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Sustainable Water Production: Utilizing Peltier Elements for Atmospheric Water Harvesting

Ajaz Rashid
Department of Chemical Engineering
University of Bahrain
Kingdom of Bahrain
arashid@uob.edu.bh

Muhammad Rizwan
Department of Chemical Engineering
University of Bahrain
Kingdom of Bahrain
mrizwan@uob.edu.bh

Ahmed Al-Samahiji
Department of Chemical Engineering
University of Bahrain
Kingdom of Bahrain
20164533@stu.uob.edu.bh

Fatema Salman
Department of Chemical Engineering
University of Bahrain
Kingdom of Bahrain
20178702@stu.uob.edu.bh

Mohamed Al-Hamaqi
Department of Chemical Engineering
University of Bahrain
Kingdom of Bahrain
20180873@stu.uob.edu.bh

***Abstract*— This study aims to investigate the viability of using Peltier elements as a sustainable solution to produce water from dehumidification of humid air over a cold surface. COMSOL-Multiphysics has been applied as a Computational Fluid Dynamics tool to simulate the physics of electric current, heat transfer in solids, laminar flow, and moisture transport in air. The effect of the weather conditions on the condensation process has been simulated by investigating the performance of the condensation at different two months, January for winter conditions and June for summer conditions. Additionally, the effect of the current change on the condensation process has been studied using four different currents 1, 2, 3, and 4 A. The simulation has been carried out for a period of 24 hours. For the weather effect, the condensation process is enhanced during the summer rather than during the winter conditions. For the current effect, as the current increases, the relative humidity decreases due to the increase in the air temperature, which depends mainly on the current value through the joule heating effect. The optimum current was found to be 4 Amperes, and it produced 7.98 L of condensed water.**

Keywords—Peltier elements, desalination, dehumidification, sustainable water production

I. Introduction

Freshwater is becoming increasingly limited as a result of high consumption beyond the natural replenishment capability, the continuing deterioration of both groundwater and surface water quality [1]. The global climate change is also having an impact on the availability of freshwater. Water availability is also becoming an issue in parts of the world that had not previously been in such dire need of water solutions [2]. Hence, the dependency on desalination for freshwater is on the increase. Desalination processes, are, in general, energy intensive. For instance, it is estimated that Saudi Arabia uses 50% of its oil for desalination, while Kuwait uses 70% of its fossil-fuel generated electricity for desalination [3]. It is therefore, a necessity to look for alternative renewable energy sources and sustainable techniques for desalination [4].

Of the available water resources, the most unexploited one is the water vapor present in the air. Water-from-air technologies currently are more energy-demanding than the traditional seawater desalination technologies [5]. Of the various technologies used for dehumidification of air to condense water, the thermoelectric modules stand out. This is because they don't have any moving parts and hence have a much longer life [6]. The Peltier principle states that when a direct current is introduced to a thermoelectric module, a temperature gradient is produced between the hot and cold facets of the module. In thermal distillation systems, Peltier modules are utilized to produce freshwater by utilizing the cold side of the module to enhance water condensation [7].

In this study, the effect of using Peltier element to produce water from humid air in the Kingdom of Bahrain conditions is investigated. Numerical studies were conducted using the COMSOL Multiphysics software.

II. System Description

A. System Schematics

The system in consideration is merely a space filled with humid air in which a Peltier element is located. A schematic of the system is shown in Fig. 1.

The Seebeck effect is when a voltage difference is created between a thermocouple as a result of a temperature difference between the ends of the thermocouple junctions. The Peltier effect is the opposite. It occurs when a temperature difference is created between the junctions of two dissimilar metal wires by applying a voltage difference across the terminals. As Direct Current (DC) passes through the Peltier element, it causes one surface to be at a lower temperature than the other, As the water vapor in the humid air comes into contact with the cold surface, it begins to condense and this condensed water can help reduce the water shortage faced by many areas in the world.

B. Material Selection

The material was chosen based on several factors. The most important of these factors was temperature resistance. Another reason that was very important for producing potable water was using a non-toxic material. So, alumina ceramic was chosen for these and other reasons, such as its resistance to abrasion and good conductivity. Because of its properties such as high electrical insulation, mechanical strength, corrosion and wear resistance, and the ability to be recycled, alumina is the most commonly used fine ceramic material. As its price is way cheaper comparable to the other materials such as copper. Moreover, Peltier elements are mostly used and structured as two ceramic layers with N-type and P-type semiconductors sandwiched between the ceramic layers. Bismuth telluride and lead telluride were used as materials in semiconductors due to its efficiency, and because it can resist any moderate to high temperatures [8].

