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Development of Hybrid Source Thermal Desalination System using Thermoelectric Module as a Powerful Heat Pump

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ABSTRACT

Due to the natural calamities and pandemics, the need for a decentralized freshwater system is the need for a better future. Solar still is the only decentralized thermal desalination system whose efficiency depends on various parameters like solar insolation, thermal insulation, water depth from the glass covers etc. Thermoelectric modules are employed to increase the efficiency of solar still. The proposed study presents a disruptive approach of using the thermoelectric module to develop a new decentralized desalination system for a freshwater generation. In the proposed research, the thermoelectric module is used as a powerful heat pump by ensuring a very low-temperature difference between the hot surface and the cold surface of the thermoelectric module. The latent heat released after condensation is utilized in a closed-loop operation to enhance the system's efficiency. The efficiency of the proposed method is 288% and 167% when operating the thermoelectric module at the mid-current region and maximum current region of the cooling curve of the thermoelectric module. A MATLAB simulation is conducted to evaluate the system by considering valid assumptions, further a prototype of the system is fabricated, experiments are in progress.

Keywords: thermal desalination, latent heat, thermoelectric, energy conversion, coefficient of performance (COP), efficiency

NONMENCLATURE

Abbreviations	
COP	Coefficient of Performance
TEM	Thermoelectric Module
Symbols	
Q_{cmax}	Maximum cooling capacity of the TEM (W)
ΔT_{max}	Maximum temperature difference the hot surface and cold surface of TEM
I_{max}	Maximum operating current of TEM (A)
V_{max}	Maximum operating voltage of TEM (V)
n	Number of couples of TEM
A	Cross section area of Thermoelectric pellet (mm^2)
l	Length of thermoelectric pellet (mm)
Z	Figure of merit
ρ	Resistivity (Ωm)
k	Thermal conductivity (W/mK)
Γ	Thomson coefficient (nV/K)
Π	Peltier coefficient (V)
h_{fg}	Latent heat vaporization (kJ/kg)
d	Density of water (kg/m^3)
η	efficiency
$\dot{m}$	Distilled water production rate (kg/hr)

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1. INTRODUCTION

The Earth's hydrological cycle gives the world water balance by showing the occurrence, distribution, and circulation of water on the Earth's surface and atmosphere. The world water balance is 1386 million cubic kilometers, out of which 96.5% are oceanic saline water, 1% land saline water, and the rest is fresh water[1]. However, only 10.6 million cubic kilometers of freshwater are accessible as the rest is in the frozen state. A decentralized desalination system based on renewable energy is required to convert saline water into freshwater. Membrane desalination is well established decentralized system for in-home use [2].

With a conventional solar still, only 1-3 liter of distilled water per day per square meter can be produced depending on the weather condition and topography. The source of energy for these solar still is only solar thermal energy. Ravindran and Dean [3] used the thermoelectric module to cool the inner glass surface of the solar still purposes. The primary analysis found that the thermoelectric assisted solar still produces 1200 ml distilled output and conventional still got 700ml. Dehghan et al. [4] had carried out the modeling of thermoelectric-based modified single basin solar still. The thermoelectric-assisted solar still daily production was around 2.4 (L/m2 /day), of which 1.8 (L/ m2 /day) was produced on the thermoelectric surface and the rest on the glass cover. Saeed Nazari [5] used four thermoelectric modules for cooling purposes and copper oxide nanofluids to increase the evaporative coefficient in single basin solar still. They concluded 5.8 liters of distilled water per square meter per day. Parsa et al. [6] used two thermoelectric modules, one for varying the silver nanofluid employed to increase the evaporative coefficient and the other as an external condenser in solar still. They obtained 7.76 liters of freshwater per square meter per day. Shahin et al. [7] investigated the conventional double slope solar and modified one, including thermoelectric modules' simultaneous heating and cooling. Through the experiment, they obtained 330ml of freshwater per meter square per hour.

1.1 Motivation

The thermoelectric module has the capacity to achieve heating and cooling simultaneously. Several authors tried thermoelectric modules to increase the production rate and amount of fresh water in solar still. A thermoelectric module was employed to elevate the temperature difference between evaporating and compensating zones in the solar still. The authors have identified the gap in using the thermoelectric module for the thermal desalination system from the critical review. Moreover, the utilization of latent heat of energy is also one of the voids in the thermal desalination system. The present study reveals a disruptive idea of using the Peltier module as a powerful heat pump in the present thermal desalination system. Operation and placement of Peltier module are planned in a manner it improves the coefficient of performance of Peltier module working as a heat pump, and also, latent heat of energy is being utilized in the system in a novel manner.

