Sustainable humidification-dehumidification desalination system using low-grade heat source

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Saeed Dehghani.

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Executive summary

Humidification-dehumidification desalination (HDH) cycle is one of the methods for producing freshwater from seawater or saline water for small-scale and low-cost applications. Major energy source of the desalination system is thermal energy that can be provided from any available low-grade heat sources such as industrial waste heat or solar thermal collectors. The working principle of HDH system is very similar to the rain cycle which air is humidified in by evaporation of seawater. Then the humidified air moved by wind streams to cooler places where it condenses to water droplets. In this project, at first mathematical thermodynamic based models for different types of the HDH cycle are developed, and the effect of operational parameters such as temperatures and flow rates on cycle performance parameters like gain output ratio (GOR) and recovery ratio (RR) are studied. Also, the heat and mass transfer analysis of the cycle is conducted to examine the behavior of key performance parameters such as temperatures, flow rates, surface area, and air velocity on the heat and mass transfer rate. Further, a new concept of using a heat pump is investigated to simultaneously provide heating and cooling load requirements of the HDH system in an optimized way. A mathematical model is developed to investigate the optimum operating condition of the HDH system for fully coupled condition operation. Experimental investigations of the cycle performance and potential of water production at different operating conditions, including the effect of temperatures, feed salinity, air to seawater flow rate ratios, and freshwater to seawater flow rate ratios studied. The experimental findings validated with the mathematical model. To reach an environmentally sustainable solution in HDH system, brine recirculation method is proposed, mathematically modelled, and experimentally investigated. It is found that the brine recirculation method is practically feasible and can significantly reduce the rejected brine volume.

Keywords: Humidification-Dehumidification, HDH, Desalination, Heat pump, Direct Contact Dehumidifier, Brine management, Sustainability

Publications from this research

Book Chapter:

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Saeed Dehghani, Abhijit Date, Aliakbar Akbarzadeh, "Performance analysis of a heat pump driven humidification-dehumidification desalination system", ***Desalination***, Vol. 445, Pages 95–104, 2018. (https://doi.org/10.1016/j.desal.2018.07.033)

Saeed Dehghani, Abhijit Date, Aliakbar Akbarzadeh, "An experimental study of brine recirculation in humidification-dehumidification desalination of seawater", ***Case Studies in Thermal Engineering***, Vol. 14, 2019. (https://doi.org/10.1016/j.csite.2019.100463)

Conference paper:

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Nomenclature

Symbol	
T	Temperature (°C)
$\dot{m}$	flow rate (kg/s)
$\dot{Q}$	heat rate (kW)
$\dot{H}$	enthalpy rate (kW)
mr	Water to air mass flow rate ratio (–)
h	specific enthalpy (kJ/kg)
RR	recovery ratio (–)
cp	specific heat capacity at constant pressure (kJ/kg.K)
$SEEC$	Specific Electrical energy consumption
COP	Coefficient of performance
f	average slope of the saturated air enthalpy versus temperature (kJ/kg.K)
NTU	Number of transferred units
Me	Merkel Number
a	Specific area (m2/ m3)
H	Packing height (m)
CR	Heat capacity rate ratio
PR	Pressure ratio (–)
$\dot{W}$	Work (kW)
Greek letters	
ω	absolute humidity of dry air or humidity ratio (kg_w/kg_a)
φ	relative humidity (–)
ε	effectiveness (–)
Δ	difference or change
η	efficiency (–)
Subscripts	
a	air
da	dry air
dw	distilled water
b	bottom
t	top
sw	Seawater, saline water
fw	fresh water
max	maximum
m	middle

br	brine
h	humidifier
d	dehumidifier
in	input
out	output
1,2,3,4	Flow states
com	compressor
con	condenser
eva	evaporator
ref	refrigerant

Acronyms

CAOW	closed-air open-water system
CWOA	Cold-water open-air
HDH	Humidification-dehumidification
HME	heat and mass exchanger
DC	Direct contact
IWMI	International Water Management Institute
RO	Reverse Osmosis
MSF	Multi-stage Flush
MED	Multi-effect Distillation
MD	Membrane Distillation
MVC	Mechanical Vapor Compression
ED	Electrodialysis

Chapter 1:
Introduction

1.1. Background

Water scarcity around the world shows itself at different levels. There are several factors which deteriorated the water scarcity situation around the world in the recent century. Among them population growth, mismanagement of water resources, per capita water consumption, climate change, etc can be mentioned. There are numbers of engineering solutions for addressing the water scarcity around the world.

Desalination is a method of removing salt from saline water to purify to an extent which is adequate for applications such as drinking or agriculture. There are various desalination methods to achieve this. These methods can be categorized to thermal-based methods and membrane-based methods. The thermal methods usually require thermal energy while membrane-based methods need electrical energy as a primary source of energy. Reverse osmosis(RO), membrane distillation(MD), multi-stage flash distillation(MSF), multiple-effect distillation(MED) are among the most industrialized desalination technologies. Energy sources with no greenhouse gas emissions and low carbon footprint such as renewables can make the desalination system more environmentally sustainable. The saline water for the desalination process feed can be provided form seawater

or underground saline water. For the coastal areas, where seawater is easily accessible to supply the feed of the desalination plant. The outlets of the desalination process are distilled water as the main product, and concentrated brine as a by-product. Discharging the concentrated brine to the environment can be highly harmful for an ecosystem and result in catastrophic consequences. Therefore, providing an environmentally sustainable solution for brine management is highly valuable.

Humidification-dehumidification desalination works based on the evaporation and condensation principle. Humidification happens when water molecules evaporates from seawater to air, while humidification occurs when water vapor molecules in air condenses to liquid. The HDH working principle is very similar with the natural rain cycle. In both main processes, there is a heat and mass transfer between air and water/seawater which determines the thermal performance characteristics of the HDH system and eventually water production rate.

Seeking a sustainable, economically viable, and relatively simple solution for providing freshwater for small-scale desalination applications was the primary motivation of this project. However, ability of the HDH system to work with high salinity feed, makes it a possible option to be coupled with other desalination systems such as RO for reducing the environmental impacts. The energy requirements are low-grade heat as well as electricity which can be provided from solar powered thermal collectors or photovoltaic panels.

In this research project, the HDH desalination system with a direct dehumidifier is considered for both analytical and experimental studies. For the analytical studies, a thermodynamic-based model is developed to predict the thermal performance of the system under different operating conditions. For the experimental studies, a setup is designed and fabricated. Then, effect operational parameters on the HDH system performance are tested. To reduce the environmental impacts of the HDH system, a method of brine recirculation is proposed, mathematically modelled and experimentally tested. Moreover, to make the HDH system fully electric driven, new idea of using a heat pump is investigated, mathematically modelled and analysed.

1.2. Research questions and research objectives

The research questions are as following:

1. What is the influence of the key operational parameters on the characteristic and performance of the HDH system? (operational parameters like temperatures, salinity and mass flow rate of air and water on the system performance and thermal efficiency)
2. How the optimal performance of the HDH system that results in minimum energy consumption and maximum water production can be achieved?
3. How to make the HDH system more environmentally sustainable and reduce its environmental impacts?

The research objectives are as following:

- Experimentally and analytically study the HDH desalination system thermal performance behaviour
- Develop a relatively simple system design which is easy and practical to fabricate and operate.
- Develop optimal performance strategies for the HDH system.
- Reduce the environmental impacts of desalination systems.

1.3. Scope of research

In general, the scope of the research is to review the current literature of thermal desalination with low-grade thermal energy source as well as contribute to body of knowledge by presenting a highly practical solution for thermal desalination as an economically feasible technology. In addition, to analyse the performance of the humidification-dehumidification desalination cycle and optimize it for higher freshwater production while having lower energy consumption, and to make it more competitive with other currently available technologies. Humidifier and dehumidifier are essentially heat and mass exchanger which are employed for heat and mass transfer between air and water. Solar energy

in can be utilized in form of solar thermal collectors or photovoltaic are an environmentally friendly energy source to run the HDH system. Cost of the solar technology will be critical when making a design.

Initially, in this research study, mathematical and experimental investigations of the proposed humidification dehumidification systems are presented. Then a comprehensive analytical model based on mass and energy balance is developed and thermal behaviour of the HDH system is evaluated. A detailed analytical model is used to simulate and predict the HDH system performance based on system characteristics such as humidifier and dehumidifier sizes and heat and mass transfer area. The developed model is evaluated with experimental results of the fabricated HDH rig.

The idea of the HDH system with low volume rejection of concentrated brine is examined and its practical viability is discussed. A model is developed to predict the HDH system behaviour with different concentrations of feed water. Further, experimental tests are conducted to evaluate the mathematical model predictions and to observe the actual performance of the system and its practicality.

To address the thermal energy requirements of the HDH system a new concept of using a heat pump to drive the HDH system is proposed. A mathematical model is developed to study the vapour compression heat pump with R-134a refrigerant coupled with the HDH system and optimize the heat pump driven system performance. The idea is that to provide to simultaneously provide the heating load of humidification process and cooling load of dehumidification process.

1.4. Research methodology

To understand the current state of the research and development in evaporation-based desalination a literature review will be undertaken. Further, a detailed review of the studies related with humidification-dehumidification desalination working principle will be carried out.

A thermodynamic mathematical model will develop in the first stage to study the performance of the two configurations of HDH systems, one with direct contact

dehumidifier and another with indirect contact dehumidifier. The HDH systems performance with direct and indirect contact dehumidification process will be compared. The indirect HDH systems have been subject of many studies, therefore it will be used as benchmark for comparing the performance of the proposed HDH system with direct contact dehumidifier.

To understand the HDH system performance, a more detailed-oriented mathematical model of the HDH system with direct contact dehumidifier will be developed. In this model properties of the heat and mass exchange devices will be considered to build a more accurate mathematical model of the HDH system.

To practically test the performance characteristics of the HDH system an experimental rig will be fabricated using various type of the common materials that are already available in the market. Inexpensive and locally available material for fabrication considered. After fabricating the experimental setup, various experimental tests were conducted. After several test iterations of the HDH system reliable results of the system characteristics and thermal behaviour were achieved. The developed model will be validated with the experimental results.

In another study, to provide the thermal requirements of the HDH system for a fully electric driven system a heat pump will be considered to assist the HDH system. A mathematical model will be developed to analyse the performance of the heat pump driven HDH system. Electrical energy is used to drive the heat pump which will be supplying the thermal energy requirements of the HDH system.

As having a desalination system that can operate with high saline feed is helpful for reducing the environmental impacts as well as it is economically considered a competitive advantage of a desalination system, effect of high feed salinity on HDH system performance is experimentally studied. Feed salinity is an important operational parameter which there has not been enough research studies about it. Therefore, a method for minimizing the rejected brine volume of the HDH system is proposed. Then, experimental investigations are undertaken to examine the feasibility of the proposed brine recirculation method. The proposed method could be highly beneficial for making the system more environmentally sustainable.

1.5. Thesis structure

- Chapter 1: Overview and general explanation of the humidification-dehumidification systems.
- Chapter 2: A literature review of the water scarcity issue, desalination and humidification-dehumidification systems with a direct contact dehumidification as well as indirect contact dehumidification process. In this chapter both mathematical modelling and experimental studies are reviewed.
- Chapter 3: A mathematical model that incorporates thermodynamic analysis of HDH system with direct contact humidifier are presented in this chapter.
- Chapter 4: In this chapter a mathematical model using thermodynamic analysis along with heat and mass transfer which includes effectiveness of the heat and mass exchange devices are presented. Experimental test results are presented in this chapter as well.
- Chapter 5: A heat-pump assisted HDH with direct contact dehumidifier is introduced and the performance of the proposed method is analysed to make the HDH system fully electric driven.
- Chapter 6: To make the HDH system environmentally sustainable, a method to make the system more environmentally sustainable is called "brine recirculation" is introduced. A mathematical model is developed based on the proposed model and the practical feasibility of the brine recircuited HDH system is experimentally investigated.
- Chapter 7: concludes the study of the HDH desalination with direct contact dehumidifier from low grade heat source. In addition, some recommendations for future work and suggested, and research directions are presented.

Chapter 2:

Literature Review

2.1. Introduction

Freshwater is essential to continue living on Earth. Water is needed for various human activities such as food preparation, drinking, personal hygiene and laundry. Water is required for agriculture, industrial applications, and domestic usage. Major portion of the water is consumed in the agriculture sector[1].

Water is highly abundant on Earth, however; freshwater is a small percentage only about 2.5% of the total available water on Earth. The rest of 97.5% of available water is seawater which requires major treatments such as desalination to be usable. Moreover 80% of the freshwater is frozen water in glaciers, therefore only 0.5% of the total amount available water on Earth is available for utilization which can mainly be found in some lakes, rivers and aquifers. Uneven distribution of the usable water around the world affects water availability and makes the situation more complicated and limits water accessibility in some regions around the world.[2]

The hydrological water cycle makes continuous movement of water on, above, and below the Earth surface. The mass of water on Earth remains constant over time, nevertheless portion of the major reservoirs of freshwater and saline water is variable depending on geographical locations. The hydrological cycle

involves the exchange of energy and mass between water and air. Evaporation and condensation are the main processes of the cycle. Seawater evaporation happens when water vapour molecules diffuse into air which is an endothermic process. Condensation of air occurs when air is cooled down to its dewpoint which is an endothermic process. Precipitation is the main form of water release form air in nature. [2]

Freshwater consumption varies considerably depending on geographical region of the world. The World Health Organization (WHO) recommends a minimum value of 15 to 20 litre per person per day[3]. This can be adequate just for human basic needs like food preparation, personal hygiene, laundry and drinking. This value increases up 50 litre per person per day when considering social infrastructures such as schools, hospitals and so on. However, it is expected that the per capita water consumption demand will increase by the year 2040 [3].

2.1.1. Water scarcity

According to the International Water Management Institute (IWMI), around 25 percent of the world's population lives in areas where water is physically scarce, and over one billion people live where water is economically scarce. Economic water scarcity refers to the places where although water is available in rivers and aquifers, the infrastructure is lacking to provide the freshwater to people [2].Population growth, mismanagement of water resources, increased water consumption per capita in urban areas, traditional irrigation methods, drop in rainfall due to the climate change and change in weather patterns are the main reasons resulting in water scarcity around the world.

There are different approaches to address and resolve water scarcity. Desalination is a highly effective solution from the engineering perspective. Desalination is a way of removing different kind of salts from water to produce freshwater out of a solution of saline water. There are different ways to achieve this. As the salts do not separate from the water naturally, thus the process requires some energy to drive the separation process[4, 5].

The main separation process in nature is evaporation of seawater using thermal energy provided by the sun. Electrical, mechanical, or thermal power can be considered as the primary source of energy for desalination. In general, desalination technologies can be classified according to three perspectives: (i) extracted material; (ii) the type of separation process adopted; (iii) the type of energy used.

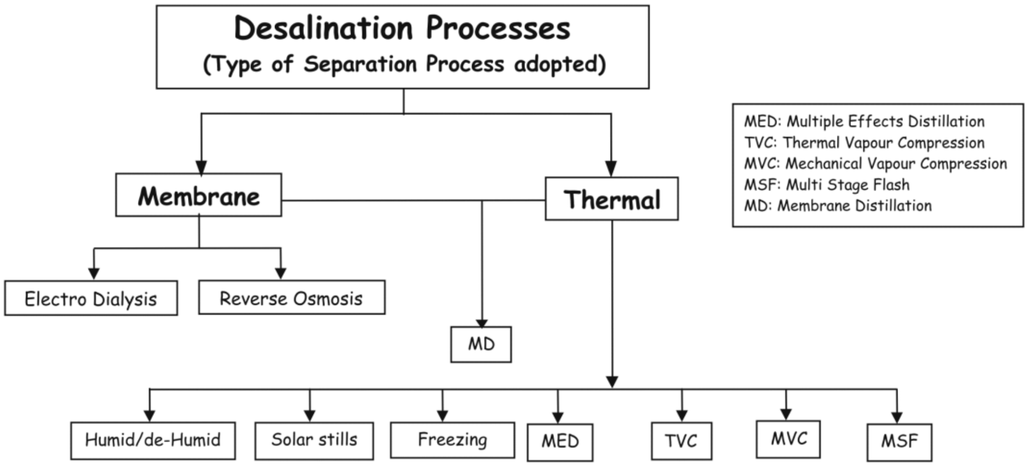

Fig. 2-1: Desalination technologies classification based on the separation process[5]

Among the various types of desalination technologies, reverse osmosis, multistage flash, and multi-effect distillation are the most commonly used around the world. Desalination is an energy-intensive technology. Thus, alternative energy sources such as industrial waste heat, and solar energy can be considered to make the process more environmentally sustainable. In Table 2.1 electrical and thermal energy consumptions of these technologies per meter cube of water produced are mentioned. It should be mentioned that the salinity of the saline water solution is an important factor in the operation of desalination technologies. For instance, reverse osmosis is not capable of working with high salinity feed. In general, the salinity of feed impacts the performance and the cost of a desalination system[6].

Table 2.1: Energy consumption of the major desalination technologies [7]

Desalination technology	Specific Energy Consumption (kWh/m^3)		Operating temperature (ºC)
	Electrical	Thermal	
RO	2.5-7	-	< 45
MSF	3-5	70-90	< 120
MED	1.5-2.5	40-110	< 70

In Fig. 2-2: desalinated water in meter cubed per day at different regions of the world is demonstrated which include all source water types including seawater, brackish water, and wastewater. In North America, brackish water accounts for the major portion of the feed source while in the rest of the world seawater feed is the major feed source for desalination. Gulf countries in Middle East have the highest seawater desalination capacity in the world[8].

