SOLAR ENERGY BASED DESALINATION SYSTEM USING HUMIDIFICATION-DEHUMIDIFICATION PROCESS

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

KUMARA

(148017 ME14P05)

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE-575025

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DECLARATION

I hereby declare that the Research Thesis entitled **"SOLAR ENERGY BASED DESALINATION SYSTEM USING HUMIDIFICATION- DEHUMIDIFICATION PROCESS"** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy in Mechanical Engineering is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any other Universities or Institutes for the award of any degree.

Register Number: **148017 ME14P05**

Name of the Research Scholar: **KUMARA**

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Place: NITK, Surathkal

Date: 18-07-2022

CERTIFICATE

This is to certify that the Research Thesis entitled **"SOLAR ENERGY BASED DESALINATION SYSTEM USING HUMIDIFICATION-DEHUMIDIFICATION PROCESS"** *submitted by* **KUMARA (Register Number: 148017 ME14P05)** as the record of the research work carried out by him, *is accepted as the Research Thesis submission in partial fulfilment of the requirements for the award of the degree of* Doctor of Philosophy.

Research Guide

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KUMARA THANAIAH

ABSTRACT

Solar desalination is one of the most promising techniques used in the production of fresh water for many decades. The technique has evolved with a number of innovations in recent years with which it can compete with water technology market as well. A combination of solar desalination and paddy grass humidifier represents a distinguished technique in solar desalination process. The current research work is aimed at addressing water scarcity problems faced across the globe. This thesis attempts to incorporate Humidification-Dehumidification Desalination Technique (HDHT) using artificial and bio-based packing materials. A detailed thermodynamic analysis was conducted for Paddy Grass Humidification Dehumidification Desalination System (PHDD) in current study through mathematical and experimental methods. In order to produce the maximum amount of fresh water, two configurations were developed and analyzed under weather conditions prevalently observed in the southern states of India. First, the experiments were carried out with artificial packing material (Polypropylene) with and without baffle plates. Next, bio-based packing material (Paddy grass) was used in the second set of configuration with and without baffle plates. The study found that 0.39, 0.46, and 0.73 kg/h of fresh water was produced respectively for without, artificial and bio-based packing materials. The rate of fresh water production got increased to 17% and 46% respectively for artificial and bio-based materials. There was an increase observed in Gain Output Ratio (GOR) as well, in the range of 0.28, 0.40, and 0.65 for without, artificial, and bio-based packing materials. GOR got increased up to 30% and 56% when using artificial and bio-based packing materials respectively. When the inlet temperature of cooling water, to the dehumidifier, was reduced from 40ºC to 20 ºC, it increased the production of distilled water significantly.

The performance of PHDD system was evaluated through various physical parameters such as solar collector area, reservoir water tank volume and the temperature of water reservoir. The author conducted cost benefit analysis of the system against other desalination methods. In this analysis, the amount of potable water produced, the amount of energy consumed and the cost incurred upon components were compared. The results revealed that irrespective of paddy grass area, the volume of the storage water tank, below and above 40 L, is not considered to be optimal. The cost analysis conducted for the present work proved that the system can function at low maintenance cost in comparison with other similar studies and the price of the yield is approximately 19\$/m^3. The solar collector area exerts a significant influence upon the augmentation of water yield. The optimal ratio of water reservoir to collector area was 13 L/m^3. The present study infers from the experimentation procedure that the bio-based paddy grass packing material is highly advantageous for small-scale fresh water production in remote regions.

Keywords: *Desalination, Humidification-dehumidification, potable water, Paddy grass packing material, heat transfer, mass transfer.*

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NOMENCLATURE

A	Area (m^2)	***Greek letters***	
C	Specific heat (kJ/kg-K)	α	Absorptivity
d/D	Diameter (m)	ε	Effectiveness
F	Friction factor	w	Humidity (kg/kg)
H	Enthalpy (kJ/kg),height (m)	τ	Transmitivity of glass
H_v	Latent heat of water evaporation	η	Efficiency
h	Convection heat transfer coefficient (W/m^2-K)	**Subscripts**	
I_s	The solar radiation (W/m^2)	a	Air
k_c, λ	Thermal conductivity (W/m-K)	c	Cold side
L	Length (m)	cal	Calculated
Le	Lewis number	D	Dehumidifier
M	Mass flow rate (kg/s)	M_w	Fresh water in the collector
NTU	Number of Transfer Units	H	Humidifier
N_U	Nusselt number	i	Inlet
P	Pressure (Pa)	o	Outlet
P_L	Transfer pitch (mm)	max	Maximum
P_T	Longitudinal pitch (mm)	s	Solution
Pr	Prandtl number	Solar	Solar energy
Q	Heat transfer rate (kW)	tot	Total
Re	Reynolds number	Test	Tested
S_h	Sherwood number	Lat	Latent
T	Temperature (^oC)	Sen	Sensible
U	Heat transfer coefficient (W/m^2-K)	th	Thermal
V	Active humidifier volume to area		
A	Contact area to humidifier volume		
K	Mass transfer coefficient (kg/sm^2)		
U	Velocity (m/s)		
W	Power (kW),width (m)		
x	Spatial coordinate (m)		
y	Spatial coordinate (m)		
T	Thickness (mm)		
X	Solution concentration		

CHAPTER 1

INTRODUCTION

1.1 Shortage of potable water and current technologies

Water and energy are the two close by and basic needs of life. Energy is required for the production and supply of potable water to all households in a community (Gude et al. 2010). Though water is abundantly available in Earth, there exists a lack of sustainable fresh water resources across the global nations. According to WHO recommendations, a person should limit their potable water consumption by 15-20 liters on an average a day to meet the community's basic needs. It is an important challenge for today's governments to provide safe, sufficient, and quality potable water in required quantities to the people and to ensure that the requirement is met in the future too. For a long known time, water resources such as lakes, rivers, and subsurface waters have been used by human beings, plants, and animals for their water needs. But, the tremendous increase in industrialization and drastic population growth in the recent decades led to multiple-fold increase towards the demand for fresh water. The global community is impaired as well, at this crucial moment with limited sources. Currently, across the globe, 3.5 million individuals (https://www.un.org/en/) are prone to pre-mature death as a consequence of insufficient water source and hygiene. This emphasizes the importance of water as a serious universal reserve. Figure 1.1(a) illustrates a forecast on water stress that would be experienced by countries in the year, 2040 (Note and Summary 2015).

The rapid shortage of fresh water occurs as a result of increase in population growth, direct discharge of high amount of pollutants from industries into water resources and vanishing fresh water reserves. Oceans constitute nearly 97% of global water reserves whereas only 3% of water is potable which is mostly present in the poles. Desalination plants which use conventional techniques such as reverse osmosis, multi-effect flash etc. are not adequate for medium scale production of fresh water (Kabeel et al. 2013). There have been continuous efforts taken to resolve the problems regarding potable water production by leveraging modern technologies. Research investigations are ongoing to find a suitable, optimum and the best technology that can help in the production of fresh potable water since it is challenging for the scientific community to find a reliable, consistent, and cost-effective technique. Among the available techniques, saltwater desalination is considered to be a suitable and optimal technique due to its simplicity and cost-effective nature. Solar-based desalination technique (Wu et al. 2016) i.e., multi-effect desalination approach is widely adopted these days. However, this technology has few drawbacks such as low gain output ratio and huge space requirement. For potable water generation, several nations depend upon desalination plants to meet their daily water requirements. Various nations shifted their attention towards water purification technologies, for instance desalination, to overcome the shortage of fresh water. To be specific, water purification using desalination method is the most common method of producing potable water in Middle East region, waterless-isolated zones and a few islands. These nations understood the potentials of desalination technique in harvesting potable water. The size of desalination plants, installed in Middle East and North Africa (MENA) countries and Iranian Gulf, accounts up to 50% of the total global capacity. Saudi Arabia has the largest desalination capacity in the world. Nearly 15,906 (Jones et al. 2019) desalination plants function across the globe and produce 95.37 million m^3/day across 177 nations and territories. However, this capacity is expected to increase up to 192 million m^3 per day.

Though a number of technologies exist to reestablish the need for reduced water demand, most of these techniques are energy-demanding and therefore cannot support in the production of potable water. The depletion of non-renewable energy sources coupled with environmental impact during energy production emphasized the need to identify sustainable energy production methods to meet future water requirements.

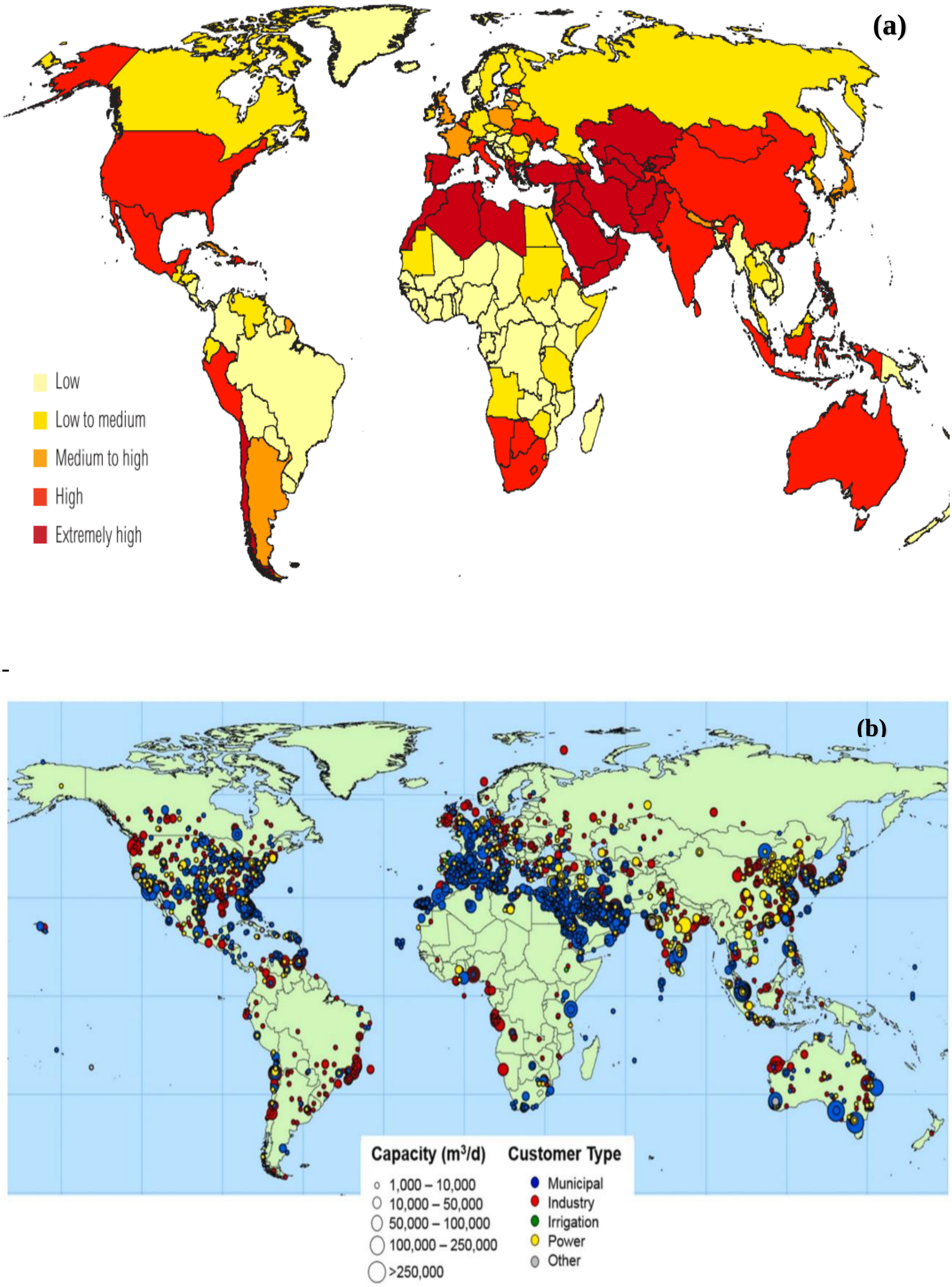
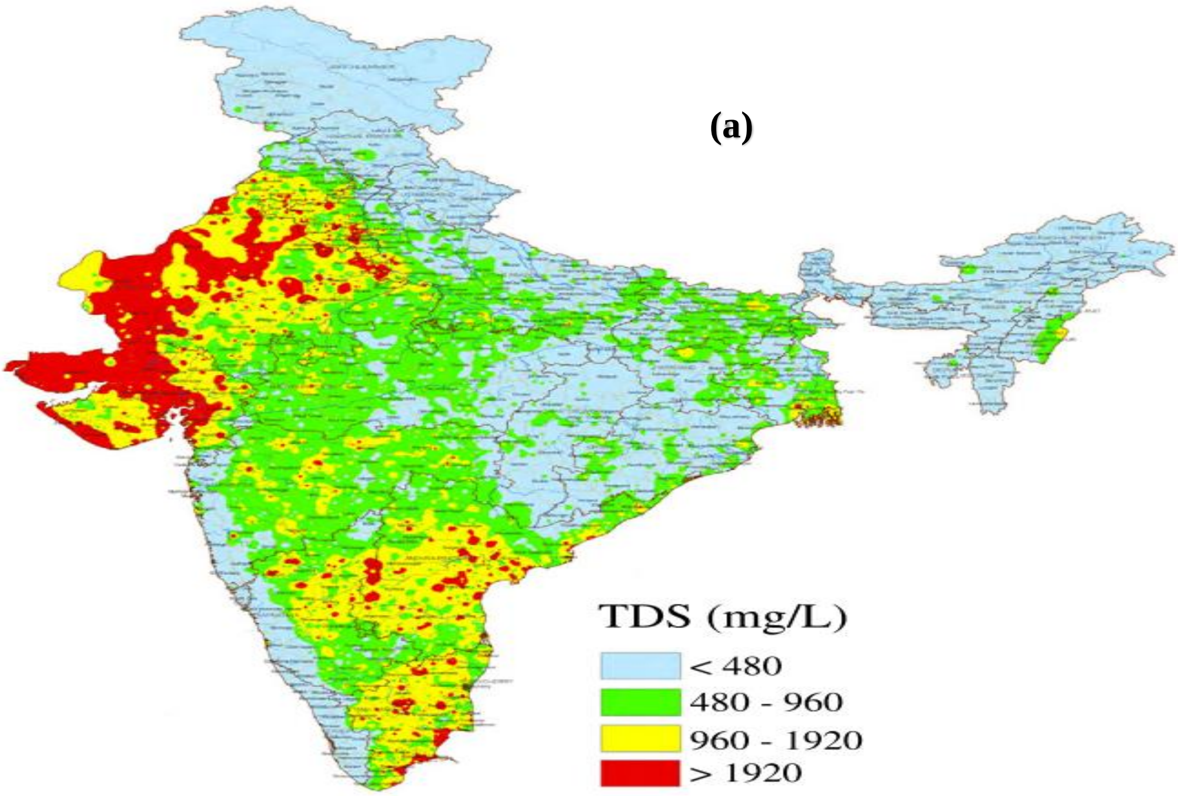


Figure 1. 1: (a) Estimated water stress in 2040 (b) World Desalination Capacity (Jones et al. 2019).

Water purification using desalination has been leveraged by several nations that face severe fresh water shortage. To be specific, water desalination plants have become the primary source of pure water production in dry and arid regions such as MENA, waterless-isolated zones and a few islands. These nations leverage desalination techniques to produce potable water from different sources of water. Middle East, Persian Gulf and North African countries occupy top positions in terms of desalination plant capacity and it accounts up to 50% of the global desalination plant capacity. Figure 1.1 (b) illustrates the prevalence and capacity of desalination plants incorporated across the globe.

India consists of nearly 0.6 million villages and the population in these villages accounts up to 0.8 billion. Out of this population, 11 % people do not have access for potable water. Nearly 73% of Indian villages utilize underground water for drinking and other basic needs (Wright and Winter 2014). In general, underground water has high biological quality compared to surface water whereas 60% of the ground water in India has more than 500 mg/L TDS concentration. So, it may not be a suitable source for drinking purposes. India's fast increasing population, rising economy and varying lifestyles account for continuous rise in fresh water requirement. This results in the scarcity of fresh water reserves and depletion of ground water reserves in various states of Indian subcontinent. Most of the regions in India experience high demand for potable and normal water due to unplanned activities and contamination generated from human activities. The yearly report published by Ministry of Water Resource (Shekhar et al. 2015) cites that several districts in Rajasthan and Gujarat face severe shortage of water. On the other hand, these regions are blessed with enough quantity of solar energy across the year. This solar energy can be tapped through affordable and sustainable techniques for the production of potable water. In states such as Haryana and Maharashtra, the underground water in most of the regions is saline in nature and remains unfit for consumption. India is blessed with abundant quantities of solar energy across the year. Energy production from solar radiation per day tend to vary from 4 to 7 kWh/m^2 based on the location. Further, the country along with its territories has a broad coastal area spanning 7,516 km.



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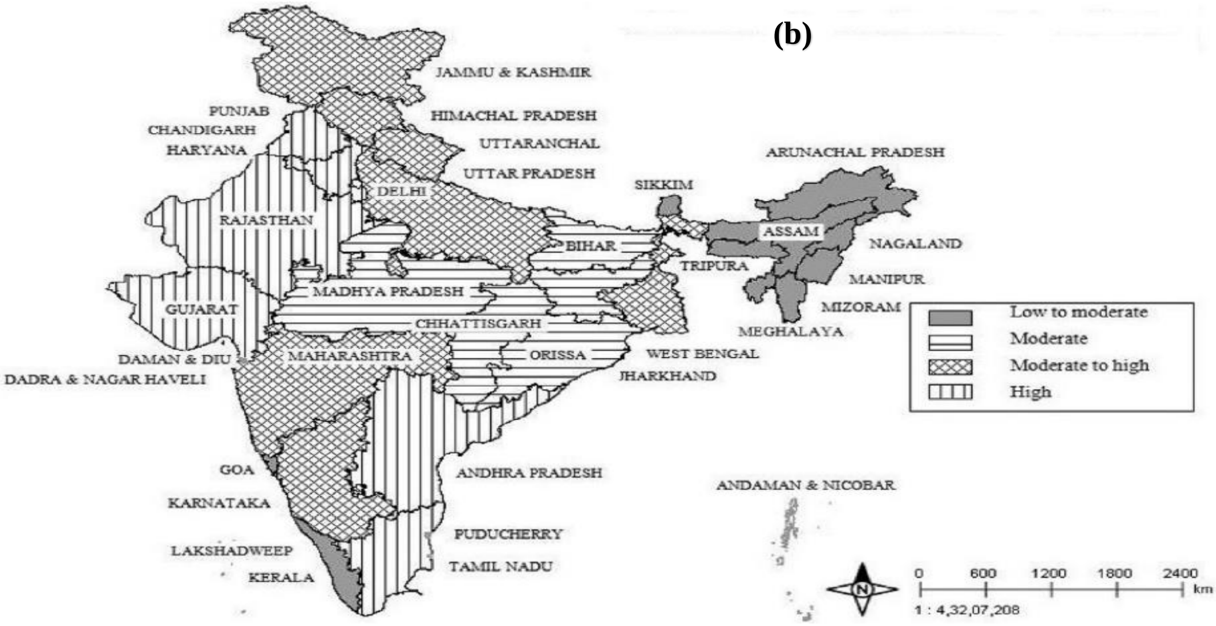


Figure 1. 2(a) Water salinity (b) Water scarcity levels in different regions of India (Wright and Winter 2014).

The application of renewable energy sources such as solar energy in desalination techniques is a promising inclination, since these techniques help in producing low-grade heat energy. According to this viewpoint, solar-based humidification-dehumidification process is a promising method for potable water production. As per this approach, solar-heated saline water is utilized to humidify the air (humidification). Then, the humidified air is cooled to produce fresh water.

1.2 Desalination Technologies

Life on earth has two primary challenges that needs to be overcome in the upcoming days i.e., energy scarcity and the shortage of fresh water. Both these challenges pose serious threats to life on earth as it plays an important role in the economic development of a nation and day-to-day activities of human beings. Figure 1.3 shows the classification of various desalination techniques under phase change and single phase. Some of the crucial and traditional desalination techniques that function on the basis of heat energy are Multiple Effect Distillation (MED), Multi-Stage Flash (MSF) and Vapor Compression (VC). In the last method i.e., Vapour Compression (VC), the compression is achieved either thermally as in Thermal Vapor Compression (TVC) or else mechanically i.e., Mechanical Vapor Compression (MVC). In general, traditional desalination techniques demand huge operation space and technology-intensive systems. Countries that are rich in energy production and economically stable can afford such traditional techniques. Having been driven with fossil fuel-based energy, these traditional technologies harm the environment and create brine disposal problem too.

On the other hand, small and remote areas gain huge benefits from Humidification-Dehumidification (HDH) systems which are much more advantageous than the traditional systems. So, it becomes essential to develop a cost-effective and environmental-savvy solar collector to achieve overall feasibility. In desalination process, salt and other minerals are removed from water source, primarily sea water or brackish water. Various desalination procedures exist such as Reverse Osmosis (RO), Humidification-Dehumidification (HDH), Multi Flash Desalination (MFD), Multi-Effect Desalination (MED), Electrodialysis (ED), solar still and Membrane Distillation (MD). Desalination process requires heat and mechanical energy which can be supplied by solar powered systems.

In Gulf and Middle Eastern countries, Multi-Stage Flash (MSF) technique is preferred for desalination process to produce fresh water. The capacity installed in these regions accounts up to 40 percent of the global capacity. The working principle behind the functioning of MSF is that the water vapour is produced by heating sea water.

Figure 1. 3: Different kinds of desalination processes (Alnaimat et al. 2021).

1.3 Reverse osmosis desalination

Reverse Osmosis (RO) is a membrane-based desalination process to produce fresh water. It was first proposed and implemented by (Müller-Holst et al. 1998). Reverse Osmosis works on the principle that in the presence of two chambers separated by a semi-permeable membrane, the translocation of molecules occurs from high concentration to low concentration. In such way, the sea water containing heavy concentration of salts is forced to pass through semipermeable membrane so as to separate the salts from it. The pressure to be applied must be higher than the than osmotic pressure in order to separate the salt from sea water (Figure 1.4). Polymeric composites are the most popular membranes since it permits only the transfer of water, not salt. The membranes are arranged as spiral wound shape through which the saline moves between the horizontal membranes, covered around the centre tube. When compared with other desalination methods, reverse osmosis method consumes less amount of energy(Hou et al. 2005). However, the main drawback of RO plant is the fouling of membranes.

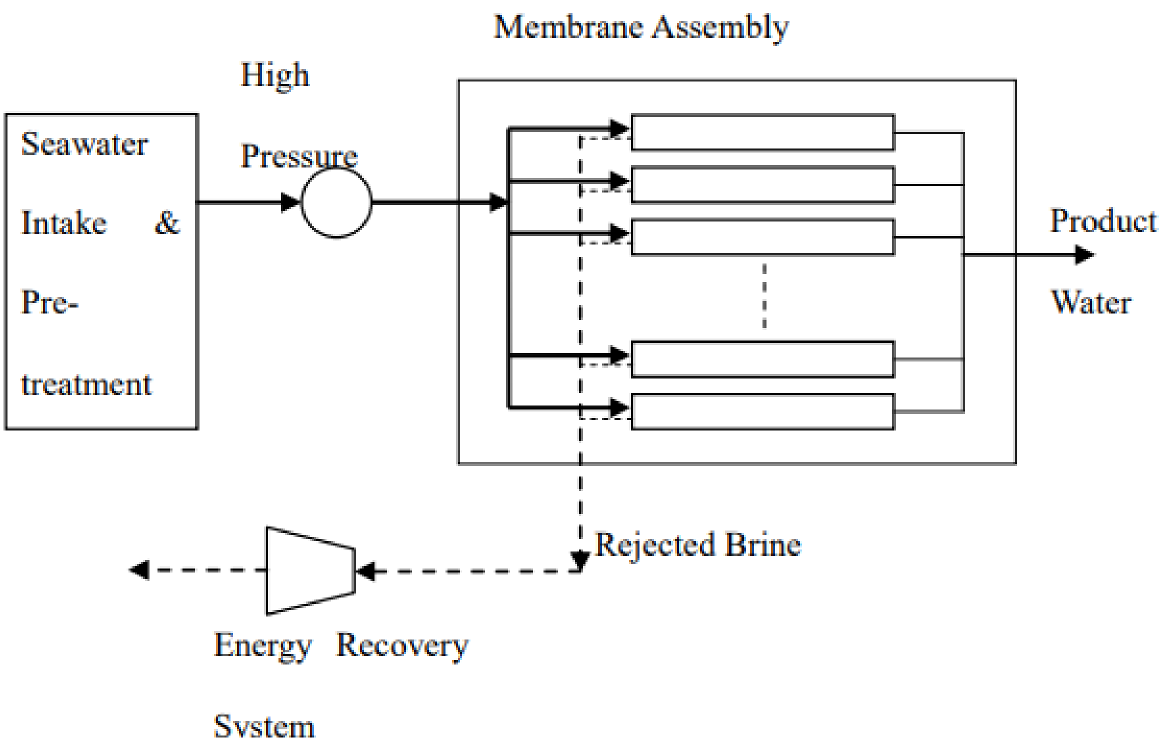


Figure 1. 4: Schematic representation of RO Plant (Müller-Holst et al. 1998).

1.4 Multi stage flash (MSF) desalination

Various components are involved in MSF method and these components participate at different stages during the process. The inlet seawater is preheated at every stage using condensing steam. The overall temperature is properly split between hot source and the seawater at different stages, thus the system achieves an ideal total latent heat recovery. Pressure gradients are required in this system for its proper functioning. Figure 1.5 shows the basic functioning mechanism of a plant. At times, some commercial plants may have a total of 30 stages too.

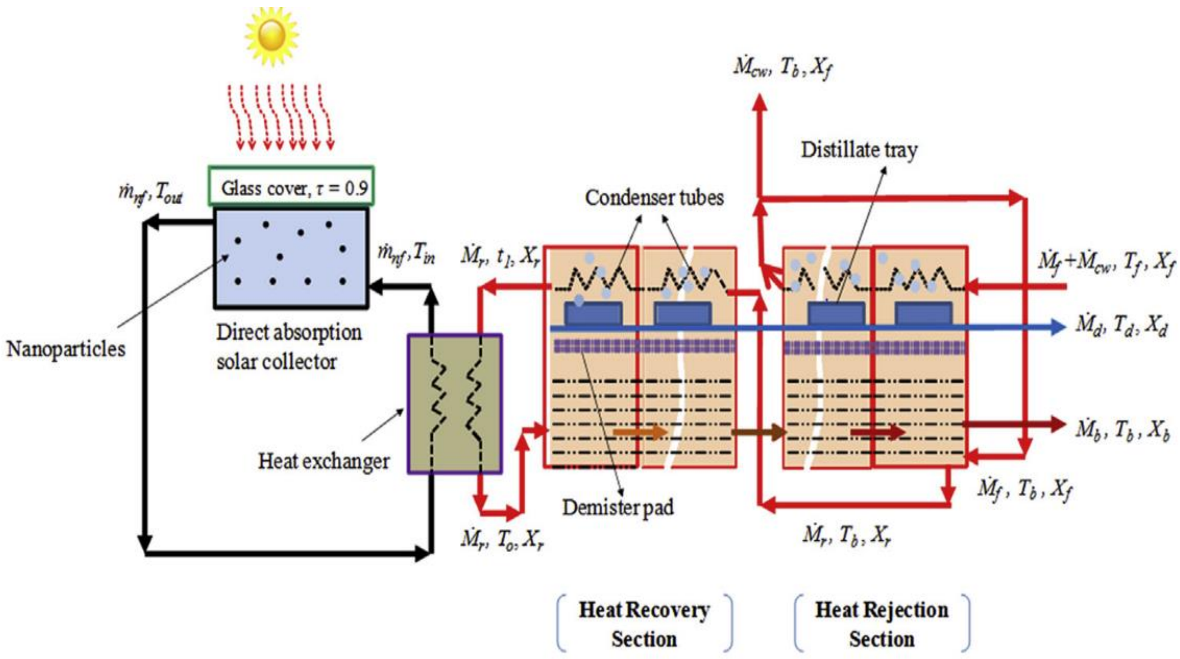


Figure 1. 5: Basic operation principle of MSF (Garg et al. 2018)**.**

1.5 Multi-effect desalination

Multi-effect Desalination, abbreviated as MED, is a thermal technology used in the production of fresh water. The primary source of water is either salt water or brackish water as shown in figure 1.6. This method is followed primarily when the production requirements exceed 20,000 m^3 per day. However, the drawback of this technology is its less energy efficiency. The system consumes up to 60 kWh_{th} per cubic meter of water which in turn increases the cost of producing fresh water (Calise et al. 2014). MED consists of many small units called vessels, which are also known as effects, and these units are maintained at low pressure upon which the sea water is sprinkled. Heat source is necessary for the evaporation of first vessel while the vapour formed gets utilised for next effect in the form of latent heat.

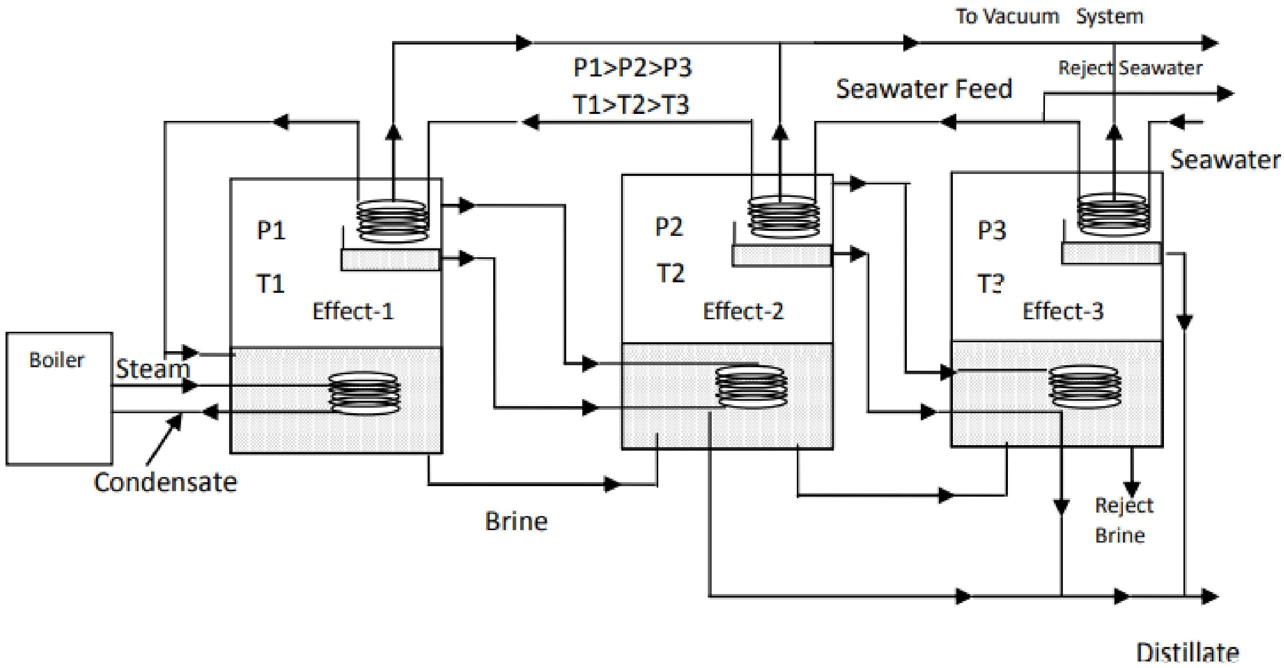


Figure 1. 6: Schematic representation of MED desalination (Calise et al. 2014).

1.6 Electrodialysis Distillation

Electrodialysis (ED), a membrane based separation method, is used to remove salt from the sea water so as to produce fresh water. Electrolysis stake contains a large number of cells present in anion and cation interchange membranes. These membranes are placed in alternative arrangement as shown in Figure 1.7. As soon as the DC voltage is supplied to the system, there is a shift of ions occur towards cathode and the anode. In other terms, the negative ions move towards the anion membrane, whereas positive ions move towards the cation membrane. Reversal of polarity, for every 20 minutes, avoids the deposition of salt on membranes.

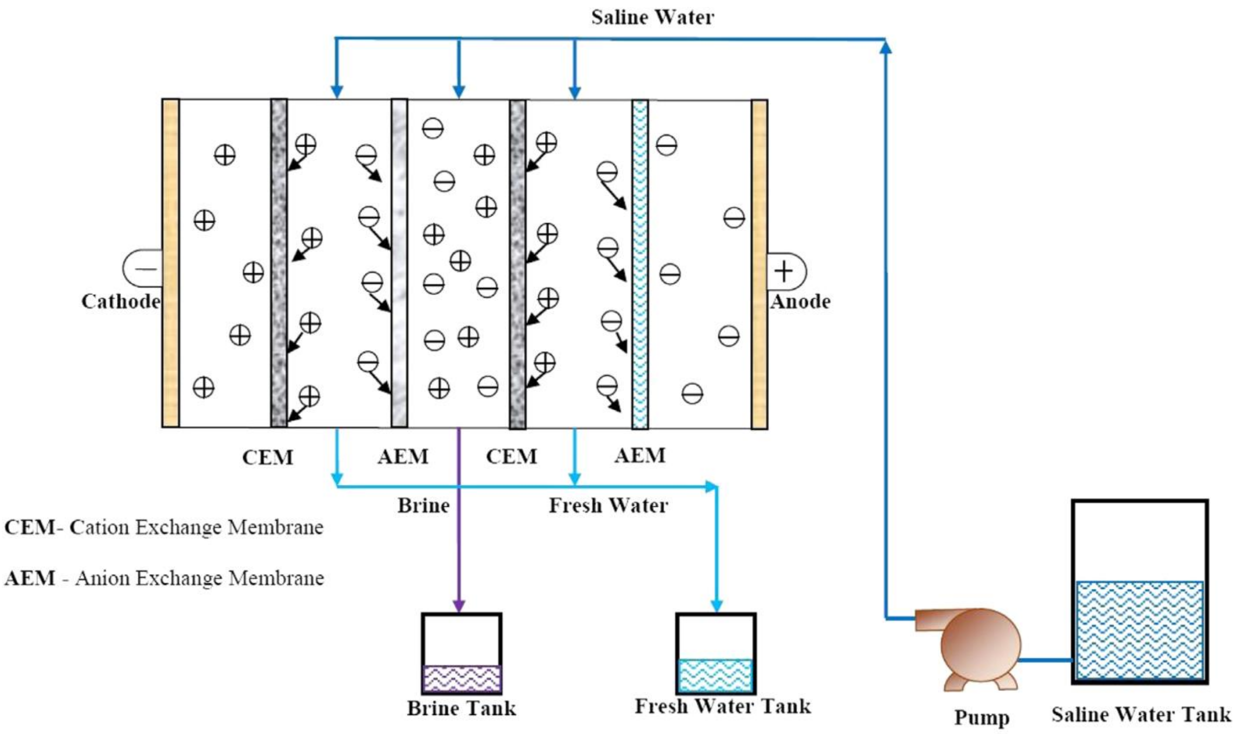


Figure 1. 7: Working principle of Electrodialysis desalination (Sharon and Reddy 2015)**.**

1.7 Membrane Desalination

The fundamental working mechanism of membrane desalination using solar collector is shown in figure 1.8. In this method, the vapours are made to pass through micropore-sized membranes in order to perform the separation process. based on the difference in vapour pressure, pure water gets separated across the surface of membrane. vapour particles migrate from hot side to cold side of the membrane, where in condensation takes place that results in the production of fresh water.

