A Solar Driven Decentralized Small Scale Water Purification System for Remote Communities

By

Salim Akhtar

Reg. No.: 00000330250

Session 2020-22

Supervised by

Dr. Sehar Shakir

U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E)

National University of Sciences and Technology (NUST)

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National University of Sciences and Technology (NUST)

H-12, Islamabad 44000, Pakistan

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THESIS ACCEPTANCE CERTIFICATE

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Signature: ____________________________

Name of Supervisor: Dr. Sehar Shakir

Date: ____________________________

Signature (HoD): ____________________________

Date: ____________________________

Signature (Dean/Principle): ____________________

Date: ____________________________

Certificate

This is to certify that the work in this thesis has been carried out by **Mr. Salim Akhtar** and completed under my supervision in Thermal Engineering Laboratory, U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology, H-12, Islamabad, Pakistan.

Supervisor:

____
Dr. Sehar Shakir
USPCAS-E
NUST, Islamabad

GEC member # 1

____
Prof. Dr. Adeel Waqas
USPCAS-E
NUST, Islamabad

GEC member # 2:

____
Dr. Majid Ali
USPCAS-E
NUST, Islamabad

GEC member # 3:

____
Dr. Sana Yaqub
USPCAS-E
NUST, Islamabad

HoD-ESE:

____
Dr. Rabia Liaquat
USPCAS-E
NUST, Islamabad

Dean/Principal:

____
Prof. Dr. Adeel Waqas
USPCAS-E
NUST, Islamabad

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Dedication

To my brave and beloved mother who embraced martyrdom while protecting her loved ones.

Abstract

In decentralized areas with modest quantum fresh water needs, the bubble column (BC) humidification dehumidification (HDH) desalination systems are attributed to have excellent outcomes. The current work comprises of a bubble column humidifier to raise the humidity level in the air and a bubble column dehumidifier to remove moisture from the air once it has been humidified. The solar thermal water heater, a sustainable energy source, supplied the thermal energy needed for the HDH system's operations. A nanofluid based flat plate solar water heater, which has a considerably greater thermal efficiency than the traditional surface absorption-based solar thermal collector, was used to heat the saline water. Titanium dioxide (TiO_2) along with the deionized water is mixed in weight percentage to make the nanofluid with Polyvinyl alcohol (PVA) utilized as a surfactant. The results illustrates that the hourly fresh water productivity is inversely connected with bubble generation hole diameter whereas it is directly correlated with the temperature of water, water height in the column, and mass flow rate of air . The system's best experimental yield was recorded to be 0.75 L/d for a saline water temperature of 60°C, 0.005 kg/s mass flow rate of air, diameter of bubble producing hole of 2.5 mm, 40 °C of air temperature, and a water height in the BC of 7.5 cm in humidifier. The hourly fresh water productivity ranged from 0.4 to 0.75 L/h throughout the investigation. For 0.005 kg/s mass flow rate of air, the system had a GOR of 0.5. The effectiveness of the system was recorded to be 0.79. The cost per liter of water productivity is merely $ 0.0334, with a system's payback period of 1.3 years

Keywords: *Bubble column (BC), Humidification dehumidification (HDH), Nanofluid, Solar water heater, Gain output ratio (GOR), Titanium dioxide (TiO_2)*

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Salim Akhtar, Hafiz M. Abd-ur-Rehman, Majid Ali, Adeel Waqas, Sana Yaqub, Sehar Shakir, **“Clean water production using bubble column humidification-dehumidification water purification system coupled with a nanofluid based solar thermal water heater”** Applied Thermal Engineering, 6 April 2023 (Under Review)

Abbreviations

Nomenclature

HDH	Humidification Dehumidification
$\dot{m}$	Mass flow rate (kg/s)
h	Enthalpy (kJ/kg)
$\dot{Q}$	Energy input (kW)
GOR	Gain output Ratio
BC	Bubble column
RR	Recovery ratio
SEC	Specific Energy Consumption
SWH	Solar Water Heater
T	Temperature
h_{fg}	Enthalpy of vaporization of water (kJ/kg)
TiO_2	Titanium dioxide
U	Uncertainty
a	Accuracy
C_{PL}	Cost per liter
SV	Salvage Value
YSV	Yearly Salvage Value
CRF	Capital Recovery Factor
A_C	First annual capital cost
C_C	Capital cost
C_M	Annual maintenance cost
C_{MP}	Average local market price
S_{ff}	Sinking fund factor
W_Y	Yearly fresh water productivity
W_D	Daily fresh water productivity
C_{PD}	Cost of daily fresh water production
r	Interest rate yearly
y	Number of years
t	Time

C_p	Specific heat capacity (kJ/kg-K)
I_s	Sun light intensity
x	Height
A	Area

Greek

ε	Effectiveness
ω	Humidity Ratio
ϕ	Relative Humidity

Subscript

a	Air
p	fresh water
w	Feed water
br	Brine
H	Humidifier
DH	Dehumidifier
i	Specific Component
in	Into the system
out	Out of the system

Chapter 1 : Introduction

1.1 Water Crisis

Water is a versatile matter naturally which is found in all three phases i.e. solid, liquid or gas. From the global water data approximately 97% of global water is salty or brackish which is found in the oceans, while 3% is fresh. In the 3 % margin 2.5% of fresh water is concentrated in glaciers and ice caps while 0.5 % fresh and portable water on the earth's surface [1]. With the escalating world population explosion, the demand and consumption of water is rapidly increasing for both domestic and industrial use. Fresh water is essential for animals and human life. Due to the rapid expansion in the human population around the globe the demand for fresh portable water is also shooting up. Many areas around the world are facing intense shortage of fresh water. Human contamination and the degradation of natural water sources are two of the key causes of the global freshwater shortage. A major problem is the lack of fresh water in many parts of the world. According to World Health organization (WHO) 1 in every 3 people lacks access to fresh portable safe water. Furthermore, around 2/3rd of the global population would face acute scarcity of water at least once a year [2]. The scarcity of fresh water has effect on some 2.4 billion individuals around the globe who are at risk of contracting diseases including diarrhea, typhoid fever, cholera and other water-borne ailments [3]. Globally, 2 billion people consume water that has fecal matter contamination, according to a recent WHO research. An estimated 829,000 individuals die from diarrhea every year as a result of consuming tainted drinking water and below the line hygiene [4]. These numbers mainly directs at the developing counties in Asia and Africa. A global risk report of World Economic Forum has highlighted the water crisis as the number 5th global risk which impacts the social life of humans [5]. Global water demand is shooting at a rate of 1% annually and is expected to do so till 2050. By 2050 the demand will be 55% more as compare to 2000 due to excessive demands of both domestic and industrial sectors [6]. The whole world generally and the third world countries specifically will face severe fresh water shortages in the decades ahead. Poor communities and remote, decentralized, far-flung places have very limited access to clean, freshwater for everyday requirements. Therefore, it is crucial to offer a low-cost, mobile, dependable, and effective desalination system that promotes the growth of those remote, isolated settlements and benefits society as a whole. The solutions to the problems of water scarcity and pollution are desalination, purification of water, and water recovery/reuse. To meet the ever increasing requirements of fresh water, the desalination of salty or brackish water is essential.

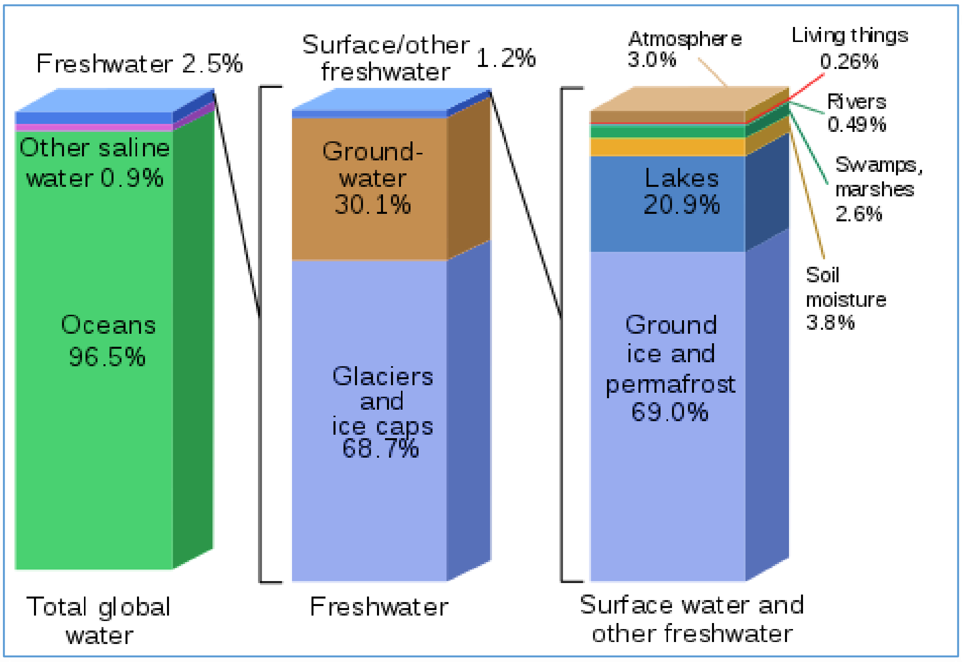

Figure 1.1 The percentage distribution of water on the planet earth [1]

1.2 Water Desalination

The WHO maintains that the acceptable limit of salinity in water should be less than 0.5 parts per thousand (ppt), even though sea or brackish water usually has a salinity in the range of 30-500 ppt, which is greater than most water on Earth's surface [7]. Taste, digestion, and gastrointestinal effects are all negatively impacted by excessive brackishness. Desalination methods may now be utilized with confidence to desalinate saltwater and brackish water from saline aquifers and rivers thanks to ongoing advancements, notably in the last decade. Several procedures can be adopted to perform the process of water purification and desalination.

The traditional methods, such as MSF, ME, VC, and RO, are only effective at producing huge amounts of fresh water, between 100 to 50,000 m^3/day [8]. For desalination procedures to successfully separate salts from seawater, a sizable amount of energy is needed. Moreover, these processes are pricey for little quantities of fresh water, and they cannot be employed in areas with insufficient maintenance facilities or energy sources.

Additionally, utilizing conventional energy from fossil fuel sources to power these desalination technologies has negative environmental implications. Environmental pollution would thus be of considerable worry and be of the highest significance in addition to fulfilling the growing energy demand.

For both small-scale and industrial uses, a number of water desalination methods have been developed. More long-term, dependable desalination techniques for generating freshwater have been sought after in recent years. HDH desalination systems are a flexible and sustainable solution to the problem of freshwater shortage since the heat energy input may come from a variety of sources, including biomass, solar, geothermal, wind, waste heat, and others. These inherent qualities make the HDH desalination system economical and environmentally benign, particularly in arid and semi-arid environments, and so these small-scale water purification and desalination units are appropriate for outlying decentralized areas and small villages.

1.2.1 Desalination Types

Numerous desalination methods exist, and the most of them are reliable and utilized both in the domestic and industrial sector. The two major process categories for the water desalination are the thermal and membrane processes as shown in the figure 1.2.

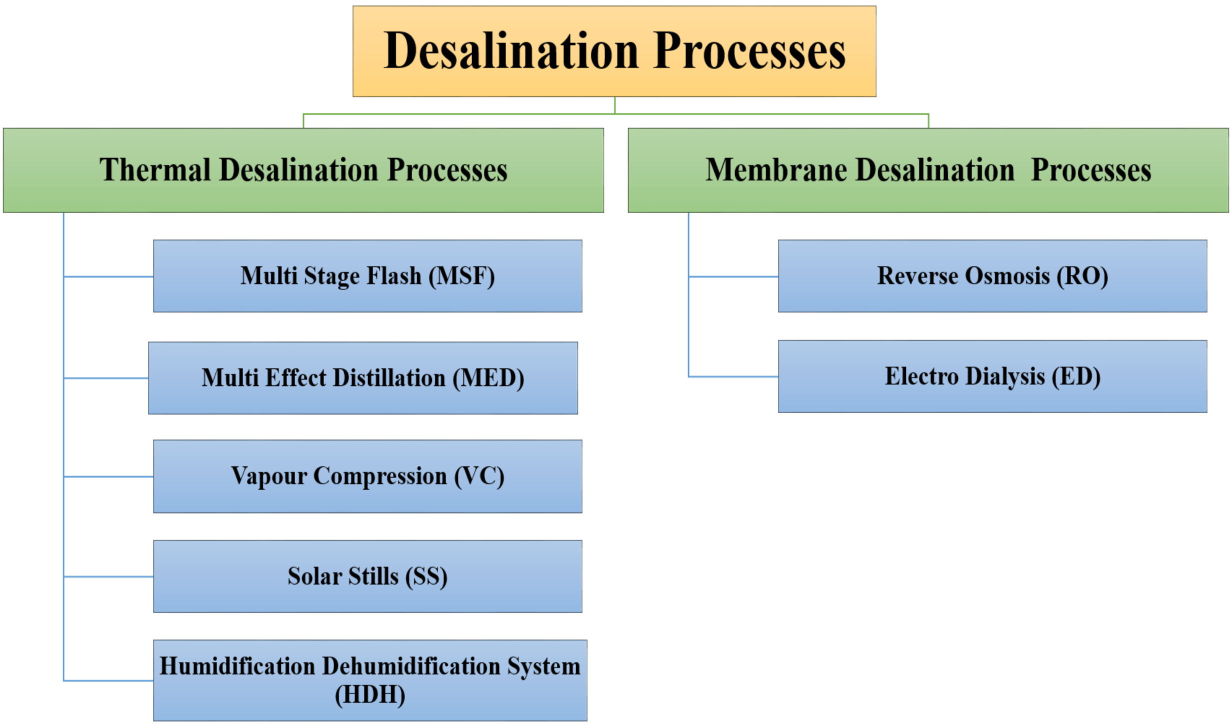

Figure 1.2 Desalination categories and sub categories

The conventional thermal method frequently uses heat transfer and is based on methods for natural distillation. Multiple Effect Distillation (MED), Vapour Compression (VC), Multi

Stage Flash Desalination (MSF), Solar Stills (SS), and Humidification Dehumidification (HDH) are a few examples of the various types of thermal processes. The second type of desalination process relies totally on electricity and is based on membrane filtering. Both Electro-dialysis (ED) and Reverse Osmosis (RO) are significant membrane-based technologies. Due to the difference in water vapour content in the air stream, SS and HDH processes may operate at low temperatures, which distinguishes them significantly from the processes previously mentioned..

1.2.2 Membrane Technologies

It is believed that membrane technologies mimic the actions of biological membranes. Semi-permeable membranes are used in membrane technologies, which trap salt and other pollutants while allowing water molecules to flow through. Prior to the introduction of membrane types, the use of this method was limited to the treatment of urban water, but it has since been expanded to various fields and applications.

1.2.2.1 Reverse Osmosis (RO)

Through semi-permeable membranes under high pressure, reverse osmosis extracts fresh water, leaving behind a highly concentrated brine solution. One of the most effective techniques for producing water production in large quantities is reverse osmosis (RO), however these systems need intensive pre-treatment of saline water [9]. They become pricey as a result, making them unsuitable for small-scale feed water treatment [10].

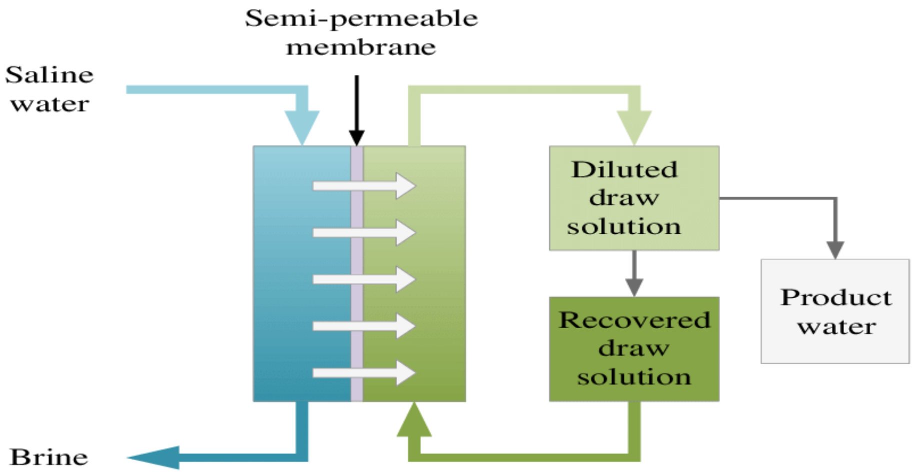

Figure 1.3 Process diagram for RO desalination [11]

Furthermore, since significant pressure must be applied in reverse osmosis in order to overcome the osmotic pressure, expensive and delicate pumps are needed [9]. Therefore, using these devices for saltwater desalination in isolated and rural areas where small-scale output is needed is neither economical nor appropriate.

1.2.2.2 Electro-Dialysis (ED)

During electro-dialysis, salts are selectively transported across a membrane with the aid of an electrical potential, leaving only clean water behind. More electricity is required for ED because to increased feed water salinity, increasing its cost and costs. However, there are very few industrial uses for electro-dialysis [12]. Furthermore, due to the nature of the voltage that must be supplied, electro-dialysis is more energy-expensive than RO and is useless for cleaning saltwater with a high salt concentration. This process works well on liquids with low salt concentrations, such brackish water.

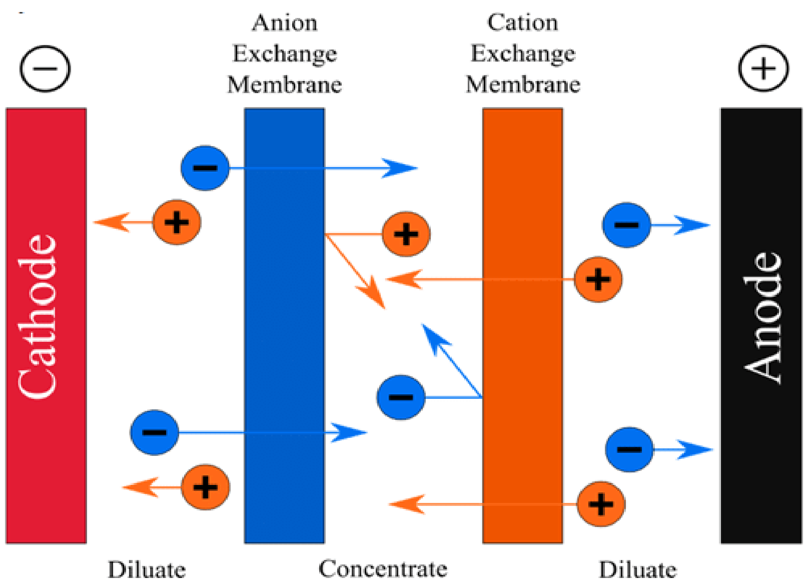

Figure 1.4 Diagram illustrating how electro-dialysis (ED) works

1.2.3 Thermal Desalination

The phase change theory is the foundation for thermal process of water desalination, which involves heating water to encourage evaporation. Condensation happens when the water vapour's latent heat of condensation is released. The condensate is drinkable portable fresh water. The need for a massive bulk of energy to accommodate the phase shift from liquid to vapour is the main issue with thermal technique.