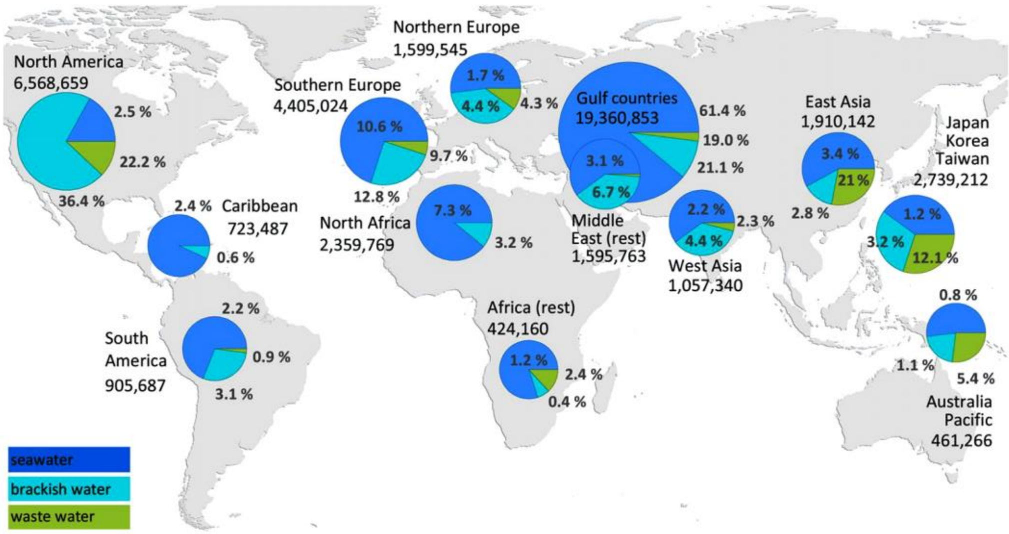

Fig. 2-2: Global desalination installed capacities in cubic meter per day.[7]

In Australia to improve the water security affected by climate change and population growth, saline water desalination plants have been constructed. Traditionally, Australian water has been supplied from surface and underground water resources. However, when the Millennium Drought that happened between

1997 and 2009 raised concerns about the security of urban water supply from these traditional sources. The five major urban centers in Australia have a total seawater desalination capacity of 535 GL per year[9]. In addition to these major plants, several smaller desalination plants provide purified water to industries and mines.

2.2. Humidification-dehumidification desalination

Humidification-dehumidification (HDH) desalination is one of the recently emerging technologies in comparison to MSF, MED and RO, which attracted the researchers' attention. Key characteristics of the HDH desalination system including simplicity in design and fabrication, water supply for remote areas, small scale production rate and solar energy coupling capability makes it a possible alternative among other desalination technologies. For example, people living in an area without accessing to water grid such as small islands, communities in the coastal regions, or any other places with small freshwater demand. HDH is a possible option for developing countries that provision of low-cost and simple technology of clean water production are needed.[6, 10]

HDH desalination technology can be considered a viable option when large-scale thermal desalination systems such as multistage flash (MSF) and multieffect desalination (MED) are not feasible due to cost and size constraints, or where there is insufficient electric power supply to operate reverse osmosis (RO). The predecessor of the HDH cycle is a simple solar still, whose efficiency is low. Even with proper insulation, the solar still produces distilled water inefficiently depending on the operating conditions. The major problem of solar stills is its low thermal efficiency which is mainly attributable to its glass cover, where water condensation results in high loss of energy in the form of latent heat. To eliminate heat loss of solar stills, consideration of more efficient methods, such as the HDH cycle are researched and studied. HDH desalination is a more efficient modified version of a solar still [11, 12].

The HDH desalination system duplicates the natural rain phenomenon for producing distilled water. In nature, the vapor is produced from seawater when the sun shines on it; next, this vapor is carried by air in cloud form until its temperature

drops, causing it to condense into rain droplets. A humidifier evaporates seawater to produce moist air, and a dehumidifier condenses that air moisture.

In Fig. 2-3 the overview of an HDH system is shown. Humidification process separates pure water from a mixture of impure saline solution. A humidifier transfers water vapor into an air stream, while concentrated seawater is collected at the bottom and rejected as brine. The vapor inside the air stream will condense out of the stream and will eventually be extracted out of the dehumidifier. Water will be heated after being preheated in a dehumidifier which is before spraying it in a humidifier. In air-heated HDH systems air will be heated before entering the humidifier[8].

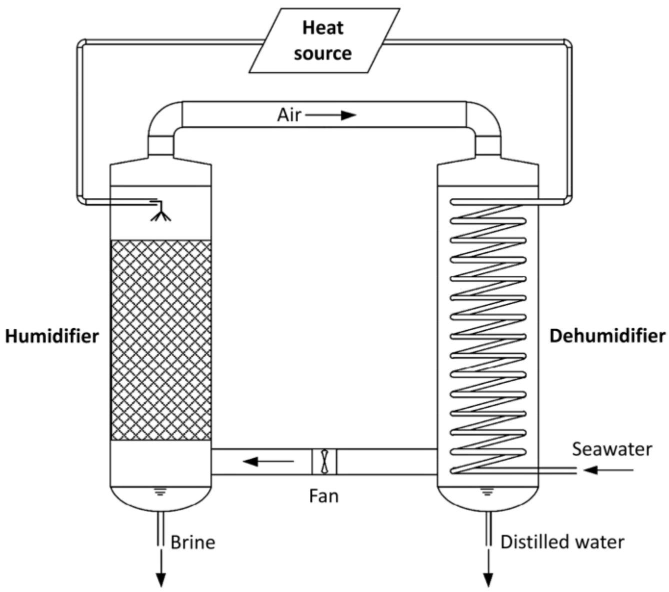

Fig. 2-3: Schematic diagram of an HDH desalination system.

It is essential to recognize the relative technical differences of each of basic HDH cycles and select the one that is most applicable to get higher thermal efficiency and water production rate. Fig. 2-4 presents different types of basic HDH desalination cycles.

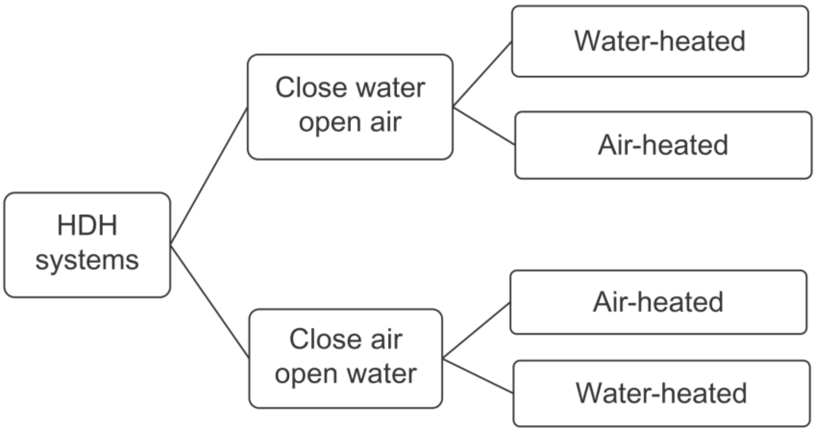

Fig. 2-4: Classification of the basic HDH systems types.

The configuration of the HDH cycles is classified based on which stream is heated up and which one stream is open or closed. It should be noted that a combination of basic HDH systems is also possible to consider. For instance, an HDH system which both air and water streams can be heated up. A closed-air open-water (CAOW) water-heated cycle is shown in Fig. 2-3. Other types such as the CAOW air-heated cycle, closed-water open-air (CWOA) water-heated cycle, CWOA air-heated cycle can be adopted [12]. In a closed air/water HDH systems, air/water flows in a closed loop between the humidifier and the dehumidifier while the water/air is flowing in an open loop. Air circulation in the HDH system can be either in forced or free circulation. [13].

2.2.1. CAOW water-heated HDH

Closed-air open-water humidification-dehumidification desalination is the most common configuration among HDH types. There have been numerous studies in this regard[14-16]. Fig. 2-3 shows the CAOW water-heated HDH system. The air stream entering the humidifier is moisturized by spraying hot saline water on air. As a result, the temperature of the air is increased, then, the hot, moist air moves to a dehumidifier, in which by decreasing the air stream temperature using cold seawater, vapour carried will condense and forms distilled water. The system involves two main processes of humidification and dehumidification of the air. A humidifier is a direct-contact, counter-flow, heat-and-mass exchange device utilised to humidify the air stream. Dehumidifiers, indirect-contact, counter-flow,

heat-and-mass exchange devices, condensed liquid water from hot, moist air. The heat source required to heat up the air or water stream can be any type of a low-grade heat source such as electric or gas heater, solar thermal collector, etc. A heat-and-mass exchanger (HME) is a device that simultaneously transfers heat and mass between air and water.

2.2.2. CAOW air-heated HDH

The other type of HDH cycle is the CAOW air-heated cycle, and a schematic diagram is shown in Fig. 2-5. Air circulates through the cycle and heats up before the humidification process. Air solar collectors are possible options for heating up the air in the air-heated system. The multi-extraction/multi-injection idea can be applied in air-heated systems as well. The main drawback of this method is that lower heat capacity of air limiting moisturization at a high temperature after the humidification process, so it leaves the humidifier at a low temperature. However, a multistage heating and humidification process can be applied [17] in this regard. To apply this, a series of air heaters and humidifiers need to be connected to achieve fully saturated air at high temperatures at the end of the humidification process. The open-air air-heated HDH is more efficient when hot air is available from the ambient.

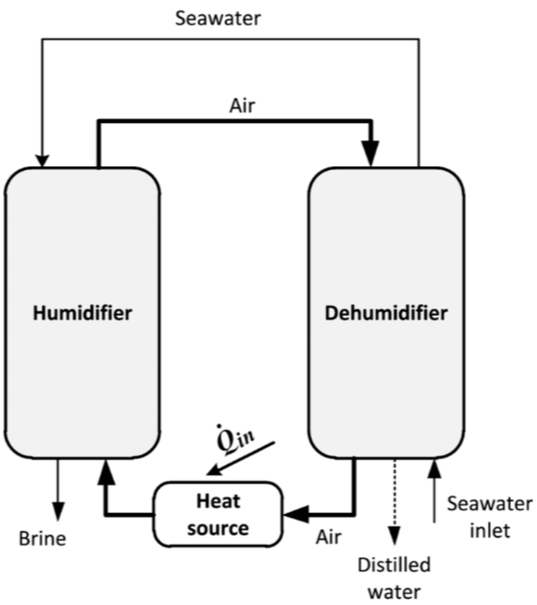

Fig. 2-5: Schematic diagram of CWOA air-heated HDH system.

2.2.3. Multi-effect HDH

One way to improve the HDH cycle thermal efficiency is to use a configuration with multiple extractions of moist air from the humidifier. Fig. 2-6 shows a schematic diagram of the multi-extraction HDH cycle in which hot, humid air can be extracted from different points of a humidifier and forwarded correspondingly to the dehumidifier. However, this configuration has more complexity in design and more expensive to fabricate. Multi-effect HDH can results in higher heat recovery. Chehayeb et al. studied the multiple extractions and injections HDH system by developing a thermodynamic based mathematical model[18]. In another study Zamen et al. [19] concluded that a two-stage process is the most suitable option which can improve parameters such as specific energy consumption, productivity and daily production per solar collector area and, investment cost.

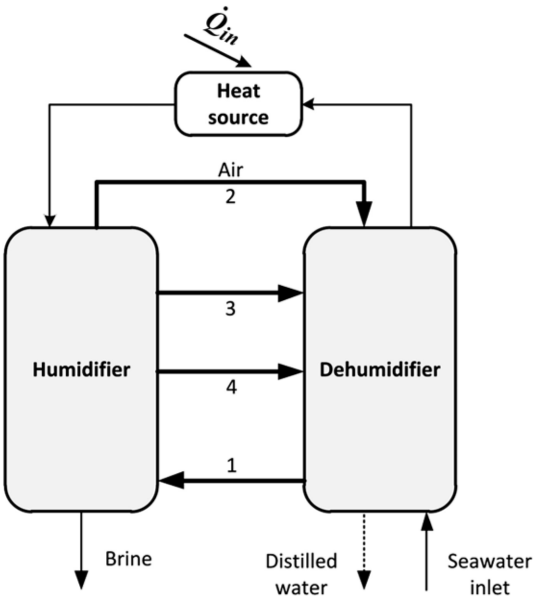

Fig. 2-6: Multi-effect of CAOW water-heated HDH system schematic diagram

2.3. HDH process on psychrometric chart

The HDH desalination works with two main processes of humidification and dehumidification of air. Large quantities of water vapor mix with air and carry by air from one process to another. Air ability to carry water vapor rises with its dry bulb temperature. For example, 1 kg of dry air can keep and carry 0.15 kg of vapor with itself at temperature is 60°C at a saturated air condition (100% relative humidity). The higher temperature of the air at a constant relative humidity substantially increases the amount of vapor that can be carried by air. Therefore, a cycle configuration that can increase moist air temperature at the humidifier outlet has more potential for water production.

Two main processes of humification and dehumidification are showed in Fig. 2-7 for an opened-air HDH system. Point 1 is dry, cool air before humidification, point 2 is hot moist air after humidification and before dehumidification processes and point 3 is cooled dry after dehumidification. As the air is in direct contact with saline water and there is enough contact surface area, air can reach saturation while is circulating in the HDH system.

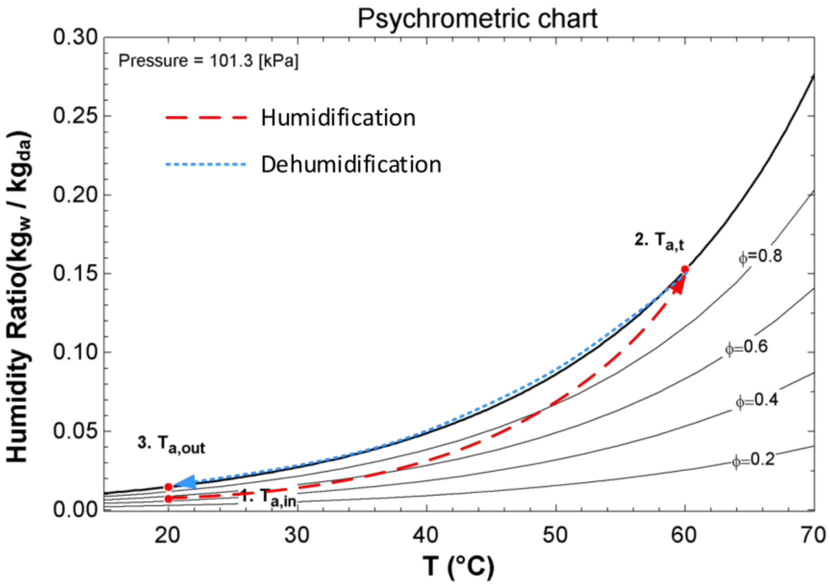

Fig. 2-7: Dry bulb temperature against vapor content of humid air (ω) at various relative humidifies (ϕ) and humidification dehumidification processes.

2.4. Humidification process

Humidification in the HDH desalination is a process in which seawater gets in contact with air for increasing the air vapor content. Water diffuses to air as vapor and increases the humidity of the air. The driving force for the humidification is the difference in concentration between the water-air interface and the water vapor in the air. This concentration difference depends on the vapor pressure at the gas-liquid interface and the partial pressure of water vapor in the air. Different techniques can be applied to fabricate humidifier devices, such as packing-filled towers, spray towers, bubble columns, and wetted-wall towers [20].

Spray towers consist of an empty cylindrical vessel made of steel or plastic, and nozzles that spray liquid into the vessel. The inlet gas stream usually enters at the bottom of the tower and moves upward, while the liquid is sprayed downward from one or more levels. This type of spray tower is simple in design, with a low-pressure drop on the gas side, low in maintenance cost, and inexpensive capital cost. The drawbacks of these devices include a substantial pressure drop on the water side caused by the spray nozzles. For better performance, drift eliminators must be installed before humid air exits the vessel [21]. The diameter-to-length ratio is a significant variable in spray tower design. When this ratio is high, air will be

completely mixed with the sprayed water, while a low ratio means that sprayed water rapidly touches the tower walls, creating a liquid film on the walls and reducing system the effectiveness. Direct heat and mass transfer principles must be implemented to design spray towers. Empirical correlations and design procedures are provided in reference [21].

bubble column is another type of humidifiers. In a bubble column, a vessel is filled with hot saline water and the air is injected through the vessel using a sparger located at the bottom of the vessel. The sparger injects a turbulent stream of air bubbles directly into the water, enabling vapor diffusion into the air bubbles and moisturizing the air. Bubble columns are simple in design, and different configurations of them can be setup. The water can be in co-current flow or a counter-current with the air. The humidification of the air bubbles depends on several parameters, such as air and water temperatures, the volume ratio of bubble to saline water, and bubble characteristics such as size and velocity.

To enhance the effectiveness of air humidification, increasing the heat and mass transfer area can be applied in design approaches. A packed bed is a heat and mass exchange device that uses the same technique to reach an effective humidification process. A packed bed is a hollow vessel or tube filled with a packing fill with high specific surface area. The packing can be randomly filled with small objects like Raschig rings, or any type of specifically designed structured packing. The saline water sprays from top of the column over the packing fills while at the bottom of the column, air blows and passes through the packing fills, resulting in humidification. Different types of the packing materials might be sourced, including ceramic Rasching rings, wooden-slat packing, honeycomb paper, corrugated cellulose material, and plastic packing.

