Decentralized Solar Water Purification System for Remote Areas

A Final Year Project Report

Presented to

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

Department of Mechanical Engineering

NUST

ISLAMABAD, PAKISTAN

In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

By

Ahmad Daniyal
Muhammad Faisal Saad
Muhammad Irtasam Hassan
Muhammad Hamza Rehman
Muhammad Umer Farooq Awan

May 2019

EXAMINATION COMMITTEE

We hereby recommend that the final year project report prepared under our supervision by:

Ahmad Daniyal	127566
Muhammad Faisal Saad	128864
Muhammad Irtasam Hassan	125722
Muhammad Hamza Rehman	133780
Muhammad Umer Farooq Awan	120107

Titled: **"Decentralized solar water purifications system for remote communities"** be accepted in partial fulfillment of the requirements for the award of **Bachelors in Mechanical Engineering degree** with grade ___

Supervisor: Hafiz M. Abd-ur-Rehman (Lecturer) SMME, NUST	____________________ Dated:
Committee Member: Dr. Rehan Zahid (Lecturer) SMME, NUST	____________________ Dated:
Committee Member: Dr. Zaib Ali (Assistant Professor) SMME, NUST	____________________ Dated:

______________________ ____________

(Head of Department) (Date)

Countersigned

Dated: ________________ __________________________

(Dean / Principal)

ABSTRACT

Water scarcity is a major crisis and is growing with the passage of time. The present water resources are either getting contaminated or being wasted, also the increase in the overall population is exerting a great pressure on the existent water sources. This problem is a greater concern for developing and under-developed countries. In order to meet the increasing freshwater demand, the desalination techniques are gaining more importance. Bubble column humidification dehumidification systems offer a great prospect for the solution as they require less maintenance and are simpler; especially for decentralized and remote area application. The project involves the detailed literature review on the different desalination techniques. Based on the review, a system comprising of a stepped multi stage humidifier and a multi stage dehumidifier is proposed. A mathematical model of the basic HDH system was studied and a parametric analysis of the performance of the system was performed. Also, experimental analysis regarding the bubbling mechanism was performed and the bubbling scheme giving the maximum effectiveness was selected. Based on the analysis and experimental investigation a 3D model of the project was developed using SolidWorks. The prototype manufactured had a productivity of 9.84 liters/day. The developed system can be used in decentralized and remote areas applications where drinking water is scarce. The system can also be used along with the desiccant cooling system to serve as an air conditioning system.

ACKNOWLEDGEMENTS

All praise is to ALLAH, who is the lord of all worlds. He is indeed the most merciful. It is he whom we worship and ask for help. We thank first and foremost our lord, for his countless blessings and aids at every step of our past and future life. Among his unlimited blessings are our parents and teachers, who have supported us in all endeavors of life.

We would like to acknowledge our supervisor Hafiz Muhammad Abd-ur-Rehman who has provided us with exceptional mentorship. He has not only provided us with continuous technical support and ideas but also with moral support and motivation for this project.

We are also thankful to "National University of Sciences and Technology (NUST)", specifically the department of Mechanical and Manufacturing Engineering (SMME) for the cooperation and support.

ORIGINALITY REPORT

FYP Thesis

ORIGINALITY REPORT

10%	2%	5%	7%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to King Fahd University for Petroleum and Minerals Student Paper	1%
2	"Desalination", Wiley, 2019 Publication	1%
3	Submitted to Coventry University Student Paper	1%
4	Hafiz M. Abd-ur-Rehman, Fahad A. Al-Sulaiman. "An experimental investigation of a novel design air humidifier using direct solar thermal heating", Energy Conversion and Management, 2016 Publication	1%
5	Submitted to Universiti Tenaga Nasional Student Paper	<1%
6	John Lienhard, Mohamed A. Antar, Amy Bilton, Julian Blanco, Guillermo Zaragoza. "SOLAR DESALINATION", Annual Review of Heat Transfer, 2012 Publication	<1%

Supervisor Signature: ____________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

HDH	Humidification Dehumidification
GOR	Gained output ratio
MR	Mass flow rate ratio

NOMENCLATURE

Cp	Specific heat at constant pressure	J/kg.K
$\dot{H}$	Enthalpy rate	W
$\dot{m}$	Mass flow rate	kg/s
T	Temperature	K
h	Enthalpy	J/kg.s

$\dot{Q}$	Rate of heat	W
$\in$	Effectiveness	---
ω	Specific humidity	kg of vapor/kg of air

Subscripts:

a	Air
w	Water
h	Humidifier
d	Dehumidifier
in	Input
max	Maximum
f	Fresh water (distillate)
b	Water at outlet of humidifier

CHAPTER 1: INTRODUCTION

1.1. Motivation

Water is arguably the most important natural resource essential for life. It is the basic necessity of our everyday life. But unfortunately, clean and safe drinking water is just a dream for billions of people. Water scarcity is a globally rising threat to mankind. Around 2 billion people are forced to drink unsafe water due to lack of clean and safe drinking water [1]. Drinking unsafe water can result in several waterborne diseases like Cholera, Dysentery and Typhoid. Waterborne diseases become the cause around 3.4 million fatalities every year and this number is increasing day by day [2]. Mostly the victims of waterborne diseases are children as they have weak immune system. Around 5% of all child deaths can be prevented just by providing safe water and sanitation [1]. This shortage of clean water is a more severe issue for developing countries like Pakistan due to lack of infrastructure for water storage. Pakistan is facing severe threat of water shortage. The existing water sources are exhausting and due to inadequate infrastructure for storage, most of the rain water drains into the ocean. This shortage is even more severe in remote communities where it is difficult to transport water and these areas also lack in awareness. Moreover, the rapid increase in population is exerting more stress on the current sources. It is expected that by 2025 Pakistan will be facing grave shortage of water and may even run dry [3]. The effects of water shortage can be devastating for a country with economy relying on agriculture. The most abundant sources of water we have are oceans. Therefore, countries around the globe are focused on desalination techniques to purify seawater to use as drinking water. Many desalination techniques like Reverse-Osmosis (RO), Multistage Flashing (MSF), Multi effect Desalination (MED), Electro-dialysis and Vapor Compression distillation, etc. are already being used extensively. Some unconventional techniques like membrane distillation and HDH desalination are also under research these days but are yet to be commercialized. Hence in the light of the discussion above, it is evident that we must focus on improving the desalination methods in order to satisfy the ever-growing demand of water in a manner to increase the productivity in a cost-effective manner.

1.2. Problem Statement

Most of the desalination techniques like MSF, MED, RO, etc. have a common drawback that they require extensive investment, large scale plants and very high maintenance in order to be continuously functional. Therefore, due to high power requirement they cannot be used in underdeveloped countries especially in remote areas. In these cases, systems like Solar Stills and HDH systems are fit to be used. They do not require extensive investment or very huge infrastructure. They are cheaper than the others, require low maintenance and can be set up as medium or small-scale stand-alone units which makes them excellent to be used in remote areas. Solar Stills are being used to purify water since old times. The only drawback they have is their low production rate and low efficiency. In preset times, when population is growing so rapidly, Solar Stills may not be the best choice for a water purification system. With the ever-increasing demand of water, the Solar Stills with their low production rates may fall short in fulfilling the need of clean water completely. What we need now, is a water-purification system with high production rate and efficiency and is also cost-effective.

1.3. Proposed Solution

The shortcomings of a Solar Still have forced us to find a better solution. HDH systems are the answer to the above problems. They cheaper to install, do not require huge infrastructure, require very low maintenance and have very low energy demands and on the other hand, they offer very high performance as compared to Solar Stills. These characteristics make HDH systems a rather obvious choice especially while considering for remote areas. A lot of research is going on in this field right now. According to research bubble column HDH Systems show even improved performance as compared to simple HDH systems. In bubble column systems the bubbling mechanism has a significant effect on the performance of the system. Hence ensuring proper bubbling is essential to ensure proper heat and mass transfer and in turn to ensure maximum efficiency and production rate of the system.

The solution proposed here is the development of a cost-effective bubble column HDH system comprising of a double stage stepped configuration bubble column humidifier incorporating the phase change material (PCM) and a double stage bubble column dehumidifier.

1.4. Project Objectives

The main objective of this work is to develop a design for multi stage bubble column humidifier and dehumidifier that can ensure effective and efficient evaporation and condensation and in turn develop a cost effective HDH system that can be used to purify saline water in remote areas. The scope of the project consists of mathematical modeling, designing and developing Prototype, experimentation on the developed prototype and techno-economic evaluation of the system.

1.5. Project Description

HDH system basically imitates the rain cycle to purify water. Saline water is heated in a heater and is transported to the humidifier where it interacts with the incoming air and heat and mass transfer takes place. The air as a result of its interaction with hot water gets hot and humid. This hot and humid air goes to the dehumidifier where it interacts with the water column and gets cooled down. As result the air gets dehumidified and the distillate can be collected. Another important thing about this design is that the dehumidifier contains several coils. The saline water before going to the heater gets preheated by the hot and humid air coming from the humidifier. This results in increasing the overall efficiency and decreasing the amount of heat required by the heater.

CHAPTER 2: LITERATURE REVIEW

The availability of fresh usable water is increasingly becoming a serious problem for mankind. Of all the water present on the surface of Earth, less than 1% of it is usable for people. Seawater being the chief source of water on the planet can be used as an alternative to fresh water if its contaminants can be removed. A review of using bubble column humidification-dehumidification (HDH) systems was conducted beginning from the very basic concept of solar stills leading to the modern technologies using HDH with modifications for maximum productivity were studied. The literature review has been described here in the chronological order in which it was conducted for an easier to understand approach for the reader:

2.1. The Solar Still

The first manmade large-scale water desalination solar still dates as far back as the 18th or the 19th century. A solar still is mad of an air-tight insulated basin covered with a tilted glass sheet. Solar radiation passes through the glass or plastic cover and is absorbed by the saline water and the process of evaporation begins. The condensate sticks to the inner side of the cover and is collected using gravity. Solar stills are an easier desalination option due to their simple construction and low maintenance. However, they are effective for smaller scales only and a big downside to the basic solar still is its low efficiency (less than 50%) [4]. Efforts have been made to provide modifications to increase its efficiency. Velmurugan and Srithar performed a review of all the factors affecting the performance of the basic basin type solar still [5]. They concluded that use of sponges, different collector plates and fins increased the heat and mass transfer by increasing the surface area and the temperature difference between water and glass. Prakash and Velmurugan also did a similar review with summarizing the existing techniques of improving solar still productivity [6]. M. Al-harahsheh et al. used external solar collectors to improve the productivity of the system by complementing the energy needed [7]. Faegh and Shafii used evacuated solar tubes and heat pipes to increase productivity [8]. However, the modified solar still is still not good enough and focus has shifted to HDH technology.

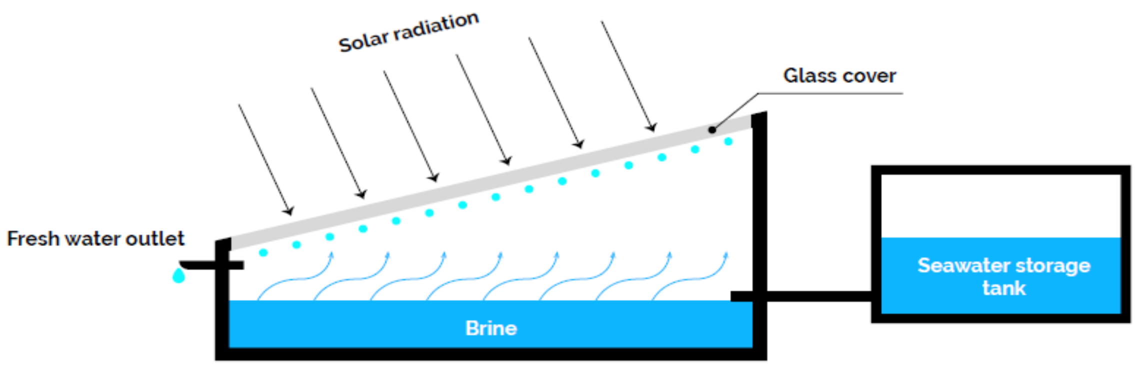

Figure 1: Basin type solar still

2.2. HDH technology

The performance issues associated with the solar still were addressed in the HDH systems. This system consists of a humidifier, a dehumidifier and a heater. These systems include a carrier fluid that is collects thermal energy from an energy source, after which it is transferred for evaporation of saline water to a humidifier and then for evaporated water condensation in the dehumidifier. A. Giwa et al. did a comprehensive review of all recent advances in the field of HDH processes [9]. Giwa et al. studied the effect of partial pressures of air and water on the mass transfer of vapour to air and also studied the effect of inlet air humidity on the mass transfer [10]. Kassim et al. carried out the initial numerical analysis of the humidifier and observed optimum productivity at low inlet air humidity [11]. Farid et al. was the first to analyze the HDH system mathematically conducted a simulation study to provide a mathematical model for the HDH cycle [12]. Narayan et al. categorized HDH systems into closed water-open air cycle and closed air-open water cycle and discussed the effect of cycle type on the productivity of the system [13]. Lienhard et al. provided comparisons different variations of the HDH systems using psychrometric coordinates [14]. They also defined the performance parameters for an HDH system, they compared the cycles by the cycle configuration of these systems i.e. water and air heating. They concluded that the closed-air open-water (CAOW) system was the most efficient system. Al-Hallaj et al. performed an economic analysis of solar HDH systems and concluded that a better understanding of this method is highly desirable for economic benefits [15]. They also the design optimization of indicated humidifier, dehumidifier and the heater were the key to unlocking the system's economic potential. Yuan et al. developed a closed air circulation system to overcome the lack of solar light during night, the system was optimized by the improvement of air flow and proper use of energy of the water being circulated [16].