1.2.3.1 Multiple-Effect Distillation (MED)

The pioneer and most earliest desalination technique is the MED process [13]. It is also the most thermodynamically productive effective method for desalination [14]. The MED method makes use of the idea of lowering the ambient pressure in a sequence of evaporators known as effects. This method enables repeated boiling of the seawater supply without the need for extra heat beyond the initial impact. After being warmed in tubes, the saltwater enters the first effect and is brought to boiling point. To encourage quick evaporation, salty water is sprayed over the surface of the evaporator tubes. A power plant that typically does two jobs supplies steam that is used to heat the tubes. In a power plant, the condensate from steam condensing on the other side of the tubes is recycled as boiler feed water.

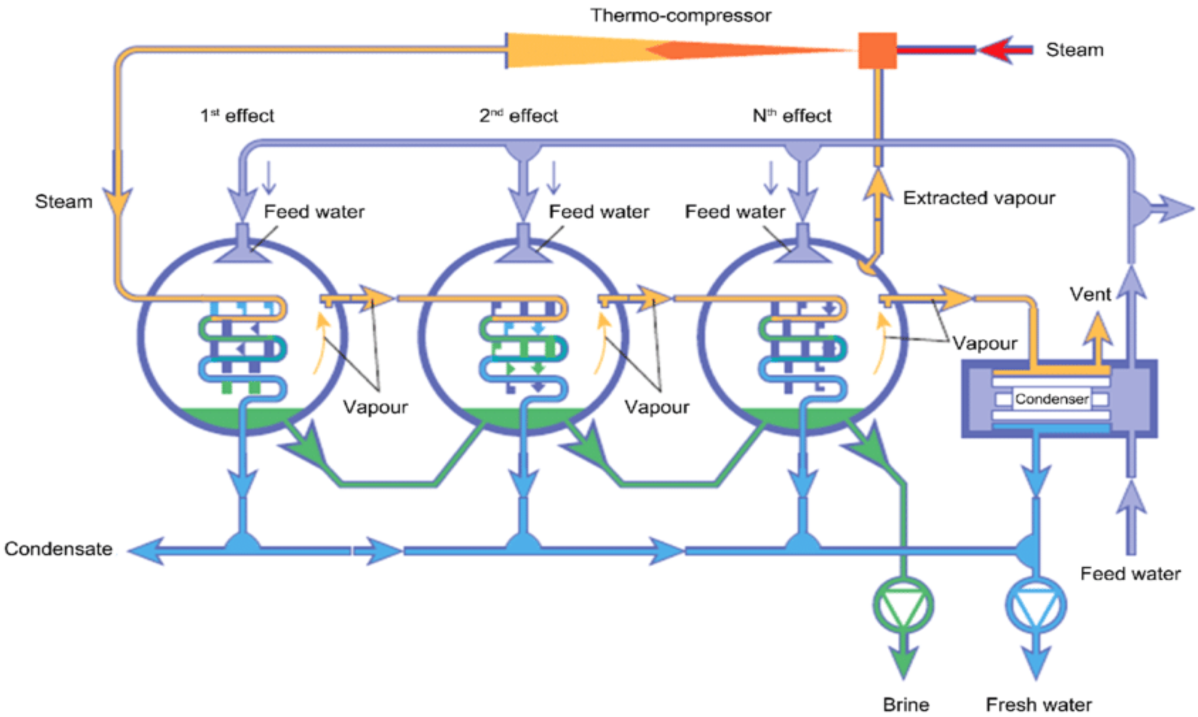

Figure 1.5 MED desalination method illustrated [15]

1.2.3.2 Multi-Stage Flash (MSF)

The concept of flash evaporation serves as the foundation for the MSF method for water desalination shown in figure 1.6 [16]. Saline water is heated and pressured in the brine heater before going into chambers. Some of it flashes into vapour as a result of the chamber's lower pressure, but the brine keeps going through the phases and flashing repeatedly without creating more heat. Flashing generates a vapour, which is then condensed on heat exchanger tubes on each cycle to provide fresh water. The temperature of the entering saltwater steadily rises due to the heat of condensation that is emitted at each step by the condensing water vapour [17].

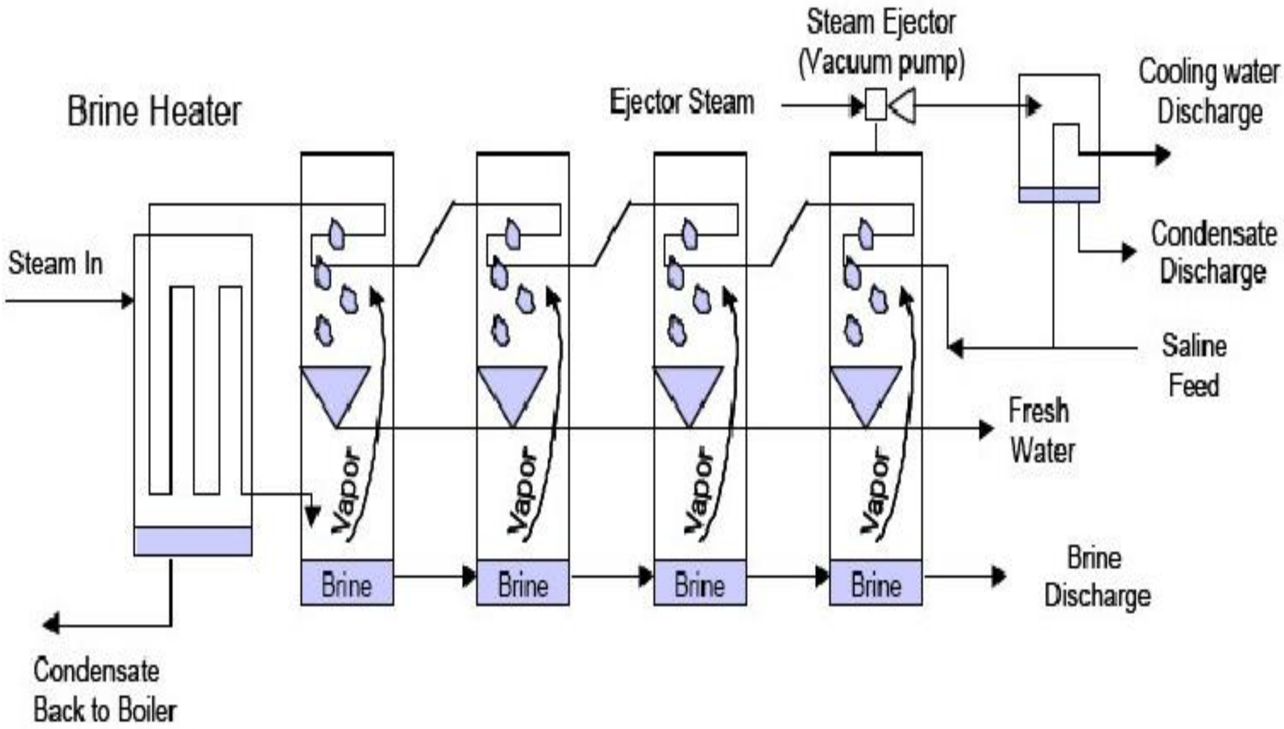

Figure 1.6 A simple MSF desalination process [16]

1.2.3.3 Vapour-Compression (VC)

The preferred technique for thermal distillation is Vapour-Compression (VC) Desalination. The vapour compressor pressurizes the evaporator's incoming vapour by using the heat-pump mechanism [18]. This compressed vapour, which has a higher condensation temperature, transmits its energy to the brine inside the evaporator before condensing to produce the distillate. The VC unit is portable, small, and kind to plants [19]. Therefore, it can deliver freshwater to isolated locations that need it. Additionally, the pre-treatment process is simpler, and high-quality water is produced. The sequence of process in VC is depicted in the figure 1.7.

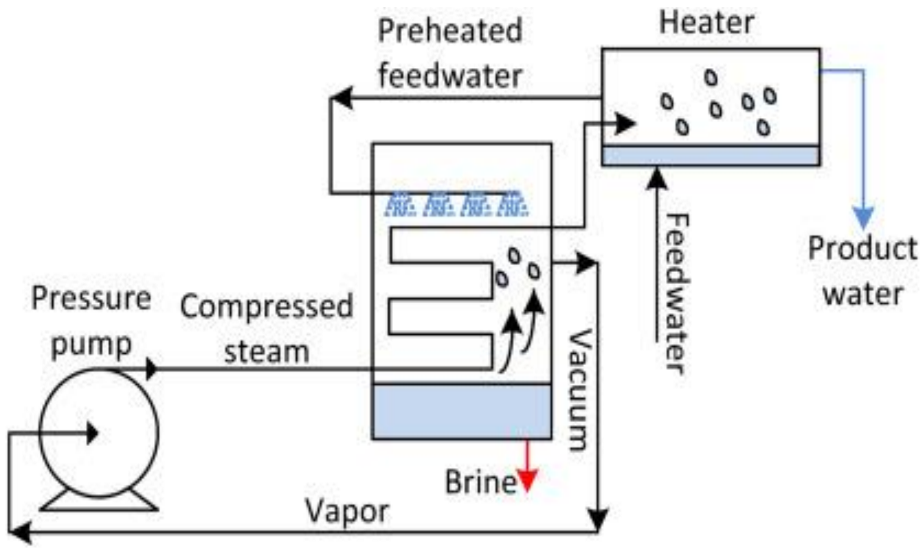

Figure 1.7 Typical vapour compression desalination process schematic [20]

1.3 Limitation of Traditional Methods

Large quantities of energy are needed for traditional procedures like MSF, MED, and RO. This energy might be thermal or electric. The majority of these systems' desalination facilities run on fossil fuels. As a result, the desalination plant has a significant carbon footprint and is sensitive to changes in the price and supply of oil. Desalination solutions based on renewable energy are widely desired to prevent these problems. The reliance on fossil fuels in traditional methods makes them less efficient for producing water from a distance. For areas without the necessary infrastructural, financial, and economic resources to operate big MSF, MED, or RO plants and that are sufficiently removed from large-scale production facilities that pipeline distribution is expensive, small-scale decentralized water production is crucial. In areas with a high incidence of solar radiation, several such locations can be identified. Peter-Varbanets et.al addressed the significance of decentralizing water supply in great length [21]. For applications requiring water production on a small scale, between 5 and 100 m^3 per day, small-scale water production systems are significantly more costly than those used for large-scale applications. Since, membrane processes such as RO are in essence the most cost-effective method, they can be more expensive for facilities with smaller capacity, with an average cost of $3/$m^3$ or more to produce waters [21]. Additionally, skilled individuals are needed for both process operation and maintenance on RO systems. This is a blatant drawback, especially when compared to the HDH system, which is more suitable for small-scale applications in less developed regions and the operations require less skilled persons.

1.4 Solar Assisted Desalination

Fossil fuels are commonly used in the majority of the world's desalination plants today to provide electrical energy for membrane technologies and heat energy for thermal operations, but they are frequently expensive and unsustainable from an environmental standpoint [45]. It would appear to be economical and ecologically responsible to develop a systems that can be powered by sources of suitable renewable sources . The apparent answer to both water scarcity and pollution in such regions is to use solar energy to generate the necessary electricity, as water shortages are typically observed in arid and isolated areas that are rich in solar energy. All other forms of energy are derived from solar energy, which is the main energy source on planet. Several research have examined the integration and utilizations of solar energy for various desalination processes. The majority of the thermal and membrane techniques described in the section above require large bulk form of energy sources, making them unsuitable for use with solar energy. The two types of solar desalination are direct and indirect. The solar energy collection and desalination unit is a key component of the direct techniques because. In the indirect method, initially the solar energy is transform into useable heat or electricity and afterwards used as a source of power for the apparatus to carry out the necessary water desalination.

1.4.1 Solar Still (SS)

The simplest sun-aided desalination technique is probably a solar still (ST), as seen in Figure 1.8 [22]. This technique combines heat absorption with water distillation in a single chamber.

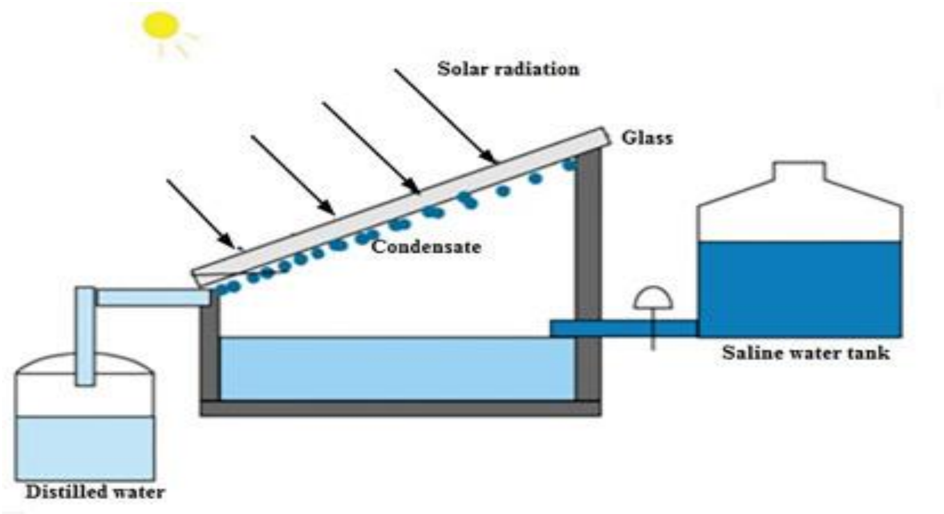

Figure 1.8 Depiction of solar still [22]

With this method, heat absorption and water distillation are combined in a single chamber. Condensation happens as a result of the water vapour that has built up as a result of solar irradiation rising to the transparent cover when heat is passed to the surrounding environment. The condensate trickles down and may be collected from the bottom side of the glass cover because of its slope. These devices release latent heat into the environment as a result of condensation on the transparent cover. As a direct technique of desalination, solar stills are also classed as having poor performance due to direct heating that raises the temperature of the glass condensing surface [23]. The yield of these systems is thus somewhat low.

1.4.2 Solar Assisted Humidification-Dehumidification (HDH)

Despite the fact that the HDH method of desalination is founded on the same principles as solar stills, in principle the three processes' heating, humidification, and dehumidification take place in distinct components, allowing for autonomous design [24]. HDH systems can therefore use a variety of different configurations [25]. The HDH desalination method removes the drawbacks of direct heating by employing a heater (solar). A HDH desalination system's block diagram is seen in Figure 1.9. If any of these components performed better, the system as a whole would perform better.

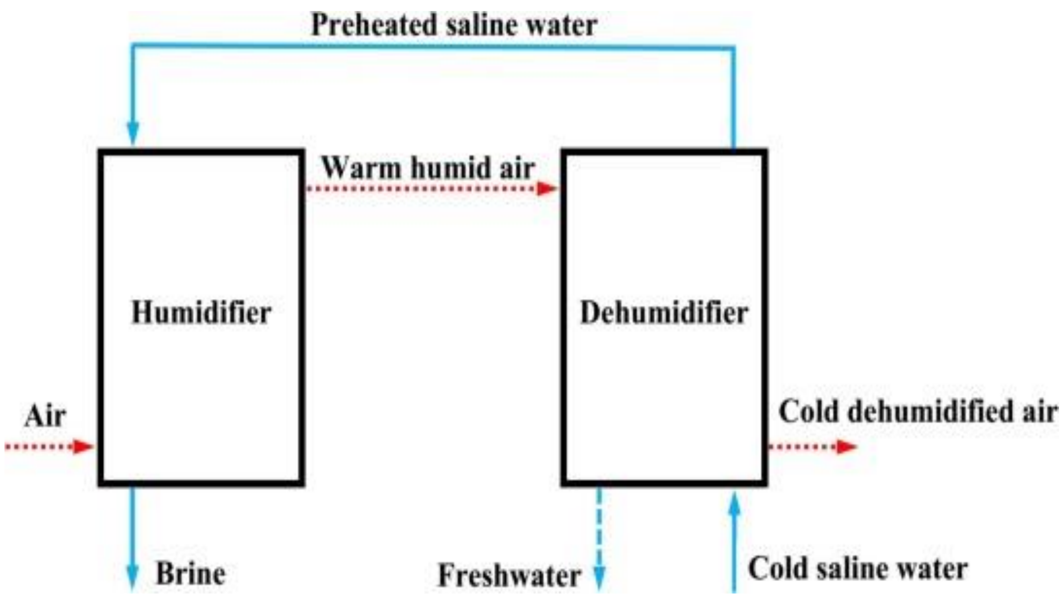

Figure 1.9 Simple HDH process schematic [25]

When ambient air reaches the humidifier, it mixes with the hot water coming in and heats up and becomes humid. After that, hot, humid air enters the dehumidifier via indirect contact heat exchanger. When hot, humid air reaches its due point temperature, which is higher than the temperature of saltwater entering a dehumidifier, the air starts to dry out. While its exhaust valves expel cool, damp air, the dehumidifier's bottom accumulates fresh water.

1.5 Research Statement

The existing literature on BC HDH depicts that the Bubble column's performance as a BC humidifier or as a BC dehumidifier were examined individually. To enhance the thermal performance and productivity, it is necessary to investigate the potential of novel HDH configuration that combines all three components: BC humidifier, BC de-humidifier and nano fluid based solar water heater. Moreover, using nanofluids in HDH systems is a largely untapped field of study. This study attempts to fill this research gap and to assess performance of the anticipated HDH setup.

1.6 Research Objectives

1. To develop a prototype of solar bubble column HDH water desalination system.
2. To study the effects on productivity of the system by incorporating a nanofluid based solar water heater with the HDH System.
3. To perform the technical and cost calculations of the system.

1.7 Limitations

1. It is a lab scale prototype so can’t be used for the massive production
2. The system operates more efficiently during daylight hours in a clear climate with sunshine.
3. All system operations are predicated on the assumption that all system components function under steady state circumstances and conditions.
4. The environment's heat loss via humidifiers and dehumidifiers has been ignored and unreported.
5. Pumping power for both air and water is ignored since feed water requires significantly more heating than freshwater does.

1.8 Scope

1. The proposed system will be will assist to reduce the likelihood of a portable fresh water scarcity in outlying decentralized communities.
2. A more evolved water purification system that is special in that it can operate independently and off the grid, allowing it to be installed in distant places without access to electricity.

3. The outcomes of the intended project will serve as valuable resource for academics and engineers working on water purification and desalination systems, air conditioning, and humidification systems for greenhouses.
4. Balancing the need for portable drinkable water with renewable energy.
5. Fresh water productivity at low capital, operations and maintenance costs.

1.9 Flow of thesis

- Chapter 2 discusses the literature review of bubble column HDH systems and nanofluid-based solar collectors.
- Chapter 3 describes the proposed setup, the methodology for the intended system, and the governing equations for the resolution of the integrated system performance analysis.
- Chapter 4 addresses the results and findings, their analysis, and discussions in relation to them.
- Chapter 5 contains the summary of findings, the conclusion, future recommendations and suggestions for more research.

Summary

The worldwide water issue, where demand and use of water are rising quickly owing to the expanding global population, is discussed in this section of the thesis. Freshwater is necessary for both animal and human life, however just 3% of the water on Earth is fresh, and many regions of the globe are currently experiencing severe freshwater shortages as a consequence of pollution and the deterioration of natural water supplies. The problems of water shortage and pollution can be solved via desalination, water purification, and water recovery/reuse. Desalination is a procedure that cleans salty water of salt and other minerals, allowing for its use in agriculture and as drinking water. Thermal and membrane procedures are the two main process types for desalinating water. While traditional desalination techniques are efficient at creating large volumes of fresh water, they are expensive and energy-intensive for producing tiny amounts of freshwater. The objective is to develop a low-cost, portable, dependable, and efficient desalination system that may encourage the expansion of remote, isolated communities and benefit society as a whole in order to solve this rising challenge. The strategy entails utilizing a solar-powered, environmentally friendly water purification system that can provide fresh water from brackish or saltwater sources. Our technology is economical and ecologically sustainable since it makes use of the sun's plentiful energy, making it the perfect answer for outlying and decentralized communities with little access to clean and safe freshwater.

