Performance Analysis of Combined Humidification Dehumidification (HDH) System Coupled with Air Conditioning System

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Dedication

To my beloved Parents who have been the source of inspiration for me at every stage.

To my supervisor for his fatherly behavior and inspiring guidance.

To my dearest homeland, Pakistan

Abstract

Humidification Dehumidification (HDH) systems are being used for small scale freshwater production using low grade heat source. For air conditioning applications vapor compression system is a widely used system. Analysis of Combined System humidification dehumidification (HDH) system coupled with vapor compression system through an enthalpy exchanger has been performed for different climate regions and several performance parameters has been studied for optimizing the performance of HDH system and to provide conditioned space at lower power consumption. Along with energy analysis exergy analysis has been performed for the components in vapor compression system. Results shows that combined system shows promising power savings for hotter regions where average summer temperature is greater than 35℃. For hotter regions combined system shows up to 20% reduction in input power. Along with reduced input power combined system shows 30% increased productivity for freshwater production. Results indicate that an average of 10l/h of freshwater production can be obtained from combined system. Exergy analysis shows that combined system shows average less exergy destruction in hot regions with a small increase in irreversibility ratio for enthalpy exchanger. Thus, combined system can be used effectively for hot regions for providing conditioned space and fresh water a product.

Keywords: *Humidification, Dehumidification, Enthalpy Exchanger, Vapor Compression System*

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1. **Muhammad Zeeshan Islam**, Dr.Adeel Waqas, Hafiz Abd-ur-Rehman, Dr.Majid Ali, Dr. Sehar Shakir, Dr. Maryiam Mehmood . *“Performance Analysis of Combined Humidification Dehumidification (HDH) System coupled with Air Conditioning System*”. International Conference on Energy Water and Environment (ICEWE 2021) 31 March 2021. (Presented)

List of Abbreviations

Nomenclature

$\dot{m}$	Mass flow fate (kg/s)
h	Enthalpy (kJ/kg)
$\dot{Q}$	Heat input (kW)
GOR	Gain output Ratio
h_{fg}	Enthalpy of vaporization of water (kJ/kg)
RR	Recovery ratio
MR	Mass flow rate ratio
Ex	Exergy (W)
s	Entropy (J/K)
ε_s	Sensible effectiveness of enthalpy exchanger
ε_l	Latent effectiveness of enthalpy exchanger
T_r	Relative Temperature
p_r	Relative Pressure
R	General gas constant
w	Constant =1.6081
C_p	Specific heat capacity (kJ/kg-K)

W_c	Compressor power (kW)
EEX	Enthalpy Exchanger
VCS	Vapor Compression System

Greek

ε	Effectiveness
ω	Humidity Ratio
ϕ	Relative Humidity

Subscripts

a	Air
sw	Sea water
fw	Fresh water
br	Brine
H	Humidifier
DH	Dehumidifier
i	Specific Component
v	Vapor
opt	Optimum

Chapter 1 : Introduction

1.1 Water and Energy Crisis

Water is the most essential and precious resource on which the life a human being and most of the other species depends. But in this time of great population increase we are facing a global water crisis. Around 2 billion people live in the areas of water scarce. And we have almost lost 83% of our freshwater. Water is also the necessity of human life and for the life of other species as well. But unfortunately, safe and clean water for drinking has become just a dream for most of the people in this water crisis era. Around 2 billion people in the world have to drink unclean water due to lack of availability of fresh water to drink [1]. Drinking of this unclean also lead to several water borne diseases Cholera, Typhoid and Dysentery. According to Government of Pakistan Economic survey in 2008 nearly 50 million people does not have access to the fresh drinking water [2]. This lack of availability of fresh water and shortage becomes more concerned when it comes to a developing country like Pakistan which does not have much infrastructure. Other than water energy or specifically electricity is the single most major element for the development of a society. So, in this era of exponentially growing population both demands of energy and water are ever increasing demands. And when the supply does not meet the demands and there is currently no significant progress in increasing the supply or infrastructure then one must think about saving the current resources to meet the demand i.e., by the means of energy savings. In Pakistan nearly 40% still does not any access to electricity [3]. More than 40% of world energy is consumed by the buildings all over the world showing a great potential of saving in the buildings [4], [5]. Out of this 40% more than 50% energy is consumed of air conditioning purposes in the building [4]. Since the energy consumption in air conditioning in the building is large therefore, it shows a great potential of saving as well.

1.1.1 Distribution of Water

Figure 1.1 shows the distribution of total water in earth's atmosphere [6]. Earth's surface is 70% of water and 30% of dry land. Out of that 70% water more than 96% of the water contained in the oceans. All the water in the oceans is saline water and hence cannot be used for drinking or other purposes for which portable water is used. Only 2.5 % is available as fresh water free from salts. Out of that fresh water about

30% is ground water and rest if frozen in the form of glaciers and icer bergs. Therefore, the quantity of useful water present earth is very low as compared to the total water present in earth atmosphere. So, we conclude that only oceans are the great source of water. But the water from the oceans needs to be purified before its use.

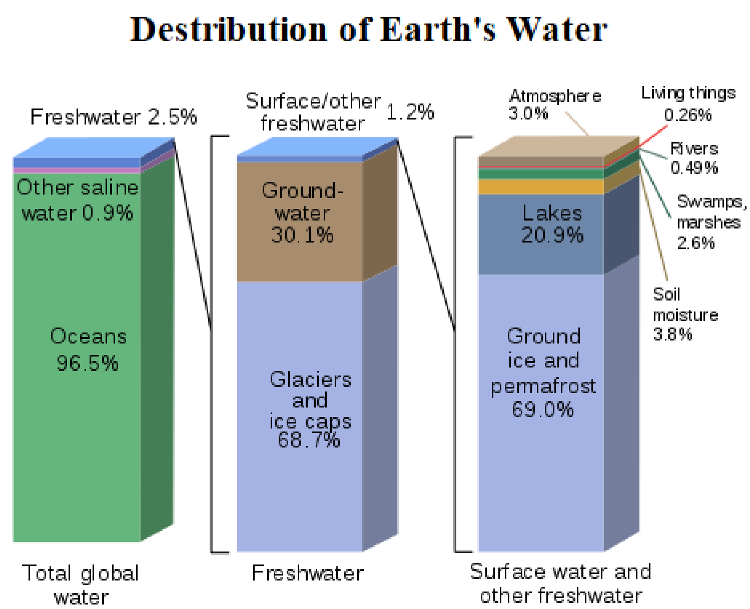

Figure 1.1:Water Distribution of Earth

1.1.2 Global Water Demand

Global water demand is ever increasing demand due to population growth and currently it is increasing at a rate of 1% per year and is expected to continue till 2050. By then it is 20-30% more demand then now [7]. And water resources are dwindling, and demand is increasing. This will create an increasing gap between supply and demand of fresh or portable water. To meet this growing demand, we must depend upon the oceans water. And oceans water must be desalinated before its used.

Water resources in Pakistan are becoming contaminating and becoming scarce according to a report of water resources and scarcity Pakistan may face severe water shortage by

2025 [8]. Moreover, water demand for Pakistan is also expected to rise by 40% in coming years. Due to this high demand and shortage of sources in Pakistan and around the globe there is a need to purify the saline water from the oceans which can be used to fill up this gap when demand will increase further. For this purpose, different techniques of desalination are in use. But in this study humidification and dehumidification (HDH) system are being analyzed for desalination and its coupling with air conditioning system because this could result in significant power savings in hot and humid regions.

1.2 Conventional Desalination Technologies

Desalination is process of removing salts and other impurities from the ocean water to make it useful and to be used as a fresh water and portable water or for drinking purposes. There are different desalination techniques currently working which uses different type of energy low quality or high quality. Depending upon the type of input power they consume there are two main categories of desalination processes.

1. Electrical desalination technology
2. Thermal desalination technology

1.2.1 Electrical desalination technology

Electrical desalination includes Reverse Osmosis, Vapor Compression and Electrodialysis. These techniques use high grade energy to purify the water. Reverse Osmosis uses a high-pressure pump which is run by electricity which forces the water to cross a membrane as shown in **Figure 1.2** [9]. Water crosses that membrane while leaving the salt and impurities behind which cannot cross the membrane and in order, we get purified water. In vapor compression desalination process heat rejected by the vapors of compressor is used and that compressor is run by using electricity [10]. Both methods use a high-grade source of energy.

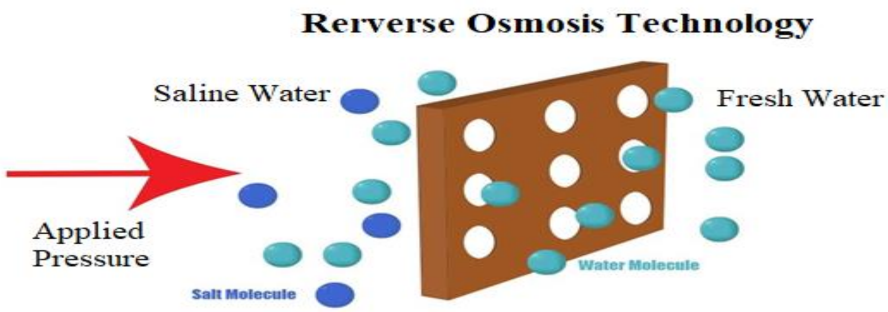

Figure 1.2: Working Principle of Reverse Osmosis

1.2.2 Thermal desalination technology

Thermal desalination is a desalination process that uses heat to purify water. In thermal desalination saline water is converted into vapors by providing proper amount of heat and then condensate of these vapors is fresh water that is collected. Thermal desalination includes Multi Flash Desalination (MSF), Multi Effect Desalination (MED). Besides these methods there are some non-conventional methods which uses low quality heat source to purify water. This includes solar still and humidification dehumidification (HDH) system.

1.2.3 Multistage Flash Desalination (MSF)

Figure 1.3 shows working principle of one the technology that has been used for large scale water purification multistage flash desalination [11], [12]. At point A steam enters the system and at point B sea waters enters. Both steam and sea water interact in heat exchanger F heating boils sea water and condensation collects the pure water at point G this completes one stage.

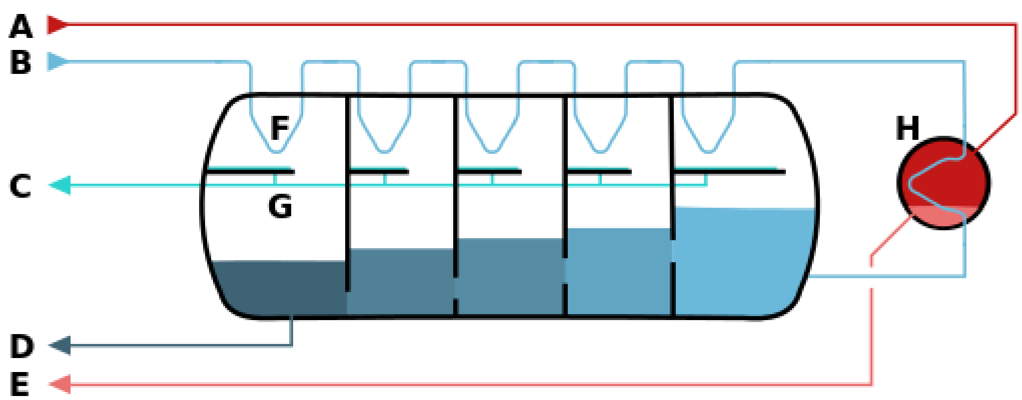

Figure 1.3: Multistage Flash Desalination

Number of stages could vary from 4-40 depending upon production required. All pure water is collected at point C and brine solution and steam exits at points D and E, respectively.

1.3 Unconventional Desalination Technologies

Conventional Desalination Technologies are those which uses electricity or high-quality steam for water purification and hence, they are more expensive and cannot be used in remote areas which are far from the city and does not have access to high grade energy. Unconventional technologies include solar still and HDH system.

1.3.1 Solar Still

Solar Still has been using for purification of water since old times. A simple working solar still is shows in Figure 1.4 [13]. Water absorbs heat from the sun which causes evaporation. Vapor moves upwards and travel in the passage. Due to its interaction with cold ground they start to condense which is pure water. They are effective for very small-scale production only. There is currently a lot of research is going on to increase their productivity so that it can be used effectively. HDH technology also uses solar heat or any other low grade heat source and sometime also referred to as a modification to solar still to increase its productivity since the basic principle is same.

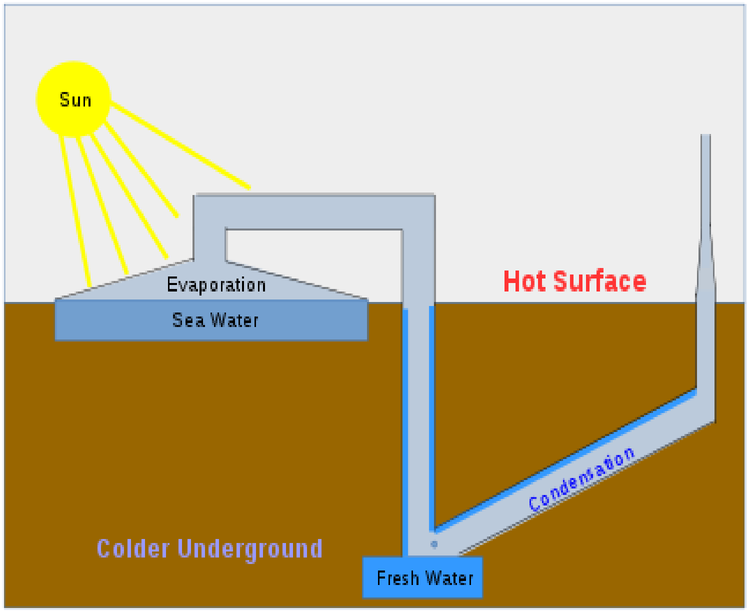

Figure 1.4: Water Desalination by Solar Still

1.3.2 Humidification Dehumidification (HDH) System

A simple schematic diagram of humidification dehumidification (HDH) system is shown in Figure 1.5 . Ambient air enters humidifier and gets hot and humid due to its interaction with incoming hot water. Hot and humid air then enters dehumidifier which is indirect contact heat exchanger. The dew point temperature of hot and humid air is above the temperature of sea water entering into dehumidifier as a result air starts to de humidify. Fresh water is collected at the bottom of dehumidifier and cold and humid air exits from the dehumidifier.

Since the air coming out of dehumidifier is cold and humid. This can be used for air conditioning application if this air is used in vapor compression system as to supply to the room or building. Its latent load will be a little bit high but sensible load will be significantly low. And it can be used with effective power savings in hot and humid areas.

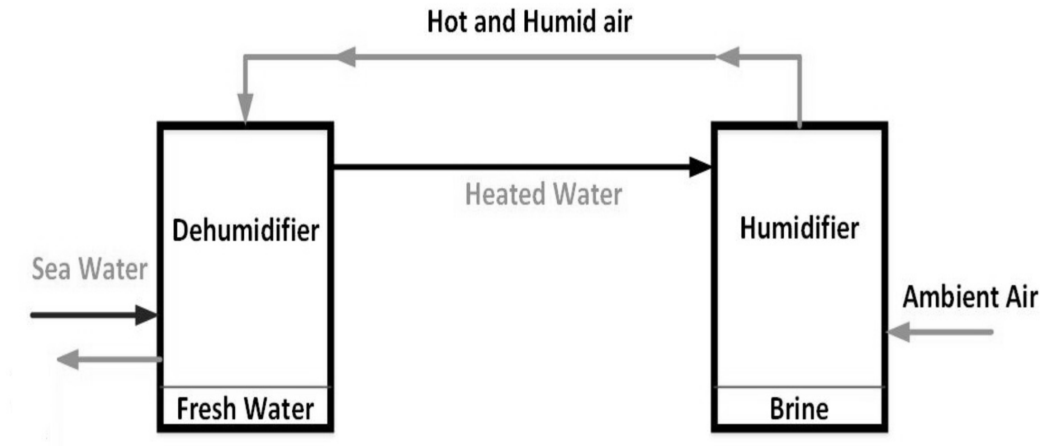

Figure 1.5: Humidification Dehumidification (HDH) water desalination system

1.4 Air Conditioning

Every human being wants comfort at least possible cost. And human body feels comfortable when it rejects a certain amount of heat all the time. During winters it starts to loss more heat therefore, we must decrease that heat rejection by using thicker cloths, using heat source or any other means. During winters it becomes difficult to reject that amount of heat due to less temperature difference. That comfort depends upon the temperature and humidity of the air. Human body feels comfortable at a temperature of $24 - 26$ ℃ and at a relative humidity of $50 - 60$ %. To maintain both the requirements of comfort Vapor Compression System (VCS) has been employed since decades.