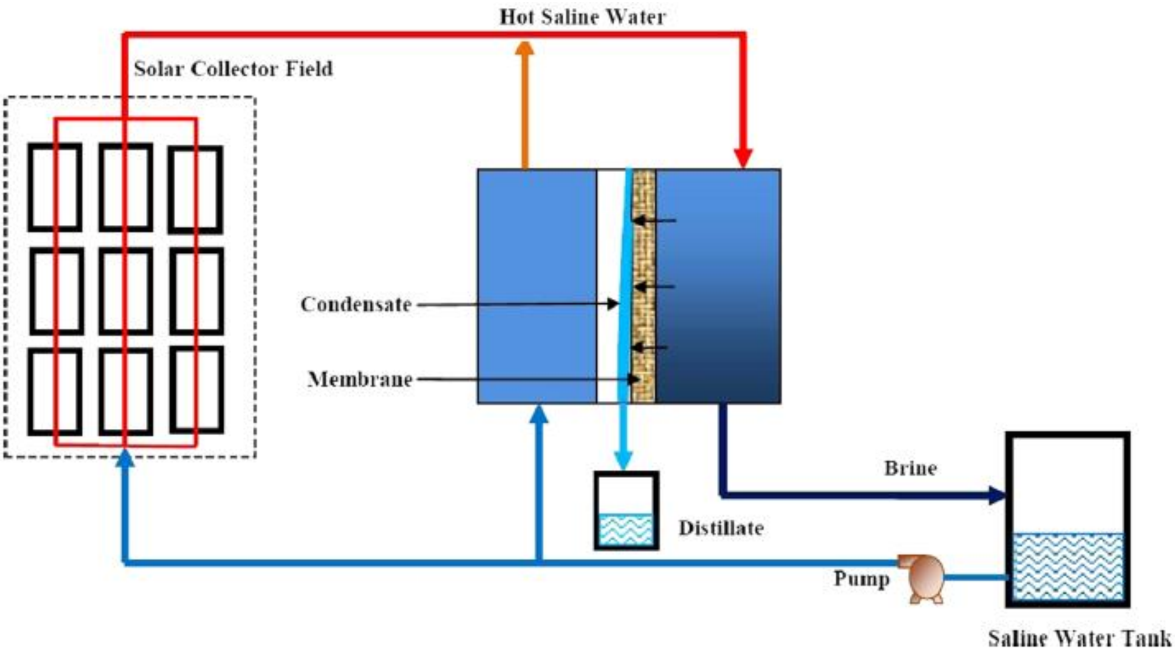


Figure 1. 8: Basic principle - Membrane distillation method (Qtaishat and Banat 2013).

1.8 Solar Still

Figure 1.9 illustrates the functioning mechanism and basic working principle of traditional solar still. It consists of container with saline water. The lower portion of the still is coated with black paint so that it gains the potential to absorb solar radiation that passes through the inclined transparent glass. The natural convection heat transfer increases water vapour inside the container which makes it to get in contact with the lower most part of the inclined glass. Once the vapour gets condensed upon the surface, the fresh water gets collected in the tank as illustrated in figure 1.9.

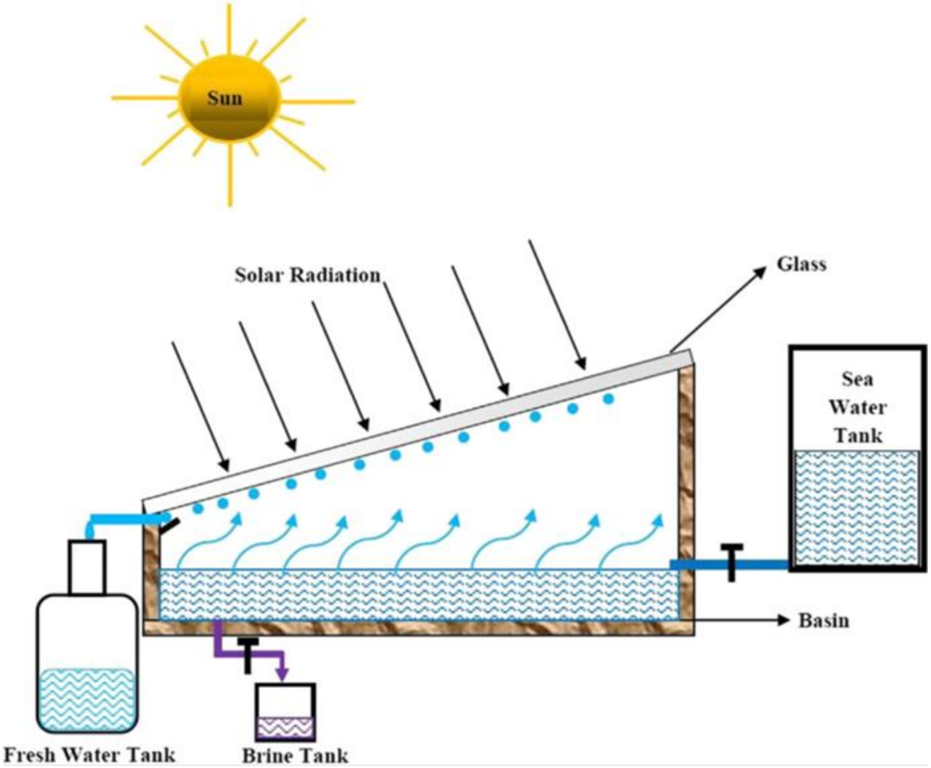


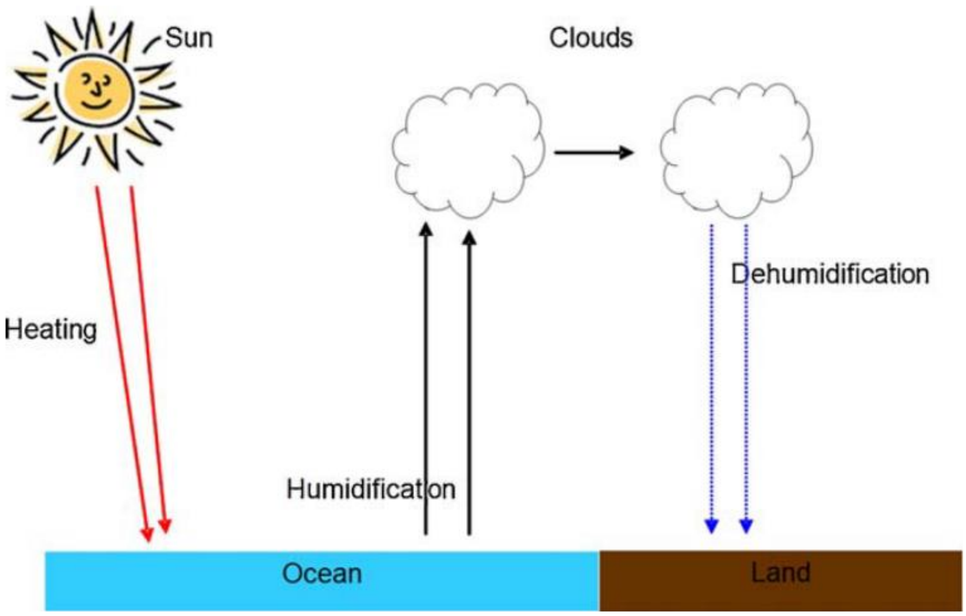
Figure 1. 9: Solar still – Working principle (Sharon and Reddy 2015).

Solar still is the best candidate to meet the increasing demand for fresh water, since it consumes solar energy which is abundantly available and free from pollution. There have been several investigations conducted upon solar still with improved designs including internal and external reflectors, clothes, pebbles, nanoparticles etc. to achieve improved results. Stepped solar still yields better results compared to conventional solar still.

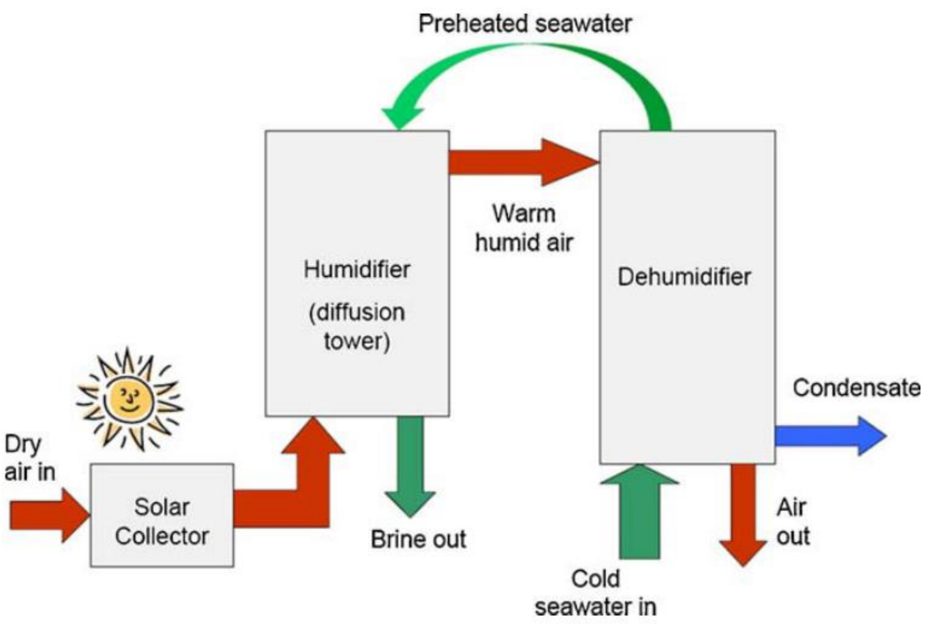
1.9 Humidification-dehumidification (HDH) desalination

Humidification-dehumidification (HDH) system primarily consists of two elements such as humidifier and dehumidifier which can be run using different heating sources. This desalination system works on rain cycle. In this process, the water is sourced from sea and heated using solar energy. Water vaporization occurs and after the formation of clouds in the atmosphere, it is finally condensed which results in rain. This sort of process to make artificial raining is named as HDH.

Figure 1.10 (a) illustrates the HDH process which simulates the naturally-existing hydro-logical cycle. Figure 1.10 (b) shows the HDH process in which the saline water is heated in a solar water heater. During the evaporation of heated saline water, it is exposed to dry air in the humidifier. When humidity-saturated air is taken forward to a dehumidifier, the humidity gets condensed which results in the production of fresh water as rain droplets. In this setup, solar air heater is one of the important components since it increases the temperature of air to an extreme temperature using the principle of solar radiation. Since air is used as a working medium, there is no need of using a heat exchanger in this setup.



(a)



(b)

Figure 1. 10:(a) Rain cycle (b) The humidification dehumidification process (Narayan et al. 2010)

Humidifiers are devices that enhance the moisture content in surrounding atmospheric air. It is mostly used in Heating, Ventilation and Air Conditioning (HVAC) equipment to provide comfort and ensure the well-being of labour and inhabitants. Industry-linked humidifiers yield benefits in terms of controlling moisture content so that the static current, generated in industries such as wrapping, plastics, fabrics, microchip technology, semiconductors, automobile fabrication, drugs, electrostatic painting, and powder coat, can be avoided. Humidifiers are also beneficial in protecting material properties. For instance, it is used in paper industry to avoid shrinkage and paper twist, besides it is also used in foodstuff business to preserve quality and freshness of food due to less cold temperatures in storage apartment. Furthermore, humidifiers are also used in health ventilators and surgical rooms. Nowadays, humidifiers are being applied in small scale water desalination units too such as Humidification dehumidification desalination technology (Narayan et al. 2010).

The working mechanism of HDH is discussed herewith. At first, the air is blended with water vapour. The potential of the mixture to carry forward the moisture gets increased, when there is an increase in temperature. Bourouni et al (2001) mentioned that one kilogram of air can hold up to 0.5 kg of vapour, in the event of temperature, increasing up to 80°C. The moisture gets carried away at the time of humidification. Then, the fresh water is collected from humid air, when it keeps in touch with the cold surface of dehumidifier. The above-discussed process i.e., condensation occurs in indirect contact heat exchanger to which the cold water is supplied.

For a long known time, solar still is considered as an established mode for the production of fresh potable water. In spite of all the advantages and best-functioning performance, solar still has the capability to produce the potable water approximately 5 l/m^2 per day only (Ranjan and Kaushik 2013). Humidification Dehumidification (HDH) desalination method is as an improved form of solar still method. At remote areas, this method can be implemented in small-scale too, to produce fresh water using waste heat source or solar energy (Mistry et al. 2011). Affordable and clean potable water remains a prominent challenge to address for large scale desalination plants, especially in remote parts of the world. In this view, HDH process is projected as a promising desalination technique for the production of potable water in remote areas (Kalogirou 2005). This is attributed to the reason that the process can occur under atmospheric pressure, with the help of low-grade renewable energy. HDH mimics the natural water cycle process i.e., air gets humidified initially and then condenses later resulting in the production of fresh water. HDH desalination unit consists of two major components such as humidifier and dehumidifier; both these components are operated by different heat sources. Heat may be produced by different sources such as solar energy, geothermal energy, or heat from process plants (Wu et al. 2017).

Desalination techniques are recognized to eliminate all impurities with dissolved particles, micro-organisms etc. Reverse osmosis technique can be used to remove even minuscule-level contaminants. However, these desalination techniques such as MSF, RO and MED are generally familiar to remove all the contaminants and these techniques are producing water in large scale quantity and high operating cost. But the key challenge exists in the form of enabling these systems function at a low cost and at a small scale (up to 100 m^3 /day) with comparatively less maintenance cost. Therefore, HDH technique may be used for producing water for small community, remote area where there is no access for electricity. The main aim of this thesis is to design and develop a small-scale desalination technique using HDH.

1.10 Organization of Thesis

The thesis is organized into **six chapters** namely, introduction, review of literature, mathematical modelling, materials and methods, results and discussion, and finally conclusion. The **second chapter** reviews the studies conducted earlier upon theoretical aspects of humidification-dehumidification, experimental work and the application of different packing materials in humidifier. A summary of the literature review, followed by research objectives, is included at the end of literature review. The **third chapter** discusses the mathematical modeling of humidification-dehumidification unit in which all the components of the unit are theoretically discussed and analyzed. Paddy grass humidifier mathematical modeling equations are used herewith.

The **fourth chapter** details about the materials and methods used in current research work. Two different packing materials were used in this study such as polypropylene and paddy grass for conducting the experimental works to analyses the performance of the proposed unit. The **fifth chapter** covers the results and discussions in which the experimental results are discussed, mathematical models are compared. The characteristics of paddy grass humidifier are analysed. Energy and economy study are also discussed at the end of this chapter. Finally, the **sixth chapter** concludes the results obtained from the present research work.

CHAPTER 2

LITERATURE REVIEW

This chapter deals with a review of literature published so far in the domain of solar desalination process. This extensive review covers theoretical and experimental studies on humidification dehumidification process using solar energy and packing materials used in humidifier.

2.1 Humidification dehumidification solar desalination

2.1.1 Theoretical studies

In the year 2009, Soufari et al. published a study on Humidification Dehumidification (HDH) desalination process in which the authors discussed the ways to optimize its performance with the help of mathematical programming. Nonlinear programming system model was proposed as a solution in this study for three objective functions namely, increment of condenser heat recovery, increasing the productivity and mitigation of specific thermal energy consumption. The study results inferred that the most important parameters to be considered in HDH system are humidifier inlet water temperature and air-to-water ratio. In the investigation conducted by Yamali and Solmus (2007), HDH system was analysed with the help of double-pass solar air heater. In this setup, two glass covers were used by the researchers. The study was conducted at Ankara (39.93° N, 32.85° E), Turkey. The authors solved the energy equations numerically for every component in the system using MATLAB software. There was an increase observed in system productivity up to 8%, when using double-pass solar air heater. However, in its absence, the productivity got reduced up to 30%. For both the experiments, same operating conditions were maintained. This study inferred that both air and water mass flow rates exert a significant impact upon the productivity of the system.

In the study conducted by Faridb et al. (2004), solar desalination process was reviewed in detail. Though solar desalination process is an established research domain for 20 years, it gained significance only in the recent years as a non-renewable energy-powered technology that can be involved in the production of fresh water. Solar desalination based on HDH cycle is deemed to be the optimum method compared to other solar desalination processes, thanks to its overall high-energy efficiency. Faridh et al. conducted a comprehensive review on all the technical aspects of solar desalination plants with multi-effect cycle. Thus, the study provided a better understanding about the whole process. The authors further placed suggestions for the betterment of system performance and efficiency so that these desalination units can be commercialized in a large quantity due to its increased efficiency and better performance.

Al-Sulaiman et al. (2015) conducted a thermodynamic analysis to evaluate the outcomes of HDH system using an integrated Parabolic Trough Solar Collector (PTSC). In this HDH system, the researcher followed two different types of configurations. In first configuration, a solar air heater is placed prior to the humidifier whereas in second configuration, solar air heater is placed between the humidifier and dehumidifier. The study inferred that PTSC is a promising method for air heating using high-intensity solar radiation. Furthermore, the performance and productivity of the second configuration were comparatively better than the first one.

Moumouh et al. (2014) reviewed a number of technologies used to desalinate the saline through HD of air and by using solar thermal energy. A particular emphasis was put on this study to research about various types of solar water heaters as well as different solar air heater designs. In the study conducted by Bourouni et al. (2001), HDH system, the state-of-the-art technique, was analyzed and decoded in detail with regards to its functioning and characteristics. In general, solar and geothermal desalination plants function on the basis of mechanical compression of humid air. These plants are installed based on the absorption of water from humid air in atmosphere. Ettouney et al. (2005) investigated the capability of HDH process to be applied in small-scale production units. Various interesting features are present in this HDH process such as low temperature operations, potential to integrate with renewable energy sources such as solar, geothermal etc., and demand for minimal technical features. This study assessed different layouts of HDH desalination processes and its features. Air humidifier is the most common feature found across these systems. At air humidifier, the humidity of ambient air gets incremented to threshold level at the expected design temperature. The key differentiation among these layouts is dehumidification process. The researcher assessed four different configurations for air HDH water desalination system such as membrane air drying system, mechanical compressor system, desiccant system and the traditional system that contains air humidifier and water vapour condenser. The results attained in this study inferred the presence of a primary disadvantage in any form of air HDH system i.e., presence of huge volume of air in addition to water vapour product.

In the study conducted by Chafik et al. (2002), the researchers proposed a seawater desalination process using solar energy. In this process, solar energy is leveraged to heat the flowing air in the range of 50-80°C temperature. Seawater is then injected into air stream for moderate heating of the solar-heated air. After this, the salt-free water is extracted from humid air by cooling process. In this experimentation, air is used as a heat carrier whereas the maximum operating temperature is maintained at less than 80°C. These parameter settings enable the researcher to leverage cost-effective polymers as construction materials. The primary feature discussed in this process is successive loading of air and vapour with a relatively high humidity i.e., up to 10-15 wt%. This subsequently results in the reduction of air volume that flows through the plant. It is possible to implement this target by redesigning the stepwise heating/humidification technique. This study also explained the thermodynamic background of new process. Further, it also covered about the information on optimizing the desalination method based on the optimal choice of process parameters. This article suggested the development of low-cost air heaters to tap solar energy. The study developed and experimented the designs specifically made for air humidification through seawater evaporation. Condensation equipment was also designed in order to extract the desalinated water from humidified air.

A theoretical model was proposed by Yildirim and Solmuş (2014) to analyze the impact of design and operating parameters upon clean water production rate. The study was conducted at Antalya (36.89° N, 30.71° E), Turkey under suitable climatic conditions. The study observed that much caution should be exercised at the time of heating the water, when it comes to production of fresh water. This is attributed to the fact that the specific heat of water is high compared to that of the air. Nematollahi et al (2013) investigated the impact of different parameters such as air temperature, water temperature, humidity of air and the dimensions of humidification tower upon whole exergy efficiency of the system. This study helped in the construction of a humidification tower to develop a solar desalination system with better output.

2.1.2 Experimental studies

In the research conducted by Elkader et al (2014), the authors executed both theoretical and experimental investigations considering a wide range of environmental conditions. The study formulated a mathematical model using thermodynamic relations to analyze about the flow, heat and mass transfer within humidifier and dehumidifier. This technique was leveraged to increment the performance of the system. Heat as well as mass balance were performed, while the study solved few governing equations with the help of finite difference technique.

Hamed et al. (2015) reviewed the performance of solar desalination system on the basis of HDH model. The study evaluated the system both theoretically and experimentally. The authors made use of a theoretical simulation model involving energy equations for each component. This is to assess the outcome and production capacity of the proposed solar HDH desalination unit. System productivity was measured during day time at different operating times and during two periods. Based on the empirical evaluation of the mathematical model, the proposed HDH model was proved to be valid in terms of simulating the heat exchange and calculating the temperatures of systematic steady-state conditions. The study also calculated the distillate production rate. The study chose an optimum operating time during day time. The authors simulated the proposed model in order to assess the impact of operating conditions upon thermal performance of the unit. The system exhibited high productivity, when it is allowed to operate for four hours a day.

In the year 2013, Narayan et al. published a study which assessed HDH technology through experimentation procedure. Though this study focused on small-scale seawater desalination, it has the potential to be applied in a wide range of water treatment systems intended for drinking and industrial purposes. The research work showed 'modified Heat Capacity Rate ratio' (HCR) as an important and unique parameter in thermal design of the HDH system, in heat exchange device and in mass exchange device. HCR gains much attention when trying to gain a basic understanding about the concept of thermodynamic balancing. The study constructed a pilot-scale HDH and conducted a series of experiments. The experimental outcomes validated the aspects proposed in theories, focused on HDH system design with or without mass extraction and injection, developed in the recent years. The authors further studied about the perspectives regarding design and optimization of heat and mass exchange devices.

In the study conducted at Suez city (29.96° N, 32.54° E), Egypt, Nafey et al. (2004) validated HDH desalination process through experimental procedure using solar energy. In this study, a test rig was designed and developed for executing the procedure under varying operating and environmental conditions. In this test rig, there exists a solar air heater (flat plate solar collector), solar water heater (concentrator solar collector type), dehumidifier exchanger and humidifier tower. The study took a wide range of variables such as cooling water flow rate, air flow rate and feed water flow rate in both dehumidifier as well as weather conditions into consideration. The results attained from the experiment were compared. From the results, it can be inferred that the mathematical model, proposed by the same author in another study, aligns with the outcomes achieved in this experimental study. Further, the results also showcased that a strong influence is exerted by the factors such as air flow rate, solar intensity, dehumidifier cooling water flow rate and saline water temperature at inlet of the humidifier upon the productivity of the system. In addition to the above, the productivity of the system tend to experience a minimal imbalance when there is a difference in wind speed and environmental temperature.

In the study conducted by Bourouni et al. (2001), HDH process was adopted to desalinate the water under decentralized demand. This techniques has numerous advantages such as simple to apply, function under low temperature energy (for instance cogeneration, geothermal, solar or recovered energy), cost-efficiency during installation and operations, capacity addition etc., The studies conducted earlier with regards to desalination of sea water mostly focused on Reverse Osmosis and distillation processes, while the studies that focus on HDH are inadequate. So, Bourouni et al. aimed at presenting the working principle and the characteristic of HDH technique in this study. The authors detailed about the state-of-the-art humidification dehumidification technique. An economic perspective study was conducted by Al-hallaj et al. (2006) in which the researchers reviewed about solar desalination process that leverages humidification-dehumidification technique. The authors opined that most of the desalination plants are heavy energy consumers, especially such plants are driven by energy generated from oil and natural gas. This results in the production of harmful carbon dioxide that poses serious threats to the environment. When solar desalination process is integrated with humidification-dehumidification process, it tends to increase the overall efficiency of desalination plant. Hence, this integrated system is a promising candidate in the domain of sea water desalination using solar energy. The authors conducted an elaborate investigation of the mechanism and detailed the same in their research article which also covered the economic aspects of the model. With cost-based comparisons made among the available solar desalination processes, this report emphasizes the need for in-depth knowledge about solar desalination method. The commercialization of solar desalination processes, based on HDH principle, should be accomplished carefully. This is crucial because simulation verification and design optimization have to be achieved by bringing changes in three major entities such as humidifier, condenser and collector surface area.

An experimental investigation was performed by Amer et al. (2009) upon HDH desalination system. It functions as an open cycle system for water whereas for air stream, it works as a closed cycle system. The air is made to circulate either naturally or by forced means. The system modelling was done on the basis of different heat and mass balance equations and their numerical solutions. The study analyzed the impact of operating parameters upon system characteristics. The authors conducted the experiment in a setup equipped with optimum measurement and controlling devices. A wide range of experiments was conducted under different operating conditions and various packing materials. Rajaseenivasan et al. (2017) conducted an experimental work on humidification-dehumidification desalination in collaboration with dual purpose solar collectors so as to heat both air and water simultaneously.

Air is heated under different tubular configurations to increase the turbulence so that the efficiency of the system gets improved. Zubair et al. (2018) carried out an experimental and thermodynamic analysis on humidification-dehumidification desalination technology using single open-air, open water and with a modified open-air closed-water setup. A substantial increase was observed in the performance, when increasing the effectiveness of every component. However, dehumidifier exerts a heavy influence than the humidifier. The authors compared the cost analysis results against the literature.

Various research investigations have been conducted so far upon renewable energy sources across the globe due to increasing awareness about global climate change. The utilization of renewable energy, in particular solar energy, got increased from 2% in 1998 to 16 % in 2016 (Abdelkareem et al. 2018). Solar energy can be used to generate thermal energy as well as electrical energy and is currently applied for the purpose of desalination too. In stage-wise research work, it is important to review, analyze and understand the works carried out earlier in the specific domain. Similarly, technical assessment of the experimental work and mathematical modelling on HDH using solar collectors from the existing studies are tabulated in tables 2.1 and 2.2 correspondingly.

Table 2.1: Summary of the literature on experimental study of HDH units with solar collectors.

Author(s)	**Brief title**	**Key Findings**
Chafik 2004	Design of a multi-stage desalination plant using multi stage heating-humidification technology	Experimental work was carried out to increase the humidification of air with water at multi stages. Optimized strategies were obtained to produce water (10 m^3/day) for small community.
Santosh et al. 2022	Review on humidifiers and dehumidifiers in solar and low-grade waste heat powered HDH desalination systems	A comprehensive review is carried out, dual-fluid preheating, closed circulation, increased wet area, optimum mass flow ratio across humidifier-dehumidifier, waste heat utilization, and adoption of thermal energy storage unit are recognized to be important aspects in improving the HDH,
Houcine et al. 2006	Solar desalination process with multi effect humidification process	An integrated HDH unit was developed and was experimentally reviewed for a period six months. Pad humidifier was used to analyze the efficiency of humidifier. The plant achieved a production capacity of 355 liters per month.
Orfi et al. 2004	Empirical and theoretical research work on Humidification-Dehumidification based desalination with the help of solar energy	An integrated HDH unit was designed, constructed and tested. Further, the unit was analyzed mathematically too. The outcomes show that there occurs an improvement in mass flow rate, with regards to high yield.

El-Ashtoukhy et al. 2022	An innovative system for water desalination based on HDH technique	Experimental work with hydrophilic plant (Loofa Egyptiaca) as packing material have been used to produce high superior quality water, an hydrous silica gel is used at the outlet of humid air.
Dayem and Fatouh 2009	Empirical and numerical analysis of a solar HDH unit	Three different experimental configurations of HDH unit were tested at Cairo, Egypt. The most efficient, effective and economic configuration was the one with salt water that flows like a collector fluid.
Khass et al. 2022	Thermal and economic assessment of HDH unit	Outcome of experimental work shows that with double humidifier water heated system to produce more water with less GOR than air heated system.
Zhani 2013	Solar desalination based on multiple effect humidification process: experimental validation	The experimental set up was designed and installed based on HDH unit and was tested at Sfax, Tunisia. Theoretical model was implemented to assess the thermal performance whereas the challenge was solved using C++ programing and was validated based on experimental results.
Abdel Dayem 2014	Solar desalination system that made use of HDH process.	An experimental investigation was conducted at Makkah using solar collector under different weather conditions. The system was able to produce 1.6 liters of fresh water for one kWh solar energy.
Zamen et al. 2014	Experimental investigation of 2-stage HDH unit	The outcomes attained display that the yield can be increased by 20% with two stages compared to one stage technique.
Ghazal et al.	This empirical research	The experiment was conducted under weather

2014	proposed an unique solar humidifier for Humidification-dehumidification	conditions prevailing in North Cyprus. The researchers found that the external reflector in humidifier increases the humidity.
Ladouy and Khabbazi 2015	Empirical research on depth of water and the impact of condensers	HDH system was air-closed with the help of solar energy. The authors found that the effectiveness of the system got improved with hot air in comparison with normal air.
Elminshawy et al. 2015	Empirical and theoretical investigation of a novel solar HDH system	In this study conducted at Saudi Arabia, the model was implemented under two scenarios such as with heat source and reflector and in the absence of these components. The performance was measured for both the scenarios and the outcomes infer that the yield got increased in the presence of heat source and reflector.
Weifeng et al. 2022	Parametric study of HDH desalination driven by photovoltaic-thermal	Thermodynamic and economic analysis with new packing in dehumidifier was carried out using photovoltaic and thermal.
Wu et al. 2016	Experiment study of multi effect isothermal heat with tandem solar heat	A porous ball humidifier was used in this study. Theoretical investigation was conducted based on mass as well as energy balance. The yield increased when the temperature got increased from 60℃ to 90 ℃.
Farshchi et al. 2016	Experimental study integrated with solar still with and without HDH unit	The experiment was done at Zahedan, Iran. The yield of HDH unit got increased from 28% to 141%.
Abu-arabi et al. 2017	The assessment of solar desalination in HDH	A rotating black surface was utilized in this study to assess the performance of system. The

	unit through an empirical study using rotating surface	yield was 9 liter/m^2/day during summer season.
Rajaseenivasan and Srithar 2017	The study assessed dual-purpose solar collector in HDH unit.	The experiment was conducted using dual purpose solar collector. The overall efficiency was 67.6% with tubular inserts in double pass solar collector.
Ladouy and Khabbazi 2017	Experimental study on various air heating methods	A new pulse heating approach was followed in which the setup is close to the evaporation surface inside the triangular shape of HDH unit. This is done so to increase the performance of the unit. The authors found an increase in the efficiency, when compared to conventional air heating approach.
Hernández et al. 2018	Experimental and numerical evaluation of an HDH system driven by solar energy	An experimental and theoretical analysis was conducted with closed air and open water systems using solar energy at Chile. The measured values were used to optimize the design.
Rahimi-ahar et al. 2020	Experimental study on solar vacuum HDH unit	An experimental work was carried out below atmospheric pressure. The authors found that when the pressure got reduced, the yield got increased.
Xu et al. 2019	The empirical research work was conducted upon a solar-based desalination process that used heat pump	A new approach with heat recovery and solar heat pump was experimentally validated. Furthermore, the study also compared two packing materials in the humidifier.

Table 2.2: Summary of the literature on mathematical modelling of HDH units with solar collectors.