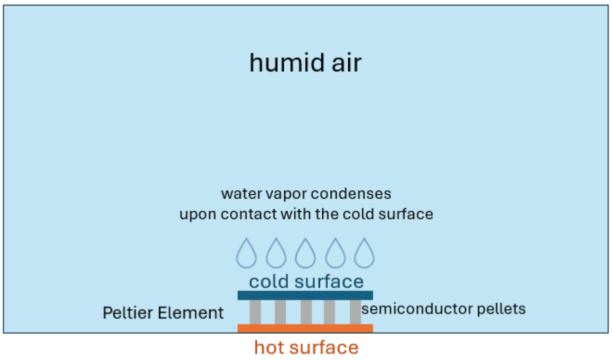

Fig. 1. Schematic diagram of the Pelteir Element condensation process

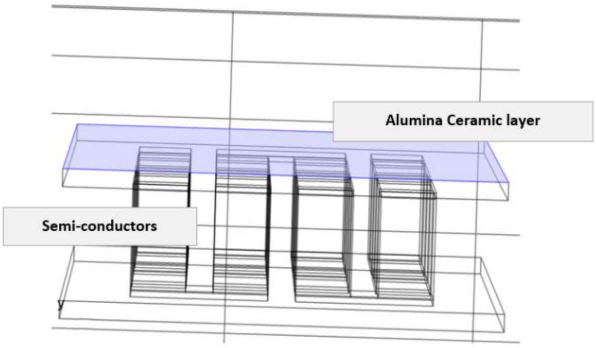

Fig. 2. Three-dimensional model of the Peltier Element used for modelling and simulation

The design was also considered using tungsten material, which is very good in terms of temperature resistivity, hardness, and strength. However, it may have an effect on human health when it's alloyed with other materials. In the case of producing potable water, a non-toxic material is required, hence alumina ceramic was the preferred choice.

C. System Modeling and Simulation

The system was modelled and simulated using the COMSOL Multiphysics software. The Peltier model was made up of two layers of ceramic and it consisted of 99.9% of alumina, with an array consisting of P-type and N-type semiconductors sandwiched between them. This can be seen in Fig. 2. Bismuth telluride and lead telluride were used as materials in semiconductors due to their efficiency and resistance to moderate and high temperatures.

The humid air around the Peltier element was simulated using a 3D block geometry, which had an inlet on one side and outlet on the other side. This was done to allow air to flow across the Peltier element. Secondly, a shared property was used to do an implementation based on Bahrain weather. This was done to use the ambient properties, such as ambient temperature and humidity, based on Bahrain's weather. This was followed by heat transfer module in the model to study the temperature distribution in the Peltier element. Then laminar flow was added as well in the model to get the velocity profile. It consists of gravity force and the inlet and outlet boundaries. Then, in order to determine the moisture and liquid content that occurred in the model, a moisture transfer in air feature was added, which included the moisture air, inlet and outlet boundaries, and the moist surface on which the condensation occurred. The final geometry of the Peltier element in the humid air environment is shown in Fig. 3. Steady-state simulations were used in the study. The surface of the Peltier element was discretized using fine mesh elements, while the humid air region was discretized by a much coarser mesh.

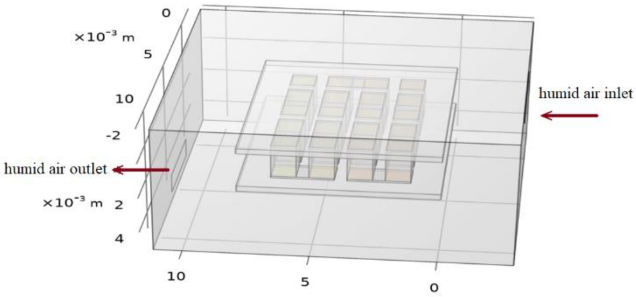

Fig. 3. Three-dimensional model of the humid air environemtn with the Peltier Element

III. Results and Discussion

This section will present and discuss the results of the designed simulation of generating potable water from condensation of humid air using a Peltier element. It will start with a discussion of the base condition, which was set using shared properties and was done in the summer, specifically in June, with a current of 2 amperes. This will be followed by studies done by varying different parameters. The results of the base condition, including humidity, heat flux, and water content will also be discussed. Finally, a comparison between the parameter variations with respect to the base case will be presented.