For selecting a packing fill, different factors should be considered, including specific surface area, maximum temperature tolerance, durability, the pressure drop across the packing fill, and cost. [22] Film fills are a packing which provides the high thermal performance along with high surface area per volume, demonstrating a lower pressure drop as it increases.

As shown in Fig. 2-8, a humidifier operation is similar to a counterflow, wet-cooling tower in which one fluid stream of hot water sprays over a packing material with a high surface area and another stream is a mixture of air and water vapor. These two streams of saline water and air are directly contacted on a packing fill surface and simultaneously heat, and mass transfer occurs from water to the air stream. Packing fills with a high specific surface area and high temperatures tolerance are more compatible with an effective humidifier requirement.

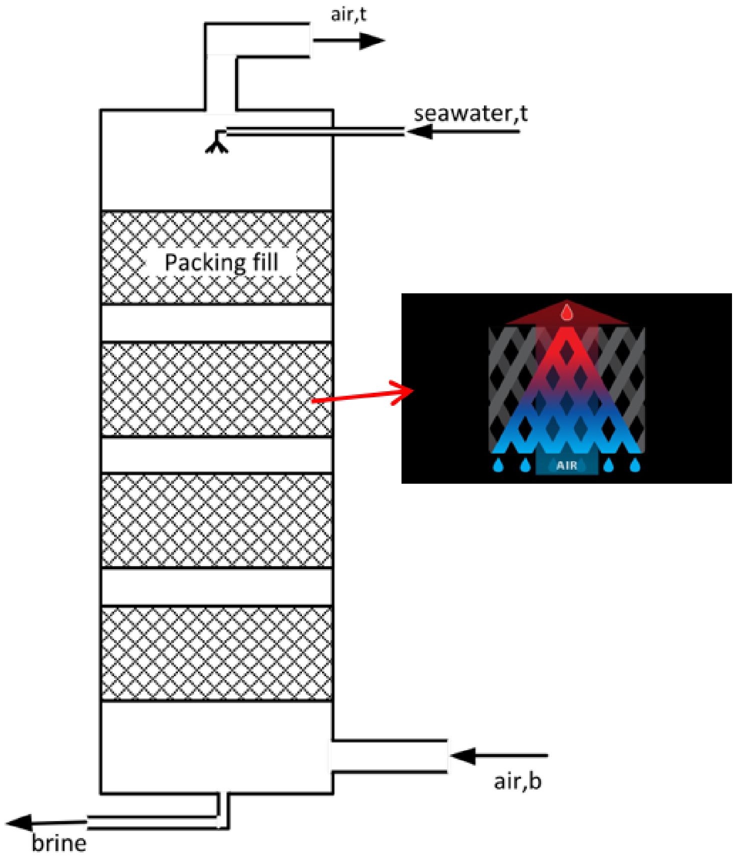

Fig. 2-8: Overview of a humidifier

2.5. Dehumidification process

There are wide ranges of heat and mass exchange devices that can be utilized as a dehumidifier, for example, flat-plate HME made of polypropylene [23]. Other most commonly used types include finned-tube heat exchangers. There have been various types of dehumidifiers introduced by researchers. For instance, Farid et al. [24], designed condensers for a pilot plant scale HDH system. The dehumidifier

made of a long copper-galvanized steel tube (3m length, 170 mm diameter) with 10 longitudinal fins of 50mm height on the outer tube surface and 9 fins on the inner side. In another study, they employed a simplified stack of flat condensers made of 2m by 1m galvanized steel plates with long copper tubes mounted on each side of the plate for supplying a large heat-and-mass transfer surface area. Due to the small heat transfer coefficient on both air and water sides, the fabricated condensers was large. In another design for dehumidifiers, they employed a copper pipe 27m in length and 10 mm in OD (outer diameter), which was shaped to form a helical coil 4m in length and fixed in a PVC pipe [25]

In another study, two types of dehumidifiers were presented in which they used galvanized steel plates for both bench and pilot proposed modules[26]. A copper tube with 11 mm OD and 18 m length was welded to a galvanized plate in a helical shape for the fabrication of a pilot unit. Further, the tube outside diameter of [27]8mm and length of 3m were used for fabricating the bench unit. Then, these condensers were connected vertically and in a series by positioning them in a duct. In one module, the condenser was a cylinder 170 mm in diameter and made of galvanized steel plates. Ten longitudinal fins were soldered to the outer surface of the cylinder, and nine similar fins were soldered to the inner surface with a height of 50 mm for both the inside and outside fins. The cylinder was made of a plate with a thickness of 1.0 mm. A copper tube with a 9.5 mm inside diameter was soldered to the surface of the cylinder. The condenser was fixed vertically in the PVC pipe 316 mm in diameter and connected to the humidifier section using two short horizontal pipes. The humidifier module proposed by Orfi et al.[27] contains two rows of long cylinders made of copper in which the feed water flows. Longitudinal fins were soldered to the outer surface of the cylinders. The condenser is characterized by a heat-transfer surface area of 1.5 m^2 by having 28m as the total length of the coil.

In addition to indirect contact dehumidifiers, direct-contact heat and mass exchangers can be utilized for dehumidifying purposes, including bubble column and packing fill dehumidifiers. In direct contact dehumidifier (DC dehumidifier),

direct heat and mass transfer between water and air streams occur as they reach each other on a surface area.

As shown in Fig. 2-9 the indirect dehumidifier is a large counterflow condenser in which cold seawater enters from the bottom and flows through a metal coil, making the coil surface cold; while hot moist air enters from the top and touches the cold surface and reaches to its dew point. And as a result, vapor condenses on the surface of the coil and produces some freshwater. Metal or plastic based materials that can resist saline water corrosion can be used for manufacturing the dehumidifiers. The high surface area in a dehumidifier is the key design factor that must be considered for material selection.

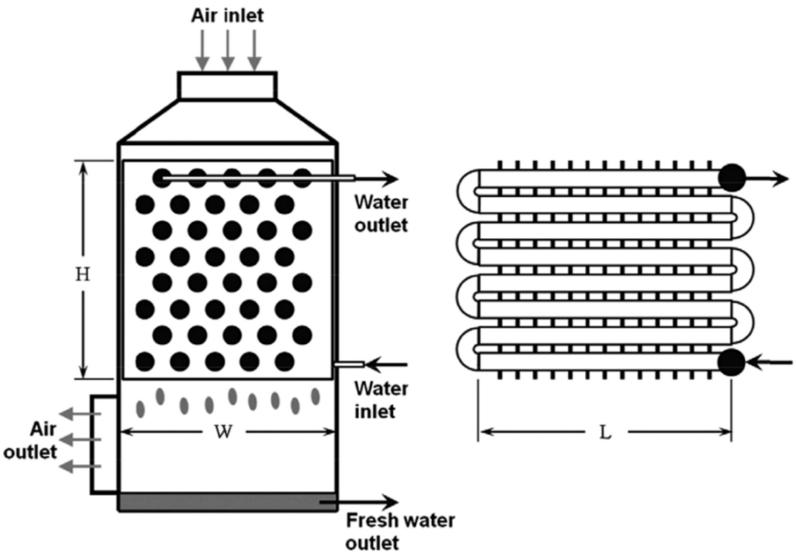

Fig. 2-9: Schematic diagram of a finned-tube dehumidifier

In a direct contact dehumidifier, humid, hot air is directly gets in touch with cold fresh water to exchange heat and mass. DC dehumidifiers are smaller in size and lower in capital cost. Besides, the corrosion related issues due to saline water is eliminated as there is no more saline water for cooling. In Fig. 2-10 schematic diagram of the bubble column dehumidifier is presented. The bubble column dehumidifier, has been shown to have high heat recovery [28-31].

In a bubble column dehumidifier, a sparger is placed at the bottom of the column to sparge the hot, moist air through a column of freshwater at a lower

cooling temperature. Then the fresh water will be cooled down by an extra heat exchanger. The heat and mass transfer area in this case is provided by the bubble surface area. The concentration gradient from the hot bubble centre to the cool bubble surface drives condensation to happen in the surface of the bubbled air. The significance of the bubble column lies in moving the condensation process off a solid surface and replace it with the surface of swarm of bubbles. The large interfacial leads to a low thermal resistance. Further, the heated freshwater can be cool down for later reuse by using an external/internal heat exchanger to preheat the saline water before final heating for humidification process with a relatively small surface area. Finally, cold dry air is collected and returned to the humidifier to repeat the process[28, 29, 32].

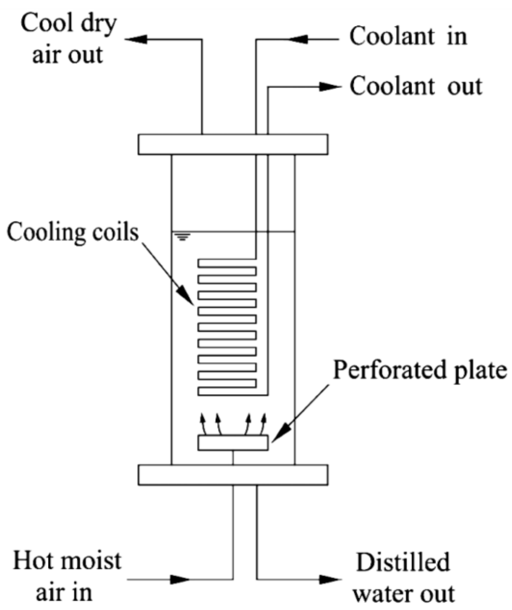

Fig. 2-10: Schematic diagram of a bubble column dehumidifier

Another type of DC dehumidifier is called packing fill dehumidifier. Fig. 2-11 displays the schematic diagram of a packing fill dehumidifier. In counter current DC packing fill dehumidifier, hot, moisturized air coming from a humidifier enters the chamber from the bottom while freshwater at lower temperature sprays from the top over a packing fill and by reducing the hot, moist air temperature to its dew point condensation occurs. The packing material placed in the chamber provides high heat and mass transfer area between the air and freshwater streams. After the dehumidification, the cooled dry air leaves the chamber and enters the humidifier

again for the humidification process. The warmed fresh water after the dehumidification process is collected at the bottom and transferred to an external heat exchanger to be cooled down using a coolant. To increase the heat recovery of the HDH system the outlet warm freshwater of the dehumidifier can be used to preheat the saline water before heating up in the main heat source of HDH system. The cooled down freshwater is circulated and sprayed again, and condensed water will be collected and separated from the freshwater. The packing-filled dehumidifier is highly economical and simple in design which makes it a viable alternative option in a dehumidification process.

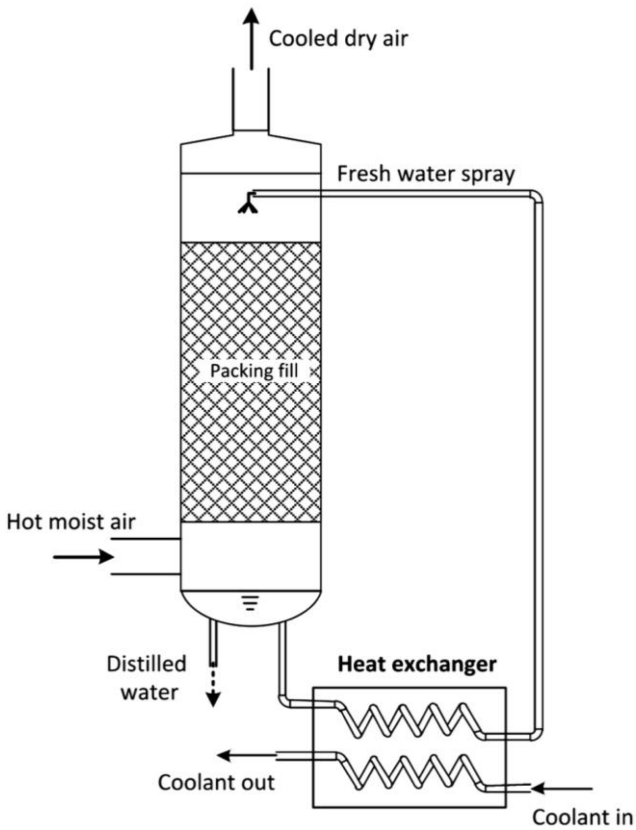

Fig. 2-11: Schematic diagram of packing fill counter-flow dehumidifiers.

2.6. Energy sources

There are several types of low-grade heat sources that can be applied to supply the thermal energy requirement for the HDH cycle. Industrial waste heat is one of the examples that can be used to transfer heat to the air/water stream in HDH cycles.

All sorts of industrial waste heat like exhaust hot gases from furnaces, boilers, and so on, can be considered as a heat source. Finned-tube heat exchangers are one of the technologies which can be used for extracting heat and delivering it to an air or water stream of an HDH system.

Energy from solar irradiation is another option that can be utilized for providing thermal energy of the HDH systems. Stationary solar thermal collectors such as evacuated tubes, and flat plate collectors are among the most viable options in terms of cost and operating temperature ranges for integration with the HDH. Sun tracking concentrating solar thermal collectors are generally more expensive and require more maintenance [33]. Solar thermal collectors are designed for both air and water heating which based on the HDH system configuration can be implemented to heat up air/water in air/water-heated HDH systems. There have been several research on using solar thermal collectors as a power source for HDH systems[16, 34-38]. Photovoltaic water heating system is economically showing better viability as a heat source recently. These systems using the PV panel to heat up an electric element. The electric element can be placed in a water tank or other configuration to heat up the water. Photovoltaic systems require more area to deliver the same thermal power in comparison to thermal solar collectors by factor of nearly 3. However, they are cheaper and can have better thermal performance in low temperature and cloudy winter days[39].

Depending on the location, available geothermal energy can be utilized as thermal source for the HDH systems[40]. The geothermal industry mainly uses the standard heat exchangers usually utilized in the chemical industry, namely, plate and/or shell-and-tube type exchangers such as are commercially readily available. A more detailed literature reviews are presented in the published papers for each chapter.

2.7. Objectives of the present research

In this PhD research project will cover the gap of HDH desalination with direct-contact dehumidifier. The direct-contact dehumidification is a new method in HDH desalination systems which is proposed and studied in the research project.

The packed fill columns are used for humidification and dehumidification processes. This project studies the thermal performance of the HDH system by implementing mathematical modelling as well as experimental investigations. An experimental setup is fabricated and examined to under various tests to understand the associated characteristics of the HDH system. The mathematical model is verified by using experimental results.

The effect of feed salinity on water production and thermal performance of the HDH system is another new experimental research study and which is investigated in this project. To address the salinity effect, experimental tests are carried out to determine effect of different salinities on the water production rate at as well as the HDH system response to different feed salinities in practice. Next, to make the HDH system more environmentally sustainable and reduce the brine management cost, a method is applied to reduce the rejected brine of the HDH system called as brine recirculation.

To make the HDH system fully electric driven as the provision of both cooling load and heating load are not easily possible for some of the applications, an idea of a heat pump driven HDH system is proposed. The idea of using a heat pump to simultaneously supply both heating and cooling loads of the humidification and dehumidification processes of the HDH system is mathematically modelled. Then, optimization of heat pump driven HDH system is performed to reach a fully coupled condition of the heat pump assisted HDH system.

Chapter 3:

Mathematical Modelling of Direct and Indirect HDH systems

3.1. Introduction

In this Chapter, by utilizing a thermodynamic-based mathematical model, performance of the HDH systems are investigated. Two HDH systems are considered for the study, one with the indirect-contact dehumidifier, another with the direct-contact dehumidifier. In HDH systems with an indirect dehumidifier, feed saline water provides the cooling load for condensation while in the direct-contact systems a cold freshwater stream cools down the moist air. Both systems have their advantages and disadvantages. In an indirect system heat recovery is higher as the saline water is preheated with the hot air. However, in direct systems, corrosion related problems are excluded from the dehumidifier. Also, water production potential is higher due to direct heat and mass transfer in these systems.

Fig. 3-1.a demonstrates the HDH system with an indirect dehumidifier. Low-temperature seawater enters the dehumidifier and will be preheated by air and leaves the dehumidifier. The preheated seawater then heated up by external heat source to be sprayed later in the humidifier. On the other hand, air is circulating throughout the systems in a closed loop. Dry cool air enters the humidifier form the

bottom and will be heated up by seawater. Then, the hot moist air moves to the dehumidifier and its vapor content condenses to distilled water. The produced fresh water will be collected from the bottom of the dehumidifier. The rejected brine exits form bottom of humidifier.

Fig. 3-1.b represents an HDH system with direct contact dehumidifier. In this method for air dehumidification a direct contact dehumidifier is used. In a direct contact dehumidifier, hot moist air is cooled down by a stream of cold freshwater spray over the air. To ensure the heat and mass transfer between air and water in a direct contact heat and mass exchange deceives (HME), packing fill with high density surface area is provided. The freshwater is cooled after dehumidification using an external cooler.