Authors	Brief title	Key Findings
Moumouh et al. 2016	Experimental and theoretical study on HDH unit	A theoretical model was developed from mass and energy equations. The projected results aligned with the outcomes generated in the experimental procedure.
Ranjitha Raj and Jayakumar 2022	Investigation humidifier packing for HDH desalination system	15 various types of packing investigated and inferred that metal packing with more surface area to volume ratio, lowest packing factor and smallest packing diameter functions as the best humidifier packing.
Mohamed and El-minshawy 2009	HDH unit using geothermal energy	Geothermal energy, an environmental-friendly and renewable natural resource, was used in this research work for heating purposes. According to the authors, the optimum ratio of water-to-air mass flow rate lies in the range of 1.5-2.5 during when a high volume of fresh water is produced.
Narayan et al. 2010	Thermodynamic analysis of HDH-solar driven	Thermodynamic analysis was conducted for different improved HDH cycle units. The researchers improved the cycle units with multi-pressure and multi-extraction features.
Yamali and Solmus 2008	Theoretically study on HDH unit using double pass solar air heater	The authors found an increase in the productivity of system up to 8%, when double-pass solar air heater is used in the system. In case of its absence, a decline in system productivity up to 30% was recorded. Both the experiments were conducted under same operating conditions. The study inferred that air and water mass flow rates exert a significant impact upon the productivity of the

		system.
Müller-Holst et al. 1998	Decentralized small scale optimization of HDH unit	Thermodynamic analysis was carried on multi-effect humidification system using unused heat or solar energy. Thermal storage was coupled in this study to optimize the system.
Nawayseh et al. 1999	HDH unit-simulation using computer program	A computer code was established by resolving the desalinating governing equations and found that air flow rate remains unproductive on the yield. The simulation allows the suitable selection of feed water flow rate.
Farsad and Behzadmehr 2011	Theoretical analysis of HDH unit using DoE using solar energy	Design of Experiment (DoE) procedure was utilized in this study to examine HDH unit so that optimized results can be obtained. First law of thermodynamics law was applied at every part of the unit.
Capocelli et al. 2018	Investigation of HDH-Adsorption	Mathematical modelling was carried out for HDH with adsorption and recirculation. A maximum of 10 GOR was achieved after multiple recirculation of brine.
Orfi et al. 2007	Air HDH unit by means of solar energy	A theoretical analysis was conducted in this study including energy and mass balancing for HDH unit. The study concluded that the best performance could be achieved by constant tuning of the sea water and air mass flow rate.
Hussain Soomro et al. 2022	A small-scale HDH desalination system	Developed mathematical model with various hydrophobic materials such as hackettes, saddles, and snowflakes and compared with experimental work.
Al-sulaiman et	Investigating of an	Theoretical modeling was carried out under two

al. 2015	HDH unit – parabolic trough solar collector(PTSC)	different configurations. In first scenario, PTSC is placed before the humidifier whereas in the second one, PTSC is placed in-between the humidifier and dehumidifier. The study found the performance of second scenario to be better.
Kabeel and El-Said 2018	Experimental investigation of hybrid HDH unit	An experimental work was conducted upon HDH unit integrated with solar energy, inserting baffles in the cooler. They found that the unit performance got improved with increasing water temperature and mass flow rate of air.
Fouda et al. 2016	Experimental work on hybrid HDH unit with A/C system	The authors found that the fresh water production increases with increase in specific humidity and mass flow rate of air.
Shatat et al. 2013	Theoretical study on HDH unit using solar energy	Mathematical model was established coupled with solar collector.
Kaunga et al. 2022	Performance study and enhancement through experimental and numerical methods using HDH process	This paper is to recommend the automatic model of the HDH desalination process with enhanced prediction model accuracy as a substitute to conventional models. Recovery ratio can be improved with an increase in packing specific area with two times the area of dehumidifier.

Appropriate selection of the packing material for humidifier is one of the additional approaches that can be followed to increase the effectiveness of the system. Various types of humidifiers are used to conduct different types of experimentation such as bubble columns (Tow and Lienhard 2014), packed bed towers (Dai et al. 2002), and spray towers (Morsy et al. 2009). The working principle of these humidifiers remain similar i.e., when liquid water interacts with the unsaturated air, the moisture diffuses in to air thereby increasing the moisture content in air. Prakash Narayan et al.(2013) have conducted the experiment on packed bed towers to analyze the effect of water-air interaction duration. The results inferred that high efficiency can be achieved when the contact time is higher. Splash and film type packings are some of the extensively-followed packing methods. Especially, film type packing is preferred at most of the times, thanks to its better thermal performance. Three arrangements of experiments were conducted in collaboration with bubble column and solar collectors to analyze the bubble column humidifier. They found an increase in overall efficiency when bubble column humidifier is integrated with solar collectors with tabulators (Rajaseenivasan et al. 2016).

A few researchers used inserts to augment the effect of air flow in air heating source of HDH system. Eiamsa-ard et al. (2010) conducted experimentation on straight and twisted tapes in the way of air path. The study findings infer the improvement of heat transfer due to these inserts. Eiamsa-ard et al. (2009) conducted an investigation on short length and full length-twisted tapes to assess the characteristics of air flow. They found that the heat transfer got increased in case of short length inserts at the inlet, due to turbulence.

In the experimental investigation conducted by Shehata et al. (2019), the authors used two variants of film type packing such as horizontal corrugate packing and vertical corrugated packing. The obtained effects displayed that the performance of humidifier is influenced by both type and orientation of the packing material. Also, the humidifier performance got reduced with an increase in liquid-to-air ratio. The results exhibit that high efficiency can be achieved from the humidifier when it is installed with vertical corrugated packing than the horizontal corrugated packing. Kabeel and El-said (2014) carried out an experiment on HDH combined with one-stage flashing evaporation system. The circular-shaped polyvinyl chloride packing material, with dimensions such as 0.4 m height and 0.8 m diameter, was used in the humidifier. The flow rate of water got heavily affected than the flow rate of air, since the humidifier is effective.

(Dai and Zhang 2000) studied a system utilizing solar energy to run humidification dehumidification plant with packed bed humidifier with cross flow arrangement. They established that the performance of a plant is decided based on the flowrate of air, seawater and temperature of inlet water against the humidifier. In the analyses conducted by Al-Enezi et al. (Al-Enezi et al. 2006), a HDH system was used including a plastic-made humidifier, a heat source to heat the water up to 45 °C, an air heater and a condenser. Based on the examination, the study inferred that the effect of entry water temperature, high mass rate of air, and low cooling water temperature exert extreme significance upon fresh water production.

Continuous efforts have been taken to find a solution and to overcome the challenges faced in freshwater production by leveraging advanced technologies. Several novel methods and technologies have been adopted in the production of fresh potable water. One of the major challenges for scientific community nowadays is to find a reliable, consistent, and cost-effective technique to produce fresh water. Among the available techniques, seawater desalination is considered to be the most suitable one, thanks to its simplicity and cost-effective methodology. Solar-based desalination technology such as multi-effect desalination is adopted widely due to independent external power operations. However, the drawbacks of this technology are low gain output ratio and the necessity for huge collector area. HDH desalination is considered to be a suitable method for pilot and mobile-type potable water production. This type of plant has simple construction design, cost-effective components, minimum maintenance and deployment of any sort of heat source such as solar and heat generated from waste heat recovery system.

Numerous studies have been conducted so far with an aim to increment the heat transfer via the introduction of inserts at both air inlet and dehumidifier of humidification-dehumidification system. The author identified the presence of a research gap herewith i.e., no studies were conducted so far in which the baffle plates are inserted in dehumidifier with the introduction of new packing material (paddy grass). Packing materials such as paddy grass and polypropylene materials are also used in humidifiers to increase the moisture carrying capacity in humidifier. The current study made use of two packing materials in humidifier to experimentally examine different parameters on the performance of HDH system such as fresh water production and gain output ratio. In this theoretical study, mathematical modeling of the entire system is also carried out to examine the performance of the system. The results obtained, in terms of fresh water productivity, were compared against the previous studies. Further, bio-based humidifier packing material was also compared with polypropylene packing material and without packing material upon the fresh water production capacity of the system. An economic study on the entire system was also carried out to understand the viability of the system.

2.1.2 Motivation of the present work

The water demand of NITK Surathkal (12.98 °N, 74.8 °E) campus is up to 14 lakhs liters per day as on 2017. Out of this whole quantity, about 50% of the demand is met by Mangalore City Corporation whereas rest of the demand is met by open wells, bored in the campus itself. However, the ever-increasing demand, due to increasing inflow of multi-faceted individuals into the campus, made the campus authorities to look for other feasible sources to avoid water scarcity in the near future. Furthermore, it is also worrying to know about the receding ground water level in this region, which further aggravates the water crisis to an extreme level. No research studies have been conducted in this domain, with specific focus upon Surathkal region though the region suffers from water scarcity issues. The researcher has chosen the study setting here, since the location receives a considerable amount of solar intensity throughout the year. This untapped solar energy can be leveraged in the production of water, using an efficient and cost-effective desalination system. The current study utilized humidification-dehumidification (HDH) method by combining double-pass flat plate solar air heater with two glass covers and a Parabolic Trough Solar Collector (PTSC). The primary objective of current research work is to observe the influence of different parameters on productivity of the configuration and to develop a theoretical model and experimental work using different packing materials such as polypropylene and paddy grass.

2.1.3 Research objectives and scope

The objectives of the research are as follows.

1. Develop a mathematical model to investigate the outcome of humidification-dehumidification process, powered by solar collectors and paddy grass humidifier.
2. Use mathematical model to assess the outcomes of HDH process on different parameters such as cooling water temperature, water flow rate and air flow rate.
3. To fabricate an experimental facility based on humidification-dehumidification. To design and develop a cost-efficient solar-powered desalination system that meets the needs of arid and remote regions.
4. To conduct experiments on solar-driven humidification dehumidification desalination for validating the mathematical results.
5. To optimize the performance of the system in order to increase the production of fresh water and mitigate the consumption of energy.

2.3 Closure

A comprehensive review about the existing studies has been carried out in this chapter. Essential, as well as parametric studies on numerical and experimental studies using HDH technique are listed in the tables. Based on the research gaps identified, the objectives have been established.

CHAPTER 3

MATHEMATICAL MODELING

3.1 Introduction

3.1.1 System description and analysis of HDH

Humidification-Dehumidification process-based desalination system is consists of multiple components such as humidifier, parabolic trough water heater, dehumidifier, double pass solar air heater and a storage tank. The system functions on the basis of open air and closed water circuits. Figure 3.1 is a schematic representation of the setup. The first pass in double-pass solar air heater, heats the air in ambient condition which is re-heated in second pass too. Then, humidification occurs through seawater in the humidifier. Here, PTSC (Parabolic Trough Solar Collector) heats the sea water and distributes it to the humidifier where the heated sea water and air are combined together. The hot humidified air is allowed to pass through dehumidifier where the condensation of water vapor occurs which in turn results in the production of fresh water. The water is collected at the bottom of humidifier, which is then stored in an insulated tank. Afterwards, the collected water is pumped into solar water heater and recirculated to the humidifier. Dehumidifier is supplied with cooling water from a water bath at constant temperature. The current research work is carried out through two ways such as analytical and experimental.

3.1.2 Mathematical modelling of the system

The current research work proposes a theoretical mathematical model for simulation of the system undertaken for the study. Both energy and mass balance equations are derived from each component, present in the system. With the help of 4^{th} order Runge-Kutta (R-K) method, the governing traditional equations were solved in parallel. The model was proposed on the basis of assumptions listed herewith.

The temperature of water in storage tank and the temperature of inlet water to humidifier are equal. The cooling water temperature remains constant throughout the day. The air temperature varies in a linear fashion. Since the effectiveness of the humidifying tower is assumed to be a value which equal to one, it is understood that the air which leaves the humidifier is saturated. So, its dry-bulb and wet-bulb temperatures are identical to each other.

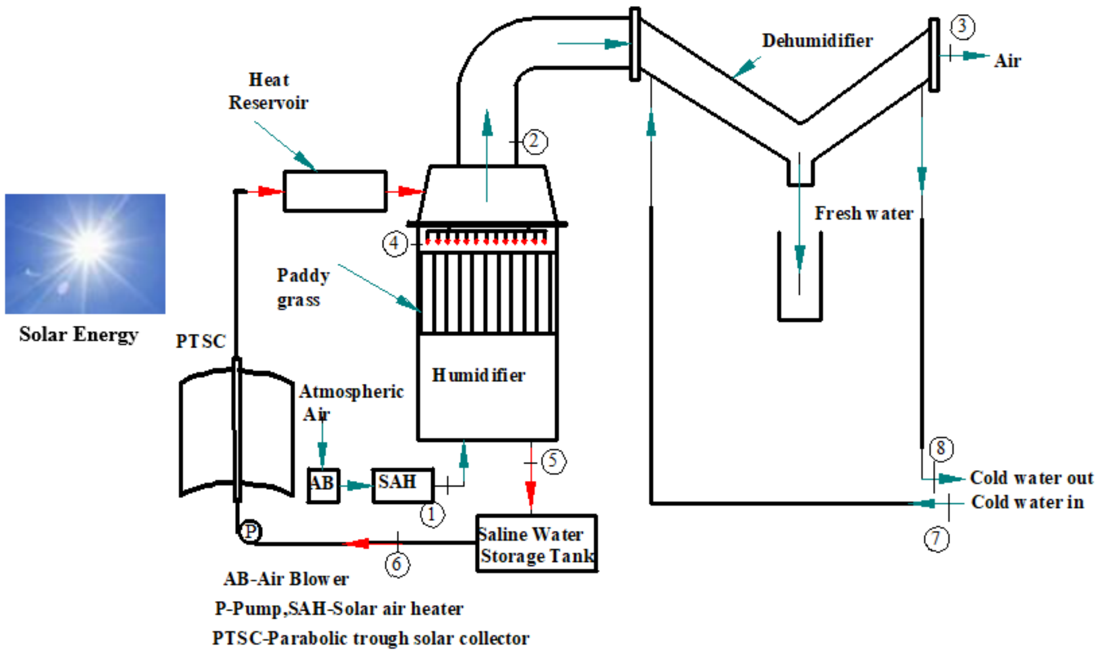


Figure 3. 1 Humidification dehumidification process with solar collectors.

Dehumidification process is shown on the saturation curve. The temperature of the outgoing condensed water and the cooling water from parallel-flowing dehumidifying exchanger remains the same alike dry-bulb temperature of the air that leaves the dehumidifier. Here, the temperature gradient, present inside the water storage tank, is not considered. Likewise, heat loss or gain that occurs from multiple places such as water storage tank, solar air heater edges, humidifier and dehumidifier are also neglected. Laminar or turbulent flow remains a completely developed structure. Equal temperature is recorded in both entities i.e., the water that leaves the humidifier and wet-bulb temperature of the air that leaves the humidifier. Radiant energy, collected by the flowing air in both channels, is utilized. Since the system reports no air leakage, the air is allowed to pass through air heater, humidifier and dehumidifier in an orderly fashion. For every instance, wind speed, ambient temperature, solar radiation and relative humidity of the ambient air are maintained as constant through 60 minutes.

3.1.3 Modelling of parabolic trough solar collector (PTSC)

Parabolic Trough Solar Collector has an element with absorber tube and is located on the central line as shown in figure 3.2.

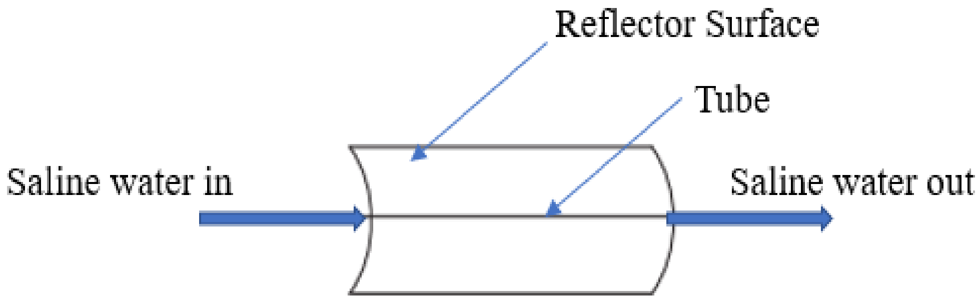


Figure 3. 2: Schematic diagram of Parabolic Trough Solar Collector.

In order to increase the utilization of solar radiation, concentrated type of collector, like PTSC, is used. It has a cylinder-profile with a tubular receiver. The radiation absorbed (Al-Sulaiman et al. 2015) by the solar collector is given as follows.

$$S = I_s \, \rho(\Upsilon\tau\alpha)_n K_{\tau\alpha} \tag{3.1}$$

Here, the existing beam radiation is denoted by I_s while *K* denotes collector reflectivity. Here, ρ is the specular reflectance, the product of transmittance whereas absorptance is denoted by $\tau\alpha$ and $'\Upsilon$ is the intercept factor.

The following equation expresses both convection and radiation heat losses.

$$Q_{Loss} = \pi D_{co} L h_w((T_{co} - T_a) + \epsilon_c \, \pi D_{co} L\sigma(T_{co}^4 - T_{sk}^4) \tag{3.2}$$

Where h_w corresponds to outside heat transfer co-efficient, while the ambient temperature is expressed as T_a. Further, the sky temperature is denoted through T_{sk}.

Radiative heat transfer loss, as expressed by Sukhatme (2012), occurs from receiver to the inner surface and is given as,

$$Q_{Loss} = \frac{\pi D_o L\sigma(T_r^4 - T_{ci}^4)}{\frac{1}{\epsilon_c} + \frac{1-\epsilon_c}{\epsilon_c}(\frac{D_o}{D_{ci}})} \tag{3.3}$$

Here, the receiver's outer diameter is shown as D_o and the glass cover's inner diameter length of the collector is denoted with D_{ci}. Here, σ corresponds to Stefan-Boltzmann's constant and the receiver temperature is denoted by T_r. Further, T_{ci} denotes the inner cover temperature and ϵ_c is used to denote the cover emissivity.

The following equation is used for calculating conductive heat loss via cover thickness.

$$Q_{Loss} = \frac{2\pi k_c L(T_{ci} - T_{co})}{\ln(\frac{D_{co}}{D_{ci}})} \quad (3.4)$$

where the thermal conductivity is denoted by k_c and T_{co} denotes the outer temperature of the cover. Here, the outer diameter is denoted by D_{co}.

Following is the equation given for total heat loss.

$$Q_{loss} = U_l A_r \ (T_i - T_a) \quad (3.5)$$

where U_l denotes the overall heat transfer coefficient whereas the receiver area is denoted by A_r. Here, hw is computed with the help of Nusselt number which correlated with air flow in a tube present outside the environment.

Nusselt Number for laminar flow (Duffie et al. 1985).

$$N_U = 0.40 + .54 R_e^{0.52} \quad \text{for } 0.1 < R_e < 1000 \quad (3.6)$$

$$N_U = 0.30 R_e^{0.6} A \quad \text{for } 1000 < R_e < 50000$$

where the Reynold's number is denoted by R_e. Here, the Nusselt number for turbulent flow is expressed in equation 3.7.

$$N_U = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1.07 + 12.7\sqrt{\frac{f}{8}}(Pr^{\frac{2}{3}} - 1)} \left(\frac{\mu}{\mu_w}\right)^n \quad (3.7)$$

0.11 denotes the n value for heating which is equal to 0.25 for cooling.

Darcy friction factor:

$$f = (0.79 ln R_e - 1.64)^{-2} \quad (3.8)$$

The following equation provides the overall heat transfer coefficient value between the fluid and its environment.

$$U_o = \left(\frac{1}{U_l} + \frac{D_o}{h_{fi} D_i} + \frac{D_o \ln(\frac{D_o}{D_i})}{2k_c}\right)^{-1} \quad (3.9)$$

Where h_{fi} is the fluid heat transfer coefficient

Useful energy gain:

$$Q_u = F_R A_a [S - \frac{A_r}{A_a} U_l (T_i - T_a)] \quad (3.10)$$

Where, F_R is heat removal factor and A_a is the aperture area.

Collector flow factor:

$$F'' = \frac{F_R}{F'} = \frac{\dot{m}C_p}{A_r U_l F'} [1 - \exp(-\frac{A_r U_L F'}{\dot{m}C_p})] \quad (3.11)$$

The following equation is helpful to compute, Collector Efficiency factor F'

$$F' = \frac{U_o}{U_l} \quad (3.12)$$

The useful energy gained with respect to inlet temperature and outlet temperature is expressed as follows.

$$Q_u = \dot{m}c_p (T_i - T_o) \quad (3.13)$$

where, T_o is the outlet temperature.

Duffie and Beckman (Duffie et al. 1985) considered the differences in absorptivity, transmissivity and reflectivity, based on which the researchers proposed the incidence angle modifier which is given below.

$$K_{\tau\alpha} = 1 - 6.74 \times 10^{-5} \times \theta^2 + 1.64 \times 10^{-6} \times \theta^3 - 2.51 \times 10^{-8} \times \theta^4 \quad (3.14)$$

where, θ is the incidence angle.

3.1.4 Modeling of water storage tank

The conservation of energy for water storage tank is expressed herewith.

$$m_{w1} c_{pw} \frac{dT_{w1}}{dt} = [M_{w1}(t) c_{pw} T_{w2}(t) + M_{mw}(t) c_{pw} T_{mw}(t) - M_{w1} c_{pw} T_{w1}(t) - q_{1w1amb}] \quad (3.15)$$

3.1.5 Modelling of solar air collector:

Solar air heater is used to heat the incoming ambient air that enters the humidifier. Following is the list of energy balance equations used for solar air heater (Yamali and Solmuş

2007). Two glasses are used to have a double pass circulation of air with first pass in second glass cover (Top) and second pass with first glass cover (bottom) respectively. This double pass solar heater is advantageous in terms of fresh water productivity.

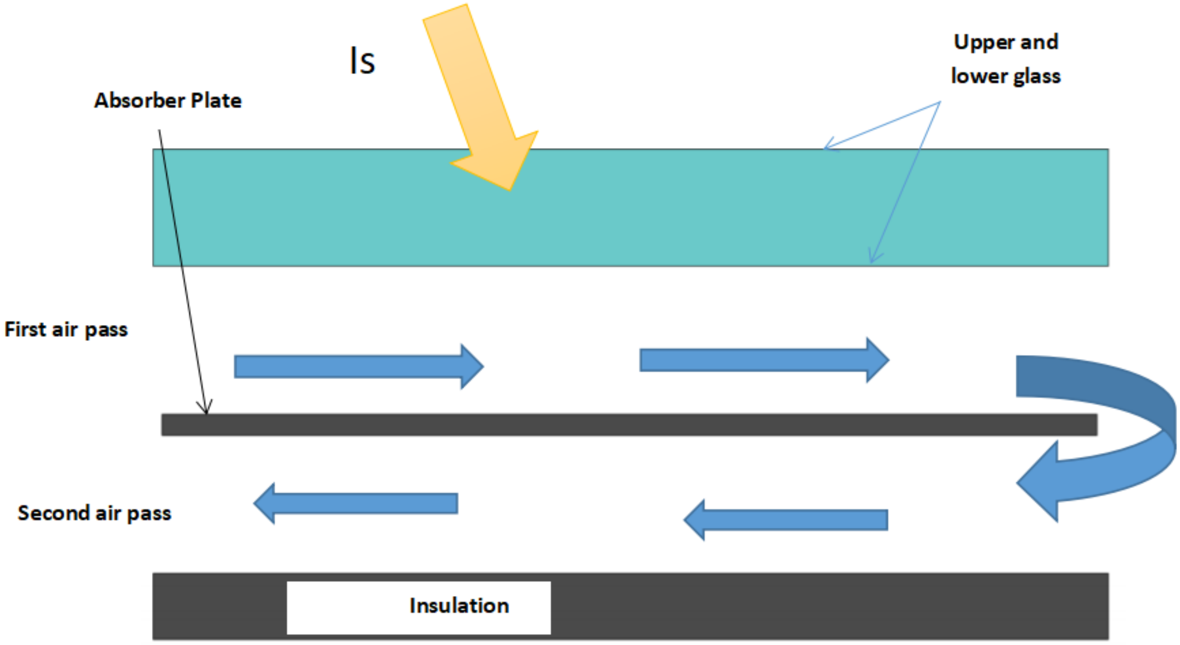


Figure 3. 3: Double pass solar air heater.

Second glass cover:

$$m_g c_{pg} \frac{dT_{g2}}{dt} = I_s\ \alpha_g A_{sc} + Q_{r,g1g2} - Q_{c,g2amb} - Q_{r,g2s} + Q_{c,g1g2} \quad (3.16)$$

The energy equation for the first glass cover is as follows.

$$m_g c_{pg} \frac{dT_{g1}}{dt} = I_s\ \alpha_g A_{sc} \tau_g - Q_{r,g1g2} - Q_{c,g2a1} + Q_{r,pg1} - Q_{c,g1g2} \quad (3.17)$$

First air pass:

$$m_a c_{pa} \frac{dT_{a1}}{dt} = Q_{c,pa1} + Q_{c,g1a1} - M_a C_{pa} \left(T_{a1e} - T_{ai}\right) \quad (3.18)$$

The incident solar energy is absorbed by the absorber plate and is utilized as sensible heat. While the sun energy emitted by this plate is also absorbed as sensible energy by the base plate.

$$m_p c_{pp} \frac{dT_p}{dt} = I_s \alpha_p\ \tau_g^2 A_c - Q_{cpa2} - Q_{c,pa1} - Q_{r,pg1} - Q_{r,pb} \quad (3.19)$$

Second air pass:

$$m_a c_{pa} \frac{dT_{a2}}{dt} = Q_{cpa2} + Q_{cba2} - M_a C_{pa}(T_{a2e} - T_{a1ep}) \quad (3.20)$$

Similarly, the energy equations for absorber plate and the base plate are given below.

$$m_b c_{pw} \frac{dT_b}{dt} = Q_{rpb} - Q_{cba2} - Q_{1batm} \quad (3.21)$$

The temperature of air (T_{a2e}) that comes from the solar air heater is obtained from the equation 3.20.

3.1.6 Modeling of humidifier:

In paddy grass packing material humidifier, hot saline is sprayed from top of the humidifier over bundles of the grass material whereas air is blown from the bottom. In the presence of huge quantity of grass filled in the humidifier, it is challenging to model directly. So, in order to simplify the problem, a counter flow heat exchanger model is considered. The simplified figure for the model is shown in figure 3.2. Both solution and the air move through the grass, where heat and mass interaction takes place between the fluids.

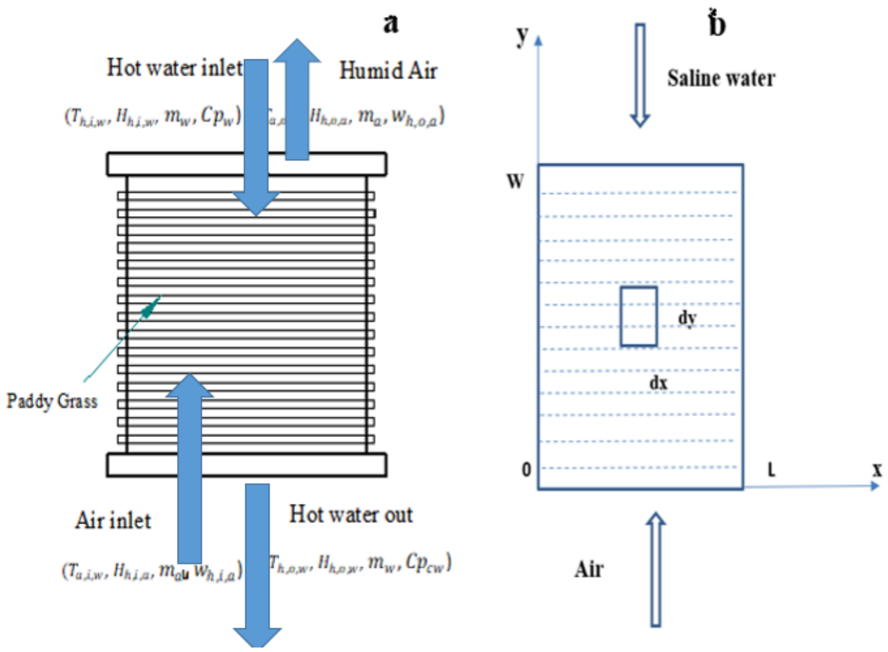


Figure 3. 4: Schematic representation of paddy grass humidifier (a) Structure of the module (b) Model calculation method.

At the time of humidification, heat and mass between saline and the air is governed by the equations given below. These equations are mass and energy balance equations applied for paddy grass humidifier.

$$\frac{\partial T_a}{\partial y} = \frac{h_{to}A_{to}}{m_a c_{pa} W}(T_s - T_a) \tag{3.22}$$

$$\frac{\partial w_a}{\partial y} = \frac{\rho_a K_{to} A_{to}}{m_a W}(w_s - w_a) \tag{3.23}$$

$$\frac{\partial T_s}{\partial x} = \frac{h_{to}A_{to}}{m_s c_{ps} L}(T_a - T_s) + \frac{\rho_a K_{to} A_{to} H_v}{m_s c_{ps} L}(w_a - w_s) \tag{3.24}$$

$$\frac{\partial X}{\partial x} = \frac{\rho_a K_{to} A_{to}}{m_s L}(w_s - w_a) \tag{3.25}$$

Here, 's' stands for solution and 'a' for air, Hv is the evaporation heat of vapour, w is humidity, w_s is phase equilibrium humidity of the air blended with saline at a concentration of X and a temperature of T_s.

$$w_s = 0.662\frac{P_v}{P_{at} - P_v} \tag{3.26}$$

The boundary conditions for the mixture are as follows.

x=0, $T_s = T_{si}$, $w_s = w_{si}$

y=0, $T_a = T_{ai}$, $w_a = w_{ai}$ (3.27)

The total resistance consists of three components such as solution, air and paddy grass. Heat transport and mass transport are written herewith.

$$\frac{1}{h_{to}} = \frac{1}{h_s} + \frac{d}{\lambda} + \frac{1}{h_a}$$

$$\frac{1}{k_{to}} = \frac{1}{K_s} + \frac{d}{D} + \frac{1}{k_a} \tag{3.28}$$

Here, 'd' shows the diameter of paddy grass whereas D denotes moisture diffusivity. Here, the thermal conductivity is denoted by λ.

As given below, Nusselt number and Sherwood number are written to denote the convective heat transfer coefficient (h) as well as mass transfer coefficient (K) of air and saline.

$$Nu = \frac{hd}{\lambda} \tag{3.29}$$

$$\mathrm{Sh} = \frac{\mathrm{Kd}}{\mathrm{D}} = \frac{\mathrm{N_u}}{\mathrm{L_e}^{\frac{1}{3}}} \tag{3.30}$$

Here, thermal conductivity is symbolized as λ whereas L_e denotes Lewis number and the diffusivity is denoted by D.

The effect of this paddy grass upon system performance is the major focus of this investigation. The parameters to be examined in this work primarily are its characteristics that depend on moisture diffusivity (D), heat diffusivity (h) and the volume of humidifier. Furthermore, the author also intends to investigate the impact of area of paddy grass. Reynolds number for air and solution, across the different types of paddy grasses, are far below 2300. Therefore, air and solution may be considered as laminar flow. Hence the following equation can be used for a fully-developed laminar heat transfer around the tubes.

$$\mathrm{Nu_s} = 3.658 \tag{3.31}$$

Nusselt number of the air stream is expressed as follows.

$$\mathrm{Nu_a} = 1.13\mathrm{c_1}\mathrm{Re_{do,max}^m}\mathrm{Pr_a^{0.33}} \tag{3.32}$$

where c1 and m are constants and are calculated using the literature (Frank et al.2011). Pr is the Prandtl number and $Re_{do,max}$ is calculated using the following equation.

$$\mathrm{Re_{do,max}} = \frac{\mathrm{u_{a,max}do}}{\mathrm{\gamma_a}} \tag{3.33}$$

The pressure drop in the solution for laminar flow, around paddy grass, is given herewith.

$$\Delta P_{sH} = \frac{64}{R_{es}}\frac{L_H}{d}\frac{\rho_s U_s^2}{2} \tag{3.34}$$

The flow characteristics for air stream have been investigated and are used in current study which is given herewith.

$$f_a = a\,{R_e}_a^{\,b} \tag{3.35}$$

$$Nu_a = cRe_a^m Pr_a^{\frac{1}{3}} \tag{3.36}$$

$$Sh_a = DRe_a^n Sc_a^{\frac{1}{3}} \tag{3.37}$$

The constants a, b, c, D, m and n (Li and Zhang 2016b) are obtained from the geometric configurations of paddy grass humidifier. The applicability of these correlations is for those conditions when Reynold numbers are up to 500 and module Packing Fraction (PF) is between 0.2 and 0.6. In this research, the Reynold number is 210 and the PF is 0.512. Hence the above correlations can be used in this analysis. The constants are a=4.299, b=0.363, C=1.98, m=0.443, D=3.402 and n=0.374. Sc stands for Schmidt number and Pr stands for Prandtl number respectively.

The pressure drop across the air stream in humidifier is given as follows.

$$\Delta P_{aH} = f_a N_l \left(\frac{1}{2}\rho_a U_{amax}^2\right) \quad (3.38)$$

Where N_l is the number of grass fibres in the humidifier which is equal to 1600 as far as current study is concerned. The dimensional specification of the humidifier is 0.4 × 0.4 m cross-section; and 1 m height with in which, 1600 number of paddy grass fibres are placed. Humidifier is designed with the above specification having the packing density 157 m^2/m^3 and surface area of 10 m^2 and diameter of paddy grass fibre is 0.005m.

$$U_{amax} = \frac{P_t}{P_t - d} U_a \qquad \text{When } P_d > (P_t + d)/2 \quad (3.39)$$

$$U_{amax} = \frac{P_t}{2(P_d - d)} U_a \qquad \text{When } P_d < (P_t + d)/2 \quad (3.40)$$

The boundary conditions for the mixture are as follows.

$$x=0, \qquad T_s = T_{si} \quad , \quad w_s = w_{si} \quad (3.41$$

$$y=0, \qquad T_a = T_{ai} \quad , \quad w_a = w_{ai} \quad (3.42)$$

In order to analyse the heat transfer and mass transfer properties of paddy grass humidifier, two terms are defined such as sensible effectiveness and latent effectiveness which are given herewith.

$$\eta_{sen} = \left[\frac{T_{ao} - T_{ai}}{T_{si} - T_{ai}}\right] \quad (3.43)$$

$$\eta_{lat} = \left[\frac{w_{ao} - w_{ai}}{w_{si} - w_{ai}}\right] \quad (3.44)$$

$$\frac{m_a}{m_s}(H_{h,i,a} - H_{h,o,a}) = \frac{Kav}{m}\left[\frac{(H_{h,i,w}-H_{h,o,a})-(H_{h,o,w}-H_{h,i,a})}{\ln\frac{(H_{h,i,w}-H_{h,o,a})}{(H_{h,o,w}-H_{h,i,a})}}\right] \quad (3.45)$$

Here, K denotes the overall mass transfer coefficient of water in air (kg/ m^2s) whereas the specific mass transfer area i.e., (m^2/m^3) is denoted via 'a' and the packing volume v corresponds to (m^3).

3.1.7 Modelling of dehumidifier

The dehumidifier component in HDH unit is a fin-tube type heat exchanger. During the process, indirect contact takes place between hot humid air and feed water through the gap between fins and tube. The humidifier is V-shaped and is a hollow structure with one end where the hot humid air enters and the other end where it leaves. The total angle of the 90 degree is provided in the dehumidifier to facilitate the condensed water to flow in downward direction easily and finally collected to the fresh water colleting jar. As reported (Huang et al. 2021) in the literature, polymeric solid hollow fibre type heat exchanger is an efficient type, when compared to shell and tube. These kinds of heat exchangers are used for saline (up to 90 ℃) or steam (up to 113℃) cooling water up to 25 ℃. Further, it was reported by (Chen et al. 2018) that high heat transfer coefficient (up to 450 W/m^2K) can be attained with such fibre type heat exchanger. However, such heat exchanger types may not be suitable for desalination process since the type of working fluid which is nothing but, moist air. The thermodynamic properties of moist air are different than that of the steam. Figure 3.3 shows that the thermal resistance of air is more, when compared to liquid side. This shows that a larger area needs to be prepared for better heat transfer effectiveness from the air side. Hence, the baffle plates are provided in dehumidifier. In order to study the performance of dehumidification process in dehumidifier, Ɛ-NTU method is followed. The effectiveness can be written as given herewith(Chen et al. 2018).