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Chapter 2 : Literature Review

2.1 Background

A thermal desalination technique called humidification-dehumidification (HDH) replicates the rain cycle in nature. As seen in the illustration below (figure 2.1), the heat from the sun's rays causes the air to become more humid by causing terrestrial water to evaporate. Moving to higher altitudes, this humid air creates clouds that later precipitate in a pure form, such as rain, snow, or other forms. HDH desalination systems use a similar procedure (figure 2.2) [1].

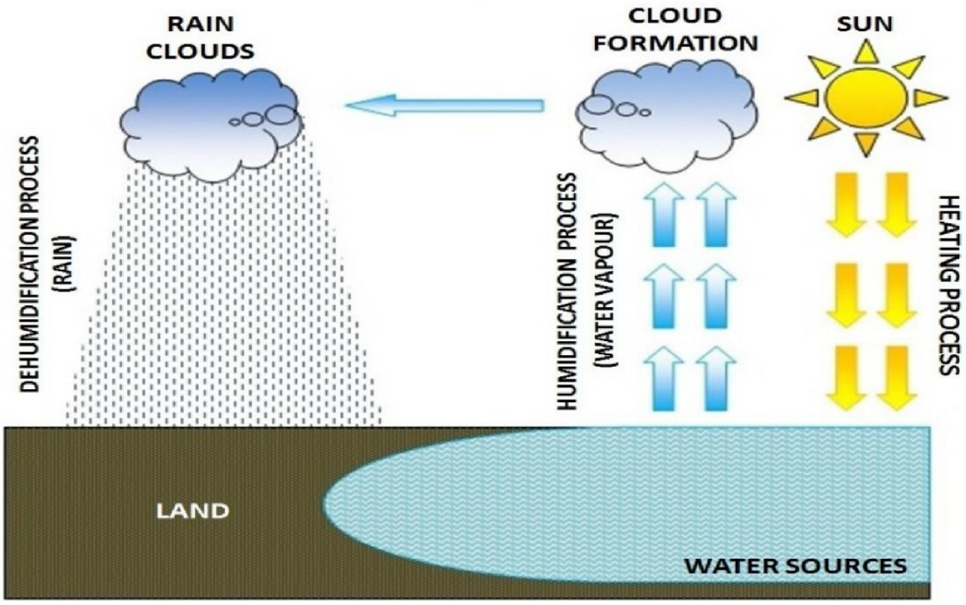

Figure 2.1 Naturally occurring rain cycle [2]

The performance and efficiency of the HDH system hinges on the design and working of the three main components (humidifier, a heat source. and dehumidifier). The process consists of humidifying the hot brackish/uncleansed water using a career gas (air) in the humidifier and then condensing the humidified air in the dehumidifier to get the required fresh water. The figure below depicts the schematic of a basic HDH system.

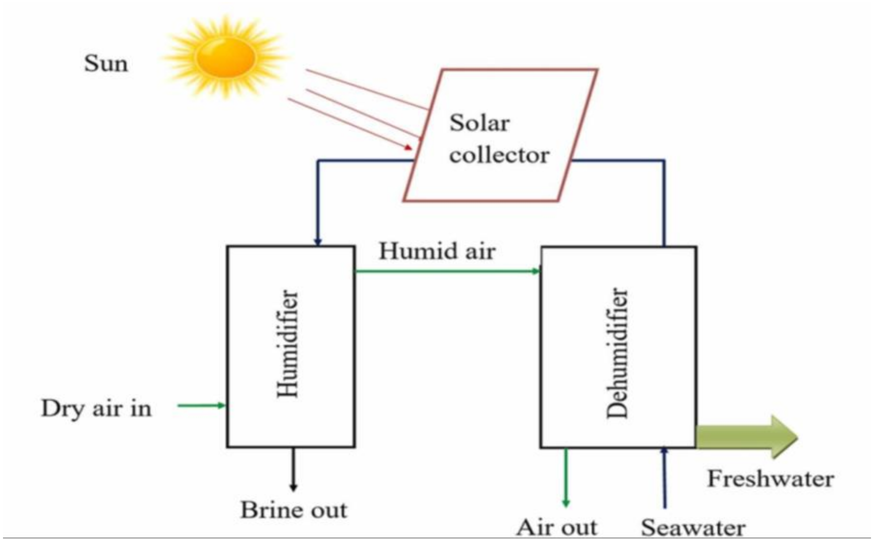

Figure 2.2 A simple HDH process [3]

A variety of humidifiers, including wetted-wall towers, spray towers, bubble columns, and packed bed towers, are used to humidify the air in HDH systems. The fundamental idea behind each of these gadgets is that when water comes into contact with air that isn't already saturated with water vapor, it diffuses into the surroundings and raises the air's humidity. This diffusion mechanism is driven by the concentration difference between the water-air interface and the airborne water vapour. This concentration difference is influenced by the partial pressure of water vapor in the atmosphere as well as the vapour pressure at the gas-liquid interface.

A viable option for small scale water desalination in isolated and rural locations is the HDH desalination process. Because of their inefficient heat and mass transfer rates, conventional HDH desalination systems produce water at higher costs and with less energy efficiency. Many design changes were made to this system to make it more functional and scaleable to manage big populations. The main task is to put forward an effective design to achieve higher heat and mass transfer in HDH system. Due to the poor heat and mass transfer coefficients of traditional humidifiers and dehumidifiers caused by the presence of non-condensable gases in the air, the HDH desalination system must be substantial in size. It has been shown that even a little amount of non-condensable gas in the condensing fluid significantly lowers the heat transfer coefficient. Nearly 60–90% of the bulk of the air in the conventional HDH desalination system consists of non-condensable gases, which results in significant thermal resistance during evaporation and condensation. Heat exchangers with bubble columns can help with this problem. Here, both evaporation and condensation are achieved by passing the air through a liquid column.

The HDH system's usage of bubble columns (BC) has shown encouraging outcomes in this area. A perforated plate or pipe is used in bubble column humidification to create bubbles in hot water, which has a higher heat and mass transfer potential and produces humid air. Similar to how hot, humid air from a humidifier is routed through a bubble column dehumidifier, where condensation occurs when hot air bubbles through cold water, increasing condensation efficiency [3]. Despite resulting in higher efficiencies, limited studies have explored the potential of bubble column in HDH water purification systems.

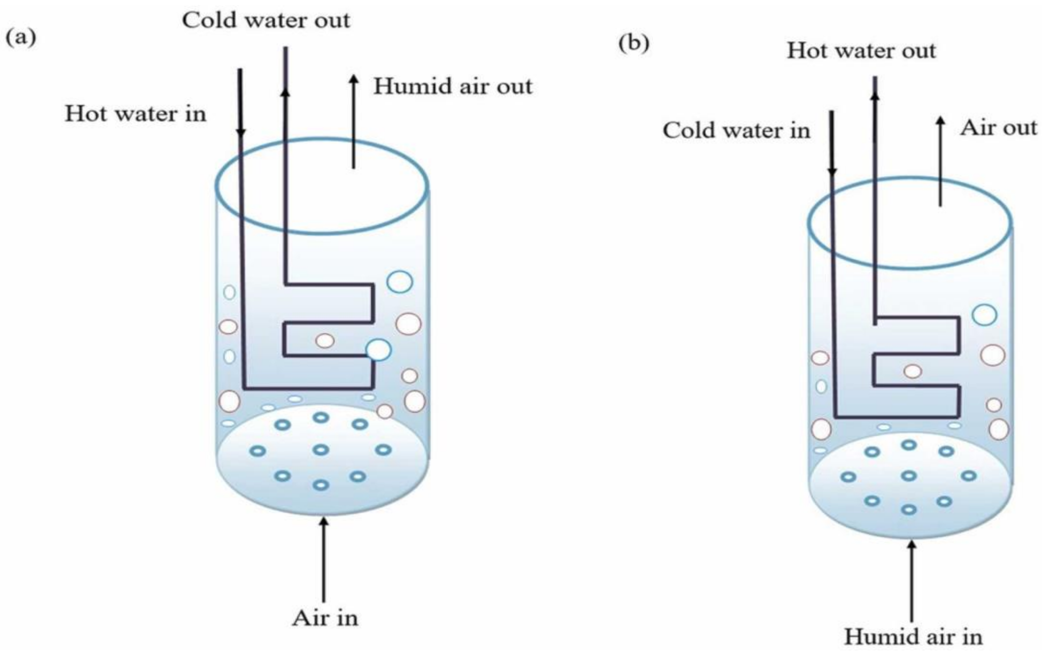

Figure 2.3 Diagrammatic representation of the operation of a BC humidifier in (a) [3] and a BC dehumidifier in (b) [3]

2.2 Bubble Column Humidification

In the area of thermal desalination, two researchers namely Francis and Pashley are known to be the very first to work on the bubble column desalination system [4]. Using a very simple, and a continuous process, fine bubble column operated at temperatures considerably below the boiling point, water vapour can be trapped, transported, and collected by utilizing this method. This results in a consistent and effective interchange of water vapour into the bubbles, which can be beneficial. Liu and Sharqawy worked on the humidifier and dehumidifier at subatomic pressure and elevated pressure respectively [5] and recorded an increase in the effectiveness and heat transfer rate by 7.1% and 27% ,respectively. In contrast, using a conventional dehumidifier at higher pressures resulted in a 3.2 % decrease in effectiveness and a boost of 27% in heat transfer rate. The superficial velocity improves heat transmission and effectiveness for humidifiers and dehumidifiers, but liquid height has no effect whatsoever [6]. Liu and Sharqawy bubble column humidifier is depicted in a schematic figure below.

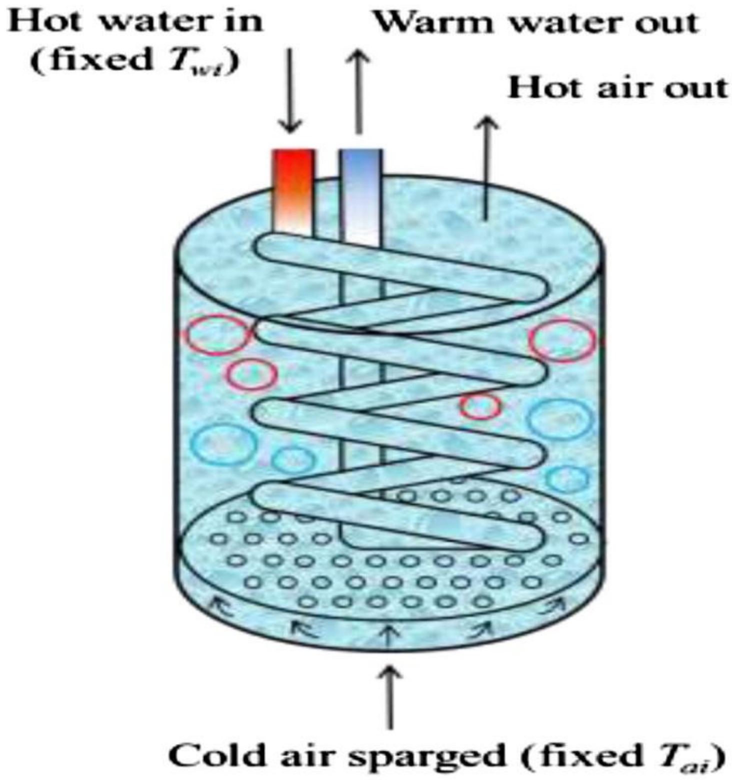

Figure 2.4 Liu and Sharqawy's humidifier based on bubble column [5]

Ghazal et al. investigated an HDH setup by incorporating a BC humidifier and a flat plate solar water heater achieved more than 90% of humidification efficiency in their system [7]. Khalil et al. [8] reported 63 % efficiency and 21kg/day of fresh water in his HDH system using BC humidifier coupled with solar water heater but a shell and tube type conventional dehumidifier was used. Mario Schmack et al. [9] developed a prototype and evaluated a bubbling type humidifier linked with a basic flat plate type of condenser. Without any external cooling aid, 73% condensate rate was recorded from the condenser under normal conditions. It was inferred that a system's yield of 19 L/day might be achieved for a scaled HDH system having a condenser of $1m^2$.

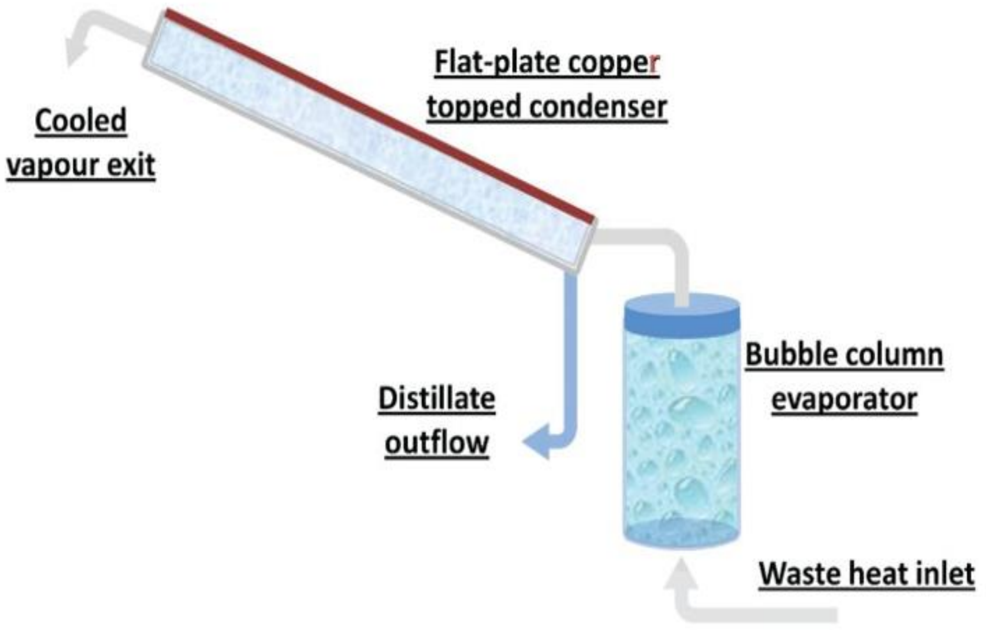

Figure 2.5 The setup by Mario Schmack et al. consists of a bubbling humidifier coupled to a simple flat plate condenser [9]

Pooria Behnam et al. [10] investigated the HDH based on air BC humidifier, evacuated tube collector and a heat pipe. Efficiency of 65 % per day , the peak water productivity of 6.275 kg/daym^2 was recorded and the anticipated cost for the per liter of fresh water touched only 0.028 $/L. Sridhar and Rajaseenivasan have investigated a solar BC HDH system in their research and gathered a top water yield of 20.61 kg/m^2 day. Abd-ur-Rehman et al. [11] used multistage BC humidifier design and found increase in absolute humidity with the rise in the temperature of feed water in the humidifier. The best of the humidifier performance at the lowest pressure drop was achieved with an air velocity of 25 cm/s and 1cm of water column height. Only the performance of the humidifier was recorded, not that of the dehumidifier, hence the removal capacity of the HDH system as a whole is unknown.

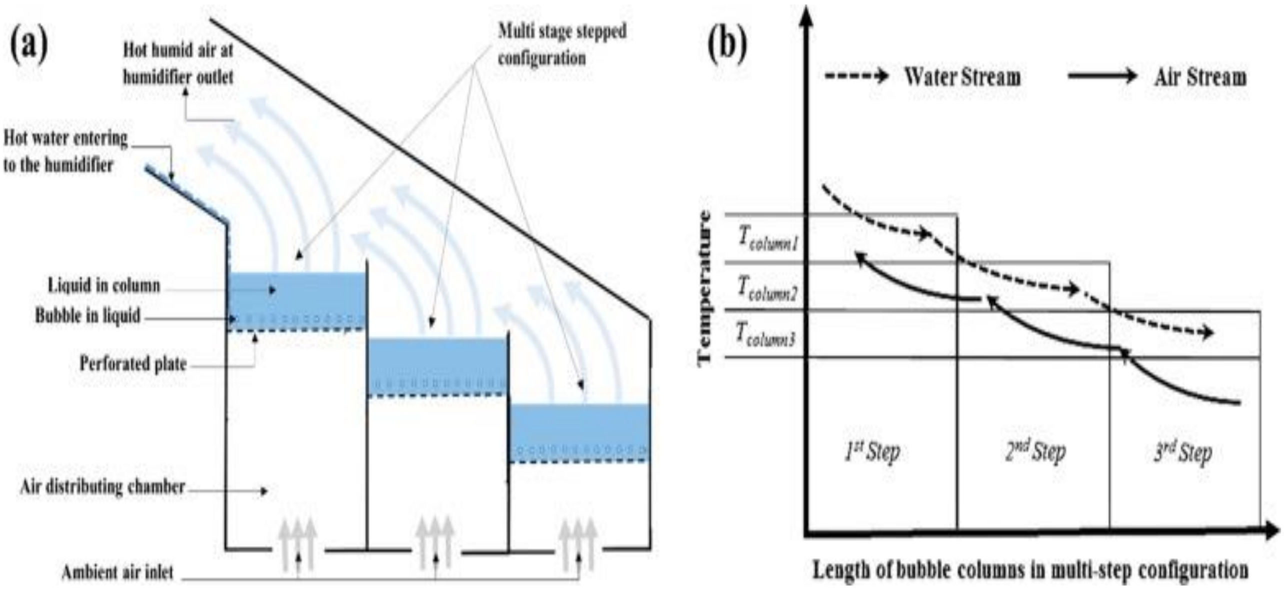

Figure 2.6 Abd-ur-Rehman's [11] work on the multistage bubble column humidifier: (a) design, (b) segmented water and air streams along the design's phases.

Halima et al. [12] investigated a simple structure of a bubble basin for a water desalination and showed that humidity rise up to 100% in the explored range of experimental settings in bubble basin setup. Water level and humidifier’s efficiency marginally affected the water vapour content, while water temperature has a major impact. Patel V et al. worked on a HDH system in which a BC humidifier is used to while thermoelectric cooling modules are used to dehumidify the humidified air and a fresh water yield of 12.96 L/d was achieved. The system utilized electric heaters to heat water and thermometric cooling modules which required considerable amount of electric power hence aren’t feasible for remote communities.[13]. Zhang et al. [14] examined the HDH system in conjunction with a heat pump. The highest output was 22.26 kg/h, while the GOR was 2.02 kg/h. The cost per kg was calculated to be 0.051 US dollars. Eder E and Preißinger [15] conducted experiments to explore the humidification of air in BC. The systems was also studied using optical instruments as it allowed flow characteristics to be assessed. Increasing the superficial velocity of air and liquid height leads to improvement in normalized system output of fresh water production by around 56% and 29 % respectively. Aref L et al. [16] utilized a closed loop pulsing heat pipe in a BC HDH desalination setup. The experimental findings revealed that the bubble basin type had a greater water yield than the BC type, with yields of 0.83 kg/hr.m^2 and 0.70 kg/hrm^2 respectively. The computed cost of suggested HDH per liter is 0.012 $/L [16]. Rajaseenivasan et al. performed the operation of HDH system by utilizing a biofuel as a heat source. The combustion of biofuel resulted in heat energy which was then directly utilized in humidifier to warm up saline water at desired temperature. Having opted for both preheated and direct air supplies, the fresh water production was reported to be 6.1 kg/h and 3.5 kg/h respectively. According to estimations, the price of distilled water is 0.0231 $/kg for ambient air and 0.013 $/kg for HDH setups with preheat air supplies [17]. Xiao has utilize a unique solar concentrator in the form of Fresnel lens to heat up sea water. A surge in heat input and air flow rate leads to an enhanced freshwater productivity. The greatest freshwater productivity was recorded to be 1.24 L/h/m^2 on a day with irradiance of 980 W/m^2. Furthermore, the results depicts a total yield 5.61 L/d/m^2 having 69 % of thermal efficiency. The fresh water production cost turns out to be 0.027 $/L [18]. El-Agouz [19] investigated an HDH system that included a BC humidifier but was also connected to a traditional dehumidifier. The production of fresh water was shown to be unaffected by column height.