A simple vapor compression system for air conditioning applications is shown in the Figure 1.6: Vapor Compression System for Air Conditioning [14]. In which compressor takes electricity as input power and dump the heat of conditioned space into the hot environment.

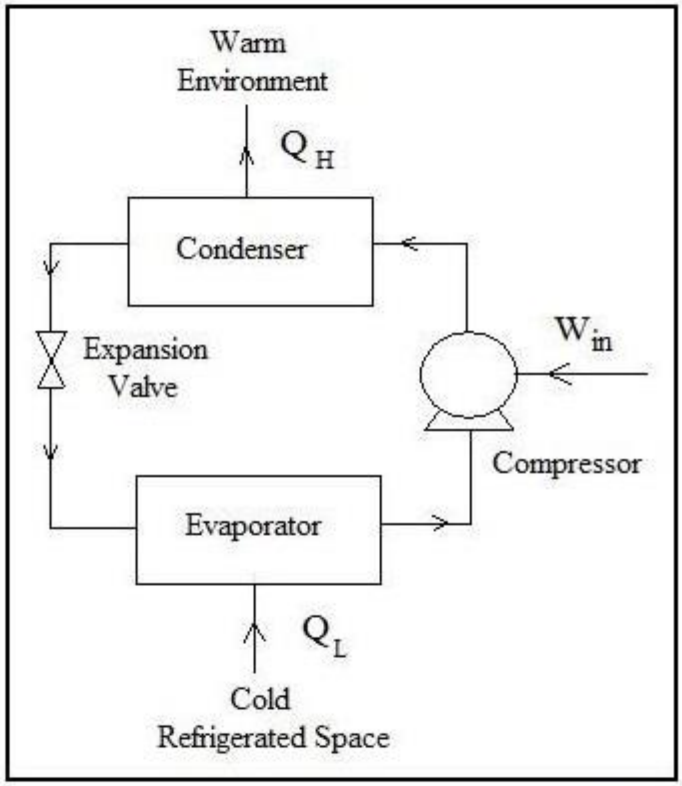

Figure 1.6: Vapor Compression System for Air Conditioning

Since air conditioning consumes most of the energy in the buildings. Any minor improvement could result in enormous savings. A currently a lot of research is on the way to make compressor more efficient so that it consumes less energy, try to save some energy by interaction of ambient air with the return air and by using adaptive cooling and some other techniques as well. Since the energy consumption is large therefore, potential for saving is also large.

1.5 Combined System

Combined system in this is referred to as Humidification Dehumidification (HDH) system coupled with vapor compression system through an enthalpy exchanger. Since air at the exit of HDH system is cold and humid it can be used in two ways with effective savings.

1. Use that cold and humid air in evaporative cooling using desiccant wheel.
2. Use that air with vapor compression system to directly supply it to the room.

1.6 Research Statement

The focus of this study is to analyze the performance of humidification dehumidification (HDH) system for water heated cycle in different configuration i.e., for open air cycle and for closed air cycle. To optimize the thermal performance of HDH system in both closed cycle and open cycle. With optimize thermal performance of HDH open air system its exit air has been used as an entry air for the vapor compression system modeling to assess the performance of vapor compression system when HDH air is used instead of ambient air. This study also includes global analysis of performance of combined system to assess at what temperature and humidity we can use combined system with significant affects for water productivity and power saving. Besides thermal performance optimization and power savings in air conditioning applications exergy modeling of vapor compression system has also been modeled in the study to compare exergy destruction rate with the literature.

1.7 Research Objectives

Following are the main objectives of this research study.

- Study and evaluate the performance of HDH system for different climate conditions. And to study the Study the optimum mass flow rates of air and water for maximum performance of HDH system.
- To study the performance of HDH open air and closed air cycle for varying mass flow conditions and different climate conditions
- To evaluate the required input power for a specific mass flow rate of air for air conditioning using vapor compression system and its comparison with required input power it is combined with HDH system.
- To evaluate the percentage increase in freshwater productivity of HDH system when each system works in combined system and to study the percentage savings in input power.
- To evaluate the value of temperature and humidity above which combined system started showing power savings.
- To find out exergy destruction of different components along with energy analysis of the system.

1.8 Thesis Outline

1. Chapter 2 describes the literature review related water purification systems, HDH system and hybrid air conditioning systems.
2. Chapter 3 describes the working of system and its representation of psychometric chart.
3. Chapter 4 describes the methodology of research work including modeling equations, procedure for solution and assumptions.
4. Chapter 5 presents the results obtained by numerical solution of modeled system and discussion of results.
5. Chapter 6 Contains the Summary of results and recommended future work.

Summary

Fresh drinking water and human comfort are the necessities of every human being which everyone wants at lowest possible cost. Demand for fresh water and energy both are ever increasing demands due to population increase. Currently available freshwater resources are either becoming scarce or getting contaminated and energy resources are also diminishing. For human comfort air conditioning systems are used which in some developed countries consumes almost 50% of their electricity. For freshwater production conventional techniques i.e. Reverse Osmosis (RO), Multi-Effect Desalination (MED), Multi-Stage Flashing (MSD) and Vapor Compression Desalination are in use for large scale production of fresh water but these conventional techniques use high quality steam or energy. Non-Conventional freshwater production techniques include solar still which has been in use since old times and a modified version of solar stills humidification dehumidification (HDH) system for higher productivity than solar stills, which uses low quality heat, waste heat or solar energy. For air conditioning purposes vapor compression systems are mostly used. Since vapor compression systems consumes major portion of energy a small improvement in the system can result in enormous energy savings. Air exiting HDH system are at lower temperature and higher humidity as compared to ambient air. When this air is introduced in the evaporator of vapor compression system through an enthalpy exchanger sensible load will be less and latent will be higher. And this results in energy savings in hot and moderately hot climates where decrease in sensible load dominates the increase in latent load.

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Chapter 2 : Literature Review

2.1 Background

Freshwater resources are becoming contaminating or becoming scarce. This becomes far more concerned when it comes to remote area where there is no access to electricity and expansive methods cannot be used to water purification there. Like freshwater energy sources are also dwindling. So, there is a global shortage for fresh water and energy as well. About fresh water oceans are the only inexhaustible sources of water [1]. Of all the other water bodies water bodies are either frozen or are in the form of ice bergs. Sea water is a chief source of water, but its water is saline and hence cannot be used directly. So there are different methods of desalination like solar still, Reverse Osmosis, Humidification Dehumidification (HDH) and Multi Flash Desalination which has been using for water purification [2], [3]. Along with water production technologies a review has also been discusses in this section about energy savings and consumption on air conditioning applications. There are a lot of recent advancements about energy savings for air conditioning applications like hybrid air conditioning, employing a heat recovery wheel and many more [4]. Which increases the performance of air conditioning system and decreases the input power so that energy can be saved. Since air conditioning consumes almost 50% of the word electricity that produced [5]. Therefore, chances of savings are large. This section presents a review of background information for different water purification technologies and there uses and advancements along with air conditioning optimization system. Review of hybrid air conditioning systems has also been included in the section.

2.2 Review of Solar Still Desalination:

Solar Still technology for water purification has been in use since 18th century. It was one of the cheapest technologies to produce fresh water that uses only solar heat for evaporation and then condenses the vapors to get fresh water as a product. There running and maintenance cost is very low. They can b installed with low capital cost and with varying capacity depending upon the needs of freshwater production. but their efficiency is very low and freshwater production rate is also low. But they are excellent when it comes to low energy consumption technologies and can b used for remote areas [6].

2.1: Review of Solar Still Desalination

Reference	Features	Results
Velmurugan et al. [7]	Review and studied different types and configuration of solar still technologies	Basin type solar still have high efficiency. Sponges and fins plates are used to increase the yield of solar still
Meysam et al. [8]	Experimentally studied the use of PCM to store the heat of condensation and use that for evaporation	The yield increased by 86% as compared when no PCM used efficiency also increased by 50%. the maximum yield found to be 6.55 kg/m^2day
Al-harahsheh et al. [9]	Performance of solar still investigated using PCM to store heat during time and use it at night times for continuous operation of solar still	Optimum flow rate was $10mls$ giving maximum productivity. Increase in water level in basin cause the productivity to decrease. Highest daily productivity was $4300ml/m^2day$
Prakash et al. [10]	Studied different parameters which effects the performance of solar still including area of adsorption, minimum water depth, glass cover temperature difference and others	Minimum water depth, high water glass temperature difference, preheated inlet water, and maintaining vacuum conditions is solar still increases its productivity

Manokar et al. [11]	Experimentally investigated the performance of solar still integrated with PV panel to produce power and desalinated water.	Maximum productivity achieved was 7.3 kg with inclined basin solar still and maximum efficiency was 72%. Due to higher heat gain in basin efficiency of PV panel decreased.
Abdullah et al. [12]	Experimentally investigated Trays Solar Still performance compared to conventional solar still for different depths of water in the trays	Due to high evaporative surface area trays type solar still shows 1.5 times higher productivity as compared to conventional for 1 cm water depth. Average thermal efficiency was about 50%
Nayi et al. [13]	Presents a review of pyramid type solar still and various methods to improve the performance of solar still.	Pyramid type solar still have higher efficiency than conventional stills it also does not require any tracking. The cost for water was found to be 0.031$/liter
Fathy et al. [14]	Experimentally studied the performance of double side solar still coupled with parabolic trough collector (PTC).	Water productivity was found to be 28% higher when there is no tracking for PTC, while with tracking increase in productivity was found to be 142% which was about $\frac{8.53kg}{m^2day}$
Elbar et al. [15]	Hybrid solar desalination with integrated solar panels has been investigated with preheated saline water.	Preheating increases the yield by 60%. Maximum productivity was reported to be $3.534\ kg/m^2$day.

2.3 Review of Reverse Osmosis Desalination

Reverse Osmosis is another desalination method which is used by many plants having a medium to large production capacity of freshwater. This method uses a membrane through which water molecules can easily passed but salts can not go through it. A high-pressure pump is used for this purpose and as a result freshwater is obtained. Some necessary minerals are also added at the end to make it more feasible to drink. Reverse Osmosis (RO) also became a hot area for researcher to solve the problem to water shortage globally. Methods are under development for the solution of biofouling, organic and inorganic fouling of the membrane [16]. RO system can also be coupled with some other conventional system for better performance. Fouling also increases the required pressure the researchers are also trying to find the techniques of reducing fouling so that required must kept minimum as low as possible [17]. Surface modification and pretreatment can also reduce the fouling. Emerging contaminants has also compelled the researchers for the upgradation of membrane which adversely affects the membrane and causes fouling at a higher rate [18]. Polymeric membranes have been in use since 1950s in RO plants. But with the development of technology and advancements nano-tech membranes have made their way in the research which can replace polymeric membranes and have great performance [19]. Pure RO plants run by electricity which is a high grade of energy and to make this electricity there is consumption of fossil fuel mostly. And hence, RO plants are also contributing to the increase in carbon dioxide content in the environment. RO plants with hybrid renewable energy resource provide promising solution for water purification and also for the cleaner environment [20].

Recently the cost of fouling in RO plants with nano filtration has been thoroughly investigated by Jafari et al. [21] and found to be least for the cases of anoxic nano filtration. Zhao et al. [22] presents a review of correlations between the properties of membrane and antifouling performance and evaluate the key strategies for thin film composition on membranes. Cordoba et al. [23] modeled a double acting batch RO configuration for reduced power consumption. high salinity of sea water increases the pressure much greater than the burst pressure of membrane and causes it curst. Das et al. [24] has designed an osmotically assisted process to face this challenge. This combination of new batch configuration can lead to increase in efficiency by 60% with increased sea water recovery.

Besides the fact that there is currently a lot of research going on for RO process to make it feasible still it uses electricity and hence, cannot be used for remote area. And can never be an alternative for cleaner environment compared to the process which uses renewable or any source of low-grade, low temperature heat source to purify the water like solar stills and Humidification Dehumidification (HDH) system.

2.4 Review of Multistage Flash (MSF) Desalination

Multistage Flash Desalination is technology used to produce distilled water at very high scale in the industries. 60% of the total water desalinated is done by multi stage flash method all over the world [25]. Large scale production reliability and developed construction is possible by MSF only. For increasing the production capacity of MSF, to reduce the brine flow out of system there is researched that are going on. Its performance depends upon temperature of sea water, temperature difference in first and last level, study reveals that last stage has significant effect on its production [26].

Combining the MSF with thermal vapor compression system increases its thermal performance by 6 to 16 percent [27] including additional power savings in the form of reduced specific flow rate of cooling water. The required size of system also reduced when MSF combined with thermal vapor compression system for the same capacity of water production.

EL-DESSOUKY et al. [28] developed different correlations for discharge coefficients, over all heat transfer coefficients for multistage flash desalination. These correlations are very valuable while modeling an MSF desalination system. Moharram et al. [29] investigated another system in which MSF worked in combination with parabolic trough collector to generate power from steam and fresh water from the waste heat of steam. The capacity of this plant was reported to be $16000\, m^3/day$. And coupling with RO plant had the capacity of $2000\, m^3/day$. This can be used when power generation and multi desalination methods are required for water desalination.

Besides the fact that MSF is a promising technology, but it can only be used for large scale production. So, a very skilled labor is required for the work. And capital cost to install such a plant would be high. And steam that is main source for MSF plant to work is also considered as a high-grade source of energy. MSF method would be best if an industry has a waste heat in the form of energy in the steam that needs to condense for its next cycle like in Rankine cycle. And hence, MSF technology also cannot be use full for remote areas.

2.5 Review of Humidification Dehumidification (HDH) Technology

Humidification Dehumidification (HDH) system are the improved version of solar stills. Solar stills have low thermal efficiency and low production for fresh water. HDH system have higher efficiency than solar still and have a higher production rate of freshwater as compared to solar stills. HDH does not require high temperature to run and does not require very much heat to run in fact at higher temperature their gain output ratio starts to decrease which means they show decrease in performance at high temperature. therefore, HDH systems provide best solution for fresh water at low cost, low maintenance and for remote locations.

Mostafa H. Sharqawy et al. [30] studied and presented the optimum thermal model of both HDH system i.e. water heated and air heated. He concluded that there is an optimum mass flow rates of air and water which maximize the Gain Output Ratio (GOR). Decreasing maximum water temperature and increasing minimum water temperature increases GOR for water heated cycle. He also presented the component design equation for a given freshwater production rate.

HDH system driven by thermal energy of Photovoltaic (PV) has been investigated by Giwa et al. [31] in which air is heated using thermal energy of PV and then introduced in humidifier and dehumidifier to get advantage of thermal energy and to get fresh water as a product as well. The also reveals that it has a productivity of 2.28 l/m^2of PV and has less environmental impacts as compared to PV Reverse Osmosis. Yuan et al. [32] experimentally studied vapor compression unit coupled to and evaporator and heat exchanger though humidifier for air conditioning and fresh water applications. V.V. Slesarenko investigated thermodynamic analysis of thermal desalination systems and concluded that incorporating a heat pump for thermal desalination units for heat recovery reduced the power consumption [33].

