid, particularly in summertime (Kalluri et al. 2020). The refrigerant used in the conventional AC system, conversely, causes permanent damage to the ozone layer, leading to the risk of exposure to ultraviolet radiation throughout life.
(Zhang et al. 2020). Peltier dehumidifiers work by pulling in damp air over the front of a coolant heat sink. As the air meets the cold surface, it gathers. The water delivered from the dense air then, at that point trickles down into the water tank and the dry air is delivered once again into the room. The dehumidification interaction is the backwards of adding water to the room with an evaporative cooler, and rather delivers heat. Along these lines, an in-room dehumidifier will in every case warm the room and decrease the relative stickiness by implication, just as diminishing the mugginess all the more straightforwardly, by consolidating and eliminating water. The objective is to improve the thermophysical system performance. Timely measurements are improved with novel approaches. This research motivates us to improve the technology in real life data and the goal is to improve the availability.

An alternative to the current dehumidifier is the thermoelectric dehumidifier (TE-D), which operates by collecting heat from one side and releasing heat on the other side (Riahi et al. 2021). A compressor can be substituted by a group of Peltier components (He et al. 2015), and a thermoelectric module can be used to create the dehumidifying system (Im et al. 2020). While a TE-D can be constructed smaller than a comparable size compressor style dehumidifier, its poor performance is a downside (Szaszák & Pozsa 2020). To investigate the performance of thermoelectric module as dehumidifier Vián et al. (2002) evaluates the low wattage (100 W) TE-D in two phases to analyze the efficiency of the thermoelectric module as a dehumidifier. The findings showed that at ambient conditions of 32 °C and 90 percent humidity, the obtained value of coefficient of performance is 0.8. The TE-D developed by Yao et al. (2017) consists of two thermoelectric modules. The experimental findings revealed that the novel prototype's moisture removal rate is up to 33.1 g/h and the resulting COP is 0.75 while the air flow rate of the air duct is 1.74 m/s. Water collection from an air stream by using TEC was developed by Tan & Fok (2013). The result shows that 16.8 mL/h of water was collected by using TE-D at an humidity level of 82%. The new hot heat sink with a rectangular fin array was built by Udomsakdigool et al. (2007) for TE-D system and they concluded that the performance was 95 percent and COP of TE-D was 0.88 at 12 V voltage and 1.9 A electric current. Joshi et al. (2017) investigated TE-D made up of ten TEM and of 0.7 m long. The result suggested that water output is increased by 81 percent by using internal heat sink. In 2017, a portable TE-D was developed by using two thermoelectric module for China climatic conditions (Liu et al. 2017). The overall water collected at ambient temperature of 23.6 °C and RH (%) of 92.1 was 25.1 g/hr. An atmospheric water generator (AWG) was developed by Shourideh et al. (2018) by using TEM with cold side expanded surface geometry optimization. The result reports a lowest real energy consumption of AWG. Recently, an AWG was developed by He et al. (2020) for Indian environment conditions by utilizing two TEC modules. The result indicates that freshwater quantities of 85.5 to 245.8 mL per 10 h of operation were obtained by using AWG respectively, within the regulated RH% values of 60 to 90%. The researchers concluded that, under indoor regulated conditions, the AWG provided the maximum amount of water with a relative humidity rate of 90 percent and an air flow rate of 70 m³/h over a duration of 10 h. In order to examine the impact of device operational and configuration parameters on the efficiency of the TEM cooling and humidification–dehumidification water desalination system, Patel et al. (2020) introduced a theoretical model and experimental work. The result showed that the system's gained output ratio was 0.8 where the air mass flow rate was 0.016 kg/s and the regular rate of fresh water output was obtained in the 7 to 15 L/day range.