A. Base Case Simulation

The base case condition was carried out for the summer, specifically in the month of June, with a current of 2 amperes. For this case the temperature difference will be discussed which was found relying on a current as a factor. The variation of the relative humidity at inlet and outlet with time will also be presented. Additionally, the moisture content collected at the cold surface will be presented.

A temperature difference was established by referring to the current in a stationary study. It was found to be 45.8 ºC on the hot surface and 35.3 ºC on the cold side. The relative humidity is a ratio expressed in percent, of the amount of atmospheric moisture present relative to the amount that would be present if the air were saturated. Relative humidity is a function of both moisture content and temperature. It is derived from the associated temperature and dew point for the indicated conditions. The main factors that the humidity rely on are firstly, the location, which was done for Bahrain, and specifically in the month of June. The ambient conditions which are ambient temperature, dew point, wind speed, and precipitation rate were taken as average values rather than a specific year. The second factor is the cold surface temperature. When the cold surface temperature is below the dew point, condensation will occur. Fig. 4 represents the relative humidity. Humid air is fed continuously into the geometry. As a result, it was fed at time zero with a value of 0.53888 and then left with a value of 0.32195, indicating a fall in humidity from the inlet to the outlet. This is expected as humidity decreases due to condensation occurring. After a

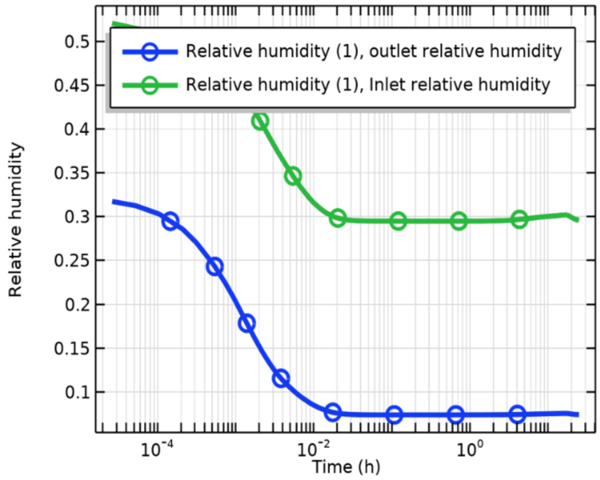

Fig. 4. Variation of relative humidity with time at the inlet and outlet

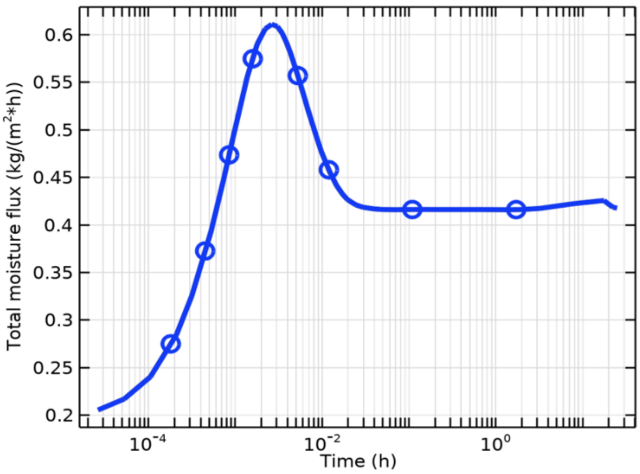

Fig. 5. Variation of moisture flux at the cold surface with time

short period of time, both inlet and outlet reached to steady state. After 24 hours, the inlet will reach a value of 0.29623 and the outlet will reach a value of 0.073995, as is seen in Fig. 4.

A moisture flux exists depending on specific parameters such as ambient conditions of Bahrain weather and the temperature of the cold surface. As shown in Fig. 5, the moisture flux rises suddenly, then with time reaches a sort of steady state. The reason for this decrease and subsequent steady state is due to the change of water content in the air due to condensation. As the condensation happens, the relative humidity decreases and will result in a reduce moisture flux at the cold surface. The moisture flux initially was at a rate of 0.19398 kg/ m^2/h, and it peaked up to 0.61211 kg/m^2/h. Eventually, it steadily decreased and reached a near-steady rate value of 0.41767 kg/m^2/h after a period of just over one hour.