2.2: Review of Humidification Dehumidification (HDH) Technology

Reference	Features	Results
Kabeel et al. [34]	Experimentally studied desiccant dehumidifier with silica gel baffle and water cooling to improve dehumidified air quality and to produce fresh water using coupled HDH desalination system	Average dehumidification capacity was increased, overall COP of the system was improved, and the system will be useful for hot and humid climate
Narayan et al. [35]	Reviewed different HDH systems driven by solar energy for small scale water production	that multi-effect CAOW water heated is most efficient one. Using this system cost for water production is about $3-7\$/m^3$
Kassim et al. [36]	Investigated numerically the effect of inlet air humidity on humidification dehumidification system	In parallel plate humidifier increasing the humidity of inlet air adversely affect the performance of humidifier. While it works well for dry inlet air
Alkhulaifi et al. [37]	Studied ejector cooling HDH desalination for water purification and cooling with two different configurations	Solar driven system shows a higher cost and higher water production rate as compared to system driven by waste heat
Yan Cao et al. [38]	Solar heat in lower zone of solar pond has been used for power generation and water desalination using HDH	Results shows that energy utilizing factor, unit cost and efficiency can be increased significantly by using the proposed system. The

	desalination system and thermo electric generators.	minimum fresh water produced was 0.152 m^3/h
Lawal et al. [39]	Investigated thermal energy based low grade energy resources to run humidification dehumidification system	Results shows that integration of HDH system with power plants would give best performance and then geothermal would be second one. Other choice are solar collectors, PV/T panels and vapor compression systems.
Abbasi et al. [40]	Presents theoretical study of optimized the performance of Thermo electric generator with HDH desalination to run at low temperature using heat from Kalina Cycle.	Results shows an exergy effieicny of 22% and cost of freshwater production to be $2.94\$/m^3$. While cost of hydrogen was $7.37\ \$/kg$
Ghaebi et al. [41]	Investigated a trigeneration system for water production, power generation and to provide heating load to work as a hybrid system.	Results shows a power generation of 1605kW, heating load of 370 kW and water production rate 345 kg/h with a numerically calculated efficiency of 85% and exergy efficiency of 63%.
Nada et al. [42]	Experimentally studied performance of HDH system integrated with air conditioning using striped finned type	The proposed system has a higher freshwater rate report up to 17 kg/h. while the lowest cost of freshwater production was about 0.7 cents per kg.

	dehumidifier and packing pad material.	
Mamouri et al. [43]	Studied the performance of HDH desalination unit integrated with greenhouse with a solar collector to provide irrigation from different sources of water	Results shows that the system can provide 85% of the water that a normal tomato crop would require and cooling also decreased by 25 %.

2.5.1 HDH system coupled with hybrid Air Conditioning systems

S.A. Nada et al. [44] theoretically investigated the performance of hybrid air conditioning system and humidification dehumidification(HDH) system for production of fresh water and energy savings using different configurations. He studied the effect of fresh air ratio, outdoor wet bulb temperatures and supply air temperature on different performance parameters like freshwater production, power saving and total cost savings (TCS). But in his study for all configurations there is not a separated dehumidifier for HDH system. After humidification, all condensate is collected in evaporator coil of vapor compression system. Another theoretical study by Wallada Mbarek has been conducted on hybrid air conditioning, ventilation and HDH desalination. In his developed design he uses solar chimney to heat the air that is to be used in HDH system and in adsorption chiller as well. Air from adsorption chiller is further cooled in evaporator cooler and then mixed with dehumidified air from HDH system before supplying it into the conditioned space. He concluded that the design can be used for effectively with promising benefits for hot regions while complying with air conditioning standards [45].

2.5.2 HDH system with bubble column humidifier

The performance of humidifier and dehumidifier depends on their design. Dehumidifier in an indirect contact heat exchanger in which water flows in the tubes and air flows outside. When water in the air starts to condense these waters, molecules stick to the sides of tube and air and other gases may entrapped between water and tube. This decreases the heat transfer coefficient for dehumidification process. To compensate for this problem a novel design of dehumidifier and humidifier is under research which is bubble column design. In bubble column design air is inserted in the humidifier and bubble rises in the water giving them high contact surface area to get saturated this also decreases the size required for humidifier and eliminated the problem of decreased heat transfer coefficient in dehumidifier. On an average bubbling mechanism increases the out put from a minimum of 37% to 47% [46].

Mostly the HDH systems are running at atmospheric pressure but change in pressure inside the system also effects the performance. Of all the variables that effects of GOR of HDH system, the contribution of pressure is 32%. For humidifier effectiveness of 80% and at the pressure of 50 kpa, the maximum GOR recorded was 3.8 [47]. Air bubble humidifier with evacuated tube solar collector has been experimentally investigated by Pooria et al. [48]. Results shows a daily productivity of $6.275\ kg/m^2$ with the daily efficiency of 65%. The estimated cost of the designed system was about 0.028$/L.

2.6 Review of Advancements in Air Conditioning Systems

Since air conditioning is the area which consumes a lot of power therefore, savings will also b large in it. Even a little improvisation to save the energy cause enormous savings. More than 50% of energy that a building consumes is consumed air conditioning systems. Vapor Compression Systems (VCS) has been using for air conditioning application since decades. And compressor is the power consumption unit of VCS. Researchers are trying their best to increase isentropic efficiency of compressor so that is consumes less load, research is also going on to decrease the power consumption on air conditioning such as employing a heat and mass exchanger, interaction of air with return air from the room, Adaptive supply of air to the rooms variable air handling units all are the methods of increasing the efficiency of vapor compression system and to decrease the load of air conditioning systems.

Several studies have been conducted on air conditioning systems for their performance optimization. Fahad A. Al-Sulaiman [4] studied the energy and exergy analysis of enthalpy exchanger coupled with vapor compression air conditioning system and found that enthalpy exchanger coupling improves 2nd law efficiency, exergy destruction of system decrease by more than 50%, and required cooling load also decrease in the presence of enthalpy exchanger due to reduction in both temperature and humidity of air prior to entering in evaporator.

Rasool Kalbasi et al. [49] performed energy analysis of an Air Handling Unit (AHU) combined with an air-to-air enthalpy exchanger and concluded that introducing enthalpy exchanger reduces power required to drive AHU, improves first law efficiency and decreases cooling load as well. Albdoor et al. [5] studied cross flow membrane enthalpy exchangers and concluded that using optimum value for heating and cooling operating conditions entropy generation can be minimized. Huang et al. [50] investigated heat transfer and fluid flow for hexagonal parallel plate type membrane for different channel heights and fluid properties.

2.3: Review of Advancements in Air Conditioning Systems

Reference	Features	Results
CHINNAPPA et al. [34]	Uses an ammonia water absorption system to cool the condenser of the vapor compression system with refrigerant R-22 in the form of a cascade system.	Increase in the ability of refrigerant R-22 to work at low pressures and low temperature. this hybrid air conditioning system provide with considerable energy savings.
Jani et al. [51]	Theoretically studied the performance of vapor compression system coupling with the solid desiccant in TRNSYS for a cooling capacity of 1.8 kW	Latent loading of cooling significantly reduced due the desiccant absorbing the humidity. System shows maximum COP at an optimum regeneration temperature.
Vakiloroaya et al. [52]	Experimentally studied vapor compression system performance with air cooled condenser and liquid pressure	At less temperatures liquid pressure amplification showed more savings and at higher

	amplification with different configurations.	temperatures evaporative cooled condenser provide good results.
Dai et al. [53]	Uses liquid desiccant to improve the performance of vapor compression system and compares evaporative cooling and hybrid air conditioning with conventional VCS.	Hybrid cooling with desiccant coupled with vapor compression system can have a cooling capacity of 20-30% more than conventional VCS. Which results in less electric power consumption and reduces size of vapor compression system.

In the discussion above the methods have been discusses which provide hybrid air conditioning to reduce the size of system, to reduce the power consumption. still there are limits and constraints in applying them to industries and commercializing them. To eliminate those constraints this field still needs to explore.

Summary

RO technique is used for water purification for medium capacity of plants while Multistage Flash methods is used for higher production of water in the industries to meet the demand. Both these system uses electricity or higher-grade energy and hence, are not suitable for the use in remote areas. Solar still uses solar energy to purify the water but have very low efficiency and low production capacity. HDH systems are somewhat higher versions of solar stills with increased efficiency and productivity. Thus, HDH systems are best solution for water production at low capital cost and low running and maintenance cost. For air conditioning we have discussed some hybrid air conditioning systems in which vapor compression system works with desiccant or other system to reduce load and reduce the size of system. The proposed also is like a hybrid air conditioning system which provide freshwater and air conditioning with reduced power consumption. In view of above discussions HDH desalinations systems are a promising solution for small scale water production while vapor compression system has been used to provide conditioned space. There is lack of study when both systems work as a combined system through an enthalpy exchanger. This study includes performance analysis of Open Air Open Water (OAOW) water-heated HDH system for different climate regions in terms of thermal performance optimization and fresh water production rate. Energy and exergy analysis of vapor compression system when it is combined with HDH system.

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Chapter 3 : System Description and Methodology

3.1 Description of proposed system

Figure 3.1 shows the working process of combined HDH system in combination with vapor compression system for fresh water production and air conditioning applications. . Air at ambient temperature and humidity enters into humidifier at state 1a exits as hot and humid air at state 2a. After humidification its dew point temperature raise above normal sea water or ground water temperature. At state 2a air enters into dehumidifier which is an indirect contact heat exchanger. Hot and humid air interacts with cold sea water and dehumidifies giving fresh water as a product and exits from dehumidifier at state 3a. At state 3a air is cold but humid. Then it enters into enthalpy exchanger at state 3a where it interacts with the return air from the room at state 7a. Since the return air is at lower temperature and humidity therefore, return air extracts some moisture and lowers the temperature and humidity of entering air. Fresh air exits at state 4a and then enters into evaporator for further cooling to lower temperatures. A small amount of fresh water also collected in the evaporator. Air exit from the evaporator at state 5a and then enter into the condenser 2 which is not the main condenser of vapor compression system. In which a small portion of refrigerant flows in order to have a good control on the temperature of air entering into the room. Then air enters into the room at state 6a at temperature $20℃$ and relative humidity $\varphi = 0.55$

Water enters into dehumidifier at state 1w. Sea water temperature or minimum temperature for HDH is assumed to be $30\ ℃$. In dehumidifier since dew point temperature of air entering at state 2a is above this temperature so water in the air condenses and sea water absorbs heat from hot and humid air. Water exits at state 2w and then remaining heat is provided to the water in the heater solar or any other low

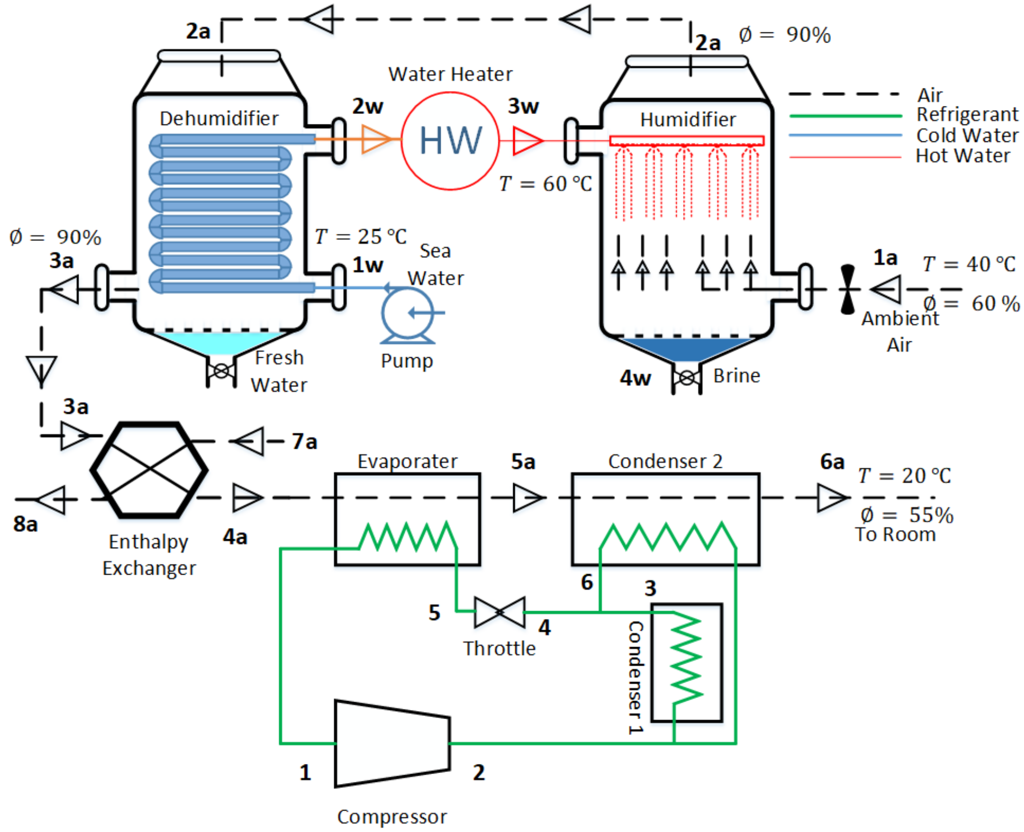

Figure 3.1: Combined HDH Desalination Unit with Vapor Compression through an Enthalpy Exchanger

grade heat source can be used for heating purpose as HDH system runs at lower temperature usually at 60℃ or 70℃ . 3w is water exit state from the heater which is also maximum water temperature in HDH system. Then this water enters into humidifier a direct contact heat exchanger for air and hot water. Air absorb this hot water and becomes saturated before exit. A high salt concentration water or brine is collected at the bottom of humidifier.

Refrigerant at point 1 enters into compressor at 300 kpa which compresses it to 1050 kpa with an isentropic efficiency of 75%. After compressor a part of refrigerant flow into the 2nd condenser and remaining refrigerant flows into the condenser 1. Refrigerant exits the first condenser at point 3 as saturated liquid and mixes with the refrigerant from 2nd condenser at point 4 then passes through throttle and then enters into evaporator at point

5 absorbing the heat from evaporator it enters into the compressor as saturated vapor thus completing the refrigerant cycle.

Proposed system have been with the design presented by Sharqaway [1] for optimum performance of HDH system. While the second system which double condenser vapor compression system is based upon the system used by Fahad[2]. While enthalpy exchanger which has been used for the coupling of both system is based on the model presented by Narayan [3] which gives fairly good results comparable with the experimental data.

3.1: Approximate Values at All States

Air States and Approximate Values			
State Description	**State Symbol**	**Value**	
Air Enters into Humidifier	1a	$T = 40$ ℃	$\emptyset = 60\%$
Air Exit from Humidifier	2a	$T = 57$ ℃	$\emptyset = 90\%$
Air Exit from Dehumidifier	3a	$T = 33$ ℃	$\emptyset = 90\%$
Air Exit from Enthalpy Exchanger	4a	$T = 24$ ℃	$\emptyset = 70\%$
Air Exit from Evaporator	5a	$T = 18$ ℃	$\emptyset = 60\%$
Air Enters into the room	6a	$T = 20$ ℃	$\emptyset = 55\%$
Water States and Approximate Values			
State Description	**State Symbol**	**Value**	
Sea Water Enters into Dehumidifier	1w	$T = 25$ ℃	
Sea Water Exit from Dehumidifier	2w	$T = 30$ ℃	
Sea Water Exit from Water Heater	3w	$T = 60$ ℃	
Brine Exit from Humidifier	4w	$T = 38$ ℃	

Refrigerant States and Approximate Values			
State Description	**State Symbol**	**Value**	
Compressor Entry	1	$T = 0.65$ ℃	$h = 250.8\ kJ/kg$
Compressor Exit	2	$T = 53.56$ ℃	$h = 285.6\ kJ/kg$
Condenser 1 Exit	3	$T = 41.19$℃	$h = 110.0\ kJ/kg$
Throttle Entry	4	$T = 38.11$ ℃	$h = 105.4\ kJ/kg$
Evaporator Entry	5	$T = 0.65$℃	$h = 105.4\ kJ/kg$
Condenser 2 Exit	6	$T = 30$ ℃	$h = 93.57\ kJ/kg$

3.2 Methodology

3.3 Modeling equations:

Key modeling equations based upon energy and mass balance analysis. And effectiveness of heat and mass exchanger components are based upon the analysis presented by Narayan et al.[3], . Other energy and mass balance equations for humidifier and dehumidifier which have been modeled are also used in literature for modeling of HDH component by Sharqaway et al.[1].

3.3.1 HDH components equations

1) Humidifier Equations
   a) Energy balance equation

$$\dot{m}_a(h_{2a} - h_{1a}) = \dot{m}_{sw} * h_{3w} - \dot{m}_{br} * h_{4w} \tag{3.1}$$

   b) Mass balance equation

$$\dot{m}_{br} = \dot{m}_{sw} - \dot{m}_{fw} \tag{3.2}$$

   c) Effectiveness of humidifier

$$\varepsilon_H = max\left(\frac{h_{2a}-h_{1a}}{h_{2a,ideal}-h_{1a}}, \frac{h_{3w}-h_{4w}}{h_{3w}-h_{4w,ideal}}\right) \tag{3.3}$$

Where, $h_{2a,ideal}$ is ideal enthalpy of air at humidifier exit, which is enthalpy of air at water inlet temperature in humidifier at state 3w, and $h_{4w,ideal}$ in enthalpy on water at wet bulb temperature of inlet air at state 1a.