Moreover, TEM also has the potential to operate directly with DC voltage and therefore directly connect with the photovoltaic panel device (Irshad et al. 2019). In order to utilize this characteristic of TEMs, a 30 Wp photovoltaic powered AWG device was manufactured using TEM and analyzed under the ambient environment of Madrid, Spain in 2012. Within an hour, the AWG device collected between 2 and 4 mL of water from air (Muñoz-García et al. 2013). Further, in another study the productivity of single slope solar still was enhanced by using heating ability of TEM (Rahbar et al. 2017). More investigation on heating and cooling behavior of TEM applied on a double slope solar still were studied by Shoiebi et al. (2020). The result shows that TEM integrated double slope solar still gave more water output as compared with normal solar still. Mahmoudinezhad et al. (2018) published both experimental and computational tests of a hybrid concentrated photovoltaic-thermoelectric generator (TEG). In experimental analysis, both solar simulator and solar collector were used. The findings indicate that TEG's contribution to the overall generation of energy improves as the strength of solar irradiation in this system increases. In addition, the experimental findings show that localized photovoltaic maximal and minimum efficiencies are around 23.02 and 35.33%, respectively, whereas these values are 0.63 and 1.2% for TEG, respectively. The TEM was also used by Nazari et al. (2019a, 2019b) to increase the efficiency of a single solar slope cooling glass. The findings of their studies were that the efficacy of adjusted solar fresh water, thermal production and energy efficiency was still higher than that of traditional solar. In other tests, four TEC modules along the walls of the exterior channel were used to assess a decent position in the vapor flow of the single solar slope (Nazari et al. 2019a, 2019b). The experimental findings showed that solar
productivity, electricity and energy efficiencies already equipped with the outer TEM condensing channel improved by approximately 31.2%, 38.5%, and 38.9%.

The critical review of numerous literature publications indicates that not much studies were reported on dehumidification characteristic of TEM powered by photovoltaic panels installed on the wall. Most of the previous studies were out either on a limited scale or under environmental circumstances that were regulated. Therefore, this study aimed to investigate the performance of a photovoltaic wall-assisted thermoelectric dehumidification system under variable power, climatic conditions and air flow rate. The real-scale PVTE-D system model was built and implemented on the test room. The PVTE-D system’s full-day running performance was investigated under variable input power and airflow rates for more than three months. The findings of this study will provide in-depth knowledge of the PV wall integrated TE-D system both numerically and experimentally.

**Numerical model**

The numerical models of the TE-D and PV wall system are presented in this section. The 1-D heat conduction unsteady-state process was assumed to be considered. The idea of HD is the assortment of consumable water by first humidifying an air momentum by contact with warm seawater and afterward dehumidifying by cooling. By this technique, the deformity (activity of refining plants at high temperatures, around 115 °C, produces scaling issues) of high temperature utilized in other refining measures is stayed away from and the desalination execution is an improvement over what is acknowledged in the customary sun-oriented stills to create more yield voltage or to deliver more current. Sunlight-based boards can be electrically associated together in series to build the voltage yield, or they can be associated together in parallel to expand the yield amperage. Three energy balance equations are therefore considered for the heat transfer model.

a) The ratio of coverage of PV cells in a photovoltaic panel is defined as

\[ e = \frac{A_{PV}}{A_{Glass}}, \]  

(1)

The photocurrent in relation with solar radiation and cell temperature as defined by:

\[ I_{ph} = \frac{G}{G_{ref}} [I_{ph,ref} + \mu_T(T - T_{ref})] \]  

(2)

The saturation current can be found as:

\[ I_o = \frac{I_{sc,ref} + \mu_T(T - T_{ref})}{\exp \left[ \frac{q(V_{oc,ref} + \mu_T(T - T_{ref}))}{nNskBT} \right] - 1} \]  

(3)

Diode quality coefficient (n) can be found as:

\[ n = \frac{q(V_{m,ref} - V_{oc,ref})}{NskBT_{ref} \ln \left( 1 - \frac{I_{m,ref}}{I_{sc,ref}} \right)} \]  

(4)

At the maximum power point, the voltage and current that corresponds to power can be determined by:

\[ V_{mpp} = \frac{nNskBT}{q} \ln \left( \frac{nNskBT \cdot I_{sc}}{qI_{oc} \cdot V_{oc}} \right) \]  

(5)

\[ I_{mpp} = I_{ph} + I_o = \frac{nNskBT \cdot I_{sc}}{q \cdot V_{oc}} \]  

(6)

\[ P_{mpp} = I_{mpp}V_{mpp} \]  

