Experimental study of atmospheric water collection powered by solar energy using the Peltier effect

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Abstract. A small-scale prototype with one thermoelectric module was constructed to collect water from the atmosphere, and studied experimentally. It was driven by a solar panel module and operated by reducing the cold side temperature to less than the dew point temperature of ambient air. The system was designed and assembled depending on the capacity of the Peltier device, of dimension (4×4 cm²), and energy needed. The system consisted of a heat sink, extended cold surface, Peltier device and fan, which were housed in a vertical rectangular section duct and used with different air temperatures, airflow rates, and humidity levels. A numerical model was used to study the temperature distribution on the cold side, which was applied to size the cooler to estimate the water production rate. The results suggest that the water production rate increased with the increasing of the moisture level in the air. The tests also showed that increasing the amount of air flowing on the heat sink increased the amount of water collected and enhanced the transfer of heat on the hot side. The achieved results show that the collection of water is reasonable with the proposed thermoelectric method using solar energy.

Keywords: Peltier effect, solar energy, water production

1. Introduction
A lot of water is wasted in the air in the forms of vapor or moisture. This water can be retrieved by condensing it into drops of water using special devices designed and manufactured for this purpose. One of the most important methods in condensation is the Peltier effect [1, 2]. A Peltier module simply consists of two layers of ceramic, representing the cold and the hot sides, along with two different types of semiconductor, connected in series. When the DC electrical source is connected to the device, the temperature of one side starts to increase while the other side becomes cold [3, 4]. When the cold side temperature reaches the dew point, the vapor in contact with cold surface begins to condense [5, 6].

Nandy et al. [7] designed a system to collect water from the atmosphere using a thermoelectric cooler and depending on solar panels as an energy source. They proposed that use of this device in regions of high humidity would allow users to collect one liter of water per hour during the day. An experimental investigation to develop a portable thermoelectric water generator was carried out in [8] and the results showed that the quantity of condensed water is influenced by the humidity level, the amount of electric current passing through the Peltier modules and mass flow of wet air.

Water condensation systems in which the solar panel is used as an energy source have a significant economic benefit, because the power source is free and the need for maintenance is virtually nonexistent [9, 10]. Another model has been tested under climate conditions in Thailand, research results have shown that the prototype can save two persons lives during water crises by producing one liter of water per day under specific conditions [11]. Haujun and Chengying [12] studied the effect of various energy sources on the performance of the thermoelectric cooler and its variation with time. Bagheri [13] has experimentally studied a commercial water collection system using a new
experimental setup and his results showed that the energy intensity ranged from 1.02 kWhr/L for warm and humid to 6.23 kWhr/L for cold and humid climates.

Srivastava and Yadav [14] used various composite materials to produce water from atmospheric air, the maximum amount of water they could collect was 90 mL/day. Shourideh et al. [15] experimentally investigated the impact of the variation in airflow velocity, humidity, and thermoelectric cooler current on the water generation rates using a prototype of a small-scale atmospheric water generator, and concluded that increasing the current of the individual thermoelectric cooler results in an increased water generation rate. The water yield is observed to increase with relative humidity.

In this work, a portable water collector device using one thermoelectric model attached to two extension surfaces and driven by solar energy was built and experimentally tested, to estimate water production rates. The prototype was studied by analyzing the impact of thermoelectric model cooling capacity on temperature distribution of the cold side to achieve low temperature difference between the Peltier model’s cold side temperature and condensation surface temperatures. With the help of a developed numerical solution, the temperature range of the condensation surface was estimated to determine its dimensions and manufactured as a cone shape to easily collect condensation water. The effects of ambient temperature between 24 °C and 31 °C, relative humidity between 60% and 75%, energy consumption and flow rate of cooling air through the hot side on the amount of condensation have all been investigated.

2. Experimental setup and procedure
2.1. Experimental setup
The collection of water from atmospheric humid air with a Peltier module is based on the concept of condensation phenomena on the cold surface. The experimental condenser is represented schematically in Figure 1, and an actual picture that shows how the components of the system were located on the frame is given in Figure 2(a). The condensate drops of water on the wetted cone surface are shown in Figure 2b.