2.3 Bubble Column Dehumidification

It has been demonstrated that adopting the direct contact dehumidification method decreases the dehumidifier's size and price [20]. The BC dehumidifier is a potential vapour dehumidification technique due to its straightforward construction. BC dehumidifiers are distinguished by their great efficiency, compactness, little cooling demand, and inexpensive cost of manufacture. In a bubble column dehumidifier, hot, humid air is pumped into a distillate water column that has been chilled by heat exchange. Bubbles created by air injection in the dehumidifier's water column circulate through the cold water column to chill and dehumidify the area. Water vapour condenses on the bubble's surface due to the concentration differential between the warm bubble core and the chilly bubble surface. Narayan et al. presented a novel idea of bubble column dehumidification by condensing the air-vapour mixture in the cold liquid. and the results practically showed that the heat transfer rate in his setup was higher than the conventional dehumidifiers [21]. Narayan and Lienhard [22] put forwarded a unique approach for using HDH systems for saline water desalination using a HDH system. Their work [22] demonstrated in the enhancement of BC dehumidifier performance and improvement in heat balance. Emily W.Tow et al. [20] analyzed a model based on bubble column dehumidifier (figure 2.7) and validated its performance with experimental results. The findings demonstrated that when coil area lowers, effectiveness declines but in contrary heat flux improves. As air temperature and air flow rate increase, more heat is transferred but effectiveness decreases. Heat flow and efficiency are unaffected by BC height or bubble on coil hit. No examination of the humidifier was conducted in this study to determine the complete effects of different settings on the HDH system as a whole.

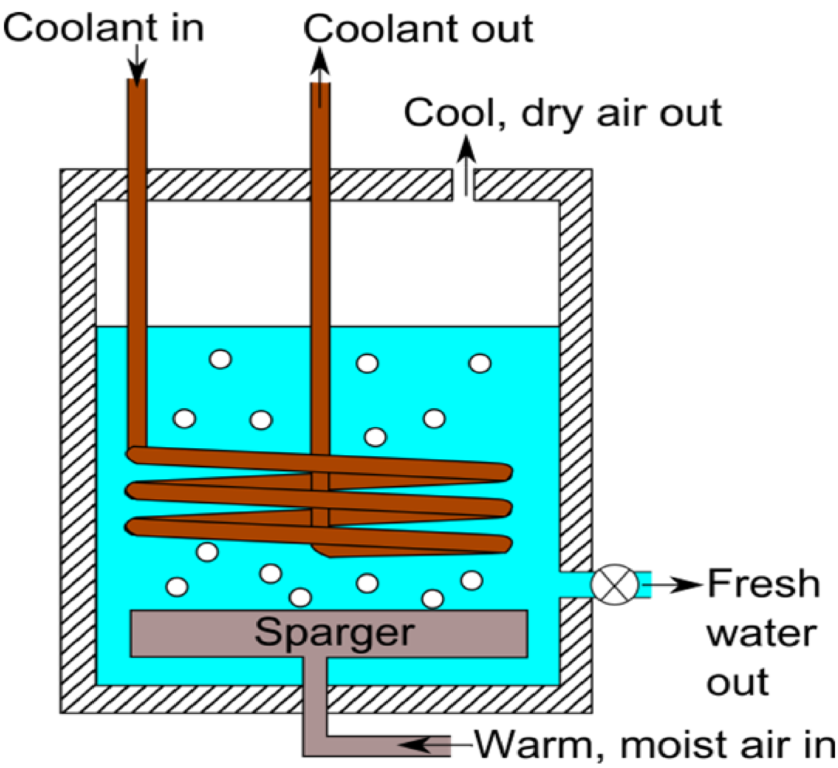

Figure 2.7 Illustration of a BC dehumidifier by Emily W. Tow et al. [20]

Liu [5] and Sharqawy [23] examined the behaviour of a BC dehumidifier under varying pressure and superficial velocity. By raising the superficial velocity, the dehumidifier's effectiveness and total heat transfer rate are both enhanced. Increased pressure reduces the effectiveness of dehumidification while speeding up the rate of heat transfer. No any analysis was performed on any heating source. Using a direct contact dehumidifier, He et al [24] created a model using mathematics to assess an HDH system. Studies have determined that the recommended system's ultimate GOR is 2.01. Additionally, cost study [25] demonstrated that the lowest capital cost in this instance is incongruent with the HDH desalination system's maximum water output.

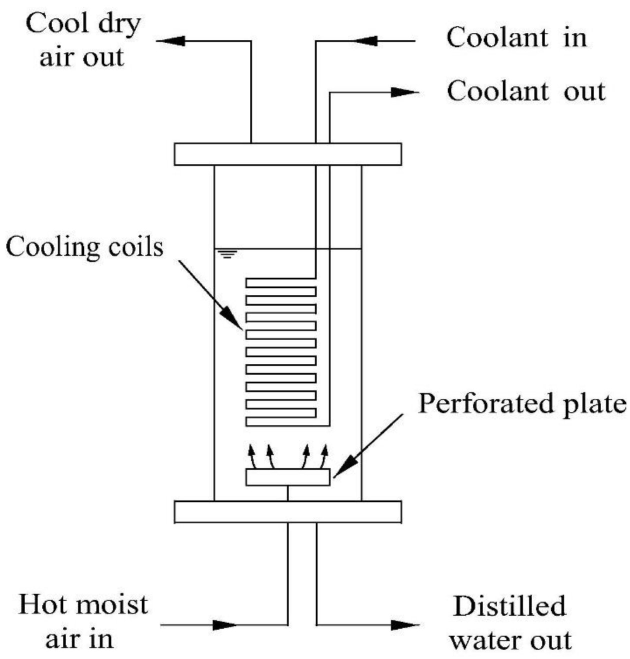

Figure 2.8 Schematic of a BC dehumidifier by Sharqawy and Liu [23]

For both a single-stage and a double-stage, Khan et al. [26] investigated the performance of a direct contact BC air heated HDH system. Raising airflow rates, air temperatures, and humidifier water levels were shown to improve the system's effectiveness. The system's cost study indicates that, the cost for generating per liter is $ 0.090. But nothing was said regarding energy analysis and heat sources to run the system. Table 2.1 gives an overview of the important studies that were conducted on HDH systems that have included bubble columns in their configurations.

Table 2.1 A review of research studies on HDH systems which have utilized bubble columns in their designs

Author	**Year**	**Bubbling Mechanism**	**Major Observations and Findings**	**Ref**
S.A. El-Agouz	2010	BC Humidifier	substantial influence of feed water temperature and airflow rate on output yield, BC height has a much less impact. 8.22 kg/h of freshwater were extracted.	[19]
Zhang et al.	2011	BC Humidifier	In BC Humidifier, 100% RH of air was attained.	[27]

			The BC height and the drop in pressure enhance the power use of the air blower.	
Tow and Lienhard	2014	BC Dehumidifier	Heat flux and effectiveness are not significantly affected by liquid height or bubble influence on the coil. As airflow and air temperature increased, heat flux increased and effectiveness fell.	[28]
Shahid and Pashley	2014	BC Humidifier	The rate of evaporation in the BC humidifier's salt solution is accelerated by higher incoming gas temperature.	[29]
Khalil et al.	2015	BC Humidifier	21 kg/day of freshwater output, an HDH system efficiency of 63%, and a GOR of 0.53. A plate with 1 mm-sized pores produced air that was nearly saturated.	[8]
Liu and Sharqawy	2015	BC Dehumidifier	The effectiveness reduces by 2% by altering 1 to 2 bar of pressure, while the overall rate of heat transmission rises by 18%. It was determined that using the BC Dehumidifier at greater pressure would reduce its effectiveness.	[23]
Behnam and Shafii	2016	BC Humidifier	The daily output of freshwater is 6.275 kg/m^2.	[10]
Rajaseenivasan et al.	2016	BC Humidifier	Efficiency of the BC humidifier reached a peak of 92%, 0.71 kg/h water yield and a cost of 19 \$/m^3.	[30]
Schmack et al.	2016	BC Humidifier	A conventional flat plate collector was linked to a BC humidifier. At temperatures below the boiling point, the suggested system functioned efficiently.	[31]
Srithar and Rajaseenivasan	2017	BC umidifier	20.61 kg/m2 of freshwater were produced each day. Specific humidity increased by 1.22 times when dry air that had been heated at the BC humidifier's intake was used.	[6]

Al-Sulaiman et al.	2017	BC Humidifier	Average air humidity increased by 9 to 11% when superficial velocity elevated from 20 to 30 cm s-1, and by 12.3% when Fresnel lens was added. Because of the system's great performance, it may be placed in isolated places.	[32]
Abd–ur-Rehman & Al-Sulaiman	2017	BC Humidifier	The use of a multistage BC humidifier produced findings that indicated an increase in absolute humidity as a function of the BC humidifier's rising water temperature. At 25 cm/s air speed and 1cm water column height, the BC humidifier functioned at its peak with the least amount of pressure drop.	[11]
Taseidifar et al.	2018	BC Humidifier	The BC humidifier leads air to absorb a more amount of water vapor.	[33]
Eder and Preißinger	2020	BC Humidifier	Freshwater production was greatly increased in the BC Humidifier by raising the air's superficial velocity and BC height.	[15]
Xiao	2021	BC Dehumidifier	The highest quantity of water produced was 1.24 l/h, while the average thermal efficiency was 69%.	[18]
Eder	2022	BC Humidifier	The BC Humidifier performed better when the water temperature and air speed were raised.	[34]
Pourghorban et al.	2023	BC Humidifier	The BC humidifier productivity was optimized at the maximum water level (50 cm) and lowest surface air velocity (0.195 m/s). GOR of 0.75 was attained	[35]

2.4 Solar Energy Driven HDH Systems

The HDH process could be powered by low-grade energy sources like renewable energy sources. Solar power is one of the most often used renewable energy sources for HDH systems. By using sun energy, solar heaters may raise the temperature of any working fluid. The water stream, carrier gas, or air all need to be heated in HDH desalination systems. In certain cases, the carrier medium and the water stream are heated concurrently. The water that is provided to the HDH system has to be heated up in order for the humidification process to work well. This may be accomplished by heating the water that is delivered to the humidifier using solar water heaters and an HDH desalination system. Given that air has a lower heat capacity than water, the solar water heating HDH system has attracted substantially greater interest than the solar air heating HDH system [36], [37]. HDH system can be powered by flat plate water solar collectors [38], [39] . Figure 2.9 provides an illustration of a flat plate solar water collector used to warm up water before it is sent to a humidifier..

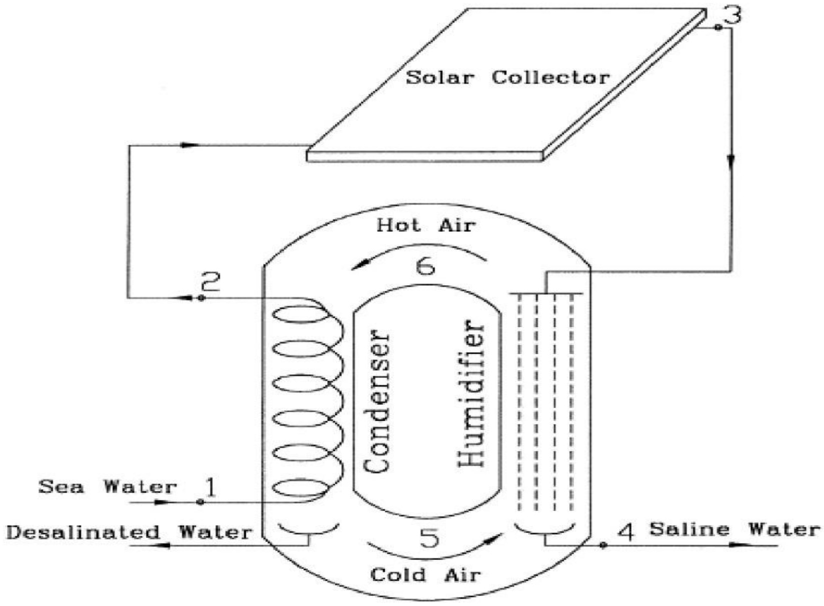

Figure 2.9 An illustration of a flat plate solar collector coupled with HDH system [38]

The most popular form of solar collector available to be used as to heat water is an evacuated tube solar collector, which also powers a number of other devices, most notably HDH desalination systems [40][41]. The literature has also suggested using a Fresnel lens solar water collector to power an HDH system [42]. The effectiveness of a 120 cm long by 42 cm wide parabolic trough solar water collector to power an HDH system linked with solar still to power the HDH systems as well was studied experimentally by Abdullah et al. [42]. Solar dishes can be used if the HDH system is equipped with the right receiver. Numerous solar receiver cavity designs, such as cubical, cylindrical, and hemispherical ones, were researched in order to power the HDH system [43]. The study on integrating HDH systems with solar water heaters from past literature is given in Table 2.2.

Table 2.2 Overview of HDH systems that use solar water heating with their water productivity

Collector	Humidifier	Dehumidifier	Productivity Kg/h	Observations	Ref	Year
Flat plate	Nozzle flash humidification	Inner cylindrical wall surface	0.431	The system's performance continuously improves as the feed water's temperature rises.	[44]	2014
Evacuated tubes	Cellulose paper packing materials	Copper tube heat exchanger	0.458	More fresh water has been produced by raising the feed water temperature.	[45]	2015
Evacuated tubes	BC humidifier	Shell and tube	0.875	In comparison to traditional humidifiers, the bubble column achieved superior performance.	[46]	2015
Evacuated tubes	BC humidifier	Shell and tube	0.026	The daily output of freshwater rose due to the incoming air flow rate.	[47]	2016
Flat plate	Absorber plate with a pasted porous fabric	Tubular heat-exchanger condenser	0.304	Due to the condenser's poor energy efficiency, GOR showed low values. The highest amount of freshwater was produced when the air flowed at 3.34 m/s.	[48]	2017
Flat plate	Packing material	Shell and coil	0.4525	Estimated cost was 25.7 $/m^3$, and system effectiveness was 68%.	[49]	2017
Flat plate	Air saturator	Shell and tube	0.564	Under hot, dry circumstances, the	[38]	2018

				system performed better.		
Evacuated tubes	Packed bed	Double pipe heat exchange	1.2	Th lowest humidifier pressure result in a maximum water yield of 1.200 L/h m^2 during summer days.	[50]	2020
Evacuated tubes	Porous activated carbon tube	Cooling system (CS)	0.55	The system's greatest GOR was 1.24, and both its energy and exergy efficiency values were 26.73% and 1.57%, respectively.	[51]	2022

2.5 Nano fluids in HDH Systems

The effects of employing nanofluids in solar thermal desalination systems have been studied by researchers. Research on the SSF method of desalination, which employs a nanofluid as the working fluid inside the flat plate solar collector, was done by Kabeel et al. [52]. It was reported that the system's GOR was 1.058. Garg K.[53] Integrated an HDH system with a solar collector based on nanofluids to offer a theoretical model. He calculated the GOR as a function of diverse parameters associated with the collector and HDH system. He concluded that different thermal desalination techniques can employ nanofluids as a working fluid, which might increase system productivity [53]. El-Said et al. [51] investigated an Al2O3/H2O nanofluid-based hybrid desalination system with a flat-plate collector that combines two stages of HDH system with a SSF unit. It has been demonstrated that the volume percentage of nanoparticles affects the efficiency of solar collectors. The productivity of solar stills having only a single slope was evaluated by Rashidi et al. [54] using the Al_2O_3 nanofluid, he found that productivity increased by 25% when the Al_2O_3 volume percentage was increased from 0% to 5% [55]. In the cascade solar stills, the hourly production increases by 22% by employing the same nanofluid. A few studies have utilized nanofluid in solar stills and the production was recorded to be enhanced, but nanofluid coupled with HDH system is still in the initial phase.

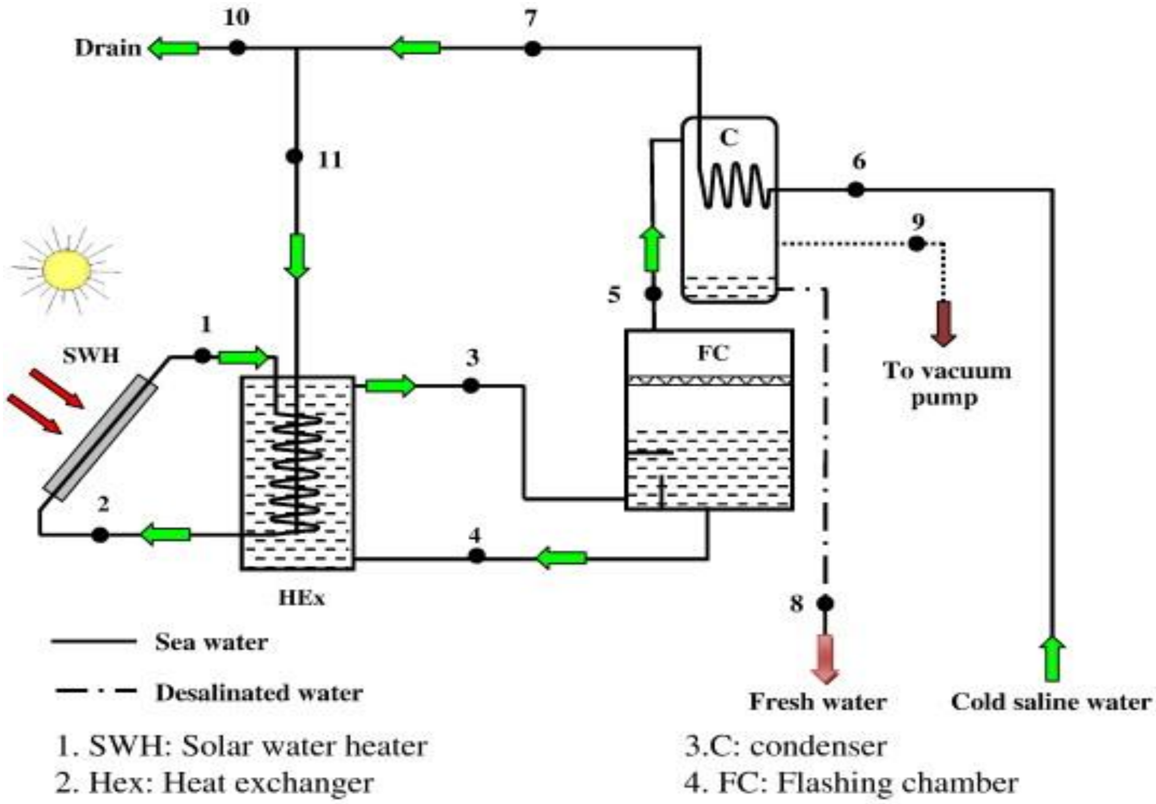

Figure 2.10 Conjunction of an SSF system with a nanofluid based solar collector [52]

The bubbling type HDH setups promotes freshwater production by increasing the humidification and dehumidification. This strategy is appropriate for the areas having brackish or saline water resources and is also effective for producing fresh water on ships. The equipment's associated with humidification-dehumidification systems can fully utilize local solar energy resources or low grade energy sources and has the benefits of low maintenance, stability, dependability, and low cost [56].