(7)
Open circuit voltage was determined by:

\[ V_{OC} = \frac{nN_A k_B T}{q} \ln \left( 1 + \frac{I_{sc}}{I_0} \right) \] (8)

b) The PV panel energy balance

The depth of the solar cells that are connected to the glass panel's back is very thin. The heat conduction between the photovoltaic panel and the glass panel is therefore very strong and the temperature can therefore be expected to differ evenly in the Y direction of the solar panels. By neglecting the heat potential of the solar cell regardless of their thickness and considering the solar cell's temperature distribution is standardized, the PV glass panel's energy balance equation is calculated according to its thickness as

\[ \rho_g c_e \frac{\partial T_p}{\partial t} = \frac{\partial}{\partial x} \left( \lambda g \frac{\partial T_p}{\partial x} \right) + \frac{\partial}{\partial z} \left( \lambda g \frac{\partial T_p}{\partial z} \right) + b \] (9)

where \( b = (S_c + S_p T_p) / \delta \)

1. A glass with solar cell having heat transfer as:

\[ S_c = [\alpha \tau + (1 - \tau)]G - E + h_{co} T_a + \xi_1 h_{ro} T_a + h_{ci} T_e + \xi_2 h_r T_{wo} \] (10)

\[ S_p = -(h_{co} + \xi_1 h_{ro} + h_{ci} + \xi_2 h_r) \] (11)

2. A glass without solar cell having heat transfer as:

\[ S_c = [G(1 - \tau) + h_{co} T_a + \xi_1 h_{ro} T_a + h_{ci} T_e + \xi_2 h_r T_{wo}] \] (12)

\[ S_p = -(h_{co} + \xi_1 h_{ro} + h_{ci} + \xi_2 h_r) \] (13)

The solar glass panel surface radiant heat transfer coefficients are given as:

\[ h_{ro} = \sigma (T_p^2 + T_a^2)(T_p + T_a) \] (14)

\[ h_r = \sigma (T_p^2 + T_{cold}^2)(T_p + T_{cold}) \] (15)

The emissivity factors \( \xi_1, \xi_2 \) can be determined by:

\[ \frac{1}{\xi_1} = \frac{1}{\varepsilon_o} + \frac{1}{\varepsilon_e} - 1, \] (16)

\[ \frac{1}{\xi_2} = \frac{1}{\varepsilon_i} + \frac{1}{\varepsilon_{te}} - 1, \] (17)

The coefficients of convective heat transfer caused by wind on the both side of solar glass panel surface are estimated by Lin et al. (2019):

\[ h_o = 5.7 + 3.8V \] (18)

Thermophysical properties are attributes that control the diurnal, occasional, or climatic surface and subsurface temperature varieties (or warm bends) of a material. The first thermophysical models depended on the investigations of lunar temperature varieties. Thermophysical properties include explicit warmth limit, warm conductivity, coefficient of direct warm development, warmth of vaporization, and warmth of burning. Thermo physical extents of the materials are given...
above, in segments where powder creation is provided. The heat transfer coefficient can be estimated as:

\[ h_t(X) = \frac{(N_a \lambda_a)}{X} \quad (19) \]

The turbulent and laminar layer as:

\[ N_{lx} = 0.120(G_{rx}P_1)^{1/3} \quad \text{for Turbulent boundary layer} \quad (20) \]

\[ G_{rx} = g \beta (T_p - T_a) X^3 / \nu^2 \quad (21) \]

\[ Pr = \nu / \alpha_a \quad (22) \]

For thermoelectric dehumidification four basic characteristics equations are used to identified every TECs such as \( I_{max}, V_{max}, \Delta T_{max} \) and \( Q_{max} \) are defined as follows

\[ S_m = \frac{V_{max}}{T_{hot}} \quad (23) \]

\[ R_m = \frac{(T_{hot} - \Delta T_{max}) V_{max}}{T_{hot}I_{max}} \quad (24) \]

\[ K_m = \frac{(T_{hot} - \Delta T_{max}) V_{max} I_{max}}{2T_{hot} \Delta T_{max}} \quad (25) \]

The energy dissipate and absorbed from both side of TEMs can be estimated as

\[ Q_{cold} = S_m I T_{cold} - \frac{I^2 R_m}{2} - K_m \Delta T \quad (26) \]

\[ Q_{hot} = S_m I T_{hot} - \frac{I^2 R_m}{2} - K_m \Delta T \quad (27) \]

The hot and cold side of TEM temperature difference can be estimated as

\[ \Delta T = T_{hot} - T_{cold} \quad (28) \]

\[ P_{TEC} = Q_{hot} - Q_{cold} \quad (29) \]