2) Dehumidifier Equations

a) Energy balance equation

$$\dot{m}_a(h_{2a} - h_{3a}) = \dot{m}_{sw}(h_{2w} - h_{1w}) + \dot{m}_{fw} * h_{fw} \tag{3.4}$$

b) Mass balance equation

$$\dot{m}_{fw} = \dot{m}_a(\omega_{2a} - \omega_{3a}) \tag{3.5}$$

c) Effectiveness of dehumidifier

$$\varepsilon_{DH} = \max\left(\frac{h_{2a} - h_{3a}}{h_{2a} - h_{3a,ideal}}, \frac{h_{2w} - h_{1w}}{h_{2w,ideal} - h_{1w}}\right) \tag{3.6}$$

Where, $h_{3a,ideal}$ is enthalpy of air at sea water inlet temperature at state 1w and $h_{2w,ideal}$ is enthalpy of water at air inlet temperature in dehumidifier at state 2a.

3) Amount of heat required for water heating in case of water heated cycle.

$$\dot{Q} = \dot{m}_{sw}(h_{3w} - h_{2w}) \tag{3.7}$$

4) Following performance parameters has been calculated for HDH system.

Gain Output Ratio (GOR) which is the ratio of produced freshwater rate multiplied by its latent heat of vaporization to that of heat supplied to the heater for water heating.

$$GOR = \frac{\dot{m}_{fw} * h_{fg}}{\dot{Q}} \tag{3.8}$$

Recovery Ratio (RR) is the ratio of rate of fresh water produced to that of rate of sea water supplied to the system.

$$RR = \frac{\dot{m}_{fw}}{\dot{m}_{sw}} \tag{3.9}$$

Mass flow rate ratio (MR) is another important parameter in term of which the performance is measured in HDH system. MR value is the ratio of flow rate of sea water to that to air

$$MR = \frac{\dot{m}_{sw}}{\dot{m}_a} \quad (3.10)$$

3.3.2 Exergy modeling equations

a. Exergy is another important parameter to assess the performance of vapor compression system based upon 2nd law analysis which tells us about how far the system moves from its ground state or equilibrium position. High exergy means the system has more potential to do work or more useful work can be extracted from it. From exergy balance exergy destruction can be calculated to assess which component of the system is more irreversible or where is the potential for more saving in the system. Exergy at any state of refrigerant can be calculated using the equation.

$$Ex_i = (h_i - h_0) - T_0(s_i - s_0) \quad (3.11)$$

While, the physical exergy of moist air is defined by Ibrahim Dincer & Marc Rosen [4] as follows

$$Ex_{air} = T_0(C_{pa} + \omega C_{pv})[T_r - 1 - ln(T_r)] + R_a T_0(1 + w\omega)\, ln(p_r) + R_a T_0[(1 + w\omega) * ln\left(\frac{1+w\omega_0}{1+w\omega}\right) + w\omega ln\,(\frac{\omega}{\omega_0})] \quad (3.12)$$

Exergy balance equation of a system is

$$\frac{d\dot{E}_x}{dt} = \sum_i \left(1 - \frac{T_0}{T_i}\right)\dot{Q}_i - \dot{W} + \sum_{in} \dot{m}_{in}\dot{Ex}_{in} - \sum_{out} \dot{m}_{out}\dot{Ex}_{out} - \dot{Ex}_d \quad (3.13)$$

While in case of steady state system involving no heat transfer from external source it is reduced to the following equation which can be used to determine exergy destruction of each component.

$$\dot{Ex}_d = \sum_{in} \dot{m}_{in}\dot{Ex}_{in} - \sum_{out} \dot{m}_{out}\dot{Ex}_{out} - \dot{W} \quad (3.14)$$

3.3.3 Vapor compression system equations

Vapor compression system to be coupled with humidification dehumidification system is modeled as a double condenser system to have a better control on the temperature on air entering into the room as used in literature by Fahad et al.[2]

1) Energy and Exergy equations of compressor

$$\dot{W}_c = \dot{m}_r(h_2 - h_1) \quad (3.15)$$

$$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1} \quad (3.16)$$

$$\dot{E}xd_c = \dot{E}x_1 - \dot{E}x_2 + \dot{W}_c \quad (3.17)$$

2) For condenser, no # 1

$$\dot{Q}_{condenser\ 1} = (1 - y) * \dot{m}_r * (h_2 - h_3) \quad (3.18)$$

$$\dot{E}xd_{cond1} = (1 - y)(\dot{E}x_2 - \dot{E}x_3) \quad (3.19)$$

3) For condenser, no # 2

$$y * \dot{m}_r * (h_2 - h_6) = \dot{m}_{air}(h_{6a} - h_{5a}) \quad (3.20)$$

$$\dot{E}xd_{cond2} = (y)\left(\dot{E}x_2 - \dot{E}x_6\right) + \dot{E}x_{5a} - \dot{E}x_{6a} \quad (3.21)$$

4) Energy and mass balance equations for evaporator are.

$$\dot{m}_r * (h_1 - h_5) + \dot{m}_{evap,fw} * h_{fw} = \dot{m}_{air}(h_{4a} - h_{5a} \quad (3.22)$$

$$\dot{m}_{evap,fw} = \dot{m}_{air}(\omega_{4a} - \omega_{5a}) \quad (3.23)$$

$$\dot{E}xd_{evap} = \dot{E}x_5 - \dot{E}x_1 + \dot{E}x_{4a} - \dot{E}x_{5a} \quad (3.24)$$

5) Sensible and Latent effectiveness of Enthalpy Exchanger Modeling are based upon the equations provided by Liang et al. [5] which provide good agreement with experimental results

$$\varepsilon_s = \frac{\dot{m}_{air} C_p (T_{3a} - T_{4a})}{(\dot{m}_{air} C_{p(3a,4a)})_{min}\ (T_{3a} - T_{7a})} \quad (3.25)$$

$$\varepsilon_l = \frac{\dot{m}_{air} C_p (\omega_{3a} - \omega_{4a})}{(\dot{m}_{air} C_{p(3a,7a)})_{min}\ (\omega_{3a} - \omega_{7a})} \quad (3.26)$$

$$\dot{E}xd_{EEX} = \dot{E}x_{3a} - \dot{E}x_{7a} + \dot{E}x_{4a} - \dot{E}x_{8a} \quad (3.27)$$

3.4 Performance of HDH and VCS with varying ambient conditions

Since the performance of HDH systems depends upon the temperature and humidity of ambient air [6]. And power consumption of vapor compression system also depends ambient air temperature and humidity which we call sensible load and latent load respectively [7]. Therefore, when both systems work in combination then the performance of HDH will depend on ambient conditions while for vapor compression system its affect will be much less. Since when the goes into vapor compression system it had already been passed through two heat exchangers i.e., from humidifier and from dehumidifier. Therefore, temperature and humidity of air exiting the dehumidifier will remain almost constant. Due the fact that water will not show much difference in temperature due its high value of specific heat. And since the air will be interacting with water which has same temperature without much variation therefore, ambient conditions will become same for vapor compression system. Then, workload of second condenser will be reduced significantly and it might not need to install. Because the sole purpose of installing second condenser is to have a better control on the condition of air entering the room. For example, its air exiting the evaporator is at much lower temperature then the comfortable range then condenser will heat it up to make its temperature in the comfortable zone.

Since air entering the vapor compression system will have same temperature and humidity no matter what the temperature outside the system is. Its performance will become independent of ambient conditions. So, now we can calculate a certain temperature above which combined system will show power savings and similarly a certain value of humidity above which combined system results in power savings. At higher humidity of ambient condition simple VCS will increase its power consumption but combine system will not. And similarly, at higher temperatures simple VCS will consume more power but combine system will not. In both situations combine system will provide energy savings and freshwater.

Calculations have been performed for four different cities of Pakistan for Islamabad, Lahore, Bahawalpur, and Karachi. The required weather data have been acquired from world weather [8] from the months of April to October.

After performing the analysis for these cities bar charts have been plotted by importing the data from F-Charts software into Excel to have a better control on bar charts. After performing the analysis for the city's calculations have been to do a global analysis. For global analysis, a constant ambient temperature has been chosen and energy consumption calculated for varying humidity and then kept the humidity constant and vary the ambient temperature. this gives exact value of temperature and humidity above which combined system can be effectively used.

3.5 Proposed system representation on psychometric chart

Figure 3.2 shows all the states of air on psychometric chart of a combine system. 1 to 2 shows humidification process where air interacts with hot water. 2 to 3 shows dehumidification process freshwater if a product of this stage and 3 to 4 is enthalpy exchanger where exit air of dehumidifier and return air form the room interacts and finally 4 to 5 is evaporator which provide cooling to supply the air to the room. it is evident from Figure 3.2 that instead of going from state 1 to state 4 now vapor compression has to work only to take the air from state 4 to state 5 which very less as compared to previous state. But increase in latent load also decrease that savings to some extent.

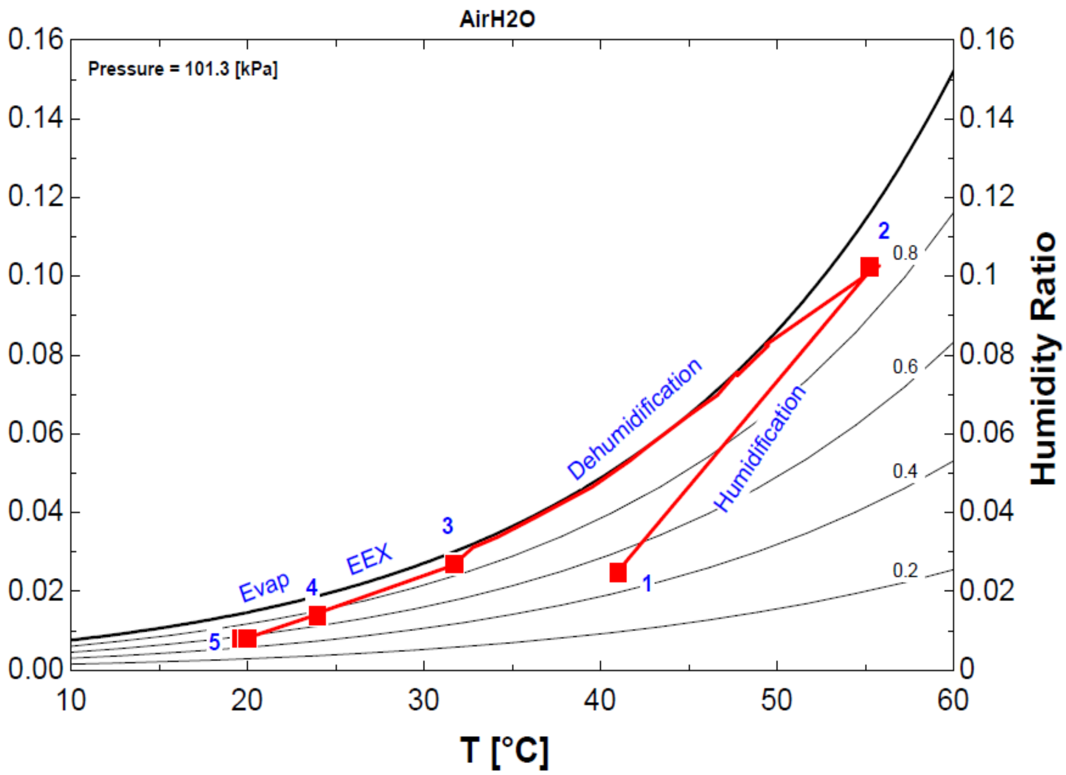

Figure 3.2: Psychometric Representation of Combined System Working

3.6 Assumptions

For the solution of modeled equations following assumption have been made adapted from the literature [1], [2]

- All components are assumed to work in steady state conditions.
- Heat loss from humidifier and dehumidifier to the environment has been ignored.
- Pumping power for air and water can be ignored being very small as compared to heating required.
- All the air in vapor compression system goes through HDH system.
- Same effectiveness has been assumed for both humidifier and dehumidifier.

Summary

Modeling equation have been solved iteratively in F-Chart software Engineering Equation solver by providing the constraints to the variables. Stopping criteria for iterative solution was that the error should be less than 10^{-6}. After solving the equations for both systems i.e., HDH and couple condenser vapor compression system the results have been verified with the literature to verify the model. After successful comparison of results with the literature these modeling equations have been used for combined system to assess its performance and several performance parameters have been studied for combined system.

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Chapter 4 : Results and Discussions

4.1 HDH closed air open water system

Figure 4.1 shows the plot of Gain Output Ratio (GOR) versus Mass Ratio. The figure depicts that increasing MR increases the GOR but after an optimum point it starts to decrease. This shows the optimum flow rates for both water and air for optimum system performance. If MR is less than its optimum value at given conditions, then air at the exit of humidifier will be dry and if MR is greater than its optimum value then air is already saturated, and more water is flowing as compared to air which is not necessary. And as more water is flowing that means we are wasting heat is heating that much amount of water which is not necessary. Changing the

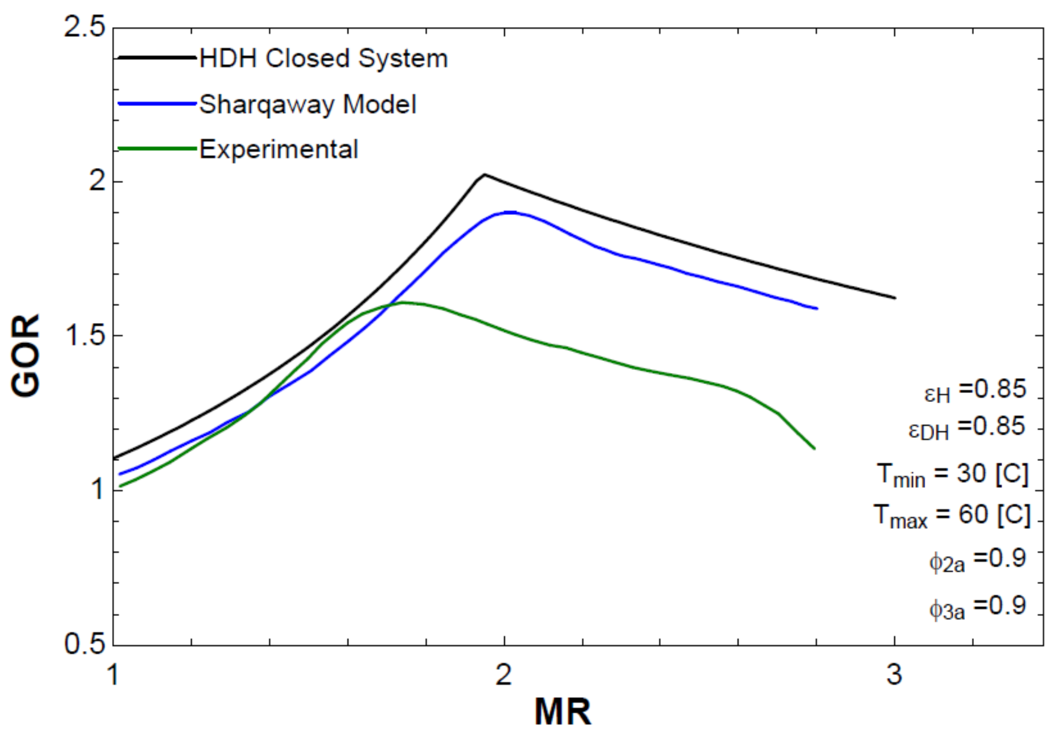

Figure 4.1: Variation of GOR against mass flow rate ratio

conditions of temperatures for water will the optimum MR value accordingly. This plot is at $T\_\min = 30℃$, $T\_\min = 60℃$, and effectiveness of both humidifier and dehumidifier 85%. The result obtained from HDH closed model system is very similar to model presented by Sharqaway. An experimental result has also been plotted. Experimental results show a similar trend, but it shows highest GOR at lower MR value this might be due to different experimental conditions.

