PERFORMANCE STUDY OF SOLAR HYBRID ADSORPTION DESALINATION SYSTEM INTEGRATED WITH THERMOELECTRIC DEHUMIDIFIER

PROJECT REPORT

submitted by

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to

the APJ Abdul Kalam Technological University
in partial fulfilment of the requirements for the award of Master of Technology in Industrial Refrigeration and Cryogenic Engineering

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May 2023

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CERTIFICATE

This is to certify that the report entitled *'Performance Study of Solar Hybrid Adsorption Desalination System Integrated With Thermoelectric Dehumidifier'* submitted by **HARIKRISHNAN S, TKM21MEIR07** during **2022-2023** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Industrial Refrigeration and Cryogenic Engineering is a bonafide record of the project work carried out by him under my guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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ACKNOWLEDGEMENT

Any attempt at any level cannot be satisfactorily completed without the support and guidance of learned people. I owe to great many people whose constant support and motivation that has encouraged me to come up with this project.

Firstly, I would like to express my heartfelt thanks to **Dr. Baiju V**., Assistant professor, Department of Mechanical Engineering, TKM College of Engineering for being instrumental in the completion of my project with his guidance. I express my deep sense of gratitude to thank **Dr. Dileep P.N.,** Professor and Head of Department, Department of Mechanical Engineering, TKM College of Engineering for the support to complete this project. I thank **Dr. Shafi K.A.,** PG coordinator, Department of Mechanical Engineering, TKM College of Engineering for giving their constant support for doing this project.

I thank **Abhishek P**., Research scholar, Department of Mechanical Engineering for his constant support regarding the proceedings of the project. I take this opportunity to extend my deep appreciation to family and friends, for all that they meant to me during the crucial times of the completion of this project. Finally, I thank **Almighty God** for being with me all the time and guiding me with their divine light.

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ABSTRACT

The desalination of saline water to produce fresh water is an increasing concern around the world. Adsorption desalination is one of the most energy efficient systems for freshwater production. Conventionally, many desalination techniques, such as multi-stage flash, multi-effect distillation, and reverse osmosis, have been used, but they have drawbacks such as high energy consumption, low water productivity, and high cost. The adsorption desalination system has the primary advantage of producing both cooling and potable water. This study focuses on the thermodynamic modelling and experimental study of a hybrid solar adsorption desalination and cooling system. The efficiency of the adsorption desalination and cooling system operating with silica gel as an adsorbent is initially determined through a numerical analysis. The proposed work introduces the integration of a thermoelectric dehumidifier with the solar vapour adsorption desalination system existing at the Energy Research Lab, TKMCE. The integration of the TEC unit will enhance the yield of desalinated water. The study comprises of detailed performance investigations of the modified system to assess the percentage yield, quantity of water, and coefficient of performance. Thermoelectric cooling (TEC) in thermoelectric dehumidifiers has various advantages over conventional techniques, such as lightweight, compact size, noise-free, and eco-friendly operation. Dehumidified air and fresh water can be produced, which increases the overall performance of the adsorption desalination system. The result indicates that the water yield from adsorption desalination and the cooling system is 1.3 litres per hour. For the hybrid system integrated with the thermoelectric dehumidification unit, the water productivity is found to be 3 l/hr, which is 56% more than the conventional system, and the Coefficient of Performance (COP) for the integrated TEC is 0.4.

Keywords: Adsorption, Desalination, Dehumidification, Thermoelectric Cooling, Thermoelectric Dehumidifier

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ABBREVIATIONS

AD	Adsorption Desalination
AWG	Atmospheric Water Generator
COP	Coefficient of Performance
GA	Genetic Algorithm
GI	Galvanized Iron
HDH	Humidification Dehumidification
MOF	Metal Organic Framework
RHT	Rainwater Harvesting Tank
RO	Reverse Osmosis
SDWP	Specific Daily Water Production
SMPS	Switched Mode Power Supply
TEM	Thermoelectric Module
TEC	Thermoelectric Cooling
TED	Thermoelectric Dehumidification
TTEC	Two-Stage Thermoelectric Cooler

NOTATIONS

C_p	Specific heat [kJ/kg K]
D_c	Diffusion coefficient [m^2/s]
E_a	Activation energy [kJ/kg]
E	Characteristic energy [kJ/mol]
H	Isosteric heat of adsorption / desorption [kJ/kg]
h	Enthalpy [kJ/kg]
h_{fg}	Latent heat [kJ/kg]
K_L	Adsorption kinetic constant
m	Mass [kg]
n	D-A constant
P	Pressure [kPa]
P_{sor}	Sorption pressure [kPa]
R	Universal gas constant [kJ/mol K]
R_p	Adsorbent particle radius [m]
T	Temperature [K]
q	Concentration ratio [kg/kg]
q_{eq}	Maximum concentration ratio [kg/kg]

CHAPTER 1

INTRODUCTION

Around 75% of the Earth’s surface is covered with water; it holds 97% saline water and the remaining 3% is fresh water present in the atmosphere, ice-mountains, and ground water. Ground reservoirs for rainwater storage have been built by numerous countries, but they are not practical for semi-arid and desert regions with low rainfall. The scarcity of water primarily results from the world's population growth and economic development, which leads to increased water usage in major industrial sectors. Therefore, an eco-friendly and cost-effective solution must be discovered (Rahul et al. 2019). Desalination is a widely used process to obtain fresh water for human and industrial use, which involves removing salts and other contaminants from seawater. Thermoelectric dehumidification can also be a viable option to produce water from the air in which they are environment friendly, quiet in operation and compact in size.

1.1 ADSORPTION DESALINATION SYSTEM

Adsorption desalination (AD) is a process that uses adsorption to remove salt and other impurities from seawater or brackish water to produce fresh water. The process typically involves passing water through an adsorbent material, such as activated carbon, which attracts and removes salt ions and other contaminants. The purified water is then collected and the adsorbent material is regenerated for reuse. Adsorption desalination is a promising technology for water purification, particularly in areas with limited water resources, as it is relatively low-cost and energy-efficient.

Desalination is the process of removing salts and other minerals from seawater or brackish water to produce fresh water. The main aim of desalination is to provide fresh water in areas where there is a shortage of usable water resources. There are several methods for desalination, including reverse osmosis, thermal distillation, and adsorption. Each method has its own advantages and disadvantages and the choice of method depends on factors such as cost, energy efficiency, and environmental impact. Desalination has become increasingly important as global demand for fresh water continues to rise, particularly in coastal areas and arid regions. Adsorption desalination is one of the emerging techniques which is energy efficient and environmentally friendly. Unlike the other techniques, in the desalination system water and cooling effect can be produced. Adsorption is the process in which the water vapour on the surface of the adsorbent is taken by van der Waal’s or polar bonding forces.

1.2 DEHUMIDIFICATION TECHNIQUES

A dehumidifier is a device that can modulate the level of moisture in an enclosed space. It can either raise the humidity for comfortable air or lower the humidity and collect the condensation that results. Dehumidifiers can be used for a variety of tasks, including restoring structural elements that have been harmed by moisture and enhancing indoor thermal comfort for people to engage in activities. For different sizes and types of dehumidifiers, especially portable ones where dehumidification is crucial, there are numerous approaches available. By employing hygroscopic materials to cool or heat the air, dehumidification can be carried out. The moist air is dehumidified during the cooling and dehumidification process by passing over a cold surface, where it condenses. On the other side, the heating and dehumidification process uses hygroscopic materials. Throughout the cooling and dehumidification process, air is cooled below its dew point temperature, maintaining the cooled surface below the air's dew point temperature. As a result, as the moist air travels over this surface, the dry bulb temperature gradually decreases until it reaches its dew point temperature.

The two primary categories of dehumidification are cooling-based and heating-based, as shown in Figure 1.1. Vapour compression and desiccants are the two methods of dehumidification that are used most frequently. In vapour compression, the refrigerant circulates through cooling coils as the incoming wet air passes over them to cool. The coolant in the coils acts as the evaporator in the vapour compression refrigeration cycle, causing the moisture content of the air to condense over them and collect in a water container. In contrast, moisture-absorbing components like silica gel or liquid desiccants like LiCl are utilised in desiccant-based dehumidifiers. When moist air passes through desiccants, the moisture is held on the surface, creating dry air. To bring the dry air into the reasonable thermal comfort range, a cooling element or cooling agent must be used on the desiccant-based dehumidification process because it has a higher temperature. Thermoelectric cooling, which is a new method for compact and portable dehumidifiers and is currently offered as a commercial product on the market (Raj *et al*. 2021).

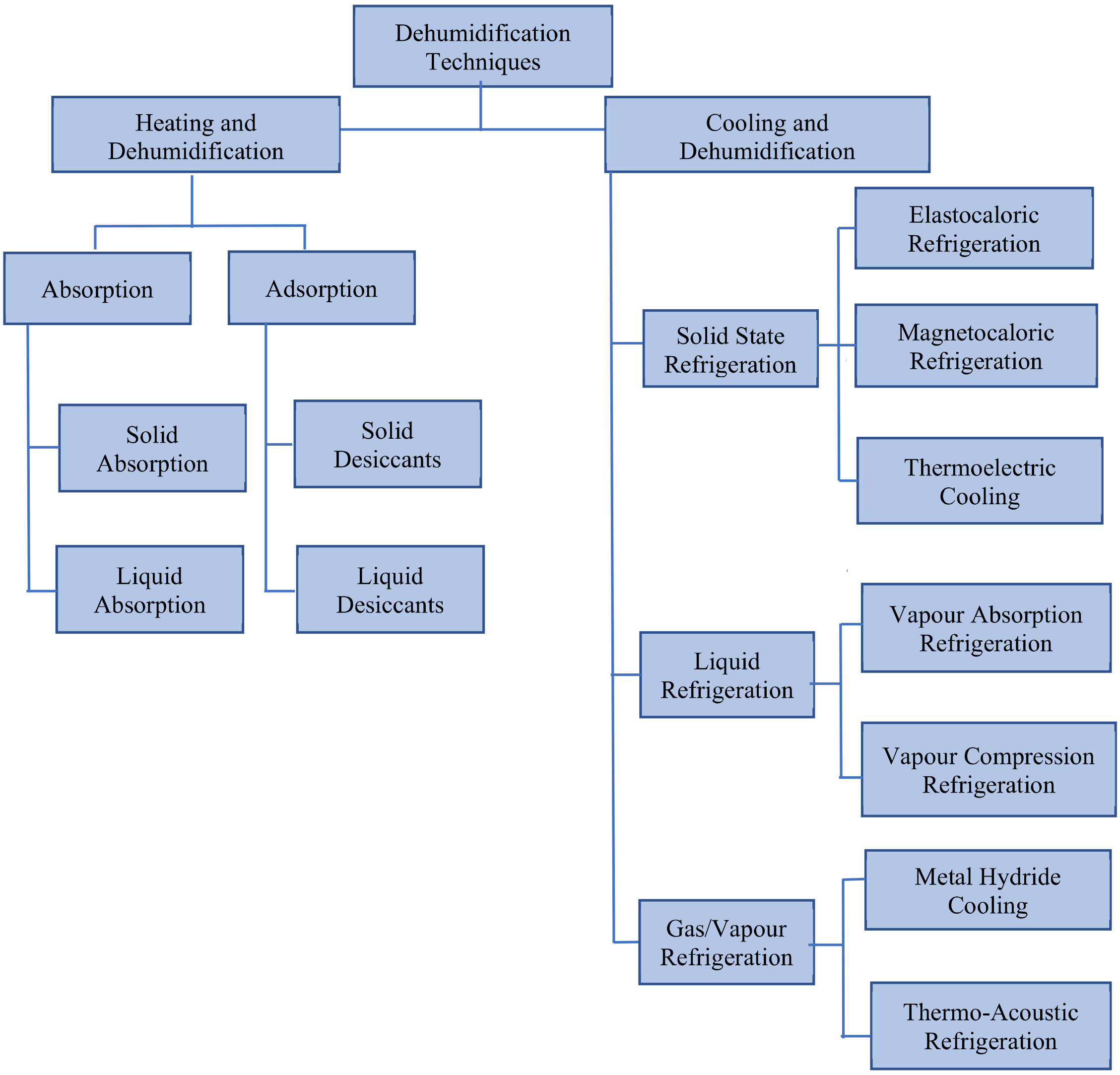


Fig 1.1 Classification of different techniques of Dehumidification (Raj *et al.* 2021)

1.3 THERMOELECTRIC COOLING

Thermoelectric cooling, also known as Peltier cooling, is a cooling technology that uses the Peltier effect to remove heat from one side of a device and transfer it to the other. The Peltier effect is a phenomenon that occurs when a voltage is applied across two different materials, leading to heat transfer from one material to the other. (Julian, 2017).

Thermoelectric cooling is commonly used in various applications, such as cooling electronic devices, refrigeration, and air conditioning. It has several advantages over conventional cooling technologies, including the absence of moving parts, low noise and vibration, and the ability to provide precise temperature control. Additionally, thermoelectric cooling is environmentally friendly, as it does not rely on refrigerants that contribute to global warming.

1.4 PROBLEM FORMULATION

Adsorption desalination is one of the desalination processes that uses less energy than other traditional processes. There have been many new developments in hybrid desalination systems, which integrate different approaches to water purification. However, the topic of merging the adsorption system with other types of systems receives very little attention overall. Adsorption desalination is one of the desalination processes that uses less energy than other traditional processes. There have been many new developments in hybrid desalination systems, which integrate different approaches to water purification. However, the topic of merging the adsorption system with other types of systems receives very little attention overall. The researches were focused mainly on the solar powered adsorption systems experimentally and numerically. The experimental and computational investigations using the thermoelectric dehumidification system in conjunction with the adsorption system have not been extensively investigated. From this motivation, this work is proposed to investigate theoretically and experimentally the operation and performance of an adsorption desalination system integrated with thermoelectric dehumidification system.

1.5 THESIS OUTLINE

This thesis consists of six chapters. The first chapter introduces the project topic and its background. The second chapter discusses the various desalination systems which uses the adsorption techniques, thermoelectric cooling systems and infers the performances of each system. It also includes the objective and the methodology of the work. The third chapter shows the description, working and the results obtained from the numerical simulation of adsorption desalination system. The fourth chapter presents a new hybrid system, its working, and the numerical results. The performance of the thermoelectric dehumidification unit is numerically analysed. The fifth chapter shows the experimental results of the hybrid system and validate with the numerical results. Chapter six gives the conclusion of this study and the scope for future work.

CHAPTER 2

LITERATURE REVIEW

The literature study on adsorption desalination, the numerous advancements in the desalination sector and development in thermoelectric cooling are presented in this chapter. Water is an essential necessity for all life on Earth, and a shortage of it prevents an economy from developing economically. Water is adequate for agriculture, industry, recreation, and human consumption. Three-quarters of the Earth is submerged in water. The most effective solution for the global water shortage is the conversion of brackish water into potable water with minimal production costs. The adsorption desalination process is one of the desalination technology's most energy-efficient ways to produce drinkable water. The adsorption desalination technique lessens the drawbacks that the present desalination technologies experience, namely their high energy consumption and high maintenance costs.

2.1 ADSORPTION DESALINATION

In the year 1984, Broughton offered advancements in the field of adsorption desalination. He used a thermally driven two-bed system and anion retarded resin for the water uptake in his investigation.

In 2005, Wang *et al.* introduced a four-bed AD system. The measurement of Specific Daily Water Production (SDWP) involved changing several operating parameters. Using a cycle duration of 180 seconds, the maximum SDWP obtained was 4,7 kg per kilogram of silica gel. It has been noted that lowering the cooling water temperature by 1.60°C or boosting the chilled water temperature by 1.80°C can result in an increase in SDWP of 10%. The coefficient of performance (COP) as well as the Specific Dynamic Work (SDWP) are both known to rise in proportion to the source temperature.

The performance of an AD system using silica gel as the adsorbent and two beds or four beds was presented by Thu *et al.* in 2009. For different heat sources, the SWDP, performance ratio was discovered. The experiment yielded a maximum daily production of potable water per tonne of adsorbent of around 10 m^3, and the performance ratio was 0.61. For maximal water production at a lower source temperature, a longer cycle time is required.

A thermodynamic model of a water adsorption system employing silica gel as the adsorbent and the Langmuir isotherm was introduced by Wu *et al.* (2010). From this, he deduced that there is an ideal temperature at which fresh water is created with the least amount of energy consumption, and that this temperature depends on the system's various operating parameters as well as the temperature of the cooling water. The temperature of cooling water entering the bed has a major impact on both water productivity and energy use. As a result, the cooling water temperature has a significant impact on both the system performance and the required budget. This suggests that an air-cooled condenser would be appropriate for the cooling water entering the condenser.

The effectiveness of an adsorption desalination system with internal heat recovery between the condenser and the evaporator was examined by Kyaw Thu *et al.* in 2011. The energy that is rejected from the condenser for the evaporation of the saline water is recovered in the evaporator. At a hot input temperature of 70°C, this cutting-edge system generated SDWP of 9.24 m^3/ tonne of silica gel per day, and the performance ratio was 0.77, which was significantly higher.

Ng *et al.* (2012) investigated the performance of a 4-bed waste heat-powered adsorption system that can provide cooling and drinkable water. The system generated cooling power of 51.6 TR per tonne of silica gel per day and SDWP of 8 m^3 per kilogram of silica gel per day.

Thu et al. (2013) investigated the improvement of the adsorption desalination system with internal heat recovery between the condenser and the evaporator. The advanced system either used an integrated evaporator-condenser unit or provided a water circulating loop between them in order to recover heat. The SDWP per tonne of silica gel was raised to 15 m^3. The water productivity was determined to be 4.3 m^3 per tonne of silica gel for the source temperature of 50°C.