By putting equations of \( Q_{hot} \) and \( Q_{cold} \) in Equation (7) we get

\[ P_{TEC} = S_m I \Delta T + \frac{I^2 R_m}{2} \quad (30) \]

\[ Q_{cold} = m_{cold} C_{p,cold}(h_{air,in,h} - h_{air,out,h}) \quad (31) \]

\[ Q_{hot} = m_{hot} C_{p,hot}(T_{air,out,h} - h_{air,in,h}) \quad (32) \]

The enthalpy of humid air can be given as

\[ h = C_p (T - 273) + \omega (2501.5 + 1.86(T - 273)) \times 1000 \quad (33) \]
Through the application of the heat transfer method of LMTD in the air duct, the temperature difference between the sides of TEMs and air flow rate can be estimated as

\[
Q_{\text{cold}} = \frac{\Delta T_{\text{LMTD,cold}}}{R_{\text{cold}}} \tag{34}
\]

\[
Q_{\text{hot}} = \frac{\Delta T_{\text{LMTD,hot}}}{R_{\text{hot}}} \tag{35}
\]

The cold and hot side temperature difference of TEMs is given as

\[
\Delta T_{\text{LMTD,cold}} = \left[ \frac{(T_{\text{air, out}} - T_{\text{cold}}) - (T_{a} - T_{\text{cold}})}{\ln \left( \frac{T_{\text{air, out}} - T_{\text{cold}}}{T_{a} - T_{\text{cold}}} \right)} \right] \tag{36}
\]

\[
\Delta T_{\text{LMTD,hot side}} = \left[ \frac{(T_{h} - T_{\text{air, in}},h) - (T_{h} - T_{\text{air, out}},h))}{\ln \left( \frac{T_{h} - T_{\text{air, in}},h)}{T_{h} - T_{\text{air, out}},h) \right)} \tag{37}
\]

The heat sink overall efficiency can be estimated as

\[
\eta_0 = 1 - \frac{N_{\text{fins}}A_f}{A_f} (1 - \eta_f) \tag{38}
\]

\[
A_{\text{fins}} = 2\omega_{\text{fin}}l_c \tag{39}
\]

\[
l_c = l_{\text{fin}} + \frac{t_{\text{fin}}}{2} \tag{40}
\]

\[
A_{\text{total}} = l_{\text{hole}}l_{\text{channel}}N_{\text{hole}} + (2N_{\text{hole}} - 2)H_{\text{hole}}l_{\text{channel}} \tag{41}
\]

By considering the tips of adiabatic fins, performance can be measured as

\[
\eta_f = \frac{\tan m l_c}{m l_c} \tag{42}
\]

\[
m = \sqrt{\frac{h_{\text{conv}}p}{k_e A_c}} \tag{43}
\]

\[
p = 2(w_{\text{fin}} + t_{\text{fin}}) \tag{44}
\]

\[
A_c = w_{\text{fin}}t_{\text{fin}} \tag{45}
\]

It was assumed that both side of air duct i.e. hot and cold air duct have turbulent and can be formulated as

\[
N_u = 0.023Re^{0.8}Pr^{0.4} \quad \text{for heating} \tag{46}
\]

\[
N_u = 0.023Re^{0.8}Pr^{0.3} \quad \text{for cooling} \tag{47}
\]
The convection based heat transfer coefficient is calculated as:

\[ h_{\text{conv}} = \frac{Nuk_f}{D_{\text{hyd}}} \]  

(48)

\[ Re = \frac{\mu \text{avg} D_{\text{hyd}}}{\nu} \]  

(49)

\[ \mu \text{avg} = \frac{\mu_s}{N_{\text{hole}}} \rho_{\text{hole}} H_{\text{hole}} \]  

(50)

\[ D_{\text{hyd}} = \frac{4A_{\text{hole}}}{\rho_{\text{hole}}} = \frac{4l_{\text{hole}} H_{\text{hole}}}{2(l_{\text{hole}} + H_{\text{hole}})} \]  

(51)

\[ V_w = \frac{m_d (\omega_{\text{air,in}} - \omega_{\text{air,out}}) \times 1000}{\rho_{\text{average}}} \]  

(52)

Humidification and dehumidification (drying) of air are needed in numerous business and modern applications for the control of air dampness content inside the consumed space to guarantee the prosperity of human, creature, or vegetation and the control of air dampness content inside a space for measure control or to ensure items available.