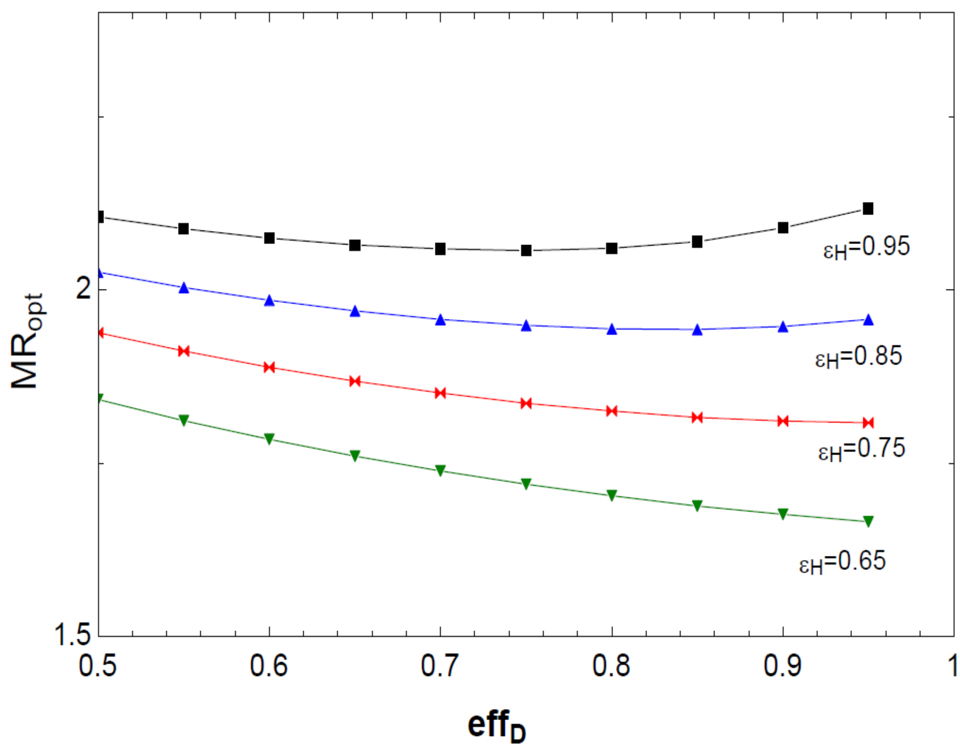

Figure 4.2: Variation of Optimum MR for effectiveness of humidifier and dehumidifier

Figure 4.2 shows variation of MR ratio for changing values of effectiveness of humidifier and dehumidifier. Changing the effectiveness of any of both main components i.e., humidifier and dehumidifier will also change the optimum value of flow rates of both water and air. Higher value of humidifier effectiveness corresponds to a higher value of MR at given effectiveness of dehumidifier. Higher humidifier effectiveness requires more water flow rate to make air saturated at humidifier exit. This will also increase the pumping power required for water flow. A higher effectiveness of any of component also increase the cost of the component and size

Any change in sea water temperature or maximum temperature will also affect the flow rates or MR value. Figure 4.3 shows the variation of optimum MR value with minimum water temperature which sea water temperature and maximum water temperature which is temperature of water at the entry of humidifier. A high maximum temperature requires less water flow rate as it is easier for air at higher temperature to pick up water and become saturated. Increasing the minimum water temperature for a constant value of dehumidifier effectiveness will decrease its performance to keep up same performance water flow rate has to be increased or dehumidifier size as to be increased. That is why increasing the sea water or minimum temperature requires a higher MR value for optimum performance.

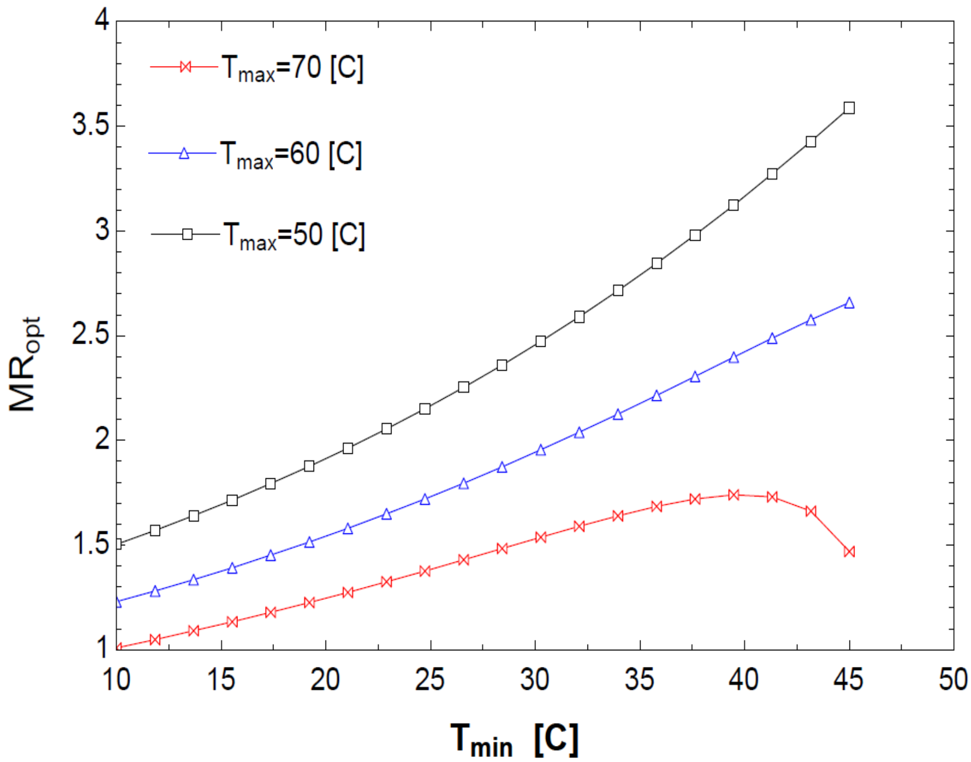

Figure 4.3: Variation of Optimum MR value against maximum and minimum sea water temperature

Figure 4.4 shows the plot of Gain Output Ratio (GOR) with minimum and maximum water temperature and maximum water temperature in the system. Maximum value of GOR is obtained when there is minimum temperature difference between both temperatures. Minimum temperature difference also corresponds to less freshwater production, but heat required will also be less and heat required dominated the freshwater production rate and it show maximum GOR at lower maximum temperature and higher minimum temperature.

Figure 4.1 to Figure 4.4 are the results for closed air open water HDH system which are in exact agreement with the results in literature [1], [2]. This also verify that the modeling of HDH system is correct and can be used for open air cycle.

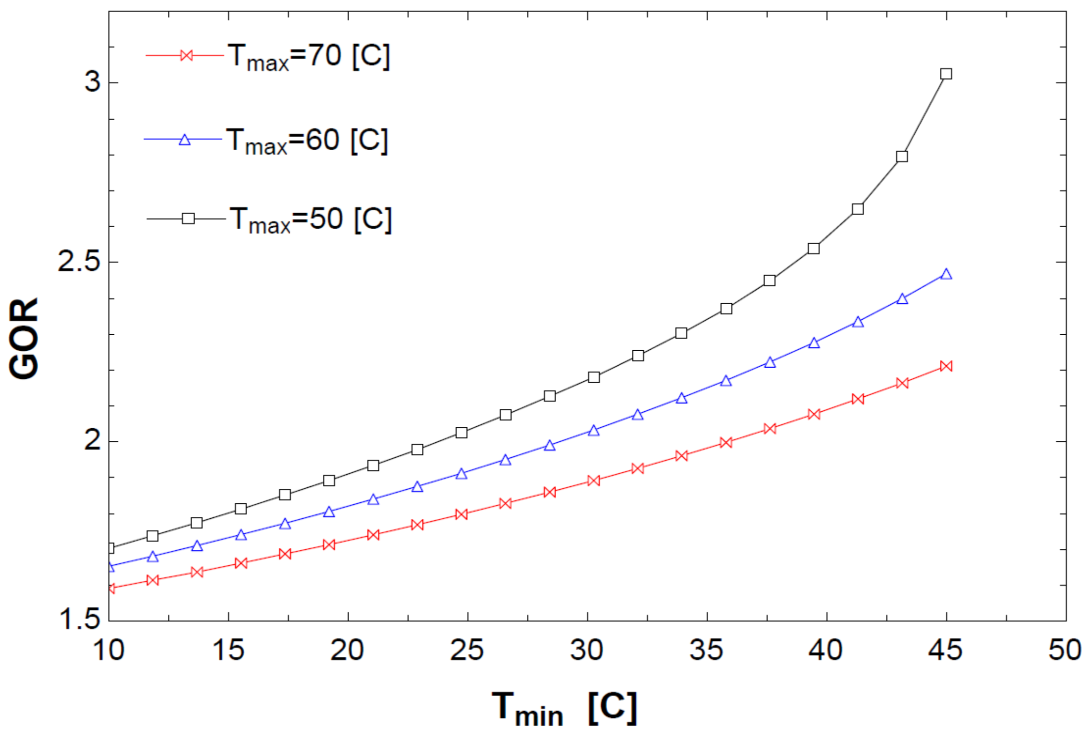

Figure 4.4: Variation of GOR with minimum and maximum water temperatures

4.2 Vapor compression system with air membrane

A double condenser vapor compression system has been modeled with ambient air directly entering the vapor compression system through an enthalpy exchanger or air membrane. The purpose of air membrane if to exchange heat and mass between return air from the room and ambient air before entering the evaporator. Ambient air is assumed to be at $T = 35$ ℃ and relative humidity of $\emptyset = 0.62$. While the air that needs to supply into the room is assumed to be at $T = 20$ ℃ at relative humidity of 55%. Compression ratio for compressor is chosen 3.5 with an isentropic efficiency of 72% low side pressure in vapor the vapor compression system is chosen 300 kpa. The return air leaves the room at 22℃ temperature which will interact with ambient air in enthalpy exchanger. The sensible and latent effectiveness of enthalpy exchanger is assumed to be 0.8 and 0.72, respectively.

All these values have been chosen to run the modeled system and to compare the data with the literature to confirm the modeling [3]. The solution of the system is shown in Table 4.1 and Table 4.2

Table 4.1: Refrigerant properties at all states

State	$\boldsymbol{T}$ (℃)	$\boldsymbol{h(kJ/kg)}$	$\boldsymbol{s(\frac{kJ}{kg.K})}$	$\boldsymbol{Ex\ (Watt)}$
1	0.6527	250.8	0.931	5641
2	53.56	285.6	0.9579	10928
3	41.19	110	0.4004	7332
4	38.11	105.4	0.3857	10170
5	0.6527	105.4	0.4	9286
6	30	93.57	0.3471	2850

Table 4.2: Air properties at all states

State	$\boldsymbol{T}$ (℃)	$\boldsymbol{h(kJ/kg)}$	$\boldsymbol{\omega\ (kg/kg)}$	$\boldsymbol{s(\frac{kJ}{kg.K})}$	$\boldsymbol{Ex\ (Watt)}$
3a	35	92.09	0.02219	5.929	0
4a	24.6	56.66	0.01255	5.81	607.6
5a	10.83	31.03	0.008	5.721	2135
6a	20	40.38	0.008	5.754	1403
7a	22	44.46	0.0088	5.768	1167
8a	32.4	79.77	0.01844	5.888	66.4

These values of air properties and refrigerant properties are in exact agreement with the literature [3]. After verification of the model some graphs has been plotted to confirm latent and sensible modeling of the system.

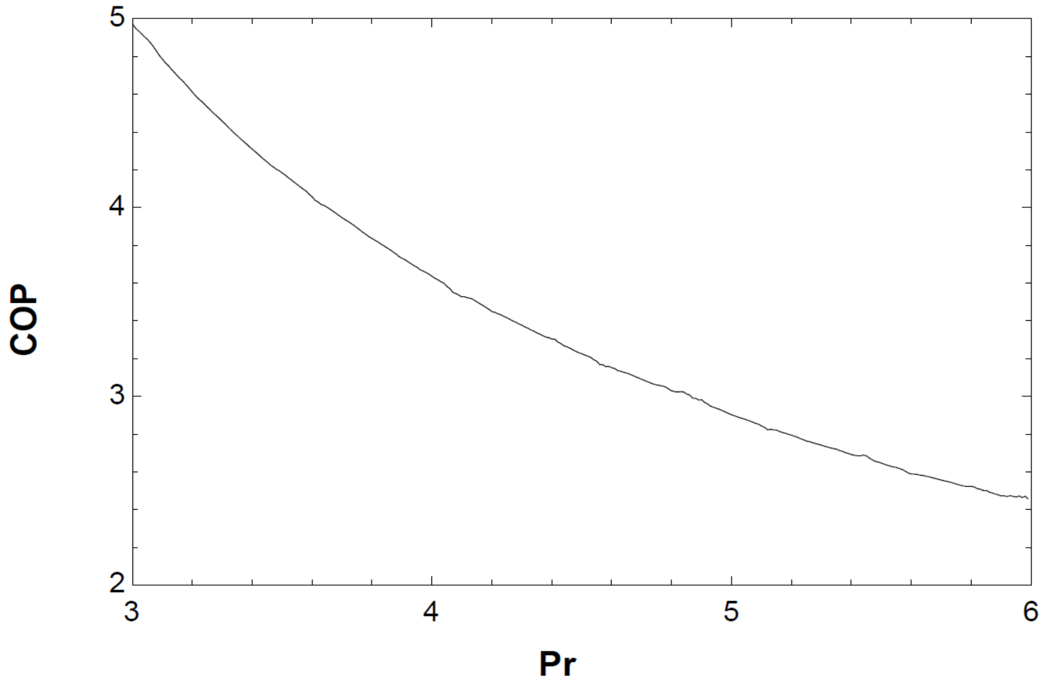

Figure 4.5: Variation of COP against Pressure ratio

Figure 4.5 shows the variation of Coefficient of Performance (COP) with pressure ratio. It decreases from 5 at pressure ratio 3 to 2.5 at pressure ratio 6. Which is in the agreement with the result given by Fahad Al. A Salman [3].

Figure 4.6 shows the effect of sensible effectiveness on compressor power and required cooling power. Both decreases with increased sensible effectiveness as increased sensible effectiveness of Enthalpy Exchanger lowers the temperature at which air is entering into the evaporator casing both compressor power and cooling power to decrease.

The Figure 4.6 also confirms that sensible effectiveness of enthalpy exchanger has been modeled correctly and incorporated equations are giving the results accurately.

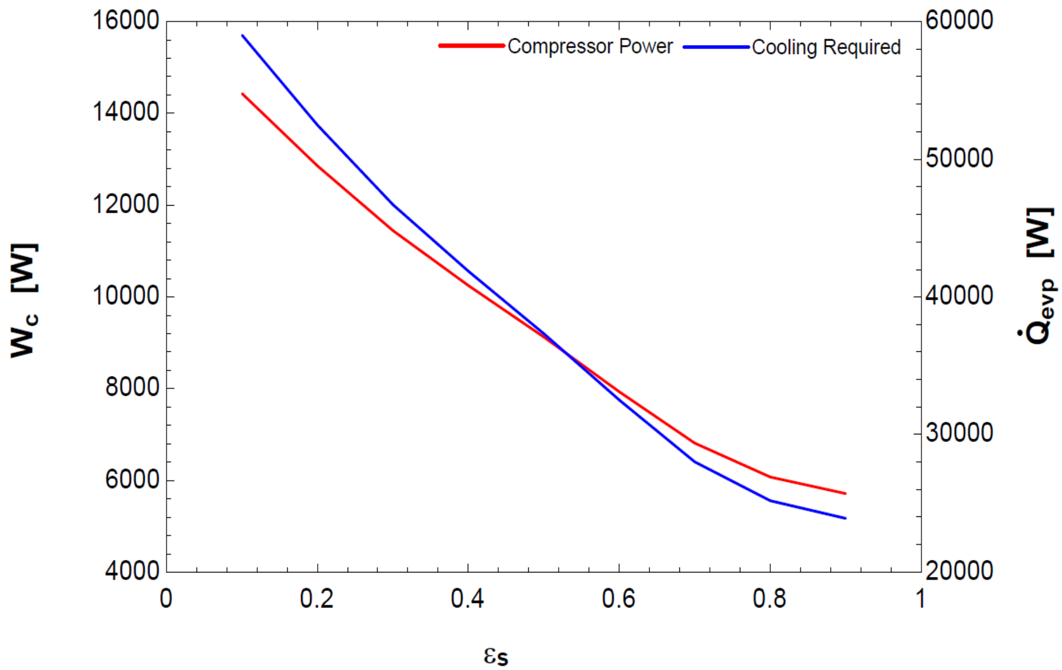

Figure 4.6: Compressor power and Cooling load variation with sensible effectiveness of EEx

Figure 4.7 shows the effect of varying latent effectiveness of enthalpy exchanger of compressor power and cooling. Effect of Latent Effectiveness is similar to the sensible effectiveness except the fact that now increased latent effectiveness lowers or humidity of entering air by interacting with the return air causing the latent load of evaporator to decrease and hence compressor power also decreases.