In order to assess the performance and productivity, Hamed *et al.* (2014) proposed a desalination system based on an air Humidification-Dehumidification (HDH) unit. They did this by creating a theoretical model and considering the energy equations of each component. The outcome demonstrates that the water productivity was found to be 22 L/day when the system was operated for 4 hours.

Youssef *et al.* (2015) used two distinct adsorbents (advanced zeolite material AQSOA-Z02 and silica gel) to study the efficiency of a four-bed adsorption desalination system. According to the experiment, silica gel only produced 3.5 m^3 SDWP and 15 TR per tonne at low chilled water temperatures below 200C while AQSOA-Z02 produced 6.2m^3 SDWP and 53.7 TR per tonne of AQSOA-Z02. Silica gel and AQSOA-Z02 produced equivalent SDWP values of about 7 m^3 and specific cooling rates of about 60 TR for chilled water temperatures over 20°C.

In a two-stage cooling and desalination system, Ali *et al.* (2016) modelled the first stage as an adsorption cooling system and the second stage as an adsorption desalination system. The performance of the system was improved by the heat recovery between the condenser and the evaporator. When compared to the traditional adsorption desalination and cooling systems, the system produced 26% more water and 45% more cooling capacity.

A desalination system that combines mechanical vapour compression and adsorption desalination technologies was proposed by Askalany *et al.* in 2016. The system was simulated under various operational circumstances. It was observed that, depending on the temperature of the source, daily water production increased by 10–45%.

Metal Organic Frameworks (MOFs) are employed in the membrane desalination and water treatment processes, according to Deng *et al.* (2018). The preparation of MOFs using various techniques is introduced and helps with water filtration applications like desalination, nanofiltration, microfiltration, and ultrafiltration. Due to their structure and characteristics, MOFs improve the performance of the membrane.

Naef *et al.* (2019) modelled a novel hybrid desalination system that incorporated HDH and AD in two distinct schemes. Scheme 1 is exclusively used to desalinate saltwater that has already been precooled by an AD evaporator, whereas Scheme 2 is utilised to provide cooling effects as well as desalinate water. The HDH unit contributes more to the water productivity and performance of the hybrid HDH-AD system than the AD system.

By combining an adsorption system with two ejectors and using silica gel as the adsorbent, Ali *et al.* (2020) established a novel hybrid system. According to the numerical findings, the ideal half cycle duration is 400 seconds, and the SDWP is 23.0 m^3 per tonne of silica gel at a COP of 1.64 and a regeneration temperature of 85°C.

A hybrid multi-effect distillation adsorption desalination system fuelled by solar thermal energy was proposed by Yassin *et al.* in the year 2021. It has been noted that the addition of the adsorption desalination stage enhanced the rate of fresh water production by 2.68 times and resulted in 57.78% reduced specific energy consumption.

A scaled-up adsorption system that operates at a low desorption temperature and consists of several heat exchanger modules filled with commercially available metal-organic framework material was introduced by Albaik *et al.* in 2021. Aluminium fumarate, which was packaged in 16 modules, was the MOF that was employed. The findings indicate that the cooling capacity is 5.25kW and the water productivity is 201L/day.

2.2 THERMOELECTRIC COOLING

Yi-Hsiang *et al.* in 2006 introduced a Genetic Algorithm (GA)-based technique to optimise cooling capacity and COP for two-stage thermoelectric coolers. The optimal parameters obtained by GA were confirmed by being compared with the data received from analytical methods. After the verification, the optimisation was carried out to generate the optimal parameters for a target temperature difference of 90°C.

Vian *et al.* in 2008 developed a heat exchanger for the cold side of Peltier pellets in thermoelectric refrigeration, based on the principle of a thermosyphon with phase change and capillary action. The device improves the thermal resistance between the cold side of a Peltier pellet and the refrigerated ambient by 37%. Additionally, it has been proven through experimentation that incorporating the created device can boost thermoelectric refrigerators' COP by as much as 32%.

The use of thermoelectric coolers in a dehumidification system to condense atmospheric moisture and produce renewable freshwater was examined by Milani *et al.* in 2011. It was discovered that energy use, rather than the dehumidification system's capital cost, was responsible for more than 95% of the water cost. Priced at an estimated $82 per kL, generated water can be integrated and programmed to supplement rainwater harvesting tank (RHT) production and completely meet end-user's freshwater needs. One of the key benefits of this strategy is its ability to relieve pressure on freshwater resources and associated aquatic ecosystems while also supplying end users with a reliable and clean water supply.

Kaushik *et al.* in 2015 investigated the exo-reversible and irreversible thermodynamic models of a Two-Stage Thermoelectric Cooler (TTEC) considering Thomson effect in conjunction with Peltier, Joule and Fourier heat conduction effects using exergy analysis. The findings indicate that the energy efficiency is higher than the exergy efficiency. For instance, in an irreversible TTEC with a total of 30 thermocouples, a heat sink temperature of 300 K, and a heat source temperature of 280 K, the maximum cooling power, maximum energy, and exergy efficiency were all obtained to be 20.37 W, 0.7147, and 5.10%, respectively. It has been discovered that the Thomson effect boosts the TTEC system's cooling capacity and energy efficiency.

Yu Yao *et al.* in 2017 conduct an experimental investigation on the influences of structural parameters and operating conditions on the moisture removal rate of TED. A novel prototype is proposed and investigated to enhance the moisture removal rate. It reveals that when the air flow velocity of the air duct is 1.74 m/s, the moisture removal rate of this unique prototype is up to 33.1 g/h, and the corresponding COP is 0.75.

A small-scale Atmospheric Water Generator (AWG) prototype that uses the Peltier effect for cooling was designed and built by Amir *et al.* in 2018. In this study, a methodical design approach was used, and the cooling capacity and COP behaviours of the thermoelectric cooler (TEC) regarding the current were used to size the AWG system. The tests also indicate that increasing the current of the individual TECs increases the rate of water production; however, this increase is accompanied by a higher specific energy consumption because of the reduced COP.

The review by Raj *et al.* in 2021 introduces the fundamental dehumidification principle and various techniques. Additionally, prototypes based on thermoelectric dehumidifiers are examined and their design and functionality are evaluated. The patents and commercially available products that have been produced on thermoelectric dehumidifiers have also been briefly examined and contrasted. The study also depicts the current condition of thermoelectric dehumidifiers and offers prospective avenues for their growth in the future.

Lucas *et al.* (2022) explores the use of TEC to enhance the passage of heat from the motor's core and casing to the surrounding air. The heat sink system is the first of three test configurations employed because of its straightforward construction and ability to be easily altered to a motor's external casing. Due to the extremely high number of motors positioned in small spaces, the second option is a heat displacement system known as "heat pipes," and the third option is a water-cooled heat sink arrangement that is frequently employed in crucial locations. The purpose of this study is to assess whether adding TEC to each of these systems would enable it to remove waste heat more effectively than the existing ones. According to experimental findings, the installation of the TEC-equipped systems mentioned above lowers slot temperatures by 14.9%, 12%, and 18.96%, respectively.

2.3 RESEARCH GAP IDENTIFIED

The challenges in the adsorption desalination and cooling system lies in improving the percentage of yield of water and cooling capacity. To integrate a dehumidification unit with AD system is one of the methods to improve the water productivity. Thermoelectric dehumidifiers are proved to be a viable option for dehumidification unit, but its utility with adsorption desalination systems is not much explored.

2.4 OBJECTIVES

Broad Objective

The main aim of this project is to carry out the theoretical and experimental studies on the hybrid adsorption desalination system integrated with thermoelectric dehumidification unit.

Specific Objectives

1) To conduct numerical study on the existing adsorption desalination system.
2) Numerical analysis of the system integrated with thermoelectric dehumidification unit.
3) Design, fabrication, and performance study of hybrid system

2.5 METHODOLOGY AND CONCEPTUAL FRAME WORK

The detailed methodology of the above work is described:

Objective 1: Numerical study on the existing adsorption desalination system

The study on the performance of the adsorption desalination system and analyze the yield of the system by varying the hot water temperature, condenser temperature and cooling temperature.

Objective 2: Numerical analysis of the system integrated with thermoelectric dehumidification unit

Thermodynamic modeling of the thermoelectric dehumidification unit by introducing governing equations and analyze the performance of the system by varying flow rate, relative humidity, temperature difference, etc.

Objective 3: Design, fabrication, and performance of hybrid system

Design a thermoelectric dehumidification unit and developed by selecting suitable thermoelectric modules and heat sink. Then integrate the developed TED unit with the adsorption system and measure the parameters like water productivity, COP and compare it with the theoretical values to validate the results.

Figure 2 represents the conceptual diagram of the proposed work which includes the method of work in detail.

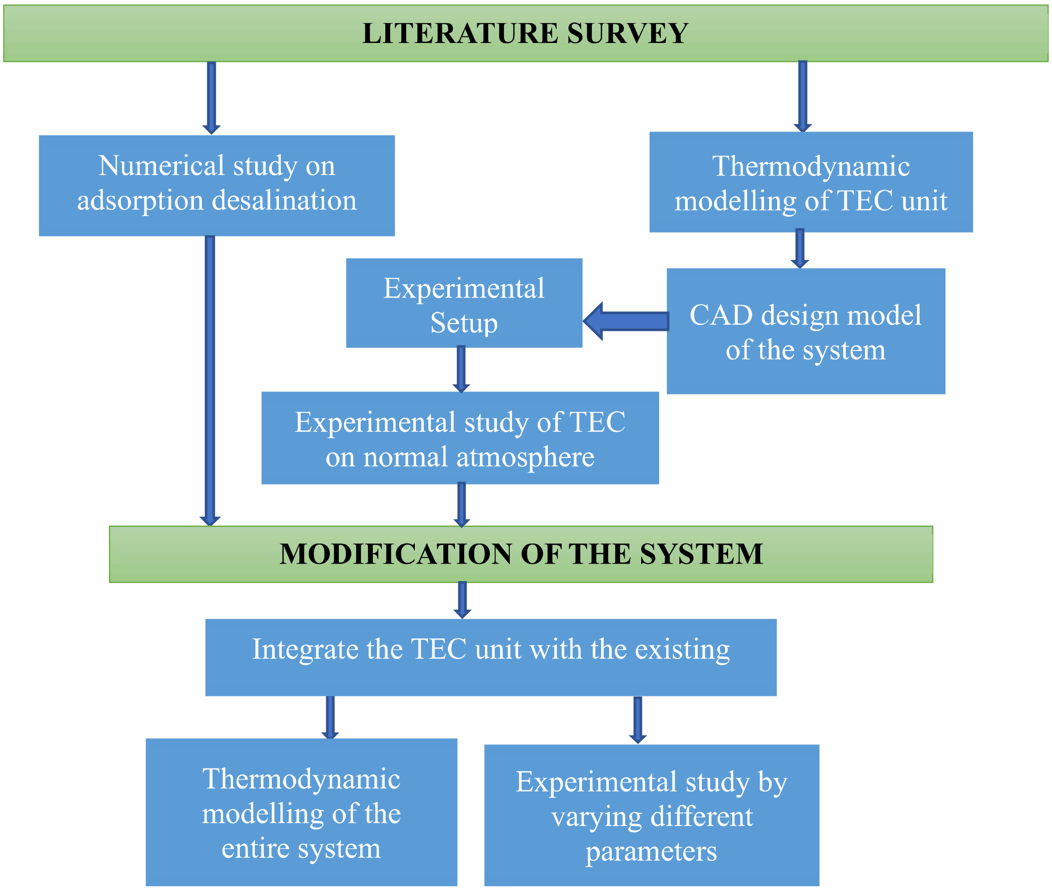


Fig. 2. Conceptual diagram of the proposed work

CHAPTER 3

NUMERICAL MODELING OF ADSORPTION DESALINATION AND COOLING SYSTEM

A desalination system technology known as the adsorption desalination cycle produces potable water from brackish or ocean water. It heats the water using sustainable sources of energy, such as the heat from the sun or the exhaust from a manufacturing activity. An adsorption desalination plant typically consists of the components namely (1) the evaporator, (2) single or multiple adsorbent bed, and (3) the condenser. The working of adsorption desalination system, various components, thermodynamic cycle, and numerical simulation are presented.

3.1 WORKING PRINCIPLE OF ADSORPTION DESALINATION AND COOLING SYSTEM

The evaporator, adsorbent bed, and condenser are the main elements of the adsorption desalination and cooling system. Figure 3.1 depicts the overall layout of the system in the form of a schematic diagram.

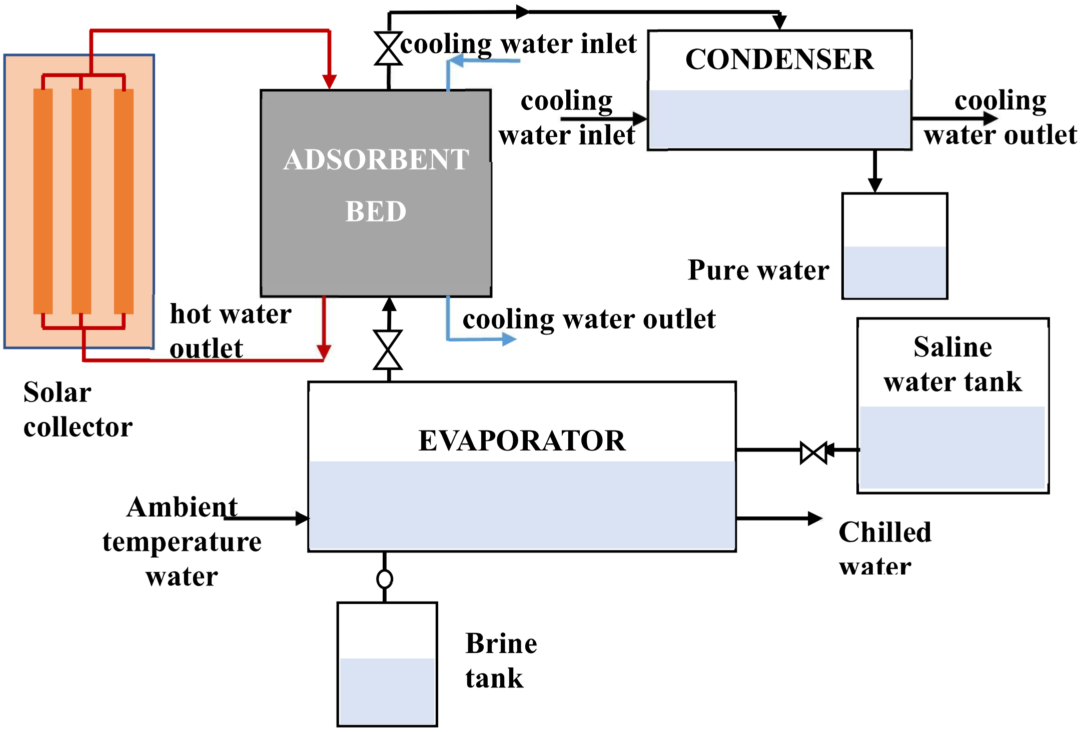


Fig.3.1. Schematic diagram of an adsorption desalination and cooling system

At first, brackish or saline water is charged in the evaporator. In the evaporator, the water is flash evaporated at reduced pressure. The chilled water, which can be utilised for cooling, is circulated in order to maintain the evaporation process. The discharge of brine solution from the evaporator is done on a regular basis for the purpose of controlling both the level of salt in the sea water and the overall concentration of salt. When the valve between the evaporator and the adsorption bed is opened, water evaporates and moves from the evaporator into the adsorbent bed where it is absorbed by the silica gel. During the adsorption operation, the cooling water circulates in the adsorption bed to eliminate the heat from adsorption. When the silica gel is completely saturated with water during the adsorption process, the valve between the evaporator and the adsorption bed is opened. The desorption process is the method used to regenerate the silica gel while hot water is circulated through the bed. The hot water that passes through the adsorption bed now releases the regenerated water vapour into the condenser after the valve between the adsorbent bed and the condenser is opened. Condensation generates heat that is rejected to the cooling water flowing via the condenser, where the condensate can be recovered as pure water. Once this process is complete, the water that has been desalinized can be collected. In the sections that follow, details about the components are discussed.

3.1.1 Evaporator

The evaporator is the component in which the process of cooling and the evaporation of water vapour take place respectively. The salty water is fed into the evaporator by way of the valve that is in the sea water intake. The seawater is turned into vapour inside the evaporator. Low pressure is required for the evaporator since the evaporation should occur at a lower temperature. As water transitions from liquid to vapour in the evaporator, heat is seen emanating from the cooling space. In addition to serving both the evaporation process and the chilling function, chilled water can be pumped through the evaporator in a continuous circulation. As a result of the water in the evaporator being evaporated, there will be a significant increase in the salt content. This highly concentrated salt solution, as well as the brine, needs to be drained at regular intervals.

3.1.2 Adsorbent Bed

The main component in an adsorption desalination and cooling system is adsorbent bed, and its performance has a significant impact on the overall functionality of the system. It functions in a manner that is analogous to that of the compressor in a standard system for the compression of vapor, but in this case, it is powered by the thermal energy.

The adsorbent material must be a hydrophilic, porous material with a high surface area that forms transient hydrogen bonds with water molecules. The most popular adsorbent is silica gel because it can adsorb a significant amount of water (up to 40% by mass) without altering its structure or volume and can release the water upon gentle heating. As silica gel is capable of regeneration at lower temperatures, it is the finest adsorbent that can be used.

During the adsorption phase, the adsorbent bed adsorbs low-temperature, low-pressure water vapour from the evaporator. As it produces the cooling effect, the water will evaporate. Due to the exothermic nature of the adsorption process, the heat of adsorption will be eliminated by circulating cooling water through the adsorption bed. During the desorption procedure, heated water is circulated through the bed to raise its temperature and pressure. When the regeneration temperature is attained, desorption begins. During the desorption procedure, the bed desorbs the high-temperature, high-pressure vapour to the condenser. The adsorption also includes the flow control valves on the condenser and evaporator sides.