METHOD

The performance of the photo-thermoelectric dehumidification (PTE-D) system was measured under real climatic conditions of Seri Iskandar, PERAK, Malaysia from February 2018 until December 2018. The system configuration of PTE-D was installed on the test room at location 4°23′11″N and 100°58′47″N. The thermophysical properties of the test room have been described in previous work. The photovoltaic panel covered the south side wall of the test room as it not only harnesses electrical energy by transforming solar irradiation into direct electrical current, but also eliminates direct exposure of solar radiation on south wall. The DC current produced from the PV wall was used to operate the thermoelectric dehumidification system under variable input power configuration. The specification and configuration of thermoelectric dehumidification system have been given in the previously published work. The PV module of dimension 1,205 mm × 655 mm × 34 mm, with maximum peak power of 100 W, and cell size of 156 mm × 104 mm and number of cell equal to 36, was installed on the south facing wall of the test bed. A supportive structure was made up of aluminum (with a rotating facility) and was used to install the three PV modules on the south wall with a capacity of 100 Wp each. The area available for installation of the PV panel on the wall was small and it was necessary to fit only three 100 Wp panels, as the output power produced by the PV device is inadequate for a full-day thermoelectric dehumidification system. In the event of a power shortage, the grid-connected DC power supply was mounted along with a PV system to establish power breakdown. The hours of sunshine in Malaysia range from 5 to 6 hours a day. For the measurement of temperature i.e. PV glazing surface, ambient, and inside outside wall of test bed, twenty K-Type thermocouples were used. A 20 channel Graphitec data logger was used to collect the temperature data and record in the system. The weather outside is constantly tracked and registered by the Davis Vantage Pro 2 weather station. TESTO 480 equipment is mounted within the test chamber for indoor weather conditions. The data were continuously registered in the Graphitec data logger for 5 minutes (GL 840). The PVTE-D device output was continuously analyzed for 4 days or 4 cloudless days with equivalent environmental conditions for each stage of input current supply. This experiment was conducted on the PVTE-D device under various input incremental current supplies, i.e. 3 A, 4 A, 5 A, and 6 A.

The PVTE-D system consists of a frame made up of an aluminum sheet, 24 TEMs (TEC1-12730), heat sinks, fan, acrylic insulation sheets. The acrylic sheet was installed at the center of the PVTE-D system to clamp the 24 TEMs and split the duct into two intersections, namely, hot and cold air duct. The cold duct consists of pan collector. The water condensate deposit on the surface of TEMs of cold side of PVTE-D system was gradually transfer to the water collector pan. Furthermore, detailed descriptions of experimental setup and uncertainty analysis of parameters have been given in a previous work.
RESULTS AND DISCUSSION

The experimental results obtained at different input power supply from PV system to TE-D system are presented in Figures 1–4. Statistical analysis was conducted by using SPSS software in order to analyze the significance of each parameter on PVTE-D water condensation. Water quality boundaries incorporate synthetic, physical, and organic properties and can be tried or checked depending on the ideal water boundaries of concern. Boundaries were occasionally examined or observed for water quality incorporate temperature, disintegrated oxygen, pH, conductivity, ORP, and turbidity. Multivariate analysis of variance (MANOVA) was performed on the data of perceived i.e. relative humidity, ambient temperature, TEMs both sides temperature and water condensate. The results of MANOVA are presented in Table 1. The result shows that variation in the input current to the PVTE-D system had a significant effect on the water condensate production and temperature variation of hot and cold sides of TEMs. Furthermore, it was observed that variation in environmental parameters such as ambient temperature and relative humidity have significant effects on water condensate production and temperature variation of hot and cold sides of TEMs. However, compared to other parameters, i.e. cold and hot sides temperatures of TEMs, a less significant effect of solar radiation on water condensate production was observed. In addition, the combined effects of input power to the PVTE-D on weather conditions, i.e. ambient temperature, relative humidity and solar radiation, are listed in Table 1. The statistical result shows that there was a significant difference in water condensate production and temperature on both sides of the TEM in the combined effects of input power, ambient temperature and relative humidity. The combined effects of solar radiation and input power on the production of water condensate and temperatures on both sides of TEMs, however, was less significant, as shown in Table 1.