2. PRESENT WORK STRUCTURE

2.1 Thermoelectric module

The thermoelectric module is a device that acts as a generator and heat pump depending on the employment of the thermoelectric module into the system for the application. When the hot source is applied on one surface, the cold source is applied on another surface of the thermoelectric module, and the load is connected to its terminal end; it acts as a generator. When a voltage source is applied to the thermoelectric module terminal, one surface becomes cold and another surface becomes hot depending on the direction of current flow; then, it acts as a heat pump, represented in fig. 1.

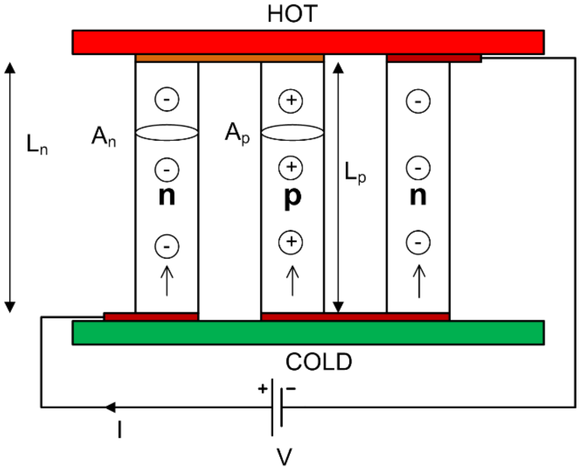

Fig. 1. Schematic of Thermoelectric module

When electrons move from semiconductor leg doped with pentavalent element (n-type) to semiconductor leg dopped with trivalent element (p-type) connected through the metallic junction (copper); then, they crossover to higher energy state and absorb energy from the surroundings making that surface cold shown by green stripe in the Fig 1. When electrons move from the p-type leg to the n-type leg through the metallic junction, they move to a lower energy state and release energy to the environment, making the surface hot, as shown by the red stripe in fig. 1. Both p-type and n-type pellets arranged in pairs are known as couples. On a system level, five physical phenomena are the Seebeck effect, Peltier effect, Thomson effect, Joules' heating, and Thermal conduction happening in the thermoelectric module simultaneously.

2.2 System Block diagram and Energy Conversion

The proposed hybrid thermal desalination unit using the Peltier effect is a complex process involving the energy conversion between various domains, as shown in fig. 2.

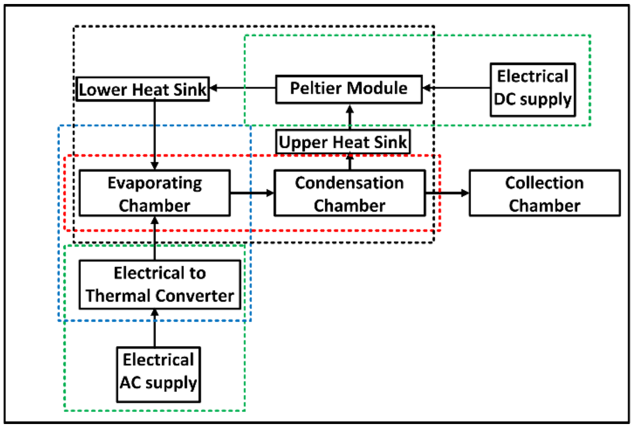

Fig. 2. Block diagram of the System

The Peltier module is the main component of the system. This system is similar to a hydrological cycle where evaporation and condensation happen in the system, and the source of energy is the Sun. Here, the Peltier module is the source of energy for both condensation and evaporation within the system. Electrical heating is incorporated in the system to analyze the effect of sample water temperature, which will affect the evaporation and condensation within the system.