3.1.3 Condenser

The adsorption refrigeration system utilises predominantly two types of condensers: air-cooling and water-cooling. After desorption, the vapour at a higher temperature and pressure reaches the condenser from the adsorbent substrate. Circulating cooling water through the condenser captures the latent heat from the vapour, causing it to condense. The condenser temperature is a key parameter that influences the system's water productivity rate and COP. The produced potable water is collected in the condenser.

3.2 THERMODYNAMIC CYCLE OF ADSORPTION DESALINATION AND COOLING SYSTEM

As shown in Figure 3.2, the thermodynamic cycle of an adsorption desalination system consists of two isosters and two isobars. Consider the P-T-X diagram on lnP vs -1/T coordinates for a convenient approach of depicting the thermodynamic cycle of the adsorption desalination system (where X is the quantity of adsorbate adsorbed by the adsorbent under equilibrium conditions, kg of adsorbate/kg of adsorbent).

Process 1-2

The process begins at point 1, where the silica gel becomes saturated with water (i.e., the concentration of water in the silica gel reaches its maximum), the valve between the adsorption bed and the evaporator is closed, and circulation of cooling water through the adsorption bed ceases. Warm water is circulated through the bed in order to enhance its temperature and pressure along the line of constant concentration. This procedure will proceed until point 2 is reached. The pressure is determined by the saturation pressure of water at condenser temperature, which is slightly higher than the temperature of the cooling water.

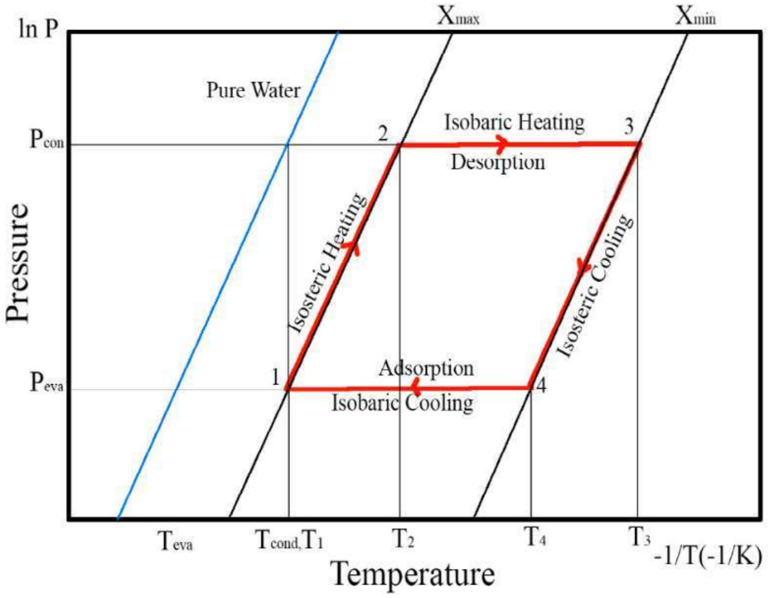


Fig.3.2 Adsorption desalination cycle

Process 2-3

When the valve between the adsorbent bed and the condenser is opened at point 2, water vapour begins to desorb from the silica gel. Due to the heated water circulating through the adsorbent bed, desorption occurs. As cooling water circulates through the condenser, vapour condenses in the condenser. The condenser is fixed until the bed temperature reaches its optimum and the amount of water adsorbed reaches its minimum. This process is also known as the regeneration or condensation of silica gel and the production of pure water.

Process 3-4

At point 3, the greatest temperature of the adsorbent silica gel is 90°C, and the minimum amount of water is adsorbed. When cold water is circulated through the bed, the temperature of the silica gel decreases at a constant concentration until point 4, where the bed pressure equals the saturated pressure of pure water at the temperature of evaporation. At that point, the bed temperature will be between 60-70°C.

Process 4-1

At the point 4, the valve that is located between the bed and the evaporator will be opened. The cooling water circulates continuously through the adsorbent substrate. The water in the evaporator begins to evaporate and then moves to the adsorbent bed, where silica gel adsorbs it. The pressure in the bed and evaporator remains constant, but the temperature will decrease, as determined by the temperature of the chilling water supply. The initial concentration of silica gel will attain its maximum value.

3.3 ADSORPTION EQUILIBRIUM MODEL

The modelling is done based on the following assumptions:

1. The temperature across the silica gel is uniform which can significantly reduce the computational cost and time required for the simulations
2. The adsorption rate of water in the silica gel inside the adsorbent bed is uniform which simplifies the ease of modeling
3. The adsorbent (silica gel) and the adsorbate gas phase are in equilibrium state which can reduce the time for modeling.
4. Heat losses from evaporator, condenser and adsorbent bed are neglected which is considered as fully insulated
5. The specific heat capacities of water, adsorbent, and metallic wall remain constant for simplification purpose

The Dubinin-Astakov (D-A) equation can be used to determine the silica gel's capacity to adsorb water vapour at various temperatures and pressures. (Ng et.al, 2012).

$$q_{eq} = q_{max} \exp \left[- \left[\frac{RT}{E} \ln \left(\frac{P_{bed\,sat}}{P_{sor}} \right) \right]^{n} \right] \quad (3.1)$$

The adsorption process is exothermic, in which heat is rejected, whereas the desorption process is endothermic, in which heat is absorbed. Latent heat or isosteric heat of adsorption or desorption refers to the quantity of heat required to adsorb or desorb a unit mass of adsorbate.

3.4 THERMODYNAMIC MODELLING OF THE SYSTEM

Mass balance and energy balance are applied to each component of the adsorption desalination and cooling system.

(a) Evaporator

In an adsorption desalination system, the evaporator is a crucial component due to its participation in the desalination mechanism and the production of a chilling effect. Consequently, the mass balance and energy balance equations are essential. The expressions are:

$$m_{sw} = m_{pw} + m_b \tag{3.2}$$

$$((mc_p)_{tube} + (mc_p)_{fin} + (mc_p)_{sw})\ \frac{dTevp}{dt} = m_{sw}h_fT_{evp} - m_bh_fT_{evp} + (mc_p)_{ch}\ (T_{in}-T_{out}) - m_{sw}h_{fg}T_{evp}\ (\frac{dq}{dt}) \tag{3.3}$$

(b) Condenser

The condenser is utilised to condense the water vapour that has been desorbed from the adsorption bed. The mass and energy balance of the input and output of the condenser is given as:

$$(\frac{dm}{dt})_{cond} = m_s\ (\frac{dq}{dt})_{des} \tag{3.4}$$

$$(\frac{dm}{dt})_{cond} = m_s(\frac{dq}{dt})_{des} \tag{3.5}$$

$$((mc_p)_{tube} + (mc_p)_{fin} + (mc_p)_w)\ \frac{dTcond}{dt} = m_s\ c_{pwv}\ (T_{des} - T_{cond})\ (\frac{dq}{dt})_{des} + m_sh_{fg}T_{cond}\ (\frac{dq}{dt})_{des} + m_a\ (h_{out} - h_{in}) \tag{3.6}$$

(c) Sorption Bed

The energy conservation of sorption (adsorption and desorption) involves the heat stored in the bed, the heat transfer between the bed and the heating or cooling water, and the heat of adsorption or desorption. The equations for the mass and energy balances are:

$$((mc_p)_{tube} + (mc_p)_{fin} + (mc_p)_s + m_sc_vq)_{bed}\ \frac{dTbed}{dt} = m_s\ \Delta H\frac{dq}{dt} + (mc_p)_w\ (T_{wi} - T_{wo}) \tag{3.7}$$

$$\Delta H = h_{fg} + E\ \ln\ (\frac{qmax}{qeq})^{\frac{1}{n}} + E\ T_\alpha \ln\ (\frac{qmax}{qeq})^{\frac{1-n}{n}} \tag{3.8}$$

Dubnin-Ashtackov (D-A) model for water vapor sorption

$$q_{eq} = q_{max} \exp [- [\frac{RT}{E} \ln (\frac{Pbed\,sat}{Psor})]^{n}] \tag{3.9}$$

$$(\frac{dq}{dt}) = K_L (q_{eq} - q) \tag{3.10}$$

$$K_L = \frac{Ao\,Dc}{(rp)2} \exp[\frac{-E}{RT}] \tag{3.11}$$

In the adsorption bed most commonly, used adsorbent is the silica gel and the regular density type silica gel is used. The unknown values in the Dubinin-Astakhov equation for the regular density type silica gel are taken from the literature (Ali et al., 2016) is shown in the table 3.1. The mathematical modeling equations of the adsorption desalination system are solved using MATLAB 2019.

Table 3.1: Values of the parameters used in simulation

Parameter	**Numerical Value**
q_{eq}	0.592 (kg/kg of silica gel)
E	3.105 (kJ/mole)
n	1.1
R	8.314 J/mole. K
m_{bed}	10 kg
m_{wall}	12 kg
ΔH	2800 kJ/kg
C_{wall}	0.510 kJ/kg
C_{bed}	0.92 kJ/kg
C_{water}	4.18 kJ/kg

3.5 RESULTS AND DISCUSSIONS

The simulation of the adsorption desalination system and the hybrid system has been carried out using MATLAB 2019. The parametric analysis has been done to see the effect of different parameters on the performance of the system. The parameters used to simulate the system performance are water produced per cycle, energy required per cycle and COP.

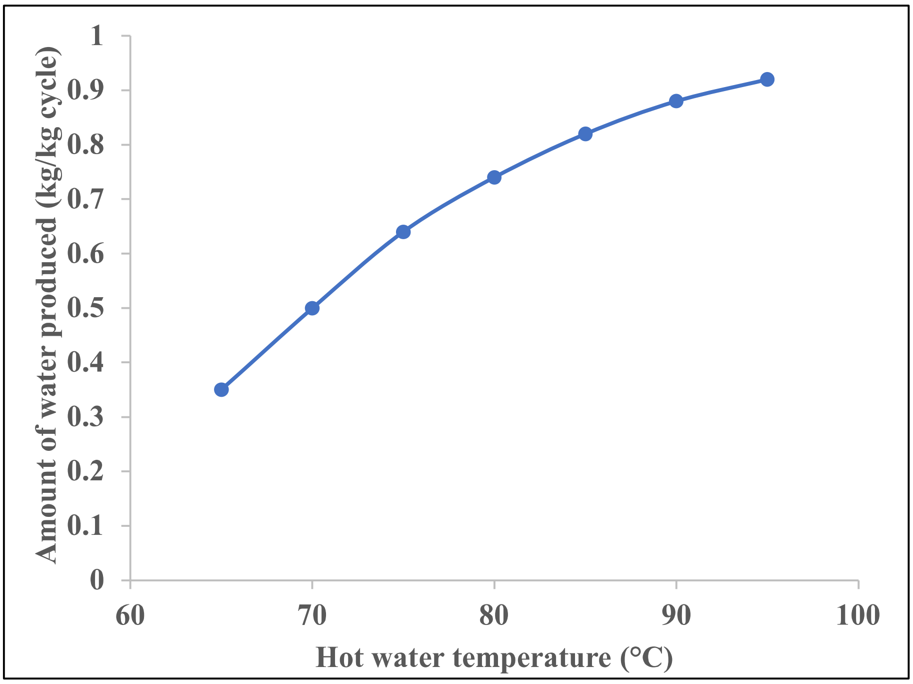


Fig. 3.3 Effect of water productivity on hot water temperature

In Figure 3.3, the hot water temperature varies between 65 ºC to 95 ºC. The water production rate rises with increasing hot water temperature. This rising trend in water production is characterised by the increase in the quantity of water desorbed from the adsorbent due to an increase in the adsorbent bed temperature. Maximum water production is achieved when all adsorbed water is removed from the adsorbent. At this point, the adsorbate concentration in the adsorbent is at its lowest. It has been observed that desorption occurs at a temperature of approximately 65 ºC.

Figure 3.4 depicts the variation in the quantity of water produced based on the temperature of the cooling water. The lower the chilling water temperature, the higher the water productivity, as more adsorption heat is removed and the adsorption rate can be increased. Due to the elevated bed temperature, water productivity will increase. The higher the bed temperature, the more desorption will occur, increasing the water productivity rate.

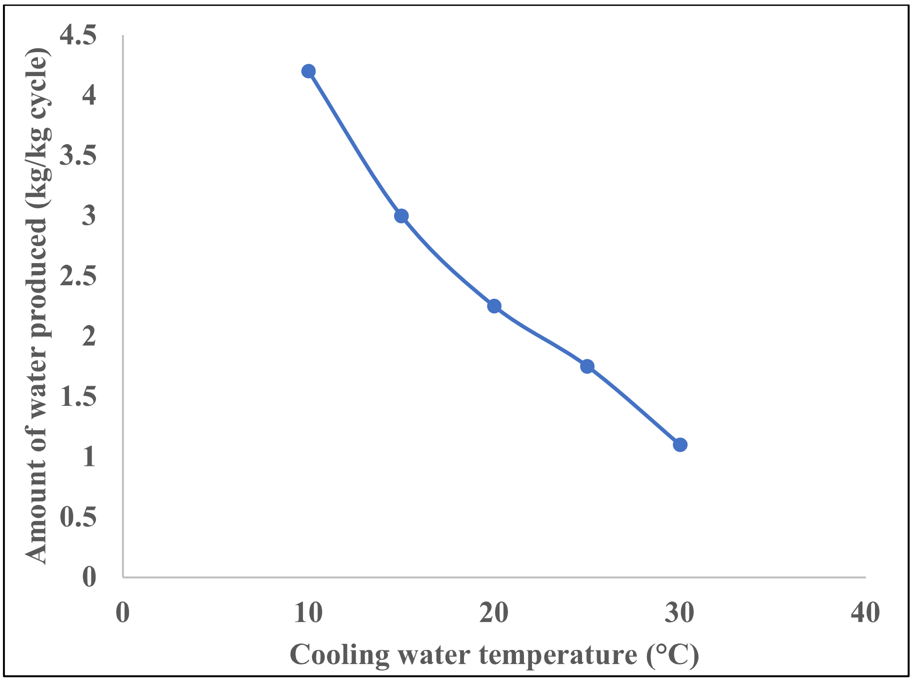


Fig. 3.4 Effect of water productivity on cooling water temperature

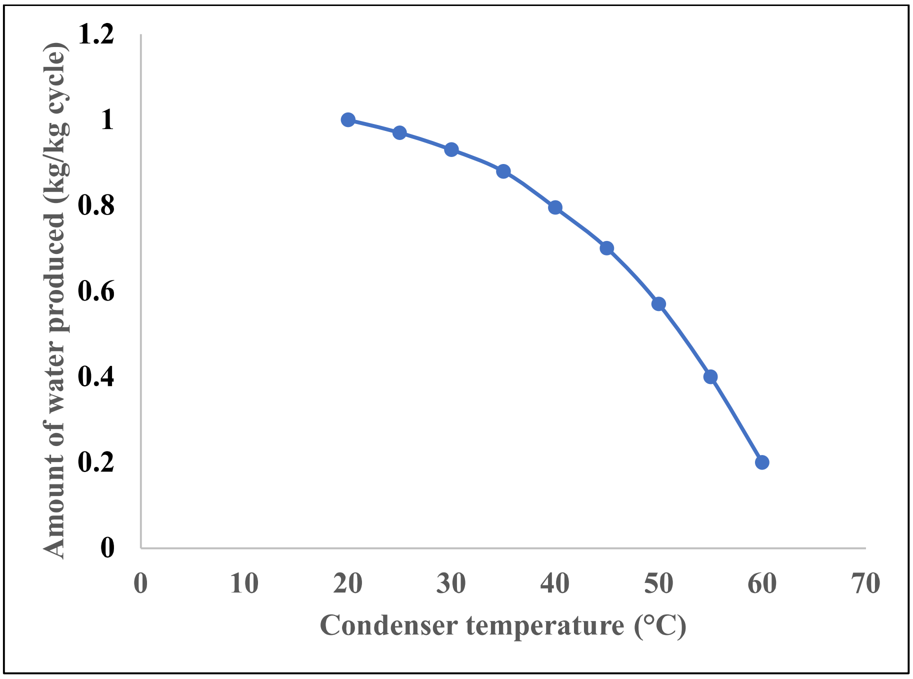


Fig. 3.5 Effect of water productivity on condenser temperature

Figure 3.5 shows the variation in the quantity of water produced based on the condenser temperature. When the condenser temperature increases, the adsorbent bed pressure increases and the increase in bed pressure reduces the desorbed amount from the bed, which reduces the water production.

Figure 3.6 depicts the dependence of the system's COP on hot water temperature. COP increases significantly with bed temperature, reaches a maximum at 85˚C, and then decreases gradually. Because the increase in refrigeration effect is initially greater than the increase in heat input. After 85˚C, the required heat input is extremely high.