![Figure 1. Scheme representing the water collector.](image-url)
In this work, the experimental system consisted of a thermoelectric module, heat sink fin, cold side fin, fan, vertical housing duct, solar panel, storage battery bank, charge controller and metal structure made of tubes to hold all of these components. The specifications of the experimental components are detailed in Table 1. The components that formed the condenser (thermoelectric cooler, heat sink fin, cold side fin, and fan) were arranged in a polycarbonate PVC rectangular cross-section duct, safely enclosed in the device.

Table 1: Specification of the experimental components.

| Equipment        | specification                                      |
|------------------|----------------------------------------------------|
| Heat Sink        | Material : Aluminum - 6063T-5                      |
|                  | Dimension : 13 cm x 10 cm x 2.5 cm                 |
|                  | Surface Area : 1270 cm²                             |
| Cold Side        | Material : Aluminum                                 |
|                  | Dimension : 6 cm Diameter and 13 cm Height          |
|                  | Surface Area : 150 cm²                             |
|                  | Roughness : 300μm                                   |
| Peltier Module   | Max. Current : 5(A)                                |
|                  | Max. (∆T) : 65(C°)                                 |
|                  | Max. Voltage: 15(V)                                |
| Solar panel      | Max. Power : 80.54W                                 |
|                  | Max. Voltage : 17 (V)                              |
|                  | Max. Current : 4 (A)                               |
| Battery          | Max. Voltage : 12 (V)                              |
The duct was placed on a metal structure to protect the entire condenser and to hold other components. The housing duct holds one fan at the top which sucks the air out directly through the heat sink, installed on the hot side of the Peltier module. The duct was divided into two chambers: a cold one, where the cooler fixed, and the second was the hot space, where the heat sink and fan were assembled. The chambers were separated by the polycarbonate sheet with the Peltier module. The housing duct was 30 cm length and 10 cm × 10 cm cross-sectional area which was manufactured in a way that forced the air to pass through the heat sink before exiting into the surrounding fluid.

2.2. Experimental procedure
The system was tested in different working conditions, in a room prepared for this purpose where the temperature and humidity are controlled. The experiments were divided into groups of different fan airflow velocities that varied between 0.59 m/s and 1 m/s, relative humidity (RH) levels ranging from 60% to 80%, and different dry air temperatures that varied between 24 °C and 31 °C. The experiment covered more than thirty tests.

Different RH levels were controlled by the humidifier, then the humidified air made contact with the cooler side into the lower part of the housing duct. The upper part of the vertical duct involved a fan to decrease the temperature of the hot side by sucking air through fins of the heat sink, while the lower one contained the aluminum cone by placing it in contact with the cold side of the Peltier module.

As a current (DC) passes through Peltier device, heat transfers from one side to the other one, resulting in one side becomes warmer and the other side colder. Once the air which is in contact with the cooler becomes cold enough, the condensate droplets grow when the ambient air temperature falls below its dew point and these fall down into the water pan. In our study the collected water was measured every hour by measuring the volumetric of water quantity. The temperatures of the surrounding air and cone base (cold side) were measured by thermocouples and recorded by a data acquisition instrument. All thermocouples were calibrated over a temperature range between 0 °C and 100 °C with a maximum error of ±0.6 °C. Five measured flow rates were used in this work. Input power was measured throughout the experiments. Since the system needs some time to reach a steady state, the actual tests were performed after half an hour of operation. Most of the tests were carried out twice, to confirm stability and repeatability.

3. Results and discussion
3.1. The effect of air velocity
An axial fan was used to draw out air from the rectangular duct over the heat rejecting side with the stated mass flow rate. The amount of water generated during one hour of operation for the different velocities of the air flow with constant RH and surrounding fluid temperature (T<sub>amb</sub>) is shown in Figure 3. The model was tested in two values of ambient temperature, to determine the optimum velocity of air in the case whereby the maximum quantity of water is generated. In each test, the ambient conditions were controlled to be constant. This figure implies that the generated water increased as the air velocity increased. Also, there was a significant increase in water collection after using air velocity of 0.8 m/s and this reveals the impact of air velocity on water collection in both cases of different ambient temperatures with a relative humidity of 65%.