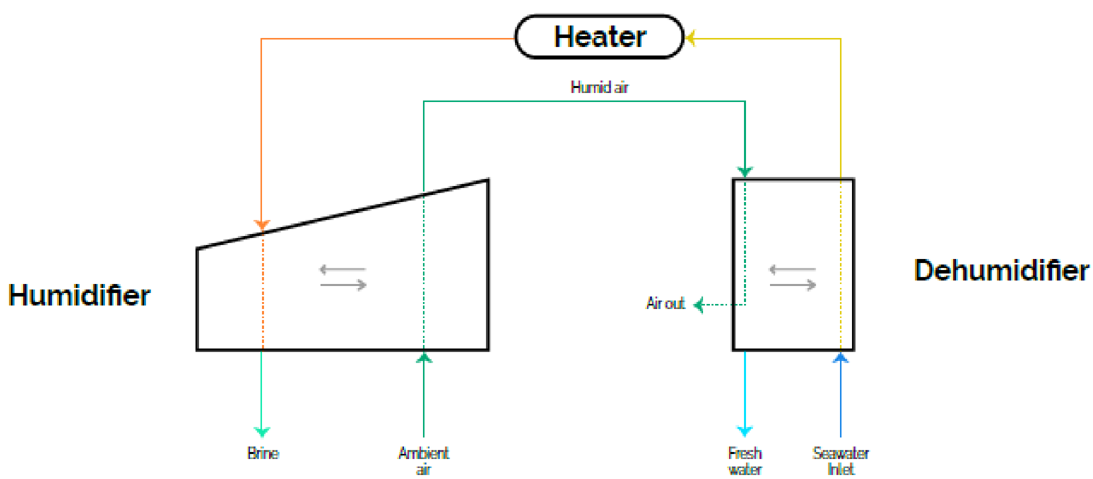

Figure 2: Basic HDH Cycle

Mohammed et al. used a parabolic trough collector to optimize and water production [17]. Elminshawy et al. studied the impact of external reflectors, induced air and weather condition on the performance [18]. They used a blower at the inlet for forced induction of air to the humidification chamber and a condenser on the outlet for the humidification portion. Performance of the system was observed both with and without the accessories, and system productivity was observed to be significantly improved with the external reflectors and water heater. The specific cost was observed to be $0.035/L. Shalaby et al.

recommended solar water collectors and discouraged the use of solar air heaters due to insignificant effect of air temperature at the inlet [19].

2.3. Comparison of HDH with other desalination techniques

The current desalination plants are mainly used for large-scale applications therefore requiring large amounts of energy and materials leading to ecological footprints. Many desalination processes still consume too much fossil fuels for heat production. Müller-Holst et al. compared several configurations of solar HDH systems and found the most energy efficient one with specific cost of \$3-7/m^3 [20]. This cost was in excess in that of the reverse osmosis process but other advantages have been associated with this technology due its possible small-scale applications. Small maintenance with simpler water pre-treatment are some of the system's advantages. Lienhard et al. investigated the potential of solar driven HDH systems and concluded that HDH technology has great promise for decentralized water desalination systems on a small scale, and additional research is needed to reduce the capital cost [14]. A. Giwa et al. concluded in their review of HDH technologies' advancements that mechanical compression based HDH will have a great potential mainly due to the reduced capital cost [9]. But the thermal vapor compression driven HDH cycle is a promising technology which can be used for large scale purposes. Nada et al. analysed the operation of hybrid systems that coupled HDH with other technologies such as RO (Reverse Osmosis) and SSF (Single Stage Flashing) [21]. Narayan et al. studied the combined system of HDH and RO using high pressure steam energy and found the Gain Output Ratio (GOR) to be much higher than that of the conventional still. Their system is shown in figure 3 [22].

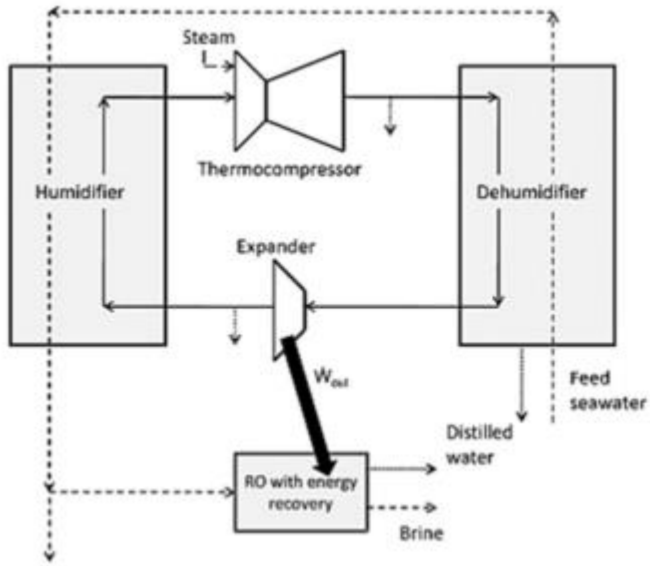

Figure 3: HDH using thermal compression hybridized with RO

As it has been described earlier, solar stills and later the HDH systems have been used for water desalination with necessary modifications. Researchers have been attempting to improve the system performance for years and in the recent years, the focus has shifted to the use of air bubbling in HDH systems.

2.4. HDH technology with air bubbling

The use of air bubble columns in HDH desalination is an excellent method to achieve greater rates of heat and mass transfer and thus achieving greater productivity. G.C. Pandey was among the first to attempt both forced and dried air bubbling in a solar still with cooling of the glass cover simultaneously [23]. He found the increase in distillate output to be 33.5 and 47.5 per cent respectively. The reason for this increase was due to increase in rate of evaporation due to the air bubbling. H. Ben Halima studied the influence of air bubbling in a simple basin to determine the heat and mass transfer coefficients and found the effect of water temperature and airflow rate to be moderate and more significant than the effect of the water level [24]. Kabeel et al. coupled air bubbling with Phase Change Materials (PCMs) and compared the results with the conventional solar still [25].

2.5. Review of bubble column humidifiers

A bubble column reactor is the equipment used for generation and control of gas-liquid interaction. The bubble column allows for greater heat and mass transfer due to larger surface area.

Table 1: Review of variations in bubble column humidifiers

Sr. No.	Reference	Features	Output	Focus
Pressure Variation				
1.	**M. Vlachogiannis et al. [26]**	• Mechanical vapour compression with HDH using a compressor. • Laboratory Unit	50% increase in thermal coefficient	Effect of variable conditions on compression energy and capacity.
2.	**O.K. Siddiqui et al. [27]**	• HDH at different pressures. • CAOW cycle	GOR of 8.2 and 3.8 for effectiveness of 0.9 and 0.8 respectively	Effect of pressure on HDH and maximum GOR, higher exergy destruction.
3.	**H. Liu, M.H. Sharqawy [28]**	• Bubble column humidifier and dehumidifier • Internal cooling • Sparger Plates	• 10.7% increase in humidifier effectiveness • 2.4% decrease in dehumidifier effectiveness	Effect of sub-atmospheric pressure and column height on effectiveness
Multi-staging				
4.	**H.M. Abd-ur-Rehman, F.A. Al-Sulaiman [29]**	• Multi-stage bubble column humidifier • Perforated plates	Increase of 7-9% and 18-21% in absolute humidity for double stage and triple stage respectively.	Study of pressure changes with column height at variable superficial velocity, effect of multi-staging on absolute humidity.

5.	**Kabeel et al. [30]**	• Stepped Basin • Vacuum Tube Solar Collector • Wicks	• 57.3% higher productivity than conventional still • Daily efficiency of up to 53%	Effect of depth and width of trays on performance, preheating of feed water
6.	**Garg et al. [31]**	• Multi-effect HDH system • Natural Convection • Packed bed humidifier	Vapour content difference value is 66 g/kg_a at 70^0 C	Enhancement of evaporation process
7.	**Kang et al. [32]**	• Regenerative and air-extraction multi-stage HDH system. • Pinch analysis models	• GOR of air-extraction system was greater. • Performance increase for more stages but the effect weakens at higher values	Effect of pinch temperature difference on performance.

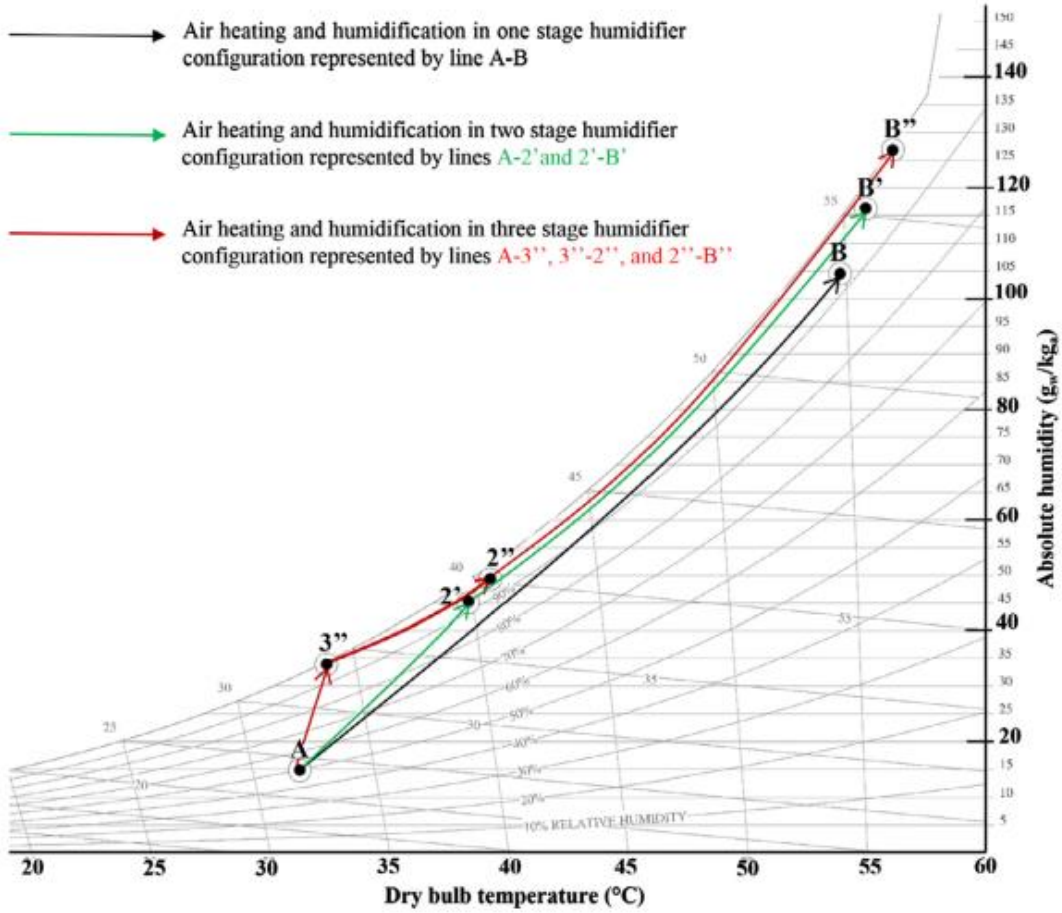

Figure 4: Psychometric chart of air humidification in single, double and three stage configurations [29]

H.M. Abd-ur-Rehman et al performed an experimental analysis on the multi stage humidifier, the results showed that the multi staging improve the overall heat and mass transfer in a way that the outlet absolute humidity of the air increased by 7-9% for two stage and 18-21% for three stages. Also the effectiveness was increased as the heat transfer achieved was closed to the maximum possible as the temperature difference of the two streams at the outlet was decreased as shown in figure 5 .Whereas figure 4 plots the data and explains the multi staging effect through a psychrometric plot [33].