Figure 1 shows the hourly variation in the production of water condensate, ambient climate, and temperature variation on both sides of the TEMs. This experimental variation was observed when the PVTE-D system was operated at 3 A and 5 V. The data were collected from 9 March 2019 until 12 March 2019. The maximum water condensate collected from the PVTE-D system was 1,358.8 mL/h, while the minimum condensation collected was 950.3 mL/h and the standard deviation was 109.47 mL. Based on the experimental results, it was found that the cold side temperature of TEMs systems of PVTE-D system has more impact on water condensate production as compared to the ambient temperature and relative humidity. The effect of solar radiation on water condensation was minimal; however it has greater influence on cooling load of test bed.

![Figure 1](image-url)
Figure 2 | Hourly water condensate, ambient climate and TEMs hot and cold sides temperature variation PVTE-D system operated at 4 A and 5 V.

Figure 3 | Hourly water condensate, ambient climate and TEMs hot and cold sides temperature variation PVTE-D system operated at 5 A and 5 V.
Further, by increasing input power to 4 A and 5 V to PVTE-D system, hourly variation in the production of water condensate, ambient climate, and temperature of both sides of the TEMs was measured and is presented in Figure 2. The experiment was performed from 23 March 2019 until 26 March 2019. The maximum water condensate collected from the PVTE-D system was 1,430.6 mL/h, while the minimum condensation collected was 1,016.6 mL/h and the standard deviation was

![Figure 4](image)

**Figure 4** | Hourly water condensate, ambient climate and TEMs hot and cold sides temperature variation PVTE-D system operated at 6 A and 5 V.

**Table 1** | The result of MANOVA performed on PVTE-D system output

| Source | Dependent variable | Sig. (p-value) |
|--------|--------------------|----------------|
| Current to TE-D system (ampere) | Water condensate | 0.905 |
| | Temperature of hot side TEM | 0.840 |
| | Temperature of cold side TEM | 0.941 |
| Amb_Temp (°C) | Water condensate | 0.780 |
| | Temperature of hot side TEM | 0.890 |
| | Temperature of cold side TEM | 0.910 |
| RH (%) | Water condensate | 0.992 |
| | Temperature of hot side TEM | 0.817 |
| | Temperature of cold side TEM | 0.823 |
| SR (W/m²) | Water condensate | 0.703 |
| | Temperature of hot side TEM | 0.831 |
| | Temperature of cold side TEM | 0.867 |
| Current to TE-D system * RH | Water condensate | 0.992 |
| | Temperature of hot side TEM | 0.902 |
| | Temperature of cold side TEM | 0.917 |
| Current to TE-D system * Amb_Temp | Water condensate | 0.871 |
| | Temperature of hot side TEM | 0.782 |
| | Temperature of cold side TEM | 0.924 |
| Current to TE-D * SR | Water condensate | 0.783 |
| | Temperature of hot side TEM | 0.654 |
| | Temperature of cold side TEM | 0.732 |
122.2 mL. To see the statistically significant difference in the water condensate production of PVTE-D system when operated at 3 A, 5 V and 4 A, 5 V, a paired sample t-test was conducted. There was a statistically significant increase in water condensate production from $M = 1,089.97$ mL, $SD = 109.47$ mL, operated at 3 A, 5 V to $M = 1,159.7$ mL, $SD = 122.2$ mL, operated at 4 A, 5 V.

The PVTE-D system’s water condensation behavior is improved by increasing the input power. The hourly variation of the different environmental conditions and water condensate production of the PVTE-D system when operated at 5 A and 5 V is shown in Figure 3. The experiment was conducted from 13 April 2019 until 16 April 2019. The maximum water condensate collected from the PVTE-D system was 1,579.4 mL/h, while the minimum condensation collected was 1,123.6 mL/h and the standard deviation was 134.8 mL. To see the statistically significant difference in the water condensate production of PVTE-D system when operated at 4 A, 5 V and 5 A, 5 V, a paired samples t-test was conducted. There was a statistically significant increase in water condensate production from $M = 1,159.7$ mL, $SD = 122.2$ mL, operated at 4 A, 5 V to $M = 1,298.6$ mL, $SD = 134.8$ mL, operated at 5 A, 5 V.