Electrical energy is converted into thermal energy by heating element and the Peltier module, as shown in Fig. 2 with green dash line. The thermal energy produced by heating element is transferred to sample water in the evaporating chamber, which will increase the enthalpy of the sample water. Water starts boiling when the vapor pressures of water molecules become equal to or greater than the external pressure outside the water molecules. Thus, energy conversion occurs between the thermal and hydraulic domains in the evaporating chamber, indicated by the blue dash line in Fig. 2. Water vapor gets condensed in the condensation chamber after releasing the latent heat of energy. Therefore, hydraulic energy conversion into thermal takes place in the condensation chamber, indicated with red dash line in Fig. 2. The freshwater, after condensation, gets collected outside the chamber. Water vapor molecules release the latent heat of energy, and after condensation, the same energy is again fed back into the system by the Peltier module. A potential is applied across the Peltier module to convert electrical domain energy into thermal domain energy, as shown in Fig. 2 by the green dashed line. The Peltier module acts as a powerful heat pump as the temperature difference between the hot surface and the cold surface is very low. Thus, the evaporating chamber, the condensation chamber, the Peltier module, and the heat sink make a closed-loop system for the latent heat of energy flow. The Peltier module acts as a heat pump and a controller for operating the latent heat of energy in a closed-loop manner.

2.3 Assumption and simulation parameters

For the present simulation study, the following assumptions are considered:

- A steady-state condition is assumed.
- Heat capacity of thermoelectric surface, evaporating surface, and condensing surface are negligible.
- No leakage of vapor and heat to the outside surroundings
- Sampled water is maintained at a constant level.
- The properties of sampled water is considered similar to the distilled water.
- Uniform temperature distribution on the hot side and cold side heat sink of the Peltier module.
- Thermoelectric coefficients α, Π, Γ, are temperature independent.

For thermal desalination of water, two kinds of heat processes are required to complete the distillation process: sensible heat and latent heat. Sensible heat is needed to raise the temperature of the sample water to the saturated liquid state where the inner water bubble pressure equals the external water bubble pressure. Latent heat is required to complete the boiling process at constant temperature finally. To get the distilled water, the vapor produced after the boiling process needs to be condensed. Therefore, for simulation total energy required to convert the sample water at room temperature into vapor is calculated based on the topographical condition of Bangalore, Karnataka, India which is given in Table2. The condensation process is supported using the thermoelectric modelling which can be calculated by the cooling capacity of the thermoelectric module. The latent heat extracted by the thermoelectric module again aids the total energy required for the boiling process. By applying the heat transfer concept and energy conservation concept, one can quickly obtain the necessary equation for energy transfer within the system[8].

The manufacture does not provide the thermoelectric pellet's material properties and geometric configuration in the thermoelectric module datasheet. Parameters provided by the manufacturer to specify their products are ΔT_{max}, which is the maximum temperature difference that can be created between the cold ceramic surface and hot ceramic surface when hot side temperature is defined, I_{max} and V_{max}, which are the maximum input dc current applied and the maximum input dc voltage applied to get maximum temperature difference across both ceramic surfaces, and Q_{cmax}, which the maximum cooling power of the thermoelectric module at the maximum input dc current and maximum input dc voltage when the temperature difference between the ceramic plates are zero. Therefore, there is a need to evaluate the effective material properties of thermoelectric pellets by using the rating of the thermoelectric module provided in the datasheet. By applying the energy balance concept at a steady state, one can obtain the required equation to solve the cooling capacity and COP of the TEM[9]. For simulation purposes, the energy conversion process is considered instantaneous so that it will not affect the dynamics of the thermal system. Following are the simulation parameters shown in Table 1 considered for the thermoelectric module HiTemp ETX Series ETX15-28-F2-5252-TA-RT-W6:

Table 1: Parameters for the thermoelectric modeling

Parameters	Value
Q_{cmax}	367.5 W
ΔT_{max}	95.3 ^{0}C
I_{max}	14.8 A
V_{max}	43.3 V
n	127
A	1 mm^2
l	1.25 mm
Z	0.0203
α	428 µV/K
ρ	6 µΩm
$K_{(Bi2Ti3)}$	1.5 W/mK
Γ	15.67 nV/K

The parameters shown in Table 2 are considered for the simulation of the desalination unit:

Table 2: Parameters for System Evaluation

Parameters	Value
Elevation of Bangalore(H)	920 m
Atmospheric Pressure of Bangalore	0.907 bar
Boiling temperature of water	97.6 ^{0}C
d	997 kg/m^3
h_{fg}	2264.3 kJ/kg
$K_{(Al2O3)}$	202 W/mK