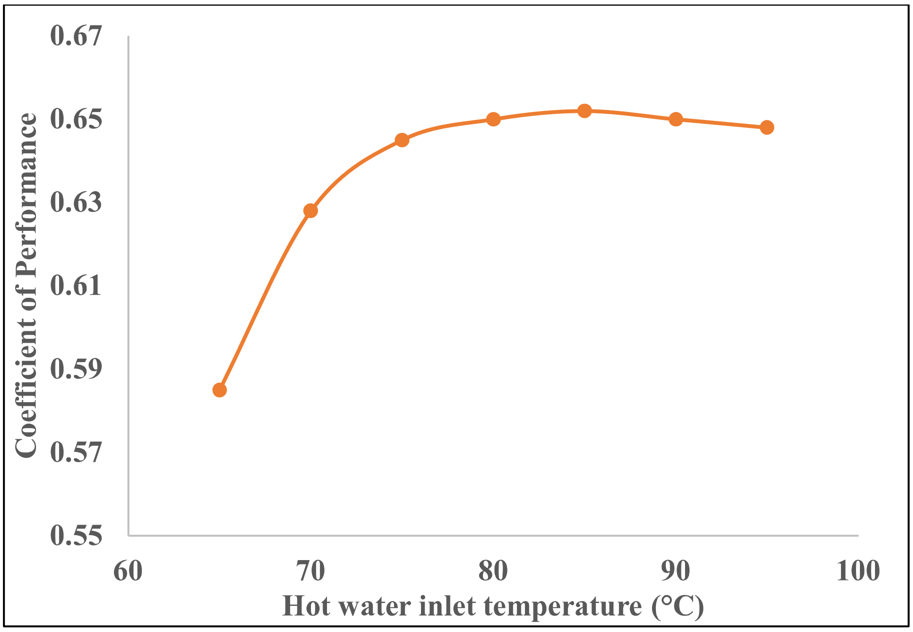


Fig. 3.6 Effect of COP with the hot water temperature

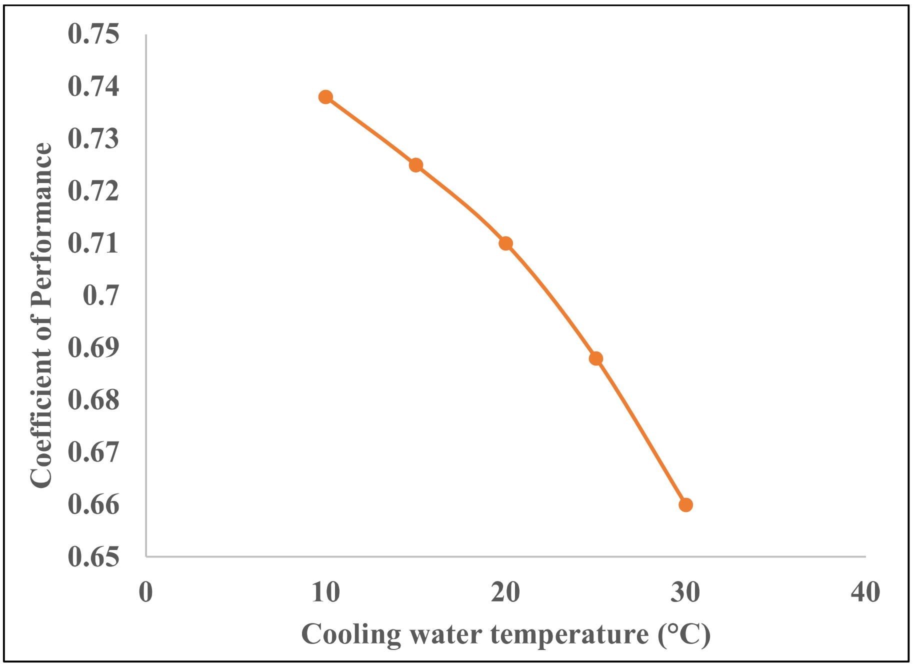


Fig. 3.7 Effect of COP on cooling water temperature

In Figure 3.7, the COP of the system increases as cooling water temperature decreases. It is because of the greater amount of water vapour that is absorbed by the adsorbent when the temperature is low, which amplifies the refrigeration effect. The COP of the system decreases with increasing condenser temperature as shown in Figure 3.8. It is because of the decreased desorbed amount as well as the increased heat input at higher condenser pressures that the refrigeration effect is less. The heat input at these pressures is also increased.

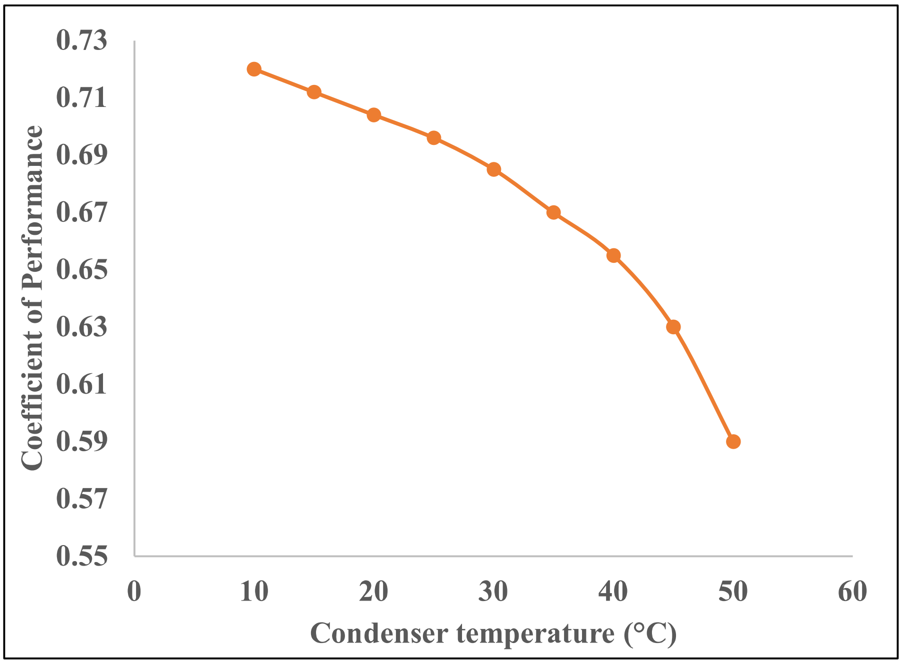


Fig. 3.8 Effect of COP with the condenser temperature

The energy required for the water production also varies according to the various operating parameters and they are discussed below:

The variation in the amount of energy required per kilogram of water generated with hot water temperature is shown in Figure 3.9. The ratio of the amount of water produced throughout a cycle to the amount of heat energy that is required by the system is the energy that is required per kilogram of water that is produced. The quantity of energy required to produce one kilogram of water initially reduces up to the point where the temperature of the hot water reaches its maximum, and then it increases. The tendency towards lessening is because there has been a rise in the amount of water that has been produced, while the total heating need has not changed significantly within the range of 60 °C to 80 °C. Above 80°C, water production is low in comparison to the requirement for heating, which results in a decrease in the amount of energy required per kilogram of water produced.

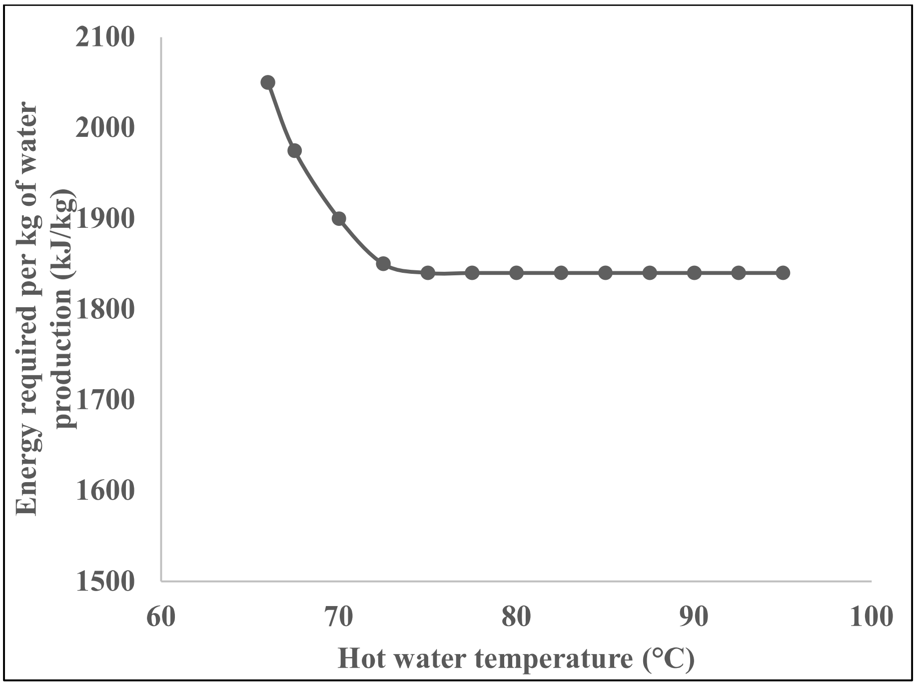


Fig. 3.9 Effect of energy required per kg of water produced with hot water temperature

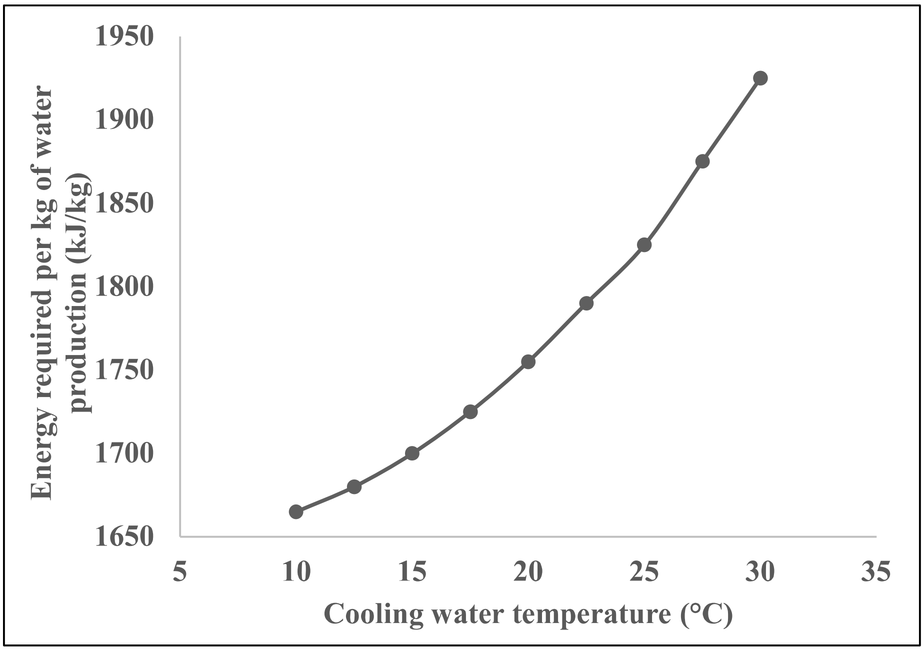


Fig. 3.10 Effect of energy required per kg of water production with cooling water temperature.

As cooling water temperature decreases, energy consumption per kilogram of water produced also decreases, as seen in Figure 3.10. It is due to the increased water production that occurs at low water chilling temperatures. Therefore, the heat needs are low for producing a unit amount of water.

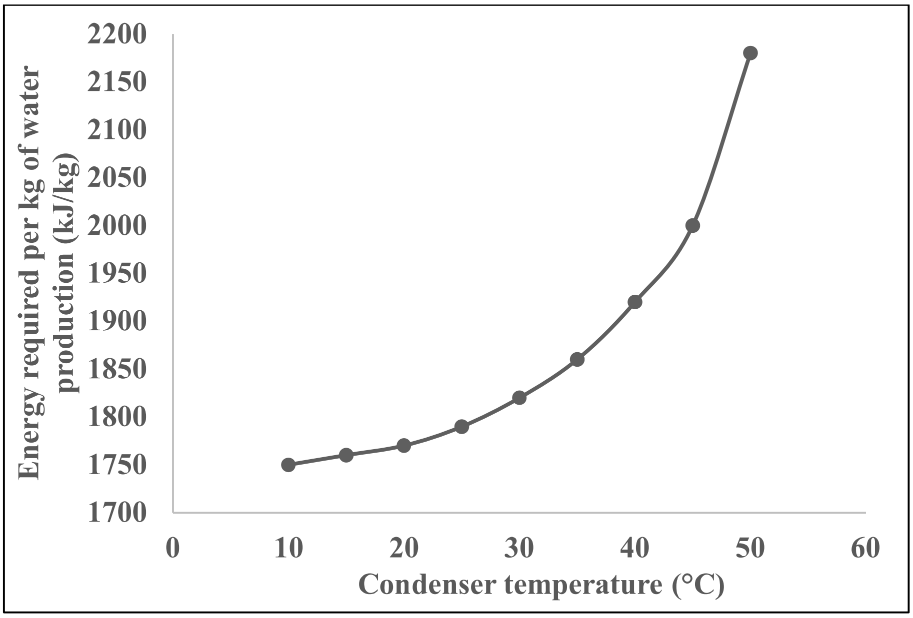


Fig. 3.11 Effect of energy required per kg of water production with condenser temperature

As shown in Figure 3.11, the energy consumption per kilogram of water production increases quickly as the condenser temperature rises. It is because of the extremely high heat input and minimal water output at the higher condenser temperature.

3.6 SUMMARY

The numerical simulation of the current desalination system concludes that the optimum water productivity is 1.3 kg/cycle with a cycle time of 30 minutes using silica gel as the adsorbent and COP of 0.75. The parameters such as cooling water temperature, hot water temperature, and condenser temperatures play a significant role in the system's efficacy, as described in the preceding sections. According to the performed numerical simulation, it is evident that the present system has a lower water yield. Therefore, there is a need to modify the infrastructure. The two possible modifications are as follows:

(i) Integrating humidification dehumidification unit with the existing desalination system.

(ii) The replacement of the existing system's adsorbent (silica gel) with a composite adsorbent.

CHAPTER 4

NUMERICAL ANALYSIS OF SYSTEM INTEGRATING THERMOELECTRIC DEHUMIDIFICATION UNIT

The conventional adsorption desalination systems have a very low water productivity. Productivity can be improved by integrating the system with any other system to make it as hybrid system. The Thermoelectric Dehumidification (TED) system is one such unit that can be combined with the adsorption desalination system. The cold side of the Peltier module can be used for dehumidification to produce water, while the hot side heated temperature can be circulated through the evaporator to increase the evaporation rate of an adsorption system. This chapter discusses the operation, various components, and performance of the hybrid adsorption desalination system integrated with the TED unit.

4.1 WORKING OF THE HYBRID SYSTEM

The major components of the adsorption desalination and cooling system are the evaporator, the adsorbent bed, the condenser, the humidifier, and the dehumidifier. The schematic diagram of the system is shown in the Figure 4.1.

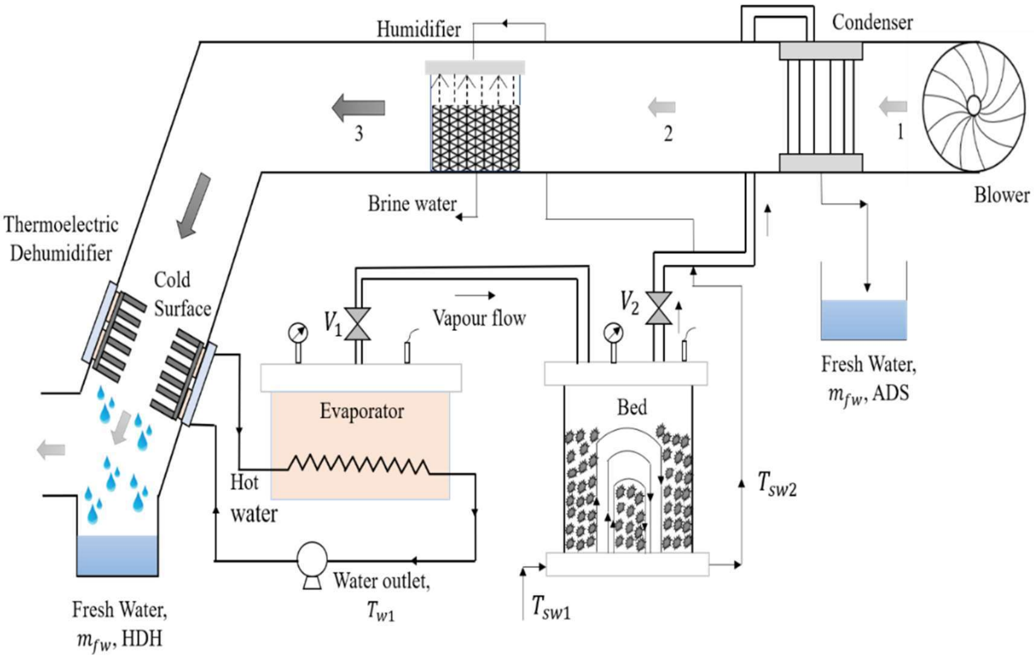


Fig. 4.1 Schematic diagram of TED integrated hybrid adsorption desalination system

The evaporator is initially saturated with salt water. The evaporator rapidly evaporates the water. In order to maintain the evaporation process, water is circulated through the evaporator and can be used for cooling purpose. Periodically, concentrated brine must be extracted for the regulation of the salinity level and salt concentration. When the valve between the evaporator and the adsorption bed is opened, the water evaporates and travels to the adsorption bed. The water vapour reaches the adsorbent layer, where it is adsorbed by the silica gel used as the adsorbent. During the adsorption process, heat of adsorption is generated, which can be mitigated by circulating cold water through the bed. The valve between the adsorbent bed and the evaporator is closed when the silica gel reaches its saturation level. The circulation of heated water through the bed now enables the desorption process. This can also be referred to as the regeneration of silica gel. The valve between the adsorbent bed and condenser is opened to allow the desorbed water vapour to enter the air-cooled condenser. In the condenser, the heat of condensation is rejected into the air passing through the condenser, resulting in condensation. Pure water is collected from the condensate. The top of the humidifier is sprayed with residual water from the adsorption bed, which is used to humidify the air moving towards the humidifier. This humidified air enters the thermoelectric dehumidifier, which heat sinks are placed at the cold side to transfer the cooling. When humidified air comes in contact with the heat sink, the heat is absorbed by the cold surface, resulting in condensation of the humidified air. Thus, the dehumidifier can produce purified water in addition to dehumidified air. The heat rejected from the hot side is transfer to the water which circulates through the water block in contact with the hot side of Peltier module, where the hot water can be used to circulate through the evaporator to increase the evaporation rate. This system enables the production of more purified water, a cooling effect, and dehumidified air. The evaporator, adsorbent bed, and condenser serve the same purpose as the previously described adsorption desalination system. The operation of the humidification and dehumidification systems is described in detail below:

4.1.1 Humidifier

A humidifier is used to enhance the air's moisture content. Utilizing the water which is circulated through the adsorption bed, the air from the air-cooled condenser is humidified. The water is discharged from the humidifier's top. When air flows into the humidifier, the air and water particles come into contact. The moisture will be added to the gases, resulting in the production of humidified air. Thus, the humidification process occurs.