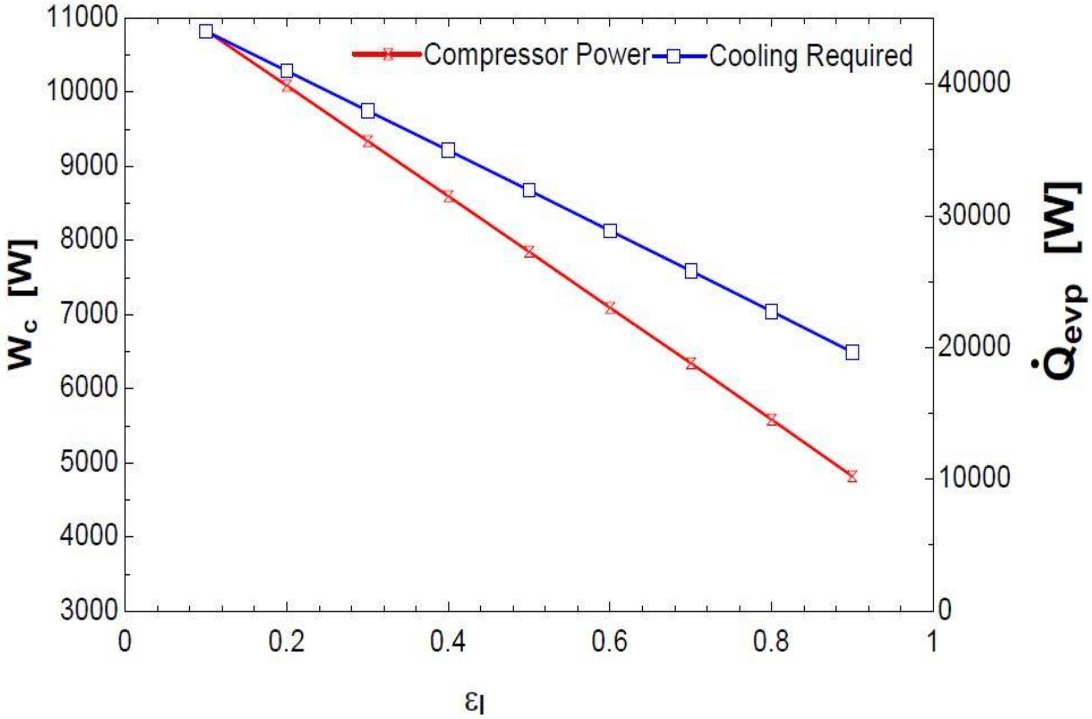

Figure 4.7: Variation of Compressor power and cooling load with latent effectiveness of EEx

Figure 4.8 shows the effect of variation in relative humidity of ambient air. At constant sensible and latent effectiveness increased humidity of ambient air increases both latent load and input power or compressor power as evident from the Figure 4.8. This also verifies the validity of Mathematical modeling and solution of system equations.

These plots verifies that sensible and latent both type of loads has been accumulated in the solution. And sensible and latent effectiveness of enthalpy exchanger is also working perfectly. We can only fix one mass flow rate either for air or for refrigerant. For combined system analyses Since, we are interested in compressor power for a constant cooling load. we have chosen a constant mass flow rate of air and varying mass flow for refrigerant. Any change in cooling is then not due to change in mass flow it is due to changes in temperature. And mass flow of refrigerant changes accordingly to decrease or increase in compressor power.

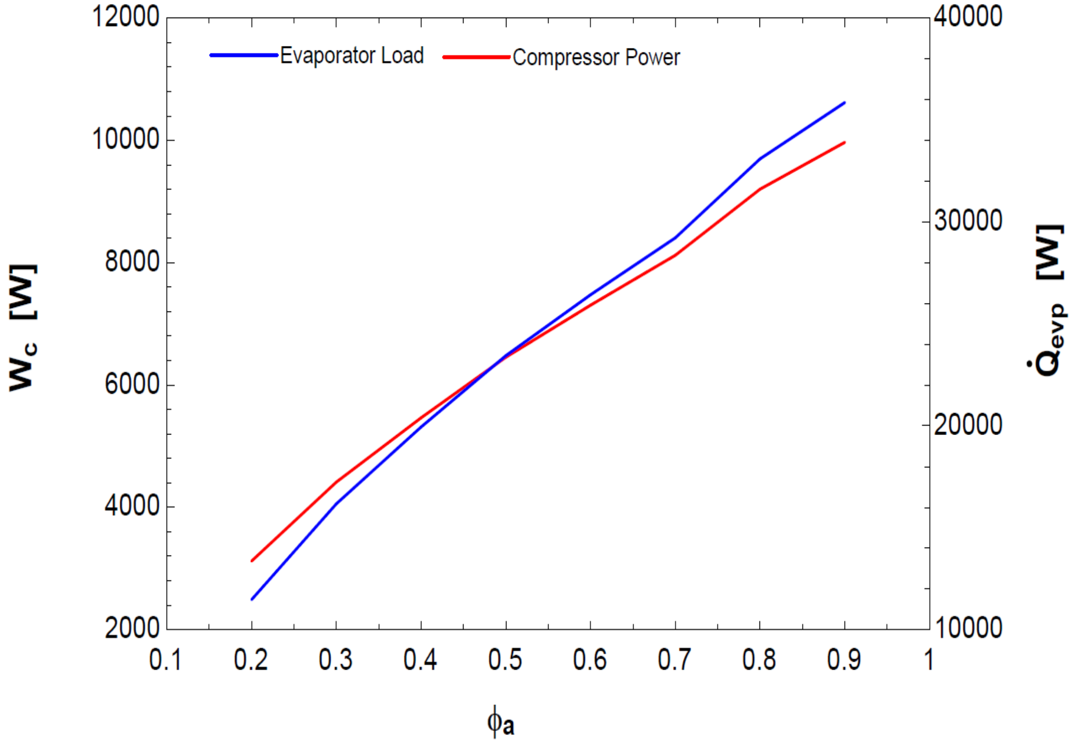

Figure 4.8: Effect of varying humidity on compressor power and cooling load

4.3 HDH open air open water system

Since we want to use the air at the exit of dehumidifier for air conditioning purposes in a hybrid air conditioning system then HDH system must work as an open-air system. In the following section the thermal performance of HDH open system has been investigated and analyzed for different performance parameters.

Figure 4.9, Figure 4.10 & Figure 4.11 shows the variation of Gain Output Ratio (GOR) versus Mass Ratio of HDH system for different months and for different climate conditions. Variation is almost like the one in closed cycle expect the fact that now GOR is higher almost in every climate condition than the closed water cycle. And lower humidity region is also showing more GOR because a dry air will absorb more water as compared to a humid air that's why Karachi region being more humid has less GOR than the other two regions Islamabad and Bahawalpur. And at higher temperature regions it is showing decrease in the GOR. This is due the fact that any increase in ambient air temperature with constant high temperature supply of water will decrease the temperature different in humidifier which is the main driving force in humidifier therefore, at higher temperatures of ambient air either water temperature has to be increased or GOR will decrease as shows in the Figure 4.9 to Figure 4.11. these are also similar to results presented by Zubair et al. [2]

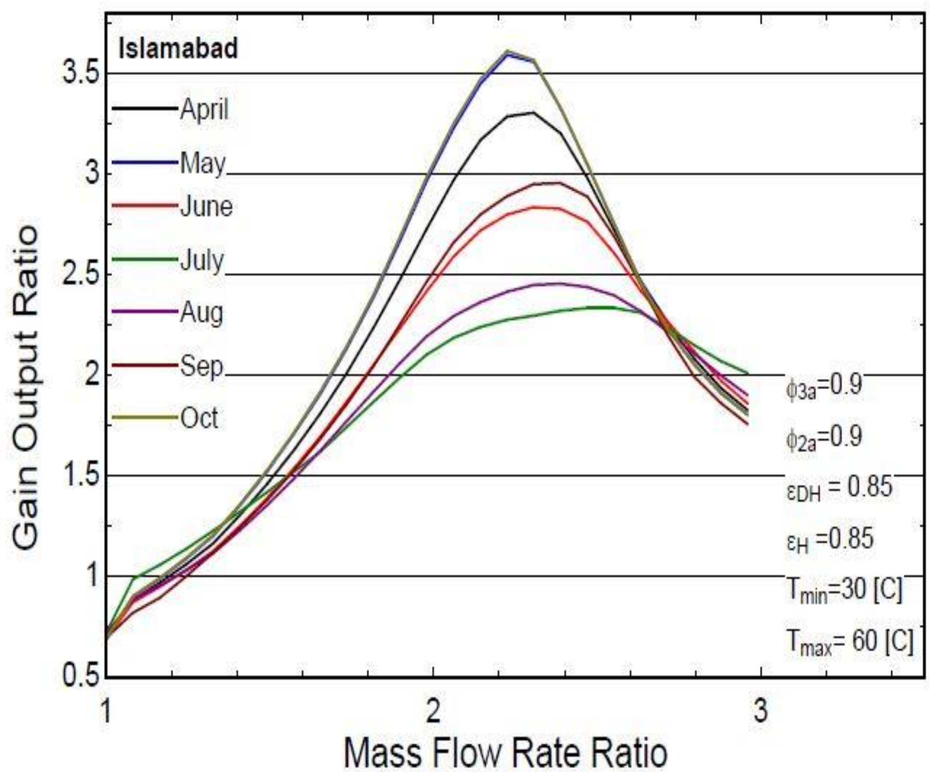

Figure 4.9: GOR variation against Mass Flow Rate Ratio for Islamabad

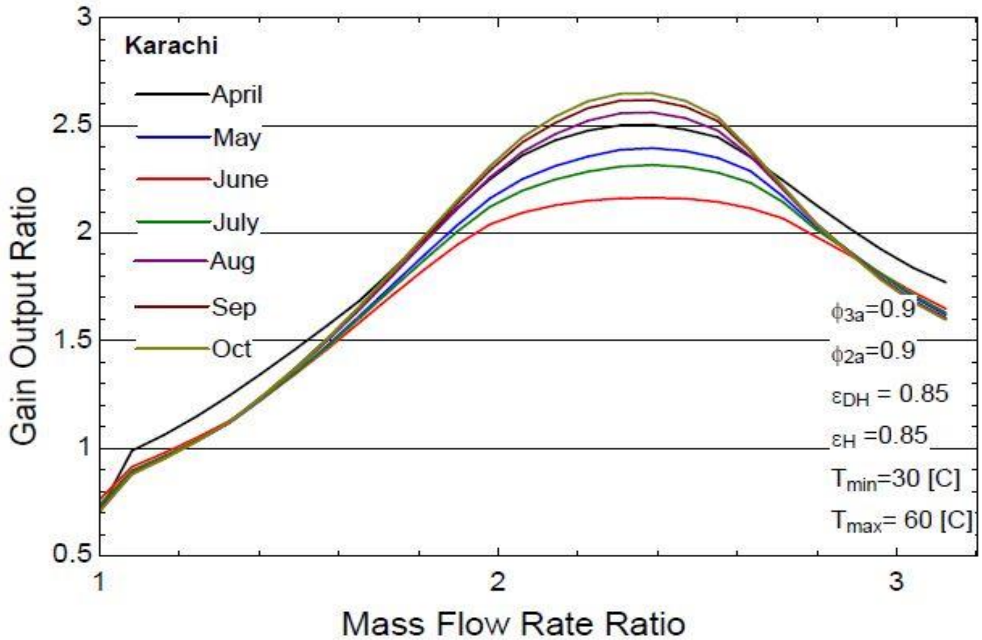

Figure 4.10: GOR variation against Mass Flow Rate Ratio for Karachi

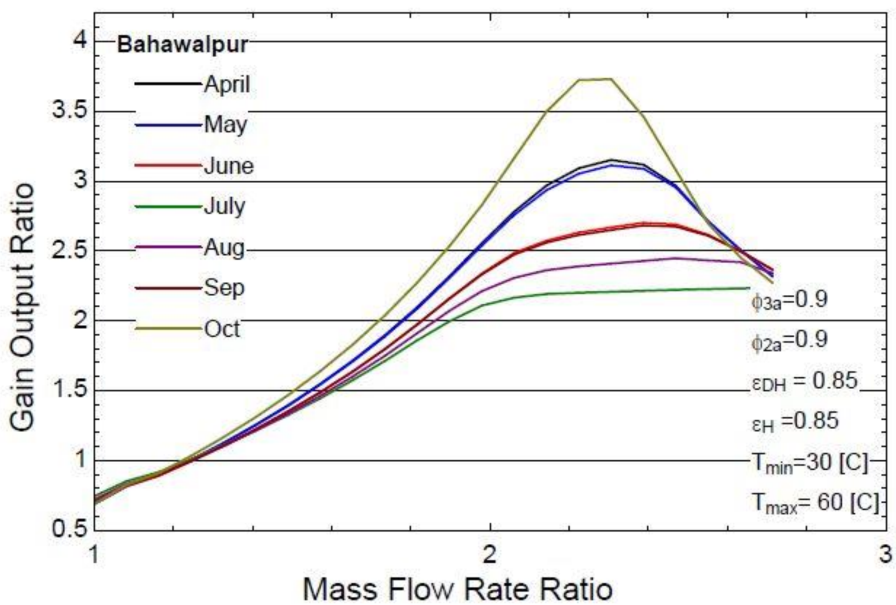

Figure 4.11: GOR variation against Mass Flow Rate Ratio for Bahawalpur

Figure 4.12 shows the dependence of GOR on relative humidity of air entering the humidifier at sea water temperature of 30℃. At lower humidity values system shows a high GOR. As humidity starts to increase GOR decreases. As air gets started saturating GOR starts to converge at a lower GOR. It also shows that at ambient air temperature 35

°C GOR is high. This shows that when the temperature difference between hot water and ambient in the humidifier is high then it shows high GOR. As air temperature starts to increase graphs shifts downwards towards lower GOR. This plot also confirms that increase in humidity decreases the GOR which is less for Karachi due to higher humidity.

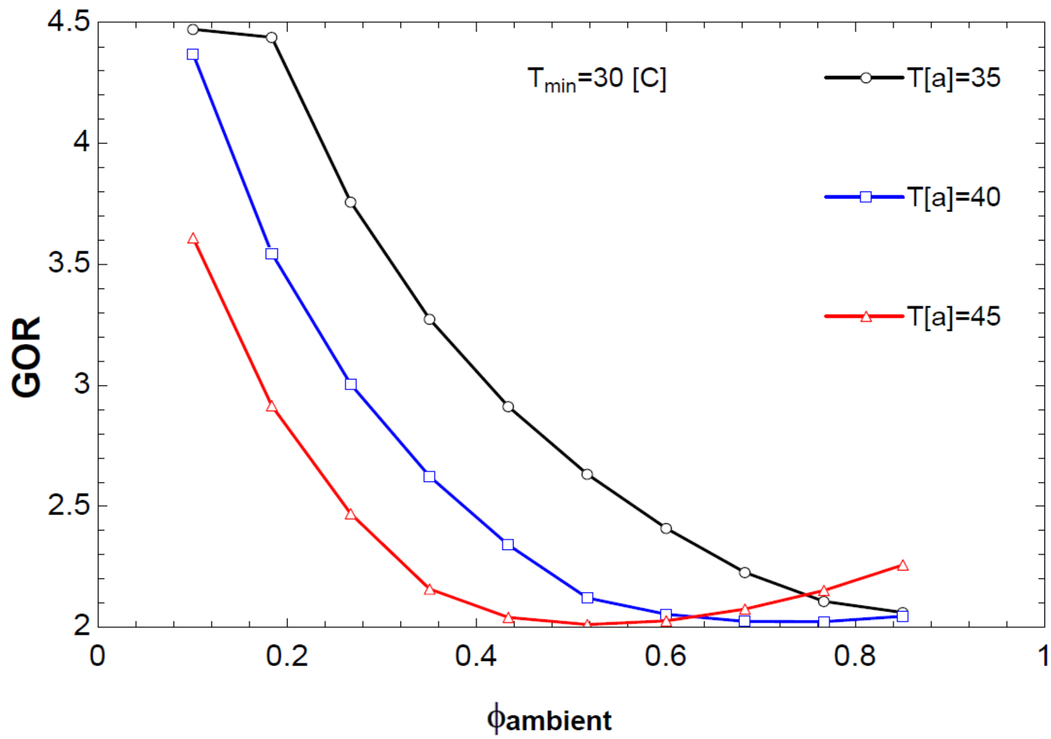

Figure 4.12: GOR variation against relative humidity of air

Figure 4.13 shows the Optimum MR ratio for a given humidity and temperature of ambient air. For realistic values of humidity and temperature in different climate region this graph shows that an MR value of around 2 provides us the optimum system performance that corresponds to the maximum value of GOR. Beside the fact that a little variation in any condition could change optimum value of MR ratio this plot shows that MR value must be around 2 for water heated cycles.