Input power to PVTE-D system was further increased to 6 A and 5 V and results obtained are presented in Figure 4. The experiment was performed from 13 May 2019 until 16 May 2019. The maximum water condensate collected from the PVTE-D system was 1,852.2 mL/h, while the minimum condensation collected was 1,278.6 mL/h and the standard deviation was 184.3 mL. To see the statistically significant difference in the water condensate production of PVTE-D system when operated at 5 A, 5 V and 6 A, 5 V, a paired samples t-test was conducted. There was a statistically significant increase in water condensate production from $M = 1,298.6$ mL, $SD = 134.8$ mL, operated at 5 A, 5 V to $M = 1,522.3$ mL, $SD = 184.3$ mL, operated at 6 A, 5 V. This was a maximum water condensate production and further increment of power deteriorate water condensation capacity of the system.

This improvement in the potential for convection cooling and absorption of TEMs mounted within the PVTE-D system improves the output of water condensate. This shift in behavior is attributed to the TEM configuration, which has several pairs of bismuth telluride sandwiched between ceramic layers. Each pair is made up of N-type and P-type materials that simultaneously produce a pair of electron having different densities. These pairs are thermally and electrically linked to one another. The P-type pair has insufficient electrons while the N-type pair has surplus electrons pairs. A new equilibrium was formed within the materials as DC started moving up and down through the module. The input DC current starts to consider the N-type as the cold side that wants to be hot while considering the P-type as the hot side that wants to be cool. As the material is at a comparable temperature, the warm side ends up hotter while the cold side ends up colder. The hotness and coldness of the pair are calculated by input current position and a shift in polarity would result in change of TEMs’ cold and hot sides. Additionally, during the conditioning progression, water droplets were observed on the heat sinks connected to the TEMs cold side. The development of liquid droplets as seen in Figure 4, revealed that the humidity ratio in the air was...
decreased after going through the PVTE-D system cold junction. In addition, Figures 1–4 also indicate the difference in the output of water condensate of the PVTE-D system at different input power supply and weather conditions. The inlet air moves through heat sinks attached at the cold side of TEMs, lower than its dew point temperature, throughout the activity of the PVTE-D system. At this time, the temperature of the dry bulb drops, and its relative humidity grows. The air becomes further saturated owing to more cooling at the cold junction. Eventually, when extracting the moisture by the condensation process, the humidity ratio in the air reduces. Thus, at higher input power, more water condensate was produced.

Furthermore, PVTE-D system performance operated in different months was presented in Figure 5. One day having similar weather condition were chosen from each month i.e. March 2019 to June 2019. It was observed that having higher relative humidity percentage in the month of May as compared to the other months, there was a higher water condensation accumulation.

Furthermore, it was found that water condensate production was also dependent upon the airflow rate. As shown in Figure 6, different optimum water condensates were obtained at different incremental power operation to the PVTE-D system. The optimum water condensate was obtained at 0.012 kg/s for the power supply of 3 A to the PVTE-D system. Optimum water condensate production was attained at 0.011 kg/s when current supply to the PVTE-D system was increased by 1 A. Furthermore, rise of input current to 5 A shifts the optimum airflow rate to 0.010 kg/s for the highest condensation of water. Through evaluating Equation (54), which also indicated airflow and water output relationship; experimental behavior of the PVTE-D system can be further justified. The maximum water condensate output was achieved when the PVTE-D system was operated at 6 A and 5 V. The airflow rate was regulated from 0.003 kg/s to 0.016, and optimum water production was achieved at 0.011 kg/s.

There are two explanations for the difference in optimum water production at varying airflow speeds. Next, the amount of heat absorption and dissipation from both sides of the thermoelectric module is determined by the airflow velocity. Higher and lower airflow rates were unable to retain and disperse heat significantly from the surface of thermoelectric module until it is expelled from the duct system. Accumulation of heat thus decreases output of water condensation. The close interaction of air with the thermoelectric module ceramic surface triggers the development of ice. This happen because of lower average temperature of the thermoelectric module on the cold side, resulting in airborne dew crystal deposition at the TEM surface. This deposition causes a rise in the thermal resistance of the system and blockage of airflow passage.