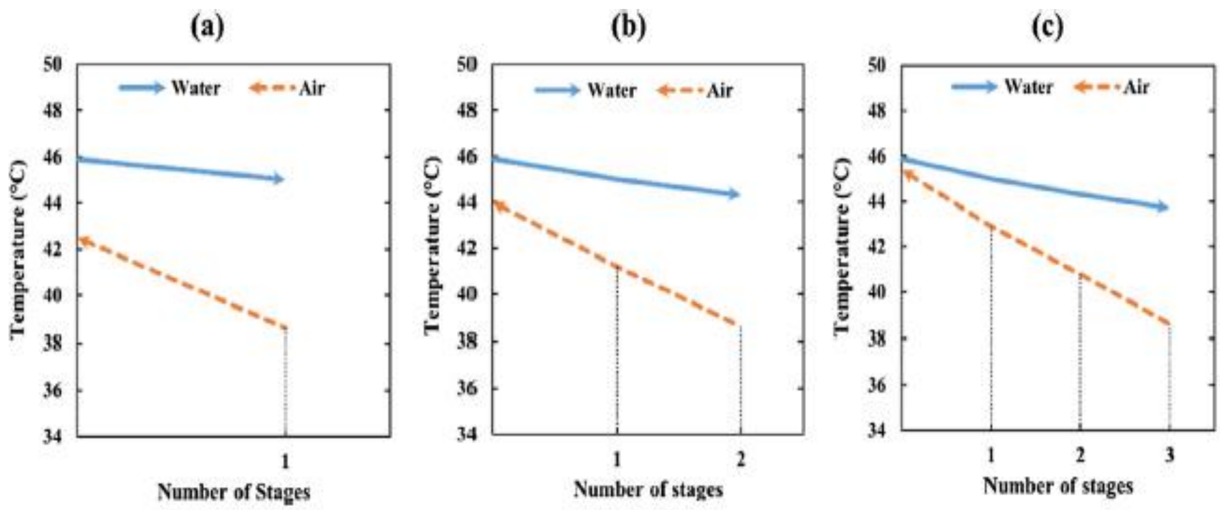

Figure 5: Effect of multi staging on heat transfer

2.6. Review of bubble column dehumidifiers

The literature on bubble column dehumidifiers is generally scattered. The bubble column multi stage dehumidifier was proposed to overcome the large resistance for heat and mass transfer in the dehumidifier. The usual response to this has been an increase in size of the component but this of course leads to greater cost. The following table summarizes the literature available on bubble column dehumidifiers:

Table 2: Overview of bubble column dehumidifier variations

Sr. No.	Reference	Features	Results
Initial Design			
1.	**Narayan et al. [34]**	• Proposal and development of bubble column dehumidifier • Experimental verification of heat transfer model to predict temperature and heat flux inside the dehumidifier.	• Bubble column dehumidifiers have greater heat rates than existing ones. • The design should have high superficial velocity, low bubble dia. and maximum bubble impact.
Multi-staging			

2.	**Lam [35]**	• Development of a multi stage dehumidifier. • A single stage setup was also tested. • Various parameters were studied in this setup.	• The multistage column achieved a maximum effectiveness of 89.4%. • Heat transfer rates of 4 kW/m^2 up to 20 kW/m^2 were shown to be possible. • Column height had no effect on heat flux. • Increase in the superficial velocity increased heat flux as did the increase in the inlet mole fraction.
Mathematical modelling			
3.	**Tow et al. [36]**	• Horizontal cylinder immersed in air-water column • Effects of flow regime, bubble impact and column height	• Heat transfer coefficients increase with increase in liquid height up till a critical height. • Above the critical region, highest coefficients occur when the cylinder is aligned with the holes of the sparger.
4.	**Tow et al. [37]**	• Direct contact bubble column dehumidification. • Heat flux prediction model. • Study of heat flux and parallel flow effectiveness.	• Decrease in coil area leads to high heat flux and decreases effectiveness. • Bubble on coil impact and column height are found to be insignificant.
5.	**Tow et al. [38]**	• Defined a parallel flow effectiveness to complement the heat flux. • Performed experiments to improve understanding of the parameters effecting bubble column dehumidifier performance.	• Heat flux can be elevated drastically by decreasing coil area, but this rise is coupled with a loss of effectiveness. • Liquid level should be minimized. • Increase in liquid-side pinch increases heat transfer

2.7. Review of phase change materials (PCMs) and nanoparticles

Phase Change Materials (PCMs) and nanoparticles have been used in the past to overcome certain hurdles faced by solar desalination plants including the bubble column HDH systems. A problem that occurs with solar run systems is their inability to function during the dark hours this has been helped by the use of Phase Change Materials (PCM) that are able to store energy in latent form in themselves. Therefore, during the day they store the energy of the sun, and at night they turn into a source themselves and provide the energy to keep the system running. It has been generally observed that a greater productivity is obtained by use of a higher melting point PCM. Similarly, nanoparticles have been used to improve the performance of PCM and also in the basin of the solar still itself. The following table provides an overview:

Table 3: Review of PCM and nanoparticles in solar desalination

Sr. No.	Reference	Particle used	Area of use	Results
Phase Change Materials (PCMs)				
1.	A.E. Kabeel et al. [25]	Paraffin wax with hot air injection	Beneath the absorber plate	26% increase in productivity
2.	A.E. Kabeel, M. Abdelgaied [39]	Paraffin wax of mass 17.5 kg	Under the collector plate	67.18% more productivity than the conventional still
3.	Shalaby et al. [40]	Paraffin	Beneath absorber plate	Increase in yield up to 12%
4.	F. Dashtban, F. Tabrizi	Paraffin wax	Beneath the absorber plate	Productivity of 6.71 $kg/m^2/day$. A 31% increase over PCM-less system.
5.	M. Asbik et al. [41]	Stearic Acid	Under the basin liner	Increase in evaporative heat transfer coefficient of 27%.
6.	El-Sebaii et al. [42]	Stearic Acid	Beneath collector	Daily efficiency of up to 85.3%
Nano-particles with PCM				
7.	Rufuss et al. [43]	CuO with paraffin wax	Nanoparticles in PCM	35% increase in productivity
Nano-particles in the basin				

8.	Sahota and Tiwari [44]	Al_2O_3 with two different masses	Nanoparticles in the base fluid (water)	Increase in yield of 12.2% and 8.4% for 35kg and 80kg water respectively
9.	Sellami et al. [45]	Several	Coated on blackened sponges	Yield increase up to 58% for 1cm thick coating
Nano-Particles in Solar Collectors				
10.	Leong et al. [46]	0.2% wt. of Al_2O_3 20nm of silver particles at 10,000 ppm	In flat plate collectors	28.3% increase in efficiency for Al_2O_3. Double heat transfer coefficients for silver particles
11.	A.H. Elsheikh et al. [47]	CuO/water	In evacuated tube collectors	12.4% increase in collector efficiency

CHAPTER 3: METHODOLOGY

In the previous section several desalination techniques were discussed along with their comparison. It was concluded that the system involving the bubble columns had the room for further exploration. Also, their thermal performance was greater than the other techniques. Furthermore, multi staging these systems further enhances their efficiency. Hence, the system proposed for the project consisted of a stepped multistage bubble column humidifier and a multistage bubble column dehumidifier. System involves the incorporation of phase change material to utilize the available thermal energy in the maximum possible manner. The basic focus of the project is regarding the humidifier and dehumidifier; the solar water heating and the solar panels required are included in terms of their cost.

This section involves the explanation of the experimentation regarding the selection of the mechanism for bubbling phenomenon. Also, the mathematical model used for performing the parametric analysis is discussed.

3.1. Mathematical Modelling

To understand the working of the proposed system a mathematical model of basic humidification dehumidification (HDH) system was considered. The simultaneous heat and mass transferred is studied for both humidifier and dehumidifier. The heat transfer through the heater is also considered and the performance of the system is analyzed. The performance of the system is analyzed for several parameters. The model is solved in MATLAB and the resulting data and graphs are plotted using Microsoft Excel.

The figure shows the HDH system which compromises of a humidifier, dehumidifier and a heat

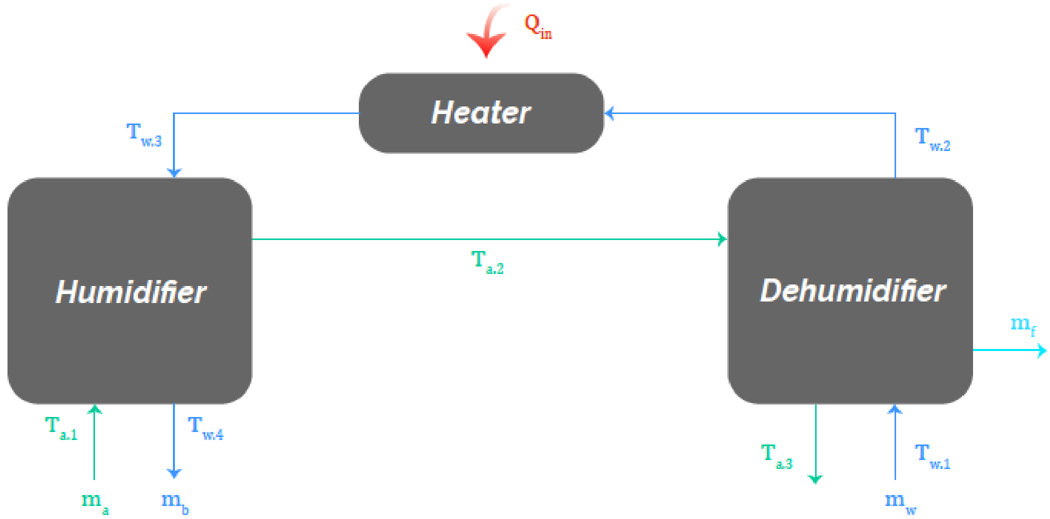

Figure 5: HDH Schematic

3.1.1. Humidifier:

The ambient air at temperature (Ta_1) and mass flow rate $\dot{m}_a$ enters the humidifier. The hot water after the heater enters the humidifier at the temperature (Tw_3) where its flow rate is '$\dot{m}_w$'. Simultaneous heat and mass transfer takes place and the air gets heated to the temperature (Ta_2) whereas the water gets cooled down to the temperature (Tw_4). The flow rate of the water leaving the humidifier is '$\dot{m}_b$'; as some of the water is humidified.

The basic heat and mass transfer is given by the following equations:

Energy balance:

$$\dot{m}_a \times (ha_2 - ha_1) = \dot{m}_w \times Cp_w \times Tw_3 - \dot{m}_b \times Cp_w \times Tw_4$$

Where 'ha' is the enthalpy of the air and 'Cp' is the specific heat of the water.

Mass balance:

$$\dot{m}_b = \dot{m}_w - \dot{m}_a \times (\omega_2 - \omega_1)$$

Where ω_1 and ω_2 are the specific humidity of air at the point 1 and 2.

The above equations have more number of unknowns so another equation is introduced regarding the effectiveness [48] which is:

'The ratio of actual change of enthalpy rate to the maximum change of enthalpy rate.'

For the humidifier; mathematically:

$$\epsilon_h = \frac{\Delta \dot{H}}{\Delta \dot{H}_{max}}$$

For the humidifier the maximum change in enthalpy rate is when the all the available energy is exchanged between the two streams i.e. pinch point temperature difference gets equal to zero. This will happen when the air outlet temperature gets the same as the water inlet temperature. And the water outlet temperature gets the same as the air inlet wet bulb temperature [48].

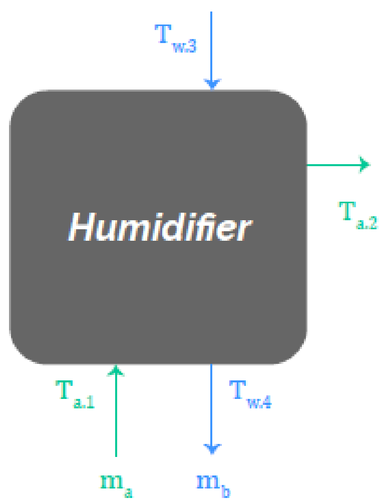

Figure 6: Basic Humidifier Layout

These conditions are used to calculate the maximum change in enthalpy rate for both the streams i.e. water and air. The stream having the lesser value will control the process as only that energy will be exchanged. This can be explained by the fact that air will only reach at the water inlet temperature as long as water has the heat capacity rate. If it does not have the heat capacity rate then water will be cooled down to the air inlet wet bulb temperature and air outlet temperature will be lesser than that of the water inlet temperature [49]. The above equations are solved for the unknowns.

Mass flow rate ratio (MR) is defined as the ratio of flow rate of water to that of air; mathematically:

$$MR = \frac{\dot{m}_w}{\dot{m}_a}$$

3.1.2. Dehumidifier:

The humid air from the humidifier enters the dehumidifier at temperature (Ta_2) and mass flow rate '$\dot{m}_a$'. The water to be purified enters the dehumidifier at the temperature (Tw_1) and flow rate '$\dot{m}_w$ '. Simultaneous heat and mass transfer takes place and the air gets cooled to the temperature (Ta_3) whereas the water gets heated to the temperature (Tw_2). As air is cooled down some of the water gets condensed and is collected its flow rate is to be '$\dot{m}_f$'.

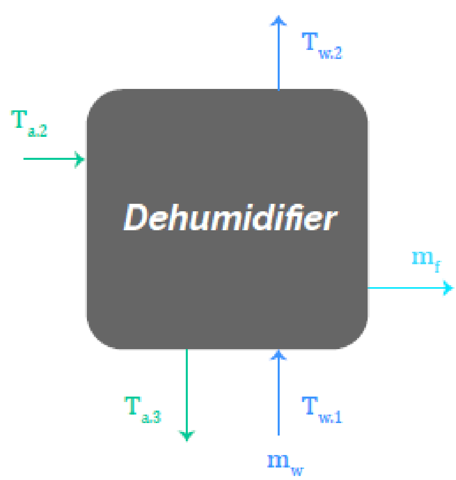

Figure 7: Basic Dehumidifier Layout

Energy balance:

$$\dot{m}_a \times (ha_2 - ha_3) - \dot{m}_f * h_f = \dot{m}_w \times Cp_w \times (Tw_2 - Tw_1)$$

Where ha_2 and ha_3 is the enthalpy of air at points 2 and 3.

Mass balance:

$$\dot{m}_f = \dot{m}_w - \dot{m}_b$$

Again, effectiveness is defined for dehumidifier to solve for the unknowns:

$$\epsilon_d = \frac{\Delta\dot{H}}{\Delta\dot{H}max}$$

Now, for the dehumidifier the maximum change in enthalpy rate occurs when the air outlet temperature gets the same as water inlet temperature. Also water outlet temperature gets the same as the air inlet temperature [48]. Again, the maximum change is calculated for the both streams and the least of them is used for the further calculations for the same facts as stated in the humidifier section. The equations are then solved for the unknowns.

3.1.3. Heater:

The heater involves the sensible heat change and raises the temperature of water from Tw_2 to the Tw_3. The top temperature is that of water after the heater i.e. maximum temperature of water in the cycle. Whereas the bottom temperature is least of water in the cycle i.e. at the inlet of dehumidifier.