Water content is the amount of water accumulated after condensation. The water content accumulated over the cold surface is shown as a function of time in Fig. 6. The content of water increased until it reached 3.08 L in a period of around 25 hours. This shows a promising result from an element with a surface area of just 80 mm^2. A study in tropical conditions shows that Peltier elements could be used to produce from 2

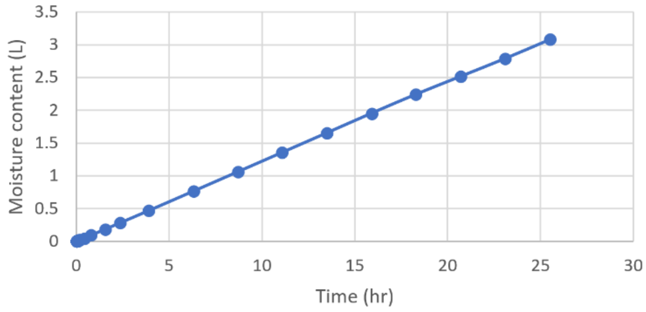

Fig. 6. Water conent accumulation on the cold surface with time

to 3 kg/h using seven Peltier elements [9]. This is around 3 times higher than the results obtained in the current study. However, these results depend on the climatic conditions and the Peltier elements used. Another study showed a water production amount of 7.148 L accumulated in a one month period by operating the Peltier element intermittently with a current of 3 Amperes [10]. Hence, the production amount appears to be less than that found in the current study.

B. Effect of Climatic Variation

The simulation was also done for the winter season. The month of January was chosen because it is the coldest month in Bahrain. The humid air entered the system at a value of 0.67236 at time zero, which is the midnight time. It then decreased with time as the day proceeds, which is very much expected. As a result, the humidity of the outlet air was found to be 0.48460 at time zero and ended with a value of 0.047464 after 24 hours. A comparison was done to compare the results with the summer time. This can be seen in Fig. 7.

The humidity is higher in the winter time and hence we can see difference in the inlet conditions. The change in the relative humidity for the winder conditions was noted to be smaller than that of the summer conditions, showing that more condensation happened in the summer time. This depends on the degree of superheat of the humidity and how far below the dew point the temperature of the cold surface can be maintained. A comparison was also made for the moisture flux for the two months. A similar behaviour was observed for January as June as seen in Fig. 8. The steady state moisture flux in summer was found to be higher than that in the winter.

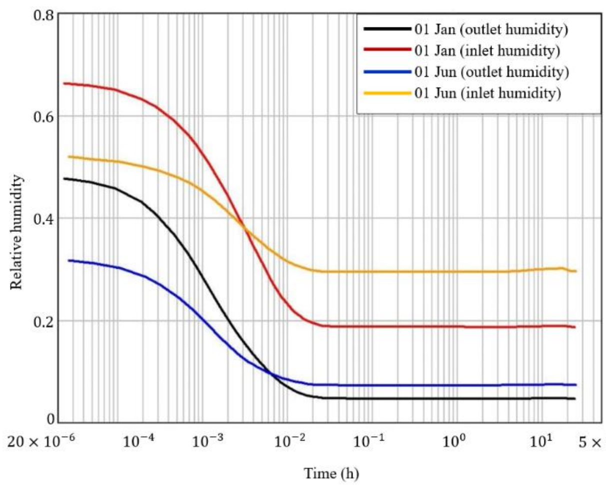

Fig. 7. Comparison of relative humidity at inlet and outlet in the summer and winter time