The model worked more efficiently with increased airflow, which improved the heat transfer coefficient. The amount of condensed water was 9.5 mL/hr at an air velocity of 1 m/s and as a result, this air velocity has been chosen to cover a good range of relative humidity and ambient temperature. Performance was better when the ambient temperature was high, especially for higher air velocity, due to the increment in air dew point temperature. As is shown in figure 4, the air flow rate has a great impact on cold side temperature. The rising of the fan flow rate led to a decrease in cold side temperature and as a result, a growing condensation
rate. With a decrease in contact time between the cooling air and a hot side surface, the temperature difference between the hot side and cold side, which are in contact with the Peltier device surfaces, will decrease. According to the outcomes shown in this figure, again the best air velocity with various dry air temperatures (24, 27 & 31 °C) will be 1(m/s).

![Figure 3.](image)
The effect of air velocity on water production (RH=65%).

![Figure 4.](image)
The temperature of the cold side with different fan air velocity for 65% RH and temperature between 24 and 31 °C.

3.2. The impact of relative humidity level

Figure 5 shows the amount of water that was collected at different RH. After around half an hour for most cases, gradually that quantity of water became constant. This behavior supports the notion that the condensate droplets were small at first, and that the gravitational effect cannot compensate for adhesion. Therefore, the droplets adhered on the cooler surface. A small thermoelectric cooler capacity and the property of the cooler surface were the most important reasons for the low efficiency of condensation. Naturally, on a cooler surface, in order to separate water droplets from the surface, their diameter should be between 2 and 3 mm although they have a negative impact on the condensation process. To promote droplets’ departure and improve the condensation process, the condensation surface properties require modification, such as the reduction of roughness to 250 μm [16]. Increased ambient air temperature is associated with an increase in relative humidity and as a result, the water generation rate will increase. About 20 mL/hr of fresh water can be produced from atmospheric air using this system with 75% RH. Because of higher relative humidity and temperature, more water is expected to be produced in a climate of high temperature and humidity [17].

The moisture content in the surrounding air is shown in Figure 6. When the ambient temperature is constant, the increase in relative humidity leads to an increase in the water vapor content in the air. In our study the water content in the air was determined by using the psychrometric chart. Increasing relative humidity also increases the dew point of the surrounding air. As a result of that, the difference in temperature between the dew point and the ambient air decreases with increasing relative humidity, as is shown in Figure 7. This decrease facilitated condensation. In summary, increased moisture content has an important role to play in increasing the condensation rate and volume of generated water, which agrees with the result shown in Figures 5 and 6.

A comparison between the present work and various studies was performed. The experimental
system in our study, with one cooler, achieved well with a low rate of RH and moderate energy consumption for all RH levels (65% to 75%). This is relevant because power consumption is the important condition for evaluating productivity. The comparison results are shown in Table 2.

![Figure 5](image1.png)  ![Figure 6](image2.png)

**Figure 5.** Variation of generated water with different RH levels. **Figure 6.** Ambient moisture content at different RH.

| Study         | Water generation rate (mL/hr) | Power consumption (W) | T<sub>am</sub>(°C) | RH (%) | Number of thermoelectric coolers |
|---------------|-------------------------------|-----------------------|---------------------|--------|---------------------------------|
| Present study | 8.1                           | 70                    | 31                  | 60     | One                             |
|               | 10.1                          | 70                    | 31                  | 65     |                                 |
|               | 16                            | 70                    | 31                  | 70     |                                 |
|               | 20                            | 70                    | 31                  | 75     |                                 |
| [15]          | 32                            | 60                    | 30                  | 60     | Four                            |
|               | 66                            | 61                    | 33                  | 80     |                                 |
| [18]          | 45                            | 100                   | 27                  | 80     | Two                             |
|               | 65                            | 100                   | 27                  | 90     |                                 |
|               | 74                            | 100                   | 32                  | 90     |                                 |
| [19]          | 20                            | 30                    | 80                  |        | Ten                             |
|               | 24                            | 30                    | 90                  |        |                                 |

3.3. **The impact of dry air temperature**

The vapor compression method is used to extract water from humid air by condensation. When the surface of the cold side has a temperature below the dew temperature, the steam condensation will occur on that part, and as a result, small droplets or a thin film of water will form and finally be gathered in a bowl of water. Throughout the condensation and cooling operation, a large amount of heat is dissipated by wet air down to the temperature of the dew point. The effect of ambient temperatures on the cooler base temperature as a function of time is depicted in Figure 8. It is clear that the time increases with increasing temperature of the surrounding air. The cone base temperature
gradually decreased and after 15 minutes it reaches the minimum value of 1 °C with 17.5 °C for ambient temperature, while for 24 °C was 2.6 °C after 37 minutes. This happened because the cone temperature decreased over time and the rising surrounding air temperature increased the time required to reach the coldest cooler surface.