3. *RESULTS AND DISCUSSION*

3.1.1 Thermoelectric results

Simulation of the thermoelectric module is carried out using MATLAB software. The simulation result is compared with the datasheet of the chosen thermoelectric module. Fig. 3 shows the cooling power curve of the thermoelectric module. The curve indicates that cooling power follows the linear curve up to 4A, where Peltier cooling dominates other effects. After 4A, it slightly bends downward, taking the nature of the

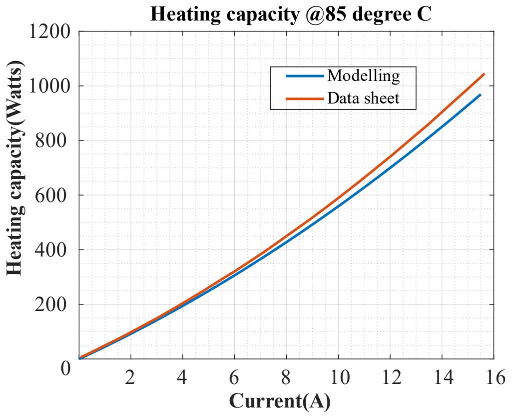

Fig. 3. Cooling curve

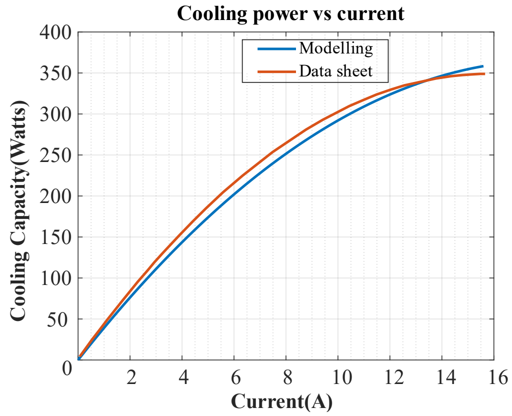

Fig. 4. Heating curve

parabolic curve, which shows the joules heating effect, and tries to deteriorate the cooling power of the thermoelectric module. Fig. 4 shows the heating curve of the thermoelectric module. Up to 4A, Peltier heating dominates the other effect, making the curve linear as Peltier heating or cooling is directly proportional to the junction current passing through it. After that, joules' heating effect starts dominating and aid to the Peltier heating, making the curve's nature parabolic upward. Result of the simulation matches with the datasheet provided by the manufacturer. There is slight variation in modelling curve and datasheet curve is due to parameter assumed for the simulation. This is because the manufacturer does not reveal the material properties and internal geometrical configuration of the thermoelectric pellets. Both the curves are evaluated at 85 ^{0}C as the datasheet curve is provided for 85^{0}C. However, it may be assessed to 97.6^{0}C by simulation. The reason for evaluating 97.6^{0}C is the boiling point of water at the topography condition of Bangalore, Karnataka, India.

Fig. 5 shows the COP curve along with the cooling curve. The reason for comparing both curves is to get the optimum operating point of the thermoelectric module. When the COP curve cuts the cooling curve, we get the optimum operating point. However, it can be evaluated mathematically by formulating Lagrange's function for optimization. At the optimum operating point, the COP is 30.06 and cooling capacity is 30.06 Watts when the current through the junction is 0.7A. At a mid-operating point, COP is 2.08 and cooling capacity is 247.35 Watts when the current is 7A. At maximum operating point, COP is 0.79 and cooling capacity is 376.25 Watts when 14A current flow through the junction. For a reasonable COP and cooling capacity, the mid-current operating point is one of the best choices for operating the thermoelectric module.

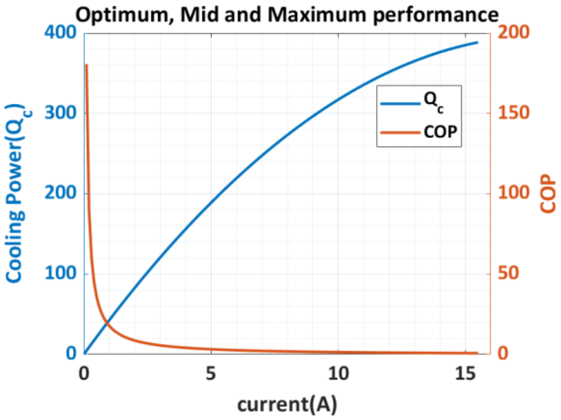

Fig.5. Performance and cooling curve

3.1.2 Water production results

Simulation of the proposed system is carried out by considering the assumption mentioned in section 2.3. Production of water depends on the operating point of the thermoelectric module. Fig. 6 shows the production of one kilogram of water with the time at the various operating points of the thermoelectric module. When the thermoelectric module operates at the optimum operating point, mid operating point, and maximum operating point, then a kilogram of water produces in 20.83 hours, 1.82 hours, and 47 minutes respectively.