Furthermore, Figure 7 indicates a difference in the output of the water condensate with energy usage at various input current supplies to the PVTE-D system. It was observed that energy usage and water condensate output increased with the rise in the supply of input power to the PVTE-D system. When the PVTE-D system was operated at 6 A and 5 V with an energy intake varying from 158 kWh/month, the maximum daily water output of 34.7 kg was achieved. A further rise in input capacity allows electricity demand to increase, with a dramatic reduction in the supply of water.
Validation

The numerical result obtained by using TRNSYS simulation software and numerical equations based on Methods were validated by using experimental data. The detail modelling part using TRNSYS was presented in a previous work. As discussed previously, the temperature of both sides of TEMs are important parameters for water condensate production, that is why temperature variations of both sides of TEMs were used for validation using three statistical indicators i.e. mean deviation (MD), percent coefficient of variation of the root mean square error (CVRMSE) and percent root mean square deviation error (RE). As per ASHRAE standard, these three metrics are supposed to be correctly and fairly reliable in validating the simulation performance and can be calculated by using:

\[ MD = \frac{\sum_{i=1}^{k} (M_i - S_i)}{\sum_{i=1}^{k} M_i} \]  

\[ CVRMSE = \sqrt{\frac{\sum_{i=1}^{k} (M_i - S_i)^2}{k}} \]  

\[ RE = \sqrt{\sum_{i=1}^{k} \left[ \frac{100 \times (M_i - S_i)}{M_i} \right]^2} \]

where, \( M_i \) and \( S_i \) are measured and simulated data, \( k \) indicates the number of observations, ‘i’ indicates different data points, and \( M \) represents the average of the measured data.

Figure 8 shows the four-day temperature variation of the experimental and simulation cold side temperature data of the PVTE-D system operated at the input power supply of 6 A and 5 V. These data were further analyzed using three statistical indicators and the results obtained are presented in Table 2. The percentage of statistical errors in the simulation and experimental cold side data of the PVTE-D system shows a low value, i.e. the MD percent is 0.6, the RMSE percent is 4.2 and the RE percent is 5.8. Thus, compared to experimental data, the numerical data obtained varied statistically significantly.

Figure 9 shows the four-day temperature variation of the experimental and simulation hot side temperature data of the PVTE-D system operated at the input power supply of 6 A and 5 V. These data were further analyzed using three statistical indicators and the results obtained are presented in Table 2. The percentage of statistical errors in the simulation and experimental hot side data of the PVTE-D system shows a low value, i.e. the MD percent is 0.5, the RMSE percent is 5.3 and the RE percent is 5.1. Thus, compared to experimental data, the numerical data obtained varied statistically significantly.
CONCLUSIONS

This paper discussed the possibility of utilizing a thermoelectric module for extracting water condensate from ambient air in the dehumidification phase and to provide pure, clean and sustainable freshwater. In addition, operational the feasibility of the TE-D system with the PV system was analyzed for developing a renewable dehumidification system. The following observations were made:

Figure 8 | Experimental and simulation data variation of cold side of PVTE-D system.

Table 2 | Comparison of the statistical indicators

|                      | Cold side temperature of PVTE-D | Hot side temperature of PVTE-D |
|----------------------|---------------------------------|-------------------------------|
| MD%                  | 0.6                             | 0.5                           |
| RMSE %               | 4.2                             | 5.3                           |
| RE                   | 5.8                             | 5.1                           |

Figure 9 | Experimental and simulation data variation of the hot side of the PVTE-D system.
Simulation modelling has been performed by using TRNSYS software and successfully implemented for the PVTE-D system. Results obtained were validated using experimental data with RMSE% of 4.2 for the cold side and 5.3 for the hot side of the PVTE-D system.

The PV wall system was effectively integrated with the TE-D system for long-term operation. This combination reduces the indoors temperature, relative humidity and increases the production of water condensate.

For the climatic conditions of Perak, Malaysia, the highest water condensate was generated in the month of May among the other testing months from March to June.

The optimum performance of the PVTE-D system was achieved when the PV wall system supplied 6 A and 5 V input power to the TE-D system.

Air flow rate influenced the water condensate production and optimum air flow rate was 0.011 kg/s. Further increases in the rate of airflow rate decreased the production of condensed water molecules due to an imbalance between heat dissipation and absorption.

In future, the work may extend with real life data availability experiments and increasing the technology applicability for better performance.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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