In light of the aforementioned literature on HDH desalination and the use of direct contact BC humidifier and BC dehumidifier, it should be emphasized that the BC's performance as a humidifier or a dehumidifier was examined individually in these investigations. Therefore, the purpose of the present study is to evaluate a novel HDH configuration that uses both a BC humidifier and a BC dehumidifier in an air and water heated cycle in order to optimize the HDH desalination system. To enhance the thermal performance of HDH desalination systems, the use of nanofluids in HDH technology should be investigated. A solar water heater with TiO_2 nanofluid is utilized as a water heating resource in this setup. The TiO_2 based solar water heater is not utilized till now in the HDH system. Moreover, the setup is powered by solar energy. The equipment's which require electrical power are water pump and air blower which are powered by a solar PV panel. According to the acquired results and economic analyses, this distinctive HDH design operates admirably and excels in terms of GOR, water productivity, specific energy, and reasonably priced production expenses. The effectiveness is excellent when compared to the typical humidifier and dehumidifier configuration. Performance metrics for the water heated cycle are consistent with past HDH system findings.

Summary

The performance and effectiveness of HDH (humidification-dehumidification) systems are covered in the literature study. These systems depend on the layout and operation of the three major parts: humidifier, heat source, and dehumidifier. The HDH system's usage of a bubble column has shown encouraging results in terms of increasing the potential for heat and mass transfer for humid air. Using a carrier gas to humidify hot brackish water, the procedure condenses the humidified air in the dehumidifier to produce fresh water. In order to uplift and enhance the heat and mass transfer in HDH systems, the study highlights the requirement for an efficient design. Using a bubble column (BC) has demonstrated promising results in this respect. The literature review covers a number of investigations on the potential of BC in HDH water purification systems and records various HDH system efficiency. The utilization of solar water heaters, the introduction of nanofluids in it to enhance heat transmission, and BC humidifiers and dehumidifiers are just a few of the research that have looked into various facets of HDH systems. Solar energy is frequently used to power HDH systems, and several studies have demonstrated good productivity and efficiency when employing solar collectors. The use of nanofluids in solar water heaters has the potential to eventually improve HDH system performance by increasing thermal conductivity and heat transfer rate. Overall, the research points to HDH systems as having potential as an affordable and long-lasting water purification technique, particularly in rural places with limited access to clean water sources.

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Chapter 3 : System Description and Methodology

3.1 Experimental setup

The schematic illustration of the suggested experimental HDH setup for water desalination is depicts in figure 3.2. To form air bubbles in the humidifier's column of hot saline water, the unsaturated ambient atmospheric air passes through the drilled holes PVC pipe (figure 3.1) present which is at the bed of water column. The phenomenon of energy and mass transfer between the two steams of hot saline water and unsaturated air raises the relative humidity (RH) and temperature of the air when air bubbles move through hot saline water. The formation of bubbles enhances the surface contact area, which speeds up the process of air humidification. The warm and moist air is expelled from the BC humidifier and is subsequently sent via the leaked proof piping to the BC dehumidifier. The humid air in the BC dehumidifier is cooled substantially below the saturation temperature by direct contact with cold water, resulting in dehumidification of the air. The condensate droplets combine with the already existent cold water, causing the water level in the BC dehumidifier to rise. The cold water in the BC of the dehumidifier is maintained by an immersed copper coil in which cold saline water is running (feed water).

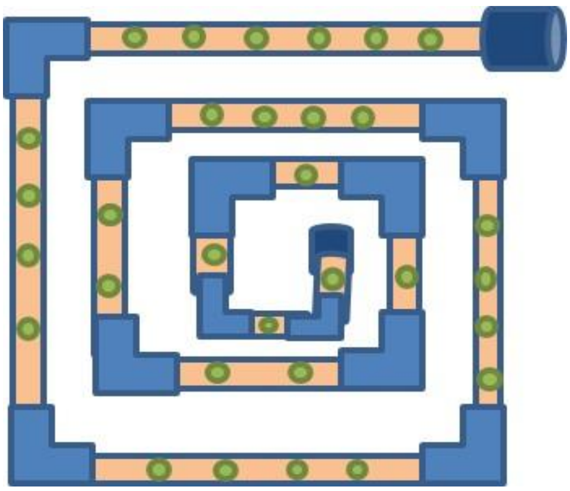

Figure 3.1 Bubbling mechanism used in the BC humidifier

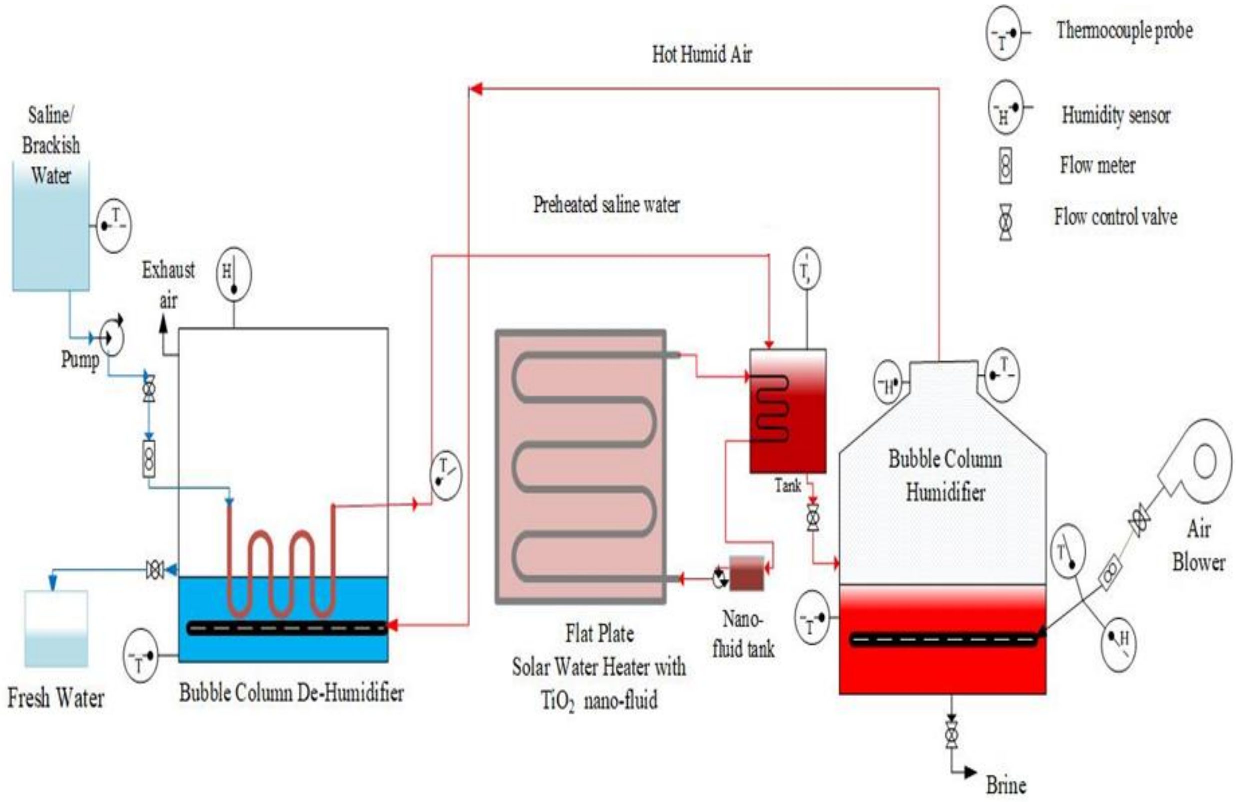

Figure 3.2 Anticipated experimental HDH configuration is shown schematically

3.1.1 Nanofluid Incorporated Solar Water Heater (SWH)

The SWH (Figure 3.3) is made up of copper pipes that have been welded to a copper plate. To enclose the SWH, a wooden frame with good insulation is used. Inside the copper pipes, TiO_2 nanofluid is used as the heat transmission medium. The interior of the heater's frame wall is covered in an aluminum sheet that converts solar energy into usable heat. An insulating material is placed to the SWH's lower portion and lateral sides in order to reduce heat loss. Glass is placed on the top for sunlight transmission onto the copper plate. The geometrical characteristics of SWH employed in this investigation are provided in Table 3.1.

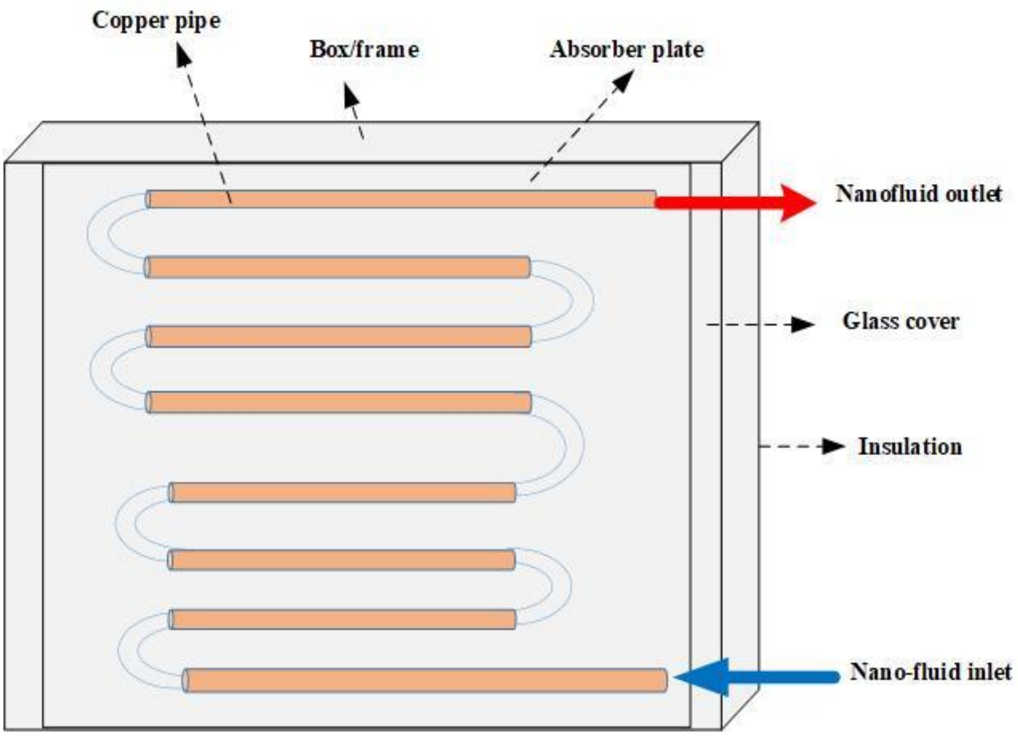

Figure 3.3 Labeling of the proposed SWH

Table 3.1 Technical characteristics of the solar water heater (SWH

Feature	Value
Length (cm)	44
Width (cm)	42
Height (cm)	8
Absorber material	Copper
Pipe diameter (cm)	1.25
Pipe length (cm)	330
Gross Area (cm^2)	1848
Net Area/Absorber area (cm^2)	1700
Fluid capacity in pipes (L)	0.40
Absorber thickness (mm)	0.2
Cover glass thickness (mm)	0.4
Cover glass thickness (mm)	0.4
Insulation material	Glass wool

3.1.2 Preparation of Nanofluid

The term "nanofluid" refers to a fluid that has nano sized particles of a particular substance floating in it, such as TiO_2, Al, Cu, $Al20_3$, etc. These particles have the ability to scatter and absorb light, which allows them to absorb solar energy that is incident on them. The Titanium dioxide (TiO_2) powder corresponds to the pure nano-crystalline anatase phase, is used since colloidal phase nanofluid production techniques for TiO_2 typically prefer the anatase structure [1], [2]. Anatase phase TiO_2 nanoparticles with a stated chemical purity of 99.5% were utilized. TiO_2 nanoparticles were examined using scanning electron microscopy (SEM) as a way to explain the size, structure, and morphology. Using a SEM (VEGA3 TESCAN, USPCASE-E NUST) and the Using a field emission gun running at a 20 kV accelerating voltage to create a backscattering electron picture, a SEM image was created. This apparatus includes an energy-dispersive X-ray (EDS) spectrometer for chemical analysis of a material sample. A SEM image may be seen in figure 3.4 of a nano-crystalline TiO_2 structure. The conclusion that the particles are of the sponge type is reached by magnifying close agglomerates in micrometers. Using SEM micrographs, average particle sizes were calculated by counting at least 100 particles, yielding values of 89 ± 10 nm for anatase phase TiO_2.

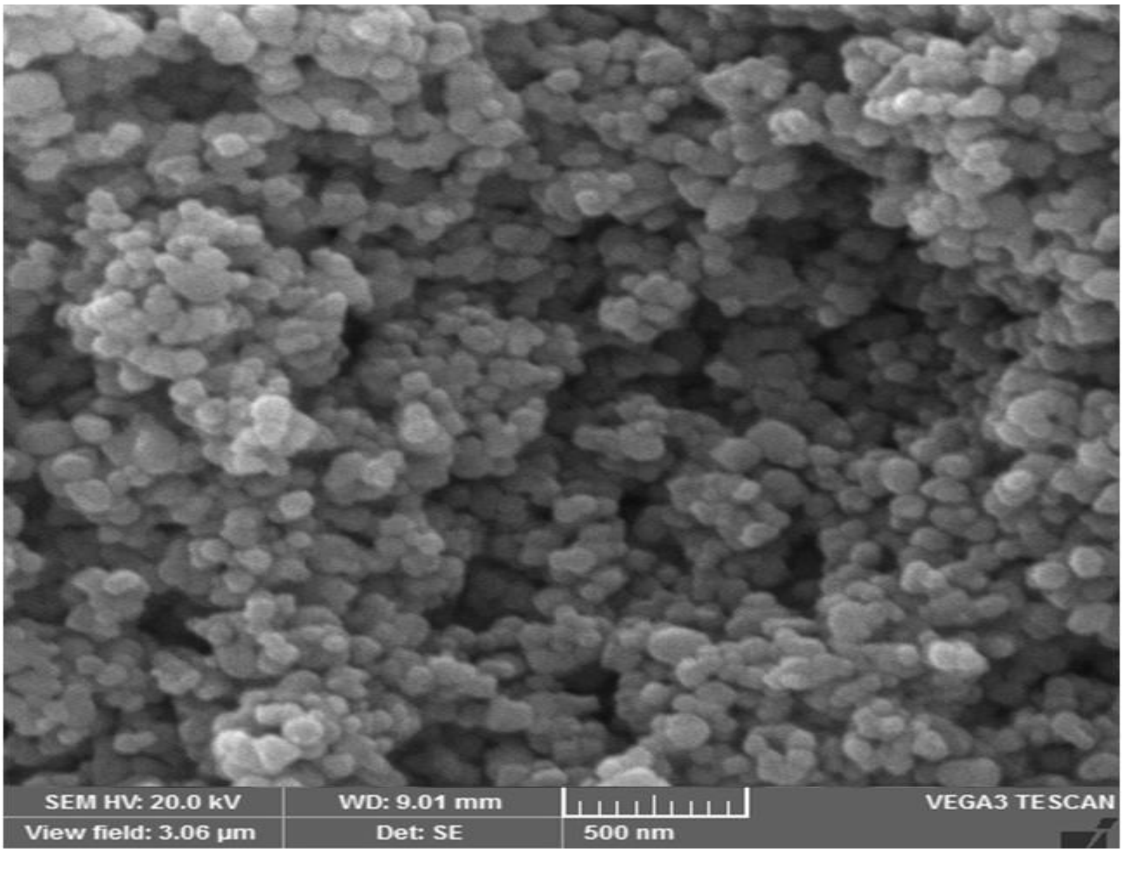

Figure 3.4 SEM image of TiO_2 nanoparticles

The chemical makeup of the samples is depicted in Figure 3.5 based on the EDS spectra. EDS of TiO_2 nanoparticles revealed that the only elements present in considerable quantities were Ti and O, with less than 1% by mass of C present, most likely because of the carbon support. For the samples analyzed, no significant concentrations of additional elements were found.

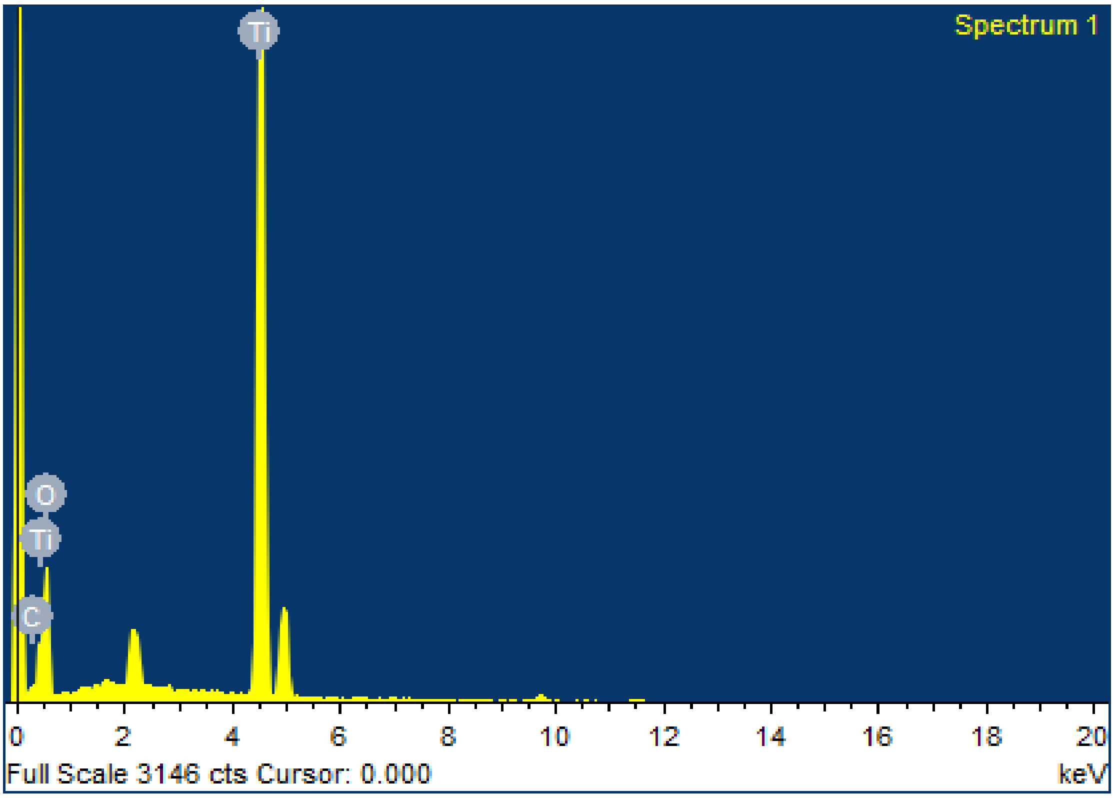

Figure 3.5 EDS image of TiO_2 nanoparticles

Numerous research have shown that even if the specific heat capacity increases, the precipitation issue grows worse when the nanofluid's nanoparticle ratio rises. In this study, the TiO_2 weight percentage of 2% is selected as it showed lower precipitation and good heat capacity [3]. In deionized water, the TiO_2 nanoparticles were mixed, first by the magnetic stirring (figure 3.6) and then by continuous pulsing for the appropriate duration of time using an ultra-sonication technique (figure 3.7). To increase the stability of the TiO_2 nano-fluids, a polymer surfactant called polyvinyl alcohol (PVA) of 0.2 wt. % is utilized [3]. The optimal nanofluid with the least degree of agglomerate was created with a surfactant content of 0.2 weight percent. Before and after the testing, the synthesized TiO_2 nanofluid suspension demonstrated stability and exhibited no precipitation or distillation problems. Figure 3.8 provides a step by step approach and the stages involved in preparing TiO_2 nanofluid .