Figure 4.13 only shows optimum MR for a water heated cycle which around a value of 2 with a small variation but for air heated cycle value of optimum MR always remain less than 1.

From these plots we can see that water mass flow rate must be greater than the mass flow rate of air for optimum performance at all times for water heated cycles. And HDH open air cycle have high GOR, and it performs best for cold and dry regions. It we want to use it for hotter regions which is the case for its use in combine system then maximum water temperature must be increased to increase the driving force of humidifier.

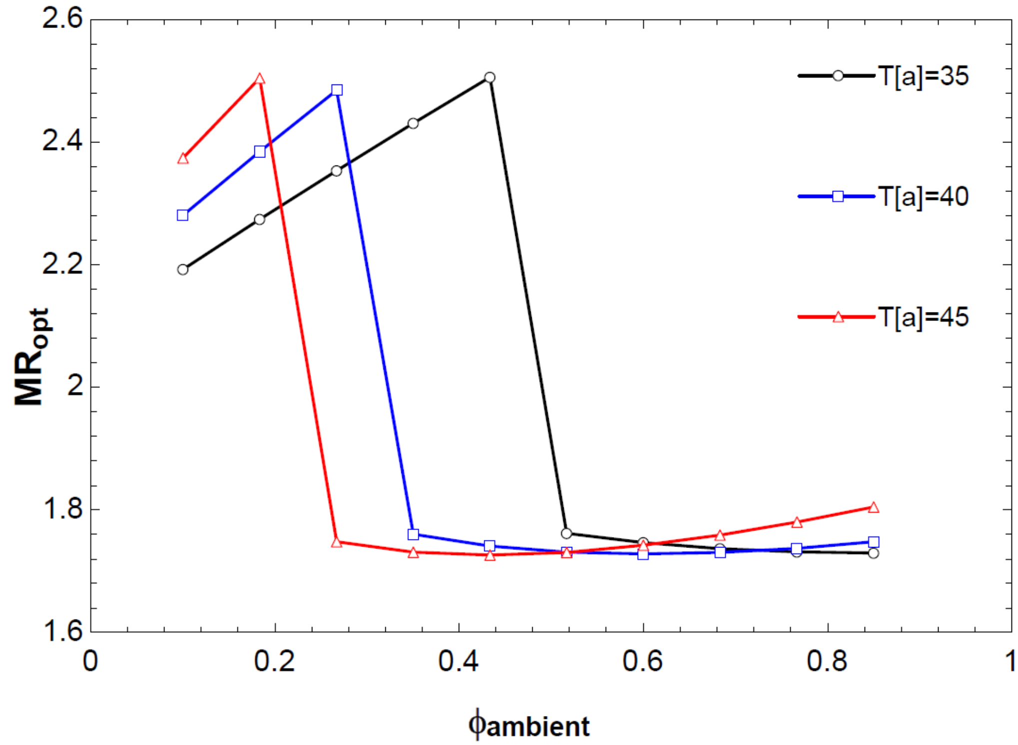

Figure 4.13: Optimum MR variation against relative humidity of air

4.4 Combined system input power for different climate regions

Air exiting from HDH system has low temperature and high humidity due to which when it enters vapor compression system through an enthalpy exchanger sensible load will be less and latent load will be high as compared when ambient enters directly into vapor compression system. Is sensible load reduction being significant than the increase in latent load then compressor input required will be less. This depends upon the ambient conditions of air and HDH system as well.

Figure 4.14 to Figure 4.17 shows the bar plot of required compressor input for a constant air flow rate of 1.12 kg/s and room air delivery temperature of 20 ℃ at 55% relative humidity for four cities of Pakistan i.e., Islamabad, Bahawalpur, Karachi, and Lahore for the months April to October. It can be seen in the plots that air entering directly into vapor compression system have highest required input at all conditions. While combined system for the region Islamabad, Lahore and Bahawalpur requires lowest input power in months where ambient air is at higher temperatures while in other months combined system have comparable power input with enthalpy exchanger vapor compression system. On average combined shows highest of 20% reduction in input power for Lahore region and 11% for Islamabad and 9% for Bahawalpur.

Karachi region is not showing a significant reduction in load when a combined system is used this is because k climate of Karachi is cold and humid. Sensible load does not reduce much as compared to increase in latent load when a combined system is used. Therefore, for this region combined system have slightly larger input power than a simple enthalpy exchanger vapor compression system.

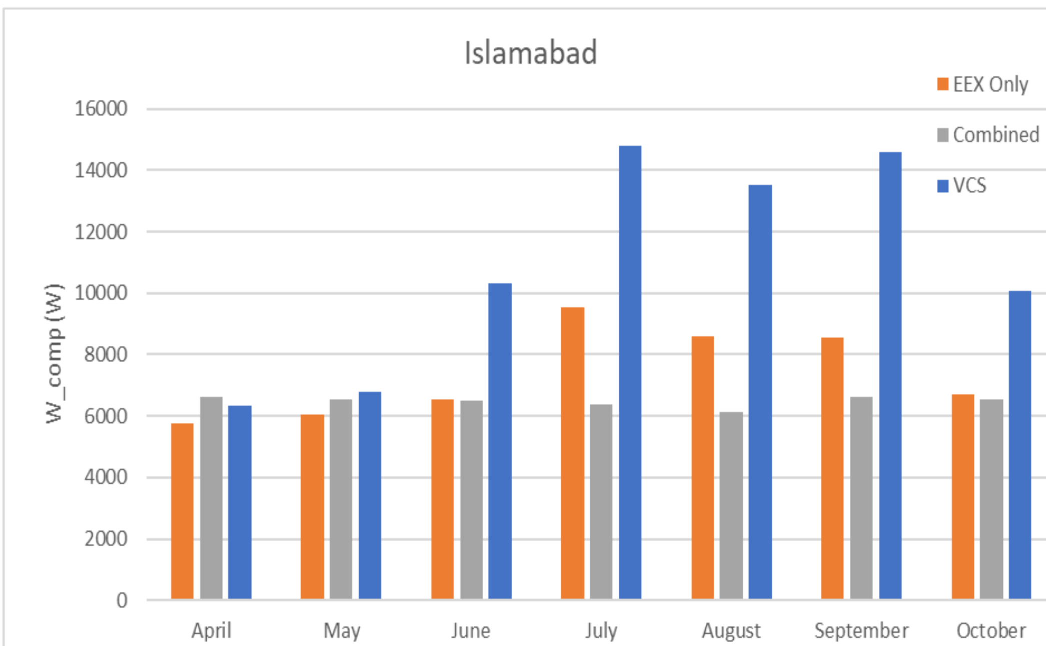

Figure 4.14: Comparison of Input Power of different systems for Islamabad

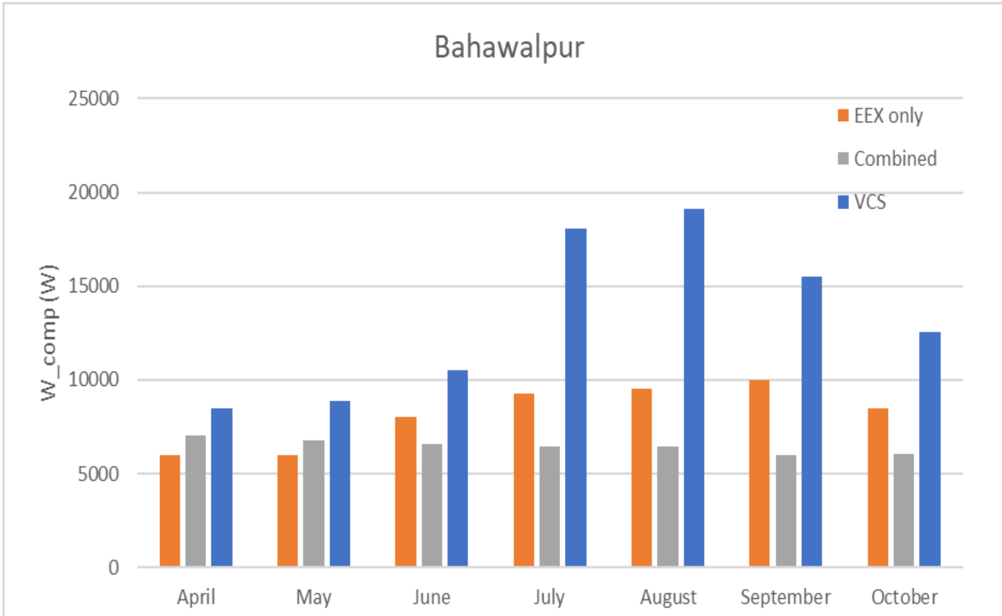

Figure 4.15: Comparison of Input Power of different systems for Bahawalpur

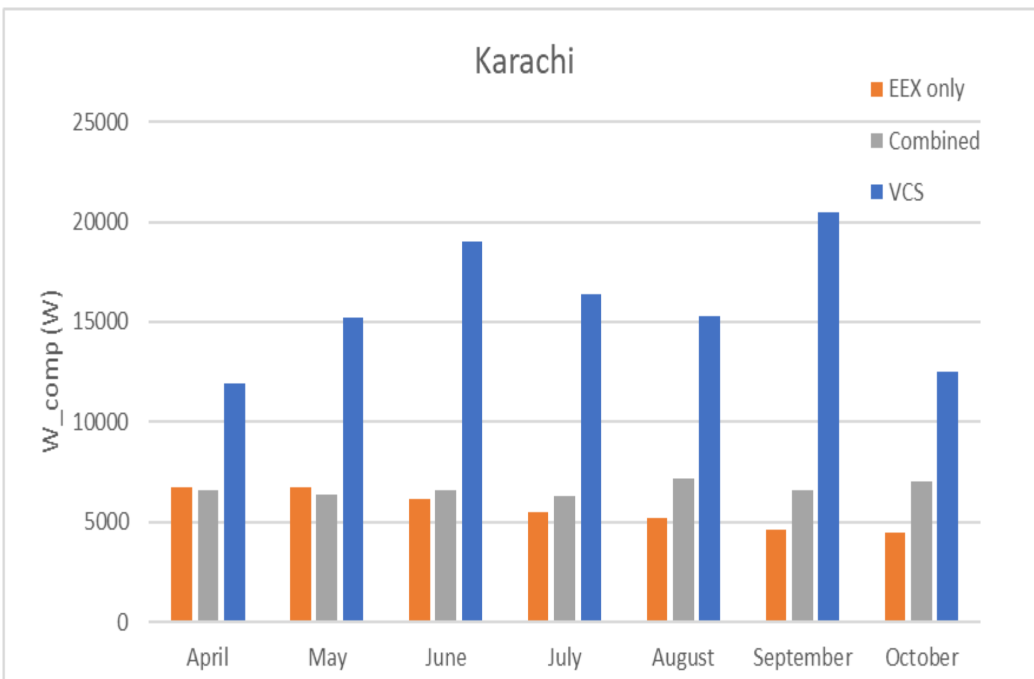

Figure 4.16: Comparison of Input Power of different systems for Karachi

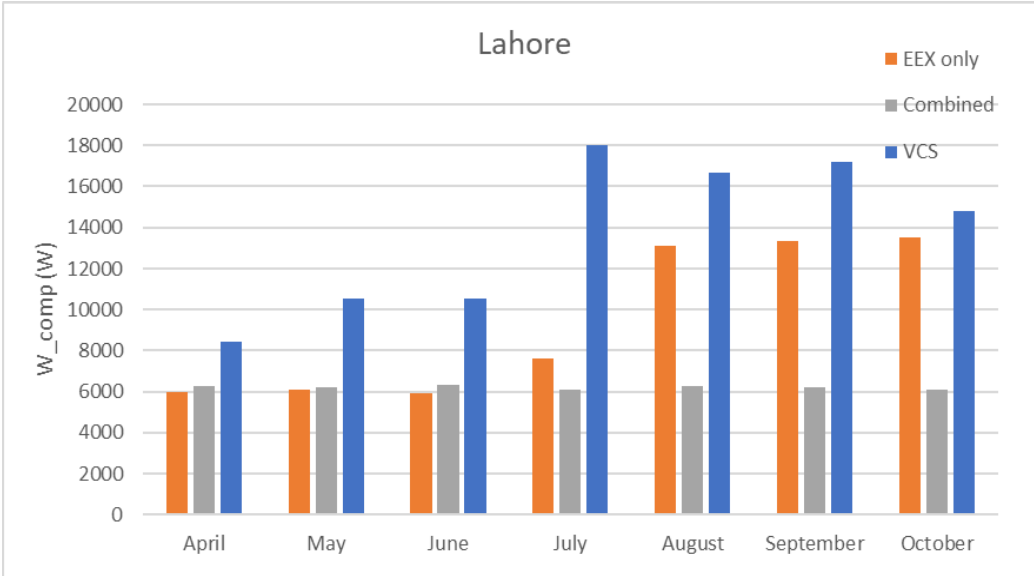

Figure 4.17: Comparison of Input Power of different systems for Lahore

These plots show in some regions combined system shows significant power savings and in others it shows less savings. A similar hybrid air conditioning is also examined by Nada et al. [4] but he did not use a separate dehumidifier like in HDH system [5]. To have an exact value of temperature and humidity a global analysis is also performed.

4.5 Global analysis of Combined System

A global analysis has been performed for determination of input power required for air conditioning when vapor compression system has been used with enthalpy exchanger and when combined HDH system has been coupled with them Figure 4.18 shows required input power for combined system at 50% relative humidity for different ambient air temperatures. Above 40 °C combined system results in power savings and at 80% relative humidity combined system showing significant power savings even at lower temperature of 30 °C as well in . This is because air exiting HDH system will be almost of similar conditions making the required input power almost constant but varying conditions effects vapor compression system and increased humidity results in higher power consumptions for vapor compression system.

Both the plots shows that above 38°C combined started showing power savings at normal values of humidity and any increase in humidity adds value to combine system making it more suitable at constant temperature.