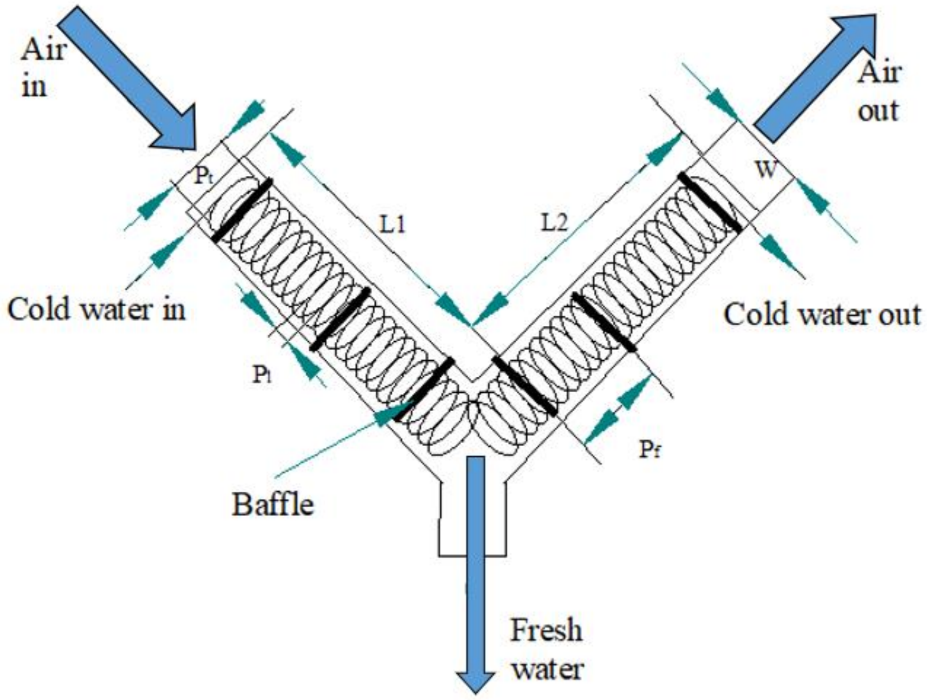


Figure 3. 5: Schematic drawing of the dehumidifier.

$$\mathcal{E} = 1 - exp\left\{\frac{NTU^{0.22}}{C_R} - [exp(-C_R NTU^{0.78}) - 1]\right\} \tag{3.45}$$

(3.46)

NTU=$\frac{UA}{m_a c_{pa}}$

$$C_R = \frac{m_a c_{pa}}{m_c c_{pc}} \tag{3.47}$$

and

Total heat resistance (1/UA) is expressed as follows.

$$\frac{1}{UA} = \frac{1}{h_i A_i} + R_{wl} + \frac{1}{\eta_f h_a A_a} \tag{3.48}$$

In RHS, the middle term i.e., R_{wl} denotes resistance of the wall, η_f is the efficiency of fin, A_i is the inner surface area of copper tube and A_a is the heat exchanger area in air side. In RHS, the first term denotes 'tube side resistance' whereas the last term denotes 'air side resistance'.

During experimental work, the cold water flow rate was 0.05 kg/s and the corresponding Reynold number was 15300 which is more than 4000. Therefore, flow is considered to be turbulent. Hence, the convective heat transfer coefficient of water h_i, in the expression (3.49), can be calculated from the following expression(Chen et al. 2018).

$$h_i = \left(\frac{K_i}{D_i}\right)\frac{\left(R_{e_{Di}} - 1000\right)(F_i/2)P_r}{1.07 + 12.7\sqrt{F_i/2}({P_r}^{0.7} - 1)} \tag{3.49}$$

$$F_i = \frac{1}{\left(1.58lnR_{e_{Di}} - 3.28\right)^2} \tag{3.50}$$

Heat transfer coefficient h_a for air side of the dehumidifier is expressed herewith.

$$h_a = j\frac{m_a c_{pa}}{{P_r}^{2/3}} \tag{3.51}$$

$$j = 0.4R_{edc}^{-0.468+0.04076N_r}\left(\frac{A_o}{A_{po}}\right)^{0.159}{N_r}^{-1.261} \tag{3.52}$$

where m_a denotes the mass flow rate through fins, Ao is the external surface area of the tubes and A_{po} denotes the total heat exchange area.

Performance indices: In order to assess the outcomes of the system, the author chose four parameters such as Gain Output Ratio (GOR), Coefficient of Performance (COP) and electric COP (COP_E) which are defined herewith.

Gain output ratio is the ratio of latent heat of evaporation to the total heat supplied to the desalination unit. It is an important performance parameter utilized in HDH process. It describes the energy evaluation of desalination plant and all other thermal desalination techniques. The value of GOR should be higher as far as possible because any desalination plant is evaluated based on the amount of total heat supplied or the same amount of fresh water produced with less amount of total heat energy.

$$COP = \frac{AP.H_w}{\int\left(q_{Solar} + w_{Pump} + w_{Blower}\right)dt} \tag{3.53}$$

This can be accomplished by increasing the fresh water production. Here, the latent heat of condensation of water is denoted by H_w.

In line with this, COP, with respect to electric energy, is defined as the ratio of product of accumulated water production and latent heat of evaporation to the sum of electrical energy supplied to the pump and blower.

$$COP_E = \frac{AP.H_w}{\int (w_{Pump} + w_{Blower})dt} \tag{3.54}$$

Where W_{pump} and W_{blower} are the power consumption values of pump and blower respectively and are expressed as follows.

$$w_{pump} = \frac{m_s \Delta P_s}{\rho_s \eta_{pump}} \text{ and}$$

$$w_{Blower} = \frac{m_a(\Delta H_{ah} + \Delta H_{ad})}{\rho_s \eta_{Blower}} \tag{3.55}$$

where η_{Blower} and η_{pump} denote the efficiencies of blower and pump respectively.

Following is the equation to calculate the power spent upon electric heat source to increase the temperature of water that flows through paddy grass humidifier.

$$w_{ewh} = c_{pw} m_w (T_{wo} - T_{wi}) \tag{3.56}$$

Similarly, for air heater, the equation is as follows.

$$w_{eawh} = c_{pa} m_a (T_{ao} - T_{ai}) \tag{3.57}$$

Instantaneous fresh water production (IP) and Accumulated water production (AP) are well-defined as follows

$$IP = m_a(\omega_{dai} - \omega_{dao}) \tag{3.58}$$

$$AP = \int m_a(\omega_{dai} - \omega_{dao})dt \tag{3.59}$$

where ω_{dai} and ω_{dao} denote the moisture content values at 'in' and 'out' of the dehumidifier respectively. Specific Energy Consumption (SEC) is the electric energy used per unit against volume of the water produced.

$$SEC = \frac{\rho_w \int (w_{pump} + w_{blower}) dt}{AP} \tag{3.60}$$

3.2 Calculation Procedure

Figure 3.4 shows a comprehensive overview of the method as a flow chart.

1. The operational conditions of inlet such as mass flow rate, fresh water volume collected, inlet temperature, humidity (input and output states), mass flow rate of air, saline and cold water are required to enter the initial concentration (x) and equipment parameters such as solar collector, humidifier, dehumidifier, water reservoir tank etc. The time interval chosen in current study was 30 sec.
2. The starting values of the temperature as well as volume of saline within saline reservoir tank are assumed to be (T_{si}, V_{si})
3. Based on the entire mass of sodium chloride and according to the volume of reservoir tank at temperature, the concentration of salt water is calculated.
4. The value for initial temperature difference (dt) is assumed.
5. The set inlet temperature (T_i), at the water collector reservoir, is assumed to be (T_i+ dt). Take the solar intensity data and atmospheric temperature. Equations (3.1)-(3.13) are used to compute the outlet temperature of the solar collector, energy received from the collector and its efficiency.
6. Compute the temperature of heat reservoir. Now, estimate the temperature difference freshly. If the deviation is within the limits, then go to step 7, or else re-assign and go to step 5 until the convergence is achieved.
7. The values of both inlet temperature and the present solution temperature, followed by the concentration to humidifier with that of concentration in heat reservoir tank, remain equal. The equations (3.18)-(3.28) are calculated for the humidifier after which both outlet temperature and saltwater concentration are calculated from the humidifier. Both air temperature and humidity for the humidifier are calculated. Finally, exit heat load is calculated.

8. By taking the values of exit temperature, humidity of air present in the humidifier as 'input temperature' and air humidity as input for the dehumidifier, compute the equations (3.40)-(3.48) to obtain the exit temperature, humidity and enthalpy of the air that comes out of the dehumidifier. Compute the output cooling water temperature of the dehumidifier.
9. Equations are used to compute temperature as well as volume of the heat storage reservoir. If the computed and initial assumed values are within the limit, then proceed to step (10) or consider the average of those values and move to (3) till convergence is achieved.
10. Now, move to time interval i=i+1 and send it back to (2) till the expected time is achieved. Finally, the performance parameters are computed.

MATLAB software was used in this study to execute computer-based simulation based on energy equations. The author executed the functions to assess the impact of different parameters namely, temperature, mass flow rate of seawater and mass flow rate of air upon the outcomes. The energy equations (differential form) are resolved in parallel during the simulation process with the help of 4^{th} order R-K method and is used solve the differential equations having smaller step value to get reasonable accuracy with an error of 10^{-5}.

At the beginning, mean parabolic trough water heater temperature was assumed. Afterwards, it was calculated on iteration basis. Due to this, once the inlet water and air temperatures of the humidifier are known for every time interval, equation 3.22 is applied to calculate the temperature of air that leaves the humidifier. Further, equation 3.23 is also applied to determine the temperature of air that leaves the dehumidifier. Equation 3.47 is used to compute the quantity of fresh water produced by the dehumidifier. Figure 3.5 shows the flow chart of the entire process involved in desalination plant.

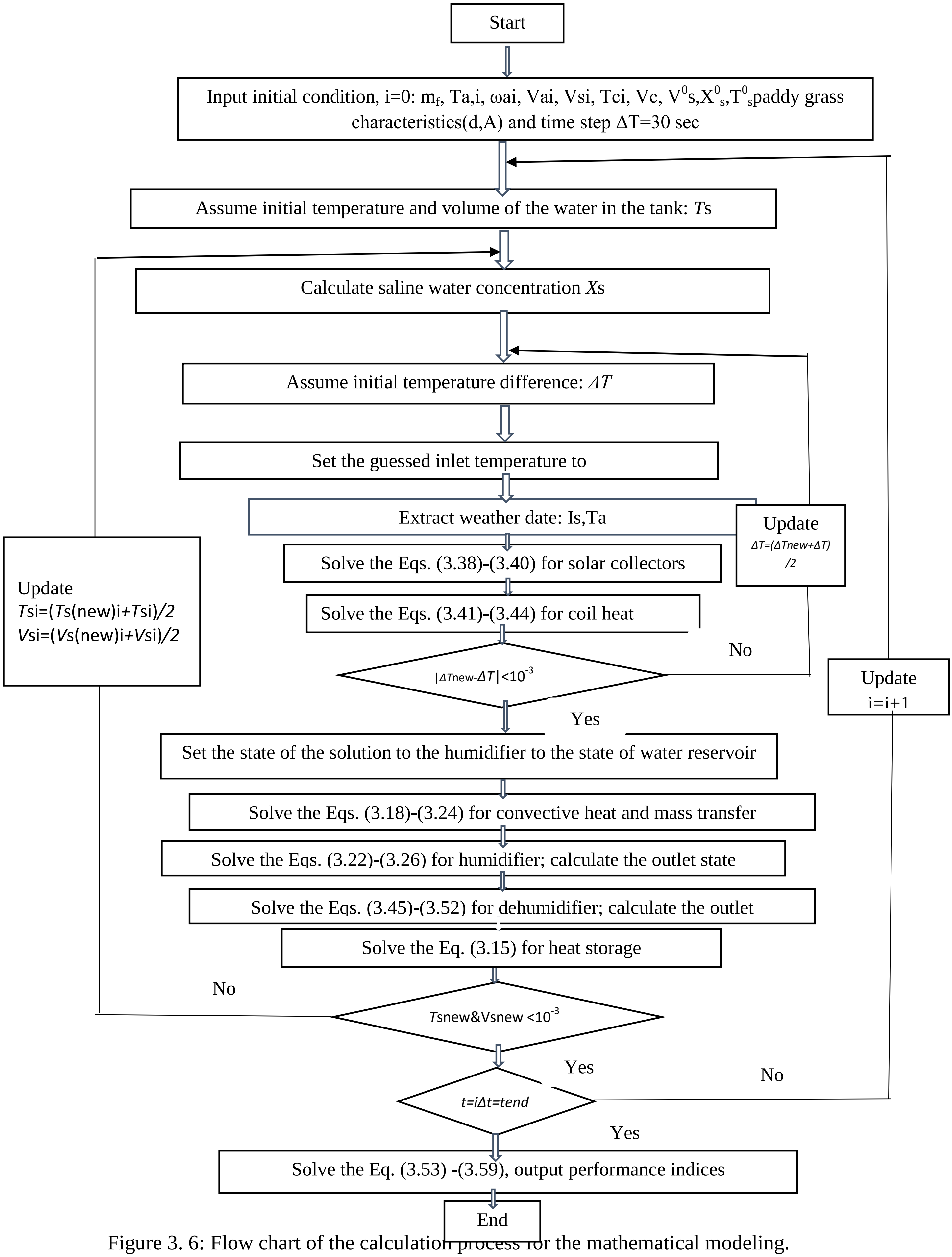


Figure 3. 6: Flow chart of the calculation process for the mathematical modeling.

Table 3. 1: Weather data for the typical day in September 2007 in Surathkal

Solar intensity(W/m^2)	500
Ambient temperature Ta (˚C)	25
Relative humidity (%)	65
Sea water temperature T_{sw} (˚C)	25
Speed of the wind (m/s)	5

Table 3. 2: Weather data for the typical day in September 2007 in Surathkal (Ramachandra et al. 2007).

Weather data	**Value**
Solar intensity(W/m^2)	400
Ambient temperature Ta (˚C)	25
Relative humidity (%)	75
Sea water temperature T_{sw} (˚C)	25
Speed of the wind (m/s)	7

Table 3. 3: Weather data for the typical day in December 2007 in Surathkal (Ramachandra et al. 2007)

Weather data	**Value**
Solar intensity(W/m^2)	450
Ambient temperature T_a (˚C)	25
Relative humidity (%)	60
Sea water temperature T_{sw} (˚C)	25
Speed of the wind (m/s)	6

Table 3. 4 Physical and operating parameters of the desalination system (Yamali and Solmuş 2007).

Design parameters:	**Operating parameters:**
w = 0.5 m, L = 1 m, D = 0.05 m,	m_{ws}=500(kg)
x = 0.025 (m),	M_a=0.027 kg/s
m_g = 3.75 kg, m_b = m_p = 4.5 (kg)	M_{w1}=0.028 (kg/s),
C_{p_g}=800, (J/kgK)	M_{w3}=0.05 (kg/s)
Cp_b=Cp_p=385(J/kgK)	T_{wm} = T_{w3} = 20 ˚C
Cp_a=1006, (J/kgK)	Trough length=1m,
Cp_w=4178 (J/kgK)	width=1 m
A_s=1(m^2)	d_o=0.09 m
U_{loss} = 0.75 (W/m^2K)	d_i=0.082 (Fahad et al. 2015)

The out let temperature of PTSC was calculated using the equation (3.13). The variation of solar data for three months in a typical day and physical and operating parameters of the desalination system were used from the literature and used as input values for the programming.

CHAPTER 4

MATERIAL AND METHODS

4.1.1 Polypropylene

Polypropylene, a group of polyolefins, possesses non-polar as well as partially-crystalline features. In comparison with polyethylene, polypropylene is mildly harder and shows resistance to high heat (Ayati et al. 2019). In figure 4.1, the author shows the actual photograph of polypropylene packing material.

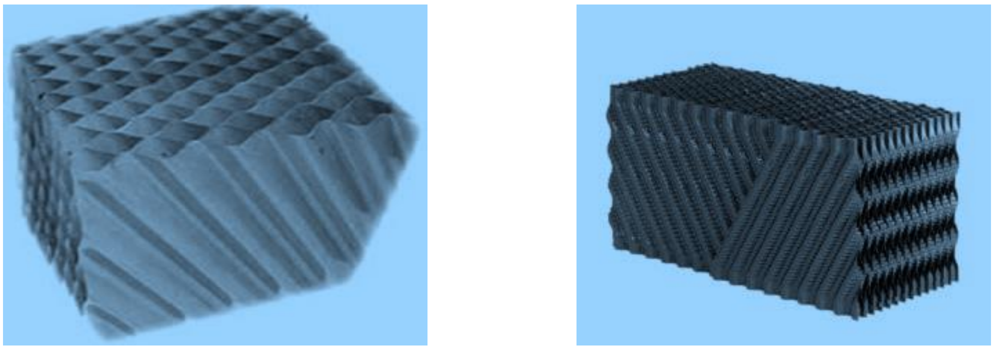


Figure 4. 1: Actual picture of polypropylene packing material

It is a white, mechanically rough material with better chemical resistance. The density of polypropylene is 0.855 g/cm^3 and it has a melting temperature of 130°C to 171°C.

4.1.2 Paddy grass

Paddy grass, a by-product of paddy cultivation practice, is nothing but the dry stalks of paddy plants. Once the harvesting is over, paddy grains are winnowed and the husk is removed. The grains are stored whereas body of paddy grass plant is left behind. The yield of paddy is equal to half the yield of other paddy-like crops namely, barley, oats and wheat. This is a widely-available, cost-effective, user-friendly and non-polluting material. Figure 4.2 shows the actual picture of paddy grass packing material. Paddy grass can be packed through two ways i.e., first one being horizontal and second one being vertical. The number of paddy grass used per stack is 1600 with each one having a diameter of 0.005 m and a length of 0.4 m. The packing density of the paddy grass is 157.07 m^2/m^3 with a surface area of 10.05 m^2.

Figure 4. 2: Actual picture of paddy grass packing material

Figure 4. 3: Picture of the paddy grass packing material in humidifier

4.1.3 Methods

The present study is carried out by two methods such as analytical method and experimental analysis method in order to evaluate the humidification and dehumidification processes. Thermal performance was evaluated in this study by solving continuity, mass balance, and energy equations for humidifier with paddy grass as well as for dehumidifier with baffle plates. Under same specifications, the experimental setup was developed. The results obtained through analytical and experimental methods were compared and validated against the previously published results.

4.2 Experimental system description

The experimental setup includes binary units such as humidification and dehumidification units. Between these, humidification unit consists of different accessories like water circulating pumps, water sprayers, air blower, and air heater. The dehumidification unit consists of a bunch of coiled copper tubes and baffle plates to produce cooling effect and to condense the air moisture. Hot and dry air that passes through the humidifier duct interacts with sprayed water, absorbs it and reduces the air temperature. This phenomenon further increases the moisture content of air. Warm and moist air is sent to dehumidifier unit i.e., a copper coiled heat exchanger of indirect contact type where warm, moist air and chilled water come in contact between each other through a copper tube. Finally, warm humid air is converted into water droplets at the outer surface of dehumidifier, where the fresh water is collected.

4.2.1 Working Procedure

To initiate the humidification process, atmospheric air is first introduced into air chamber, which is then heated using a heat source (location 1: to measure the inlet temperature and humidity of inlet air). This heating process reduces the humidity of air and increases moisture absorption capacity (Ghofrani and Moosavi 2020). Then, hot air is passed through lower portion of the humidifier. Water that continuously circulates is heated with the help of second heat source to increment its temperature. This preheated water is then sprayed using a water sprayer which is fixed onto the top surface of the humidifier (location 4: to determine both inlet temperature as well as humidity of inlet hot water). Then, the preheated water is sprayed using two water sprayers to increase the surface area for water-air contact. The sprayed hot water droplets interact with dry air; through this mechanism, the air absorbs the moisture and gets humidified (He et al. 2019). Meanwhile, the unabsorbed excess water is collected in water storage tanks and are safely maintained at the base of humidifier unit (location 6: to determine the outlet temperature of water). Again the same water is circulated with the help of water pump. Humid air (location 2: to calculate both temperature and humidity of outlet air) is circulated through dehumidifier unit. This unit has a copper tube fixed in the form of a coil. Through this tube, cooling water (location 7 and 8: to determine the temperatures of both inlet and outlet cold waters) flows and condenses the humid air. The condensed water droplets are then collected using fresh water collector which is placed at the bottom of dehumidifier unit; after losing its moisture content, the dry air (location 3 : to measure the dry air temperature) is let out.

Air flow rate is measured with the help of anemometer whereas water flow rate is determined using rotameter. The fresh water collected is then quantified using one liter capacity-water collector which is placed below the dehumidifier. Psychrometers are located at three different locations such as humidifier's inlet, humidifier's exit and dehumidifier's exit as shown in figure 4.3.

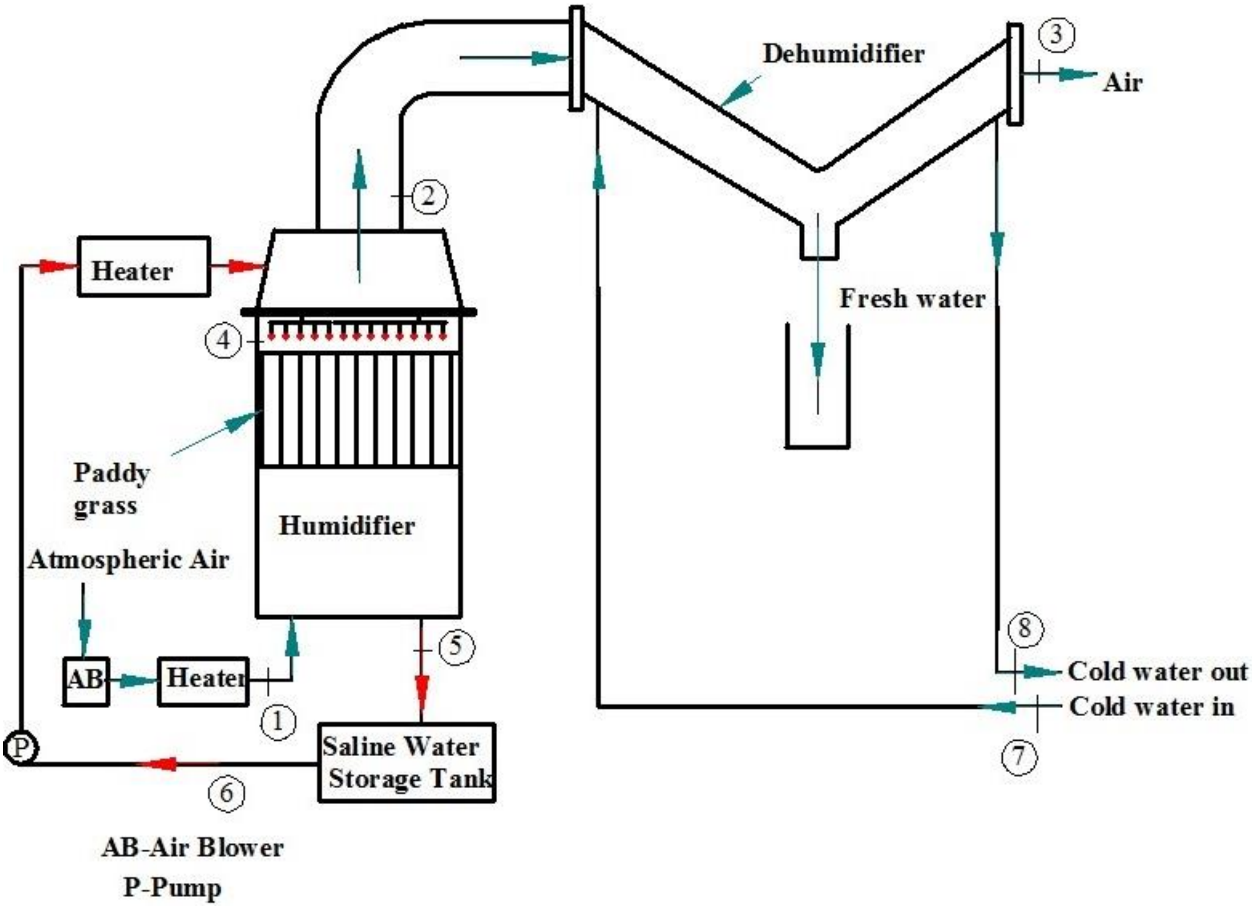


Figure 4. 4: Block diagram of humidification dehumidification unit

4.2.2 Experimental Setup Components

(a) Heat source: Two different heat sources were used in this experimental work between which one was used for heating air and another for heating water. In order to heat the air, the author used a 500 W capacity heater, while a 10 kW capacity heater was used for heating water. The actual pictures of the heat source are displayed in figure 4.5 (a).

(b) Humidifier: The process of adding moisture to dry air is carried out in a hollow square-shaped humidifier. The dimensional specifications of the humidifier are as follows; 0.4 × 0.4 m cross-section; and 1 m height set up made up of mild steel material. Air entrance and exit channels are provided at bottom as well as top portions respectively. The actual pictures of the humidifier are displayed in Figure 4.5 (c).

(c) Dehumidifier: Dehumidifier is modeled as a V-shaped hollow channel in which different baffles are attached inside the channel. This dehumidifier was developed based on mild steel material with a thickness of 1 mm. The cross-sectional specifications are as follows; 0.2 × 0.2 m with 0.8 m length, whereas the copper coils and baffle plates are attached along this length. The actual pictures of the dehumidifier are shown in figure 4.5 (d).

(d) Copper coils: To condensate the moisture content present in the humidified air, a copper coil is inserted into dehumidifier. Through this copper coil, cooling water is circulated so as to reduce the temperature of humid air. Copper coil has few specifications, in terms of dimensions, such as 90 mm inner diameter, 4.4 m total length, 100 mm outer diameter and total outside surface area of 0.124 m^2. The actual pictures of the copper coil are shown in figure 4.5(e).

(e) Baffle plates: Baffle plates are welded within dehumidifier channel to increase the condensation process. The technical specifications of the baffles used are 3 mm thick and 0.15 length. Six baffle plates were welded inside the channel with 0.16 m gap in between. The actual pictures of the baffles used are shown in figure 4.5(f).

(f) Water sprayer: In order to increase the contact area between water and dry air, hot water is sprayed using two water sprayers which are mounted at the top of humidifier. Each sprayer consisted of 36 ports at a distance of 0.8 cm, which breaks the liquid flow into dispersed droplets. The actual pictures of the water sprayers are shown in figure 4.5 (g).

(g) Saline storage tank: In order to supply the humidifier with saline continuously, a saline storage tank of 50-liter capacity was used in this research work.

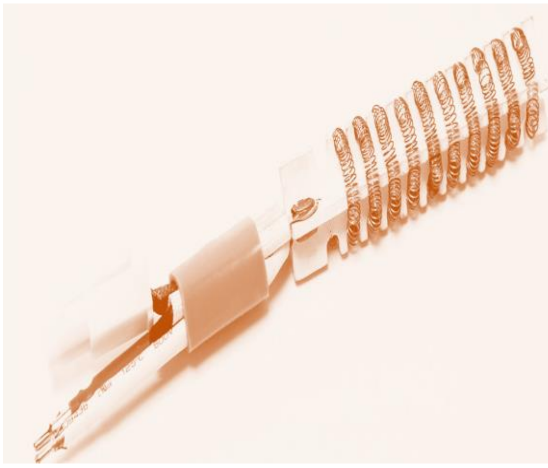
(h) Air Blower: Atmospheric air was sucked through air chamber, heated with the help of a heat source and then sent to a blower. The air blower capacity was 500 m^3/h with inlet and outlet diameters of 7.5 cm and 8 cm respectively. The speed was 1000 rpm and dry air was supplied up to 20-50 meters to the humidifier. The actual pictures of the air blower are shown in figure 4.5 (h).

(i) Potable water collector: A measuring jar with a capacity of one liter is placed below the dehumidifier unit. Through this water collecting jar, the amount of fresh potable water collected at different time instances can be analyzed.

(j)Thermocouples: To determine the temperature at different positions, eight thermocouples are installed. The thermocouples used are of K-type thermocouples with specifications such as 3 mm diameter, 2 m cable length and a working range of -200 ºC to 1200ºC with an accuracy of ±0.15ºC and an uncertainty of 2%.

(k) Psychrometer: Psychrometer is helpful in analyzing the intensity of humidification of dry air-dry bulb as well as wet bulb temperatures. In general, three such devices such as humidifier inlet, dehumidifier inlet and dehumidifier outlet are installed at these places. When dry bulb and wet bulb temperature are determined, the humidity of air is also calculated using psychrometric chart at atmospheric pressure.

(a) Heat source for water



(b) Heat source for air

(c) Humidifier

(d) Dehumidifier

(e) Copper coils

(f) Baffle plates

(g) Water sprayer

(h) Air Blower

Figure 4. 5: Photo of the experimental setup.

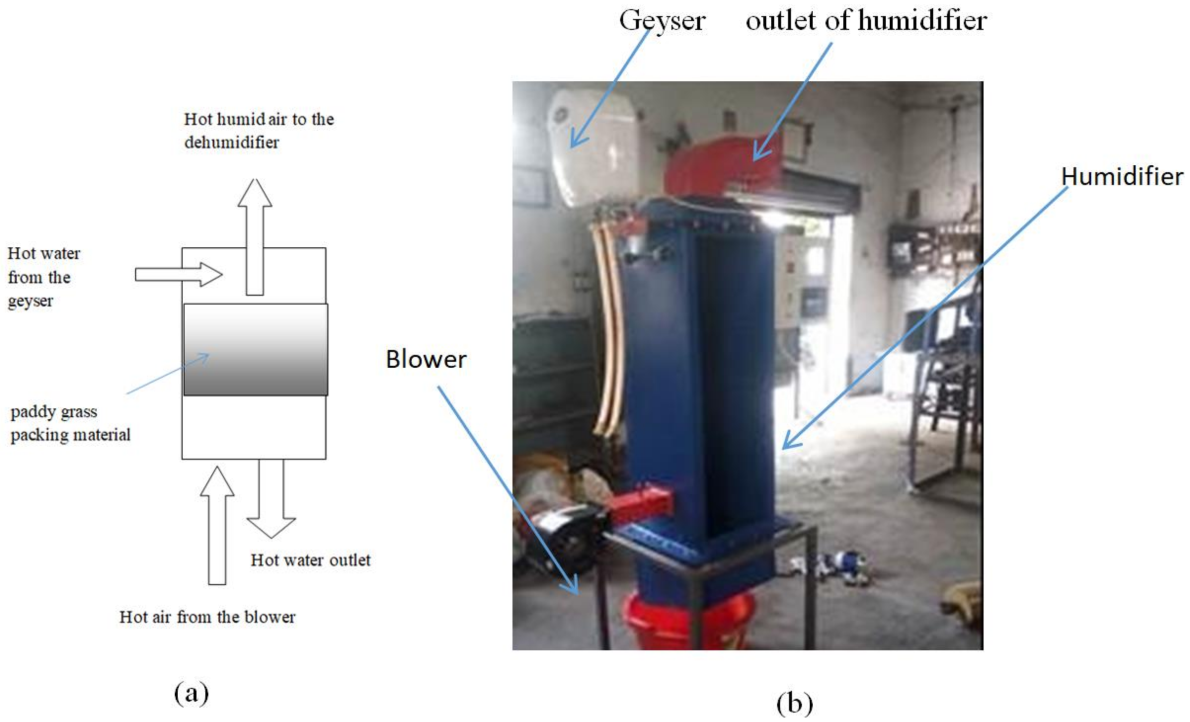


Figure 4. 6: Schematic view of (a) Humidifier with packing material (b) Experimental view with inlet duct to humidifier, blower and water heat source.

Experimentations were conducted for different performance parameters such as cooling water, air temperature, air mass flow rate, water temperature and water mass flow rate. The study is also aimed at analyzing the impact of different packing materials upon the performance of humidifier.

Figure 4. 7: Different components before the final assembly of the experimental setup.

Numerous experiments were conducted for different packing materials which include polypropylene, paddy grass and without packing material by changing the mass flow rate of water under varying temperatures produced from water heater source. K-type thermocouple was used in the measurement of water and air temperatures. Relative humidity was obtained by measuring wet and dry bulb temperatures at inlets and outlets of each part. Relative humidity was operated in the range of 0-100%, while the temperature operating range was up to 70°C. Feed water flow rate was regulated by valve whereas fresh water was collected and measured using measuring jar. Digital anemometer was determined with the help of air flow. The average value was noted for every 60 seconds.

4.2.3 Measuring devices and uncertainty analysis

Many parameters were measured while conducting experiments to evaluate the production of fresh water. These parameters include mass flow rate of air, relative humidity of inlet air at humidifier and dehumidifier, mass flow rate of water, relative humidity of outlet air at humidifier and dehumidifier, temperature of inlet air and water at humidifier and dehumidifier, temperature of outlet air and water at humidifier and dehumidifier and the volume of fresh water produced. Rotometers were utilized to calculate flow rate of water (range: 0.01-5 LPM) at an accuracy of ±0.01 LPM. The calibration was done by comparing the quantity of water collected for a specific time interval. With ±0.1 m/s accuracy, digital anemometer was utilized to determine air velocity. Three Psychrometers (to measure wet and dry bulb temperature, K-type thermocouple was used with error range being 1.75 %) were used to measure humidity at different locations (accuracy: ±2 RH). The quantity of fresh water produced was measured by gathering the fresh water in a graduated flask, at specified time intervals.

(a)

(b)

(c)

(d)

Figure 4. 8: Actual picture of the measuring instruments (a) and (b) Psychrometers at inlet of dehumidifier and dehumidifier (c):Thermocouple (d) Digital anemometer.