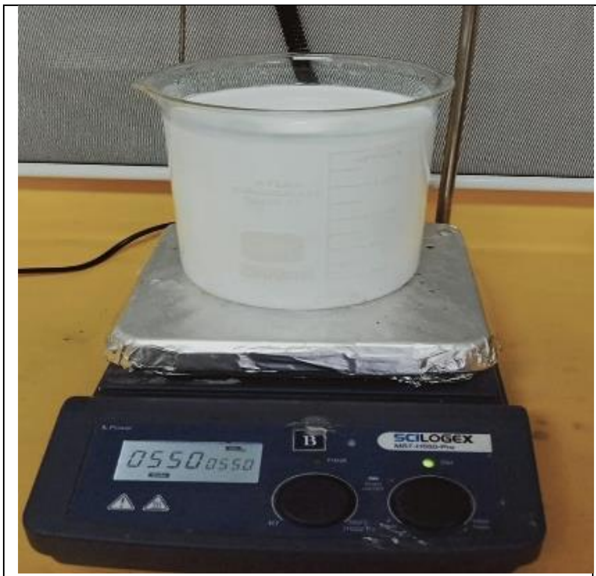

Figure 3.6 Magnetic stirring of TiO_2 nanofluid

Figure 3.7 Magnetic stirring of TiO_2 nanofluid

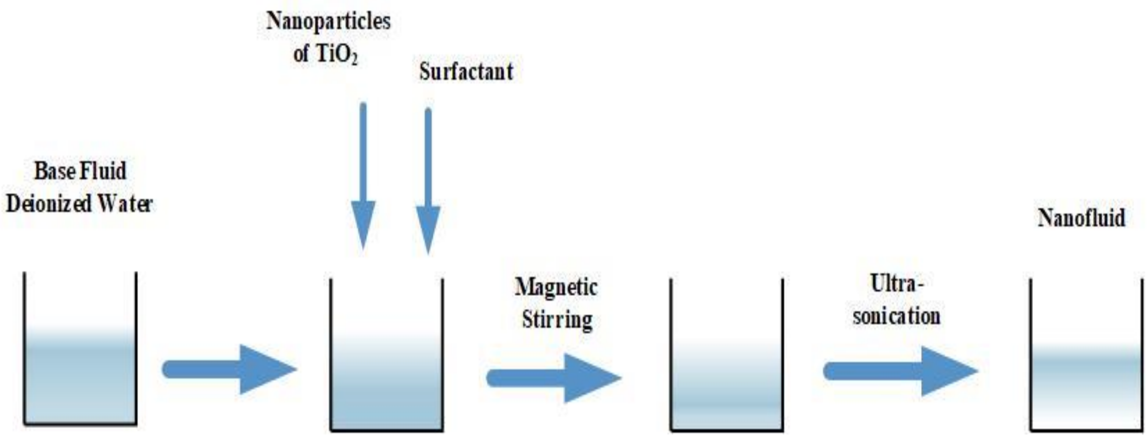

Figure 3.8 Schematic depiction for the preparation of nanofluid.

3.2 HDH System Drawings

The anticipated HDH system components, a BC humidifier in figure 3.9 and a bubble column dehumidifier in figure 3.10, are depicted in 2D drawings with their respective dimensions (in inches).

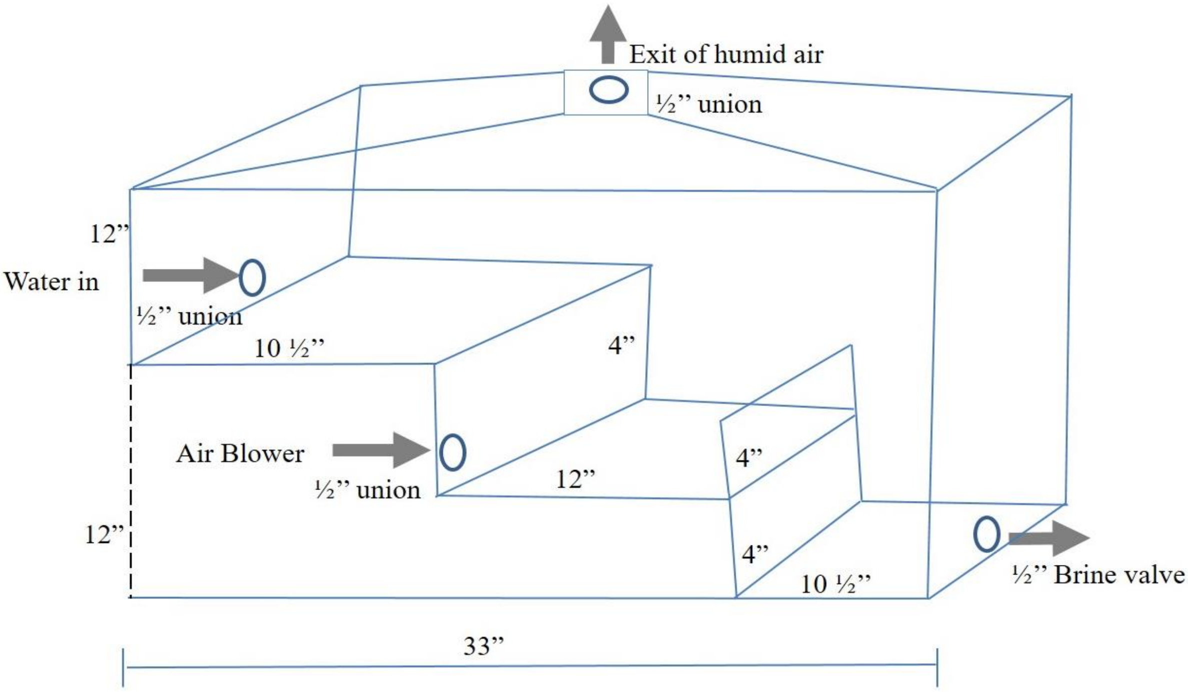

Figure 3.9 Dimension of BC humidifier

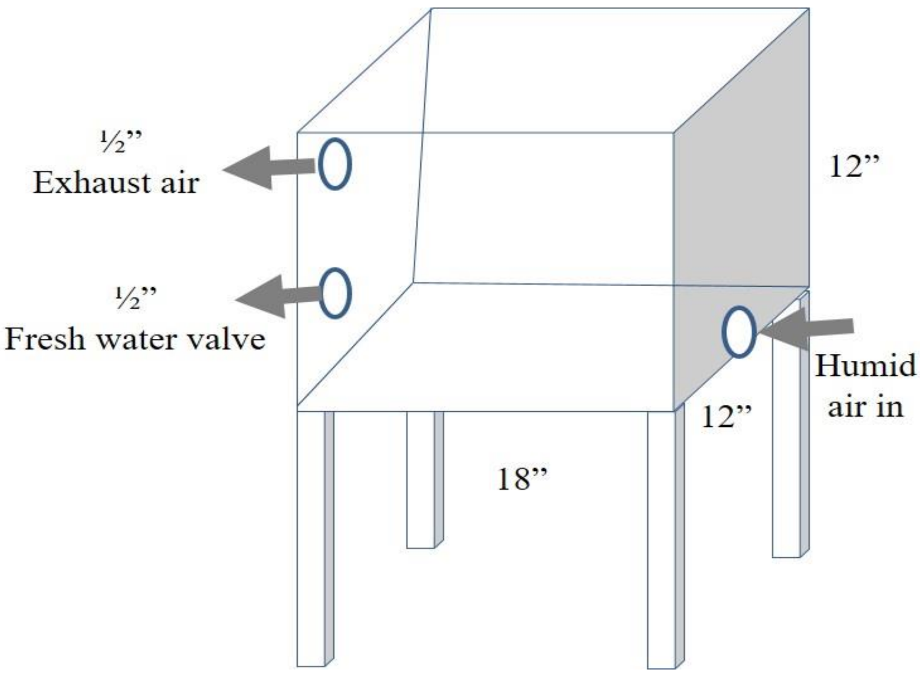

Figure 3.10 Dimension of BC dehumidifier

3.3 Methodology

3.3.1 Process Description

The proposed HDH system's process flow diagram is depicted in figure 3.11. The saline water at state 1 having temperature T_{w1} is preheated in the tubes of the de-humidifier which is then fed into the in to the system of SWH leading to state 2 at temperature T_{w2}. The SWH is equipped with a nano-fluid namely TiO_2 to heat up the saline water in a transition tank. A copper plate with copper tubes fixed (welded) to it makes up the flat solar collector or solar water heater. The plate is encased in a wooden frame and covered with glass to prevent temperature losses caused mostly by convection and radiations to the environment. With the aid of a pump and a nanofluid tank, the nanofluid is made to flow in the copper plate's pipes. The bottom end of the collector is where the nanofluid enters, travels through the copper pipe, and then absorbs heat from the solar energy from the sun. At the opposite end, the heated nanofluid exits the collection. With the aid of a heat exchanger, the nanofluid fluid warms the water in the tank leading to state 3 at temperature T_{w3}. After exchanging heat with the water the nanofluid enters a transition nanofluid tank and kept on circulating in the solar heater. Nextly, the hot saline water at the intended temperature is fed into the BC humidifier. In the BC humidifier, the hot saline water tank receives ambient air at state 5 having temperature T_{a1} via a through a concentric piping with air bubble-forming holes that is placed at the base of the BC. The mass and energy exchanges that occur between the heated saline water and the air are improved by the presence of air bubbles. Air bubbles ascend up the water column at state 6 having temperature T_{a2}. Humid air exits approaching the state of saturation through the top of the BC humidifier where a hygrometer is installed to record reactive humidity. The brine at state 4 having temperature T_{w4} is gathered at the BC humidifier's bottom outlet. The water heated HDH system was evaluated in order to gauge and analyze the effects of numerous elements on the system's overall production. The main variables utilized to evaluate the system's performance were the saline water temperature, air temperature, water level, hole sizes in the bubbling system, and air flow rate. The results leads us to find system productivity in terms of distillate per hour (L/h), gain output ratio, setup effectiveness, recovery ratio, and specific energy consumption. The hot humid air makes its way into the bottom (at state 6) of the BC dehumidifier through the holes pierced in the pipe place at the bottom of the column. The BC dehumidifier is maintained at ambient temperature by being replenished with cold fresh water (20 °C to 25 °C). The copper coil, into which the feed water is running, maintains the BC dehumidifier's water column's temperature constant. The cold water present in the BC dehumidifier condenser the hot humid air which is a type of direct condensation. A rise in the water level inside the BC dehumidifier indicates how much fresh water was produced. The fresh water is collected via valve at state 7. The BC humidifier and dehumidifier are configured to operate at the ambient standard atmospheric pressure. The sate 8 depicts the exhaust air.

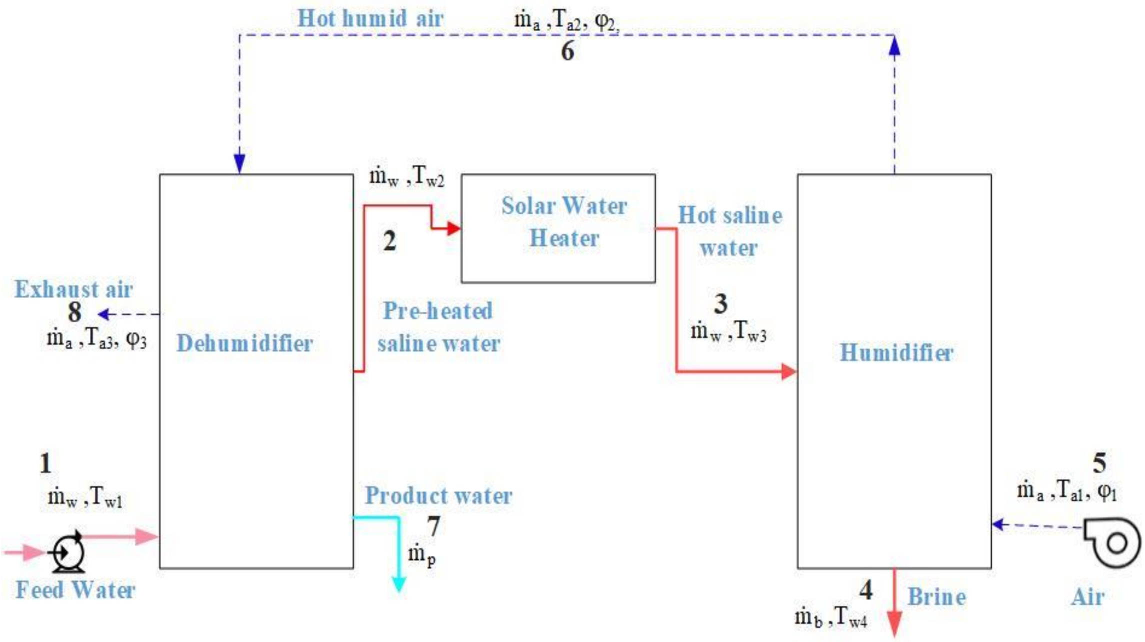

Figure 3.11 A block diagram depiction of different states related to air and water in the BC HDH System

The real time HDH desalination system along with equipment labelling is depicted in the figure 3.12. The system shown has the following parts: Saline water tank, water circulating pump, humidifier, air blower/compressor, dehumidifier, air blower, solar water heater, control board, humidity sensor, thermocouples, brine collecting tank, and fresh water tank.

To assess system performance and conduct system analysis, system parameters like relative humidity, steam and water temperature, specific humidity, and flow rate data are used. The temperature of the saline hot water in the BC humidifier varies from 45°C to 60°C. The water temperatures in the range of 45 °C to 60 °C with an increment of 5 °C were studied independently to look into the system performance. Air is pumped with flow rates between 0.02 to 0.05 kg/s. Three different water levels are considered in BC humidifier: precisely 2.5 cm, 5.5 cm, and 7.5 cm, respectively. For the whole testing, the level of water in the BC dehumidifier is controlled at 8 cm. The hole diameter of the helical pipe periphery was kept at 2.5 mm for dehumidifier, while for the analysis purpose the hole diameter in bubbling producing pipe at the bed of the humidifier was varied from 2.5 mm to 3.55 mm with an increment of 1mm. The water within the dehumidifier is kept at ambient room temperature of 20 to 25 °C for the purpose of dehumidifying incoming humid air from the BC humidifier.

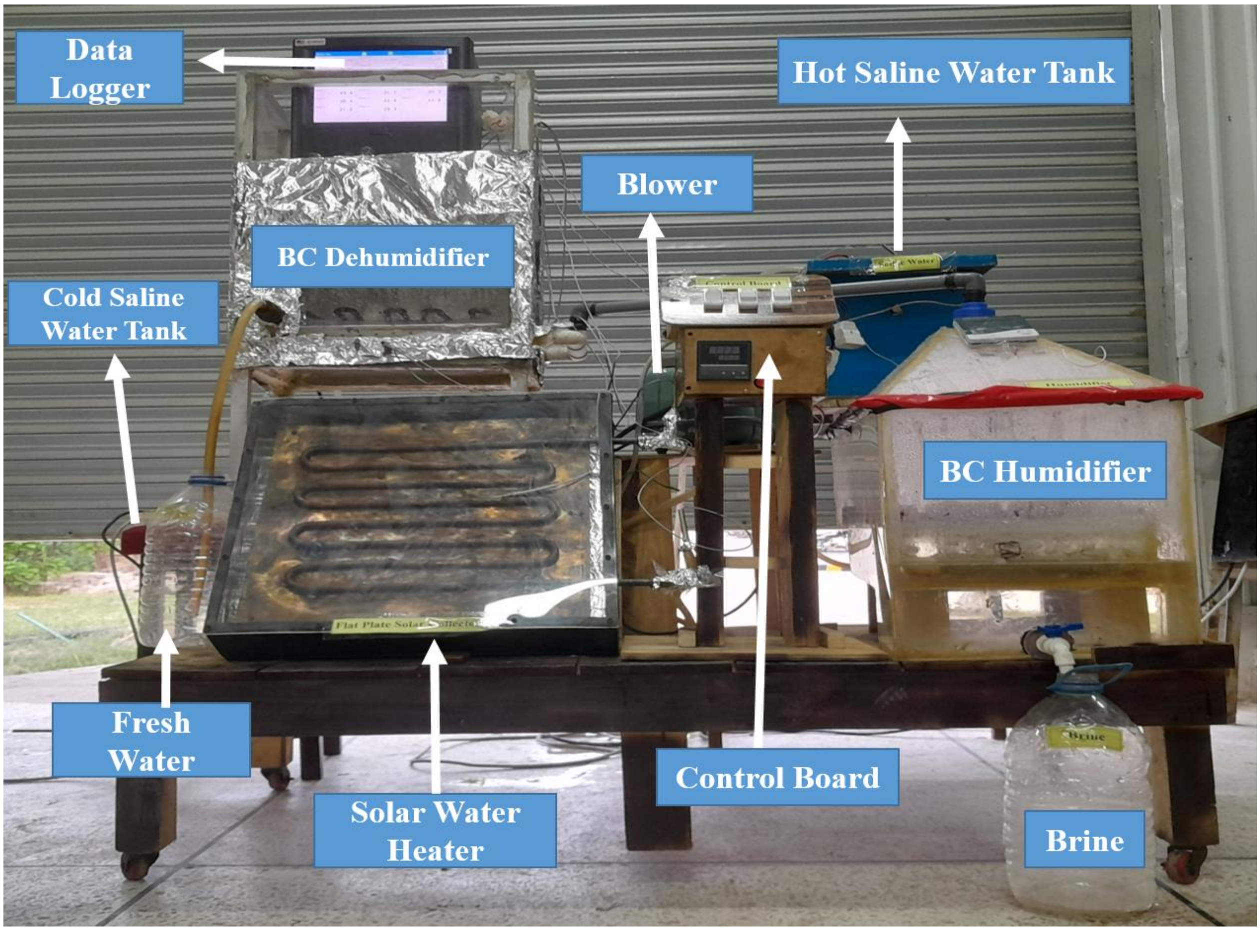

Figure 3.12 Photographic view of the designed Bubbling type HDH Setup

3.4 Data Analysis

3.4.1 Uncertainty

The uncertainty is assessed in the estimated real-time experimental observations. The operational parameters are measured using temperature sensors at various points, a flow meter, and a hygrometer. The column height in the BC humidifier and BC dehumidifier is marked on the outside acrylic surface of the walls with a meter rod. A simple stopwatch is used to keep track of the time, and a sun meter is used to gauge the sun's irradiance. The evaluation of uncertainty is essential in order to determine how the aforementioned variables will affect the system's performance. The usual estimation of measurement uncertainty (U) using instrument accuracies (a) is accomplished using the equation 1 below [4] [5] and is provided in the table 3.2.

$$U = \frac{a}{\sqrt{3}} \qquad (1)$$

Table 3.2 List of the measurement devices' ranges, accuracies, and uncertainties

Tool	Property	Accuracy	Uncertainty	Measurement range
K-type thermocouple	Temperature	0.5 °C	0.29 °C	-100-1200 °C
Hygrometer	Humidity	± 5% RH	2.88 RH	0-100% RH
Flow meter	Flow rate	0.225 CFM	0.05 CFM	0.5-5 CFM
MAF sensor	Mass flow rate	±0.001 kg/s	±0.0005 kg/s	0.001-0.5kg/s
Solar meter	Solar irradiance	± 10W/m^2	± 5.7W/m^2	0-2000W/m^2
Stop watch	Time	0.1 s	0.057 s	0-1 hour
Meter rod	Length	± 1 mm	0.57mm	0-30 cm

The suggested configuration is analyzed by measuring and computing the freshwater productivity, energy input, GOR, effectiveness and the SEC of the components. Furthermore the system's economic analysis is also performed.