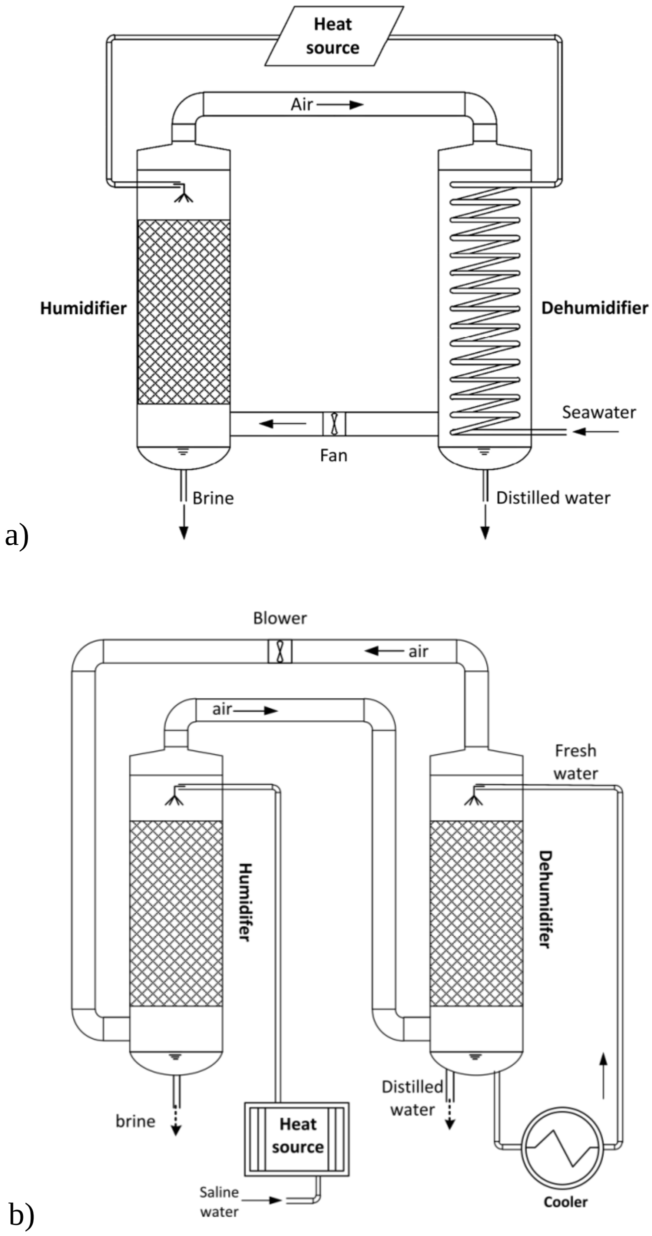

Fig. 3-1: Overview of HDH system a)with indirect dehumidifier b)with direct dehumidifier

3.2. Mathematical model

To evaluate the performance of the indirect HDH cycle and study the effect of operating parameters each of system components are considered as a black box. The energy and mass balance are applied on each of the system components to thermodynamically investigate the relationship between inputs and outputs variables.

3.2.1. Indirect contact HDH

Fig. 3-2 presents the schematic diagram of the indirect HDH system including all the related variables at each process point.

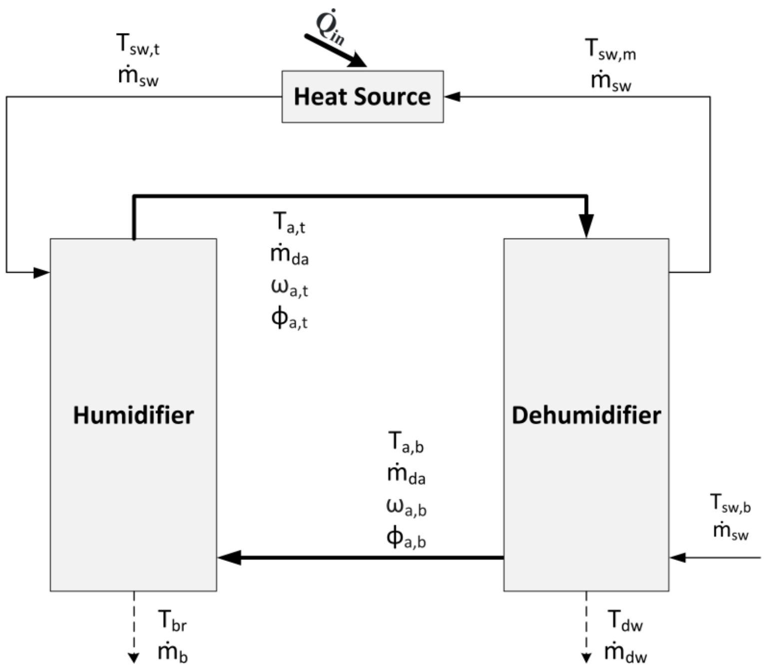

Fig. 3-2: Schematic diagram of an indirect HDH system

The following assumptions are considered for applying mass energy balance of each HDH system components including humidifier, dehumidifier, heat exchangers.

- The HDH system works at steady state and steady flow conditions.
- Humidifier and dehumidifier are adiabatic so there is no heat transfer.
- Pumping and fan electric powers are negligible compared with total thermal energy consumption of the system.[13, 15]
- Kinetic and potential energy terms are excluded in the energy balance.

It should be note that the amount of electrical power comparing to thermal power is negligible. This is also observed in the experimental studies which is the subject of upcoming chapters. Based on the first law of thermodynamic, governing equation of the CAOW water-heated HDH cycle can be extracted by applying energy and mass balance for each cycle component. A control volume is drawn for

the cycle components including humidifier, dehumidifier and heat source as following:

Humidifier energy and mass balance:

$$\dot{m}_{sw} + \dot{m}_{da}\omega_{a,b} = \dot{m}_{br} + \dot{m}_{da}\omega_{a,\mathrm{t}} \tag{2.1}$$

$$\dot{m}_{sw}h_{sw,t} + \dot{m}_{da}h_{a,b} = \dot{m}_{br}h_{br} + \dot{m}_{da}h_{a,\mathrm{t}} \tag{2.2}$$

It should be noted that, enthalpy of humid air is considered as a binary mixture of dry air and water vapour, in other words: $h_a = h_{da} + \omega h_v$

Dehumidifier energy and mass balance:

$$\dot{m}_{sw} + \dot{m}_{da}\omega_{a,t} = \dot{m}_{sw} + \dot{m}_{da}\omega_{a,t} + \dot{m}_{dw} \tag{2.3}$$

$$\dot{m}_{sw}h_{sw,\mathrm{b}} + \dot{m}_{da}h_{a,t} = \dot{m}_{sw}h_{sw,m} + \dot{m}_{da}h_{a,\mathrm{b}} + \dot{m}_{dw}h_{dw} \tag{2.4}$$

Heat source energy balance:

$$\dot{Q}_{in} = \dot{m}_{sw}c_p(T_{sw,t} - T_{sw,m}) \tag{2.5}$$

To find out outlet streams conditions in the HME device, effectiveness equations of them should be added to the abovementioned equations. Effectiveness compares the actual versus ideal thermal energy transferred from each stream and is defined as actual enthalpy variation to the maximum possible enthalpy variation, in other words $\varepsilon = \Delta\dot{H} / \Delta\dot{H}_{\max}$ [41]. Therefore, effectiveness of humidifier and dehumidifier would be expressed as following:

$$\varepsilon_h = \max\left(\frac{\dot{H}_{a,t} - \dot{H}_{a,b}}{\dot{H}_{a,t}^{ideal} - \dot{H}_{a,b}}, \frac{\dot{H}_{sw,t} - \dot{H}_{br}}{\dot{H}_{sw,t} - \dot{H}_{br}^{ideal}}\right) \tag{2.6}$$

$$\varepsilon_d = \max\left(\frac{\dot{H}_{a,t} - \dot{H}_{a,b} + \dot{H}_{dw}}{\dot{H}_{a,t} - \dot{H}_{a,b}^{ideal} + \dot{H}_{dw}}, \frac{\dot{H}_{sw,m} - \dot{H}_{sw,b}}{\dot{H}_{sw,m}^{ideal} - \dot{H}_{sw,b}}\right) \tag{2.7}$$

In both humidifier and dehumidifier, the ideal outlet air enthalpy happens when the outlet air is fully saturated at the water inlet temperature, and the ideal outlet seawater enthalpy is when its temperature is equivalent to the inlet air dry-bulb temperature.

In addition to consider effectiveness equations, relative humidity of air at bottom and top air streams should be known. Moreover, distilled water temperature is assumed as average of the humid air temperatures at inlet and outlet of the dehumidifier, in other words $T_{dw} = (T_{a,t} + T_{a,b})/2$.[13]

3.2.2. Direct contact HDH

Fig. 3-3 presents the schematic diagram of the HDH system with direct contact dehumidifier. The fresh water is circulated in dehumidifier while is cooled down after dehumidification process.

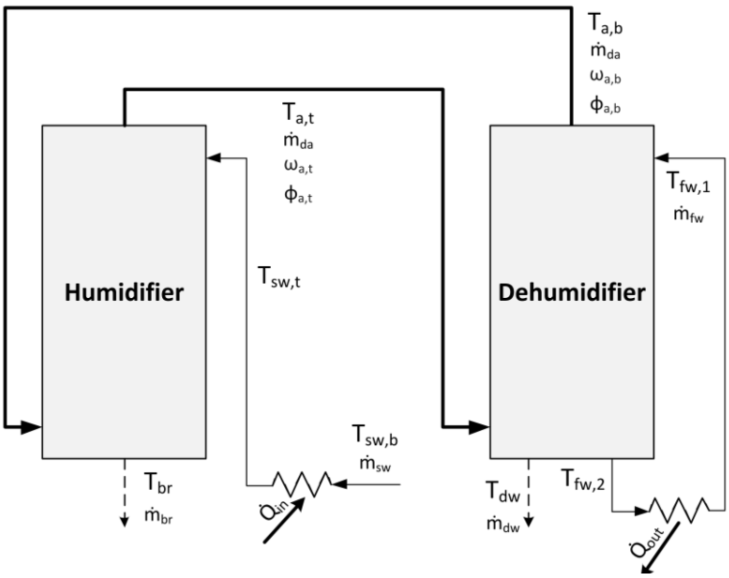

Fig. 3-3: Schematic diagram of the HDH with direct contact dehumidifier

Considering the same assumptions applied to extract the governing equations in HDH with indirect dehumidifier as well as applying mass and energy balance to each of the HDH cycle components, governing equations of the HDH system with direct contact humidifier can be extracted as following:

Humidifier energy and mass balance:

$$\dot{m}_{sw} + \dot{m}_{da}\omega_{a,b} = \dot{m}_{br} + \dot{m}_{da}\omega_{a,\mathrm{t}} \tag{2.8}$$

$$\dot{m}_{sw}h_{sw,t} + \dot{m}_{da}h_{a,b} = \dot{m}_{br}h_{br} + \dot{m}_{da}h_{a,\mathrm{t}} \tag{2.9}$$

Dehumidifier energy and mass balance:

$$\dot{m}_{da}\omega_{a,t} = \dot{m}_{dw} + \dot{m}_{da}\omega_{a,b} \tag{2.10}$$

$$\dot{m}_{fw}h_{fw,1} + \dot{m}_{da}h_{a,t} = \dot{m}_{fw}h_{fw,2} + \dot{m}_{da}h_{a,b} + \dot{m}_{dw}h_{dw} \tag{2.11}$$

The dry mass flow of air is constant through the humidifier. Also, enthalpy of moist air is considered as a binary mixture of dry air and water vapour, in other words: $h_a = h_{da} + \omega h_v$

Heater and cooler energy balance:

$$\dot{Q}_{in} = \dot{m}_{sw}\left(h_{sw,t} - h_{sw,b}\right) \tag{2.12}$$

$$\dot{Q}_{out} = \dot{m}_{fw}\left(h_{\mathrm{fw},2} - h_{fw,1}\right) \tag{2.13}$$

To discover outlet streams conditions in the humidifier and dehumidifier, effectiveness equations need to be defined and considered for mathematical solution. Conceptually, effectiveness compares the actual thermal energy versus ideal thermal energy transferred from each stream and is defined as actual enthalpy rate variation to the maximum possible enthalpy rate variation, in other words $\varepsilon = \Delta\dot{H} / \Delta\dot{H}_{\max}$ [41]. Therefore, effectiveness of humidifier and dehumidifier would be extracted as following:

$$\varepsilon_h = \max\left(\frac{\dot{H}_{a,t} - \dot{H}_{a,b}}{\dot{H}_{a,t}^{ideal} - \dot{H}_{a,b}}, \frac{\dot{H}_{sw,t} - \dot{H}_{br}}{\dot{H}_{sw,t} - \dot{H}_{br}^{ideal}}\right) \tag{2.14}$$

$$\varepsilon_d = \max\left(\frac{\dot{H}_{a,t} - \dot{H}_{a,b} + \dot{H}_{dw}}{\dot{H}_{a,t} - \dot{H}^{ideal}_{a,b} + \dot{H}_{dw}}, \frac{\dot{H}_{fw,2} - \dot{H}_{fw,1}}{\dot{H}^{ideal}_{fw,2} - \dot{H}_{fw,1}}\right) \tag{2.15}$$

In both humidifier and dehumidifier, the ideal outlet air enthalpy happens when the outlet air is fully saturated at the water inlet temperature, and the ideal outlet seawater enthalpy is when its temperature is equivalent to the inlet air temperature. It should be note that, effectiveness practically related to variables of a heat and mass exchange device such as heat and mass transfer area, air to water flow rates and temperatures. One way to reach a higher effectiveness value is to increase the heat and mass transfer area which a key design variable in both the humidifier and the dehumidifier of direct/indirect HDH systems.

Thermodynamic properties of the moist air and water provided in ASHRAE handbook.[42] Moreover, Engineering Equation Solver (EES) software[43] calculates moist air properties by the formulation presented by Hyland and Wexler[44] as well as water properties using the formulation of IAPWS (International Association for Properties of Water and Steam) [45] which are accurate equations of state to model the properties of moist air and water.

The system of governing equations was solved using the EES software, which calculates moist air and water properties using built-in functions. These functions are previously defined in the software and evaluate the thermodynamic properties of various materials based on the property database, which is collected in it. EES is a numerical solver, using an iterative procedure for solving the system of equations. The EES automatically identifies and groups equations that are solved simultaneously. The convergence of the numerical solution is verified by using two methods: (i) ‘Relative equation residual’ which is the difference between left-hand and right-hand sides of an equation divided by the magnitude of the left-hand side of the equation; and (ii) ‘Change in the variables in which the change in the value of the variable within an iteration. The calculations converge if the relative equation residuals are less than certain value for example 10^{-6} or if the change in variable is less than 10^{-9}. Both relative equation residuals and change in variables are adjustable. Besides, there are two stopping criteria the (i) ‘number of iteration’ and

(ii) ‘elapsed time’ that can be set for obtaining variables with higher accuracy. EES software which is widely used by the scientific community for thermodynamic system evaluations for thermodynamic analysis.[46, 47]

3.3. Performance metrics

To evaluate the HDH cycle performance in terms of thermal energy recovery, energy efficiency and amount of water production rate, performance parameter of the cycle are required to be defined.[12] Using these parameters the effect of input parameters such as top brine temperature, dehumidifying temperature, effectiveness of the humidifier and the dehumidifier, flow rate of seawater, flow rate of cooling water and flow rate of air on performance parameters can be determined. The output parameter which represent the performance of the system are as follow:

Gain output ratio (GOR): GOR is the ratio of the latent heat of evaporation of the distillate water produced to the total heat input to the cycle from the heat source. It represents the amount of heat recovery in the cycle.

$$GOR = \frac{\dot{m}_{dw} h_{fg}}{\dot{Q}_{in}} \tag{2.16}$$

Recovery ratio (RR): recovery ratio is amount of distilled water over humidifier feed saline water, which is an index for water production potential of the cycle. It souled be noticed that for low recovery ratios, brine disposal process is not required.

$$RR = \frac{\dot{m}_{dw}}{\dot{m}_{sw}} \times 100 \tag{2.17}$$

Modified heat capacity ratio(HCR): this parameter is maximum enthalpy change in cold stream divided by maximum enthalpy change is hot stream which is used for evaluating performance of cycle components like humidifier and dehumidifier form the second law of thermodynamic standpoint. In other words, when a heat and mass exchange device working at the HCR=1 the amount of

entropy generation is minimized [46, 48]. The idea is similar with a heat exchanger when the temperature difference in terminals are minimized.

$$HCR = \frac{\Delta \dot{H}_{\max,cold}}{\Delta \dot{H}_{\max,\mathrm{hot}}} \tag{2.18}$$

$$HCR_h = \frac{\dot{H}_{a,t}^{ideal} - \dot{H}_{a,b}}{\dot{H}_{sw,t} - \dot{H}_{sw,b}^{ideal}} \tag{2.19}$$

$$HCR_d = \frac{\dot{H}_{sw,m}^{ideal} - \dot{H}_{sw,b}}{\dot{H}_{a,t} - \dot{H}_{a,b}^{ideal}} \tag{2.20}$$

3.4. Results and discussion

In this section based on the thermodynamic model the performance parameters including recovery ratio and GOR of the indirect and direct HDH systems are compared by varying the operating parameter of the system such as top brine temperature, water dehumidifying temperature, flow rates of waters and air, effectiveness of the HME devices and relative humidity of air.

The base operating condition for the parametric study is, humidifying temperature of 70ºC, dehumidifying temperature of 25 ºC, and effectiveness of humidifier and dehumidifier of 0.85, air relative humidity of 0.9.

3.4.1. Dehumidifying temperature effect

In Fig. 3-4 the effect of dehumidifier inlet saline water temperature from the indirect HDH and dehumidifier inlet fresh water temperature of the direct dehumidifier on performance parameters is presented. Increasing the dehumidifying temperature enhances the GOR of indirect HDH, while it reduces the GOR of direct HDH system. The highest GOR of the indirect HDH is higher that the direct HDH system. On the other hand, decreasing the dehumidifying temperature improves the RR of both type HDH systems. The RR of direct HDH system is higher that indirect HDH system for all inlet temperatures. Further,

increasing the inlet dehumidifying temperature shifts the optimum flowrate ratio of seawater to air, mr_h, to the higher values.