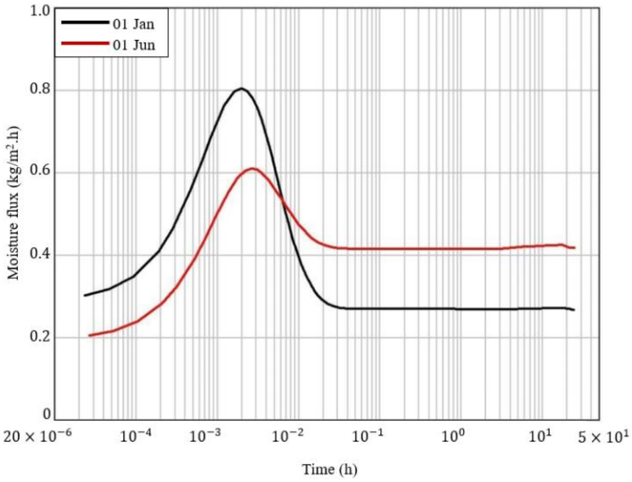

Fig. 8. Comparison of moisture flux in the summer and winter time

The accumulated water content in the winter time, specifically in the month of January, was found to be 2.89 L. This is almost 6% less than the winter time. A study for extracting water from humid air was done in Sharjah [11]. This study shows that more water could be extracted in the month of February. However, the device they used was based on a separate process. The proposed system works on achieving the cold surface temperature below the dew point for moisture extraction. Hence, we observed the opposite.

C. Changes in Current

The current ranges were differed in the simulation software in order to determine the optimum conditions in terms of heat flux, humidity as well as moisture content, and to see how the change of current can be affected the temperature difference between the hot and cold surfaces. The current was changed from 1 Ampere to 4 Amperes with steps of 1 Ampere. The ambient conditions were same as the base case. The temperature gradient was found to increase with the increase in current. The moisture flux was also higher for the higher current as can be seen in Fig. 9. This is very much predictable because higher current means a higher power supply which will result in a higher temperature gradient between the hot and cold surfaces. Table 1 shows the results for the different current settings.

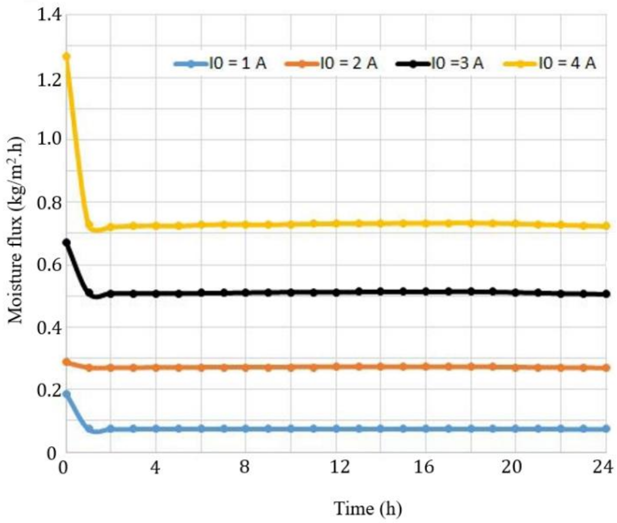

Fig. 9. Comparison of moisture flux at different current settings

TABLE I. RESULTS AT DIFFERENT CURRENT SETTINGS

Current (A)	Relative Humidity at outlet	Steady State Moisture Flux ($kg/m^2.h$)	Temperature Gradient (°C)	Net Water Accumulated in 24 hours (L)
1.0	0.26489	0.073509	5.2	0.82
2.0	0.25387	0.268160	10.5	2.96
3.0	0.23293	0.505490	18.9	5.58
4.0	0.19829	0.732500	26.3	7.98

It can be seen that the maximum production was 8 L approximately in a period of 24 hours. This seems less than the amount reported by Gupta et al. [12]. They have reported a production rate of 1 L/h at optimum conditions. However, they have also added a fan in their system to enhance the convection effects. This could explain their higher production rates.

IV. CONCLUSION

In the present study, the effect of using a Peltier element to generate a cold surface for condensing water from humid air was studied. The temperature gradient, moisture flux and net water accumulation was investigated. Two months, January and June, representing the Winter and Summer climatic conditions for the Kingdom of Bahrain, respectively, were studied. Additionally, the impact of changing the current from 1 A to 4 A was also studied. The main results are presented in the following:

- The net amount of water accumulated in a 24-hour period was 3.08 L for summer and 2.89 L for the winter conditions.
- The water production amount increased with the increase in the current. The maximum amount of water collected in a 24-hour period was 7.89 L with a current of 4 A.
- Moisture flux increased as the temperature gradient between the hot and cold surface increased.

Hence, it can be concluded that the Peltier elements can be used in real life to produce water because the results were plausible.

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