4.1.2 Thermoelectric Dehumidifier

A dehumidifier is a device that removes air's moisture content. Humidified air from the humidifier enters the TED unit. By condensing the moisture, the humidity can be removed from the humid air. In order to condense it, the Peltier module cold side is used. To increase the cold surface area, heat sinks are placed which causes the moisture content in the air to get condensed so that the moisture is removed. Therefore, the air is dehumidified. Pure water can be collected from the condensate.

4.2 THERMODYNAMIC CYCLE OF ADS

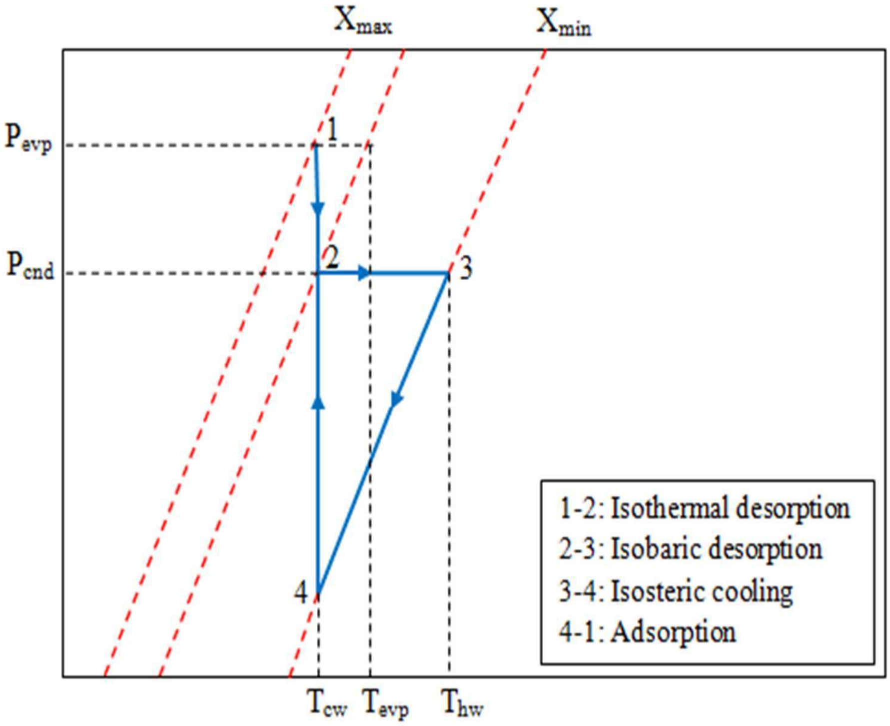


Fig 4.2 Thermodynamic cycle of ADS

At first vacuum is created within the evaporator; once the required vacuum level is reached, the V_1 and V_2 valves must be closed. Activate the power supply to the TEC unit, which will induce a cooling effect on the fins and release thermal energy on the hot side, which is supplied by circulating water to the evaporator. As a result, the saline water undergoes rapid evaporation under vacuum conditions when it receives thermal energy. To initiate the adsorption process, the valve V_1 must be opened between the evaporator and adsorbent bed. To remove the heat of adsorption, cooling water needs to be circulated through the heat exchanger passages of the adsorbent bed simultaneously. The adsorption process proceeds until the adsorbent bed is saturated with water vapour at the evaporator pressure, as depicted in Figure 4.2

After reaching the saturation state, the valve V_1 needs to be shut off in order to separate the adsorbent bed from the evaporator. Then, the valve V_2 must be opened to establish a connection between the bed and condenser, which results in a sudden decrease in bed pressure from P_{evp} to P_{cnd}, by process 1-2, causing the bed to transition to state 2. At this point, boiling saline water is circulated through the bed in order to initiate the desorption process and reach state 3. Using an air compressor, the desorbed water vapour from the bed is then condensed in the condenser. After steps 2-3, the valve V_2 must be shut off to separate the adsorbent bed from the condenser. The heat exchanger bed should then be circulated with cooling water in order to attain an optimal temperature for the adsorption process. This process is depicted by the line 3-4, while the concentration of the bed remains constant. Meanwhile, hot water is supplied to the evaporator from the TEC to facilitate rapid evaporation. Once the bed reaches state 4, the valve V_1 between the evaporator and adsorbent bed should be opened to initiate the adsorption process, allowing the bed to attain saturation at state 1. This procedure should be replicated for various conditions.

4.3 ADSORPTION DESALINATION MODEL

For the modelling of the AD system, following assumptions are considered:

1. The adsorbent material is homogenous for reducing the computational cost
2. All the system components are well insulated
3. The thermal resistance between the adsorbent tubes and the adjacent adsorbent is neglected
4. Pumping energy of the heating and the cooling water is neglected when compared with the amount of energy provided for heating

The Dubinin-Astakov (D-A) equation, which was employed before in the adsorption desalination system, can be used to calculate the uptake of water vapour by the adsorbent.

4.4 THERMODYNAMIC MODELLING OF TED

The modelling is done based on the following assumptions:

1. The TED components and the connecting tubes are well insulated
2. Temperature of the inlet moist air kept constant
3. The Peltier module's hot side temperature is maintained constant
4. The energy consumption for the air blower and the sea water pump is neglected

Thermoelectric Cooling system for dehumidification enhances the water productivity of the system. The rate at which water condenses, cooling capacity and COP can be determined by using the following equations:

Cooling Capacity, Q_c of TEM at the cold side,

$$Q_c = n \times (\alpha I T_c - 0.5 I^2 R - K (T_h - T_c)) \qquad (4.1)$$

Cooling Capacity (Q_h) of TEM at the hot side,

$$Q_h = n \times (\alpha I T_c + 0.5 I^2 R - K (T_h - T_c)) \qquad (4.2)$$

where, α = See beck coefficient (V/K)

R = electric Resistance of TEM (Ω)

K = Thermal conductance (W/K)

I = Electric Current (A)

T_h = Temperature at hot side of TEM (K)

T_c = Temperature at cold side of TEM (K)

n = Numbers of Peltier modules

$$\alpha = \frac{U_{max}}{T_h}$$ U_{max} = Maximum Voltage

$$R = \frac{(T_h - dT_{max})\, U_{max}}{(T_h \times I_{max})}$$

$$K = \frac{(T_h - dT_{max}) U_{max} I_{max}}{(2 \times T_h \times dT_{max})}$$

Input Electric Power of TEM,

$$P_{TEM} = n\ (I^2 R + \alpha I (T_h - T_c)) \qquad (4.3)$$

Input Electric Power of water pump,

$$P_{pump} = V \times I \qquad (4.4)$$

Coefficient of Performance of TED,

$$C.O.P = \frac{Q_c}{P_{TEM} + P_{Fan}} \tag{4.5}$$

Mass flow rate,

$$m = \rho\, A\, v \tag{4.6}$$

where, ρ = fluid density (kg/m^3)

A = Area (m^2)

v = Velocity (m/s)

Humidity Ratio,

$$w = 0.622 \times \frac{P_v}{P_b - P_v} \tag{4.7}$$

As a result, the amount of water condensate (m_{cw}) can be expressed as;

$$m_{cw} = [m_i w_i - m_i w_o] \tag{4.8}$$

where, m_i = mass flow rate of inlet moist air (kg/s)

m_o = mass flow rate of outlet dry air (kg/s)

w_i = inlet absolute air humidity ratio in kg(water)/kg(air)

w_o = outlet absolute air humidity ratio in kg(water)/kg(air)

4.3.1 Water Block Cooling

Energy Balance in the water block cooling placed on the hot side of the thermoelectric cooling for the removing heat.

$$Q_{in} + m_1 h_1 = m_2 h_2$$

$$Q_{in} = m\,(h_2 - h_1)$$

where, $Q_{in} = Q_h$

$$Q_h = m\, C_p\, (T_2 - T_1) \tag{4.9}$$

where, T_1 – Temperature of Cold water inlet

T_2 – Temperature of Hot water exit

4.3.1 Fin Efficiency Calculation

The fin efficiency of the heat sink can be calculated as follows (C.P. *et al.*, 2018):

Heat transfer coefficient:

Hydraulic diameter of square duct, $D_H = \frac{4a^2}{4a} = a$ (4.10) where, a = area of square duct

Average temperature, $\overline{T} = \frac{T_{in} + T_{out}}{2}$

where, T_{in} = inlet temperature of air

T_{out} = outlet temperature of air

Fully developed turbulent flow in Duct, $Re = \frac{U_\infty D_H}{\vartheta_f}$ (4.11)

where, U_∞ = velocity of air

ϑ_f = Kinematic viscosity of air

Dittus-Boelter Correlation,

$$Nu = 0.023\, Re_D^{4/5}\, Pr^n \qquad (4.12)$$

Heat transfer Coefficient, $h = \frac{Nu \times K_f}{D_H}$ (4.13)

where, K_f = Thermal conductivity of air

Fin Efficiency, $\eta = \frac{\tan h(mL)}{mL}$ (4.14)

where, $m = \sqrt{\frac{h\,P}{K\,A}}$

Area of fin cross-section, $A = t \times w$

Perimeter, $P = 2\,(t + w)$

L = length of the fin, t = thickness, w = width

Number of fins, $N_f = \frac{z}{spacing}$

Area of fin, $A_f = N_f \times P \times L$

Area of un-fin, $A_{uf} = (z \times w) - (N_f \times z \times t)$

Total Area of Fin, $A_{Total} = A_f + A_{uf}$

Overall-Fin Efficiency, $\eta_o = 1 - \frac{A_F}{A_{Total}}(1 - \eta_{fin})$ (4.15)

The mathematical modeling equations of thermoelectric dehumidification system are solved using MATLAB 2019. The unknown values of the equations are taken from the literature (Yu Yao *et al.*, 2017) is shown in table 4.1.

Table 4.1: Parameters used in the numerical study of TED (Yu Yao *et al.*, 2017)

Parameters	**Numerical Value**
Voltage (U)	16 (V)
Inlet Temperature (T_d)	308 (K)
Temperature Difference (dt_{max})	65
Hot Side Temperature (T_h)	300 (K)
Resistance (R)	2 (Ω)
Barometric Pressure (P_b)	101308 (N/m^2)
Gas Constant (R_a)	287 (J/kg K)
No. of Peltier Modules (n)	2-12
Duct Area (A)	0.0529 (m^2)
Air Flow Rate (F)	1813.877 (m^3/hr)

4.5 RESULTS AND DISCUSSIONS

The TED system is integrated with the adsorption desalination and cooling system with an aim to increase the water productivity, where the water productivity was increased in the TED unit.

Table 4.2: Comparison range for various numbers of Peltier modules at maximum operating conditions (T_h = 27 °C, RH = 90%)

Number of Peltier Modules	**Power Input (W)**	**COP**	**Water Productivity (g/hr)**
2	103.83	0.7180	147.20
4	294.40	0.7253	207.72
6	441.60	0.7349	311.66
8	588.80	0.7398	415.66
10	736	0.7428	519.71
12	883.2	0.7448	623.82

The table 4.2 illustrates the comparative range for utilising various numbers of modules at their maximum functioning condition. It has been determined that by increasing the number of Thermoelectric Modules (TEM) from two to twelve, water productivity increases with minimal variation in the coefficient of performance. However, as TEM is increased, input power is also increased. For this study, we are utilising eight TEMs in order to reduce the input power and obtain the optimal COP range.

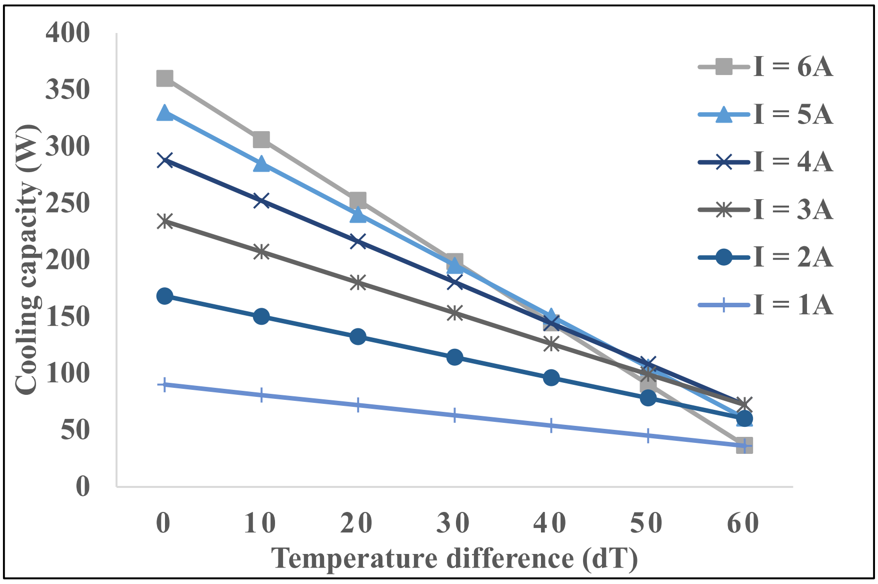


Fig 4.3 Variation in cooling capacity (Q_c) with the temperature difference (dT) for different current in 6 TEM at T_h=27 °C

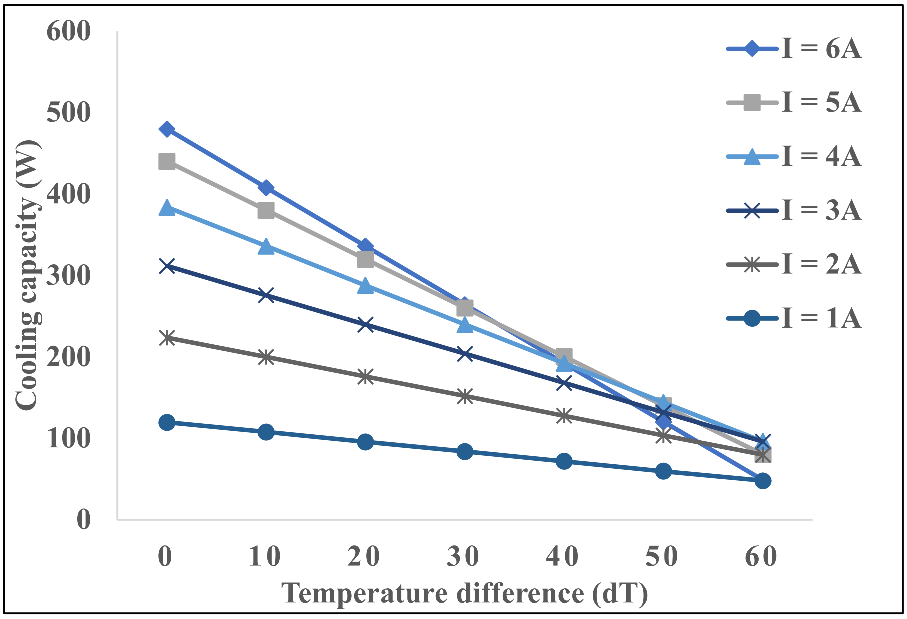


Fig 4.4 Variation in cooling capacity (Q_c) with the temperature difference (dT) for different current in 8 TEM at T_h = 27 °C

Figure 4.3 and 4.4, shows the variation in cooling capacity with the temperature difference between the hot and cold side of the thermoelectric module by using 6 TEM and 8 TEM. From the graph, it has been seen that the cooling capacity increases at maximum input current and it also depends on the temperature difference because with increase in the input current, the capacity of heat pumping of TEM rises and more energy is absorbed on cold side, while on the hot side more heat is released. When the hot side temperature is at 27°C, maximum cooling capacity will get at minimum temperature difference.

Figure 4.5 and 4.6, shows the variation in COP with the current at different temperature difference between the hot and cold side of the thermoelectric module by using 6 TEM and 8 TEM. From the graph, it has been seen that the COP increases at minimum input current and it also depends on the temperature difference because with the increase in the input current, cooling load increases along with the input power. It has been also found that the increase in the number of modules will not affect the COP of the TEC system.