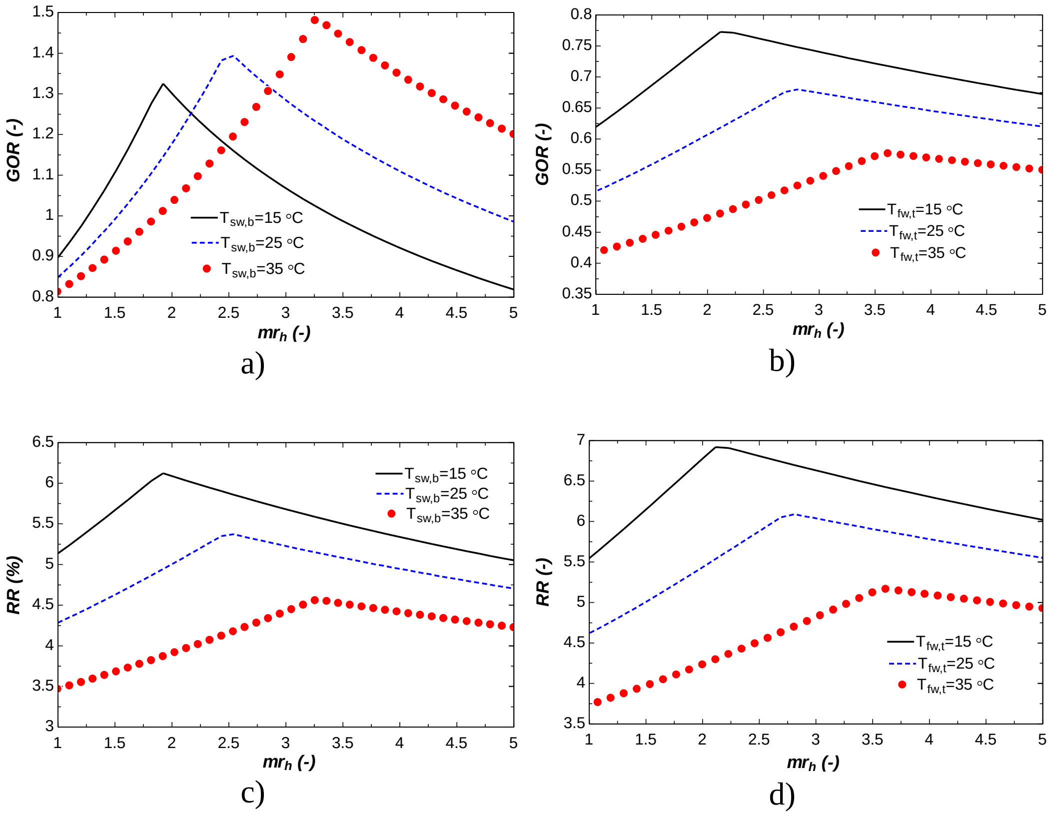

Fig. 3-4: Effect of inlet saline water dehumidifier temperature on a)GOR and c)RR of indirect HDH and effect of fresh water dehumidifier temperature on b)GOR and d)RR of direct HDH

3.4.2. Humidifying temperature effect

In Fig. 3-5 the effect of humidifier inlet saline water temperature on performance parameter (top brine temperature or top seawater temperature) for both HDH systems are compared. Increasing the humidifying temperature slightly decreases the GOR values in both HDH systems. The GOR of an indirect HDH system is higher than direct HDH system for all temperatures. Higher humidifying temperature enhances the RR of both systems. However, the RR value of direct HDH system is always higher than the indirect HDH system. Increasing the top brine temperature moves the optimum working point towards the higher mass flow rate ratio of saline water to air.

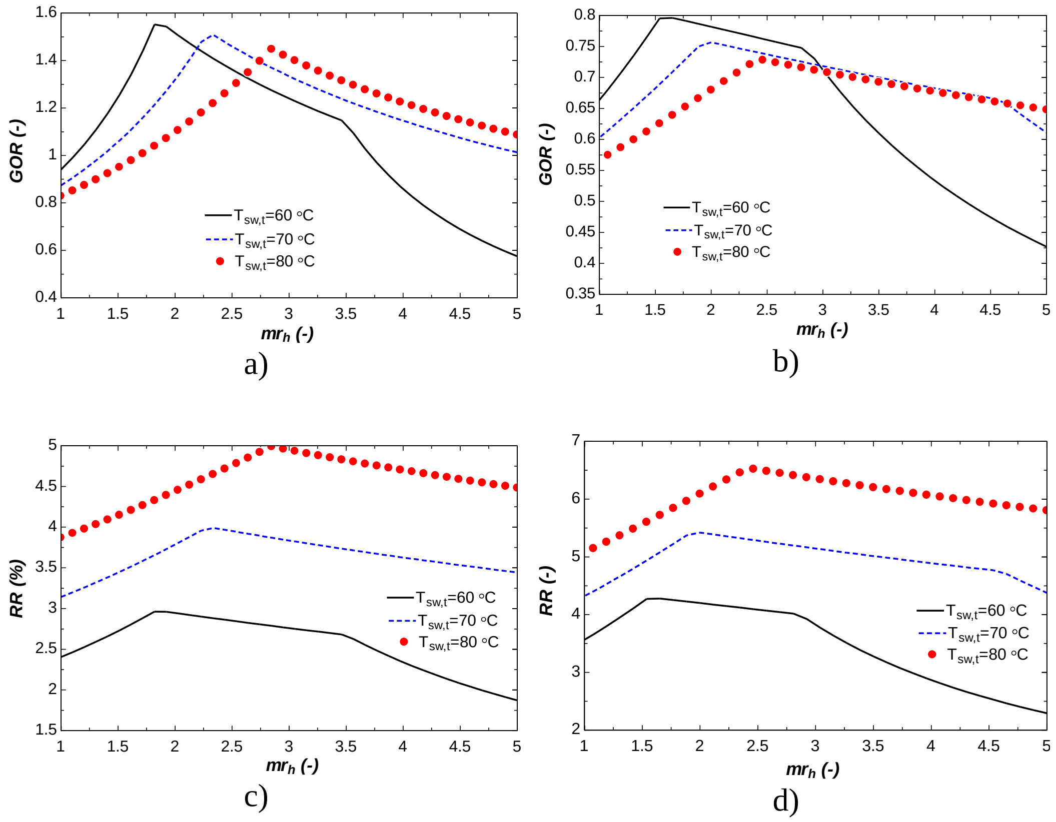

Fig. 3-5: Effect of humidifier feed inlet temperature on a,b)GOR and c,d)RR. (a,c are for direct HDH and band d are for indirect HDH)

3.4.3. Effect of heat and mass exchange devices effectiveness

In Fig. 3-6 relationship between humidifier effectiveness and performance parameters are presented for both HDH systems. Higher effectiveness value of humidifier enhances both RR and GOR of the either indirect or direct HDH system. GOR value of the indirect HDH system is higher for each effectiveness value while the RR of the direct is higher in the direct HDH system. Higher humidifier effectiveness increases the flow rate ratio of seawater to air. GOR values of indirect HDH system at same effectiveness of direct HDH system are always higher. However, the RR of the direct contact system is higher at the same effectiveness.

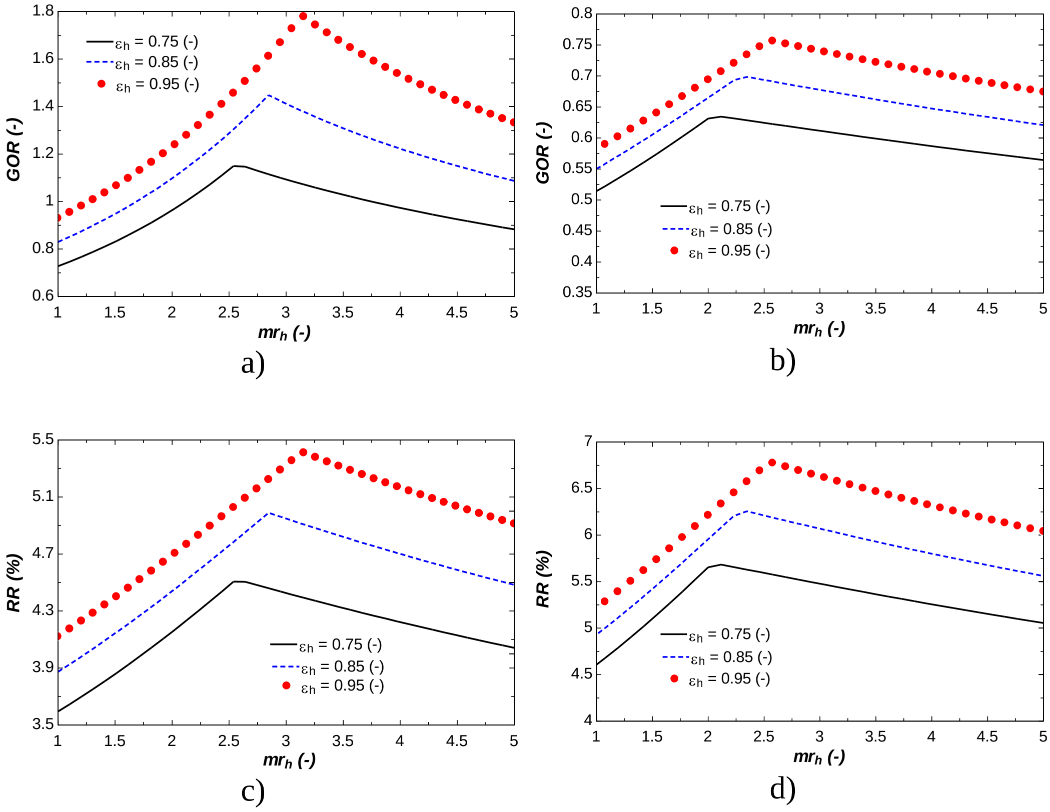

Fig. 3-6: Effect of humidifier effectiveness on a,b) GOR and c,d) RR of direct and indirect HDH systems. (a,c are for indirect HDH and b,c are for direct HDH)

Fig. 3-7 demonstrates the relationship of dehumidifier effectiveness and performance parameters of the direct and indirect HDH systems. Having a dehumidifier with higher effectiveness can enhance the GOR and RR of the both HDH systems. Increasing the dehumidifier effectiveness slightly shifts the optimum point of flowrate ratio of seawater to air toward higher values.

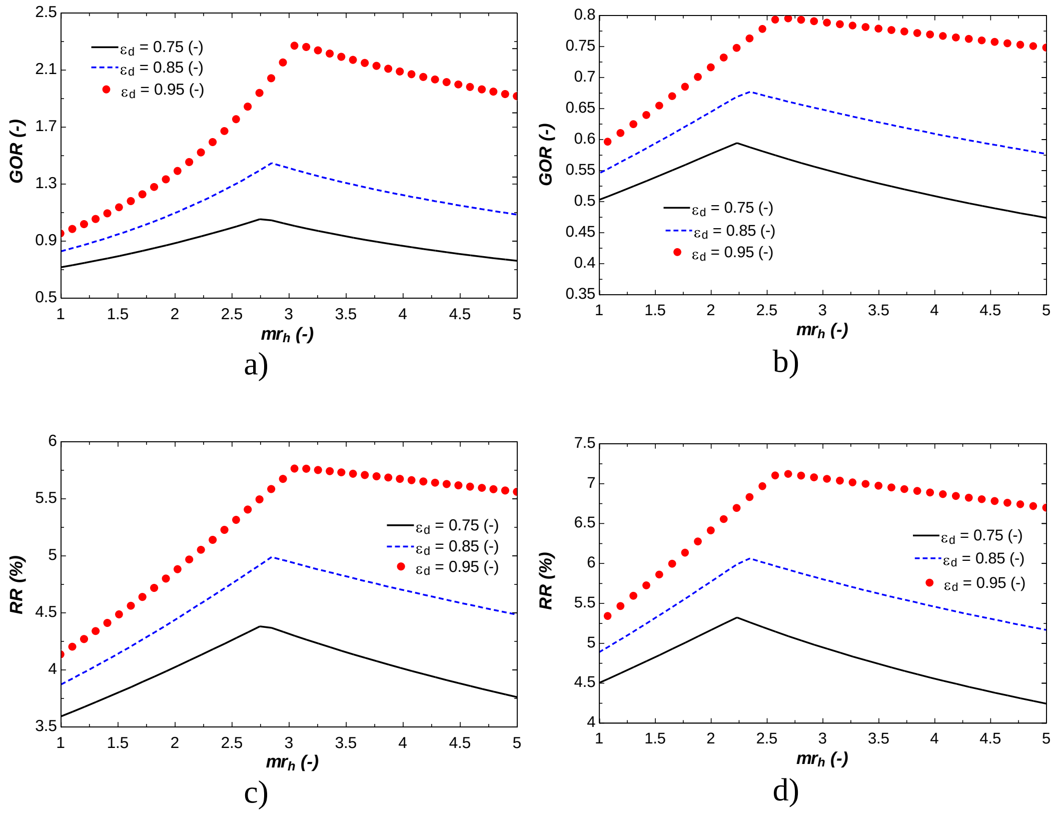

Fig. 3-7: Effect of dehumidifier effectiveness on GOR and RR in direct and indirect HDH system. (a,c are for indirect HDH and b,c are for direct HDH)

3.4.4. Air relative humidity effect

The effect of air relative humidity of dehumidifier outlet on performance parameters of both HDH systems are shown is shown in Fig. 3-8 variation of the outlet relative humidity of dehumidifier does not have considerable impact on GOR and RR values of the both indirect and direct HDH systems. In the indirect HDH system GOR is always higher than the direct HDH system at a specified relative humidity. However, the RR ratio of the direct HDH system is higher than the indirect contact in all similar relative humidity cases. Also, the change in relative humidity does not significantly alter the flow rate ratio of seawater to air.

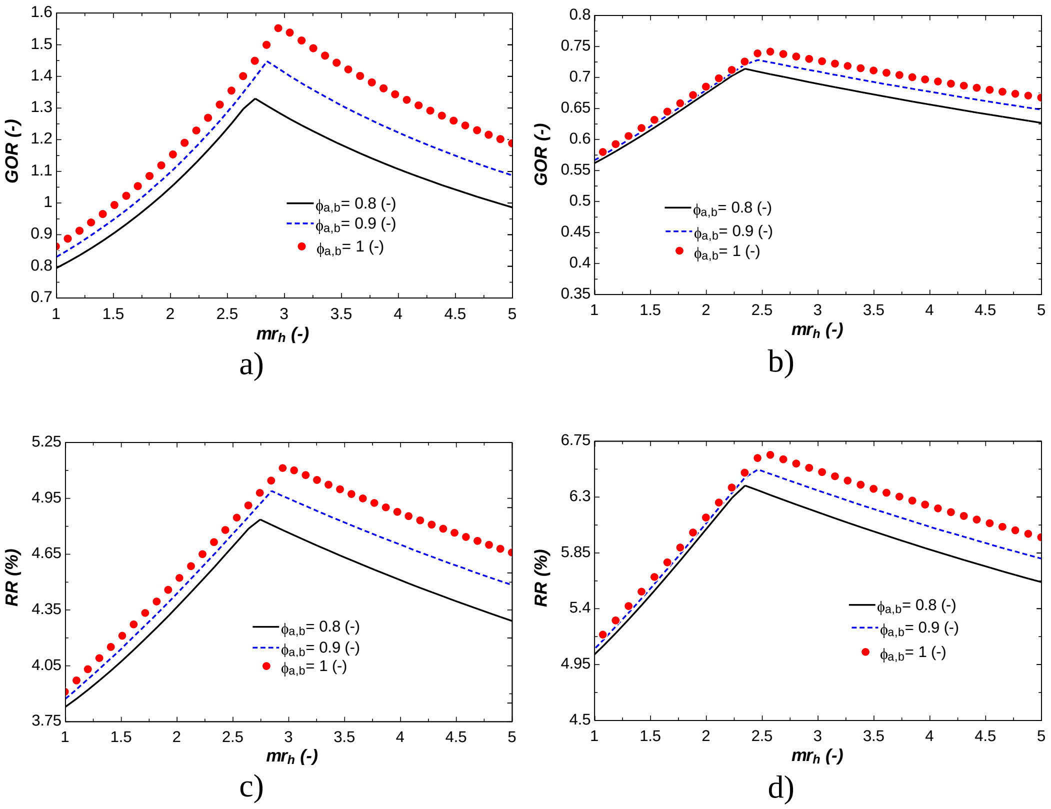

Fig. 3-8: Effect of outlet air relative humidity of dehumidifier on HDH performance parameters. (a,c are for indirect HDH and b,c are for direct HDH)

In Fig. 3-9 the effect of outlet air relative humidity of humidifier on performance parameters of both indirect and direct HDH systems are shown. Varying the outlet relative humidity of air in the outlet of humidifier does not considerably affect the GOR and RR in the both HDH system. Optimal point of the seawater to air flow rate ratio of the indirect HDH system are slightly more sensitive than direct HDH system to the humidifier outlet air relative humidity. GOR of the indirect HDH system is higher that direct HDH system for all the relative humidity values. However, the RR of the direct HDH system shows a higher value compared to indirect HDH system.