It is important to have accurate output when conducting an experiment and it is necessary to perform error analysis for the devices used in the measurement of various parameters. Two major types of errors are usually considered such as random error and systematic error. Random error occurs due to ability and skill of the experimentation, whereas systematic error occurs as a result of inaccuracy in the instrument itself. The influencing parameters are closely monitored to attain the accuracy of results. Some of the parameters that prominently affect the results are airflow rate, hot water spray flow rate, air temperature, and relative humidity. Also, ambient temperature, the temperature of water that enters and exits the heat source, temperature of water that enters and leaves the dehumidifier and condenser unit are measured. The uncertainties in the system are calculated using the following equation (Al-otoom and Al-khalaileh 2020).

$$Uncertainty = \sqrt{\left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]} \tag{4.1}$$

Where: R = Inputs function $\{x_1, x_2 \ \ldots x_n\}$. And $w_1, w_2, \ldots w_n$ refers to uncertainties of these variables.

Table 4. 1 : Uncertainties observed in different measuring instruments

Measuring Instruments	**Range**	**Accuracy**	**Uncertainty**
Thermocouple	-200 - 1200 ˚C	± 0.15 ˚C	2 ˚C
Humidity sensor	0 - 100 % RH	± 2.0 RH	1.75 RH
Airflow meter	0.02 - 5 m/s	± 0.1 m/s	1.5 m/s
Water flow meter	0.01 - 4 m/s	± 0.1 m/s	0.5 m/s
Water collector	0-1000 ml	±10 ml	5.5 ml

The percentage of uncertainty was observed in the range of 0.202 to 0.543 for the overall system whereas individual component uncertainty is calculated and tabulated below. Table 4.1 shows the uncertainty observed for different measuring instruments and table 4.2 indicates some of the experimental data measured during experimentation procedure.

Uncertainty for fresh water production

The quantity of fresh water (M_w) can be measured by taking the difference between flow rate ($\dot{m}_{hiw}$) inlet to the humidifier and the flow rate that leaves ($\dot{m}_{how}$) the humidifier at the bottom.

$$M_w = [(\dot{m}_{hiw}) - (\dot{m}_{how})] \times \rho \qquad (4.2)$$

If error is w_1, then the equation 4.1 (Rahbar and Esfahani 2012) is followed.

$$\partial M_w = \left[\left(\frac{\delta M_w}{\delta \dot{m}_{hiw}} \delta \dot{m}_{hiw} \right)^2 + \left(\frac{\delta M_w}{\delta \dot{m}_{how}} \delta \dot{m}_{how} \right)^2 \right]^{0.5} \qquad (4.3)$$

$$\partial M_w = (\rho \times \delta \dot{m}_{hiw})^2 + (\rho \times \delta \dot{m}_{how})^2 \qquad (4.4)$$

By substituting the value in the above equation, the measurement error for fresh water is obtained as follows.

∂M_w=0.02 kg/h

The percentage of error in fresh water production is as follows.

$$\partial M_w = \left(\frac{\partial M_w}{M_w}\right) \times 100 \tag{4.5}$$

Where M_w is the fresh water yield per hour and for specific run, the fresh water production was 0.7 kg per hour. Then, the uncertainty in measurement was ± 2.85%.

Table 4. 2 Some of the experimental data measured in the system.

$T_{a,i,h}$	$T_{a,i,d}$	$T_{a,o,d}$	$T_{w,i,h}$	$T_{w,o,h}$	$T_{cw,i,c}$	$T_{cw,o,c}$	m_{fw}	m_w	m_a	m_{cw}
(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(kg/hr)	(kg/s)	(kg/s)	(kg/s)
26.78	33.78	30.15	35.43	34.01	28.89	30.87	0.312	0.051	0.012	0.045
25.87	34.56	30.57	36.02	34.71	30.01	31.43	0.328	0.051	0.013	0.045
25.14	37.97	31.34	40.12	30.45	30.04	31.84	0.341	0.051	0.012	0.045
26.67	37.78	31.45	40.15	31.89	30.06	31.67	0.345	0.051	0.021	0.045
26.87	38.34	31.98	41.5	30.56	30.12	31.89	0.349	0.051	0.012	0.045
26.78	40.45	32.09	43.76	33.17	30.17	32.04	0.355	0.051	0.017	0.045
25.98	40.23	32.45	43.56	32.19	29.99	32.02	0.356	0.051	0.012	0.045
25.14	40.65	32.34	43.66	32.67	30.13	32.21	0.361	0.051	0.013	0.045
26.67	48.45	34.65	50.11	37.98	30.12	33.98	0.365	0.051	0.012	0.045
26.87	48.56	34.21	50.91	37.65	30.13	33.79	0.368	0.051	0.021	0.045
26.78	48.23	34.67	50.02	36.88	30.12	32.86	0.362	0.051	0.012	0.045
25.42	48.61	34.37	54.33	34.87	28.97	35.08	0.398	0.051	0.021	0.045
25.14	48.22	35.02	54.67	34.12	28.78	34.98	0.391	0.051	0.012	0.045
26.67	49.67	40.87	55.01	33.78	28.98	34.65	0.392	0.051	0.017	0.045
26.87	51.55	41.9	60.78	41.34	27.08	37.32	0.432	0.051	0.012	0.045
26.78	51.62	42.01	60.43	42.22	28.12	37.87	0.453	0.051	0.013	0.045
25.87	51.72	42.45	60.32	43.12	30.12	37.53	0.495	0.051	0.012	0.045
25.14	52.33	41.88	61.76	42.45	30.13	38.21	0.521	0.051	0.021	0.045
26.67	53.89	34.89	65.19	41.91	30.12	39.32	0.589	0.051	0.012	0.045
26.87	53.34	35.12	65.09	41.56	28.97	39.63	0.612	0.051	0.021	0.045
26.78	55.34	40.45	68.45	35.34	29.78	40.31	0.63	0.051	0.012	0.045
25.9	55.71	41.01	69.01	34.45	29.98	40.88	0.719	0.051	0.017	0.045
25.14	56.88	39.99	70.01	34.34	29.76	40.93	0.729	0.051	0.012	0.045

CHAPTER 5

RESULTS AND DISCUSSION

5.1.1 Model Validation

The researcher compared the output from theoretical model against the experimental output in order to verify the validity of the system proposed in current study. The current work considered a number of influencing parameters (Li and Zhang 2016a) from the literature. Such parameters are inlet saline water, air flow rate into humidifier unit and the packing fractions. The specification of the humidifier is as follows; square cross section of 40 cm by 40 cm with a flow rate of saline being 0.04 kg/s, inlet flow rate of air as 0.004 kg/s at 35 ℃ and relative humidity of 60 %. The initial saline temperature of the storage tank was fixed at 50℃ with 3.5% concentration at a capacity of 90 L. The cold water flow rate to the dehumidifier was maintained at 0.04 kg/s. The experiment was conducted on 12th August 2018 and the solar radiation and atmospheric temperature were measured at Surathkal, India as represented in figure 5.1.

From the figure 5.1, it can be inferred that the understandings between the determined and the experimental outputs are acceptable. The relative deviations between the determined and the tried estimations of T_s and accumulated production were 2% and 4.5% respectively as shown in figure 5.2. Accordingly, the theoretical model is proved to be valid and can be utilized to examine the performance.

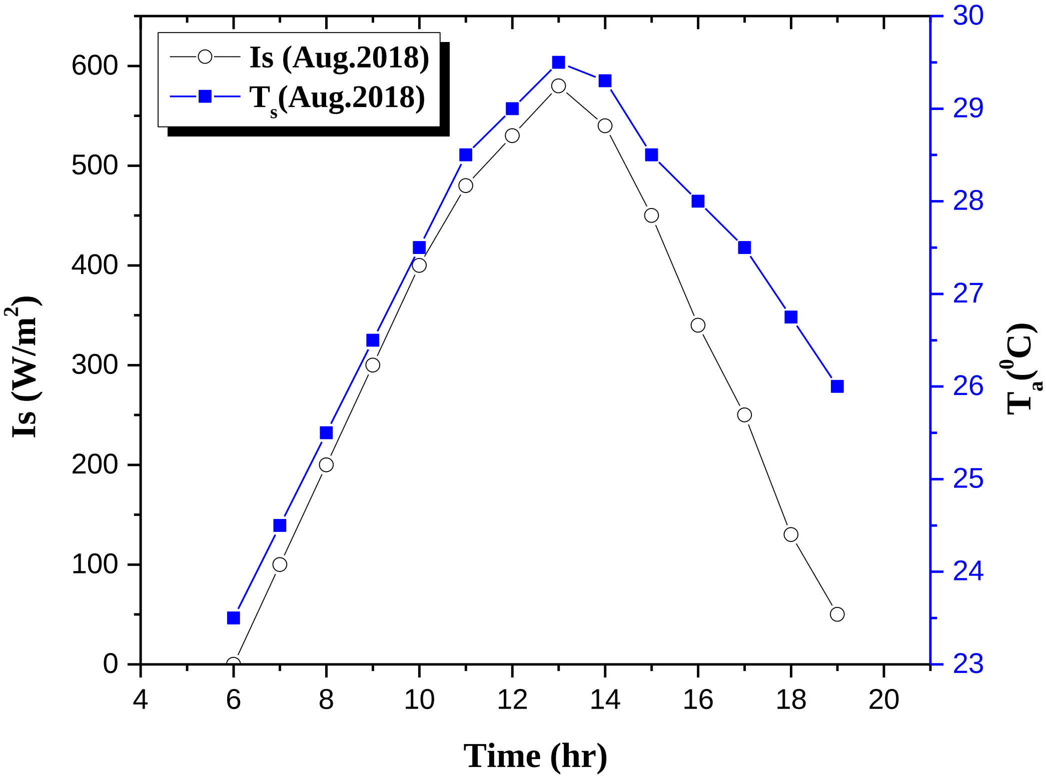


Figure 5. 1: Solar radiation and atmospheric temperature against time duration on a typical day in the month of August 2018, at Surathkal, India.

5.1.1Experimental and computational results

To evaluate the production of fresh water and paddy grass humidifier's outlet temperature, some of the input values were fed into numerical model such as inlet water and air temperature. To confirm the model, a reasonable study was carried out between mathematical modeling and the experimental results and the output is shown in table 5.1. The maximum variation for the above performance indices was 6.1%. As per figure 5.3, the variations are less than 2% for tank water temperature. The variations of the measured and experimental values were within 5% and 6% for latent effectiveness and sensible effectiveness respectively. Therefore, the theoretical mathematical model can be used to analyze the system performance for three different cases such as paddy grass packing, polypropylene and without any packing material. Paddy grass packing exhibits few properties namely, moisture diffusivity, thickness and area which are considered in detail for the study.

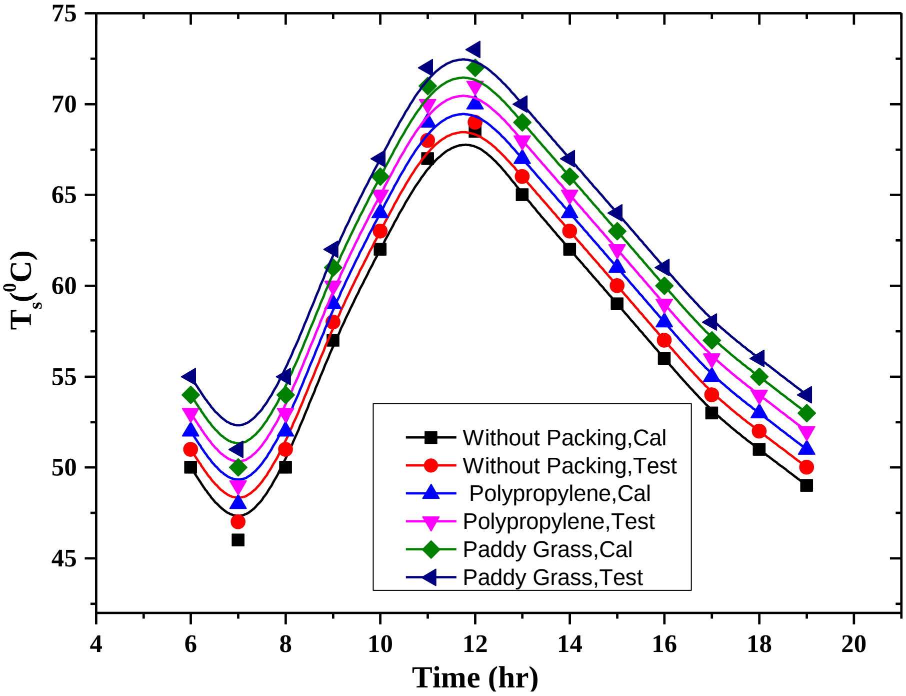
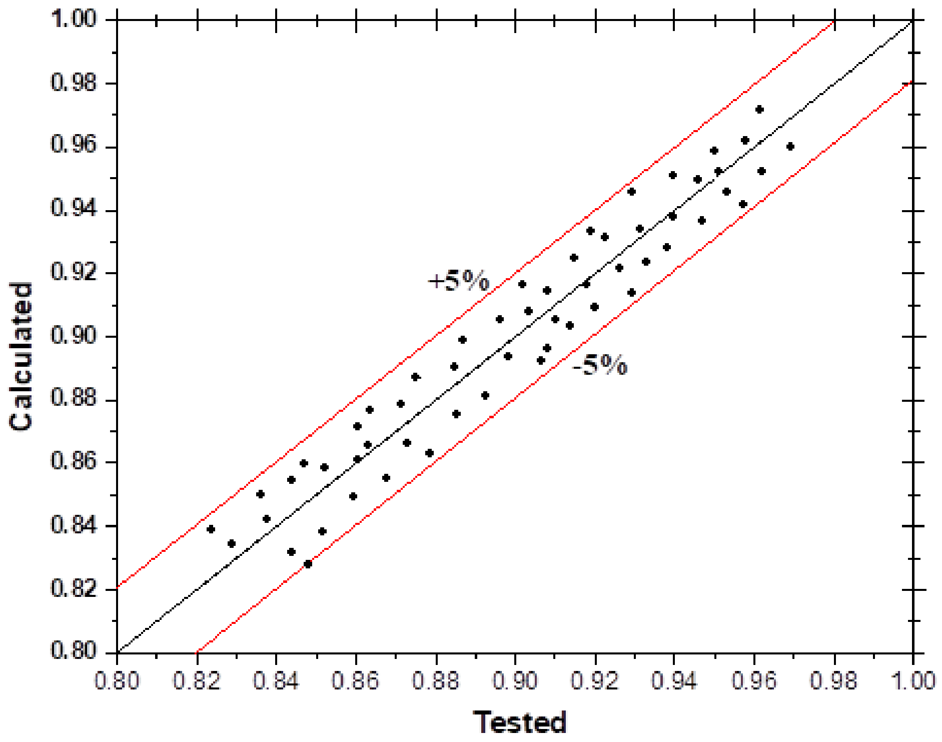


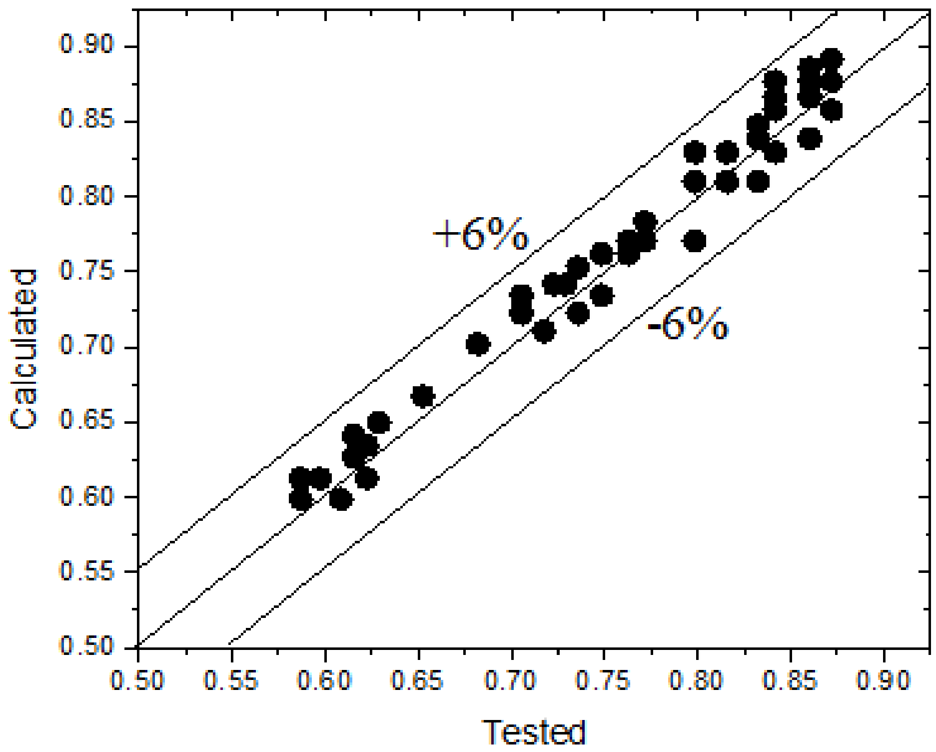
Figure 5. 2: Tested and calculated water tank temperature for different two different packing.

Table 5. 1: Calculated and measured system performance during the operation of packing materials

Packing material	**AP_{cal} (kg/day)**	**AP_{tes} (kg/day)**	**Error (%)**	**SEC_{cal} (kWh/m^3)**	**SEC_{tes} (kWh/m^3)**	**Error (%)**	**COP (cal)**	**COP (Test)**	**Error (%)**
Paddy grass	7.35	7.14	2.91	22	21	4.5	0.65	0.61	5.3
Polypro pylene	4.65	4.23	4.2	23	22	4.3	0.4	0.37	5.2
Without packing	3.5	3.3	5.7	20	21	4.7	0.3	0.28	6.1



(a)



(b)

Figure 5. 3 Deviancy between the experimental and calculated latent effectiveness and sensible effectiveness (a) Latent effectiveness (b) sensible effectiveness

5.1.2 Solar collector performance

Solar collector is one of the significant components in HDHT system. The maximum amount of energy is collected from this component. Accordingly, it is important to evaluate the performance of solar collector in order to assess the performance of entire system. Hence, the degree of performance can be understood from collector efficiency and is given in the equation (5.1). It is well-defined as useful solar energy, collected over a period of time, to avail solar radiation. Under these conditions, the instantaneous collector efficiency is plotted as a linear function of the term, $(T_{fi} - T_a)/I_s$:

$$\eta_i = 0.64 - 2.44(T_{fi} - T_a)/I_s \qquad (5.1)$$

Based the above equation, the maximum efficiency of the collector reaches 64 percent, when second term of RHS is zero i.e., the temperature of the water collector is same as that of the atmospheric temperature. The instantaneous collector efficiency with time is shown in figure 5.4. The variation of efficiency was from 0.42 to 0.52 and attained peak at about 10 AM (nearly 80 percent of the noon period) because the solar energy was nearly 450 W/m^2, whereas the change in temperature T_{fi} and T_a was not very high. Consequently, the ratio of temperature difference to I_s was also very low. Hence, efficiency reached the highest value.

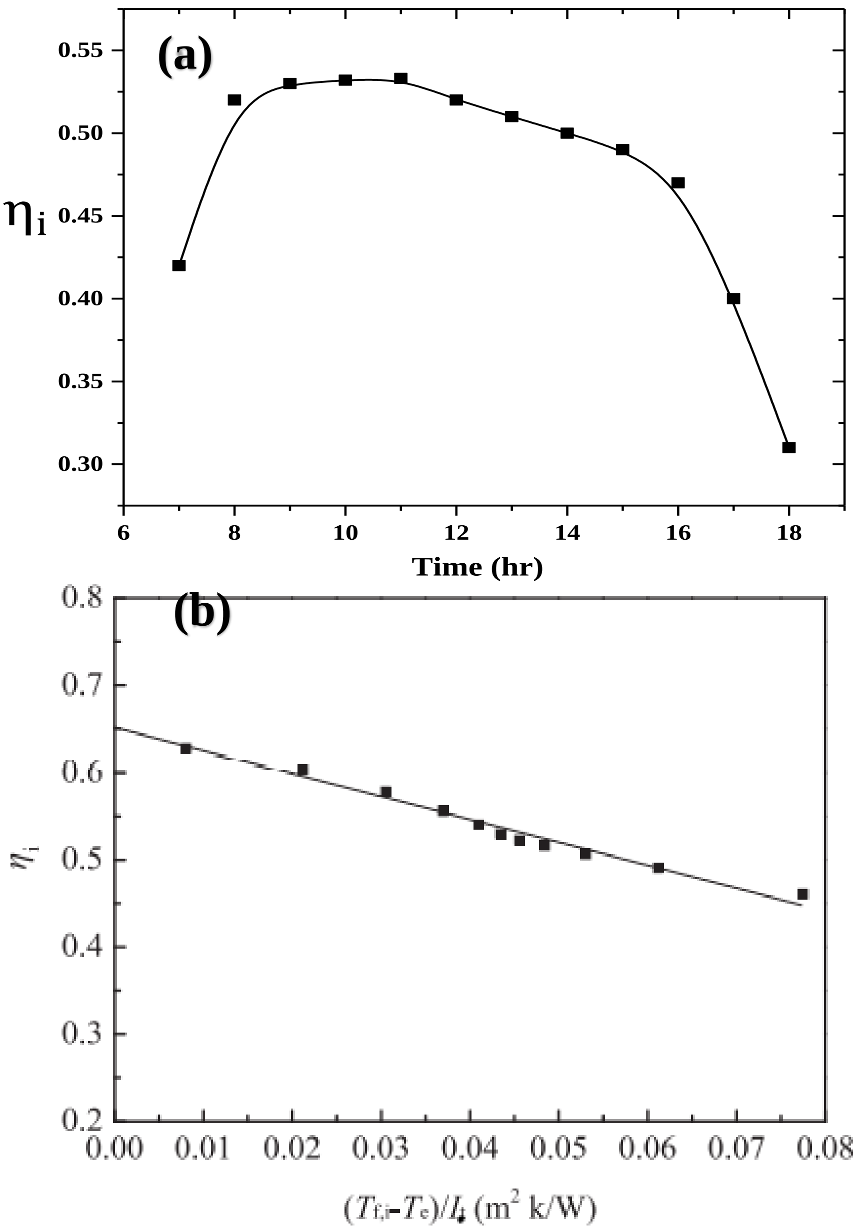


Figure 5. 4(a): Variation of instantaneous collector efficiency with time (b). Efficiencies of solar collector.

5.1.3 Effect of volume of saline water in the storage tank

The simulation for saline tank was carried out at different volumes of water. Initially, the system was operated with saline at a temperature of 50°C from 6 AM till the temperature reaches less than 50℃ at afternoon. The optimum collecting area was 4.2 m^2. Figure 5.5 shows the difference in tank volume of saline and the effect of water temperature within the storage tank. Similarly, figure 5.6 shows the variations in instantaneous water production, according to the time. It can be understood from the figure 5.6 that the temperature inside storage tank changes with respect to solar radiation and atmospheric temperature. Conversely, a reduction in water temperature was observed between the time interval of 6 AM and 7 AM due to low solar radiation. Consequently, a drop in instantaneous water production was also observed from 7 AM to 8 AM. However, it attained the maximum value later i.e., after 30 minutes of delay. High volume tank reacts less to solar radiation compared to small-sized tank. So, a high-volume tank can be utilized as a reservoir for sensible heat from heavy solar radiation during afternoon whereas it may be used later, when the radiation is unavailable or less. The running duration of the 160 L storage tank was lengthier compared to 40L storage tank. The time took by the 160 L storage tank was nearly 2 hours extra than the 40 L storage tank as shown in figure 5.5. Hence, the system can run even if there is no solar energy after 19 hours, as shown in figure 5.5.

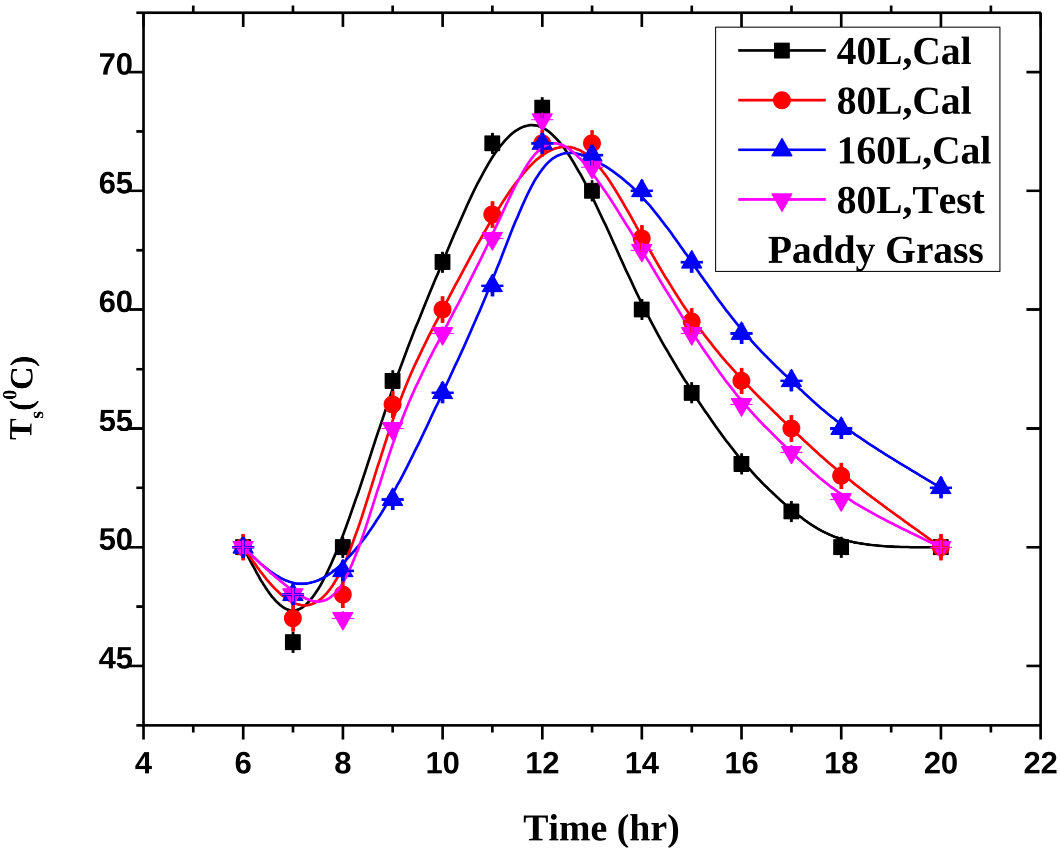


Figure 5. 5: Effect of tank volume on the water temperature in the water tank through the working time.

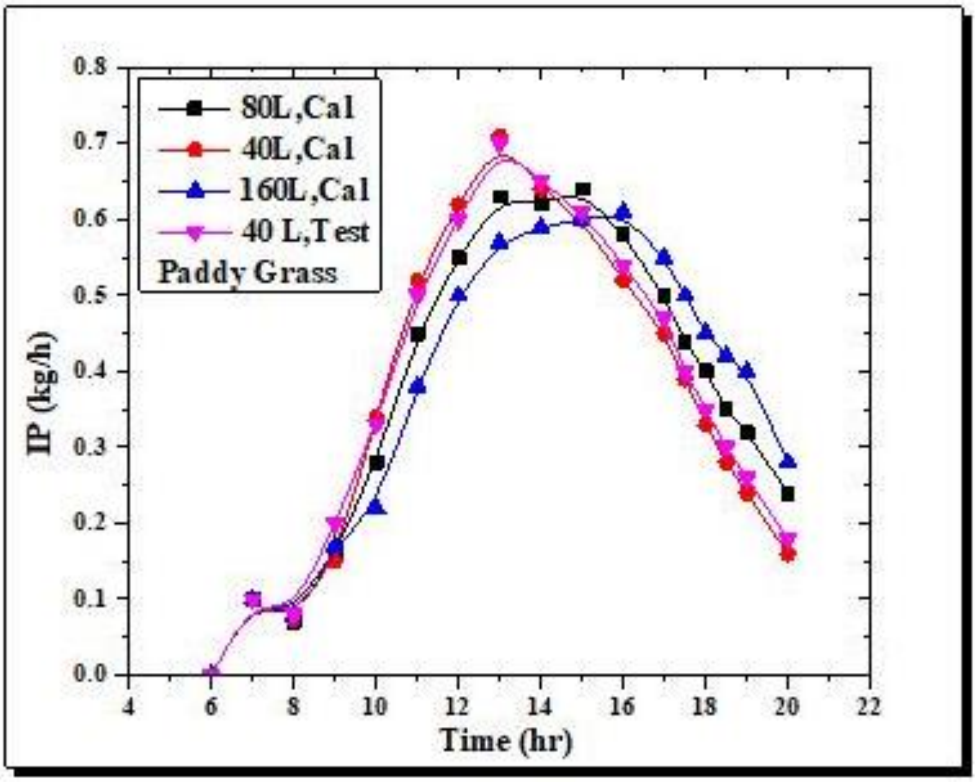


Figure 5. 6: Effect of tank volume on instantaneous water production (IP) through working time.

Figure 5.7 shows the variations in the water collected from production process and SEC with changes in storage water tank. Also, the effects of COP and COP_E with saline storage tank volume is shown in figure 5.8. If the temperature is less than 50 ℃, the system ends functioning at afternoon. It is observed from the results that the system has a volume of 160 liters whereas the working duration exceeded the usual duration taken by 40 L tank. So, the accumulated production rate experiences a negligible increase by a mere 2%. When additional hours were taken for the process, additional electrical energy was also utilized. Thus, increasing the volume of the water tank results in increased SEC and gradually decreases in COP_E as illustrated in the figures, 5.7 and 5.8. A high-volume tank maintains average water temperature during the entire day and has lengthier functioning time too. In such case, additional solar energy can be utilized. Hence, a less amount of accumulated water production rise results in a reduced COP.

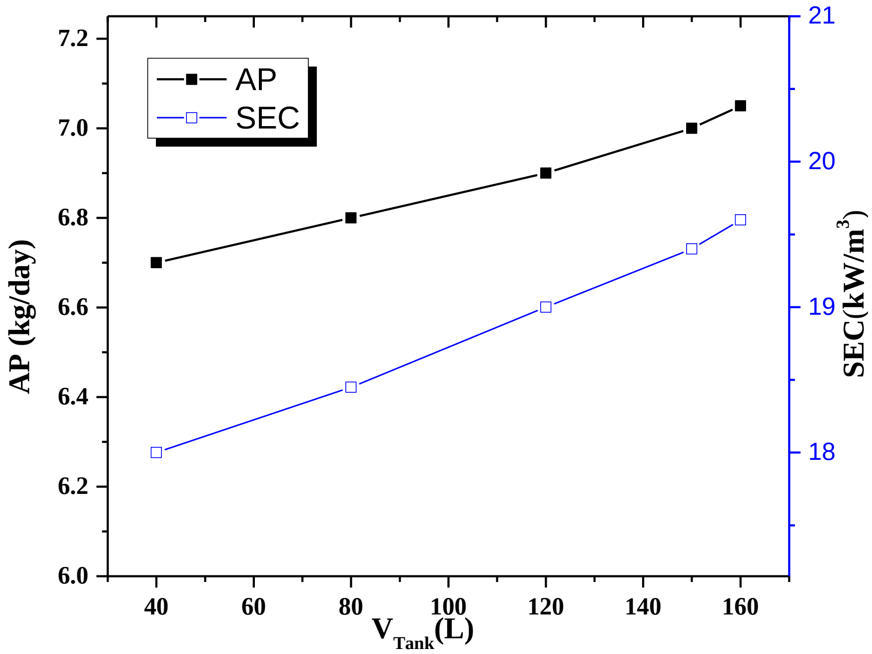


Figure 5. 7: Variations in accumulated fresh water production (AP) under different tank water volumes

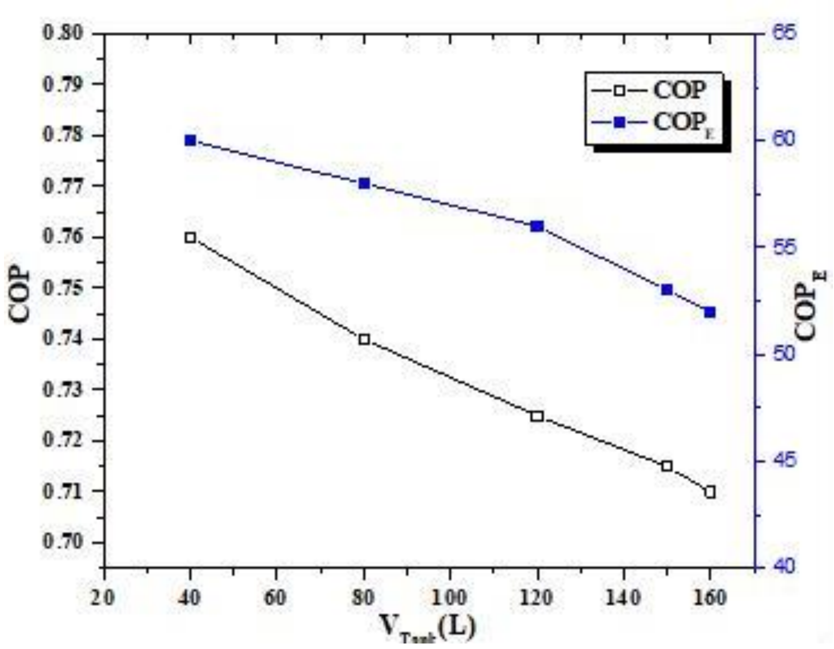


Figure 5. 8:Variations in Coefficient of Performance (COP) with different tank water volumes.

From the results discussed above, two inferences can be attained. The first being, water tank with high volume helps the system to run for a long duration by storing the unstable solar energy. The second inference is that no additional advantage is accomplished when using water tank with more than 40 L.

5.1.4 Effect of solar collector area

Solar collector is one of the most important units of heating source. In general, it is also the costliest unit in HDHT system. Therefore, it is essential to choose the optimum collector area for the system. In current study, the author selected 40 L storage water tank as optimum one whereas other settings were followed as conducted earlier. Figure 5.9 shows different collector areas on storage water tank temperature. Likewise, figure 5.10 shows the production of instantaneous water within the given time. It is natural that the collector area is highly effective on the performance. It is observed that both water temperature and IP got increased with increased area of the collector. The water temperature reached nearly 70 ℃ within 13 hours when the area was 5 m^2, and 50 ℃ in 14 hours when the area was 1 m^2. The inference is that the IP got increased 3.5 times, when 4 m^2 area was used.