3.4.2 Water productivity

Water productivity in Liters per hours is calculated as:

$$\dot{m}_w = \frac{A(x_2 - x_1)}{t_2 - t_1} \qquad (2)$$

Here, A is the area of dehumidifier, $x_2 - x_1$ is the rise in water level in the dehumidifier's bubble column, and t_2-t_1 is the time required to achieve the system's productivity.

3.4.3 Recovery Ratio (RR)

Recovery also known as the extraction efficiency is basically the amount of fresh water which is produce for per kg of the saline water which basically the feed water.

$$RR = \frac{\dot{m}_p}{\dot{m}_w} \qquad (3)$$

3.4.4 Gain Output Ratio (GOR)

The amount of fresh water generated ($\dot{m}_p$) for a specific heat input ($\dot{Q}_i$) is commonly referred to a GOR. It is determined as follows:

$$GOR = \frac{\dot{m}_p h_{fg}}{\dot{Q}_i} \qquad (4)$$

Where, h_{fg} is the latent heat of evaporation of the fresh water generated.

3.4.5 Energy Input (Q_i)

The solar water heater provides the energy needed to heat the saline water to the desired temperature.

$$Q_i = \dot{m}_w C_{Pwater}(T_2 - T_1) \qquad (5)$$

T_2-T_2 is the difference of temperature of the incoming and outgoing water.

3.4.6 Effectiveness (Ɛ)

The effectiveness of any stream, whether dry air or water, is characterized as being the ratio of the genuine actual change in total enthalpy rate (Δh) to the highest imminent change in total enthalpy ($\Delta h_{maximum}$) and is given by:

$$\mathcal{E} = \frac{\Delta h}{\Delta h_{maximum}} \qquad (6)$$

3.4.7 Specific Energy Consumption (SEC)

SEC is the amount of electricity necessary for producing one kilogram of fresh water. SEC in kWh/L is determined from the equation as follows:

$$SEC = \frac{\dot{Q}_i}{\dot{m}_p} \qquad (7)$$

3.5 Cost Analysis

Each cutting-edge desalination system's main objective is to lower the cost of generating per liter (C_{PL}) of fresh water. The HDH system is evaluated economically, and the cost analysis's phases may be summed up as follows:

C_c provides the proposed HDH setup's total primary capital cost.

The Capital Recovery Factor, often known as CRF, is the total cost of the system during its operational period or lifespan. The equation below is used to compute CRF [6]:

$$CRF = \frac{r(1+r)^y}{(1+r)^y - 1} \qquad (8)$$

In the formula y is the HDH system's lifespan years, which is generally considered to be ten years, and r represents the yearly rate of interest which is 15%. The first annual capital cost A_c is given by the relation [7]:

$$A_C = CRF \times C_c \qquad (9)$$

When a system reaches the end of its useful working life, its salvage value (SV) is its projected worth or selling price and it is computed as:

$$SV = C_C \times 0.2 \qquad (10)$$

For the HDH system, the yearly salvage value (YSV) is calculated as [6] [8]:

$$YSV = SV \times S_{ff} \qquad (11)$$

S_{ff} is the sinking fund factor is periodic or recurring payment required to repay a loan or investment over a certain duration of time frame. S_{ff} is computed as [8]:

$$S_{ff} = \frac{r}{(1+r)^y - 1} \qquad (12)$$

15% of the original yearly cost is generally the annual maintenance cost (C_M) [6]:

$$C_M = A_C \times 0.15 \qquad (13)$$

The HDH setup's total annual cost is provided by [3]:

$$C_A = A_C + C_M - YSV \qquad (14)$$

The cost per liter (C_{PL}) for the entire year, which is essentially the unit price for freshwater, is then computed as [6] [8]:

$$C_{PL} = \frac{C_A}{W_Y} \qquad (15)$$

Where, W_Y is the yield of liters of water annually.

The expense of producing fresh water per day (C_{PD}), the relation used is:

$$C_{PD} = \frac{C_{PL}}{W_D} \qquad (16)$$

Where, W_D is the daily fresh water productivity in liters.

In Pakistan, the average local market price (C_{MP}) for a liter of water is roughly $ 0.15.

$$\text{Net Profit} = C_{MP} - C_{PL} \qquad (17)$$

In the majority of instances, the payback period is the quantity period of time necessary for an investment to pay off on a project or a product to produce enough income or savings to recoup its initial cost.

$$\text{Payback period in liters } = \frac{C_C}{\text{Net Profit}} \qquad (18)$$

Now the payback period in years is computed from:

$$\text{Payback period in yeras } = \frac{\text{Payback period in Liter}}{W_Y} \qquad (20)$$

Summary

This chapter discusses a method for designing and testing a lab-scale HDH (humidification-dehumidification) water purification system prototype in real time. The setup comprises of a solar water heater, a brine collecting tank, a saline water tank, a water circulation pump, a BC humidifier, a BC dehumidifier, an air blower, a humidity sensor, and thermocouples. The salty feed water is warmed in the dehumidifier's tubes before being fed into a solar water heater using a nanofluid (TiO_2) to heat the saline water in a transition tank. Deionized water was employed as the base fluid and anatase phase TiO_2 powder served as the nanoparticles in the nanofluid. The saline water in the solar water heater was heated using this nanofluid based solar water heater. Furthermore, SAM and EDS particle characterization on TiO_2 nanoparticles was performed. The hot saline water is fed into the BC (bubble column) humidifier where it receives ambient air via a concentric pipe positioned at the bottom of the bubble column, which enhances the energy and mass exchange between the warm saline water and the air. Via the perforations drilled in the pipe placed at the bottom of the column, the humid air enters the bottom of the BC dehumidifier, which is prefilled with cool, fresh water that is at room temperature. Direct condensation occurs when the hot, humid air is condensed by the cool, fresh water in the BC dehumidifier. System parameters including relative humidity, absolute humidity, steam and water temperature, and flow rate data are used to assess the system's functioning and conduct analysis. Using temperature sensors at various locations, a flow meter, and a hygrometer to detect operating parameters, the uncertainty in the estimated real-time experimental observations is evaluated. The water level in the column of the BC humidifier and BC dehumidifier is marked with a meter rod on the outside acrylic surface of the walls. By testing and computing the freshwater productivity, energy input, specific energy consumption, gain output ratio, and system effectiveness, the recommended design is examined. Additionally, the numerous parameters and governing equations are used to analyze the system's cost and economics analysis.

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Chapter 4 : Results and Discussions

4.1 Effect of Operational Conditions on System Productivity

4.1.1 Effect of Saline Water Temperature

A configuration with an air mass flow rate of 0.02 kg/s at 40 °C, a hole diameter of 2.5 mm, and a bubble column height of 7.5 cm was used to examine the impact of salty water temperatures ranging from 45 °C to 60 °C in the BC column humidifier on the generation of fresh water. The graphical representation is being depicted in the figure 4.1. The graph indicates that fresh water output tends to grow as water temperature rises, and an exponential relationship may be noticed. As a result of the high feed water temperature, the air boost its RH because of the bubbles being created in the humidifier which enhances energy and mass transfer. Since HDH is a low-grade energy system, its peak production was measured at 0.75 L/d at feed water temperature of 60°C in the BC humidifier. The effects of air temperature change on the system's fresh water production are also shown in figure 4. In the space of 5°C, the air temperature was varied from 25°C to 40°C. The experiment with an air mass flow rate of 0.02 kg/s, a hole diameter of 2.5 mm, and a water column height of 7.5 cm. The outcome demonstrates that the fresh water production of the HDH system enhances as the air temperature at the humidifier's inlet rises. As air temperature rises, its ability to store water particles increases as well. As a result, air's relative humidity (RH) approaches saturation, which ultimately improves the efficiency of the entire system. According to observations, the highest possible water output was 0.75 L/d at an air temperature of 40°C.

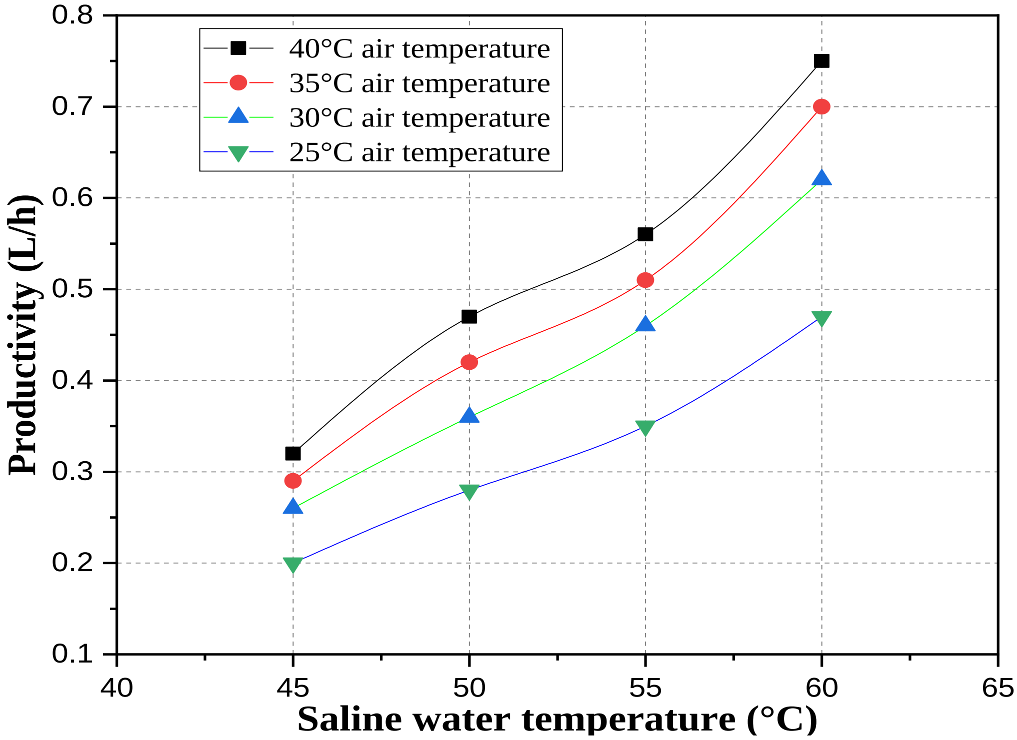

Figure 4.1 System's fresh water productivity with the varying saline water temperature in the BC humidifier for various air temperature at humidifier's inlet

4.1.2 Effect of Air Mass Flow Rate

Air mass flow rate with an increment of 0.001kg/s at a time were employed from 0.0020 kg/s to 0.0050 kg/s to determine how the performance of a system is affected by air mass flow rate. The configuration was tested with a bubble column height of 7.5 cm, a hole diameter of 2.5 mm, and air temperature of 40 °C. The saline water temperature was also kept constant at 60 °C. The higher air mass flow rate causes a higher water production yield. This is because the improved mass transfer between air and water is most practicable at greater air velocities. The high mass and heat transfer enhances the RH of the air hence high yield is achieved. For the air mass flow of rate 0.005 kg/s the highest yield of 0.75 L/h productivity was recorded. The graph in the figure 4.2 depicts the connection among air mass flow rate, saline water temperature and HDH system output yield in liters per hour.

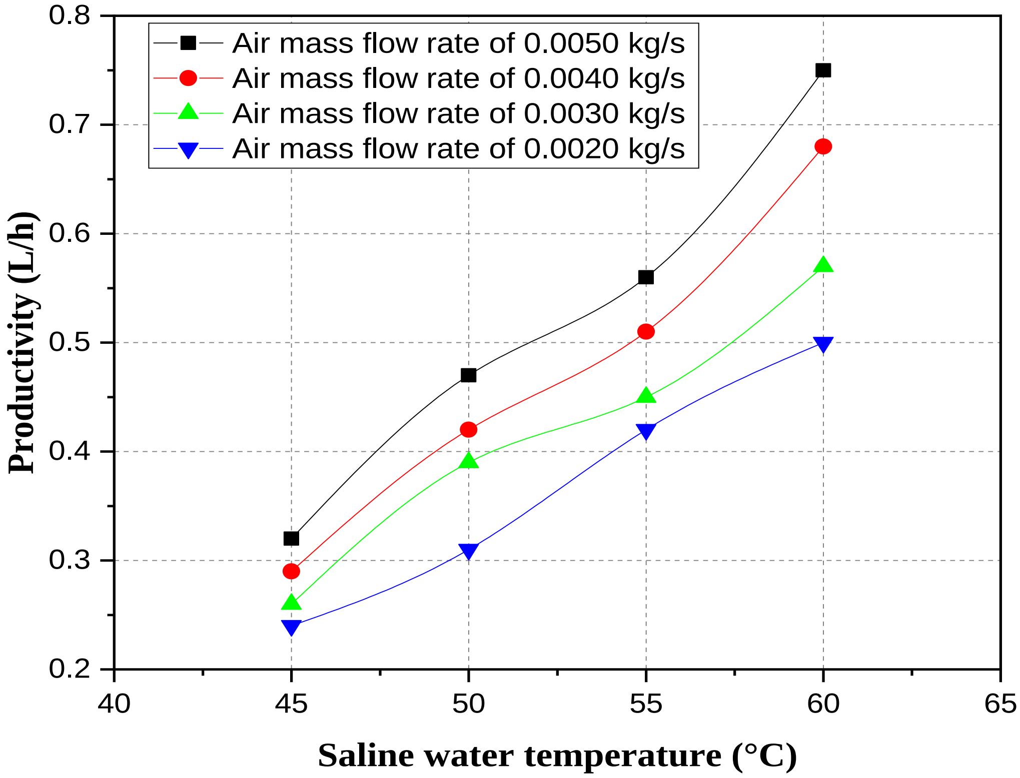

Figure 4.2 Dependence of fresh water yield on the air mass flow rate of air and saline water temperature

4.1.3 Effect of Bubble Column Height in the Humidifier

The graph in figure 4.3 shows how changes in water elevation in the BC affect fresh water generation. The height was adjusted in 2 cm increments, going from 3.5 cm to 7.5 cm. The experiment's constants were the air mass flow rate of from 0.001kg/s to 0.0050 kg/s, the hole diameter of 3.5mm, the water and air temperatures of 60 °C and 40°C, respectively. The highest production of distillate was measured to be 0.75 L/h for 7.5 cm of level of water in the BC. The rising water level of the bubble column gives the air adequate time to contact the salty water, improving mass and heat exchanges between the two streams. Better system yields are the result of this.

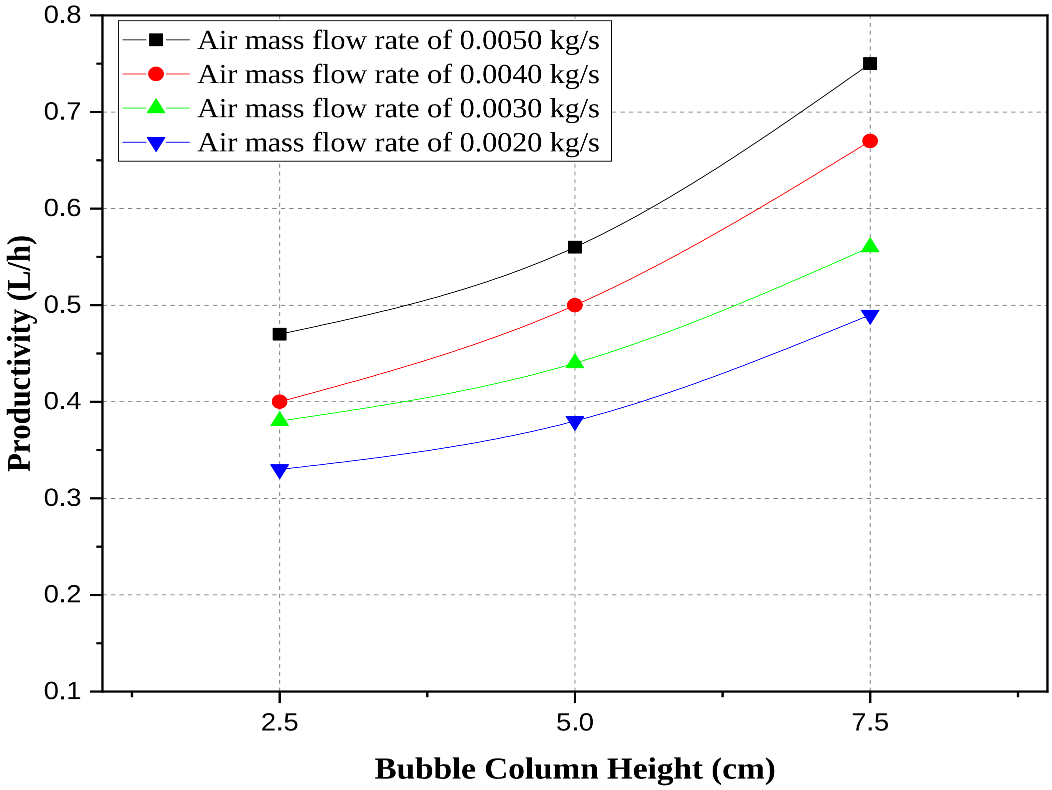

Figure 4.3 Effect of bubble column water height on distillate produced per hour at various air mass flow rates

4.1.4 Effect of Bubbling Hole Diameter

The hole diameter on the periphery of the concentric pipe in the bed of the BC humidifier has an impact on the system's output, as depicted in the figure 4.4. The hole diameters of 2.5 mm, 3 mm and 3.5 mm were drilled in the periphery of the circular pipe and tested for each type distinctly. The water and air temperatures were fixed at 60 °C and 40 °C, respectively, for the experimental test, and the humidifier's BC water level was maintained at 7.5 cm. Air mass flow rates from 0.002kg/s to 0.005kg/s were tested at an increment of 0.02kg/s at a time. The system's yield is negatively impacted by the increase in hole size. Because of the strong turbulence caused by the tiny hole diameter, there is a greater mass and heat transfer between the air and water molecules. The effective heat and mass exchange leads to rise in RH of the air right at the exit of the BC humidifier and hence the output productivity of the system hike up. From the figure 31 it can be seen at a hole diameter of 2.5mm, the maximum amount of distillate is recorded.