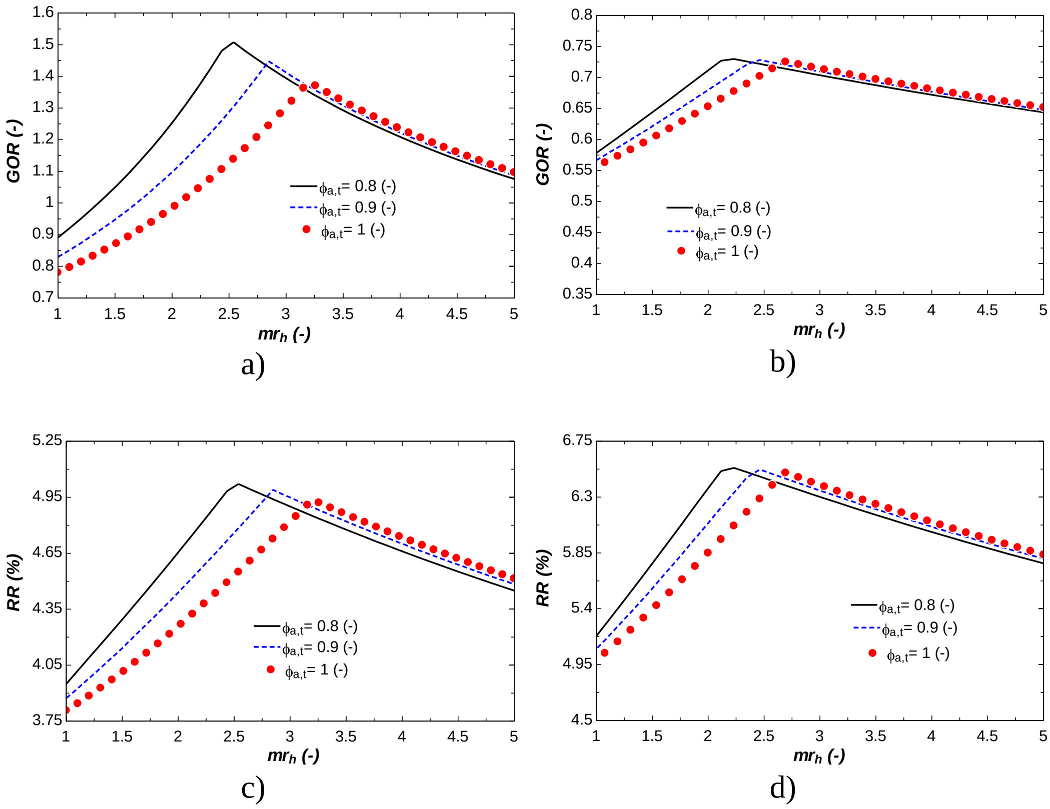

Fig. 3-9: Effect of outlet air relative humidity of humidifier on HDH performance parameters. (a,c are for indirect HDH and b,c are for direct HDH)

3.4.5. Seawater to fresh water flow rate ratio in a direct HDH system

In the direct HDH system the inlet flow rate of freshwater in the dehumidifier and flow rate of saline water in the humidifier are independent. Therefore, they can be varied. While in the indirect HDH system the inlet humidifier and dehumidifier flowrates are the same. To study the effect of humidifying and dehumidifying flow rates on direct HDH system performance a non-dimensional parameter is introduced, called as mass flow rate ratio of seawater (or saline water) to freshwater, $mr_{sw/fw}$. Fig. 3-10 shows the effect of flowrate ratio of seawater to freshwater on the direct HDH system performance. Decreasing the flowrate ratio results in higher recovery ratio of the system while the optimum point of “sweater to air flow rate ratio” shifts to the lower values.

It should be mentioned that as beforementioned comparison between the direct and indirect HDH systems, the mass flowrate ratio of seawater to freshwater is one. In other words, the flow rate of seawater and fresh water are equal.

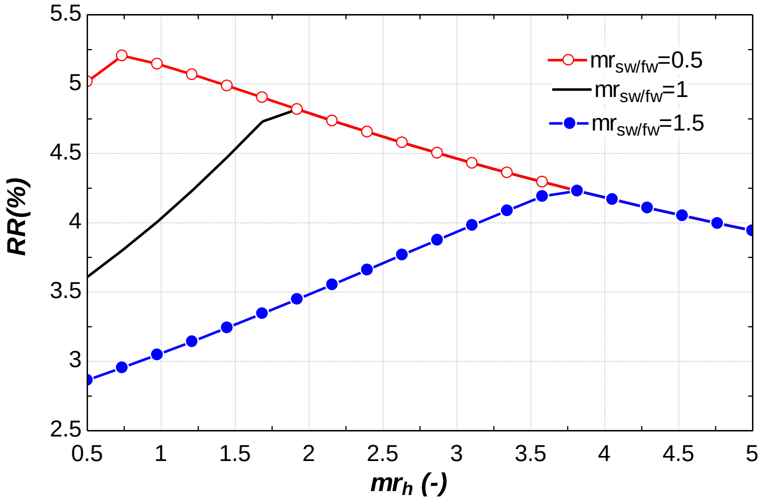

Fig. 3-10: Effect of ratio of seawater flow rate to freshwater flow rate on RR in direct contact HDH system.

3.4.6. Conclusion

Generally, RR of the direct contact HDH system is higher than indirect HDH system at a specified operating condition, therefor more water can be produced from a direct contact HDH system at a similar operating condition with the indirect HDH system. On the other hand, GOR of the indirect system is always higher than the direct HDH system at a similar operating condition, therefor more efficient heat recovery can be achieved in the indirect HDH desalination system.

To improve the heat recovery or GOR, in the direct HDH system, external heat recovery in a direct-contact dehumidifier can be considered by using an external heat exchanger to preheat the humidifier feed saline water.

Higher cooling load in the dehumidifier shifts the optimum point of the seawater to air, mr_h, to the lower values in both direct and indirect HDH systems. In the indirect HDH system higher cooling load can be obtained by having a lower humidifying temperature, while in the direct system this can be adjusted by both humidifying temperature and cold freshwater flow rate. On the other hand, higher

humidifying loads will move the optimum point of the seawater to air flow rate, mr_h, to the higher values. Providing higher heating load, in the humidifier of the indirect HDH is possible by increasing the seawater temperature without influencing the dehumidifier load, while in a direct HDH this system can be modified by both temperature and seawater flow rates. Lower/higher seawater to air flow rate refers to higher/lower air flow rate at a constant seawater flow rate.

In both HDH systems, effect of the dehumidifier effectiveness is more prominent than the humidifier effectiveness on the HDH system performance parameters. Therefore, designing a dehumidifier, with higher effectiveness could be a more beneficial approach for designing the HDH desalination systems.

To reach the best performance in rems of water production and heat recovery, using a humidifier and a dehumidifier with higher effectiveness is always beneficial. Also, keeping the air to water flowrate ratio at its optimal point for a specific operating condition results in best performance of the HDH system that can be practice using a control system. According to the parameter study and practical considerations based on performed experiments, designing a HDH system with the HME effectiveness above 0.85, top brine temperature of 70-80°C and dehumidifying temperature of 15-25°C is practically achievable considering current materials available in the market.

Chapter 4:

Experimental Investigations of HDH System Performance

This chapter is the published paper with title "Experimental performance evaluation of humidification-dehumidification system with direct contact dehumidifier". The Digital Object Identifier is: https://doi.org/10.1115/1.4044551

Contributor	***Statement of Contribution***
S. Dehghani	Conducting and analysing the experiments (100%) Developing and analysing theoretical model (90%) Writing and editing the paper (80%)
F. Mahmoudi	Editing the paper (5%)
A. Date	Editing the paper (5%)
A. Akbarzadeh	Developing and analysing theoretical model (10%) Editing the paper (10%)

Chapter 5:

Heat Pump Driven HDH System Performance Optimization

This chapter is the published paper with title "Performance analysis of a heat pump driven humidification-dehumidification desalination system". The Digital Object Identifier is: https://doi.org/10.1016/j.desal.2018.07.033

Contributor	***Statement of Contribution***
S. Dehghani	Developing and analysing mathematical model (100%) Writing and editing the paper (90%)
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A. Akbarzadeh	Editing the paper (5%)

Chapter 6:

Experimental Investigation of Brine Recirculation in HDH

This chapter is the published paper with title "An experimental study of brine recirculation in humidification-dehumidification desalination of seawater". The Digital Object Identifier is: https://doi.org/10.1016/j.csite.2019.100463

Contributor	***Statement of Contribution***
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A. Date	Editing the paper (5%)
A. Akbarzadeh	Developing and analysing theoretical model (10%) Editing the paper (10%)

Chapter 7:

Conclusions and Recommendations

7.1. Conclusions

A research study is conducted to investigate the performance characteristics of the HDH system with a direct contact dehumidifier. Experimental study of the Direct contact dehumidifier is shown to be a successful practical solution to eliminate corrosion related issues due to the saline water flow in conventional dehumidifiers. Before experimental investigations, at first, the performance of the direct HDH system is compared with the indirect HDH system by implementing a mathematical model. A parametric study is performed utilizing the mathematical model and effect of operational parameters on water production and heat recovery of the HDH system is studied.

It is found that, the HDH system with direct contact dehumidifier system shows a higher recovery ratio compared with an indirect HDH system. However, the gain-output-ratio of the direct HDH system is lower than the indirect system at the same operating condition. For instance, considering the operating condition with top brine temperature of 70ºC, dehumidifying temperature (inlet dehumidifier temperature of saline water or freshwater) of 25ºC, the effectiveness of humidifier and dehumidifier of 0.85 and relative humidity of air after humidification and dehumidification of 0.9 results in the GOR and RR of the direct HDH system of 0.65 and 6% respectively while for the indirect HDH system GOR and RR are 1.4 and 5.25% respectively.

Considering the practical design aspects of these HDH systems, the direct HDH system eliminates the corrosion-related problems in the dehumidifier as the saline water is not flowing through the dehumidifier. However, the direct dehumidification requires a cooler for cooling down the freshwater for re-dehumidification in comparison with the indirect HDH system.

In another part of the research, a more accurate mathematical model to study the HDH system with direct contact dehumidifier that incorporates the size of the heat and mass exchange devices is developed. In this mathematical model, an effectiveness-NTU relationship of the humidifier and dehumidifier are developed. The effectiveness-NTU relation can relate the size of a heat and mass exchange device to its design parameters such as size, liquid to gas flow rate ratio, and specific volume of the packing fill. Using this mathematical model, more detailed results incorporating the heat and mass transfer area are obtained while for the model presented in chapter 3 the effectiveness of the humidifier and the dehumidifier were considered constant and the size of them were subsequently unknown.

Moreover, an experimental rig is designed and fabricated at the Thermodynamic Laboratory of RMIT university to study the thermal performance of the HDH system with direct contact dehumidifier. Several experimental tests are performed to not only examine the water production rates, but also find out the optimum water production of the HDH system at different operating conditions. Also, various experiments are conducted to investigate the effect of operational parameters such as temperatures of humidifier feed, dehumidifier feed, flow rates of saline water, the flow rate of freshwater, and airflow rate. To reach a comprehensive parametric study, all the operational parameters are defined as non-dimensional variables. This helps to scale up the system without further modelling considerations.

Then, the mathematical model is verified with the obtained experimental results. It is investigated that for each operating condition of the HDH system, there is an optimum working point which results in higher water production and lower energy consumption values. Therefore, the relationship of the optimal working point of the HDH system is demonstrated both mathematically and experimentally.

To keep the HDH system working at its optimal point (Maximum RR and Maximum GOR) for any operating condition a control system can be implemented to adjust the blower speed to reach to optimum air to water flowrate ratio. Operating condition may vary due to different reasons such as change heating or cooling loads. For example, when the thermal loads are sourced from a solar energy-based technology which is intrinsically intermittent, the control system can make the HDH system working autonomously at its optimum water production rate. To take the research closer to real case application condition, the HDH system examined under the extreme working condition of high saline feed by varying the salinity from 3% to 30% saturation. It is shown that the system can work with high saline feed which is an outstanding feature. HDH desalination ability to work with high salinity feed it is an outstanding competitive advantage compared to other desalination technologies.

An important issue related to desalination systems is their environmental impacts. The concentrated brine of the desalination systems which has higher salinity usually is rejected to the environment that can have catastrophic impacts on species, land, etc. This also increases the brine management cost. To reduce the environmental impacts of the HDH desalination system a new idea of brine recirculation method is studied. To decrease the reject brine volume of the HDH system a mathematical simulation based on the brine recirculation idea is performed. Then, by conducting experimental tests at different feed salinities the mathematical simulations are confirmed in practice. Using the brine recirculation method is shown to be a practical idea to reduce the rejected brine volume in HDH desalination system.

In the HDH desalination with direct contact dehumidifier, rather than the heating load, a cooling load is required. The cooling load can be provided a conventional cooler. In addition, replacing both the cooling load and the heating load with only electrical load would be beneficial for some cases as the electrification is approached for various applications. Electrifying the HDH system makes it simple and more accessible to broader range of users. Therefore, in another part of the research, the new idea of using the heat pump to drive the HDH system

is investigated. A heat pump is used to simultaneously provide the heating and cooling loads of the HDH system in humidifier and dehumidifier, respectively. A mathematical model is developed to simulate the performance of the heat pump working with R134-a refrigerant when it is coupled with the HDH system. In this study, the optimal working condition of the heat pump driven HDH system that results in the lowest specific energy consumption is researched. Also, a fully coupled heat pump that supplies the heating and cooling loads of the HDH system is investigated and scenarios to reach a fully coupled condition at optimum operation point for any operating condition is investigated.

In conclusion, a low-cost HDH with direct contact dehumidifier system can be fabricated using conventional materials available on the market. PVC pipes for the shell and polypropylene(PP) and proved to be effectively functional in the studied HDH system and can be used for further system production. The piping and spraying nozzles must be corrosion resistance in humidifier and its corresponding piping parts. A heat pump driven HDH system can be used small-scale applications where less operating complexity and a compact HDH system is a priority. This system can be advanced by incorporating a brine recirculation option to reach higher recovery ratio and reduce the environmental impacts. The direct contact dehumidifier HDH system is preferred over the indirect HDH system as it eliminates the maintenance cost of corrosion in the dehumidifier. Energy sources of the HDH system can be provided from any low-grade heat sources such as solar thermal collectors, PV heating systems, or industrial waste heat sources. They can also be completely replaced with electrical power source which is viable when a heat pump is coupled with the HDH system.

7.2. Remarks and recommendations

The water production potential of the HDH system is limited by several variables which recognizing them will help to understand the performance limitation of the HDH system. It is obvious that increasing the humidifying temperature improves the recovery ratio of the system, but how far this temperature can be increased is a question. The maximum humidifying temperature in the about

the boiling temperature of the saline water. On the other hand, the effect of dehumidifying temperature is almost negligible compared with the humidifying temperature. The reason is that absolute humidity of air is remarkably higher in higher dry bulb temperatures. For instance, the absolute humidity of air is about 0.08, 0.17 and 0.25 kilogram of water per kilogram of air for dry bulb temperature of 50, 60 and 70 ºC, respectively. Therefore, is not beneficial to have a very low temperature of dehumidifying while it is a good idea to increase the top brine temperature as much as possible. It should be mentioned that some packing fill made by polyproline or PVC cannot tolerate the temperature above 80ºC on long-term operation. This could be a constraint by itself. A suggestion is to replace the packing fill material in humidifier and use the materials that can endure temperatures above 80 ºC and they are corrosion resistant as well.

7.2.1. Future research considerations

The water production potential of the HDH system is also limited by the psychrometric properties of the air. Another idea for improving water production is to use other types of non-condensable gases which has higher absolute humidity and can carry more water compared with air. Studying another type of working fluid can be a subject of another study.

The effect of packing fill specific surface area on the performance of the system can be a subject of another study. Clearly, a packing fill with a higher specific area will enhance the humidification and dehumidification processes. However, it implies more pressure drop of air throughout the humidifier and dehumidifier. Therefore, to identify heat and mass transfer enhancement at the cost of higher pressure drop can be a subject for another optimization study.

The GOR of the direct contact HDH system is considerably lower than the indirect HDH system to improve it an external heat recovery can be considered by using the warmed water from the dehumidifier to preheat the saline water feed of the humidifier before adding heat from the external heat source.

The capability of working with high saline feed water is shown using the HDH system. This feature can be used to achieve a zero Liquid Discharge desalination system by coupling the HDH system with other desalination systems or by using a brine recirculation method in the HDH system. For example, using a salt crystallizer connected with the brine-recirculated HDH system to reach zero liquid discharge desalination. The sizing, feasibility and performance of this kind of desalination system can be taken to further details in another study. Coupling the HDH system with other desalination technologies such as reverse osmosis that are not capable to work with high saline water feed in order to use their rejected brine to as feed for HDH system and reach zero liquid discharge desalination in another example of HDH application.

Using a solar pond to provide heating loads and saline feed for HDH system is another suggestion for a research study. A solar pond can be used for providing thermal loads requirements of the HDH system. It also can provide high temperature saline feed for HDH system from the bottom convective zone or non-convective zone for desalination purposes.

In the heat pump driven HDH system configuration, both AC and DC electrical power can be used to power the compressor which was not subject to this study. Therefore, for off-grid applications where the DC power is produced directly from renewable sources such as photovoltaic panels, a DC powered compressor can be used rather than using an AC electricity supply utilizing an inverter. A DC powered compressor with intermittent power supply results in variable pressure ratios of the compressor. Therefore, a heat pump driven HDH desalination system for an off-gird application can be a subject for further engineering studies consideration.

7.2.2. Bubble column HDH

Bubble column HDH system is another configuration of humidification-dehumidification desalination that can be subject for another research study. In this setup, air is bubbled in a bubble column filled with hot saline water using a sparger. As a result, air gets humidified by increasing its temperature and touching the saline

water in the column. Then, the hot humidified air is transferred to the dehumidifier column filled with cold fresh water for dehumidification. At the same time, seawater is fed to the humidifier column to maintain the required humidifier column height and compensate the evaporated water. While in the dehumidifier, the distilled water is extracted to maintain the required height of water in the dehumidifier column. The details of thermal loads and, flow direction, and instrumentation are given in the Fig. 7-1. The proposed system can be a possible solution for zero liquid discharge desalination. The bubble column HDH system can be used to produce water and salt as a final output with saline water and thermal energy as inputs which seems very promising idea for further investigation. Investigation of the system performance, characteristics, and practicality of the bubble column is recommended for further research in HDH desalination systems.