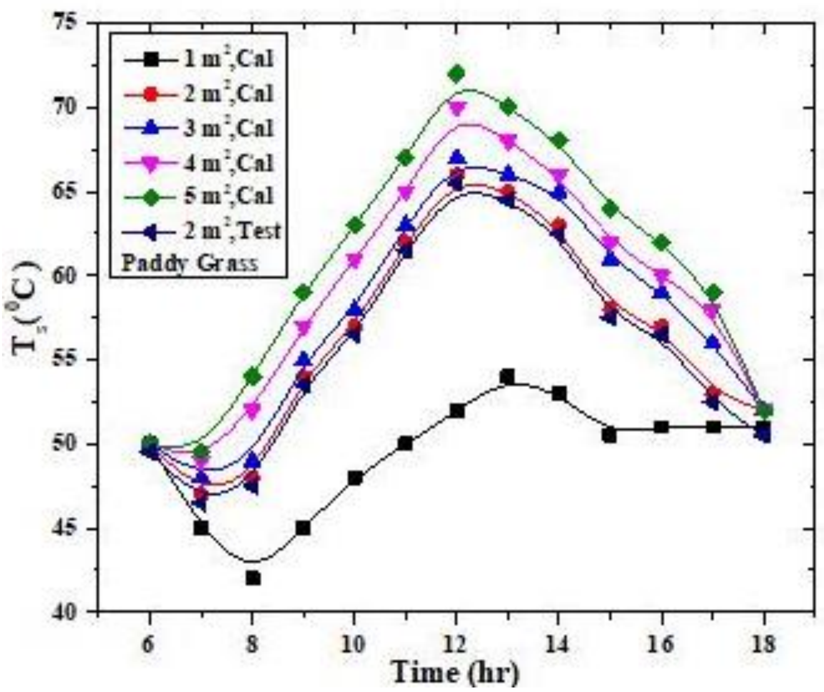


Figure 5. 9: Effect of solar collector area on the water temperature in the water tank through the working time.

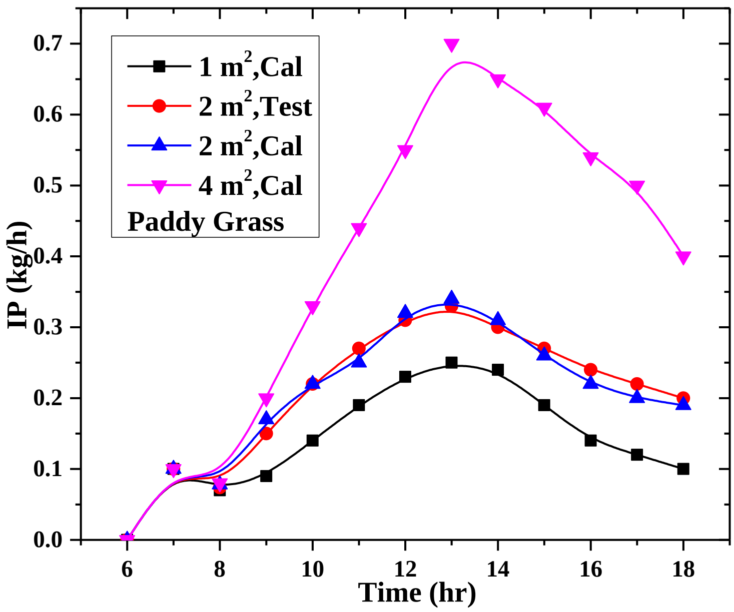


Figure 5. 10: Effect of collector area on instantaneous water production through working tim

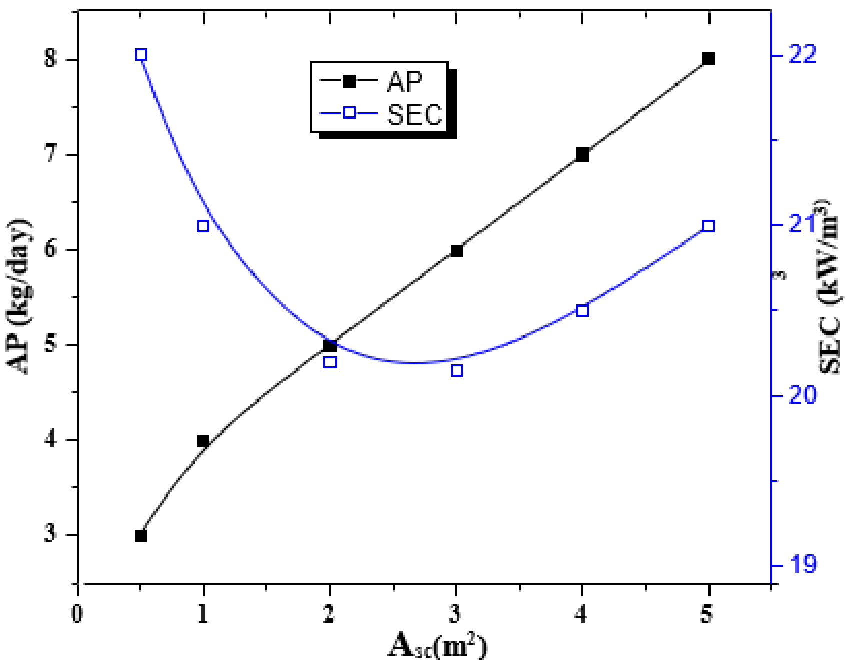


Figure 5. 11: Variation of the accumulated fresh water production (AP) with solar collector area.

The effect of the accumulated production, SEC, COP and COP_E by changing the collector area is illustrated in the figures 5.11 and 5.12 respectively. A reduction was observed in SEC, when the collector area was enlarged up to 3 m^2, post which SEC got increased. The first scenario occurred not of more collector area but due to more number of collectors. The second scenario occurred due to heavy fluid pressure drop which resulted in heavy utilization of the electrical energy for pumps. It is also observed that the increase in AP was slower with increase in collector area. So, the lowest AP of 20 kWh/m^3 occurred at 3.0 m^2, when the COP touched extreme top of 60 as illustrated in figure 5.11. A similar trend can also be observed for COP i.e., when area was higher than 3 m^2, it resulted in increased temperature and accordingly additional heat loss from the system to the surrounding atmosphere. This remains the primary reason for the decline observed in COP.

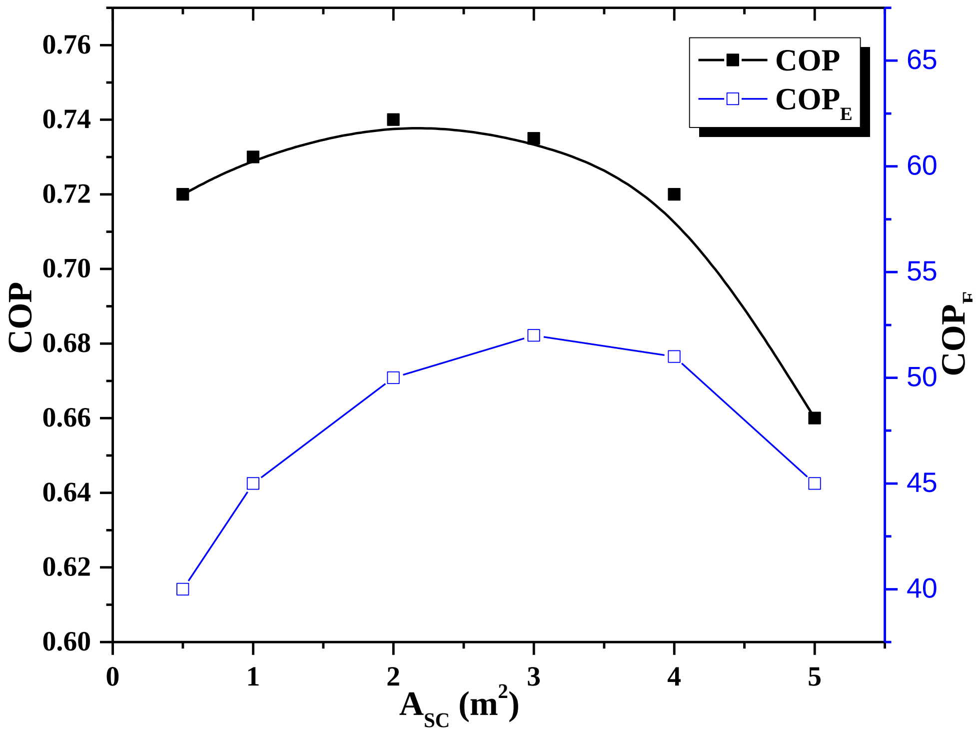


Figure 5. 12: Variation of coefficient of performance with solar collector area.

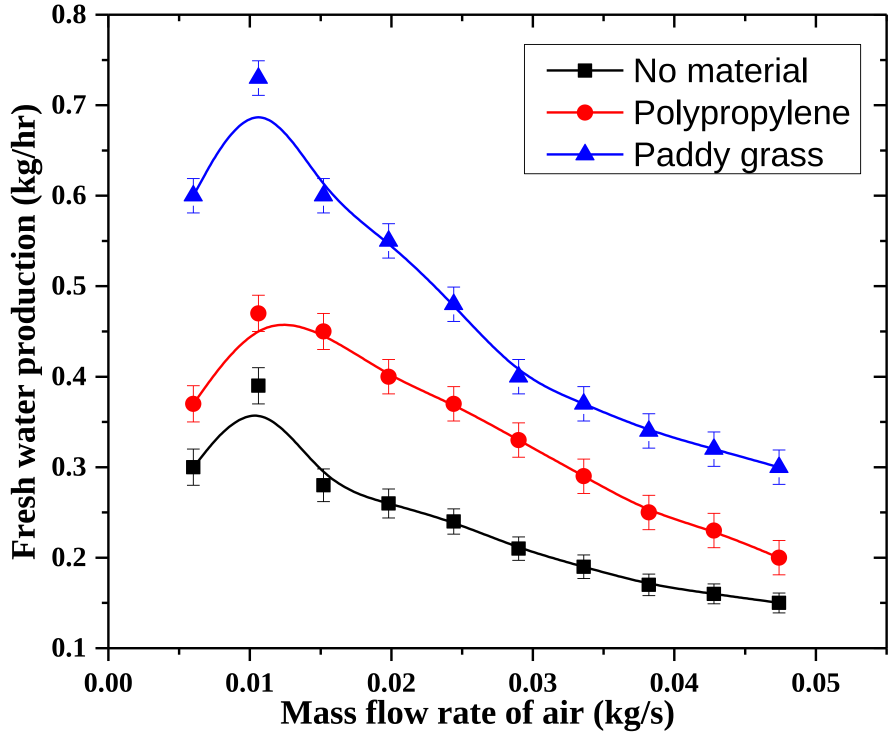
Table 5. 2: Experimental comparison of present and the previous results for different packing materials.

Mass Flow Rate of Water ($\dot{m}_w$)	**Mass Flow Rate of Air ($\dot{m}_a$)**	**Inlet Temp. (T_1)**	**Outlet Temp. (T_2)**	**Packing Materials**	**Fresh water Production (M_w)**		**Authors**
(kg/s)	(kg/s)	(˚C)	(˚C)	*NA*	(kg/h)	*(kg/m³)*	
0.040	0.01	70.0	40.0	Paddy grass	0.735	47	Present study
0.040	0.01	70.0	40.0	Polypropylene	0.465	29	Present study
0.030	0.031	44.0	28.0	Metal	3.200	19	(Moumouh et al. 2016)
0.002	0.045	36.0	33.0	Cellulose	0.512	40	(Nafey et al. 2004)
0.012	0.040	68.9	43.4	Cellulose	1.450	0.86	(Hermosillo et al. 2012)
0.115	0.045	50.0	40.0	Plastic	2.500	17	(Yamali and Solmus 2008)
0.530	0.15	49.0	38.73	Aluminum Sheets	15.000	54	(Ahmed et al. 2017)
0.04	0.01	44.69	53.6	Textile	2.6110	10.87	(Zhani and Bacha 2010)

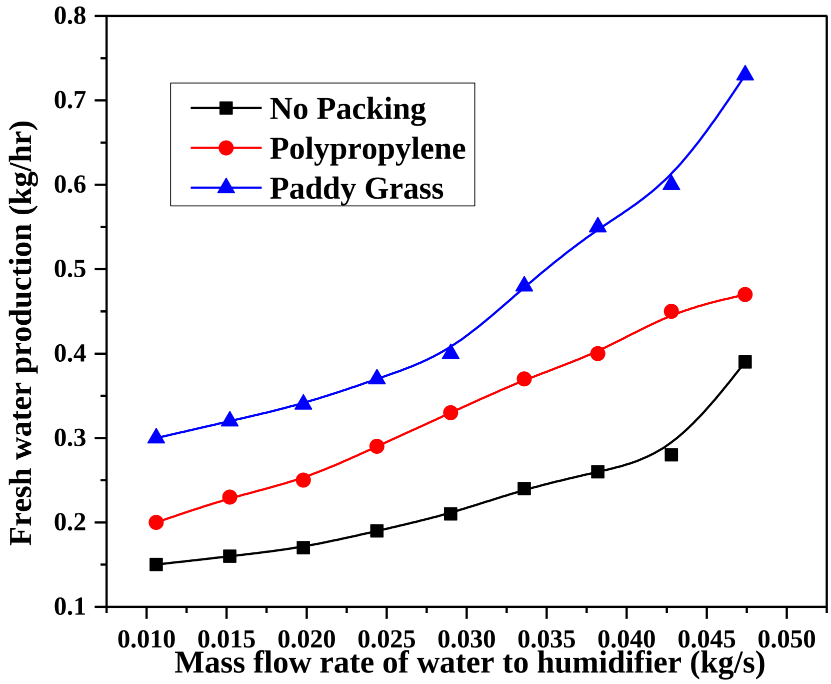
Various researchers were used different packing materials like cellulose, plastic, aluminum, textile etc. in order to produce fresh water using HDH technique. Table 5.2 shows the experimental comparison of present results and previous study results for different packing materials. In the present study, paddy grass material as a packing material produced the highest rate of fresh water compared to other packing materials. The reason behind the production of high volume of fresh water is due to large packing wetting area that increased the contact area between air and water The production of fresh water using HDH system is improved by increasing the inlet temperature, mass flow rate of saline water entering to the humidifier and the flow rate of cold water to the dehumidifier. In addition to that, decreasing the cold water temperature increases the yield of the system.

5.2 Effect of different flow rates on fresh water production

Throughout the experiment, a phenomenon was observed i.e., low mass flow rate of air resulted in high fresh water production rate. For 0.01 kg/s airflow rate, the quantity of the water produced was at the maximum. During the comparison of all three cases, similar patterns were observed. However, when compared to no-packing material, water production rate got increased with packing material. In comparison with no-packing condition, polypropylene packing produced a slightly high volume of fresh water (Lawal and Qasem 2020). Among these working conditions, paddy grass packing material produced excellent and maximum results with respect to yield. An increase in airflow to the humidifier increased the production of fresh water. But beyond 0.01 kg/s, the extension got reduced in the yield of potable water. This might be attributed to the fact that the increasing flow rate reduces the contact between air and water. This scenario would have probably decreased the moisture content present at the outlet of humidifier (Qasem and Zubair 2019). Figure 5.13 shows the variations of fresh water production with (a) mass flow rate of air and (b) mass flow rate of water.



(a)



(b)

Figure 5. 13: Variations in fresh water production with (a) mass flow rate of air and (b) mass flow rate of water

The reason behind the production of high volume of fresh water is due to large packing wetting area that increased the contact area between air and water. The water is sprayed with the help of packing materials. The degree of wetting the packing surface influences the flow rate of air and water. Paddy grass exhibited higher productivity in this experiment compared to polypropylene packing material. The enhanced interaction between water and air produced great results in terms of high quantity water particles with air. Hence, the augmented fresh water is collected at the outlet of the system.

5.3 Variations in dimensionless parameter with mass flow ratio

The present experimental analysis was carried out under three different cases i.e., without any packing material, with artificial packing material (Polypropylene), and with bio-based material (Paddy grass). The effect of these packing materials on fresh water production rate was analyzed based on few parameters such as airflow rate and water flow rate. The variation of mass flow ratio against the dimensionless factor [KaV/m] of the humidifier is shown in figure 5.14. From the graph, it can be understood that when mass flow ratio increases, it decreases the dimensionless parameter. The graph exhibits the same outcome alike the results published by Farhad (2007) in which same experimental work was carried out earlier. However, the only difference in the present work is the usage of paddy grass material with a packing density of 157 m^2/m^3.

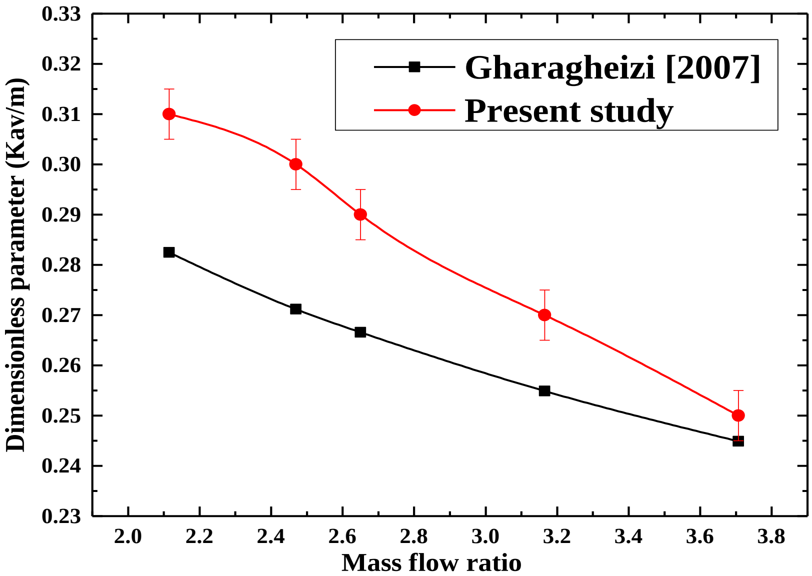
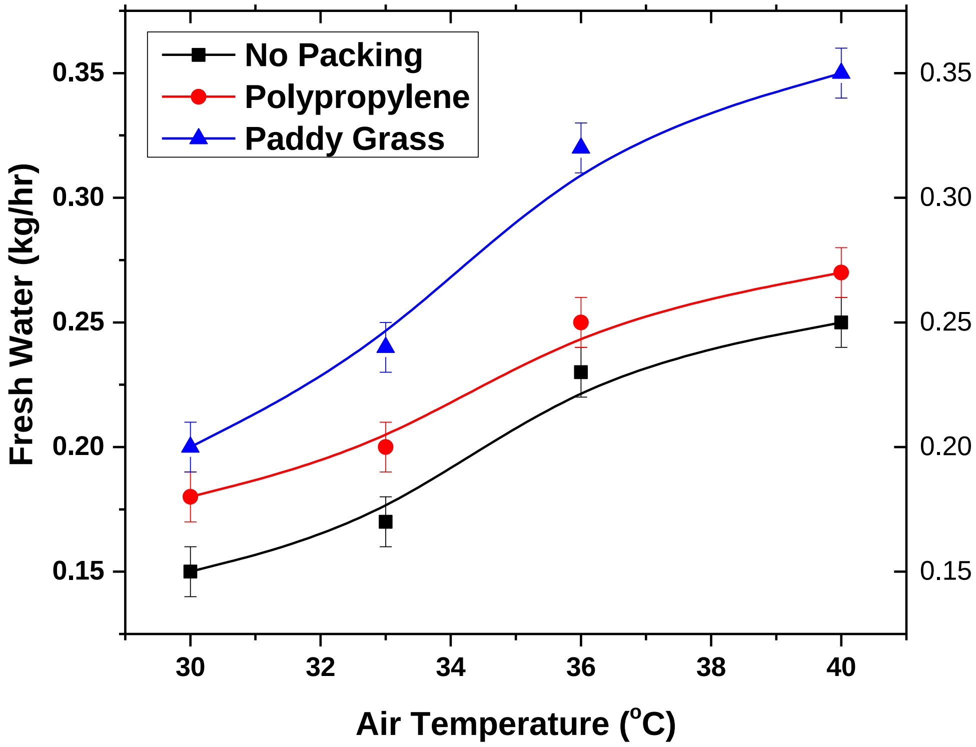


Figure 5. 14: Variation in dimensionless parameter against mass flow ratio (m_a=0.01 kg/s,m_{cw}=0.05 k g/s).

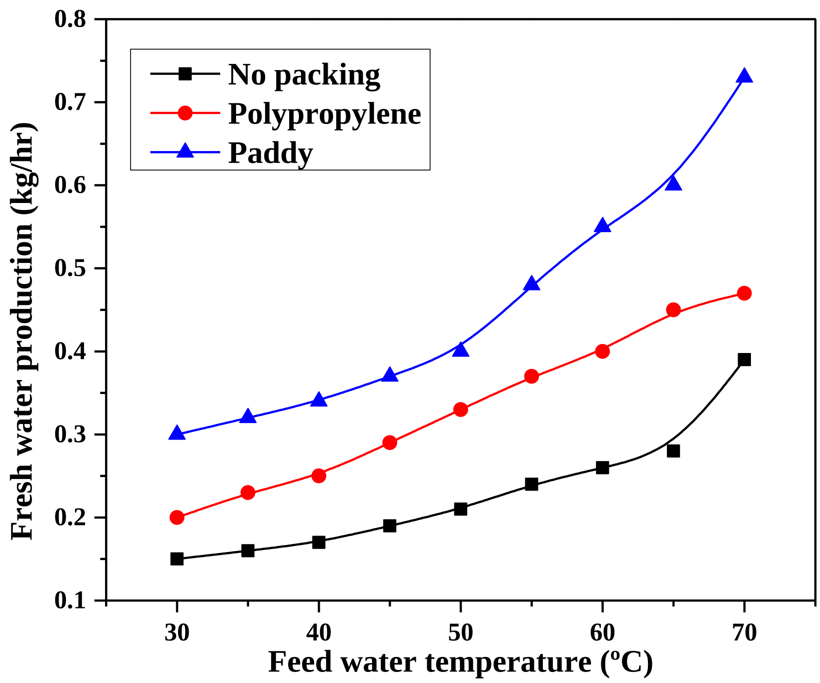
The experiment was repeated alike the previous analysis to validate the present results. The current experiment also considered the same operating parameters and working conditions. Both the results are found to be similar in an acceptable range and well matching. So, it can be considered as accurate for further analysis. In present study, paddy grass material provided the highest rate of fresh water production as a packing material compared to other materials.

5.4 Effect of water and air temperature on fresh water production

Fresh water productivity got increased with increase in humidifier inlet air temperature. A linear increase was observed in water production with air temperature. The reason behind this phenomenon is that at higher elevations, the water temperature results in better evaporation of water which in turn increases the moisture content of the air. The maximum volume of water was produced at a temperature of 40ºC under all three working conditions. Though similar trend was observed, a high production rate was obtained from paddy grass packing material. Figure 5.15 shows the differences in fresh water production against air and water temperatures. When there was an increase observed in inlet water temperature, than the inlet air temperature, it created an impact on the production of fresh water gradually. The author obtained the maximum productivity for paddy grass packing material at 70ºC humidifier inlet water temperature. This is because at elevated temperature, the humidity of the air increases. This leads to more quantity of moisture conceded by air and therefore the system produces more amount of fresh water. In addition to these, the reason behind the high yield is the presence of better packing density in paddy grass than polypropylene. The contour of the paddy grass is such that it is closely cylindrical which helps in incrementing the contact area between air and water in packing made of grass and hence better packing density. Polypropylene packing results in slight reduction of water production rate compared to paddy grass, but it produced significantly high rate compared to no-packing condition.



(a)



(b)

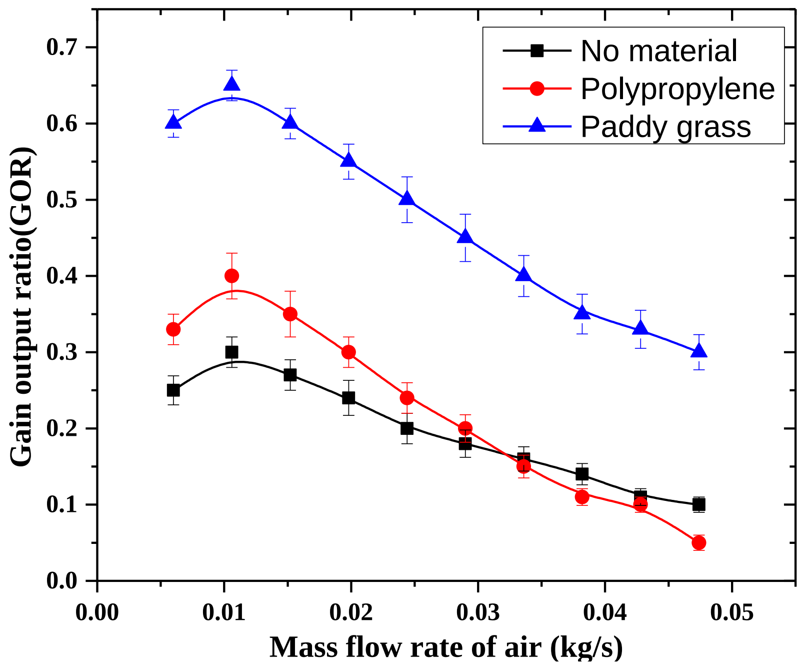
Figure 5. 15: Variations in fresh water production with (a) Air temperature and (b) Water temperature.

5.5 Effect of different operating parameters on gain output ratio (GOR)

Gain Output Ratio is the ratio of latent heat of evaporation against the total heat supplied to desalination unit. GOR is considered as an important performance parameter in humidification and dehumidification processes. It describes the energy evaluation of desalination plant and all other thermal desalination techniques. The value of GOR should be higher to the best possible whereas any desalination plant should be evaluated based on this parameter mostly. This can be accomplished either by increasing the fresh water for same amount of total heat supplied or get the same amount of fresh water with less amount of total heat energy. Figure. 5.16 shows the variations of Grain Output Ratio with mass flow rate of air, mass flow rate of water, feed water temperature and air temperature.

In case of an increase in mass flow rate of air, it reflected in increased production of fresh water up to 0.01 kg/s. Above this threshold, it got decreased due to lack of contact time between water and air within the humidifiers. The maximum amount of fresh water got produced from paddy grass packing material than the polypropylene packing material.

The influence of inlet feed water temperature to humidifier upon Gain Output Ratio is presented in figure 5.16 (c). From figure, it can be understood that a similar trend was observed in fresh water production too. In that scenario, the Gain Output Ratio got increased particularly after 50 ºC.



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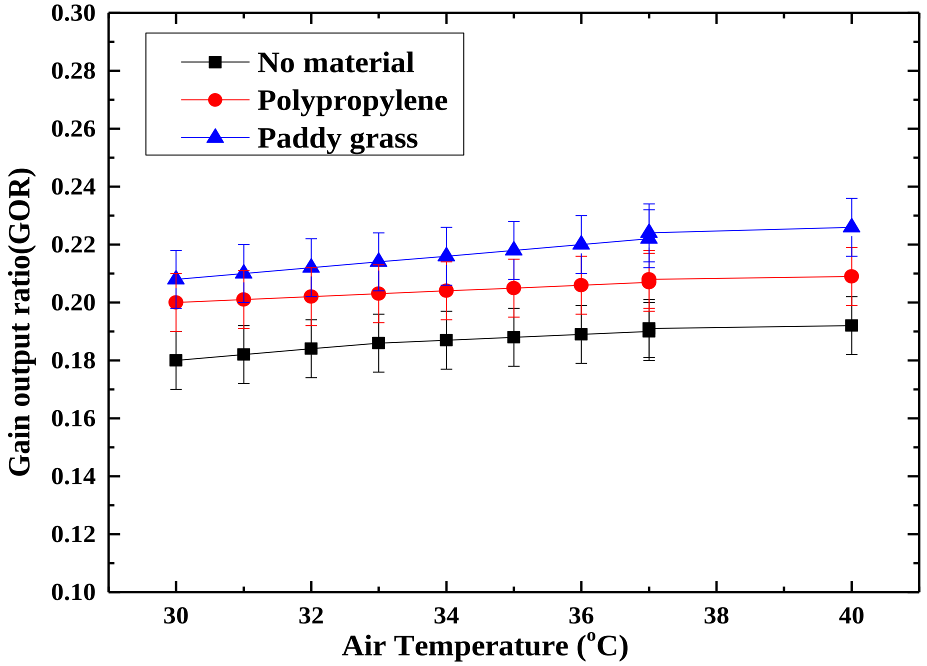
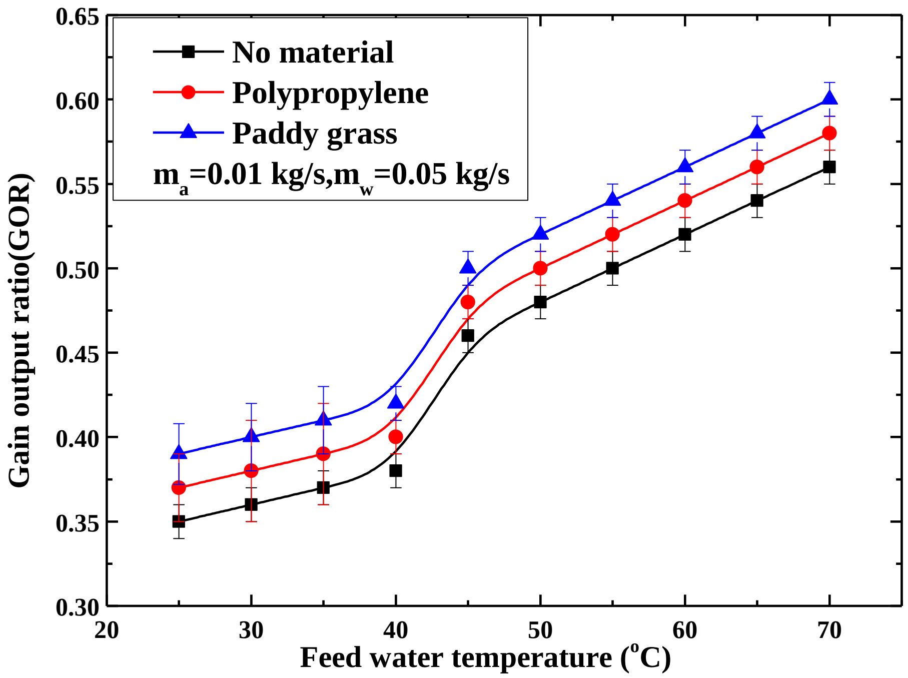


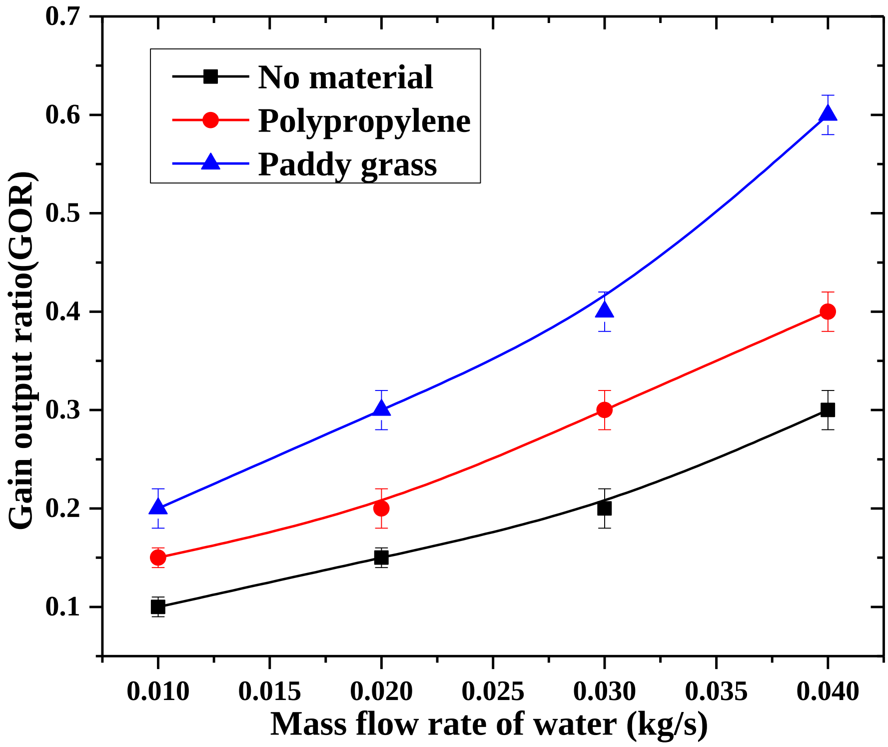
No material
Polypropylene
Paddy grass
Gain output ratio(GOR)
Air Temperature (°C)



No material
Polypropylene
Paddy grass
m_a=0.01 kg/s,m_w=0.05 kg/s
Gain output ratio(GOR)
Feed water temperature (°C)

(b)

(c)



(d)

Figure 5. 16: Variations in GOR with (a) mass flow rate of air (b) air temperature (c) feed water temperature and (d) mass flow rate of water.

5.6 Effect of baffle plates on fresh water production

As per the literature, non-condensable water vapor results in substantial reduction of condensation heat transfer (Xiong et al. 2005). The quantity of non-condensable water vapor varies in the range of 40-95% when moisture is removed from moist air in dehumidifier. In order to improve the heat transfer coefficient, some necessary action should be taken. Hence, baffle plates are placed inside the dehumidifier. At first, the turbulence of the air, generated by baffle plates increases. It consequently changes the boundary layer due to condensation. Hence, reasonable and better condensation heat transfer coefficient is achieved. Further, augmented fresh water is also produced from dehumidifier. Secondly, the prolonged time for humid air on outer copper tubes results in heavy production of fresh water. It is found from the experiment that the fresh water productivity got increased to 0.785 kg/hr-m^2, when baffle plates were inserted in dehumidifier as shown in figure 5.17. The baffled arrangement in dehumidifier increased the productivity up to 60% than the non-baffled dehumidifier.