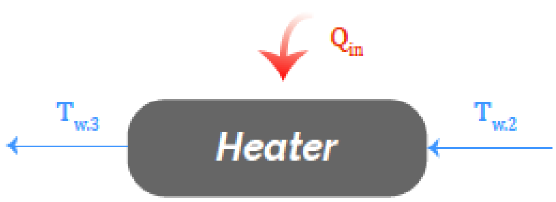

Figure 8: Basic Heater Layout

Heat input in the heater is given by:

$$\dot{Q}_{in} = \dot{m}_w \times Cp_w \times (Tw_3 - Tw_2)$$

3.1.4. Gained Output Ratio (GOR):

It is ratio of the distillate produced (in terms of heat) to the heat input in the heater [49]. Mathematically:

$$GOR = \frac{\dot{m}f * hf}{\dot{Q}_{in}}$$

It provides the measures of the system's performance.

3.2. Experimental investigation for bubbling mechanism

The equations formulated in the mathematical model stated above can be easily interpreted for experimental mechanisms that will be used in the actual system's layout. In other words, it can be seen that for maximum Gain Output Ratio, it is necessary to devise a system that is the most efficient amongst all the options available. In lieu of the parametric analysis of these mathematical equations, explained later on, it is necessary to develop a system that has a high relative humidity (in other words, high mass transfer) and maximum heat transfer in both the stages; that is, the humidifier and the dehumidifier.

It is a well-known and obvious fact that heat transfer achieved through direct mixing is much higher than that through a surface. In other words, a well-designed bubble-column dehumidifier will always have a higher heat transfer effectiveness than a surface dehumidifier or condenser [14]. Since the system under consideration uses a bubble column mechanism for heat and mass transfer in both the stages, developing an effective bubbling system will lead to a high yield.

There are two main categories of air bubbling mechanisms, based on the medium used to generate these bubbles. They include bubbling through Sparger Plates, which are further subdivided into different types depending on the type of the orifice patterns, and bubbling through holes in air pipes. Using Sparger plates has its pros and cons, although more bubbles are formed due to a high number of orifices on the plate's surface, this mechanism has a lot of problems such as leaking of water into air pipes in idle conditions and excessive splashing at a high air flow rate. Bubbling through pipes is more convenient, since water flows can be minimized using a non-return (or check) valve since the pipes have a relatively lower diameter. A few bubbling mechanisms were tested using the same flow rate of air for all of them, to observe their behavior when subjected to bubbling.

The experiments were conducted keeping in mind the workability of the material available in the market as well as its cost effectiveness since the same mechanism shall be used in the actual prototype. The size of the water column and the flow rate of air was set after a careful consideration of all the factors involved such as optimum Mass Flow Ratio and geometry restrictions. Scope of the testing phase was narrowed down to only pipe mechanisms and a few experiments were performed on different mechanisms, which are as follows:

3.2.1. Undivided unidirectional flow:

This flow, as shown in figure 10, involves a single pipe carrying the entire air flow to the water column (thus undivided) and since the pipes had holes on only one side therefore the flow was called a unidirectional flow.

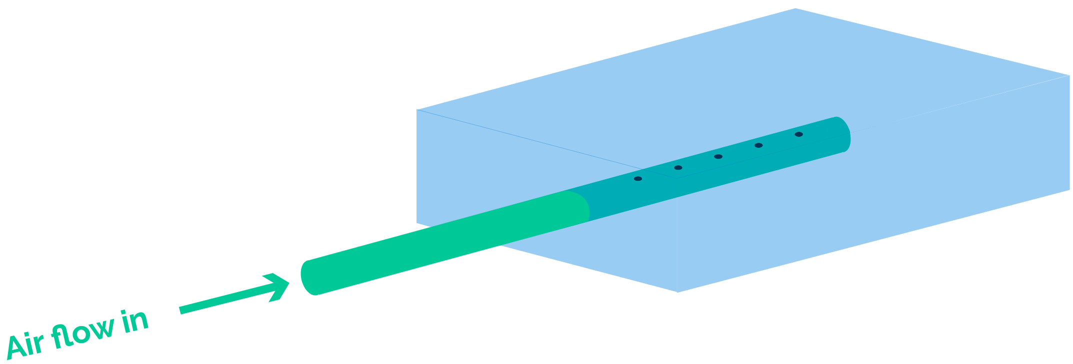

Figure 9: Undivided unidirectional flow

This flow has a few problems that ruled it out of the possible options. First of all, the excessive splashing caused water droplets to fly off to different parts of the experimental setup, resulting in water loss. The bubbles had a minute amount of time available to surface, thereby reducing the head and mass transfer. Also, major part of the water column will remain untapped using this configuration which will also lead to a major efficiency decrease.

3.2.2. Undivided two directional flow:

As shown in figure 11, this orientation again involves an undivided single pipe flow but now the pipes have holes on all sides and therefore bubble formation and flow was two directional.

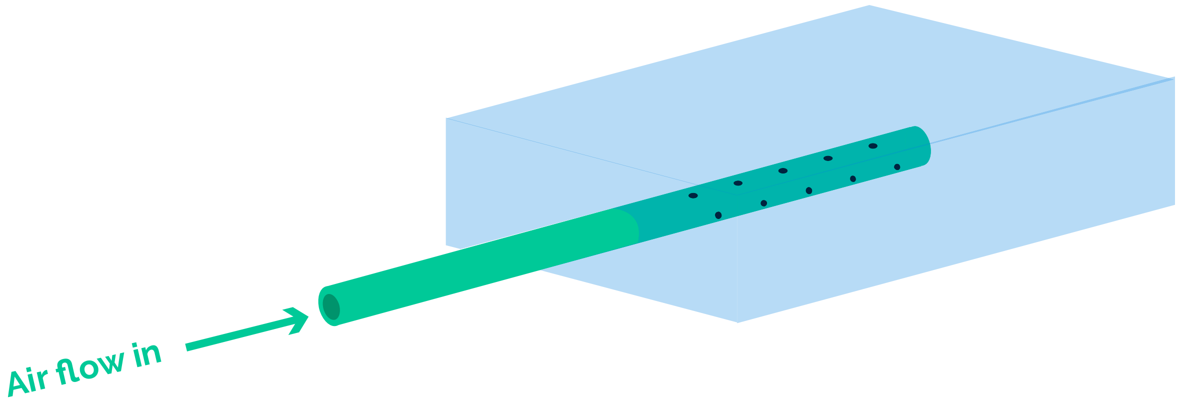

Figure 10: Undivided Unidirectional Flow

Since the bubbles emerging from the holes on the lateral sides and bottom had more time to surface, this setup has a higher heat and mass transfer effectiveness. However, water splashing was still higher than an acceptable rate and the water column off to the sides of the pipes still remained untapped. This mechanism also did not fit our selection criteria.

3.2.3. Divided two directional flow:

In order to tap the maximum part of the water column, it was necessary to divide the flow into more than one pipes such that the flow is distributed through the entire body. Both the pipes must have holes in all directions to enhance heat and mass transfer, as shown in figure 12 below.

All the problems related with both the previous setups were either resolved or brought under a satisfactory tolerance limit using this orientation. Splashing was reduced to a bare minimum while the head and mass transfer was enhanced due to an even dispersion of bubbles throughout the entire column. Another notable thing about such systems is that no part of the water body remains untouched and the bubbles emerging from holes on the

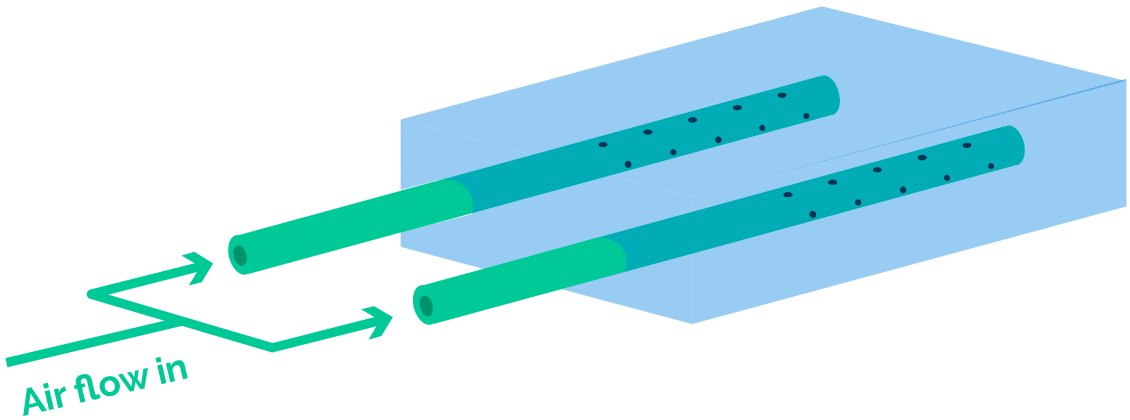

Figure 11: Divided two directional flow

interior sides of both the pipes merged in the center and formed a foam which lead to an even greater heat and mass transfer.

3.2.4. Experiments on the effect of multi-staging on bubbling:

The experiments were also performed with columns in multi stage configuration to see if bubbling through columns at different heights behaved differently with changes in elevation. It was clearly observed that bubble column height and elevation does not have a noticeable impact on the bubbling behavior, which was a predictable outcome. Therefore, the mechanisms can be easily incorporated in a multi-stage system with variable column height.

3.3. Prototype design

Based on the literature review and the parametric analysis, a two-stage bubble column humidifier and a two-stage bubble column humidifier shall be the two basic components of the desalination system. This setup is different from the long run implementation such that both the components can be combined with a solar water heater and solar panels or any other energy source. The solar water heater and solar panel integration is not included in the domain of this project, as these technologies have already been commercialized and are easily available in the market, this will be further discussed in section 3.4. The schematic of the experimental setup is as follows:

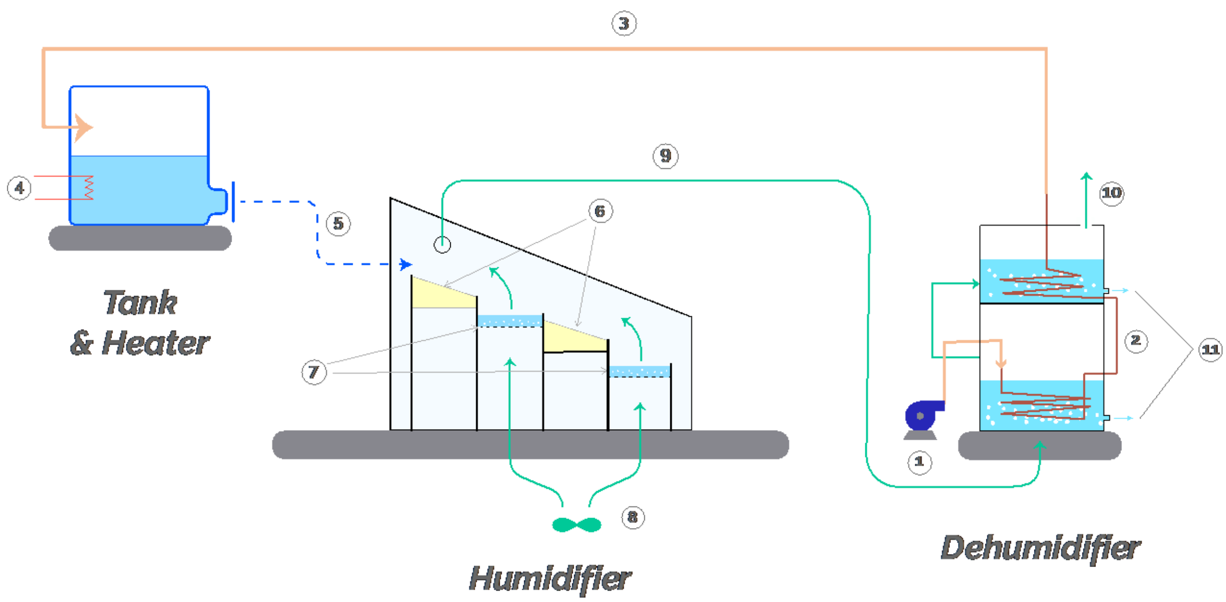

Figure 12: Schematic of the experimental prototype.

(1) Seawater pump (2) Seawater coils (3) Preheated water (4) Immersion heater (5) Hot seawater (6) PCM Beds (7) Bubble columns (8) Ambient air blow and inlet distribution system (9) Humid air to dehumidifier (10) Air outlet (11) Fresh water outlet

The seawater is pumped through coils present in the dehumidifier and gets pre-heated. It is then taken to a storage tank where it is heated to the required temperature. The water is then fed to the two-stage humidifier due to a pressure head of the storage tank. The bubbling mechanism used in this setup shall be the divided two-directional flow as discussed in section 3.2.3, where the air through the holes is forced by a blower. The bubbling mechanism causes heat and mass transfer which makes the ambient input air hot and humid. This hot and humid air is taken to the dehumidifier where the same mechanism is used to extract condensate.

3.3.1: Humidifier design:

As stated previously, a two-stage bubble column humidifier is used in step configuration as shown in figure 14. The humidifier has an aluminum frame and a 5 mm thick acrylic sheet transparent walls. There are two PCM stages that increase the heat retention capacity of the system.

The humidifier design, as shown in the figures above, has the advantage of being completely sealed for minimum air leakage and has a geometry that allows for air flow with the least hindrance.