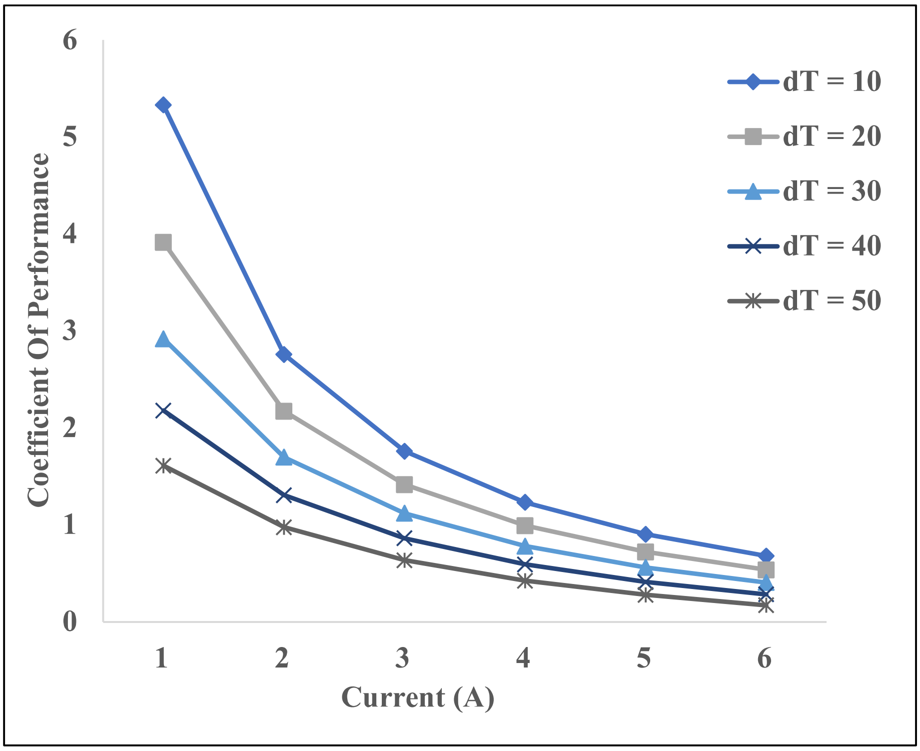


Fig. 4.5 Variation in COP with current for different temperature difference (dT) in 6 TEM at $T_h = 27$ °C

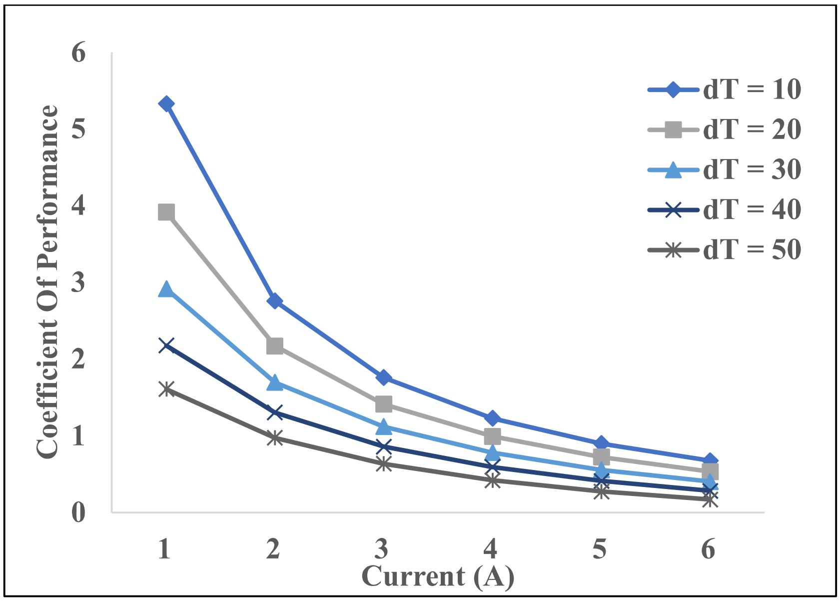


Fig. 4.6 Variation in COP with current for different temperature difference (dT) in 8 TEM at $T_h = 27$ °C

Figure 4.7 and 4.8, shows the variation in water generation rate (moisture removal rate) with the temperature difference between the hot and cold side of the thermoelectric module by using 6 TEM and 8 TEM. From the graph, it has been seen that the maximum water productivity will get at minimum temperature difference and the water productivity also increase with the increase in the Relative Humidity. It has been also found that the increase in the number of modules will also increase the water productivity.

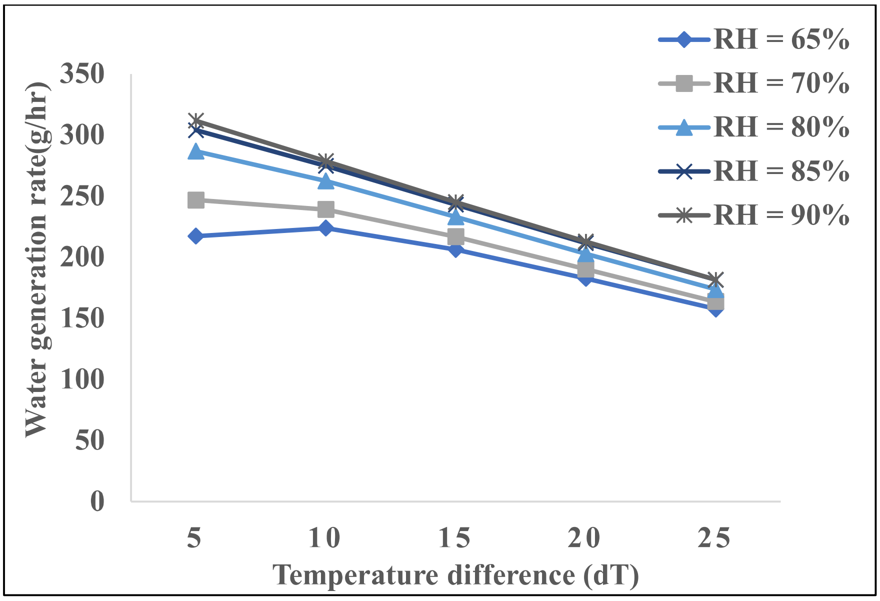


Fig. 4.7 Variation in water generation rate with the temperature difference (dT) for different relative humidity in 6 TEM at $T_h = 27$ °C

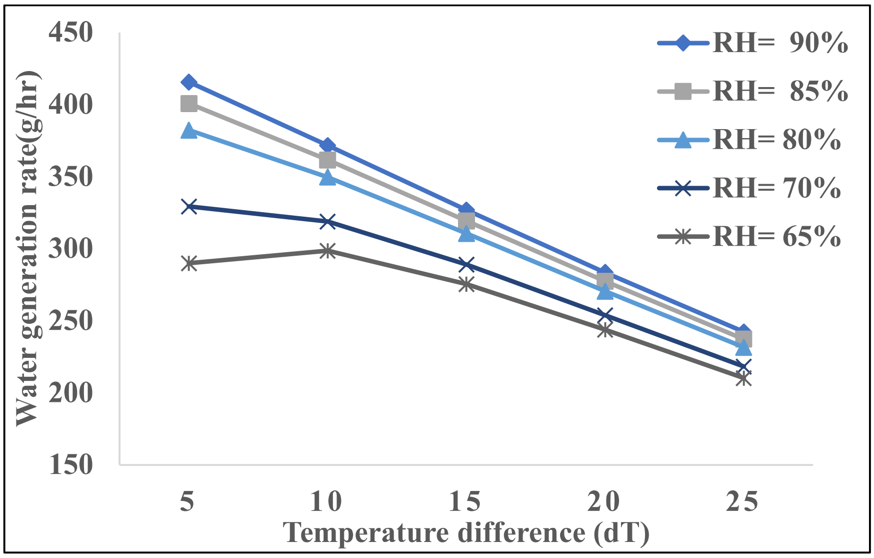


Fig. 4.8 Variation in water generation rate with the temperature difference (dT) for different relative humidity in 8 TEM at $T_h = 27$ °C

Figure 4.9 shows the variation in the hot water outlet temperature with flow rate for different time. The heat which is generated in the hot side of TEM is transfer to the cooling water which is circulating through the water block. Due to the increase in heat transfer rate, the temperature of heated water discharged from the TED unit rises when the flow rate of water decreases. By decreasing the water flow rate, the residence time for heat transmission between the water and TEM's hot surface can be increased.

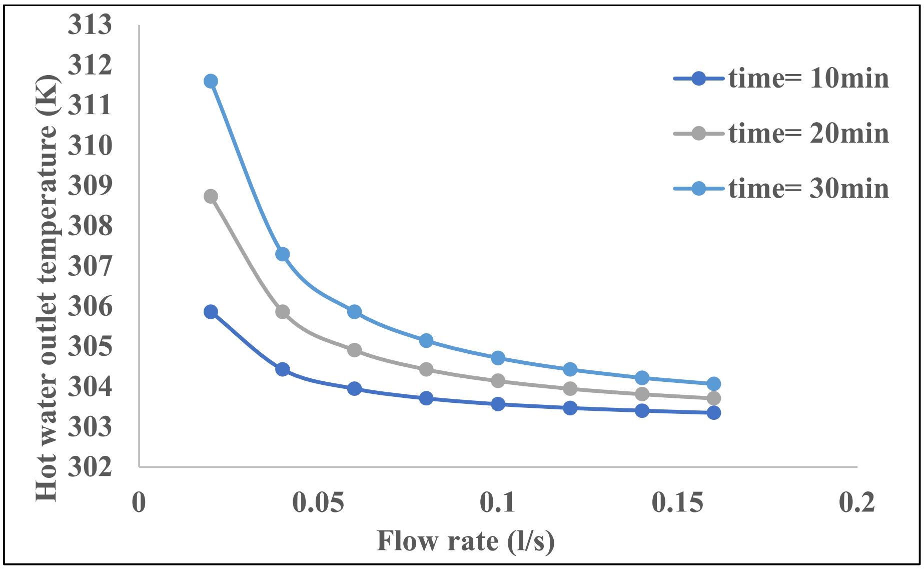


Fig. 4.9 Variation in hot water outlet temperature with flow rate for different time

Figure 4.10 depicts the variation in heat sink fin efficiency as a function of fin height. Due to an increase in the temperature difference between the base of the fin and its apex, the efficiency of a fin decreases as its height increases. Also, the total surface area of a fin increases as its height increases. Table 4.3 displays the value range for various rectangular heat sink heights.

Table 4.3: Fin efficiency of a rectangular heat sink

Height of Fin (m)	**Fin Efficiency (%)**	**Area of Fin (m^2)**
0.01	99.7	0.0166
0.03	97.5	0.0382
0.05	93.4	0.0599
0.07	88.01	0.0816
0.09	81.97	0.1033
0.11	75.65	0.1249

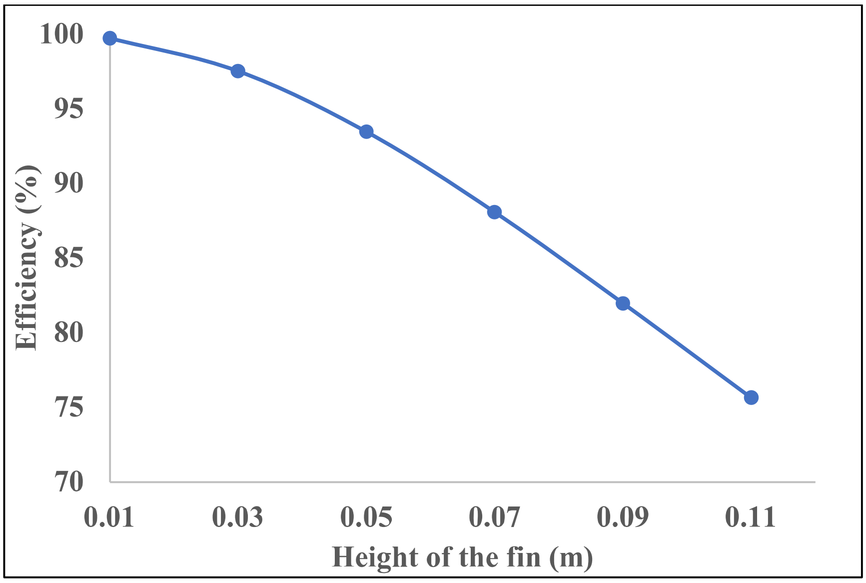


Fig. 4.10 Variation in the fin efficiency with the height of the fin

4.6 COMPARISON STUDY

The variation in the water production for the TEC alone unit and TEC integrated with existing adsorption system is shown in the Figure 4.11. The maximum water production for the TEC alone unit is 300ml/hr. When TED unit is integrated with the existing system, the water production of integrated TED can increase to 400 ml/hr.

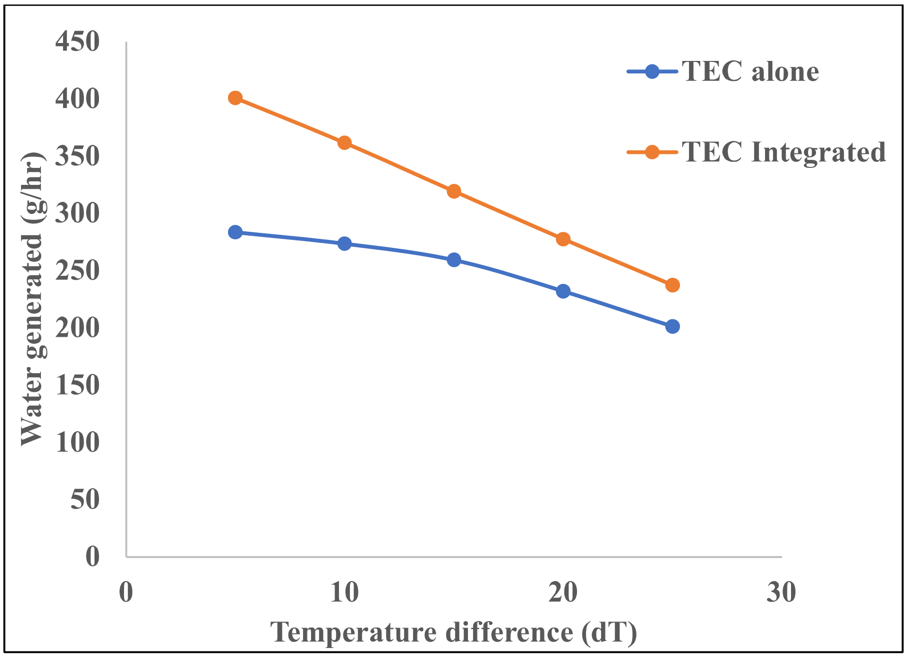


Fig. 4.11 Comparison of numerical study in TEC alone and Integrated TEC system

4.7 SUMMARY

The existing system is integrated with the thermoelectric dehumidification unit in order to increase the water productivity. The adsorbent used in this system is the silica gel and so that the water production from the adsorbent bed and the COP are same as that of the existing system. The waste water from the adsorbent bed and the chilled water from the evaporator are made use in the thermoelectric dehumidification unit and thus the fresh water is produced separately in this unit. The thermoelectric dehumidification unit alone can work with a water productivity of 300 ml in an hour. By integrating the TED unit with adsorption system may increase the water productivity up to 400 ml/hr in normal temperature. TED integrated hybrid system displays a 15% increase in the water productivity at atmospheric condition by comparing with the adsorption desalination system alone. The parameters such as the current input, relative humidity, and temperature difference between the hot and cold side of TEM play major role in the performance of the system.

CHAPTER 5

DESIGN, FABRICATION AND PERFORMANCE STUDY OF HYBRID SYSTEM

This chapter covers the design of a novel thermoelectric cooling system and the fabrication of the unit needed to carry out an experimental examination of a hybrid system that incorporates a TED unit. The various parts of the experimental setup and the parameters that are utilised to evaluate the performance of the hybrid system are covered in detail.

5.1 DESIGN MODEL OF TED UNIT

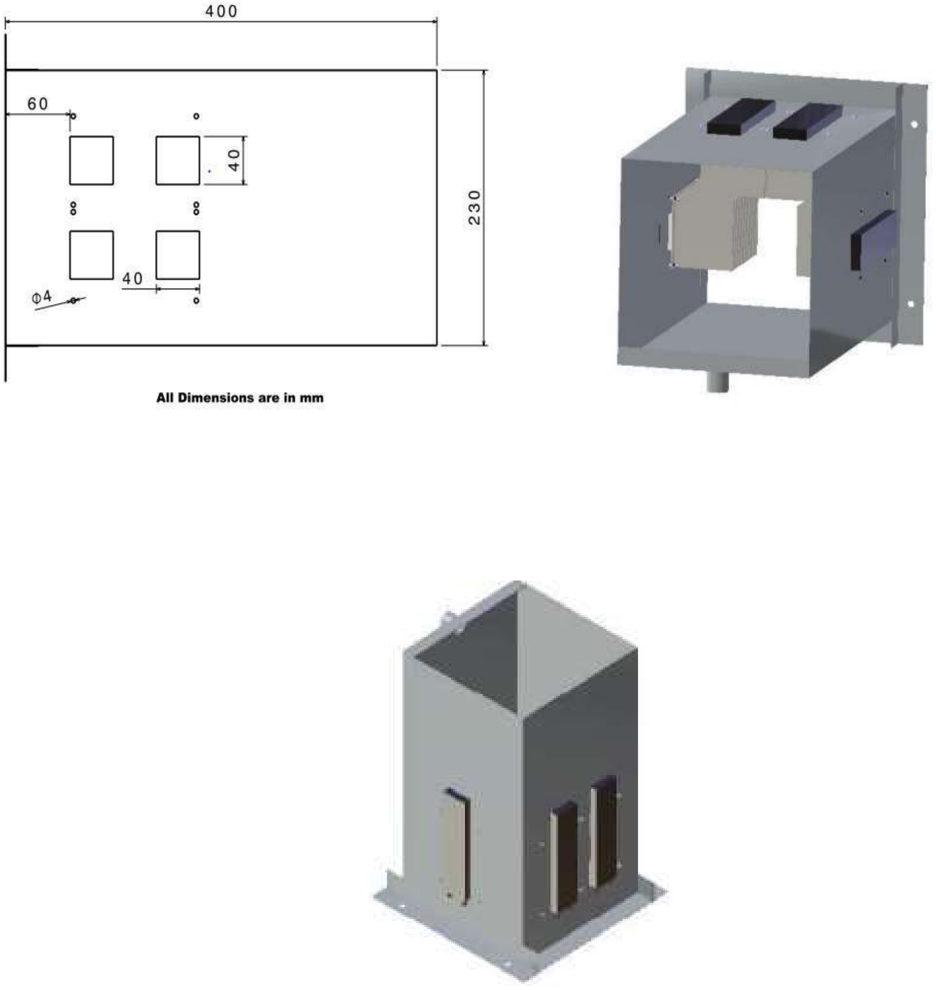


Fig. 5.1 CATIA design model of TED

In order to carry out the research, we make use of eight TEMs that have been appropriately positioned within a square duct system, as illustrated in Figure 5.1. In this configuration, four TEMs spaced equally over the top face of the duct, and two TEMs are positioned in an equal manner on opposing sides of the duct. Here, the hot side of the TEC is facing the atmosphere, while the cold side is towards the inside of the duct. On the cold side of the TEM, heat sinks are mounted in order to enhance the amount of cold surface area. The water block is connected to the hot side of the TEM, and water is made to pass through it so that the heat that is produced by the hot side of the TEM can be removed. The design model of the TED unit was made using CATIA V5 software.