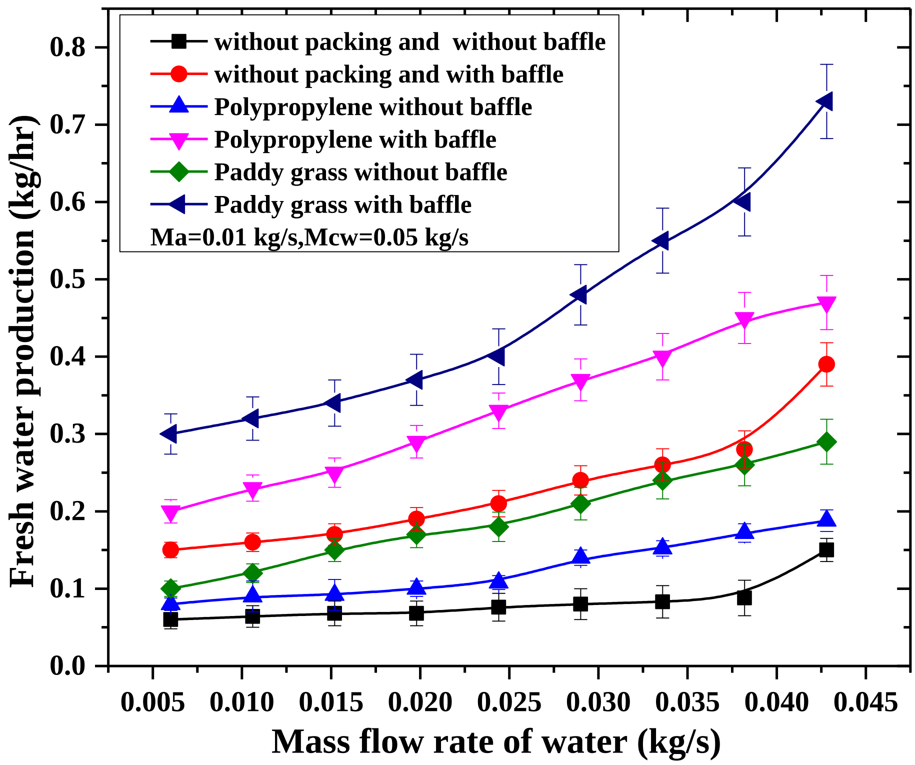


Figure 5. 17: Effect of baffle plates on fresh water production.

5.7 Influence of cooling water flow rate to dehumidifier

Figure 5.18 indicates the differences in cooling water upon the production of fresh water. As observed from the figure, the yield got increased, when there was an increase in the mass flow rate of cold water. When the flow rate of cold water got increased, it eventually led to reduction in the temperature of cold water. Accordingly, external peripheral temperature of the dehumidifier also got reduced. Hence, the heat transfer was better from hot humid air to cold water. This helped in reducing the air temperature and hence the moisture removal capacity got increased from humid air. To conclude, with more condensation of vapor from the moist air, the fresh water production rates were 0.39, 0.46 and 0.73 kg/h for without, artificial and paddy grass packing materials respectively.

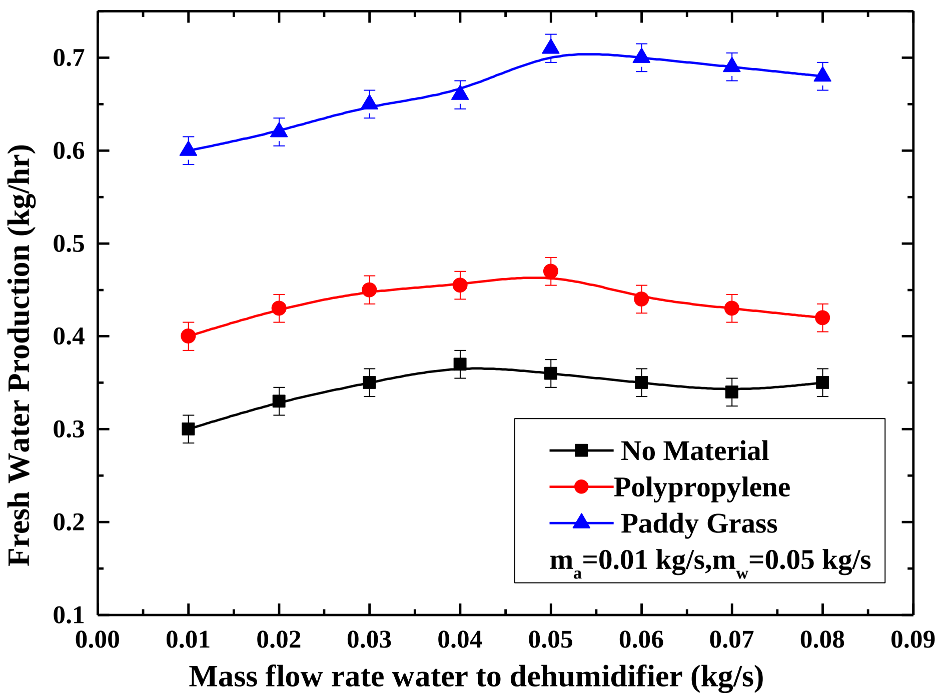
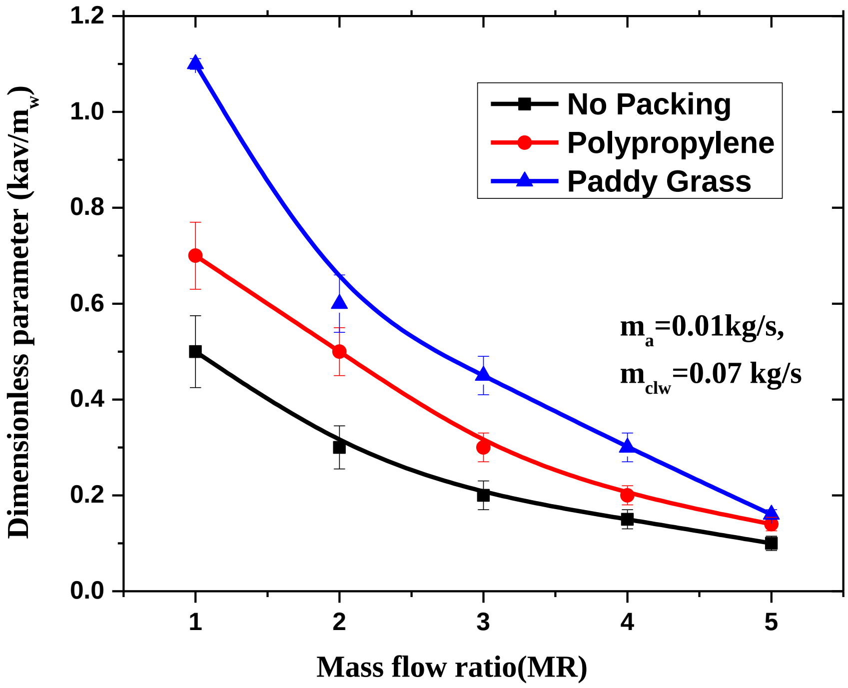


Figure 5. 18: Effect of different cooling water mass flow rates upon the production of fresh water.

5.8 Influence of mass flow ratio and temperature

The performance of the humidifier is expressed by dimensionless parameter, which is identical to what is accepted in case of cooling tower (Ghareghani and Rahimzadeh 2008). This parameter is calculated using the equation (3.44). As observed from the figure 5.19(a), the elevating mass flow ratio reduced the dimensionless parameter. Furthermore, the dimensionless parameter also got influenced with inlet sea water temperature to humidifier as exhibited in figure 5.19 (b). In this figure, the parameter increased with increasing inlet sea water temperature.



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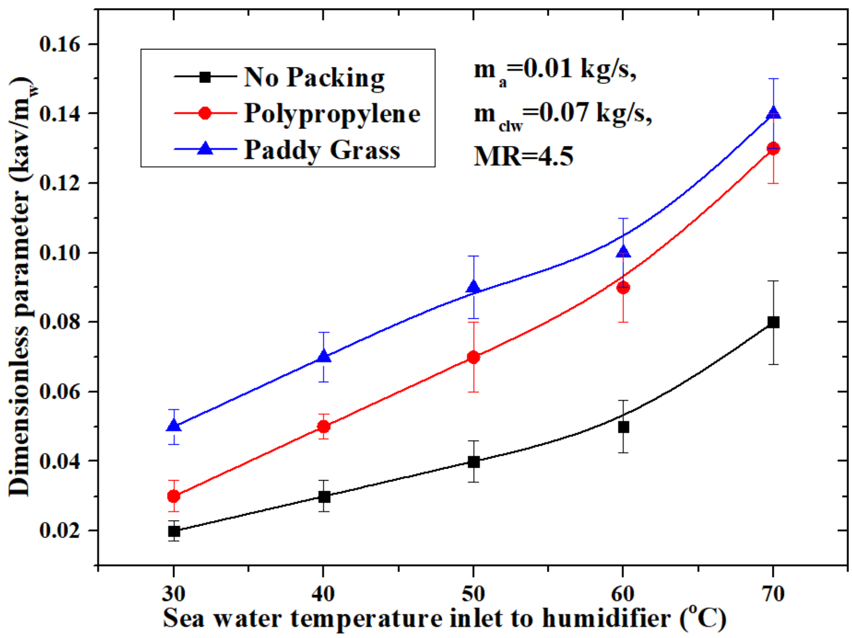
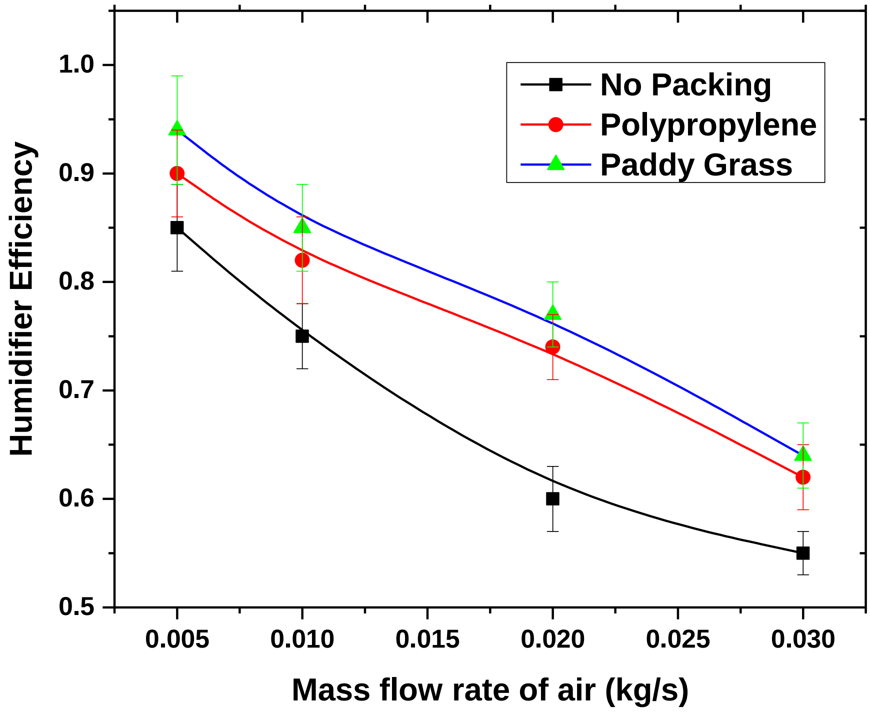


(b)

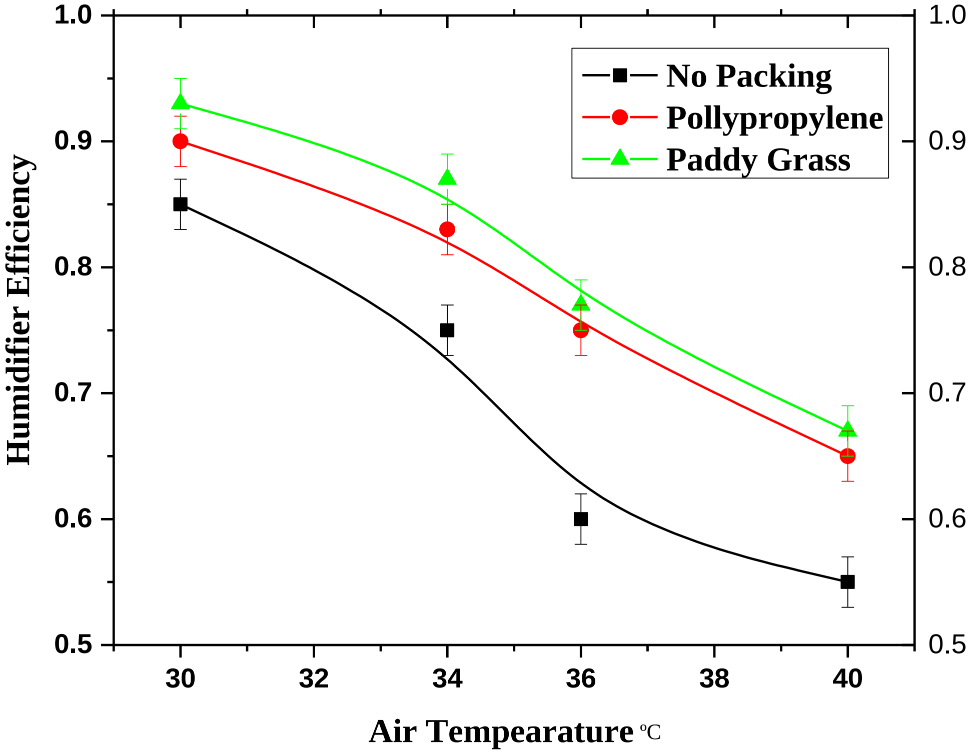
Figure 5. 19: Effect of dimensionless parameter on (a) Mass flow ratio (b) Sea water temperature inlet to humidifier.



(a)

Figure 5. 20 Displays the effect of mass flow rate of air and air temperature on the efficiency of humidifier.

It can be observed that there was a decrease in humidifier efficiency with increasing air temperature and mass flow rate. High difference between the water vapor pressure and the vapor pressure in air leads to increase in the mass transfer of moisture and due to this reason; the moisture carrying capability got increased with increase in temperature. Consequently, evaporation rate of water increases and thus air humidity rises at the outlet of humidifier. As a result, the air that leaves the humidifier was far away from saturation point at a specified moisture transfer. Furthermore, the humidifier efficiency got decreased, when mass flow rate of the air got increased. The reason behind this phenomenon is the reduced interaction time between air and water. As a result, the humidity ratio got decreased and finally, the air got unsaturated at the exit of humidifier.



(b)

Figure 5. 21: Effect of humidifier efficiency on (a) Mass flow rate of air (b) Air temperature inlet to humidifier

5.9 Effect of cooling water inlet temperature to the dehumidifier

Figure 5.22 presents the change in freshwater productivity with a change in cooling water temperature flowing through the copper pipes in the dehumidifier for different mass flow rates (0.05 kg/s to 0.15 kg/s) of cooling water. It is seen that decreasing cooling water inlet temperature from 40 ºC to 20 ºC the productivity gradually increases. This may be possible because of decreased heat transfer rate between air and water through the coil as a result of lower temperature difference according to Newton's law of cooling. Also, the increase in the cooling water rate reduces the production of freshwater due to less time for the heat transfer between the humid air and the cold water.

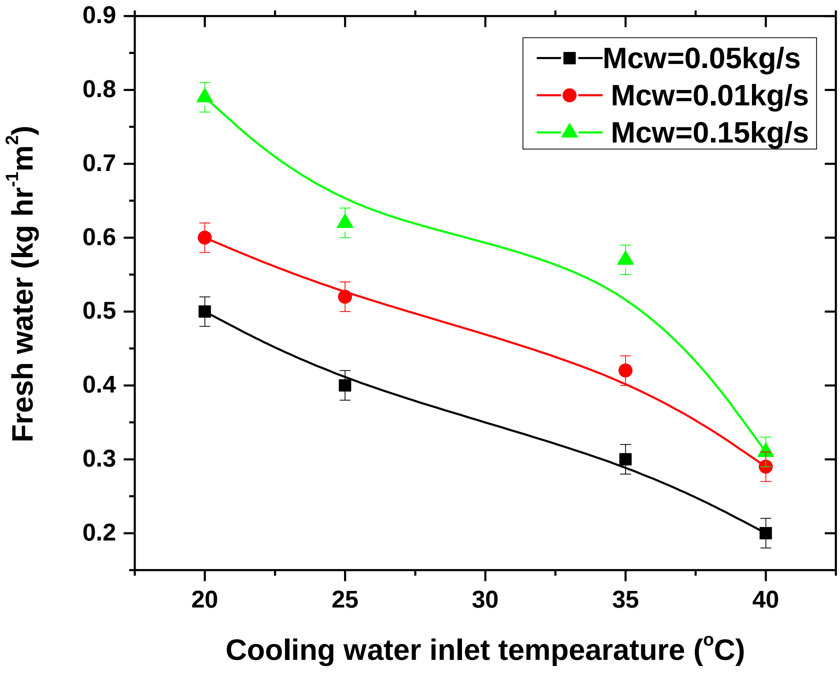


Figure 5. 22: Effect of cooling water inlet temperature on unit productivity.

5.10 Economic evaluation

Economic factor shows a vital part in making decisions for the projected desalination system. The author conducted economic calculations in current study to find out the overall cost involved in water yield.

Considering that the necessary cost for desalination system is borrowed from bank, yearly interest payment for the principal is calculated as a product of principal cost and the amortization factor 'a', which is expressed as follows.

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (5.2)$$

Where 'i' is the yearly interest rate and 'n' is the lifespan period of the system. The parameters and assumptions made for economic calculation are listed in table 5.3.

Table 5. 3: Factors used for economic analysis.

Factors	**Unit**	**Value**
System capacity (AP)	kg/day	7
SEC	kW/m^3	20
System availability (F) (Banat and Jwaied 2008)		0.9
Life span (n) (Banat and Jwaied 2008)	year	20
Interest Rate (i) (Al-obaidani et al. 2008)	-	5%
Amortization Factor (a)	-	0.08

In addition, all the factors are registered in table 5.3. The working conditions are as follows, 40 L storage saline water tank, 4 m^2 collector area and a paddy grass humidifier. Under these conditions, the AP was 7 kg/day. The Specific Energy Consumption (SEC) was 20 kWh/m^3 which indicates that the electrical energy utilization is very less compared to traditional desalination systems like Multi stage flash and Reverse Osmosis (Darwish and Al-najem 2000) and (Bouguecha et al. 2005).The consumption of electrical energy rate at Surathkal as of 2018 was 0.2 $/kWh.

Following is the expression for principal and operational cost (A_{Cost}) incurred in an year i.e., the addition of yearly direct principal cost (A_{Fixed}) and yearly operational and maintenance cost (A_{OM}).

$$A_{\text{Cost}} = (A_{\text{Fixed}} + A_{\text{OM}}) \quad (5.3)$$

$$A_{\text{Fixed}} = a(C_{\text{Fixed}}) \quad (5.4)$$

$$A_{\text{OM}} = (A_{Elec} + A_{\text{Paddy}} + A_{\text{Maita}}) \quad (5.5)$$

$$A_{\text{Maita}} = (0.2 \times A_{\text{Fixed}}) \quad (5.6)$$

Where C_{Fixed} denotes the whole asset of the system and A_{Paddy} is the paddy grass replacement price bearing in mind the fouling due to salt. A_{Elec} and A_{Maita} are yearly electricity price and yearly maintenance price respectively. The water production price of the system is expressed as follows.

$$WPC = \frac{A_{\text{Cost}}}{(AP\times F\times 365)} \tag{5.7}$$

Where F denotes the system availability and its value is 90 percent per annum (Banat and Jwaied 2008) and (Al-obaidani et al. 2008).

Fixed cost, operational cost and WPC are tabulated in table 5.4(Ali et al. 2011). It is comprehended from the table that the solar collector price adds to nearly 60 % of the entire price of system. Yearly operational and maintenance price is about 30 % of the entire water production price and the final price of water production is 19 $\$/m^3$ which is similar to other small capacity desalination systems.

Table 5. 4: Cost analysis results for principal investment, operations and maintenance.

Part	**Unit cost**	**Quantity**	**Approximate cost**
Fixed cost			
Blower	35$	1	35$
Pump	30$	2	60$
Humidifier	50$	1	50$
Paddy grass	0.5$	10.7 m^2	5.3$
Dehumidifier	80$	1	80$
Pipe fittings and instruments	25$	-	25$
Solar collector	100 $/$m^2$	2	200$
Storage tank	900 $/$m^3$	0.05	40$
Total fixed cost (C_{Fixed})			495.3$/year
Yearly Fixed cost (A_{Fixed})			99$/year
Operation & Maintenance cost			
Electrical energy cost	0.2 $/kWh	73 kWh/year	14.6 $
Paddy grass replacement (A_{Paddy})	10 % per annum	10$	1 $/year
Maintenance (A_{Maita})			15.6 $/year
Yearly OM cost (A_{OM})			31.2 $/year
A_{Cost}			81.392 $/year
WPC			19 $/$m^3$

Table 5.5 demonstrates the results for performance comparison with different desalination systems. The price is little high in the proposed system, compared to traditional desalination systems such as MSF, whose cost of production is \$ 2.66/ m^3 (Nafey et al. 2006). However, paddy grass humidification dehumidification desalination is highly attractive due to its flexible nature and simple working mechanism. In addition to these, the proposed system also offers other sources for the production of fresh water in remote areas with less maintenance price. Apart from this, solar technology price is higher than other units. If it is minimized with the upcoming research, then the water production cost will come down considerably.

Table 5. 5: Final cost of the water and comparison with other desalination systems.

Year	**Desalination process**	**Energy source**	**Humidifier area**	**Production (L/day)**	**WPC ($/m^3)**	**Authors**
2011	ED-PV	25 kWp PV	-	10000	2.38	(Ali et al. 2011)
1998	MED-solar	38 m^2 -solar collector area	-	505	80	(Müller-Holst et al. 1998)
2017	HDH	Waste heat and electric energy	14 m^2	15	10	(Ahmed et al. 2017)
2006	MSF	Steam and electric energy	-	5000	2.66	(Nafey et al. 2006)
2005	Solar still	3 m^2-basin area	-	7.5	50	(Bouguecha et al. 2005)
2020	HDH	Solar energy	Paddy grass- 10.7 m^2	13	19	Present work

5.11 CLOSURE

In this chapter, experimental results on HDHT using two different packing materials such as paddy grass and polypropylene were discussed. A comparison of theoretical and experimental work was done. The effect of various parameters upon the performance of HDHT system was also discussed. Economic analysis was finally carried out and compared with existing desalination systems.

CHAPTER 6

CONCLUSIONS AND SCOPE OF FUTURE WORK

6.1 Conclusion

The availability of fresh water in isolated and dry regions is scarce. Desalination technique is an excellent solution to overcome the scarcity of fresh water. Conventional techniques are well suitable for large-scale production. However, affordable and efficient potable water production methods have become a challenging issue especially in remote parts of the world. In this view, HDH process is considered as a promising desalination technique that can help in the production of produce potable water in remote areas.

The main objective of this thesis to propose, develop and implement a low-cost fresh water production technique for small scale desalination plant, powered by solar energy. The desalination plant must run with less energy and maintenance cost and must be appropriate for small production capacity at remote areas. The theoretical mathematical model for the simulation of HDH desalination plant was undertaken for the study. Both energy and mass balance equations were derived from each component present in the system. With the help of 4^{th} order Runge-Kutta (R-K) method, traditional governing equations were solved simultaneously. It is concluded from the numerical method that the performance output of the system depends on water inlet temperature to the humidifier, mass flow rate and cooling water inlet to the humidifier.

In present research work, a detailed thermal analysis of humidification and dehumidification system was conducted under three different scenarios such as without packing material, artificial packing material, and bio-based packing material and in the presence and absence of baffle plates for each case. The complete study was carried out following two methods such as analytical calculation and experimental analysis. The experimental comparison of present results and previous study results for different packing materials were carried out. Paddy grass material as a packing material produced the highest rate of fresh water compared to other materials.

The performance of PHDD system was evaluated through various physical parameters such as solar collector area, reservoir water tank volume and the temperature of water reservoir. The solar collector area exerts a significant influence upon the augmentation of water yield.

In addition to that the effect of different parameters such as inlet water and airflow rate and inlet temperatures on fresh water production and gain output ratio were investigated. From the present study results, following conclusions are drawn.

- ❖ The volumes of fresh water produced were 0.39, 0.47 and 0.73 kg/h for without, artificial and bio-based packing materials respectively.
- ❖ There was an increase in fresh water production rate to 17% and 46% for artificial and bio-based packing materials respectively.
- ❖ Gain Output Ratio (GOR) got increased to 0.28, 0.4 and 0.65 for without, artificial and bio-based packing materials respectively.
- ❖ The percentage enhancement in GOR was 30% and 56% for artificial and bio-based packing materials respectively.
- ❖ Thermal energy reservoir is a significant part to resolve the variations in solar radiation. So, the system can operate when there is less sunshine hours and during night time. Irrespective of the paddy grass area, the volume of the storage water tank below and above 40 L are not considered to be optimal.
- ❖ An increased productivity of 0.785 kg/h/ m^2 was observed in the presence of baffle plates in dehumidifier. The productivity got increased by almost 60 percent with baffle plates inside dehumidifier compared to without baffles.
- ❖ Solar collector area is also a significant parameter in augmenting the accumulated water yield. The present study results inferred the optimal ratio of tank volume-to-area to be around 13 L/m^2.
- ❖ When the inlet temperature of cooling water, to the dehumidifier, was reduced from 40ºC to 20 ºC, it increased the production of distilled water significantly.
- ❖ The author conducted cost analysis for the proposed system which proved that the system is completely functional with low maintenance cost, when compared to other similar studies. The price of the yield comes around 19 \$/m^3. Hence, this technology is suitable to be incorporated for smaller communities at an affordable rate.

The conclusions are summarized as follows.

The results have exhibited some interesting characteristics of the bio-based material since the material enhanced the results to a certain level. To achieve a high production rate, bio-based material can be selected instead of any artificial material. This bio-based material is cost-effective and reliable for operations in humidification and dehumidification desalination plants. Furthermore, the results of this study display low GOR value of the system. Therefore, it is recommended to adopt regeneration technology in the system.

6.2 Scope for future work

1. Simultaneous heating with air and water along with PCM materials in the humidifier can be adopted for maximum fresh water yield.
2. Twisted tape absorber can be inserted in PTSC for HDH process.
3. Usage of geothermal energy source or biomass energy source may result in constant and better yield compared to solar HDH technique.
4. HDH desalination process, with paddy grass as a packing material, may be adopted for waste water treatment in coffee processing plants.
5. The present research can be extended using nano particles with different volume fractions to increase heat transfer rate and system yield.

REFERENCES

Abdel Dayem, A. M. (2014). “Efficient solar desalination system using humidification/dehumidification process.” *J. Sol. Energy Eng. Trans. ASME*, 136(4),Abdel Dayem, A. M. (2014). “Efficient solar desalination system using humidification/dehumidification process.” *J. Sol. Energy Eng. Trans. ASME*, 136(4), 1–9.

Abdelkareem, M. A., Haj Assad, M. El, Sayed, E. T., and Soudan, B. (2018). “Recent progress in the use of renewable energy sources to power water desalination plants.” *Desalination*, 435(September 2017), 97–113.

Abu-arabi, M., Al-harahsheh, M., Tashtoush, R., and Mousa, H. (2017). “Experimental investigation of a solar desalination with humidification-dehumidification using a rotating surface.” 73(May 2016), 20352.

Ahmed, H. A., Ismail, I. M., Saleh, W. F., and Ahmed, M. (2017). “Experimental investigation of humidification-dehumidification desalination system with corrugated packing in the humidifier.” *Desalination*, 410, 19–29.

Al-Enezi, G., Ettouney, H., and Fawzy, N. (2006). “Low temperature humidification dehumidification desalination process.” *Energy Convers. Manag.*, 47(4), 470–484.

Al-obaidani, S., Curcio, E., Macedonio, F., Di, G., Al-hinai, H., and Drioli, E. (2008). “Potential of membrane distillation in seawater desalination : Thermal efficiency , sensitivity study and cost estimation.” 323, 85–98.

Al-otoom, A., and Al-khalaileh, A. T. (2020). “Water desalination using solar continuous humidi fi cation – dehumidi fi cation process using hygroscopic solutions and rotating belt.” *Sol. Energy*, 197(December 2019), 38–49.

Al-sulaiman, F. A., Zubair, M. I., Atif, M., Gandhidasan, P., Al-dini, S. A., and Antar, M. A. (2015). “Humidi fi cation dehumidi fi cation desalination system using parabolic trough solar air collector.” 75, 809–816.

Al-Sulaiman, F. A., Zubair, M. I., Atif, M., Gandhidasan, P., Al-Dini, S. A., and Antar, M. A. (2015). “Humidification dehumidification desalination system using parabolic trough solar air collector.” *Appl. Therm. Eng.*, 75, 809–816.

Ali, M. T., Fath, H. E. S., and Armstrong, P. R. (2011). “A comprehensive techno-economical review of indirect solar desalination.” *Renew. Sustain. Energy Rev.*, 15(8), 4187–4199.

Alnaimat, F., Ziauddin, M., and Mathew, B. (2021). “A review of recent advances in humidification and dehumidification desalination technologies using solar energy.” *Desalination*, 499(November 2020), 114860.

Ayati, E., Rahimi-ahar, Z., Hatamipour, M. S., and Ghalavand, Y. (2019). “Water productivity enhancement in variable pressure humidification dehumidification (HDH) desalination systems using heat pump.” *Appl. Therm. Eng.*, 160(July), 114114.

Banat, F., and Jwaied, N. (2008). “Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units.” 220, 566–573.

Bouguecha, S., Hamrouni, B., and Dhahbi, M. (2005). “Small scale desalination pilots powered by renewable energy sources : case studies.” 183(May), 151–165.

Calise, F., Dentice d’Accadia, M., and Piacentino, A. (2014). “A novel solar trigeneration system integrating PVT (photovoltaic/thermal collectors) and SW (seawater) desalination: Dynamic simulation and economic assessment.” *Energy*, 67, 129–148.

Capocelli, M., Balsamo, M., Lancia, A., and Barba, D. (2018). “Process analysis of a novel humidi fi cation-dehumidi fi cation-adsorption (HDHA) desalination method.” 429, 155–166.

Chafik, E. (2004). “Design of plants for solar desalination using the multi-stage heating / humidifying technique.” 168, 55–71.

Chen, X., Su, Y., Aydin, D., Bai, H., Jarimi, H., Zhang, X., and Riffat, S. (2018). “Experimental investigation of a polymer hollow fibre integrated liquid desiccant dehumidification system with aqueous potassium formate solution.” *Appl. Therm. Eng.*, 142(June), 632–643.

Dai, Y. J., Wang, R. Z., and Zhangb, H. F. (2002). “Parametric analysis to improve the performance of a solar desalination unit with humidification and dehumidification.” 142.

Dai, Y. J., and Zhang, H. F. (2000). “Experimental investigation of a solar desalination unit with humidification and dehumidification.” *Desalination*, 130(2), 169–175.

Darwish, M. A., and Al-najem, N. M. (2000). “Energy consumption by multi-stage ¯ ash and reverse osmosis desalters.” 20.

Dayem, A. M. A., and Fatouh, M. (2009). “Experimental and numerical investigation of humidification / dehumidification solar water desalination systems.” *DES*, 247(1–3), 594–609.

Duffie, J. A., Beckman, W. A., and McGowan, J. (1985). *Solar Engineering of Thermal Processes*. *Am. J. Phys.*

Eiamsa-ard, S., Thianpong, C., Eiamsa-ard, P., and Promvonge, P. (2009). “Convective heat transfer in a circular tube with short-length twisted tape insert.” *Int. Commun. Heat Mass Transf.*, 36(4), 365–371.

Eiamsa-ard, S., Wongcharee, K., Eiamsa-ard, P., and Thianpong, C. (2010). “Heat transfer enhancement in a tube using delta-winglet twisted tape inserts.” *Appl. Therm. Eng.*, 30(4), 310–318.

El-Ashtoukhy, E. S. Z., Abdel-Aziz, M. H., Farag, H. A., Azab, I. H. El, Sh. Zoromba, M., and Naim, M. M. (2022). "An innovative unit for water desalination based on humidification dehumidification technique." *Alexandria Eng. J.*, 61(11), 8729–8742.

Elminshawy, N. A. S., Siddiqui, F. R., and Addas, M. F. (2015). "Experimental and analytical study on productivity augmentation of a novel solar humidi fi cation – dehumidi fi cation (HDH) system." 365, 36–45.

Farsad, S., and Behzadmehr, A. (2011). "Analysis of a solar desalination unit with humidi fi cation – dehumidi fi cation cycle using DoE method." 278, 70–76.

Farshchi, F., Khosravi, M., and Shirzaei, I. (2016). "Experimental study of a cascade solar still coupled with a humidification – dehumidification system." *Energy Convers. Manag.*, 115, 80–88.

Fouda, A., Nada, S. A., and Elattar, H. F. (2016). "An integrated A / C and HDH water desalination system assisted by solar energy : Transient analysis and economical study." *Appl. Therm. Eng.*, 108, 1320–1335.

Frank P. Incroper, David P. Dewitt, Theodore L. Bergman, and A. S. L. (2011). "Incropera, Lavine, DeWitt - 2011 - Fundamentals of Heat and Mass Transfer."

Garg, K., Khullar, V., Das, S. K., and Tyagi, H. (2018). "Performance evaluation of a brine-recirculation multistage flash desalination system coupled with nanofluid-based direct absorption solar collector." *Renew. Energy*, 122, 140–151.

Ghareghani, A. A., and Rahimzadeh, H. (2008). "Experimental Invetigation And Design Of A Solar Desalination Unit Which Work With Humidification-Dehumidification Process." (July), 8–13.

Ghazal, M. T., Atikol, U., and Egelioglu, F. (2014). "An experimental study of a solar humidifier for HDD systems." *Energy Convers. Manag.*, 82, 250–258.