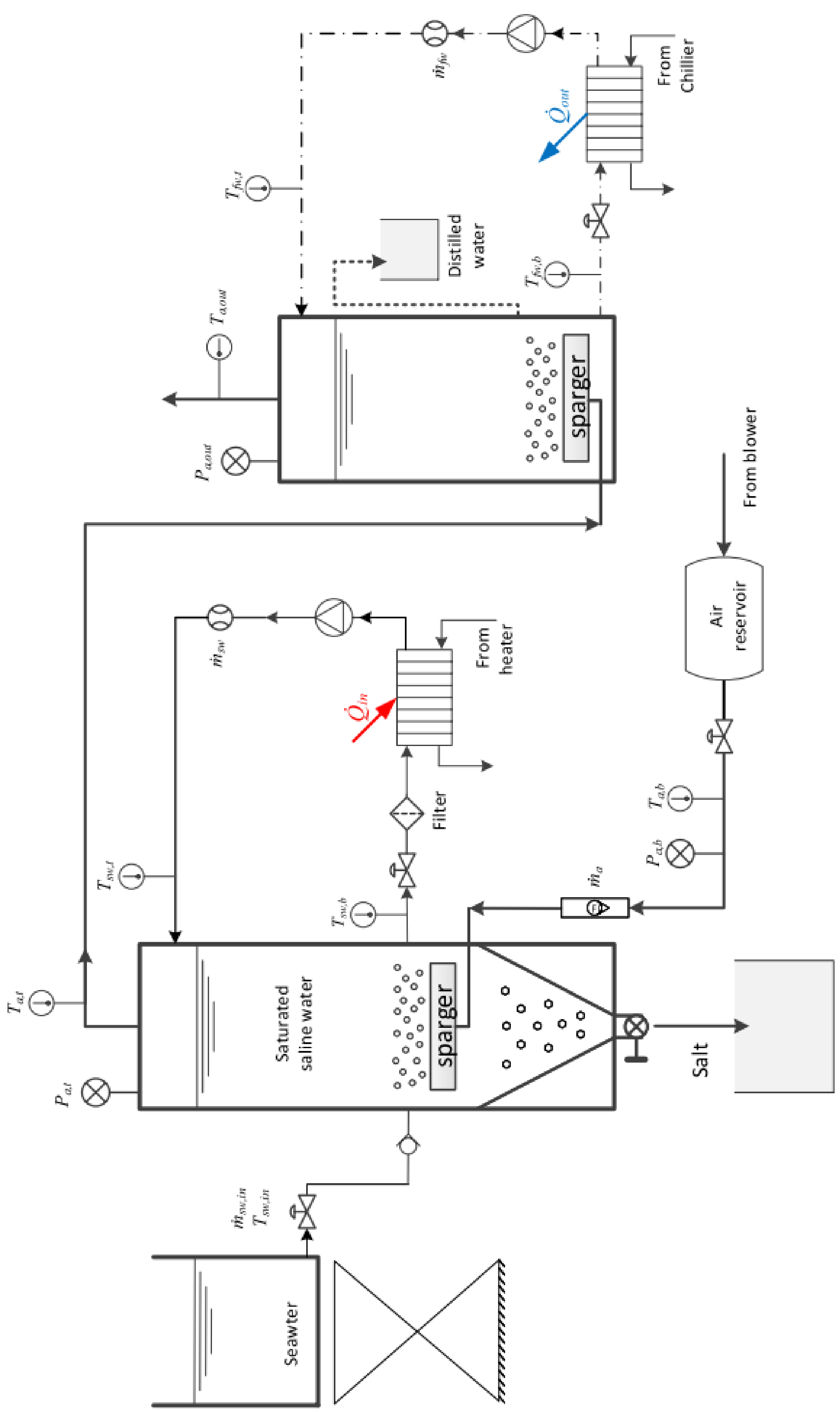

Fig. 7-1: The bobble column HDH system schematics

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Appendix

The specification of the items used in fabrication of the experimental rig are provided on this section. Full cone spray nozzles are used for spraying freshwater and saline water on the packing fill surface area.

CJ & GCJ Series - Full Cone Nozzle

CJ Nozzle GCJ Nozzle

Nozzle Features

CJ & GCJ series full cone spray nozzles feature a spray pattern with round impact area in narrow to medium spray angles, produce uniform distribution of medium to large sized droplets over a wide range of flow rates and pressures. Their uniform spray distribution result from a unique vane design, large and easy flow passages and superior spray control design.

The CJ & GCJ range is ideal for applications requiring complete coverage to a certain area. GCJ series of metal nozzles have knock down cap and vane. This design allows the working end (cap and vane) to be removed from the nozzle body, overhauled and cleaned without removing the nozzle body from the pipe.

Performance Data

NOZZLE THREAD CONN.	NOZZLE CODE	INLET BORE DIA.	OUTLET BORE DIA.	FLOW RATES (LPM @ BarG)							APPROX. SPRAY ANGLE @ 2.0 BarG
		(mm)	(mm)	0.5	1.0	2.0	3.0	5.0	7.0	10.0	DEG°
1/8	6	0.6	0.8	0.33	0.45	0.63	0.76	0.97	1.14	1.34	57
	9	0.6	1.2	0.47	0.66	0.91	1.10	1.40	1.64	1.94	63
	12	1.0	1.2	0.62	0.85	1.18	1.43	1.82	2.13	2.51	51
	19	1.0	1.5	0.97	1.35	1.87	2.26	2.88	3.37	3.98	63
	22	1.3	1.6	1.14	1.57	2.18	2.64	3.35	3.93	4.64	51
	24	1.0	2.0	1.26	1.74	2.41	2.92	3.71	4.34	5.13	82
	31	1.0	2.0	1.63	2.25	3.12	3.78	4.80	5.62	6.65	66
	38	1.3	2.3	1.98	2.74	3.79	4.59	5.83	6.83	8.08	72
1/4	41	1.6	2.4	2.12	2.94	4.07	4.92	6.26	7.33	8.67	51
	63	1.6	3.2	3.28	4.54	6.29	7.61	9.68	11.33	13.40	66
	76	1.6	3.2	3.97	5.49	7.61	9.21	11.71	13.71	16.21	71
3/8	58	2.4	2.6	3.03	4.20	5.82	7.04	8.95	10.49	12.40	51
	92	2.4	3.6	4.80	6.65	9.21	11.14	14.17	16.59	19.62	65
	125	2.8	4.0	6.50	9.00	12.47	15.09	19.18	22.47	26.57	78
	137	2.8	4.5	7.05	9.76	13.52	16.36	20.80	24.36	28.81	85
1/2	100	3.2	3.5	5.19	7.19	9.96	12.05	15.32	17.95	21.22	51
	155	3.2	4.6	8.06	11.17	15.47	18.72	23.80	27.87	32.96	65
	198	3.6	5.2	10.28	14.24	19.72	23.86	30.33	35.53	42.02	76
	249	3.6	6.2	12.98	17.98	24.91	30.14	38.32	44.88	53.07	88
	309	4.0	6.7	16.12	22.32	30.92	37.41	47.56	55.71	65.88	92
3/4	181	4.4	4.9	9.44	13.07	18.11	21.91	27.86	32.63	38.59	51
	290	4.4	6.4	15.07	20.88	28.92	34.99	44.49	52.11	61.62	67
	510	5.2	7.5	26.54	36.76	50.91	61.60	78.31	91.73	108.47	89
1	310	5.6	6.1	16.11	22.32	30.91	37.40	47.55	55.69	65.86	51
	510	5.6	8.3	26.54	36.76	50.91	61.60	78.31	91.73	108.47	69
	581	5.6	9.5	30.28	41.94	58.09	70.29	89.36	104.67	123.77	84
	729	5.6	11.9	38.00	52.64	72.91	88.22	112.16	131.37	155.35	91
	871	6.4	11.9	45.39	62.87	87.08	105.36	133.95	156.90	185.54	93
1-1/4	441	6.4	7.4	22.98	31.83	44.09	53.35	67.82	79.44	93.94	51
	729	6.4	9.6	38.00	52.64	72.91	88.22	112.16	131.37	155.35	66
	871	6.4	10.7	45.39	62.87	87.08	105.36	133.95	156.90	185.54	71
	1021	6.4	12.3	53.20	73.69	102.07	123.50	157.01	183.91	217.48	82
	1461	7.9	15.1	76.14	105.46	146.08	176.75	224.71	263.21	311.25	94
1-1/2	731	8.7	9,5	38.10	52.77	73.09	88.43	112.43	131.70	155.73	51
	1159	8.7	12.7	60.42	83.69	115.92	140.26	178.32	208.87	246.99	73
	1459	8.7	14.3	76.05	105.34	145.91	176.54	224.45	262.90	310.89	78
	2190	10.3	18.3	114.16	158.12	219.01	264.99	336.90	394.62	466.64	95
2	1241	11.1	12.7	64.67	89.57	124.07	150.12	190.85	223.55	264.35	52
	2179	11.1	17.3	113.59	157.34	217.93	263.68	335.23	392.67	464.34	75
	2550	11	19.2	132.94	184.13	255.04	308.58	392.32	459.54	543.41	79
	2909	11.1	21	151.65	210.05	290.94	352.02	447.54	524.22	619.90	81
	3640	11.1	23.8	189.74	262.81	364.02	440.44	559.96	655.90	775.61	87
	4370	14.3	28.6	227.79	315.51	437.02	528.77	672.25	787.43	931.14	101

Applications

- Gas Scrubbing
- Foam Suppression
- Cooling & Quenching
- Meat Carcass Chilling
- Fire Deluge Protection

Ordering Example

3/8-CJM-316SS-92

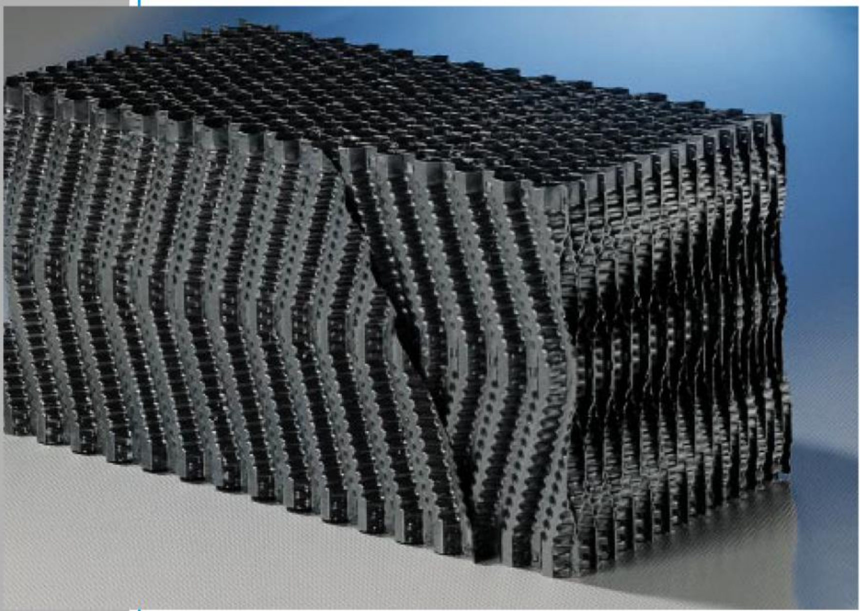
Available Materials

Brass, 303ss, 316ss

* Other materials available on request

Packing fills are used in both humidifier and dehumidifier to provide the heat and mass transfer area. The specification of the packing fills are given as follow.

2 H PP Cooling Tower Fill
FKP 312/612
welded polypropylene structured media



High temperature resistant
Minimum pressure drop
Environmental friendly
Longest service life
Superior heat exchange properties

2H Kunststoff GmbH
Dieselweg 5 · D-48493 Wettringen
Telefon +49 (0) 25 57 / 93 90-0
Telefax +49 (0) 25 57 / 93 90-49
Internet: http://www.2h-kunststoff.de
E-Mail: info@2h-kunststoff.de

2 H PP Cooling Tower Fill FKP 312/612 for counterflow applications

Standard dimensions L/W/H:
2.400 x 300 x 600 (or 300) mm

Surface of exchange: 240 m^2/m^3

Flute size: 12 mm

Material: Polypropylene UV resistant

Waterload: max. 30 $t/m^2/hr$.

Distance of supports : max. 1.000 mm

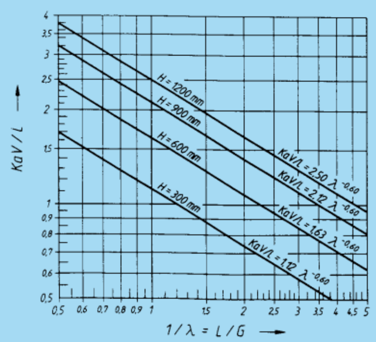
Width of supports : 50 mm

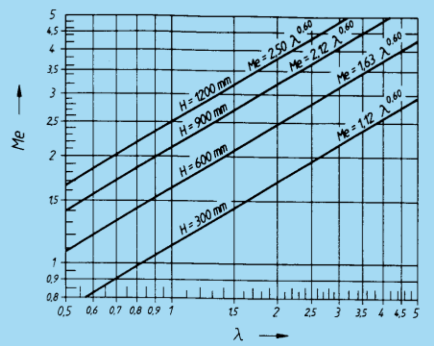
Spec. weight : 1,03 gr/cm^3

Dry weight : 29 kg/m^3

Average foil thickness : 0,35 mm

Max. service temp. : 80 °C. (short)





Options for cooling tower fill characteristic

$$Me = Me_o \cdot \lambda^m \quad \text{or,}$$
$$KaV/L = f\ (L/G)$$

Applications: Heat exchanging, serial modular cooling towers, counter- or crossflow.

Cross flow scrubbers, gaswashers.

Biotowers, nitrification.

Humidifiers.

Biorotors.

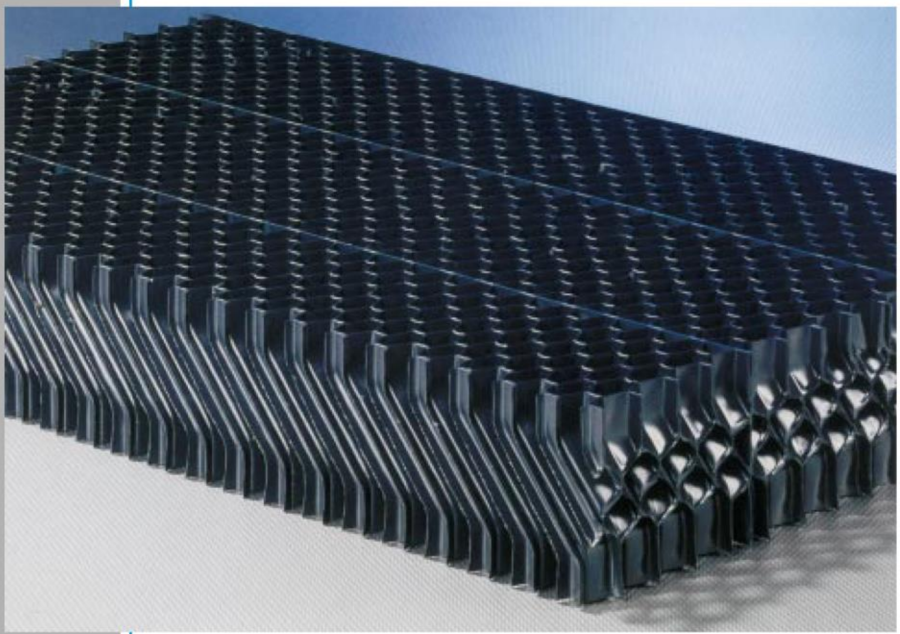
Our PP fills can also be delivered for high temp. application, permanent exposure to 100 °C.

On request we also deliver special compounded PP fills meeting fire retardant grade B_2 (DIN 4102) or UL 94 V_2.

FKP 312/612 is also available in rigid PVC version (FKC 312/612) with absolute identical heat transfer performance as showed above.

The following in the pressure drop of air through the packing with different heights of the packing fill.