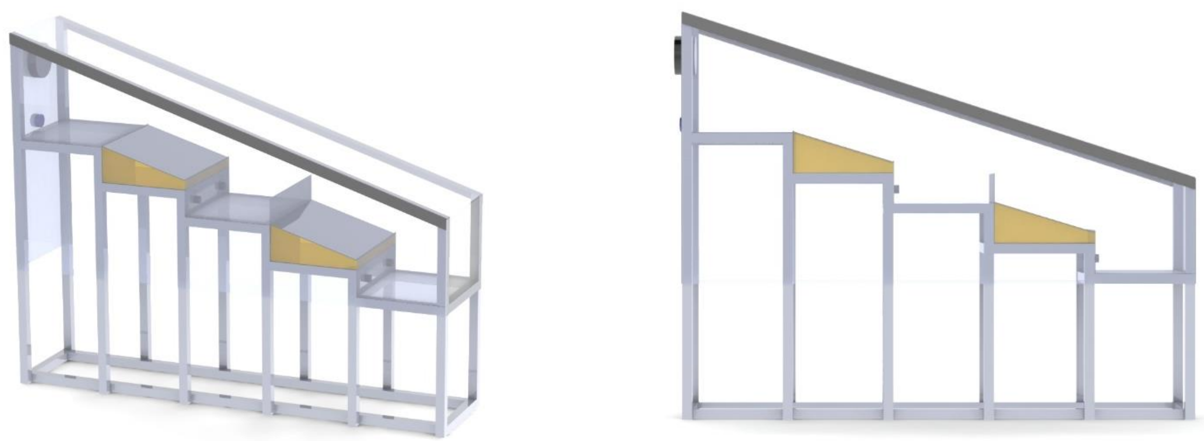

Figure 13: Humidifier Design

3.3.2: Dehumidifier design:

A two-stage bubble column dehumidifier is used in the system. It has copper coils of ¾ in diameter to preheat the seawater. Bubbling occurs through the same mechanism as in the humidifier and there is an air exhaust outlet at the end of both the stages. In comparison to the humidifier, the dehumidifier is smaller in size and has a boxed geometry for higher stability. There is an outlet for water extraction in both the stages.

Figure 14: Dehumidifier Design

The material used for this setup is similar to the humidifier. The frame structure is made up of aluminum brackets, the walls are of 5 mm thick Plexiglas or acrylic sheet and the preheat coils are made of copper.

3.4. Setup

The setup, after experiments and cost analysis prove it to be cost effective on a small scale and decentralized, will be entirely run on solar power instead of the electrical grid connection. The heater will be replaced by three Fresnel lenses while the storage tank will be in the shape of a solar collector to extract some of the condensate. Two of the Fresnel lenses will concentrate solar radiations on to the PCM stages. The water in the solar still is also heated using the third Fresnel lens. A brief cost analysis of the entire system will be conducted later.

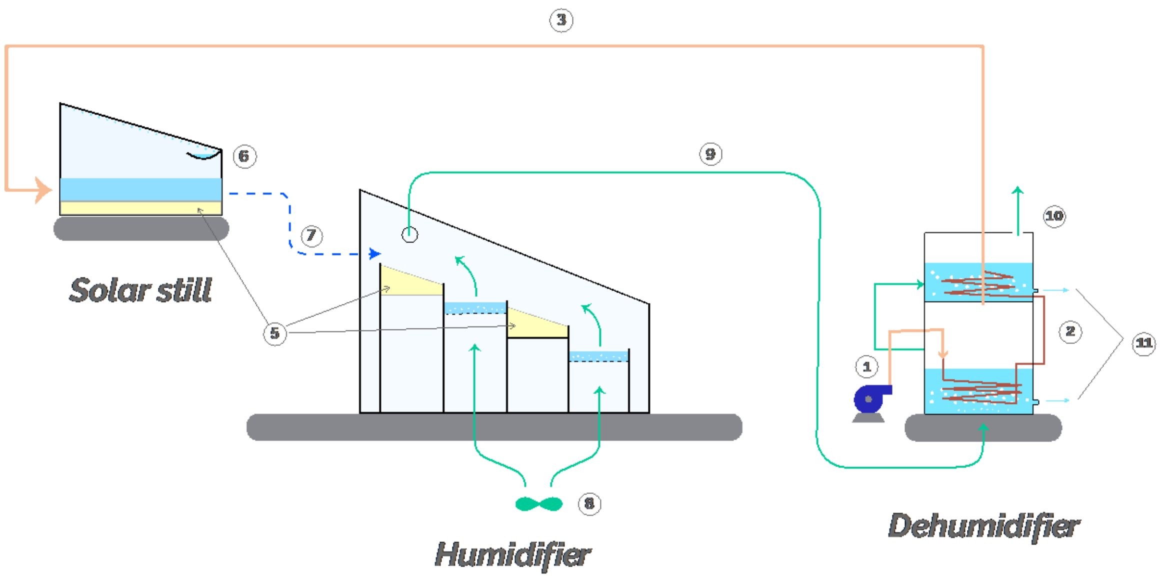

Figure 15: Schematic of real-world implementation of the system.

(1) Seawater pump (2) Seawater coils (3) Preheated water (4) PCM Beds (5) Distillate collection (6) Heated seawater (7) Ambient air blow and inlet distribution system (8) Humid air to dehumidifier (9) Air outlet (10) Fresh water outlet

3.5. Prototype Manufacturing

After the design iterations and calculations regarding the different required parameters at the specified points in the system had been completed, it was time to move on to the actual fabrication of the prototype. Special care was taken in order to cater for the issue faced in the previous prototype. The process started with the survey of markets to determine the availability and pricing of the materials we had chosen to use in our system. For this purpose, the markets of City Saddar Road, Gawalmandi and Marir Chowk and College Road in Rawalpindi were visited and the availability of the components was ensured. The fabrication process in itself went as following:

In the initial phase of the fabrication, the humidifier portion of the system was given preference due to the detailing required and the earlier availability of the material for the humidifier. For this portion, the main frame was to be made up of aluminum and the frame was fabricated before anything else. Special care was taken to keep the angle of the front plain equal to the local latitude angle i.e. 33^o in order to maximize the solar potential of the system.

The next step was the fabrication of the frame for dehumidifier, one of the most important components of the dehumidifier were the circulation coils. This process required certain iterations since the initial coils did not provide the required flow rate and a new set of coils was to be purchased in order to cater for this problem. The dehumidifier frame is essentially a rectangular box divided in tow portions and the effective part in this part is the circulation coils. In this step, both the humidifier and the dehumidifier systems were equipped with wheels at the bottom in order to ease the movement of the equipment that was otherwise too heavy to lift.

Once the metal cutting and framing part was dealt with, the next part of business was the sealing and closing of the frames. For this purpose, the material chosen was acrylic sheets, the purpose of choosing this material was the clarity and aesthetic sense that it brought with it to the system. The cutting and installation of the acrylic sheets was one of the most extensive and expensive processes of the entire project. The sheets once cut were joined with the existing metallic frames using rivets. Rubber seals were used to cut off the major leakage areas. Clearances were left in the humidifier to adjust the instrumentation components that were to be added later, the sealing of the dehumidifier was left for later in order to account for the instrumentation sensors to be added in the component later on.

Once the basic frames had been completed, the next step was to connect the entire system. For this purpose, a certain pipe network that was designed earlier during the iterations for the bubbling mechanisms. The pipe network included a set of pumps, fans and blowers essential for the appropriate movement of air and water throughout the entire system.

The next component for the system was the solar still, and the frame for this was fabricated in a manner similar to the fabrication for humidifier and dehumidifier. The purchasing of PCM, thermocol sheet and a blackened copper plate to cover it was completed. The three components were piled on top of each other with the copper sheet on top and the PCM at bottom.

The final step in the process was the assembly of the entire system. The three main components were assembled using PVC and plastic pipes connected with fans, pumps and blowers. The humidifier was equipped with sponges in order to increase the surface area and thus increase the effective heat and mass transfer. The purchase of immersion heater and power extensions was completed to complete the electrical part of the project.

3.6. Instrumentation

A set of humidity and temperature sensors were used in order to obtain and verify the experimental results of the system performance. These sensors were controlled by microprocessors with each component i.e. humidifier and dehumidifier having its own set of sensors and a microprocessor

DS18B20

The DS18B20 sensor used is essentially a thermistor since its value changes with the change in temperature. This is a waterproofed version of DS18B20. The sensor can work for a range up to 125’C. The sensor uses 1-wire digital protocol. To increase the voltage drop of the signal a pull up resistor of 4.7k is used. It has a Temperature range of -55 to 125°C (-67°F to +257°F). The resolution is around 9 to 12 bit with ±0.5°C.

DHT-22

The sensor consists of a NTC thermistor and an IC on the back. A pull up resistor of 5-10k value is used to keep the communication intact. They use the single wire protocol for transferring data. DHT library take cares of the digital communication. It can give humidity values for 0-100% with 2-5% accuracy. The readings are taken once every two second.

Arduino Uno

Microcontroller used for the data acquisition of sensors was Arduino Uno. The board has 6 analog pins and 14 Digital Pins. It can be powered by a 9-V battery or laptop. Arduino software IDE was used for coding.

16x2 Liquid Crystal Display

A liquid control display is a module for electronic display. These are cheap and easily programmable. LCD crystal display library is used to incorporate this in programming. 16x2 version shows 16 characters in each line.

The experimentation processes and the results are discussed in detail in the following section.

CHAPTER 4: RESULTS AND DISCUSSIONS

The mathematical model was solved in MATLAB and the resulting graphs were plotted in Microsoft Excel. Also, the costs for power requirement in terms of solar panel are also included at the end.

4.1. Parametric Analysis

The effect of the following parameters on the performance of the system was determined. As explained before performance of the system is characterized on the basis of GOR.

4.1.1. Top Temperature (T_{w3}):

The top temperature's effect (T_{w3}) on GOR was observed for different mass flow rate ratios (MR).

The conditions taken were:

- Air inlet temperature to the humidifier; 25º C
- Bottom temperature; 25º C
- Relative humidity at inlet of humidifier; 40%
- Relative humidity at outlet of humidifier; 90%
- Relative humidity at outlet of dehumidifier; 40%
- Dehumidifier Effectiveness; 85%
- Humidifier Effectiveness; 85%

It was observed for a temperature the GOR increases and gets maximum for a certain MR value and then decreases. As the temperature was increased the MR value also increases. Also, for each temperature a curve was obtained which indicated the optimum MR value.

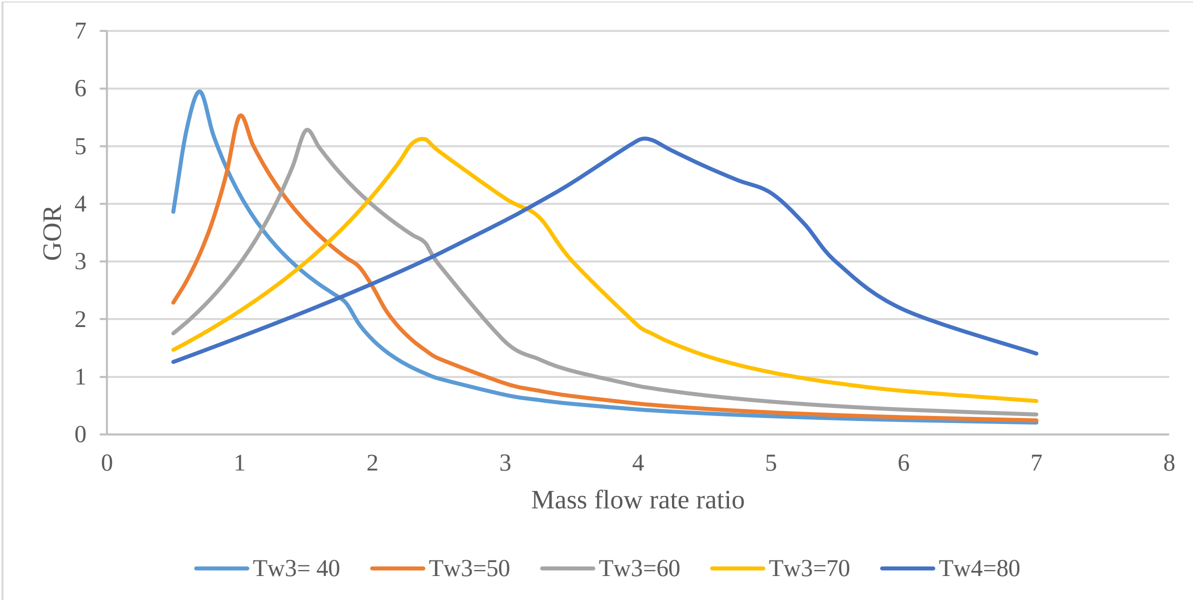

Figure 16: Effect of top temperature on GOR

4.1.2. Inlet Air Temperature (Ta_1)

The air temperature's, at the inlet of humidifier (Ta_1), effect on the Gained output ratio (GOR) was determined for different MR values.

Following conditions were taken for analysis:

- Top temperature; 70º C
- Bottom temperature; 25º C
- Relative humidity at inlet of humidifier; 40%
- Relative humidity at outlet of humidifier; 90%
- Relative humidity at outlet of dehumidifier; 40%
- Dehumidifier Effectiveness; 85%
- Humidifier Effectiveness; 85%

The air inlet temperature was varied from 25º C to 45º C whereas the MR was varied from 1 to 7.