5.2 MATERIAL PROCUREMENT

(a) Peltier Module: TEC1-12706

A Peltier module is an electronic component based on semiconductors that functions as a miniature heat exchanger. By applying DC power to a TEC, heat will be transferred from one side to the other. It produces a cold face and a warm side. The Peltier module is the primary element that constitutes the TEC unit. There are numerous variations of modules available; for the purpose of this investigation, TEC1-12706 modules measuring 40 mm × 40 mm in size were employed. Each module incorporates 127 semiconductors and has an input power of 72W (12V and 6A). In this case, the design calls for a total of 8 different modules to be used. Figure 5.2 depicts the Peltier modules that were utilised for the aim of the experiment. Table 5.1 shows the detailed performance specification of TEC1-12706.

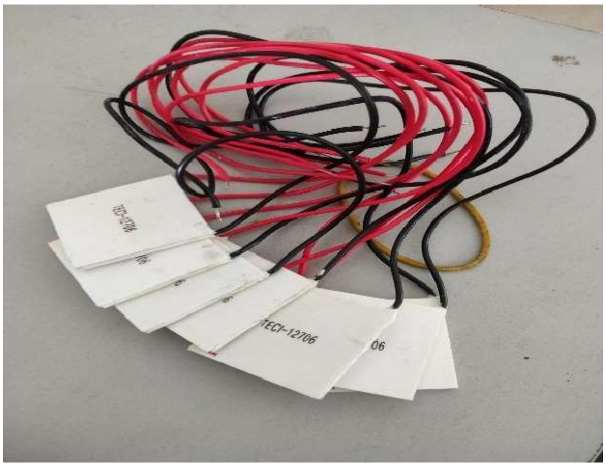


Fig. 5.2 Peltier module (TEC1-12706)

Table 5.1: Performance specification sheet of TEC1-12706

T_h (°C)	27	Hot side temperature at environment
dT_{max}	70	Temperature Difference between cold and hot side of the module when cooling capacity is zero at cold side
U_{max} (Voltage)	16	Voltage applied to the module at dT_{max}
I_{max} (amps)	6.1	DC current through the modules at dT_{max}
Qc_{max} (Watts)	61.4	Cooling capacity at cold side of the module under dT=0 °C
Resistance (ohms)	1.8 ~ 2.2	The module resistance is tested under AC

(b) Heat Sink

In this instance, rectangular heat sinks are utilised so that the cold surface of the thermoelectric module can be transferred. Each module has dimensions of 90 mm in length, 65 mm in width, and 90 mm in height, and it uses eight different heat sinks. Figure 5.3 depicts the heat sinks that were utilised for the purpose of the experiment.

Fig. 5.3 Rectangular heat sinks

(c) Water Block

On the colder side of a Peltier module, water blocks are used to circulate cold water. Here, four water blocks are used, one for each of two modules with a size of 120 mm in length, 40mm in width and 10mm in thickness. Each block has one inlet tube and one exhaust tube to transport water through it. Figure 5.4 depicts the water blocks used in the experiment.

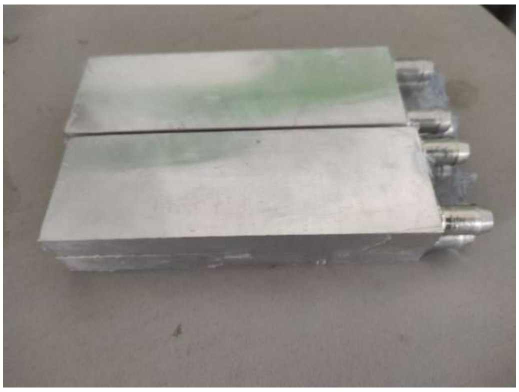


Fig. 5.4 Water blocks

(d) Thermal Paste

To improve thermal contact between electronic parts and heat sinks, solid substances called thermal paste are utilised. This substance has a high thermal conductivity and is often made of zinc oxide and silicone. Figure 5.5 displays the thermal paste (heat sink compound) that has been applied to make a thermal contact between the Peltier module and the heat sinks, as well as between the water blocks.

Fig. 5.5 Thermal paste

(e) Switched-Mode Power Supply (SMPS)

A switched-mode power supply (SMPS) is a type of electronic power supply that contains a switching regulator for efficient power conversion. An SMPS, like other power supply, transforms AC sources to DC applications. This study makes use of a 400-watt, 12-volt SMPS, as shown in Figure 5.6.

Fig. 5.6 Switched-Mode Power Supply (SMPS)

(f) W1209 Temperature Control Switch (Thermostat Sensor Module)

W1209 is a thermostat sensor module with a built-in microcontroller processor that does not require programming. The W1209 includes a high-precision NTC temperature sensor for measuring ambient temperature. The module's three tactile controls allow us to tailor the module's parameters to our specifications. It can detect temperatures ranging from -50 to 110°C and can be readily controlled via relay.

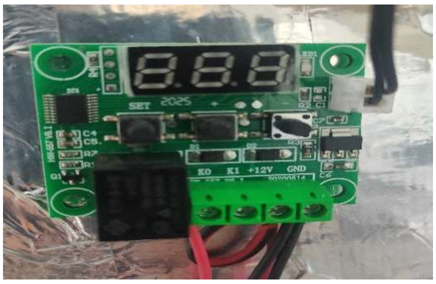


Fig. 5.7 W1209 Thermostat

5.3 DEVELOPMENT OF THERMOELECTRIC DEHUMIDIFICATION UNIT

5.3.1 Developed Initial Duct System

Figure 5.8 depicts the developed duct system that is used for TED's initial configuration. Here, a square duct measuring 230 mm in sides and 400 mm in length is utilised. 18-gauge Galvanized Iron (GI) sheet is used to construct duct. The sheet is bent into a square shape and welded. At one end of the duct, angle frames are affixed to provide bolting for connection with other systems. The duct is provided with square openings for the placement of Peltier modules.

Fig. 5.8 Developed duct system using GI sheet

5.3.2. Developed TED unit

Figure 5.9 depicts the developed TED unit. The developed duct system is used to assemble Peltier modules, heat sinks, and water blocks. After assembly, the duct unit has been insulated with aluminium tape to prevent leakage. To circulate water through the water block, hose tubes are connected to it. Parallel connections are provided to the Peltier module in order to provide voltage at an equal rate.

Fig. 5.9 Developed TED unit

5.4 OBSERVATIONS

The parameters of thermoelectric module are as follows:

Semiconductor Material – Bismuth Telluride (Bi2Te3)

Material 1 – Bismuth

Material 2 – Tellurium

See beck coefficient (α) = 5 × 10^{-2} V/K

Thermal Conductivity (k) = 0.578 W/ K

Resistivity (Ω) = 2 Ω

Table 5.2: Experimental Results of TEC

Time	Hot side temperature (°C)	Cold side temperature (°C)	Temperature difference (dT)	COP
0	30	30	0	0
5	32	28	4	0.695
10	33	26	8	0.651
15	34.5	24	10.5	0.623
20	37	22.5	14.5	0.595
25	38.5	22	16.5	0.586

Sample Case:

Test conditions for a sample case is shown below:

Peltier Dimensions = (40 × 40 × 4) mm
Current = 6 A
Voltage = 12 V
Resistance = 2 Ω
Temperature of Hot Side (T_h) = 33°C
Temperature of Cold Side (T_c) = 26°C
Ambient Temperature = 30°C
Number of modules = 8
Flow rate of water = 0.033 kg/s

Cooling Capacity, Qc of TEM at the cold side,

$$Q_c = n \times (\alpha I T_c - 0.5 I^2 R - K (T_h - T_c)) \tag{5.1}$$

$$= 8 \times ((5 \times 10^{-2} \times 6 \times 299) - (0.5 \times 6^2 \times 2) - (0.578 \times (33 - 26)))$$

$$= 397.232 \text{ W}$$

Input Electric Power of TEM,

$$P_{TEM} = n \times (I^2 R + \alpha I (T_h - T_c)) \tag{5.2}$$

$$= 8 \times ((6^2 \times 2) + (5 \times 10^{-2} \times 6) \times (33 - 26))$$

$$= 597.8 \text{ W}$$

Input power of water pump,

$$P_{\mathrm{pump}} = \mathrm{V} \times \mathrm{I} \tag{5.3}$$

$$= 12 \times 1 = 12\ \mathrm{W}$$

Coefficient of Performance of TED,

$$\mathrm{C.O.P} = \frac{Q_c}{P_{TEM} + P_{Fan}} \tag{5.4}$$

$$= \frac{397.23}{597.8 + 12} = 0.651$$

5.5 RESULTS AND DISCUSSIONS

The TED unit is integrated with the adsorption desalination and cooling system with an aim to increase the water productivity, where the water productivity was increased in the TED unit. The experimental setups and results are discussed below:

5.5.1 Experimental Setup of TEC unit alone

Figure 5.10 depicts the experimental configuration of the TEC unit with all connections made. SMPS, 12V relay, temperature controller, and digital hygrometer are connected to the developed TED unit in this instance. This configuration allows the TED unit to operate independently as an air-water generator.

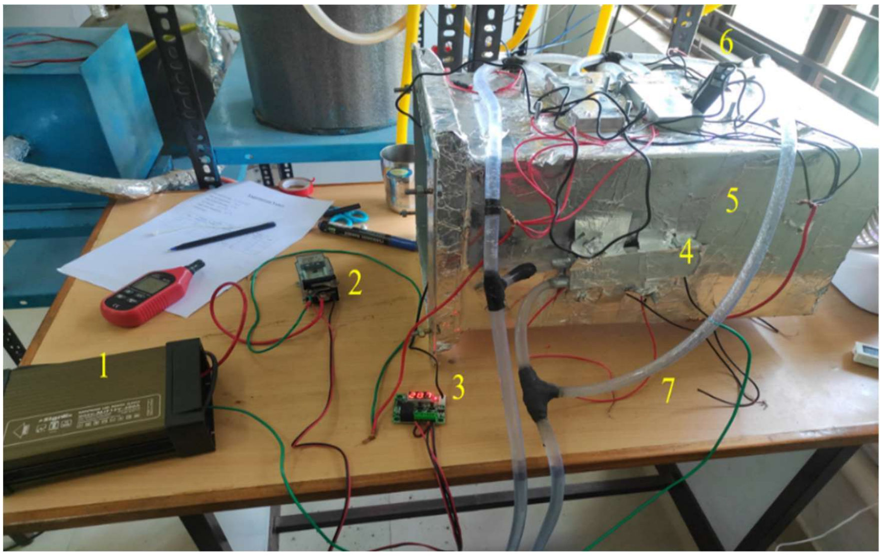


Fig. 5.10 Experimental setup of TED unit alone

(1) 12V SMPS (2) 12V 40A Relay (3) Digital temperature controller (4) Water Block (5) Duct (6) Digital Hygrometer (7) Water Hose Tubes

Figure 5.11 illustrates the variation in water production over time at various hot water temperatures on the hot side of the module. Due to the decreased condensation time, the quantity of water produced decreases as the hot side temperature rises. After 12 minutes of sustaining a temperature of 30°C on the hot side, condensation begins and water droplets form. This is due to the rapid decrease in dew point temperature. A maximum of 120 ml of water per hour has been produced by the TED unit alone.

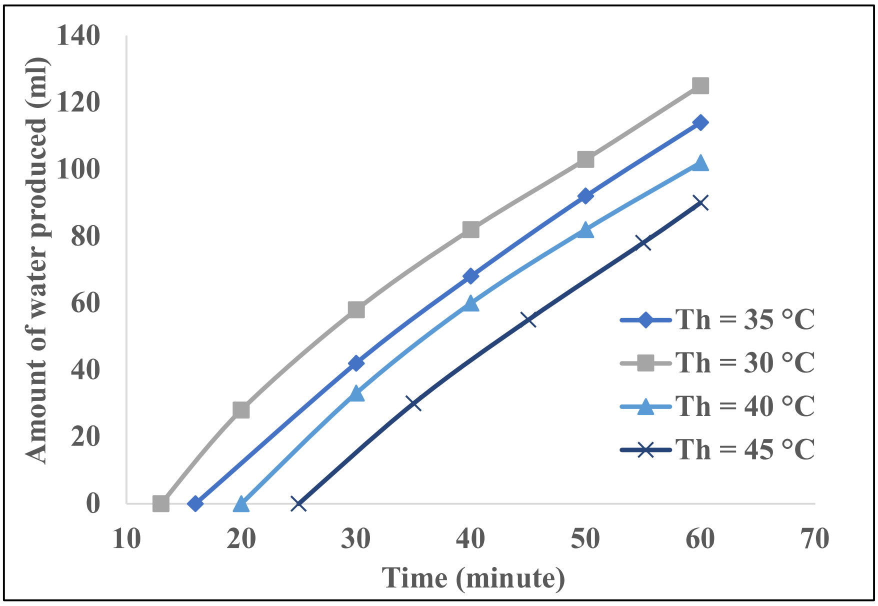


Fig. 5.11 Variation in amount of water produced with time at different hot water temperature

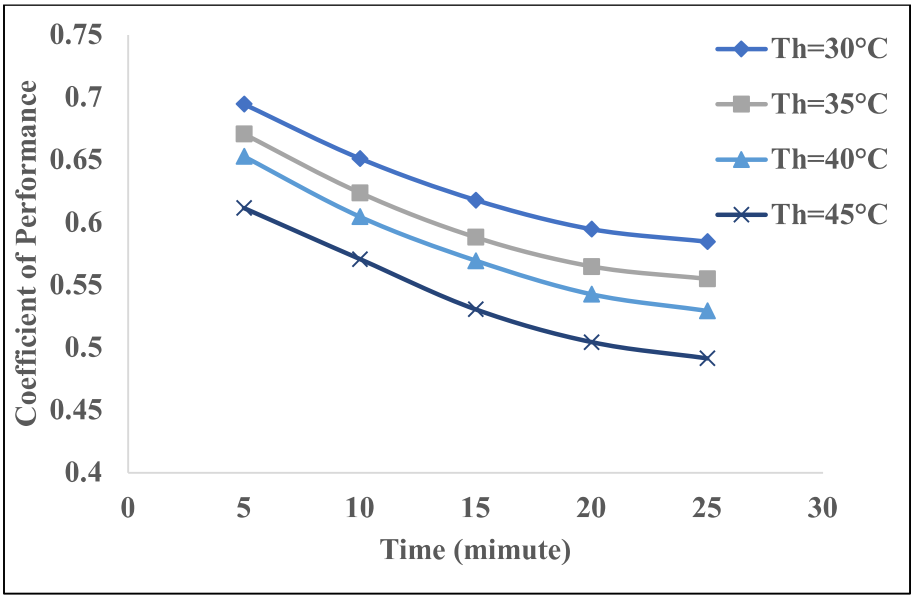


Fig. 5.12 Variation in COP with time at different hot side water temperature

Figure 5.12 depicts the change in COP over time at various heated water temperatures. It has been determined that the coefficient of performance (COP) decreases with time due to a decrease in the cold side temperature, which further reduces the cooling capacity. In addition, sustaining a minimum hot side temperature will increase the COP. By maintaining the hot side temperature at 30°C, the optimum COP will be approximately 0.70. Increasing the value of T_h decreases the COP due to the increased heat input at hot side.

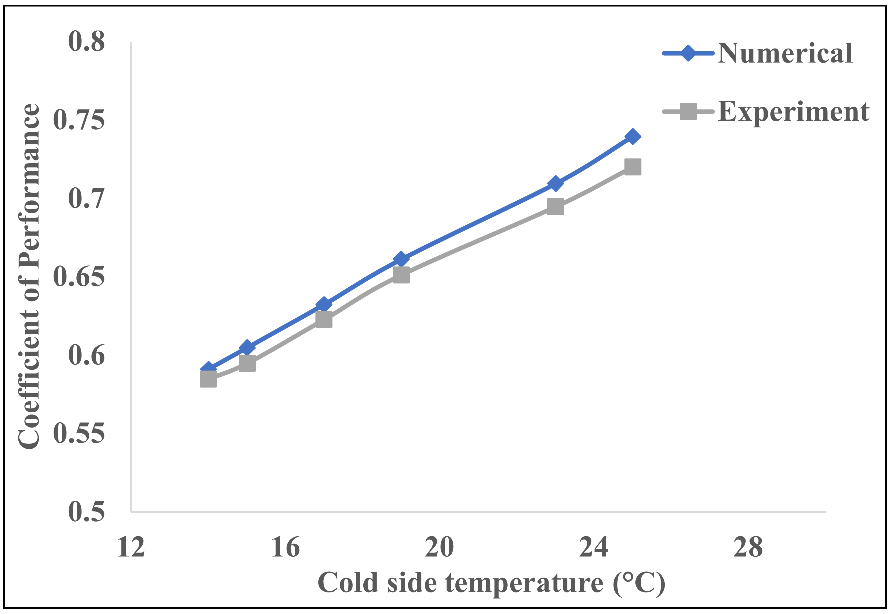


Fig. 5.13 Comparison of variation in COP with cold side temperature (T_c) at constant hot side temperature (30°C)

Figure 5.13 depicts the correlation between COP variation and cold side temperature (T_c). Compared to numerical values, there is a small variation in the COP range, which may be due to heat losses or variations in atmospheric conditions over time. The comparison range was plotted by keeping the hot side temperature at 30°C.