Ghofrani, I., and Moosavi, A. (2020). "Energy , exergy , exergoeconomics , and exergoenvironmental assessment of three brine recycle humidi fi cation-dehumidi fi cation desalination systems applicable for industrial wastewater treatment." *Energy Convers. Manag.*, 205(July 2019), 112349.

He, W., Yang, H., and Han, D. (2019). "Thermodynamic investigation and optimization of a heat pump coupled open-air , open-water humidi fi cation dehumidi fi cation desalination system with a direct contact dehumidi fi er." *Desalination*, 469(April), 114101.

Hermosillo, J. J., Arancibia-Bulnes, C. A., and Estrada, C. A. (2012). "Water desalination by air humidification: Mathematical model and experimental study." *Sol. Energy*, 86(4), 1070–1076.

Hernández, C., Reyes, M., Barraza, R., and Rheinschmidt, U. (2018). "Experimental and numerical evaluation of a humidification dehumidification desalination unit driven by solar energy Experimental and Numerical Evaluation of a Humidification Dehumidification Desalination Unit Driven by Solar Energy." 160003(November).

Hou, S., Ye, S., and Zhang, H. (2005). "Performance optimization of solar humidification – dehumidification desalination process using Pinch technology." 183(May), 143–149.

Houcine, I., BenAmara, M., Guizani, A., and Maâlej, M. (2006). "Pilot plant testing of a new solar desalination process by a multiple-effect-humidification technique." *Desalination*, 196(1–3), 105–124.

Huang, Y., Xiao, C., Huang, Q., Liu, H., and Zhao, J. (2021). "Progress on polymeric hollow fiber membrane preparation technique from the perspective of green and sustainable development." *Chem. Eng. J.*, 403(399), 126295.

Hussain Soomro, S., Santosh, R., Bak, C. U., Yoo, C. H., Kim, W. S., and Kim, Y. D. (2022). "Effect of humidifier characteristics on performance of a small-scale humidification-dehumidification desalination system." *Appl. Therm. Eng.*, 210(February), 118400.

Jones, E., Qadir, M., Vliet, M. T. H. Van, Smakhtin, V., and Kang, S. (2019). "Science of the Total Environment The state of desalination and brine production : A global outlook." *Sci. Total Environ.*, 657, 1343–1356.

Kabeel, A. E., and El-said, E. M. S. (2014). "A hybrid solar desalination system of air humidi fi cation , dehumidi fi cation and water fl ashing evaporation : Part II . Experimental investigation." *DES*, 341, 50–60.

Kabeel, A. E., and El-Said, E. M. S. (2018). "Experimental study on a modified solar power driven hybrid desalination system." *Desalination*, 443(May), 1–10.

Kabeel, A. E., Hamed, M. H., Omara, Z. M., and Sharshir, S. W. (2013). "Water Desalination Using a Technique — A Detailed Review." 2013, 286–305.

Kalogirou, S. A. (2005). "Seawater desalination using renewable energy sources." *Prog. Energy Combust. Sci.*, 31(3), 242–281.

Kaunga, D., Patel, R., and Mujtaba, I. M. (2022). "Humidification-dehumidification desalination process: Performance evaluation and improvement through experimental and numerical methods." *Therm. Sci. Eng. Prog.*, 27(November 2021), 101159.

Khass, T. M., Mohammed, R. H., Qasem, N. A. A., and Zubair, S. M. (2022). "Different configurations of humidification-dehumidification desalination systems: Thermal and economic assessment." *Energy Convers. Manag.*, 258(February), 115470.

Ladouy, S., and Khabbazi, A. (2015). "Experimental study of the water depth effect and the impact of condensers connection in a new desalination system by HDH process , using solar energy." *Energy Procedia*, 74, 952–959.

Ladouy, S., and Khabbazi, A. (2017). "Experimental investigation of different air heating methods near to the evaporation surface in closed triangular shape unit powered by solar energy, one stage – Indoor experiment.” *Appl. Therm. Eng.*, 127, 203–211.

Lawal, D. U., and Qasem, N. A. A. (2020). “Humidification-dehumidification desalination systems driven by thermal-based renewable and low-grade energy sources : A critical review.” *Renew. Sustain. Energy Rev.*, 125(February), 109817.

Li, G. P., and Zhang, L. Z. (2016a). “Investigation of a solar energy driven and hollow fiber membrane-based humidification-dehumidification desalination system.” *Appl. Energy*, 177, 393–408.

Li, G., and Zhang, L. (2016b). “Investigation of a solar energy driven and hollow fiber membrane-based humidification – dehumidification desalination system.” *Appl. Energy*, 177, 393–408.

Mistry, K. H., Mitsos, A., and Lienhard, J. H. (2011). “Optimal operating conditions and configurations for humidification- dehumidification desalination cycles.” *Int. J. Therm. Sci.*, 50(5), 779–789.

Mohamed, A. M. I., and El-minshawy, N. A. S. (2009). “Humidi fi cation – dehumidi fi cation desalination system driven by geothermal energy.” 249, 602–608.

Morsy, M. G., Ismail, I. M., and Soliman, A. M. A. (2009). “Experimental Performance of Spray Type Humidifier in Humidification-Dehumidification Desalination Unit.” 37(6), 1433–1447.

Moumouh, J., Tahiri, M., and Salouhi, M. (2014). “ScienceDirect Solar thermal energy combined with humidification e dehumidification process for desalination brackish water : Technical review.” *Int. J. Hydrogen Energy*, 39(27), 15232–15237.

Moumouh, J., Tahiri, M., Salouhi, M., and Balli, L. (2016). “ScienceDirect Theoretical and experimental study of a solar desalination unit based on humidification e dehumidification of air." *Int. J. Hydrogen Energy*, 41(45), 20818–20822.

Müller-Holst, H., Engelhardt, M., Herve, M., and Schölkopf, W. (1998). "Solarthermal seawater desalination systems for decentralised use." *Renew. Energy*, 14(1–4), 311–318.

Nafey, A. S., Fath, H. E. S., El-Helaby, S. O., and Soliman, A. (2004). "Solar desalination using humidification-dehumidification processes. Part II. An experimental investigation." *Energy Convers. Manag.*, 45(7–8), 1263–1277.

Nafey, A. S., Fath, H. E. S., and Mabrouk, A. A. (2006). "Thermo-economic investigation of multi effect evaporation (MEE) and hybrid multi effect evaporation — multi stage flash (MEE-MSF) systems." 201, 241–254.

Narayan, G. P., Sharqawy, M. H., Summers, E. K., Lienhard, J. H., Zubair, S. M., and Antar, M. A. (2010). "The potential of solar-driven humidification – dehumidification desalination for small-scale decentralized water production." *Renew. Sustain. Energy Rev.*, 14(4), 1187–1201.

Nawayseh, N. K., Farid, M. M., Omar, A. A., and Sabirin, A. (1999). "Solar desalination based on humidification process - II. Computer simulation." *Energy Convers. Manag.*, 40(13), 1441–1461.

Note, T., and Summary, E. (2015). "Aqueduct Projected Water Stress Country Rankings." (August), 1–16.

Orfi, J., Galanis, N., and Laplante, M. (2007). "Air humidification-dehumidification for a water desalination system using solar energy." *Desalination*, 203(1–3), 471–481.

Orfi, J., Laplante, M., Marmouch, H., Galanis, N., Benhamou, B., Nasrallah, S. Ben, and Nguyen, C. T. (2004). "Experimental and theoretical study of a humidification-dehumidification water desalination system using solar energy." *Desalination*, 168(1–3), 151–159.

Paper, C., Pilani, S., and Pilani, S. (2015). "Solar desalination in India : Past , present and future Solar DistiUation Technologies in India : Past , Present and Future." (July).

Prakash Narayan, G., John, M. G. St., Zubair, S. M., and Lienhard, J. H. (2013). "Thermal design of the humidification dehumidification desalination system: An experimental investigation." *Int. J. Heat Mass Transf.*, 58(1–2), 740–748.

Qasem, N. A. A., and Zubair, S. M. (2019). "Performance evaluation of a novel hybrid humidification-dehumidification (air-heated) system with an adsorption desalination system." *Desalination*, 461(March), 37–54.

Qtaishat, M. R., and Banat, F. (2013). "Desalination by solar powered membrane distillation systems." *Desalination*, 308, 186–197.

Rahbar, N., and Esfahani, J. A. (2012). "Experimental study of a novel portable solar still by utilizing the heatpipe and thermoelectric module." *Desalination*, 284, 55–61.

Rahimi-ahar, Z., Hatamipour, M. S., Ghalavand, Y., and Palizvan, A. (2020). "Comprehensive study on vacuum humidi fi cation-dehumidi fi cation (VHDH) desalination." 169(December 2019), 1–12.

Rajaseenivasan, T., Shanmugam, R. K., Hareesh, V. M., and Srithar, K. (2016). "Combined probation of bubble column humidi fi cation dehumidi fi cation desalination system using solar collectors." *Energy*, 116, 459–469.

Rajaseenivasan, T., and Srithar, K. (2017). "Potential of a dual purpose solar collector on humidi fi cation dehumidi fi cation desalination system." 404, 35–40.

Ranjan, K. R., and Kaushik, S. C. (2013). "Energy, exergy and thermo-economic analysis of solar distillation systems: A review." *Renew. Sustain. Energy Rev.*, 27, 709–723.

Ranjitha Raj, P., and Jayakumar, J. S. (2022). "Performance analysis of humidifier packing for humidification dehumidification desalination system." *Therm. Sci. Eng. Prog.*, 27(November 2021), 101118.

Santosh, R., Lee, H. S., and Kim, Y. D. (2022). "A comprehensive review on humidifiers and dehumidifiers in solar and low-grade waste heat powered humidification-dehumidification desalination systems." *J. Clean. Prod.*, 347(February), 131300.

Sharon, H., and Reddy, K. S. (2015). "A review of solar energy driven desalination technologies." *Renew. Sustain. Energy Rev.*, 41, 1080–1118.

Shatat, M., Omer, S., Gillott, M., and Riffat, S. (2013). "Theoretical simulation of small scale psychometric solar water desalination system in semi-arid region." *Appl. Therm. Eng.*, 59(1–2), 232–242.

Tow, E. W., and Lienhard V, J. H. (2014). "Experiments and modeling of bubble column dehumidifier performance." *Int. J. Therm. Sci.*, 80(1), 65–75.

Weifeng, H., Yu, L., Haohao, A., Xuan, Z., Pengfei, S., and Dong, H. (2022). "Parametric analysis of humidification dehumidification desalination driven by photovoltaic/thermal (PV/T) system." *Energy Convers. Manag.*, 259(29).

Wright, N. C., and Winter, A. G. (2014). "Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India." *Desalination*, 352, 82–91.

Wu, G., Zheng, H., Kang, H., Yang, Y., Cheng, P., and Chang, Z. (2016). "Experimental investigation of a multi-effect isothermal heat with tandem solar desalination system based on humidi fi cation – dehumidi fi cation processes." *DES*, 378, 100–107.

Wu, G., Zheng, H., Ma, X., Kutlu, C., and Su, Y. (2017). "Experimental investigation of a multi-stage humidification-dehumidification desalination system heated directly by a cylindrical Fresnel lens solar concentrator." *Energy Convers. Manag.*, 143, 241–251.

Xiong, R. H., Wang, S. C., Xie, L. X., Wang, Z., and Li, P. L. (2005). "Experimental investigation of a baffled shell and tube desalination column using the humidification-dehumidification process." *Desalination*, 180(1–3), 253–261.

Xu, H., Zhao, Y., and Dai, Y. J. (2019). "Experimental study on a solar assisted heat pump desalination unit with internal heat recovery based on humidi fi cation-dehumidi fi cation process." 452(June 2018), 247–257.

Yamali, C., and Solmus, I. (2008). "A solar desalination system using humidification-dehumidification process: experimental study and comparison with the theoretical results." *Desalination*, 220(1–3), 538–551.

Yamali, C., and Solmuş, I. (2007). "Theoretical investigation of a humidification-dehumidification desalination system configured by a double-pass flat plate solar air heater." *Desalination*, 205(1–3), 163–177.

Yildirim, C., and Solmuş, I. (2014). "A parametric study on a humidification-dehumidification (HDH) desalination unit powered by solar air and water heaters." *Energy Convers. Manag.*, 86, 568–575.

Zamen, M., Soufari, S. M., Vahdat, S. A., Amidpour, M., Zeinali, M. A., Izanloo, H., and Aghababaie, H. (2014). "Experimental investigation of a two-stage solar humidi fi cation – dehumidi fi cation desalination process." 332, 1–6.

Zhani, K. (2013). "Solar desalination based on multiple effect humidification process: Thermal performance and experimental validation." *Renew. Sustain. Energy Rev.*, 24(August 2013), 406–417.

Zhani, K., and Bacha, H. Ben. (2010). "Experimental investigation of a new solar desalination prototype using the humidi fi cation dehumidi fi cation principle." 35(October 1993), 2610–2617.

Zubair, S. M., Antar, M. A., Elmutasim, S. M., and Lawal, D. U. (2018). "Performance evaluation of humidi fi cation-dehumidi fi cation (HDH) desalination systems with and without heat recovery options : An experimental and theoretical investigation." 436(February), 161–175.

Abu-arabi, M., Al-harahsheh, M., Tashtoush, R., and Mousa, H. (2017). "Experimental investigation of a solar desalination with humidification-dehumidification using a rotating surface." Desalination and Water Treatment 73, 101-106.

Ahmed, H. A., Ismail, I. M., Saleh, W. F., and Ahmed, M. (2017). "Experimental investigation of humidification-dehumidification desalination system with corrugated packing in the humidifier." *Desalination*, 410, 19–29.

Al-Enezi, G., Ettouney, H., and Fawzy, N. (2006). "Low temperature humidification dehumidification desalination process." *Energy Convers. Manag.*, 47(4), 470–484.

Al-hallaj, S., Parekh, S., Farid, M. M., and Selman, J. R. (2006). "Solar desalination with humidification – dehumidification cycle : Review of economics." Desalination, 195,169–186.

Al-obaidani, S., Curcio, E., Macedonio, F., Di, G., Al-hinai, H., and Drioli, E. (2008). "Potential of membrane distillation in seawater desalination : Thermal efficiency , sensitivity study and cost estimation." Journal of Membrane Science, 323,85–98.

Al-otoom, A., and Al-khalaileh, A. T. (2020). "Water desalination using solar continuous humidi fi cation – dehumidi fi cation process using hygroscopic solutions and rotating belt." *Sol. Energy*, 197, 38–49.

Al-Sulaiman, F. A., Zubair, M. I., Atif, M., Gandhidasan, P., Al-Dini, S. A., and Antar, M. A. (2015). "Humidification dehumidification desalination system using parabolic trough solar air collector." *Appl. Therm. Eng.*, 75, 809–816.

Ali, M. T., Fath, H. E. S., and Armstrong, P. R. (2011). "A comprehensive techno-economical review of indirect solar desalination." *Renew. Sustain. Energy Rev.*, 15(8), 4187–4199.

Amer, E. H., Kotb, H., Mostafa, G. H., and El-Ghalban, A. R. (2009). "Theoretical and experimental investigation of humidification-dehumidification desalination unit." *Desalination,* 249(3), 949–959.

Ayati, E., Rahimi-ahar, Z., Hatamipour, M. S., and Ghalavand, Y. (2019). "Water productivity enhancement in variable pressure humidification dehumidification (HDH) desalination systems using heat pump." *Appl. Therm. Eng.*, 160(July), 114114.

Banat, F., and Jwaied, N. (2008). "Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units." *Desalination,* 220, 566–573.

Bouguecha, S., Hamrouni, B., and Dhahbi, M. (2005). "Small scale desalination pilots powered by renewable energy sources : case studies." 183(May), *Desalination* 151–165.

Bourouni, K., Chaibi, M. T., and Tadrist, L. (2001). "Water desalination by humidification and dehumidification of air: State of the art." *Desalination*, 137(1–3), 167–176.

Budihardjo, I., and Morrison, G. L. (2009). "Performance of water-in-glass evacuated tube solar water heaters." *Sol. Energy*, 83(1), 49–56.

Capocelli, M., Balsamo, M., Lancia, A., and Barba, D. (2018). "Process analysis of a novel humidification-dehumidification-adsorption (HDHA) desalination method." *Desalination* ,429, 155–166.

Chafik, E. (2002). "A new seawater desalination process using solar energy." *Desalination*, 153, 25–37.

Chafik, E. (2004). "Design of plants for solar desalination using the multi-stage heating / humidifying technique." Desalination,168, 55–71.

Chen, X., Su, Y., Aydin, D., Bai, H., Jarimi, H., Zhang, X., and Riffat, S. (2018). "Experimental investigation of a polymer hollow fibre integrated liquid desiccant dehumidification system with aqueous potassium formate solution." *Appl. Therm. Eng.*, 142(June), 632–643.

Dai, Y. J., Wang, R. Z., and Zhangb, H. F. (2002). "Parametric analysis to improve the performance of a solar desalination unit with humidification and dehumidification." Desalination,142,107-108.

Dai, Y. J., and Zhang, H. F. (2000). "Experimental investigation of a solar desalination unit with humidification and dehumidification." *Desalination*, 130(2), 169–175.

Darwish, M. A., and Al-najem, N. M. (2000). "Energy consumption by multi-stage ¯ ash and reverse osmosis desalters." Applied Thermal Engineering 20,399-416.

Dayem, A. M. A., and Fatouh, M. (2009). "Experimental and numerical investigation of humidification / dehumidification solar water desalination systems." *Desalination*, 247(1–3), 594–609.

John A. Duffi., and Beckman, W. A. (2013). *Solar Engineering*of thermal procesess.Wiley.

Eiamsa-ard, S., Thianpong, C., Eiamsa-ard, P., and Promvonge, P. (2009). "Convective heat transfer in a circular tube with short-length twisted tape insert." *Int. Commun. Heat Mass Transf.*, 36(4), 365–371.

Eiamsa-ard, S., Wongcharee, K., Eiamsa-ard, P., and Thianpong, C. (2010). "Heat transfer enhancement in a tube using delta-winglet twisted tape inserts." *Appl. Therm. Eng.*, 30(4), 310–318.

Elkader, M. A., Aref, A., Moustafa, G. H., and Elhenawy, Y. (2014). "A Theoretical and Experimental Study for a Humidification-Dehumidification (HD) Solar Desalination Unit." *Int. J. Water Resour. Arid Environmens*, 3(2), 108–120.

Elminshawy, N. A. S., Siddiqui, F. R., and Addas, M. F. (2015). “Experimental and analytical study on productivity augmentation of a novel solar humidification – dehumidification (HDH) system.”Desaliantion, 365, 36–45.

Ettouney, H. (2005). “Design and analysis of humidification dehumidification desalination process.” *Desalination*, 183(1–3), 341–352.

Faridb, M. M., Selmana, J. R., and Al-hallaj, S. (2004). “Solar desalination with a humidification-dehumidification technique - a comprehensive technical review.” Desaliantion,160, 167–186.

Farsad, S., and Behzadmehr, A. (2011). “Analysis of a solar desalination unit with humidification – dehumidification cycle using DoE method.”Desalination, 278, 70–76.

Farshchi, F., Khosravi, M., and Shirzaei, I. (2016). “Experimental study of a cascade solar still coupled with a humidification – dehumidification system.” *Energy Convers. Manag.*, 115, 80–88.

Fouda, A., Nada, S. A., and Elattar, H. F. (2016). “An integrated A / C and HDH water desalination system assisted by solar energy : Transient analysis and economical study.” *Appl. Therm. Eng.*, 108, 1320–1335.

Frank P. Incroper, David P. Dewitt, Theodore L. Bergman, and A. S. L. (2011). “Incropera, Lavine, DeWitt - 2011 - Fundamentals of Heat and Mass Transfer.”

Garg, K., Khullar, V., Das, S. K., and Tyagi, H. (2018). “Performance evaluation of a brine-recirculation multistage flash desalination system coupled with nanofluid-based direct absorption solar collector.” *Renew. Energy*, 122, 140–151.

Gharagheizi, F., Hayati, R., and Fatemi, S. (2007). “Experimental study on the performance of mechanical cooling tower with two types of film packing.” *Energy Convers. Manag.*, 48(1), 277–280.

Ghareghani, A. A., and Rahimzadeh, H. (2008). “Experimental Invetigation And Design Of A Solar Desalination Unit Which Work With Humidification-Dehumidification Process.”International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics HEFAT 2008,, 8–13.

Ghazal, M. T., Atikol, U., and Egelioglu, F. (2014). “An experimental study of a solar humidifier for HDD systems.” *Energy Convers. Manag.*, 82, 250–258.

Ghofrani, I., and Moosavi, A. (2020). “Energy , exergy , exergoeconomics , and exergoenvironmental assessment of three brine recycle humidi fi cation-dehumidi fi cation desalination systems applicable for industrial wastewater treatment.” *Energy* Convers. Manag., 205, 112349.

Hamed, M. H., Kabeel, A. E., Omara, Z. M., and Sharshir, S. W. (2015). “Mathematical and experimental investigation of a solar humidification-dehumidification desalination unit.” *Desalination*, 358, 9–17.

He, W., Yang, H., and Han, D. (2019). “Thermodynamic investigation and optimization of a heat pump coupled open-air , open-water humidi fi cation dehumidi fi cation desalination system with a direct contact dehumidi fi er.” *Desalination*, 469, 114101.

Hermosillo, J. J., Arancibia-Bulnes, C. A., and Estrada, C. A. (2012). “Water desalination by air humidification: Mathematical model and experimental study.” *Sol. Energy*, 86(4), 1070–1076.

Hernández, C., Reyes, M., Barraza, R., and Rheinschmidt, U. (2018). “Experimental and numerical evaluation of a humidification dehumidification desalination unit driven by solar energy Experimental and Numerical Evaluation of a Humidification Dehumidification Desalination Unit Driven by Solar Energy.” 160003(November).

Houcine, I., BenAmara, M., Guizani, A., and Maâlej, M. (2006). “Pilot plant testing of a new solar desalination process by a multiple-effect-humidification technique.” *Desalination*, 196(1–3), 105–124.

Huang, J., Pu, S., Gao, W., and Que, Y. (2010). “Experimental investigation on thermal performance of thermosyphon flat-plate solar water heater with a mantle heat exchanger.” *Energy*, 35(9), 3563–3568.

Huang, Y., Xiao, C., Huang, Q., Liu, H., and Zhao, J. (2021). “Progress on polymeric hollow fiber membrane preparation technique from the perspective of green and sustainable development.” *Chem. Eng. J.*, 403, 126295.

Jones, E., Qadir, M., Vliet, M. T. H. Van, Smakhtin, V., and Kang, S. (2019). “Science of the Total Environment The state of desalination and brine production : A global outlook.” *Sci. Total Environ.*, 657, 1343–1356.

Kabeel, A. E., and El-said, E. M. S. (2014). “A hybrid solar desalination system of air humidi fi cation , dehumidi fi cation and water flashing evaporation : Part II . Experimental investigation.” *Desalination*, 341, 50–60.

Kabeel, A. E., and El-Said, E. M. S. (2018). “Experimental study on a modified solar power driven hybrid desalination system.” *Desalination*, 443(May), 1–10.

Kabeel, A. E., Hamed, M. H., Omara, Z. M., and Sharshir, S. W. (2013). “Water Desalination Using a Technique — A Detailed Review.”Natural resources, 2013, 286–305.

Kalogirou, S. A. (2005). “Seawater desalination using renewable energy sources.” *Prog. Energy Combust. Sci.*, 31(3), 242–281.

Ladouy, S., and Khabbazi, A. (2015). “Experimental study of the water depth effect and the impact of condensers connection in a new desalination system by HDH process , using solar energy.” *Energy Procedia*, 74, 952–959.

Ladouy, S., and Khabbazi, A. (2017). “Experimental investigation of different air heating methods near to the evaporation surface in closed triangular shape unit powered by solar energy, one stage – Indoor experiment.” *Appl. Therm. Eng.*, 127, 203–211.

Lawal, D. U., and Qasem, N. A. A. (2020). “Humidification-dehumidification desalination systems driven by thermal-based renewable and low-grade energy sources : A critical review.” *Renew. Sustain. Energy Rev.*, 125, 109817.

Li, G. P., and Zhang, L. Z. (2016). “Investigation of a solar energy driven and hollow fiber membrane-based humidification-dehumidification desalination system.” *Appl. Energy*, 177, 393–408.

Mistry, K. H., Mitsos, A., and Lienhard, J. H. (2011). “Optimal operating conditions and configurations for humidification- dehumidification desalination cycles.” *Int. J. Therm. Sci.*, 50(5), 779–789.

Mohamed, A. M. I., and El-minshawy, N. A. S. (2009). “Humidification – dehumidifi cation desalination system driven by geothermal energy.” Desalination,249, 602–608.

Morsy, M. G., Ismail, I. M., and Soliman, A. M. A. (2009). “Experimental Performance of Spray Type Humidifier in Humidification-Dehumidification Desalination Unit.” 37(6), 1433–1447.

Moumouh, J., Tahiri, M., and Salouhi, M. (2014). “ScienceDirect Solar thermal energy combined with humidification e dehumidification process for desalination brackish water : Technical review.” *Int. J. Hydrogen Energy*, 39(27), 15232–15237.

Moumouh, J., Tahiri, M., Salouhi, M., and Balli, L. (2016). “ScienceDirect Theoretical and experimental study of a solar desalination unit based on humidification e dehumidification of air.” *Int. J. Hydrogen Energy*, 41(45), 20818–20822.

Müller-Holst, H., Engelhardt, M., Herve, M., and Schölkopf, W. (1998). “Solarthermal seawater desalination systems for decentralised use.” *Renew. Energy*, 14(1–4), 311–318.

Nafey, A. S., Fath, H. E. S., El-Helaby, S. O., and Soliman, A. (2004). "Solar desalination using humidification-dehumidification processes. Part II. An experimental investigation." *Energy Convers. Manag.*, 45(7–8), 1263–1277.

Nafey, A. S., Fath, H. E. S., and Mabrouk, A. A. (2006). "Thermo-economic investigation of multi effect evaporation (MEE) and hybrid multi effect evaporation — multi stage flash (MEE-MSF) systems." 201, 241–254.

Narayan, G. P., Chehayeb, K. M., McGovern, R. K., Thiel, G. P., Zubair, S. M., and Lienhard V, J. H. (2013). "Thermodynamic balancing of the humidification dehumidification desalination system by mass extraction and injection." *Int. J. Heat Mass Transf.*, 57(2), 756–770.

Narayan, G. P., Sharqawy, M. H., Summers, E. K., Lienhard, J. H., Zubair, S. M., and Antar, M. A. (2010). "The potential of solar-driven humidification – dehumidification desalination for small-scale decentralized water production." *Renew. Sustain. Energy Rev.*, 14(4), 1187–1201.

Nawayseh, N. K., Farid, M. M., Omar, A. A., and Sabirin, A. (1999). "Solar desalination based on humidification process - II. Computer simulation." *Energy Convers. Manag.*, 40(13), 1441–1461.

Note, T., and Summary, E. (August 2015). "Aqueduct Projected Water Stress Country Rankings." , 1–16.

Orfi, J., Galanis, N., and Laplante, M. (2007). "Air humidification-dehumidification for a water desalination system using solar energy." *Desalination*, 203(1–3), 471–481.

Orfi, J., Laplante, M., Marmouch, H., Galanis, N., Benhamou, B., Nasrallah, S. Ben, and Nguyen, C. T. (2004). "Experimental and theoretical study of a humidification-dehumidification water desalination system using solar energy." *Desalination*, 168(1–3), 151–159.

Prakash Narayan, G., John, M. G. St., Zubair, S. M., and Lienhard, J. H. (2013). "Thermal design of the humidification dehumidification desalination system: An experimental investigation." *Int. J. Heat Mass Transf.*, 58(1–2), 740–748.

Qasem, N. A. A., and Zubair, S. M. (2019). "Performance evaluation of a novel hybrid humidification-dehumidification (air-heated) system with an adsorption desalination system." *Desalination*, 461, 37–54.

Qtaishat, M. R., and Banat, F. (2013). "Desalination by solar powered membrane distillation systems." *Desalination*, 308, 186–197.

Rahimi-ahar, Z., Hatamipour, M. S., Ghalavand, Y., and Palizvan, A. (2020). "Comprehensive study on vacuum humidification-dehumidification (VHDH) Desalination." 169, 1–12.

Rajaseenivasan, T., Shanmugam, R. K., Hareesh, V. M., and Srithar, K. (2016). "Combined probation of bubble column humidi fi cation dehumidi fi cation desalination system using solar collectors." *Energy*, 116, 459–469.

Rajaseenivasan, T., and Srithar, K. (2017). "Potential of a dual purpose solar collector on humidi fi cation dehumidi fi cation desalination system." 404, 35–40.

Ranjan, K. R., and Kaushik, S. C. (2013). "Energy, exergy and thermo-economic analysis of solar distillation systems: A review." *Renew. Sustain. Energy Rev.*, 27, 709–723.

Sharon, H., and Reddy, K. S. (2015). "A review of solar energy driven desalination technologies." *Renew. Sustain. Energy Rev.*, 41, 1080–1118.

Shatat, M., Omer, S., Gillott, M., and Riffat, S. (2013). "Theoretical simulation of small scale psychometric solar water desalination system in semi-arid region." *Appl. Therm. Eng.*, 59(1–2), 232–242.

Shehata, A. I., Kabeel, A. E., Khairat, M. M., Abo, M. M., Abdalla, A. M., Mehanna, A., Khairat Dawood, M. M., Abo Elazm, M. M., Abdalla, A. M., and Mehanna, A. (2019). "Achievement of humidification and dehumidification desalination system by utilizing a hot water sprayer and ultrasound waves techniques." *Energy Convers. Manag.*, 201(July), 112142.

Soufari, S. M., Zamen, M., and Amidpour, M. (2009). "Performance optimization of the humidification-dehumidification desalination process using mathematical programming." *Desalination*, 237(1–3), 305–317.

Sukhatme, S. P. (2012). "Can India ' s future needs of electricity be met by renewable energy sources - a revised assessment." 103(10).

Tow, E. W., and Lienhard V, J. H. (2014). "Experiments and modeling of bubble column dehumidifier performance." *Int. J. Therm. Sci.*, 80(1), 65–75.

Wu, G., Zheng, H., Kang, H., Yang, Y., Cheng, P., and Chang, Z. (2016). "Experimental investigation of a multi-effect isothermal heat with tandem solar desalination system based on humidi fi cation – dehumidi fi cation processes." *Desalination*, 378, 100–107.

Wu, G., Zheng, H., Ma, X., Kutlu, C., and Su, Y. (2017). "Experimental investigation of a multi-stage humidification-dehumidification desalination system heated directly by a cylindrical Fresnel lens solar concentrator." *Energy Convers. Manag.*, 143, 241–251.

Xiong, R. H., Wang, S. C., Xie, L. X., Wang, Z., and Li, P. L. (2005). "Experimental investigation of a baffled shell and tube desalination column using the humidification-dehumidification process." *Desalination*, 180(1–3), 253–261.

Xu, H., Zhao, Y., and Dai, Y. J. (2019). "Experimental study on a solar assisted heat pump desalination unit with internal heat recovery based on humidi fi cation-dehumidi fi cation process." 452, 247–257.

Yamali, C., and Solmus, I. (2008). “A solar desalination system using humidification-dehumidification process: experimental study and comparison with the theoretical results.” *Desalination*, 220(1–3), 538–551.

Yamali, C., and Solmuş, I. (2007). “Theoretical investigation of a humidification-dehumidification desalination system configured by a double-pass flat plate solar air heater.” *Desalination*, 205(1–3), 163–177.

Yildirim, C., and Solmuş, I. (2014). “A parametric study on a humidification-dehumidification (HDH) desalination unit powered by solar air and water heaters.” *Energy Convers. Manag.*, 86, 568–575.

Zamen, M., Soufari, S. M., Vahdat, S. A., Amidpour, M., Zeinali, M. A., Izanloo, H., and Aghababaie, H. (2014). “Experimental investigation of a two-stage solar humidi fi cation – dehumidi fi cation desalination process.” 332, 1–6.

Zhani, K. (2013). “Solar desalination based on multiple effect humidification process: Thermal performance and experimental validation.” *Renew. Sustain. Energy Rev.*, 24, 406–417.

Zhani, K., and Bacha, H. Ben. (2010). “Experimental investigation of a new solar desalination prototype using the humidification dehumidification principle.” 35, 2610–2617.

Zhani, K., Bacha, H. Ben, and Damak, T. (2011). “Modeling and experimental validation of a humidification-dehumidification desalination unit solar part.” *Energy*, 36(5), 3159–3169.

Zubair, S. M., Antar, M. A., Elmutasim, S. M., and Lawal, D. U. (2018). “Performance evaluation of humidification-dehumidification (HDH) desalination systems with and without heat recovery options : An experimental and theoretical investigation.” 436, 161–175.

LIST OF PUBLICATIONS BASED ON PH.D RESEARCH WORK

Sl. No.	Title of the paper	Authors	Name of the Journal/ Conference, Vol., No., Pages	Month, Year of Publication	Category*
1	Humidification-Dehumidification Using Solar Collectors	Kumara and G Veershetty	IOP Conf. Series: Materials Science and Engineering 376 (2018) 012025,1-8. (Scopus Indexed)	*June* 2018	3
2	Experimental study on desalination system using humidification- dehumidification process with baffles in the dehumidifier	Kumara, G Veershetty, D H Ashebir	Journal of Engineering Science and Technology, Volume 15, Issue 2 (Scopus Indexed)	*March* 2020	1
3	Experimental Analysis On Humidification-Dehumidification Desalination System Using Different Packing Materials With Baffle Plates	Kumara ,G Veershetty and Gamachisa M	Thermal Science and Engineering Progress,Vol 22 (SCIE Indexed, Elsevier)	*May 2021*	1
4	Thermoeconomic analysis of humidification-dehumidification desalination system using solar energy	Kumara ,G Veershetty and Gamachisa M	Thermal Science and Engineering	*April.2021 (under review)*	1

*Category: 1: Journal paper, full paper reviewed 2: Journal paper, Abstract reviews 3: Conference/Symposium paper, full paper reviewed 4: Conference/Symposium paper, abstract reviewed 5: others (including papers in Workshops, NITK Research Bulletins, Short notes etc.)

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