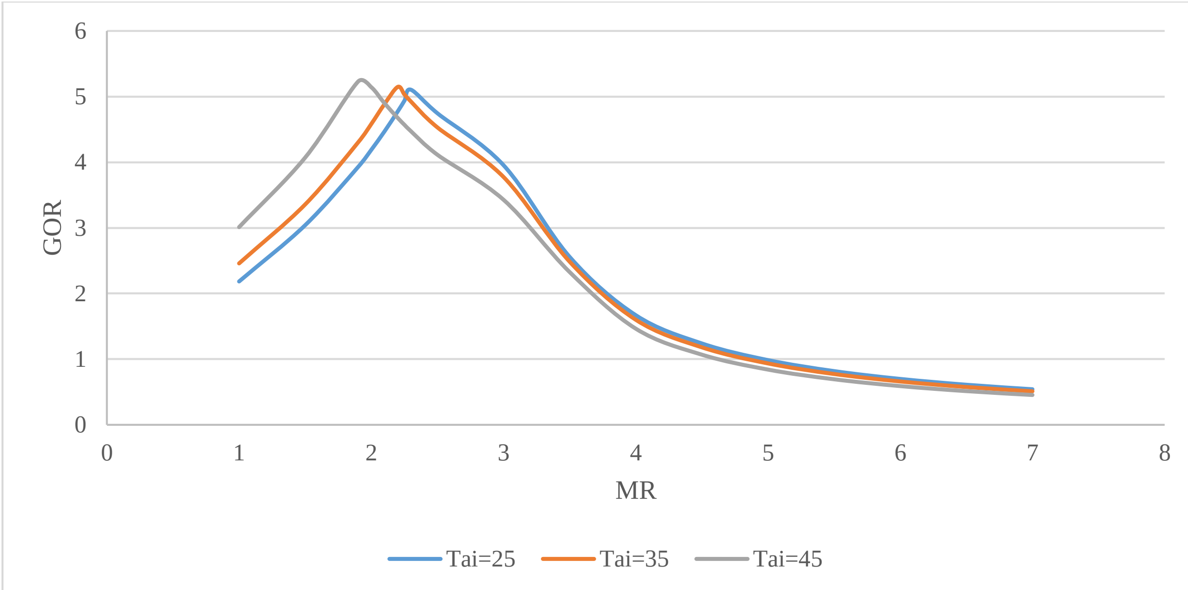

Figure 17: Effect of inlet air temperature on GOR

It was observed that for a particular temperature curve the GOR increases initially obtains a maximum value, corresponding the optimum MR value, and then decreases. Also, as the temperature is increased the MR value decreases. Trend for each air inlet temperature was observed and an optimum MR value was specified. Moreover, as the temperature was increased it was observed that the maximum GOR value increases.

4.1.3. Relative Humidity

To analyze the influence of relative humidity on GOR; air's humidity before (Ø1) and after humidifier (Ø2) and after dehumidifier (Ø3) are studied. Following conditions were taken:

- Top water temperature; 70º C
- Bottom Temperature; 25º C
- Inlet air temperature (T_{a1}); 25º C
- Dehumidifier Effectiveness; 85%
- Humidifier Effectiveness; 85%
- MR value; 4

1. For the effect of relative humidity at the inlet of humidifier (Ø1) was changed from 10% to 90%; while:
    - Ø2= 90%

- Ø3= 40%

2. For the effect of relative humidity of air at the outlet of the humidifier (Ø2) it was changed from 10% to 90% while:
    - Ø1= 40%
    - Ø3= 40%
3. And for the effect of the relative humidity at the outlet of dehumidifier (Ø3) it was changed from 10% to 90% while:
    - Ø1= 40%
    - Ø2= 90%

For above cases their influence on the GOR was determined and the following graph was plotted.

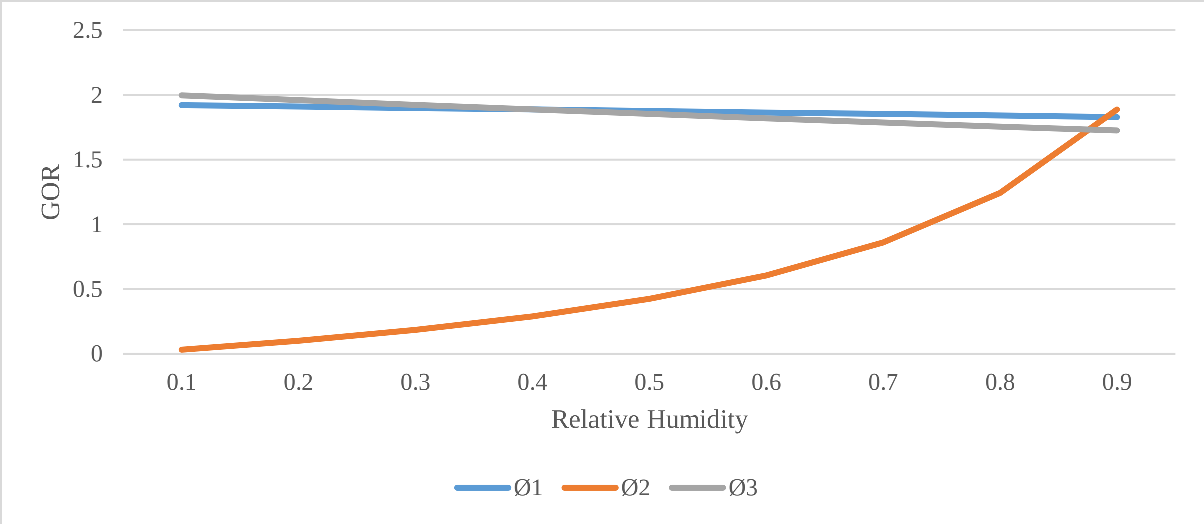

Figure 18: Effect of relative humidity on GOR

It was observed that humidity at the outlet of humidifier (Ø2) has major impact on the GOR; the GOR increases rapidly for higher relative humidity. Also when the relative humidity at the inlet of humidifier (Ø1) and at the outlet of dehumidifier (Ø3) increase the GOR decreases; though the change is small; but it indicate that the must be as small as possible for maximum output.

4.1.4. Humidifier Effectiveness (∈$_h$)

The effect of change of humidifier effectiveness (∈$_h$) on the Gained output ratio (GOR) for different mass flow rate ratios was determined.

Following conditions were taken:

- Air inlet temperature to the humidifier; 25º C
- Top temperature; 70º C
- Bottom temperature; 25º C
- Relative humidity at inlet of humidifier; 40%
- Relative humidity at outlet of humidifier; 90%
- Relative humidity at outlet of dehumidifier; 40%
- Dehumidifier Effectiveness; 85

For each effectiveness (from 50% to 100%) a curve of GOR was obtained at different mass flow rate ratios.

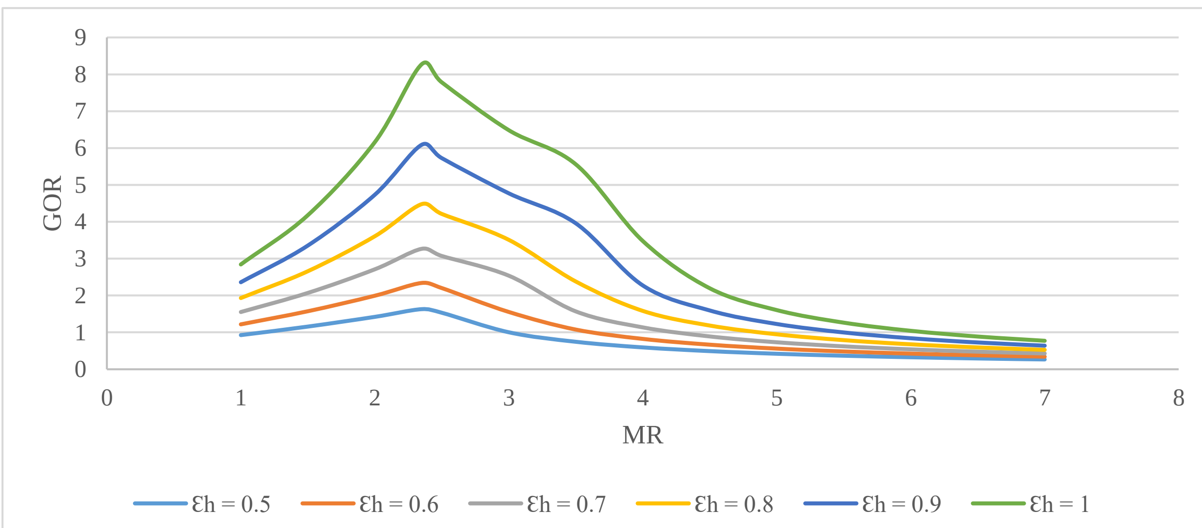

Figure 19: Effect of Humidifier Effectiveness on GOR

It was observed that increasing the humidifier effectiveness the GOR increases. The humidifier effectiveness should be maximum for maximum GOR. It was observed that the GOR peaked for a certain optimum MR value for an effectiveness.

4.1.5. Dehumidifier Effectiveness ($\in_d$)

The effect of change of dehumidifier effectiveness on the Gained output ratio (GOR) for different mass flow rate ratios was determined. Following conditions were taken:

- Air inlet temperature to the humidifier; 25º C
- Top Temperature; 70º C
- Bottom Temperature; 25º C
- Relative humidity at inlet of humidifier; 40%
- Relative humidity at outlet of humidifier; 90%
- Relative humidity at outlet of dehumidifier; 40%
- Humidifier Effectiveness; 85

For each effectiveness (from 50% to 100%) a curve of GOR was obtained at different mass flow rate ratios. It was observed that increasing the dehumidifier effectiveness resulted in increase in GOR. The increase in GOR is more for higher values of effectiveness. Also for each effectiveness the GOR increases initially reached a maximum value and then decreases. Optimum MR Value for each effectiveness was specified from the curve. Hence, the dehumidifier effectiveness influences the performance of the system more than the humidifier effectiveness and should be maximum for the system.

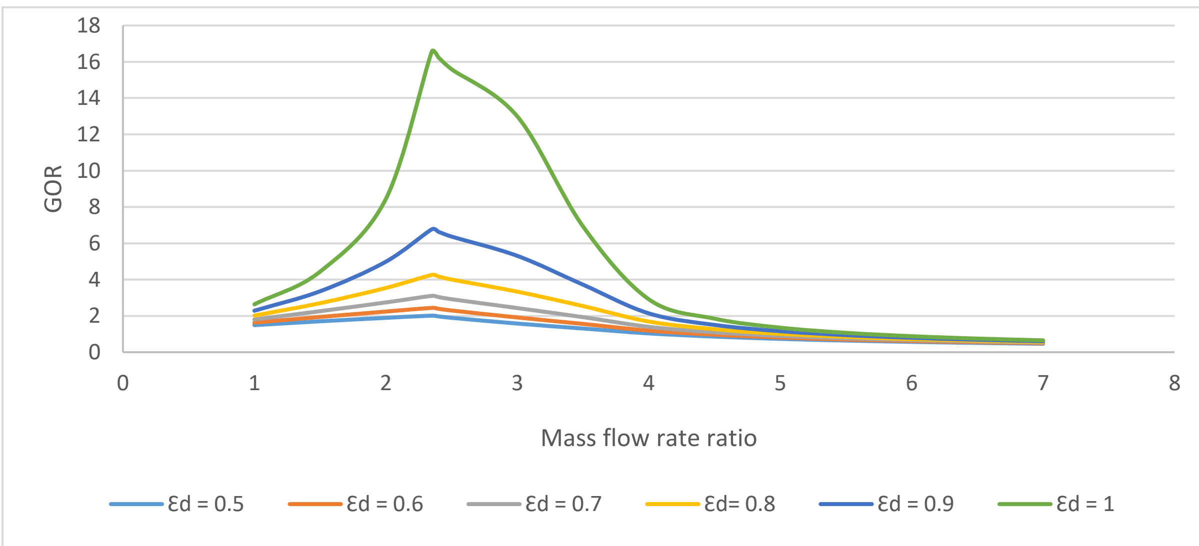

Figure 20: Effect of Dehumidifier Effectiveness on GOR

Table 4: Summary of the parametric analysis

Parameters	Significance	Conclusion
Top Temperature	Increase in the top water temperature results in higher heat and mass transfer and higher GOR. Also increasing the top temperature results in the increase in the MR required for maximum GOR.	It should be higher as possible but the heat input required must also be taken into account.
Inlet Air Temperature	The increase in the air temperature at the inlet of humidifier increases the simultaneous heat transfer and the performance of the system. As the air temperature is increased the MR value decreases for the maximum GOR.	It should be as high as possible. Mostly depends upon the ambient conditions as the cycle used is water heated cycle.
Relative Humidity	The lower relative humidity at the inlet of the humidifier results in greater effectiveness as more water can be absorbed by the air. The higher relative humidity at the outlet of humidifier significantly effects the systems performance as it categorizes the water absorbed in the humidifier. Also it gives the potential for the water to be condensed from the air in the dehumidifier.	At should be higher at the outlet of humidifier as possible. It should be minimum at the inlet of the humidifier.
Effectiveness	The higher effectiveness specifies that the performance of the system is close to the maximum possible. Also the dehumidifier effectiveness effects the system's performance more radically than the humidifier effectiveness which is more or less linear.	The effectiveness of the humidifier and dehumidifier should be maximum. (Multi staging is used to endorse the fact)

4.2. Experimental Results

The prototype developed was investigated for its performance and the results are discussed in this section.

4.2.1. Humidifier

The humidity and air temperature at the outlet of humidifier was observed for different water temperatures. The water column height in the stages is 4 inches. The experiments were performed in April 2019.