Figure 5.14 depicts the variation in the outlet temperature of heated water as a function of time and flow rate after absorbing heat from the hot side of a thermoelectric module. The outlet water temperature rises over time as the heat rejected by the heated side of the module increases. Here, three distinct water flow rates of 0.033 kg/s, 0.038kg/s, and 0.045kg/s are examined. A flow rate of 0.033kg/s will produce hot water with a maximal temperature of approximately 45°C in one hour. This is because the residence time permits greater heat transfer from the heated side of the TEM to the water.

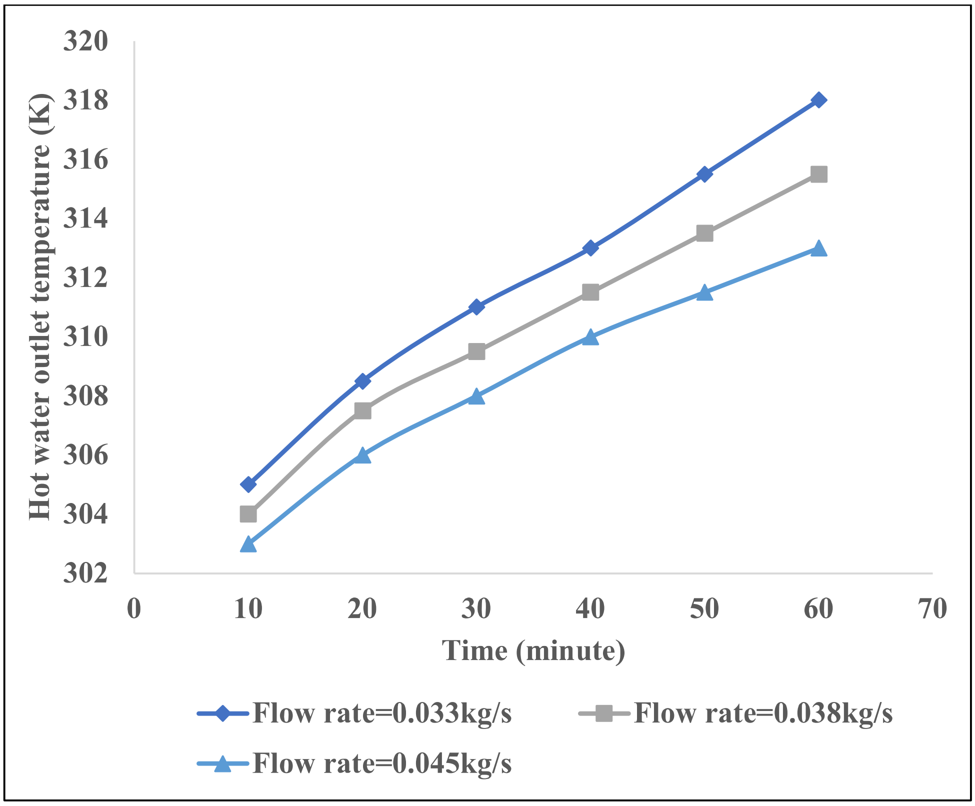


Fig. 5.14 Variation in Hot water outlet temperature at different flow rate

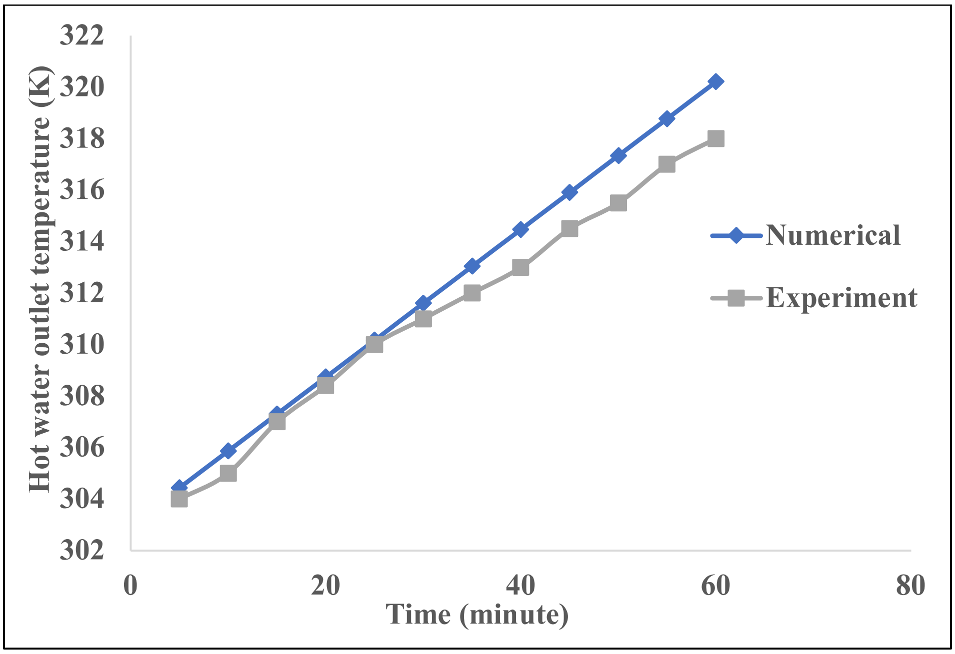


Fig. 5.15 Comparison of variation in hot water outlet temperature at constant flow rate (0.033 kg/s)

Figure 5.15 compares the variation in the outlet temperature of heated water at a constant flow rate of 0.033 kg/s. In one hour, the temperature can reach up to 50°C, according to a numerical investigation. In contrast, using the same flow rate in the experimental investigation will result in a maximum temperature of 45°C in one hour. A minor variation has occurred, which may be attributable to heat rejected to the atmosphere.

5.5.2 Experimental Setup of TED Integrated Adsorption Desalination System

Integrated TED and adsorption desalination system experimental configuration is depicted in Figure 5.16. It consists of an evaporator, adsorption bed, condenser, humidifier, and a thermoelectric dehumidification unit. Accordingly, connections have been made so that the TED unit has been attached to the duct which is connected to the humidifier. The water hose outflow tube that is connected to the coil that circulates through the evaporator in order to increase evaporation. After rejecting heat to the evaporator, cold water flows to the TED unit's inlet for circulation through the heated side of TED. In Figure 5.17 (1), (2) (3) shows the main components of the ADS system such as evaporator, adsorbent bed, and condenser.

Fig. 5.16 Experimental setup of TED integrated adsorption desalination system

(1) Evaporator (2) Adsorption Bed (3) Condenser (4) Blower (5) Humidifier (6) Thermoelectric Dehumidifier (7) Water tank

(1) Evaporator (2) Abdsorbent Bed

(3) Condenser

Fig. 5.17 Main components of ADS system

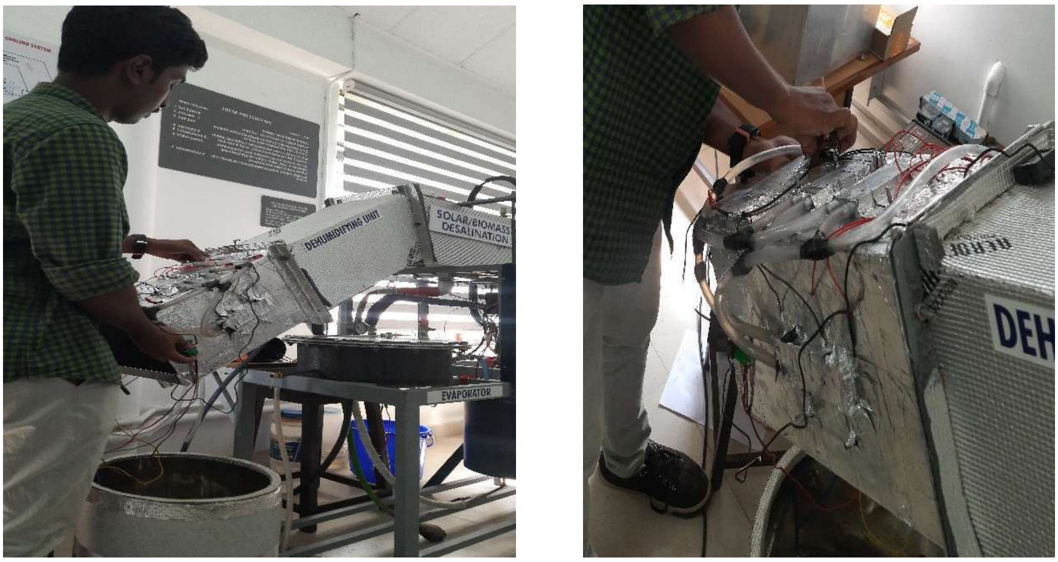


Fig. 5.18 Integrating TED with the ADS system

Figure 5.19 depicts the combined water productivity of the proposed system at various hot water temperatures that have been circulated through the bed during the desorption process. The greatest water output achievable with the combined system is approximately 3000 ml per hour. The adsorption system can generate up to 1300 ml of water per hour on its own, while thermoelectric dehumidification can produce up to 1700 ml of water per hour.

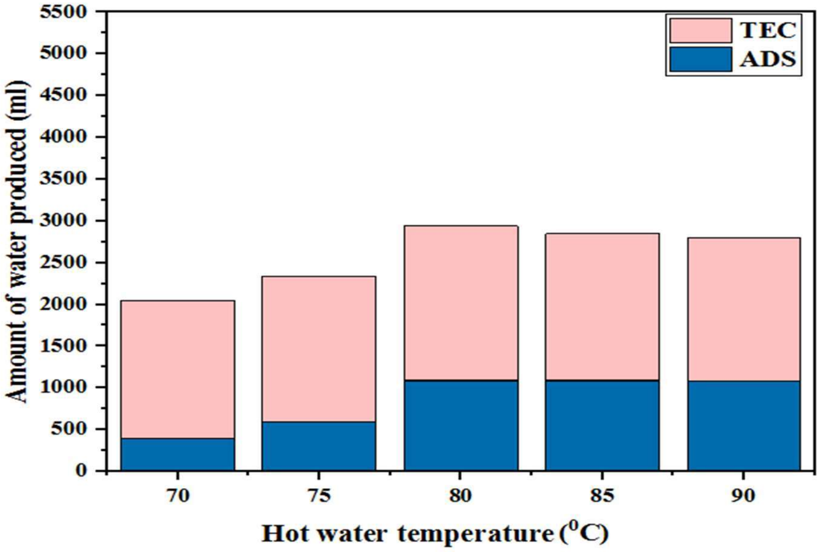


Fig. 5.19 Combined water productivity of the proposed system

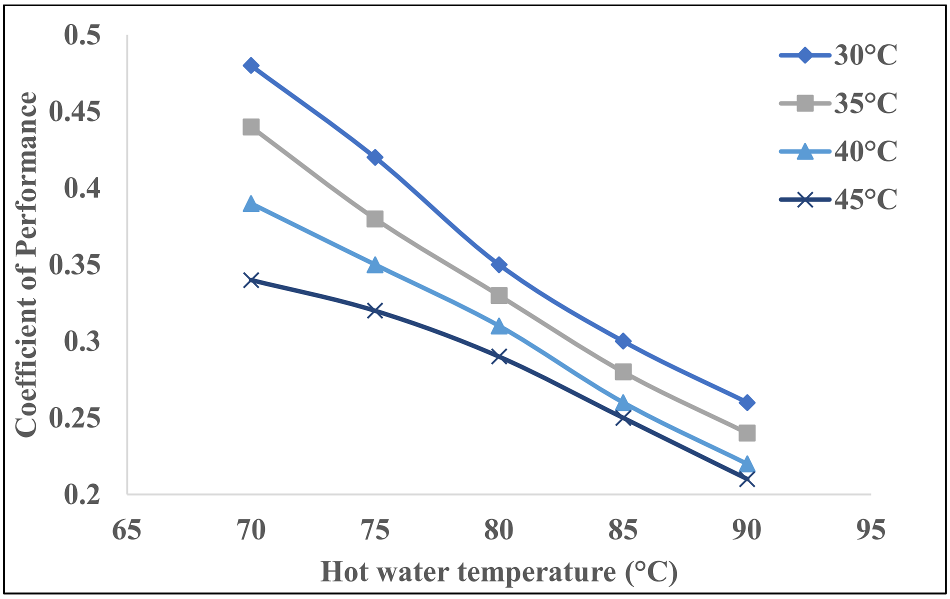


Fig. 5.20 Effect of hot water temperature variations on COP of the TEC for different evaporator water temperature

Figure 5.20 depicts how the COP varies with heated water temperature under various evaporator temperature conditions. Due to the presence of warm, humid air on the cold side of the TEC, its COP has decreased significantly. In addition, the COP of the TEC decreases regardless of the evaporator's inlet water temperature as the hot water temperature rises. Higher hot water temperatures cause more water vapour to desorb from the bed to the condenser, leading to increased condensation in the condenser. This increases the air's temperature as it absorbs latent heat from the condenser, causing more hot air to encounter the cold side of the TEC. Consequently, with a fixed temperature on the hot side, the temperature on the cold side rises, reducing the heat transmission between the cold and hot sides, thereby decreasing the cooling effect and COP of the TEC. In comparison to the functioning condition of the TEC alone unit, the COP of the TEC now varies from 0.4 to 0.1.

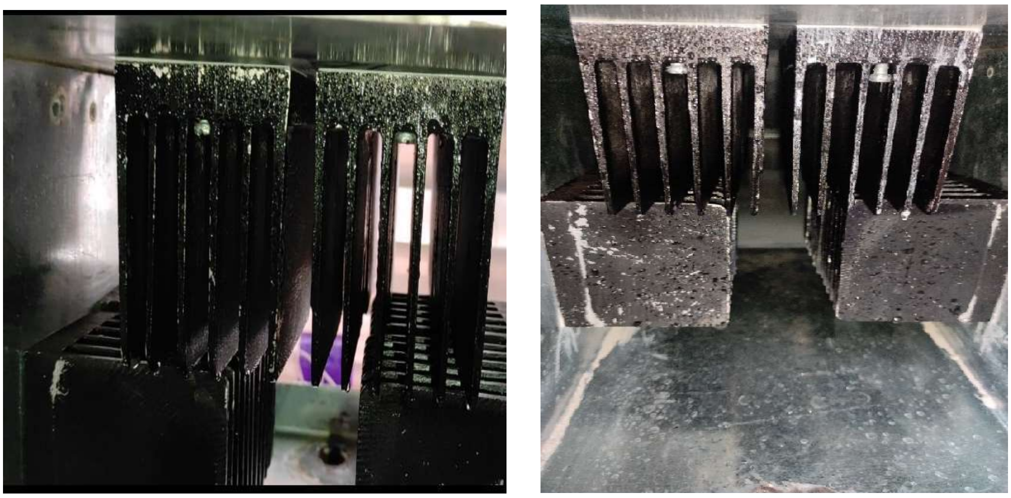
The condensation time of a heat sink is depicted in Figure 5.21. After five minutes, cooling is transmitted from the cold side of the Peltier module through the heat sinks. After 10 minutes, tiny water droplets begin to condense on the surface. After 15 minutes, water droplets are completely formed on the surface of heat sinks and starts to collect. The water droplets that are generated on the condensed surfaces of the heat sinks are collected as shown in Figure 5.22.


s

(a) (b) (c)

Fig. 5.21 Condensation time of the heat sink

(a) After 5 minutes, (b) After 10 minutes, (c) After 15 minutes



(a) (b)

Fig. 5.22 (a)Condensed surface of the heat sinks (b) water collecting from heat sinks

5.6 SUMMARY

The thermoelectric dehumidification unit is incorporated into the existing system in order to increase water productivity. The residual water from the adsorbent bed and the chilled water from the evaporator are used in the thermoelectric dehumidification unit, which produces fresh water separately and adds 3ml to the system's total productivity which is 56% more than the existing adsorption desalination system. In addition, the thermoelectric dehumidification unit's hot water outlet can be used to enhance the system's adsorption rate.

Table 5.3: Comparison of system performance

System	**Water productivity (l /hr)**
Adsorption desalination system	1.3
Hybrid system integrated with TED	3

CHAPTER 6

CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 CONCLUSIONS

This study analyses the efficiency of an adsorption desalination and cooling system. Variations of multiple parameters, such as water productivity, COP, and energy consumption, along with operating parameters are investigated. The primary operating parameters include the temperature of the heated water, the temperature of the cooling water, the temperature of the condenser, and the cycle time, among others. It is observed that this system's efficiency is lower. In order to enhance performance and reduce energy consumption, a new technology has been implemented. It is the combination of the TED system and the current system to develop a hybrid system. By integrating the TED unit, a distinct water generation can be produced and the total water productivity will increase.

(a) Using silica gel as the adsorbent, the water productivity of the current system has been found to be 1.3 kg/cycle.

(b) Various dehumidification techniques have been studied, and a thermoelectric dehumidification system has been numerically analysed.

(c) The parameters such as the current input, relative humidity, and temperature difference between the hot and cold side of TEM play major role in the performance of the system.

(d) Experimental study on the TED unit alone and TED integrated hybrid adsorption desalination system is done.

(e) TED unit can work alone as an air water generator which can produce a maximum water productivity of 0.3 l/hr.

(f) TED integrated hybrid system can produce a maximum water productivity of 3l/hr which is 56% more than conventional system.

6.2 SCOPE OF FUTURE WORK

(a) Analysis on the hybrid system by using composite adsorbents.

(b) Study on two-bed adsorption to enhance the performance of an adsorption desalination system.

LIST OF PUBLICATIONS

(1) Harikrishnan S, Baiju V, Abhishek P "*Analytical Study of TEC Integrated Solar Hybrid Adsorption Desalination System*," International Conference on Recent Advances in Materials, Processes, and Technology for Sustainability (RAMPTS 2023, GEC Thrissur)

(2) S Harikrishnan, V Baiju, P Abhishek *"Hybridisation of Adsorption Desalination System with Thermo-Electric Cooling and Humidification Process at Elevated Evaporator Temperatures: An Experimental Study"* (Energy Conversion and Management, Elsevier Publication, Communicated)

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