Figure 7. Temperatures difference between dew point and ambient air at different RH %.

Figure 8. Temperature of cold side fin at different ambient temperatures.

The temperatures of the dew point were found using the psychrometric chart, as shown in Figure 9, for a range of dry air temperatures between 24°C and 31 °C and relative humidity of 65–75%. The increase in dew point temperature is due to the increase in relative humidity of the ambient air. As a result, the difference in temperatures between dry air and dew point decreases with increasing of relative humidity. As shown in this figure, the dew point of moist air increased (15.8°C to 19.3°C) for a dry air temperature of 24°C and increased (22.3°C to 26°C) for a dry air temperature of 24°C with the increasing of the relative humidity (60% to 75%).
The fabrication of the cold side (aluminum cone) was influenced by the selection of the Peltier module. A suitable surface was needed, to condensate the water from the surrounding fluid. Therefore, a numerical solution was performed using the finite volume method based commercial software ANSYS Fluent 16.2, in order to find the distribution of temperature on the surface of the cone. In general, the increase in the area of the cooling part resulting in an increasing amount of water generated. However, the increase in the length of the cold part increases in the temperature of the surface, which adversely affects the process of water generation. When the cooler elongates it will have a temperature higher than the dew point. Reducing the effective surface area reduces the amount of condensed water. This method was adopted as an alternative to using optimum fin dimensions or fin efficiency. Figure 10 gives the temperature map on the cooler surface with dry temperatures of 23 °C and RH of 65% conditions. A small drop in temperature between the cone base and its surface was found. The maximum difference of value below than 1 °C at most has been found where condensation can certainly occur on the total surface.

Generally, a small portable water collector would not be expected to consume much energy. And from the experimental results, the device’s total power requirement per liter of collected water in specified air conditions is shown in Figure 11. It accounts for a fan and Peltier energy consumption, of which a large proportion of energy is consumed by the fan. The changes in consumption of energy of the system are demonstrated in Figure 11, and proportional to a change in fan power (9 - 20 watt) with constant Peltier power of 50 watts. By referring to this figure, the results provided are the amount of energy and power required to collect one liter of water. The minimum power consumption in the system at a velocity of 0.6 m/s and the maximum required power with 1 m/s air flow rate. When solar energy is not available, the excess energy that has been stored in the battery will be used. The results shown above are for one air temperature and one relative humidity. During experimentation, the input power to the system increased as the airflow velocity increased. Hence, the rate of energy consumption only increases when the velocity increases.
4. Conclusion

An experimental study with one thermoelectric module powered by solar photovoltaic energy has been designed and tested. This system represents a portable device consisting of solar photovoltaic, Peltier module, cold side, heat sink, and fan assembled to maximize the capacity of condensed water from the humid air with minimal energy consumption.

The components were assembled in housing which enabled air to flow from the entrance through the heat sink to improve the dissipation of heat. The system was tested experimentally under different inlet air flow rates, dry air temperature, and RH. The following conclusions can be drawn:

- Increasing air temperature and relative humidity in a hot and humid climate, result in a higher water generation rate.
- With a small capacity for cooling, the low condensation efficiency was a result of adhesion of droplets on the cone surface and receding condensation surface.
- The presence of fins on both sides of the Peltier increased the rate of heat transfer and enhanced the water condensation rate.
- The rate of water generated was positively affected by increasing airflow velocity on the hot side in most cases, and the maximum generated water was 20 mL/hr with a maximum airflow velocity of 1 m/s.

In future work, the system should be developed and more thermoelectric modules used, to increase the contact surface between the cold side and humid air. Also, future experiments should test the system under different weather conditions for the course of a year.

5. References

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