The inlet conditions were:

- Air temperature: 29.1 ºC
- Air relative humidity: 42%

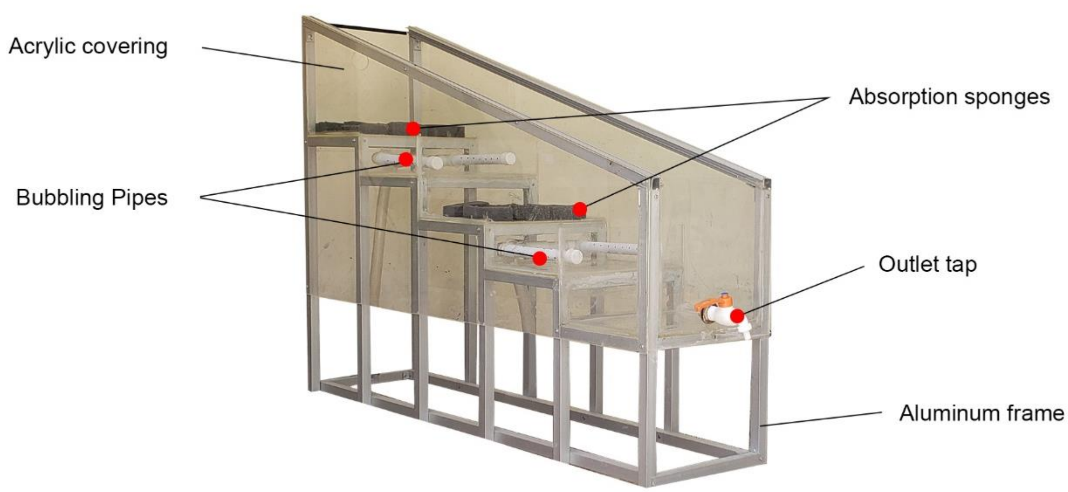

Figure 21 : Humidifier experimental investigation setup

Table 5: Humidifier experimental results

Sr. No.	Water Temperature (ºC)	Air outlet Temperature (ºC)	Air outlet Relative humidity (%)	Air outlet Specific humidity (kg of water/kg of d.a)	Humidification Efficiency (%)
1	51	50	95	0.08316	89.33
2	45	43.5	98	0.05958	87.81
3	40	38.7	99	0.04573	88.23
4	35	33.5	99	0.03376	84.05
5	30	29.8	95.8	0.02598	91.91

The results show that the humidifier effectiveness is good and the humidification efficiency ranges between 85-92%. The temperature range on which experiments were performed can also be obtained through solar heating and thus the system can be used for decentralized and remote areas application.

4.2.2. Dehumidifier

The air from the humidifier is then taken through the dehumidifier stages successively and the dehumidifier performance was observed for the different conditions. The air is passed from the bottom stage and then through the upper stage. The water temperature in both the stages of dehumidifier was:

- Top stage: 27 ºC
- Bottom Stage: 28.5 ºC

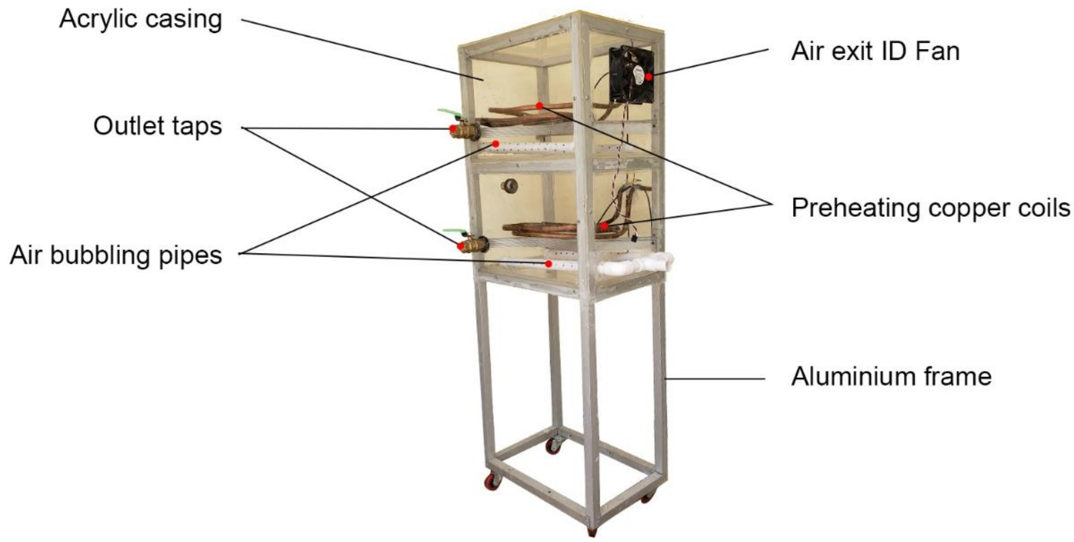

Figure 22: Dehumidifier experimental investigation setup

Table 6: Dehumidifier Experimental Results

Sr. No.	Air inlet temperature (ºC)	Air inlet relative humidity (%)	Air outlet temperature (ºC)	Air outlet relative humidity (%)
1	50	95	28.5	93
2	43.5	98	28.3	89
3	38.7	99	27.6	92
4	33.5	99	28.6	94
5	29.8	95.8	28.7	99

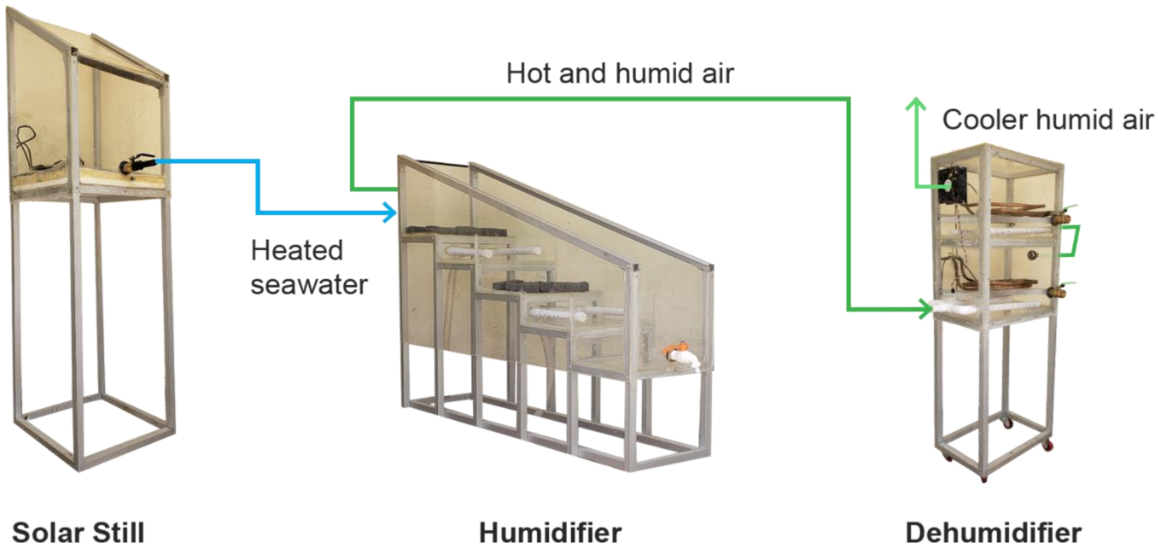

Figure 23: The experimental investigation setup layout

4.2.3. Productivity

To measure the productivity of the system; water temperature in the humidifier was kept at 35 ºC and the air was taken to the dehumidifier at 33.5 ºC and 99% relative humidity. The system was operated for 35 minutes and at the end condensate was measured from the water level rise in both the stages.

For 35 minutes operation 5.25 mm total rise in both columns was observed.

Productivity at 35 ºC for 35 min	= 5.25 mm
Area of dehumidifier=18 in × 12 in - 4 in	= 0.1367 m^2
Condensate produced for 35 min =5.25 × 10^{-3} ×0.1367	= 0.717 × 10^{-3} m^3
Condensate produced per hour = 0.717 × 10^{-3}×60 ÷35	= 1.23 liter/hr
Condensate produced for a day (8 hours)	= 9.84 liter/day

4.2.4. Water Quality Tests

The test of the produced water and their results are shown in the table.

Table 7: TDS and Turbidity tests results

Parameters	Units	Raw	Mineral	Boiled	System Output	WHO Guidelines	Pakistani Water Standards
TDS	Mg/l	17400	360	280	187	<500	<1000
Turbidity	NTU	6.5	0.34	1.11	0.6	<5	<5

The results indicate that the water produced by the system is drinkable and is acceptable by both international and Pakistani guidelines.

4.3. Power requirements and cost analysis

The total power required by the components in the real-world system can be calculated as follows:

Components that require electrical power are:

Table 8: List of components with power required

Qty.	Component	Details	Power Requirement
1	Water Circulation Pump	200 liters per hour	30 W
2	Centrifugal air blower	16000 rpm	400 W
1	ID Fan	10 cm diameter, 1500rpm	3.6W

Therefore, the total power requirement is estimated to be 433.6 W.

The cost breakdown of all the supporting components and solar panels required to generate the electrical power will be as:

Table 9: Cost of the Components

Qty.	Component	Details	Cost/ unit	Cost (PKR)
2	Solar Panels	2x250 W	USD 0.3/W	21000 [50]
1	Water pump	200 l/h	USD 6.2	1100 [51]
2	Centrifugal air blower	16000 rpm	PKR 1500	3000 [52]
1	ID Fans	10 cm dia., 1500 rpm	USD 6/fan	840 [53]
1	Fresnel Lenses	400 mm focal length	USD 25/piece	3500 [54]

Thus, the total expenditure on power and supporting equipment is PKR 29,440.

4.3.1. Techno-economic evaluation

Keeping in view the daily productivity of the system, a techno-economic evaluation was conducted on a manufacturing plant of 5 units, each with a dehumidifier base area of 1 m^2; that used electricity as the main energy source, since the plant setup is not required to be decentralized. All the units utilize solar water heating for the feedwater and have relatively low fixed costs. The overhead costs account for monthly maintenance, labor charges etc. The estimated monthly profit from such a manufacturing plant is around PKR 45,880. Details of this evaluation are as follows:

Table 10: Expenditure of energy on water production

Hourly Production	1.23075
Daily Production (L/m2*day)	36
Energy demand/Productivity	0.186667
Tariff of electricity for less than 100 unit per month	8.11
Total energy cost per litre	1.513867

The economic analysis of the aforementioned desalination plant can be simply stated as:

Table 11: Economic evaluation of desalination plant

No. of years	10
Daily water production	36
Production for full life	108000
Manufacturing cost per litre	0.740741
Energy cost per litre	1.513867
Total cost per litre	2.254607
Maximum possible overheads	10
Commercial cost of 1 litre mineral water	25
Profit for single device	12.74539
Daily profit for production of 5 units	2294.171
Monthly profit	45883.41

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

A comprehensive review of the available literature was performed which gave us an insight into the basic working and comparison of HDH system. From the literature review we concluded that the best approach for the design of an efficient HDH system was to use multi-staging with bubble columns, multi-staging increased the residence time while bubble columns helped in increased time of contact for heat transfer. It was also noted that by adding phase change materials in the system, productivity can be increased to a great extent. Hence, a novel design of two stage stepped humidifier and two-stage dehumidifier with incorporation of PCM in the system was suggested. Using energy balance, mass balance and effectiveness mathematical modeling was performed. To get a clear understanding of which parameters to be optimized, a parametric analysis was then carried out. Graphs were plotted using MATLAB and excel for different configurations from which we can deduce the following:

- When plotted for different humidifier air inlet temperature we observe that the value of GOR increases with the Water/Air inlet mass flow rate ratio, reaches a maximum and then decreases. The MR required for optimum GOR decreases with an increase in the humidifier air inlet temperature.
- For variation in the humidifier water inlet temperature we can observe a similar trend, we can see that GOR increases with increase in humidifier water inlet temperature. Hence for increase in top temperature, the mass flow rate needs to be adjusted accordingly for maximum GOR.
- The GOR when plotted with humidifier air inlet relative humidity as well as dehumidifier exit relative humidity did not show much difference. However, relative humidity of the air at the exit of the humidifier has significant effect on GOR and it must be kept as high as possible.
- It was also observed that when effectiveness of the humidifier or dehumidifier is improved, we see an increase in the GOR which is a predictable result.

The parametric analysis indicated that the water to air mass flow ratio must be in a suitable range and the effectiveness of heat transfer must be as high as possible. In this regard several tests were performed on different bubbling configurations to find the most effective process in increasing heat and mass transfer. Experiments were performed with single unidirectional flow, single two directional flow and divided two directional flow. From the experiments, the divided two directional flow was chosen to be the most effective configuration due to the following reasons:

- It had less splashing than other configurations due to the flow rate division.
- Bubbling occurs uniformly through the entire water column.
- We have higher heat and mass transfer.

The setup included a water circulation pump, air blower and ID fans for which the power requirements were estimated to be 306.6W. The cost of the setup was estimated to be PKR 35,780 (excluding the manufacturing costs).

The developed prototype was tested and its productivity was found to be 9.84 liter/day. The system has great prospect and can be used in decentralized and remote areas application without any grid connectivity.

5.2. Future recommendations

The system can be used with a solar air heater and the heated air can be used in the humidifier which will increase the performance and productivity.

Also, since the air at the outlet of dehumidifier is cold but is almost saturated that can be coupled with the desiccant based system to lower its humidity and can be used as a cooling system in the summer.