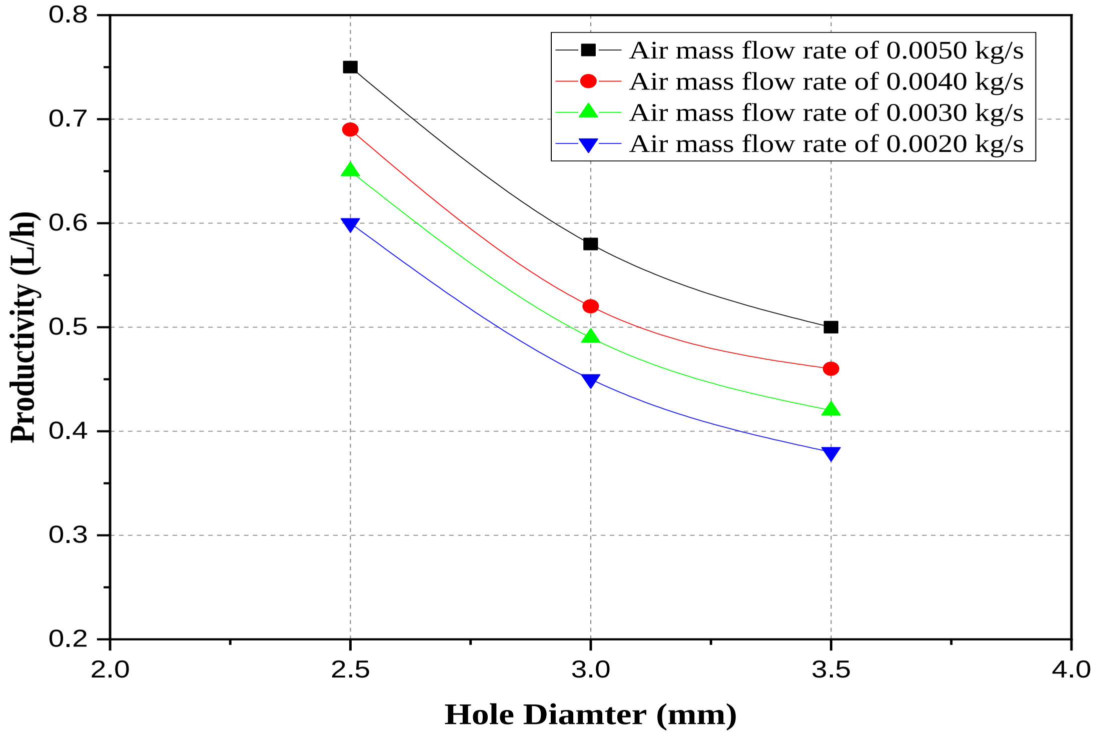

Figure 4.4 Effect of the hole size in pipe periphery on system's productivity taking different air mass flow rates

4.2 Effect of Nanofluid and Irradiance

The system's hourly fresh water yield is shown in Figure 4.5 for both the heat transfer nanofluid and without nanofluid in the solar water heater, along with solar radiation at its optimum levels for each parameter. On each day of the experimentation and testing, the peak solar irradiance and temperature were over 900 W/m^2 and 30 °C, respectively. Since the sun radiation was almost the same across all of the test days, the productivity and effectiveness of the under consideration desalination system were largely unaffected. The tests were carried out on 10^{th}, 20^{th}, and 30^{th} July, 2022 and the average results have been published. Fresh water output was seen improve as irradiance grew; it peaked at midday and then slightly declined afterwards. The graph shows that TiO_2 nanofluid based solar water heater captures more energy than pure water. $Ti0_2$ nanofluid has a 27% higher gain in productivity than water based solar water heater.

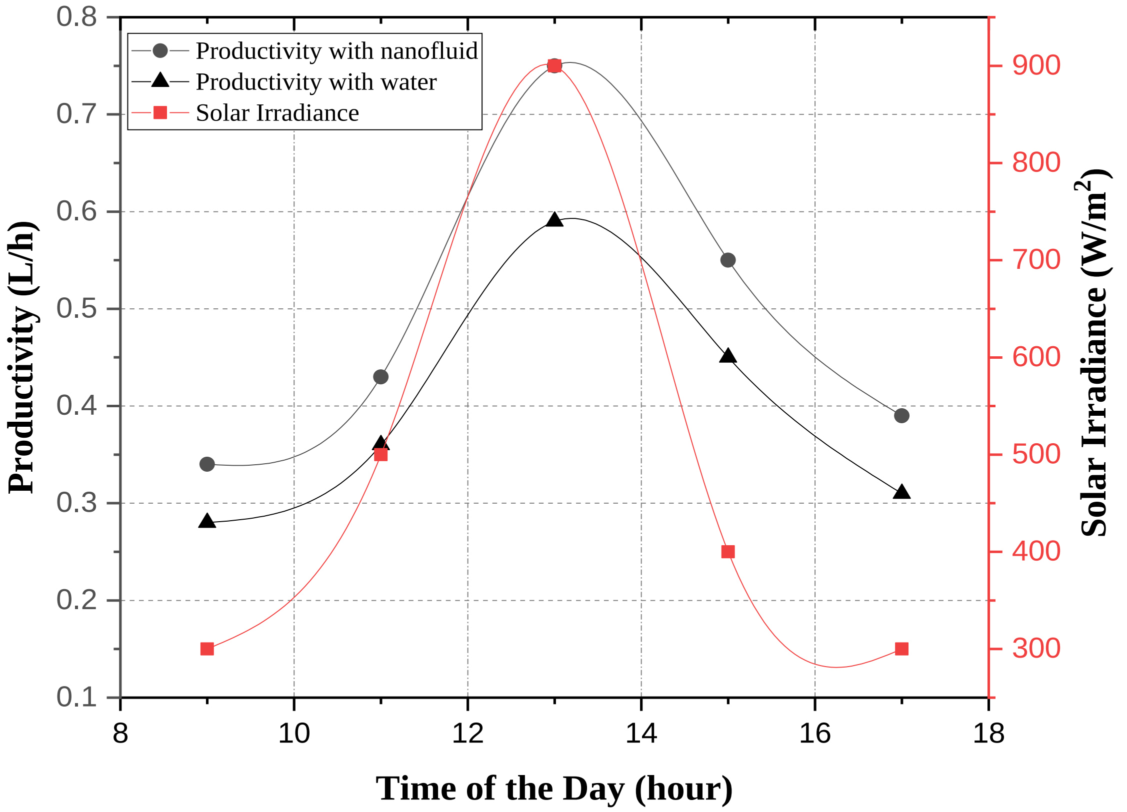

Figure 4.5 Fresh water productivity and solar radiation are compared with the time of the day

4.3 Comparison of System's Productivity with Previous Literature

The fresh water output in L/h of several HDH systems employed in the current study and other past investigations is compared in Table 4.1. The combination of BC humidifier, BC dehumidifier and nanofluid based solar thermal water heater is first time utilized the present research. The output of fresh water is fairly reasonable than the other system listed. The peak productivity was recorded to be 075 L/h and cumulative productivity for the whole day comes out to be 4.61 L/d (average per hour is 0.51L/h).

Table 4.1 Comparison of various HDH system, their heating sources and fresh water productivity per hour.

Author and Year	Heating source	Humidifier	Dehumidifier	Peak Productivity (L/h)	Ref
Zhang L et al. 2011	Solar water and air heater	BC Humidifier	Coil type heat exchanger	0.26	[7]

Adel M et al. 2014	Flat plate solar collector	Nozzle flash humidification	Inner cylindrical wall surface	0.431	[5]
H.Hamed et al. 2015	Flat plate collector	Plate-absorber with a porous pasted fabric	Condenser with a tubular heat exchanger	0.304	[8]
Behnam et al. 2016	Evacuated tube combined with thermosiphon heat pipe	BC Humidifier	Shell and tube type	0.026	[2]
Rajaseenivasan et al. 2016	Flat plate air-water collector (dual purpose)	BC Humidifier	Shell and tube type	0.71	[3]
Farshchi et al. 2016	Flat plate collector	Combination of HDH system and cascade solar still.	-	0.225	[6]
Patel V et al. 2020	Electric water heating rod	Bubble column	Thermoelectric cooler	0.54	[4]
Present work	Nanofluid based solar thermal water heater	BC Humidifier	BC Dehumidifier	0.75	-

The graphical depiction of comparison with the past literature is depicted in the figure 4.6 below. The cost for one liter of fresh water productivity of various systems shows much variations with one another. In contrast, the cots for per liter of water productivity of current study shows much coherence with that of the system proposed by Rajaseenivasan et al [3].

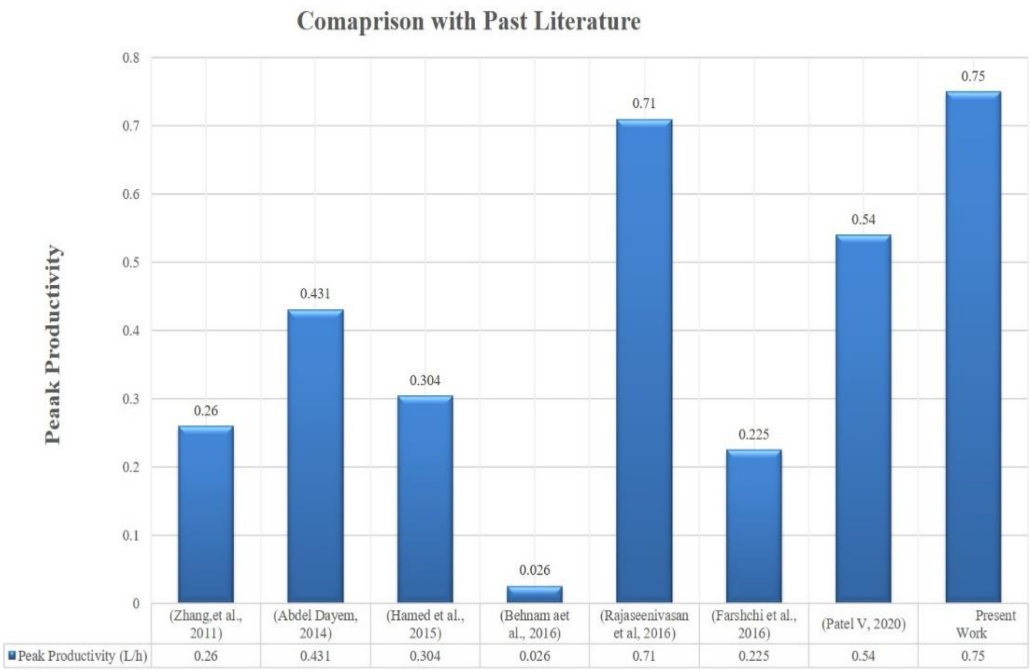

Figure 4.6 Comparison with the previous literature in terms of peak productivity

4.4 Energy Analysis

Energy analysis is crucial to understanding how well a system performs in relation to numerous energy-related elements. The table 4.2 below lists the electrical equipment's involved with the suggested HDH system and their respective energy consumption.

Table 4.2 Power ratings expressed in watts for the electrical equipment's linked with the HDH system.

Device	**Units**	**Power Rating (Watts)**	**Combined Power Rating (Watts)**
Air blower	1	300	300
Water Pump	2	12	24
DC fan	1	8	8

The total power required is 332 W. Considering 8 hours of operation a day, the total energy demands come out to be 2.65 kWh. The highest freshwater yield per hour is recorded to 0.75 L, and the maximum daily output is 4.61 L (for 8 hours operation a day). Hence, 0.57 kWh/Liter of energy is needed to generate one liter of water.

5.5 Cost Calculations and Analysis

A vital step in determining the viability of the HDH system's operation and its payback period is to understand its economic aspect. The primary goal is to determine if the HDH system is economically viable in respect to the fundamental base cost, the cost of water productivity per liter, and lastly for a whole year. The total capital cost of a common water purification or desalination system comprises costs for associated equipment, pipe expenditures, land and building costs, labour, transportation of the system, power (PV panels), solar collector, maintenance, and operating costs.

The system is designed for outdoor, dispersed rural regions, thus land costs are disregarded. The system may be placed and installed with just extremely elementary technical skills, necessitating no additional construction costs. The cost of operation, maintenance and upkeep, is incorporated as 15% of the capital cost of the intended system, is necessary on a modest scale. A significant portion of the total cost in the cost analysis is attributable to the cost of the equipment. Table 4.3 enlist and includes local market prices for several pieces of equipment used in the planned HDH system.

Table 4.3 Cost breakdown of the system components in $

Equipment	Quantity	Unit Price	Cost ($)
BC Humidifier	1	55	55
BC Dehumidifier	1	60	60
Air Blower	1	12.5	12.5
Water Pump	2	4	8
Solar PV Panel	1	70	70
Solar Water Heater	1	50	50
Piping	1	7.5	7.5

Temperature controller	1	7.5	7.5
Portable stand	1	5	5
Temperature probes	6	3	18
Humidity sensors	2	4	8
Flow meter	1	12.5	12.5
Water tanks	2	5	10
Miscellaneous	-	5	5
Total			334

The proposed HDH system has a $334 as the total primary capital cost (C_c)

The calculations leads us to results in which the unit liter cost for fresh water comes out to be $ 0.0334. Considering the market price in the local market this price is very feasible for the remote communities which are scare of fresh water. The precise results of the economic and cost parameters for the HDH System are shown in Table 4.4.

Table 4.4 Values of several metrics associated with the HDH system's cost analysis

Type	**r (%)**	**y (yr)**	**C_C ($)**	**CRF**	**A_c ($)**	**SV**	**YSV**	**S_{ff}**	**C_M ($)**	**C_A ($)**	**W_Y (L)**	**C_{PL} ($/L)**
Value	15	10	334	0.19	66.53	13360	657.31	0.05	9.97	73.22	2190	0.0334

In Pakistan, the average local market price (CMP) for a liter of water is $ 0.15.

Payback period in liters comes out to be 2684.5 L while the payback period in years comes out to be 1.30 years (16 months).

4.4.1 Comparison of System's Cost with Previous Literature

The table 4.5 below compares costs based on the cost per liter of fresh water for the current study and from earlier publications. The current study shows coherence with previous literature.

Table 4.5 Comparison of system's productivity with previous literature

Author	System Description	GOR	Cost of Productivity ($/L)	Ref
Zhani and Bacha	Cross flow humidifier; solar water and air collectors	-	0.098	[8]
El-Agouz	Electric water heater with air compressor	0.8	0.052–0.095	[9]
M A Hamed et al	Solar water collector; Counter-flow humidifier.	2.2	0.0578	[10]
Rajaseenivasan et al.	BC humidifier and Solar air collector	0.78	0.019–0.032	[5]
Deniz and Cinar	Solar collector (air and water); Counter-flow humidifier.	0.3154	0.0981	[11]
Xu et al	Solar water collector: Cross-flow humidifier	1.24	0.04188	[12]
Y Zhang et al	HDH system: heat pump	2.052	0.051	[10]
Current study	Solar water heater; BC humidifier and BC dehumidifier	0.5	0.0334	-

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Chapter 5 : Conclusions and Recommendations

5.1 Conclusions

HDH desalination systems have demonstrated significant promise for supplying clean water in off-the-grid locations with sparse access to energy. The HDH systems may be powered by low-grade waste heat and renewable energy sources, such as geothermal energy, solar thermal energy, and waste heat from industrial processes. Therefore, HDH systems are a viable and affordable method of providing freshwater in remote decentralized areas. A lab scale HDH system was developed in this thesis project. The arrangement was based on the HDH water desalination phenomena and included a bubble column humidifier, bubble column dehumidifier, and nanofluid based solar collector.

- The per hour fresh water productivity was 0.4 to 0.75 L/h during the investigation, but the system's best experimental yield was recorded at 0.75 L/d considering a hole diameter of 2.5 mm, an air mass flow rate of 0.016 kg/s, a saline water temperature of 60 °C, an air temperature of 40 °C, and a height of 7.5 cm for the BC water height
- The system's GOR was 0.5 at 0.005 kg/s air mass flow rate.
- The results show that the daily production is inversely connected with bubble generation hole diameter in BC humidifier but directly correlated with air and saline-water temperature, water column height in BC humidifier, and air mass flow rate.
- The system has a very minimal production cost per liter of water produced, at $ 0.0334 per liter, with a payback period of 1.3 years.
- According to the findings, utilizing 2 wt. % TiO_2 nanofluid in flat plate solar water heaters leads in a 27% increase in fresh water output when compared to using water as the working fluid.

These results, findings and outcomes are crucial in the process of designing, developing and fabricating of an HDH system's components namely BC humidifier, BC dehumidifier and the relevant solar water heater. In order to use sustainable energy and lower the cost of input power, solar air and water heating is also necessary and practical. A multi-stage process can be quite effective in obtaining increased yields. Additionally, a significant quantity of energy from the dehumidifier's hot side is lost to the environment. The dehumidifier portion's lost energy can be avoided and utilized in subsequent tasks..

5.2 Recommendations

- In areas where solar energy is scarce, investigate the viability of employing a modest wind turbine or a geothermal source to power the motors and blowers. The cost of the electricity, the power supply, and the wiring may be decreased if the electrical equipment of the HDH system is powered by renewable sources. It is more beneficial for isolated places without power connections and more ecologically friendly.
- Continuous freshwater production can be achieved using energy storage technologies (such as phase change materials).
- Research has to be done on the use of substitute carrier gases other than air, such as He and CO_2.
- Utilize this improvement in combination with any other HDH system upgrades. It will need further research to determine whether combining several improvements or alterations into one system won't have a significant combined impact on productivity.
- Pumping energy for air and water has not been considered in the current analysis since it is less significant than the energy needed for heating. However, on an industrial or big scale, it cannot be disregarded, particularly when the mass flow rate is considerable.
- Given the HDH system's unquestionable benefits, it is clear that the method may be considerably improved by integrating it with other processes and technologies. The HDH desalination system may be linked with vapour compression refrigeration cycles (VCR) to simultaneously deliver freshwater and create thermal comfort inside the conditioned space.

Appendix

Publication Extended Abstract

Clean water production using bubble column humidification-dehumidification water purification system coupled with a nanofluid based solar thermal water heater

Salim Akhtar [1], Hafiz M. Abd-ur-Rehman [2], Majid Ali [1], Adeel Waqas [1], Sana Yaqub [1], Sehar Shakir [1, *]

1. *U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology Islamabad, Pakistan.*
2. *School of Mechanical & Manufacturing Engineering (SMME), National University of Sciences and Technology Islamabad, Pakistan.*

[*] Corresponding author

Abstract

In decentralized areas with modest quantum fresh water needs, the bubble column humidification dehumidification (HDH) water purification systems are attributed to have excellent outcomes. The current work comprises of a bubble column humidifier to raise the humidity level in the air and a bubble column dehumidifier to extract moisture from the humidified air. The system was coupled with a nanofluid based flat plate solar water heater to fulfil its thermal energy requirements. Experiments were performed at different design and operational conditions to determine the hourly freshwater production. The result indicated that the BC HDH system's hourly freshwater output increases in correlation with increases in water temperature, water height in the BC column, and air mass flow rate, but decreases in correlation with increases in bubble generating hole diameter.. The hourly freshwater productivity ranged from 0.4 to 0.75 L/h with highest experimental yield was achieved between 12 – 1 pm when solar irradiance was maximum 900 W/m^2. The use of nanofluid Titanium dioxide (TiO_2, 2 % by weight) in solar water heater resulted in an increase of freshwater productivity by 27%. The cost analysis revealed a payback period of 1.3 years, justifying its economic viability with an added advantage of its decentralized deployment in remote communities.

Keywords: *bubble column, humidification-dehumidification, nanofluid, solar water heating, TiO_2, decentralized*