2H PP-Tropfenabscheider TEP 130
2H PP-Drift Eliminator TEP 130



TEP 130

Hochtemperatur- und UV-beständig (bis 80 °C)
High temperature (up to 80 °C) and UV-resistant

Keine Deformation bei direkter Sonneneinstrahlung
No deformation under direct sunlight

Gute Umweltverträglichkeit (PVC- und Lösungsmittelfrei)
Environmentally friendly (PVC and solvent free)

Keine Versprödung und keine scharfen Kanten
No brittleness and no sharp edges

Minimaler Druckverlust
Minimal pressure drop

Optimaler Tropfenfang
Optimal droplet capture

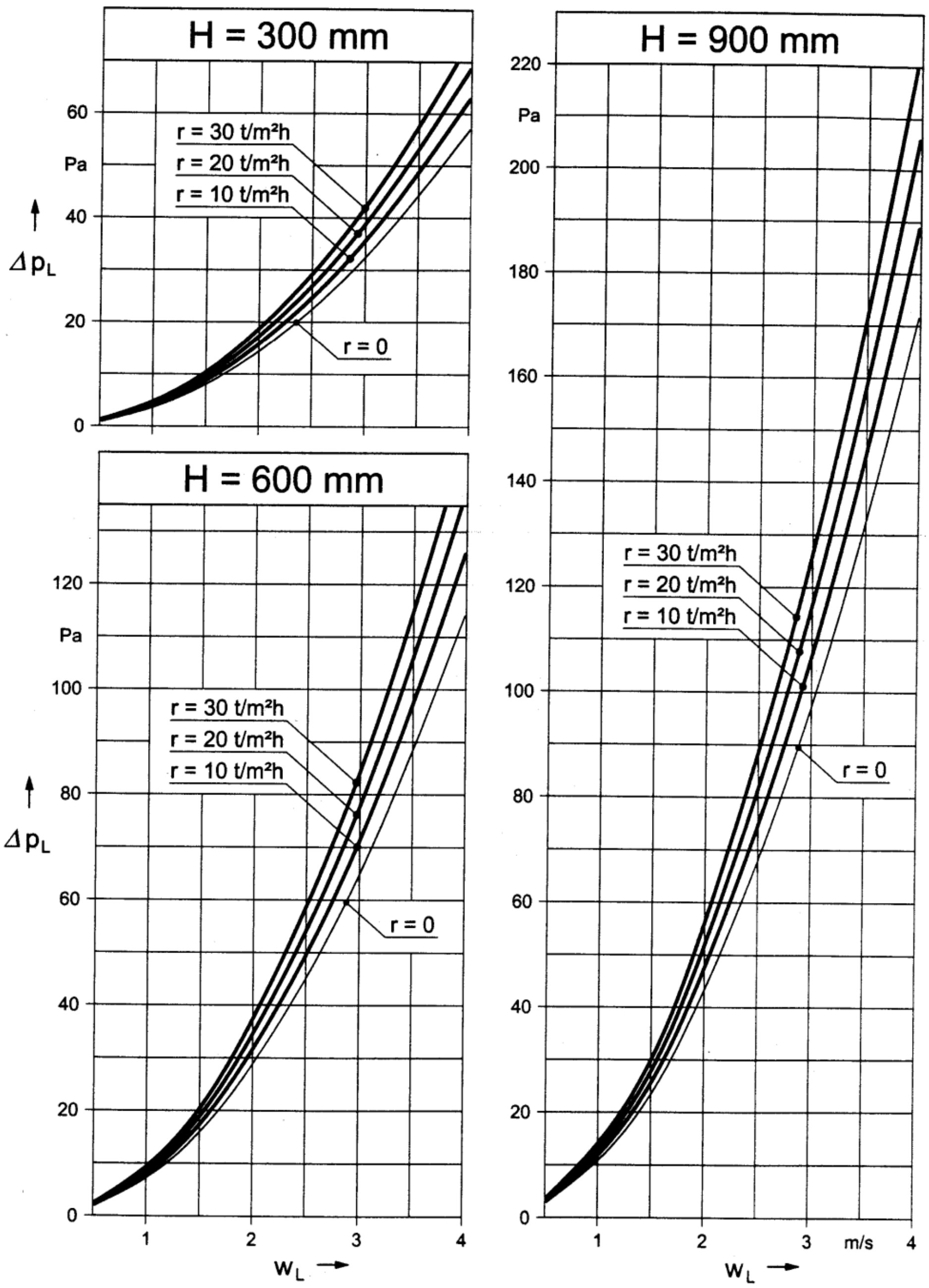
TÜV CERT
DIN EN ISO 9001

2H Kunststoff GmbH
256 Princes HWY
Dandenong 3175
Telefon ++ 61(0)3 9793 6166
Telefax ++61(0)3 9793 6050
Internet: www.2h.com.au
E-Mail: sales@2h.com.au

Kühleinbau / Cooling tower fill **2H - FK_ 312** *(612)*

2H Kunststoff GmbH

Druckverlustdiagramme / pressure drop diagrams



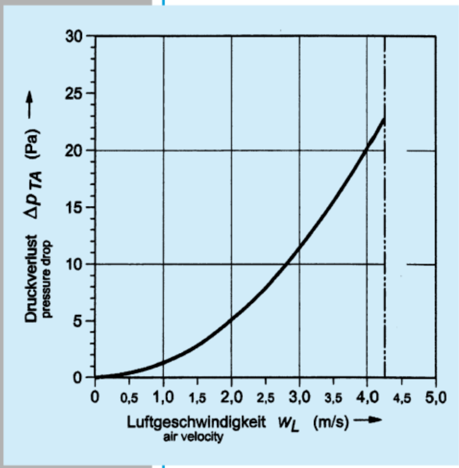
Ausgabe: 07/98

2H Kunststoff GmbH * Dieselweg 5 * D-48493 Wettringen * Tel.: 02557 / 9390-0 * Fax.: 02557 / 9390-49

The following is the specification of the drift eliminator which is used to eliminate droplet of water transfer with the air that pass through the packing fill. It is installed at the outlet of humidifier/dehumidifier to prevent the droplets moving out with the air.

2H PP-Tropfenabscheider TEP 130
2H PP-Drift Eliminator TEP 130

Abmessungen *(Dimensions)*: Länge *(Length)*: 400 – 2.400 mm
Breite *(Width)*: 300 – 650 mm
Höhe *(Height)*: 125 / 260 mm



Technische Daten *(Technical Data)*:

Werkstoff: *Material:*	hochwertiges, UV-beständiges Polypropylen (PP) *high-performance, UV-resistant Polypropylene (PP)*
Gewicht: *Weight:*	ca. 4 kg/m² *approx. 4 kg/m²*
Tropfenverlust[1]: *Drift loss[1]:*	0,001 % *0,001 %*
Durchrissgeschwindigkeit: *Max. air velocity:*	ca. 4,25 m/sec. *approx. 4,25 m/sec.*
max. Betriebstemperatur: *Max. service temperature:*	80 °C *80 °C*
Max. Unterstützungsweite: *Max. spacing of supports:*	800 mm *800 mm*

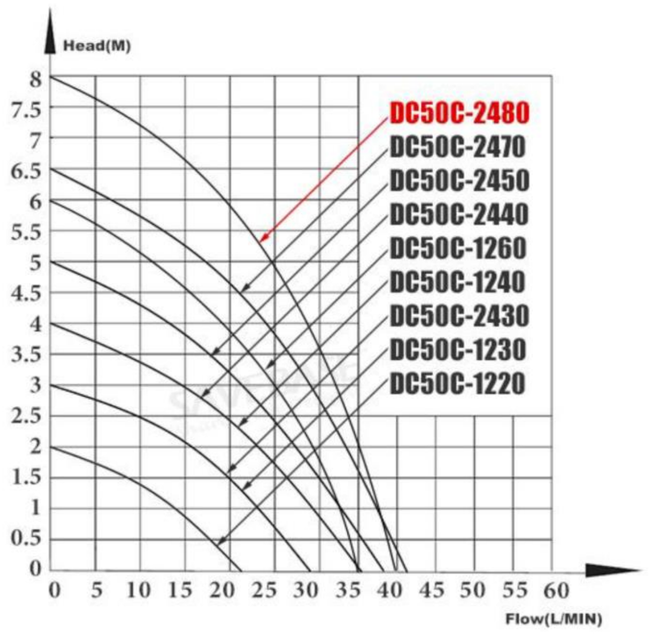
[1] Die Angaben basieren auf der CTI ATC-140 Testmethode (Isokinetic Drift Test Code) und verstehen sich als Richtwerte. Unter Abscheideleistung des Tropfenabscheiders ist das Verhältnis Tropfenauswurf/Wasserstrom ($M_{W,S}/M_W$) zu verstehen. Der Abscheidegrad bezieht sich auf eine konstante Luftgeschwindigkeit und einer absolut dichten Montage der Tropfenabscheiderelemente.

[1] *Based on the CTI ATC-140 test method (Isokinetic Drift Test Code). These limits are guidelines only. The performance of the drift eliminator is indicated by the ratio drift loss/water flow rate. The efficiency of droplet separation depends on constant air velocity and an absolutely tight assembly of drift eliminator elements.*

TÜV CERT DIN EN ISO 9001

The table and graph below show the DC brushless pump that where used to supply the water to the spray nozzle in humidifier and dehumidifier.

DC50C SERIES (Available Models)					
Model	Voltage(V)	Max Current(A)	Max Head(m) at zero flow	Max Flow(L/H) at zero head	Max Power(w)
DC50C-1230T	12	2.0	3.0	1680	24W
DC50C-1230S	12	2.0	3.0	1680	24W
DC50C-1230A	12	2.0	3.0	1680	24W
DC50C-1260S	12	4.5	6.0	2100	54W
DC50C-1260A	12	4.5	6.0	2100	54W
DC50C-2440T	24	2.0	4.0	1920	48W
DC50C-2440S	24	2.0	4.0	1920	48W
DC50C-2440A	24	2.0	4.0	1920	48W
DC50C-2480S	24	3.6	8.0	2400	86.4W
DC50C-2480A	24	3.6	8.0	2400	86.4W



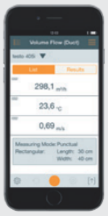
The following data sheet shows the anemometer which is used to measure the air velocity in the experiments.

Technical data/accessories

testo 405i

testo 405i, thermal anemometer operated with smartphone, incl. batteries and calibration protocol

Order no. 0560 1405



testo Smart Probes App
The App turns your smartphone/tablet into the display of the testo 405i. The operation of the measuring instrument as well as the display of the measurement values take place by Bluetooth via the Testo Smart Probes App on your smartphone or tablet – independently of the measurement location. In addition to this, you can use the App to create measurement reports, add photos and comments to these, and send them by e-mail. For iOS and Android.

Sensor type	**Hot wire**
Measuring range	0 to 30 m/s
Accuracy ±1 digit	±(0.1 m/s + 5 % of m.v.) (0 to 2 m/s) ±(0.3 m/s + 5 % of m.v.) (2 to 15 m/s)
Resolution	0.01 m/s

Sensor type	**NTC**
Measuring range	-20 to +60 °C
Accuracy ±1 digit	±0.5 °C
Resolution	0.1 °C

General technical data

Compatability	requires iOS 8.3 or newer / Android 4.3 or newer
	requires mobile end device with Bluetooth 4.0
Storage temperature	-20 to +60 °C
Operating temperature	-20 to +50 °C
Battery type	3 micro batteries AAA
Battery life	15 hrs
Dimensions	200 x 30 x 41 mm
	Telescope extendable to 400 mm
Warranty	2 years

The following data sheet shows the water flow meter which is used to measure the volumetric flow rate of the saline and fresh water.

FT-110 Series – TurboFlow™ Economical Flow-Rate Sensors

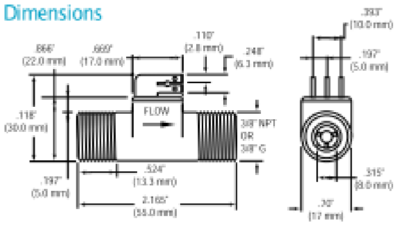
- Low Cost Plus High Accuracy ±3% of Reading
- Measures Low Liquid Flow Rates of .1 to 8 GPM
- FDA Approved Materials
- Lightweight Plastic Design Enables Mounting in any Position

Gems hall effect turbine flow rate sensor is ideal for OEM applications involving low flow liquid monitoring. The low cost coupled with 1/2% repeatability makes it an ideal candidate for replacing dispensing timer systems. Unlike existing timing systems, turbine technology is not influenced by changes in system pressure caused by aging filters. The sensor's standard power and output specifications make it easy to retrofit to existing controllers.

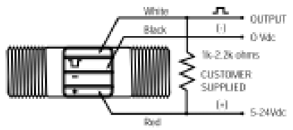
Specifications

Wetted Materials	
Body	Nylon 12
Turbine	Nylon 12 Composite
Bearings	PTFE/15% Graphite
Operating Pressure	200 PSIG
Burst Pressure	2500 PSIG
Operating Temperature	-4°F to 212°F (-20°C to 100°C)
Viscosity	32 to 81 SSU (.8 to 16 Centistokes)
Filter	<50 Microns
Input Power	5 to 24 VDC @ 8mA
Output	NPN Sinking Open Collector @ 50mA Maximum (1 to 2.2K Ohm Pull-Up Resistor Required) (Hz Output)
Accuracy	±3% of Reading
Repeatability	0.5% of Full Scale
Electrical Connection	Spade Terminals .110"/.248" x .031" (2.8/6.3 x .8 mm)
Inlet/Outlet Ports	3/8" NPT Male and 3/8" G Male

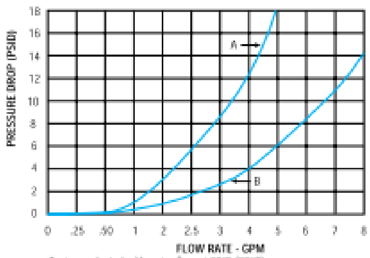
Dimensions



Wiring



Pressure Drop—Typical



Tests conducted with water flow at 68°F (20°C).

A) Part #173931 173936 173932 173937 173933 173938

B) Part #173934 173935 173939 173940

How To Order - Standard Models

Specify Part Number based on desired body material and port size.

Flow Range		Pulses per		Frequency Output	Part Number	
GPM	Liters/m	Gallon	Liter		3/8" NPT	3/8" G
.13-1.3	.5-5	26100	6900	58-575 Hz	173931	173936
.26-2.6	1-10	12500	3300	55-550 Hz	173932	173937
.26-4.0	1-15	17400	4600	76-1150 Hz	173933	173938
.26-4.0	1-15	8300	2200	37-550 Hz	173934 ⚡	173939
.53-7.9	2-30	3800	1000	33-500 Hz	173935 ⚡	173940

⚡ – Stock Items.

FT-110 Accessories

Description	Part Number
Mating connector w/3 feet, 3 conductor, PVC pigtail leads	173941
Mating connector w/10 feet, 3 conductor, PVC pigtail leads	173942

The following shows the data sheet for the humidity sensor which is used to measure the air humidity at different points during the experiments.

LinPicco™ Axxx Basic

Capacitive Humidity Module

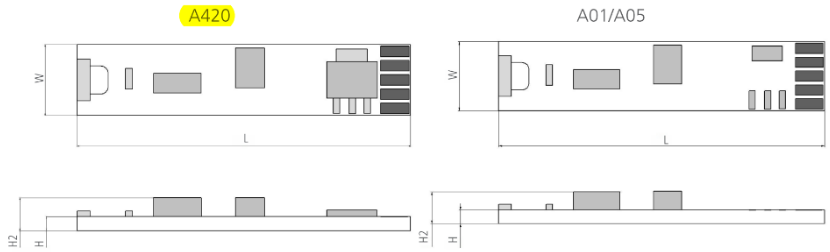
With calibrated and linearized analog output signal

INNOVATIVE SENSOR TECHNOLOGY

Benefits & Characteristics

- Precise humidity measurement
- Fully calibrated
- Very low drift due to wide sensor area
- Various analog output signals
- Easy to integrate
- Module with external sensor available
- PCB moisture protected
- Customer specific module available upon request

Illustration[1)]



1) For actual size, see dimensions

Technical Data

Dimensions (L x W x H / H2 in mm):	47 x 10 x 1 / 2.8		
Operating humidity range:	0 % RH to 100 % RH (maximal dew point = +85 °C)		
Operating temperature range:*	Module:	With external sensor:	
		P14:	MK33:
	-25 °C to +85 °C	-50 °C to +150 °C	-40 °C to +190 °C
Humidity sensor:*	P14 SMD		
Temperature sensor:*	Pt1000 or Pt100, class B (IEC 60751 F0.3), loop-through		
Accuracy:	< ±3 % RH (15 % RH to 85 % RH at +23 °C) < ±5 % RH (0 % RH to 15 % RH and >85 % RH at +23 °C)		
Response time t_{63}:	< 5 s (50 % RH to 0 % RH) at +23 °C		
Storage conditions:	-40 °C to +80 °C at max. 95 % RH non condensing		
Cable (external sensor version only):*	PTFE, 1 m		
	A420	A01	A05
Operating voltage (V_{CC}):	8 to 10 V_{DC} (max. load resistor 300 Ω)	7 to 32 V_{DC} (recommended 7 V to 9 V)	7 to 32 V_{DC} (recommended 7 V to 9 V)
Current consumption:	4 mA to 20 mA (two wire operation)	< 3 mA	< 3 mA
Output signal (0 % to 100 % RH):	4 mA to 20 mA	0 V to 1 V	0 V to 5 V

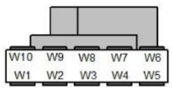
* Customer specific alternatives available

LinPicco™ Axxx Basic
Capacitive Humidity Module
With calibrated and linearized analog output signal

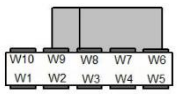
INNOVATIVE SENSOR TECHNOLOGY

Pin Assignment

A420



A01/A05



	W5 1)	W6 1)	W7	W8	W9	W10
A420	Pt1000 / Pt 100	Pt1000 / Pt 100	Current loop return			Current loop V_{CC}+
A01	Pt1000 / Pt 100	Pt1000 / Pt 100		GND	Analog output	V_{CC}+
A05	Pt1000 / Pt 100	Pt1000 / Pt 100		GND	Analog output	V_{CC}+

1) Does not apply for module with cable and external sensor

Order Information - Modules

Nominal resistance:	100 Ω at 0 °C	1000 Ω at 0 °C
A420	LinPicco (TM) Basic A420-G	LinPicco (TM) Basic A420-G
Order code	150.00016	150.00010
A01	LinPicco (TM) Basic A01-G	LinPicco (TM) Basic A01-G
Order code	150.00029	150.00007
A05	LinPicco (TM) Basic A05-G	LinPicco (TM) Basic A05-G
Order code	150.00018	150.00008

Order Information - Modules with PTFE cable, 1m

Nominal resistance:	1000 Ω at 0 °C
A420	LinPicco (TM) Basic A420-G.S
Order code	150.00091
A01	LinPicco (TM) Basic A01-G.S
Order code	150.00031