REFRENCES

[1] H. Gilbert, "Nature-based solutions for water," UNESCO2018, Available: https://unesdoc.unesco.org/ark:/48223/pf0000261424, Accessed on: 25 January 2019.

[2] Vestergaard, "Waterborne Diseases," 2014.

[3] U. N. Pakistan. (2017, 28 October 2018). *Water Insecurity*. Available: https://www.un.org.pk/water-insecurity/

[4] A. Kaushal and Varun, "Solar stills: A review," *Renewable and Sustainable Energy Reviews,* vol. 14, no. 1, pp. 446-453, 2010/01/01/ 2010.

[5] V. Velmurugan and K. Srithar, "Performance analysis of solar stills based on various factors affecting the productivity—A review," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 2, pp. 1294-1304, 2011/02/01/ 2011.

[6] P. Prakash and V. Velmurugan, "Parameters influencing the productivity of solar stills – A review," *Renewable and Sustainable Energy Reviews,* vol. 49, pp. 585-609, 2015/09/01/ 2015.

[7] M. Al-harahsheh, M. Abu-Arabi, H. Mousa, and Z. Alzghoul, "Solar desalination using solar still enhanced by external solar collector and PCM," *Applied Thermal Engineering,* vol. 128, pp. 1030-1040, 2018/01/05/ 2018.

[8] M. Faegh and M. B. Shafii, "Experimental investigation of a solar still equipped with an external heat storage system using phase change materials and heat pipes," *Desalination,* vol. 409, pp. 128-135, 2017/05/01/ 2017.

[9] A. Giwa, N. Akther, A. A. Housani, S. Haris, and S. W. Hasan, "Recent advances in humidification dehumidification (HDH) desalination processes: Improved designs and productivity," *Renewable and Sustainable Energy Reviews,* vol. 57, pp. 929-944, 2016/05/01/ 2016.

[10] A. Giwa, H. Fath, and S. W. Hasan, "Humidification–dehumidification desalination process driven by photovoltaic thermal energy recovery (PV-HDH) for small-scale sustainable water and power production," *Desalination,* vol. 377, pp. 163-171, 2016/01/01/ 2016.

[11] M. A. Kassim, B. Benhamou, and S. Harmand, "Effect of air humidity at the entrance on heat and mass transfers in a humidifier intended for a desalination system," *Applied Thermal Engineering,* vol. 31, no. 11, pp. 1906-1914, 2011/08/01/ 2011.

[12] M. M. Farid, S. Parekh, J. R. Selman, and S. Al-Hallaj, "Solar desalination with a humidification-dehumidification cycle: mathematical modeling of the unit," *Desalination,* vol. 151, no. 2, pp. 153-164, 2003/01/10/ 2003.

[13] G. Prakash Narayan, J. H. Lienhard, and S. M. Zubair, "Entropy generation minimization of combined heat and mass transfer devices," *International Journal of Thermal Sciences,* vol. 49, no. 10, pp. 2057-2066, 2010/10/01/ 2010.

[14] G. P. Narayan, M. H. Sharqawy, E. K. Summers, J. H. Lienhard, S. M. Zubair, and M. A. Antar, "The potential of solar-driven humidification–dehumidification desalination for small-scale decentralized water production," *Renewable and Sustainable Energy Reviews,* vol. 14, no. 4, pp. 1187-1201, 2010/05/01/ 2010.

[15] S. Al-Hallaj, S. Parekh, M. M. Farid, and J. R. Selman, "Solar desalination with humidification–dehumidification cycle: Review of economics," *Desalination,* vol. 195, no. 1, pp. 169-186, 2006/08/05/ 2006.

[16] G. Yuan and H. Zhang, "Mathematical modeling of a closed circulation solar desalination unit with humidification–dehumidification," *Desalination,* vol. 205, no. 1, pp. 156-162, 2007/02/05/ 2007.

[17] N. A. S. Elminshawy, F. R. Siddiqui, and M. F. Addas, "Experimental and analytical study on productivity augmentation of a novel solar humidification–dehumidification (HDH) system," *Desalination,* vol. 365, pp. 36-45, 2015/06/01/ 2015.

[18] A. M. I. Mohamed and N. A. El-Minshawy, "Theoretical investigation of solar humidification–dehumidification desalination system using parabolic trough concentrators," *Energy Conversion and Management,* vol. 52, no. 10, pp. 3112-3119, 2011/09/01/ 2011.

[19] S. M. Shalaby, M. A. Bek, and A. E. Kabeel, "Design Recommendations for Humidification-dehumidification Solar Water Desalination Systems," *Energy Procedia,* vol. 107, pp. 270-274, 2017/02/01/ 2017.

[20] H. Müller-Holst, M. Engelhardt, M. Herve, and W. Schölkopf, "Solarthermal seawater desalination systems for decentralised use," *Renewable Energy,* vol. 14, no. 1, pp. 311-318, 1998/05/01/ 1998.

[21] S. A. Nada, H. F. Elattar, and A. Fouda, "Performance analysis of proposed hybrid air conditioning and humidification–dehumidification systems for energy saving and water production in hot and dry climatic regions," *Energy Conversion and Management,* vol. 96, pp. 208-227, 2015/05/15/ 2015.

[22] G. P. Narayan, R. K. McGovern, S. M. Zubair, and J. H. Lienhard, "High-temperature-steam-driven, varied-pressure, humidification-dehumidification system coupled with reverse osmosis for energy-efficient seawater desalination," *Energy,* vol. 37, no. 1, pp. 482-493, 2012/01/01/ 2012.

[23] G. C. Pandey, "Effect of dried and forced air bubbling on the partial pressure of water vapour and the performance of solar still," *Solar Energy,* vol. 33, no. 1, pp. 13-18, 1984/01/01/ 1984.

[24] H. Ben Halima, N. Frikha, and S. Gabsi, "Experimental study of a bubble basin intended for water desalination system," *Desalination,* vol. 406, pp. 10-15, 2017/03/16/ 2017.

[25] A. E. Kabeel, M. Abdelgaied, and M. Mahgoub, "The performance of a modified solar still using hot air injection and PCM," *Desalination,* vol. 379, pp. 102-107, 2016/02/01/ 2016.

[26] M. Vlachogiannis, V. Bontozoglou, C. Georgalas, and G. Litinas, "Desalination by mechanical compression of humid air," *Desalination,* vol. 122, no. 1, pp. 35-42, 1999/05/25/ 1999.

[27] O. K. Siddiqui, M. H. Sharqawy, M. A. Antar, and S. M. Zubair, "Performance evaluation of variable pressure humidification-dehumidification systems," *Desalination,* vol. 409, pp. 171-182, 2017/05/01/ 2017.

[28] H. Liu and M. H. Sharqawy, "Experimental performance of bubble column humidifier and dehumidifier under varying pressure," *International Journal of Heat and Mass Transfer,* vol. 93, pp. 934-944, 2016/02/01/ 2016.

[29] H. M. Abd-ur-Rehman and F. A. Al-Sulaiman, "A novel design of a multistage stepped bubble column humidifier for the humidification of air," *Applied Thermal Engineering,* vol. 120, pp. 530-536, 2017/06/25/ 2017.

[30] A. E. Kabeel, A. Khalil, Z. M. Omara, and M. M. Younes, "Theoretical and experimental parametric study of modified stepped solar still," *Desalination,* vol. 289, pp. 12-20, 2012/03/15/ 2012.

[31] H. P. Garg, R. S. Adhikari, and R. Kumar, "Experimental design and computer simulation of multi-effect humidification (MEH)-dehumidification solar distillation," *Desalination,* vol. 153, no. 1, pp. 81-86, 2003/02/10/ 2003.

[32] H. Kang, T. Wang, and H. Zheng, "Comparative analysis of regenerative and air-extraction multi-stage humidification–dehumidification desalination system using pinch technology," *Desalination,* vol. 385, pp. 158-166, 2016/05/02/ 2016.

[33] H. M. Abd-ur-Rehman and F. A. Al-Sulaiman, "An experimental investigation of a novel design air humidifier using direct solar thermal heating," *Energy Conversion and Management,* vol. 127, pp. 667-678, 2016/11/01/ 2016.

[34] G. P. Narayan, M. H. Sharqawy, S. Lam, S. K. Das, and J. H. Lienhard V, "Bubble columns for condensation at high concentrations of noncondensable gas: Heat-transfer model and experiments," *AIChE Journal,* vol. 59, no. 5, pp. 1780-1790, 2013.

[35] S. Lam, "Development of a multi-stage bubble column dehumidifier for application in a hymidification dehumidification desalination system," Mechanical Engineering, Massachusetts Institute of Technology. Dept. of Mechanical Engineering., Massachusetts Institute of Technology, Massachusetts Institute of Technology, 2012.

[36] E. W. Tow and J. H. Lienhard V, "Heat transfer to a horizontal cylinder in a shallow bubble column," *International Journal of Heat and Mass Transfer,* vol. 79, pp. 353-361, 2014/12/01/ 2014.

[37] E. W. Tow and J. H. Lienhard, "Experiments and modeling of bubble column dehumidifier performance," *International Journal of Thermal Sciences,* vol. 80, pp. 65-75, 2014/06/01/ 2014.

[38] E. W. L. Tow, John H., "Heat Flux and Effectiveness in Bubble Colum Dehumidifiers for HDH Desalination," *Proceedings of the IDA World Congress on Desalination and Water Reuse 2013,* 2013.

[39] A. E. Kabeel and M. Abdelgaied, "Improving the performance of solar still by using PCM as a thermal storage medium under Egyptian conditions," *Desalination,* vol. 383, pp. 22-28, 2016/04/01/ 2016.

[40] S. M. Shalaby, E. El-Bialy, and A. A. El-Sebaii, "An experimental investigation of a v-corrugated absorber single-basin solar still using PCM," *Desalination,* vol. 398, pp. 247-255, 2016/11/15/ 2016.

[41] M. Asbik, O. Ansari, A. Bah, N. Zari, A. Mimet, and H. El-Ghetany, "Exergy analysis of solar desalination still combined with heat storage system using phase change material (PCM)," *Desalination,* vol. 381, pp. 26-37, 2016/03/01/ 2016.

[42] A. A. El-Sebaii, A. A. Al-Ghamdi, F. S. Al-Hazmi, and A. S. Faidah, "Thermal performance of a single basin solar still with PCM as a storage medium," *Applied Energy,* vol. 86, no. 7, pp. 1187-1195, 2009/07/01/ 2009.

[43] D. D. Winfred Rufuss, S. Iniyan, L. Suganthi, and D. Pa, "Nanoparticles Enhanced Phase Change Material (NPCM) as Heat Storage in Solar Still Application for Productivity Enhancement," *Energy Procedia*, vol. 141, pp. 45-49, 2017/12/01/ 2017.

[44] L. Sahota and G. N. Tiwari, "Effect of Al2O3 nanoparticles on the performance of passive double slope solar still," *Solar Energy*, vol. 130, pp. 260-272, 2016/06/01/ 2016.

[45] M. H. Sellami, T. Belkis, M. L. Aliouar, S. D. Meddour, H. Bouguettaia, and K. Loudiyi, "Improvement of solar still performance by covering absorber with blackened layers of sponge," *Groundwater for Sustainable Development*, vol. 5, pp. 111-117, 2017/09/01/ 2017.

[46] K. Y. Leong, H. C. Ong, N. H. Amer, M. J. Norazrina, M. S. Risby, and K. Z. Ku Ahmad, "An overview on current application of nanofluids in solar thermal collector and its challenges," *Renewable and Sustainable Energy Reviews,* vol. 53, pp. 1092-1105, 2016/01/01/ 2016.

[47] A. H. Elsheikh, S. W. Sharshir, M. E. Mostafa, F. A. Essa, and M. K. Ahmed Ali, "Applications of nanofluids in solar energy: A review of recent advances," *Renewable and Sustainable Energy Reviews,* vol. 82, pp. 3483-3502, 2018/02/01/ 2018.

[48] G. P. M. Narayan, Karan H; Sharqawy, Mostafa H; Zubair, Syed M; Lienhard, John H, "Energy effectiveness of simultaneous heat and mass exchange devices," *Frontiers in Heat and Mass transfer (FHMT),* 2010.

[49] G. P. Narayan, M. H. Sharqawy, J. H. Lienhard V, and S. M. Zubair, "Thermodynamic analysis of humidification dehumidification desalination cycles," *Desalination and Water Treatment,* vol. 16, no. 1-3, pp. 339-353, 2010/04/01 2010.

[50] S. Shop. *Jinko Solar Panel 250 Watt*. Available: http://solarshop.pk/63-jinko-solar-poly-crystalline-250-watt.html

[51] Amazon. *200 l/h pump- Adjustible Water Flow*. Available: https://www.amazon.com/dp/B07DCDFCV5/ref=sspa_dk_detail_0?psc=1

[52] M. i. China. *Air blower*. Available: https://zjkelong.en.made-in-china.com/product/oXDmifeUbghs/China-110V-Ablower-Function-with-Cheap-Price-HER-7025B-.html

[53] Ebay. *Cooling Fan*. Available: https://www.ebay.com/itm/Mute-Quiet-5V-0-2A-1500rpm-120mm-120x120x25mm-12cm-Brushless-Case-Cooling-Fan/272046462326?hash=item3f573b9576:g:Yo4AAOSwwTlUm61b

[54] A. Express. *Fresnel Lens*. Available: https://www.aliexpress.com/store/product/1pcs-lot-big-size-400-300MM-Rectangle-DIY-projector-Fresnel-Lens-Focal-length-500-mm-High/213760_32622604016.html?spm=2114.12010612.8148356.2.4ad474abVfLZ1s