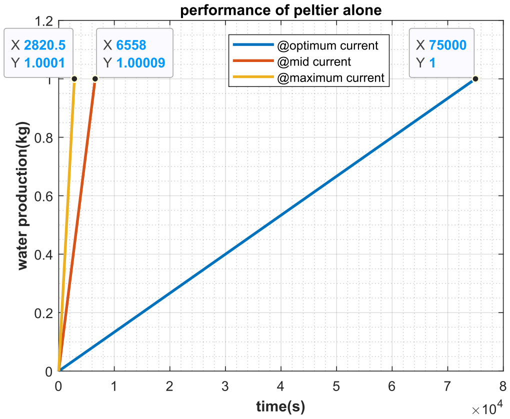

Fig. 6. Water production

Efficiency of system can be defined by equation1

$$\eta = \frac{\dot{m} h_{fg}}{W * 3600} \qquad (1)$$

Following the efficiency equation (1), we obtain 30.68, 2.88, and 1.67 efficiencies at the optimum operating point, mid operating point, and maximum operating point, respectively.

4. CONCLUSION

From the simulation results and analysis, we observe freshwater production depends on the operating point of the thermoelectric module, and the selection of operating depends on COP and cooling capacity of the thermoelectric module. The nature of the performance curve and cooling curve are opposite to each other. Therefore, a trade-off between COP and cooling capacity has to be done to get the best results. The mid-current operating point gives the satisfactory trade-off between the COP and cooling capacity to get the system's reasonable efficiency of 288%. The simulation results need to be verified with the experimental results.

5. FUTURE OUTLOOK

A prototype of the proposed system is fabricated for experimental evaluation, as shown in fig.7.According to the block diagram mentioned in section 2.2, relevant portions are indicated in fig.7. Experimentation and evaluation are in progress for the designed prototype. High gain converter is analyzed for the proper control and integration of the thermoelectric module to the system by the hybrid sources[10].

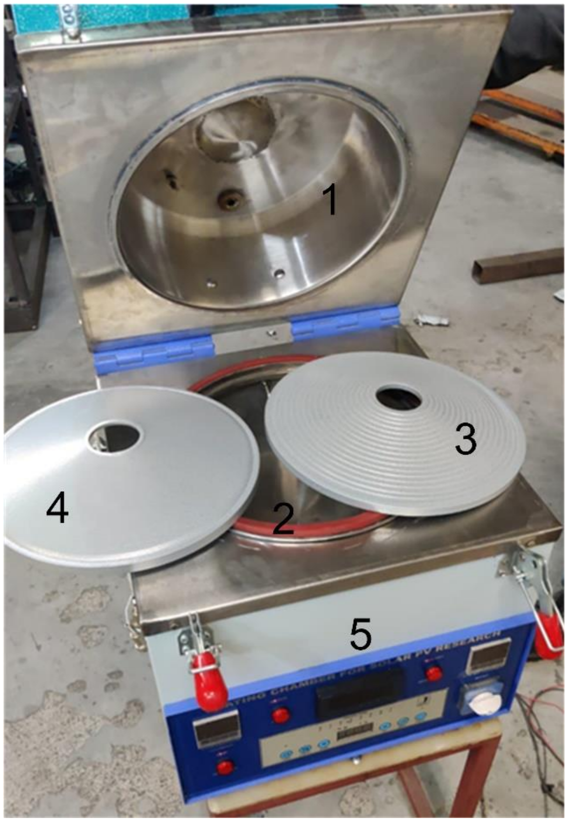

Fig.7. Proposed design of system (1) Condensing chamber (2) Evaporating Chamber (3) Upper heat sink of TEM (4) Lower heat sink of TEM (5) Controller of heating element

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