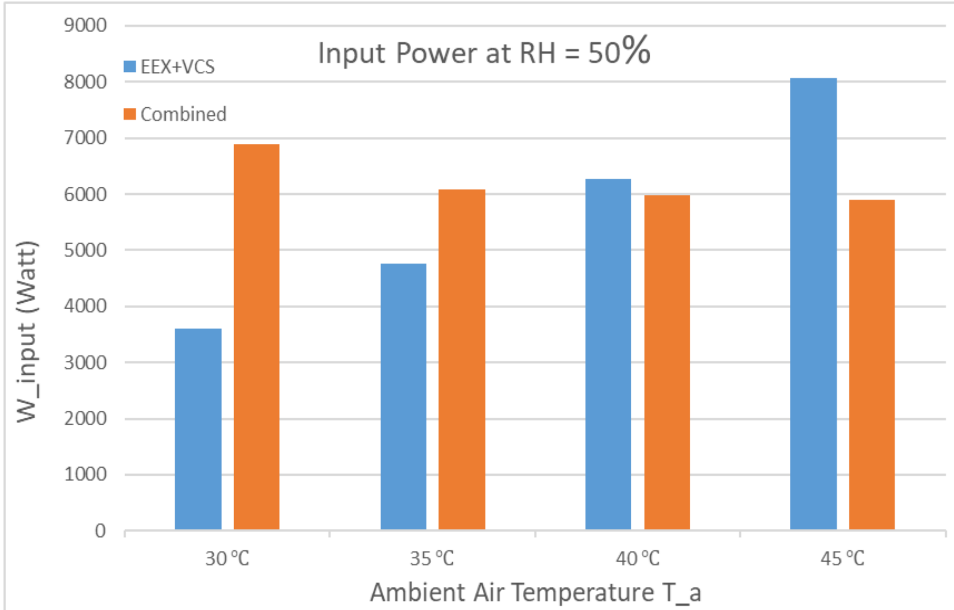

Figure 4.18: Comparison of Input Power at constant Humidity and Varying Temperature at 50% humidity

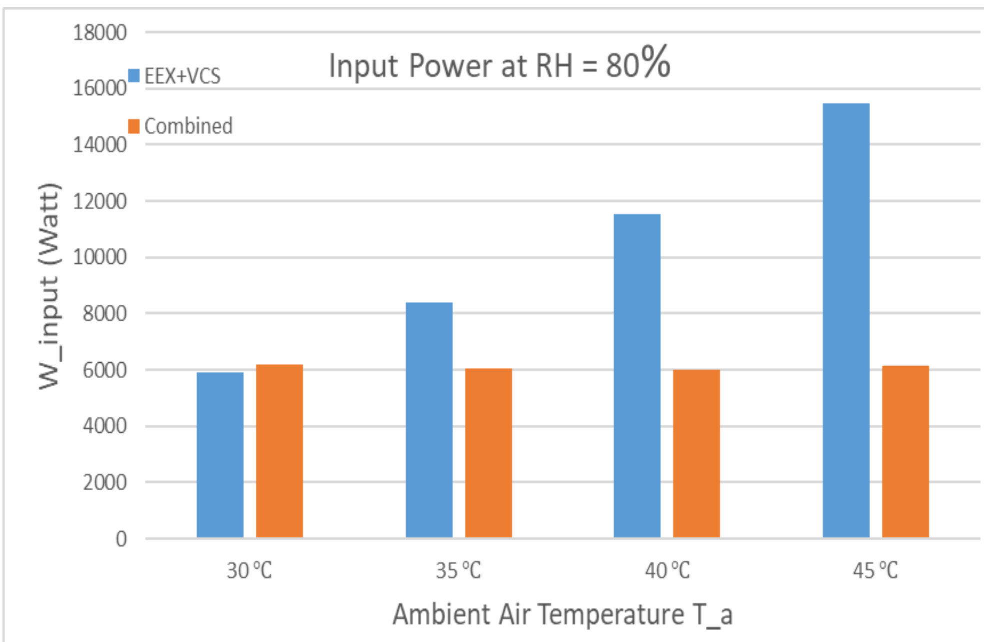

Figure 4.19 :Comparison of Input Power at constant Humidity and Varying Temperature at 50% humidity at 80% humidity

Similarly, Figure 4.20 and Figure 4.21 shows required input power comparison at constant ambient air temperature and variable humidity of air. It can be seen in the plots that at 35 °C combined system proved effective above 50% relative humidity but at 45 °C combined shows marginal power savings almost at all levels of humidity. For hot and humid regions combined could always be effectively used with promising savings.

From the global analysis it can be concluded that combined will be most effective in hot and humid regions. Because in both regions simple compression system will consume more power but that will be almost constant for combined system which results in power savings.

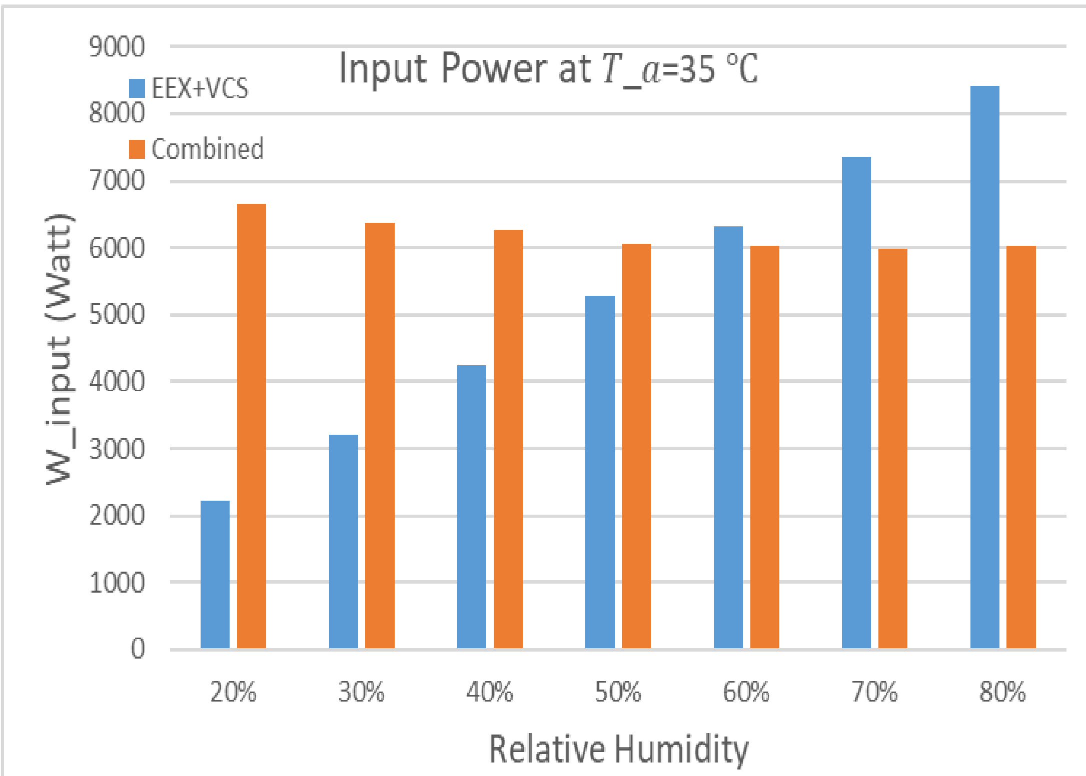

Figure 4.20: Comparison of Input Power at constant Temperature and Varying Humidity

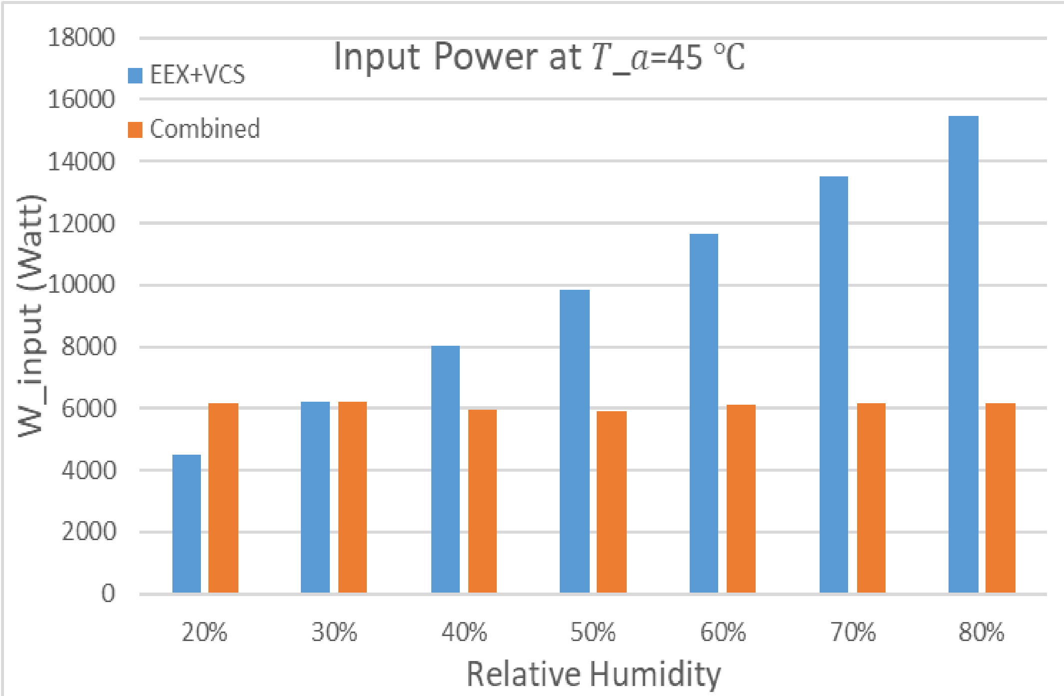

Figure 4.21: Comparison of Input Power at constant Temperature and Varying Humidity

4.6 Freshwater production

Figure 4.22 shows an average of 30% increase in Fresh Water Productivity when a combined system is used. This shows almost constant freshwater production rate of 10L/h. Increasing the flow rate of air will increase the freshwater production rate as well but increase in flow rate also require a large amount of heat to heat the water in HDH system. Freshwater production rate is almost constant here due to constant supply of maximum water temperature, in case where supply of heat will be constant then temperature of water would be changing according to the flow rate of water. Then freshwater production will change according to the water flow rate. And water flow rate needs to be adjusted to have maximum GOR and every condition there is an optimum MR which maximized GOR which has been calculated for both open air and closed air HDH system in previous sections. [6], [7], [8]

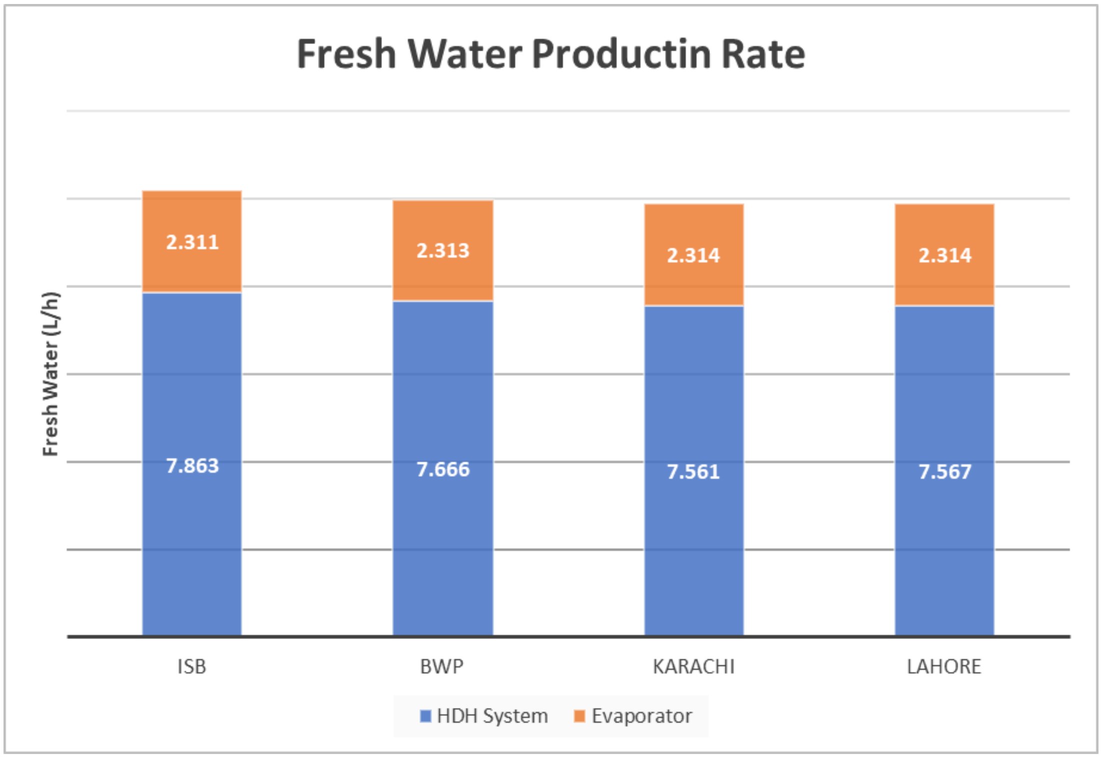

Figure 4.22: Average freshwater production rate

4.7 Exergy Analysis

Exergy modeling has also been verified for different components of vapor compression system when they perform alone in the presence of enthalpy exchanger only. After model verification the same model has been used to check the exergy destruction of all the components involved in vapor compression system when it worked in hybrid air conditioning coupled with HDH system. Then instead of ambient air which is meant to be used at the entry to vapor compression system air exiting the dehumidifier of HDH will be used to air conditioning purposes.

Exergy destruction of all components in vapor compression system has also been calculated with combination of HDH system and without HDH system and plotted. Figure 4.23 shows that exergy destruction is lower when a combined system is used except for

Karachi. For combine system compressor and evaporator have highest exergy destructions showing the highest potential of saving and highest irreversibility as well.

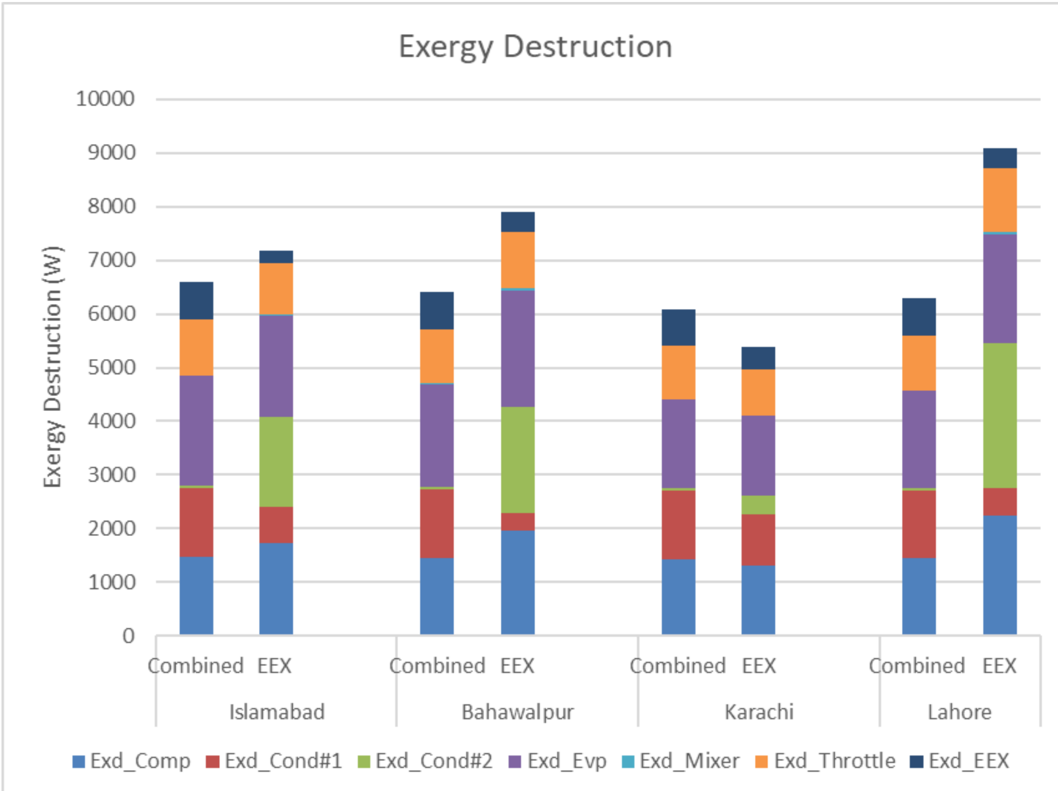

Figure 4.23: Comparison of exergy destruction for combined system

Irreversibility Ratio at average temperature and humidity has been calculated and plotted in the Figure 4.24 bar plot which shows that for a combine system 2nd condenser and mixer as have lowest irreversibility ratio. While enthalpy exchanger becomes more irreversible in combined system. While other components have almost similar irreversibility's. Irreversibility ratio of 2nd condenser has decreased significantly this is due the fact that 2nd condenser is used for having a better control on air condition when ambient air temperature fluctuates. When a combined system is used then air entering in enthalpy exchanger or vapor compression system have same temperature and humidity removing the possibility of any sudden fluctuation in the condition of air. Thus, flow rate of refrigerant in 2nd condenser can be reduced significantly which also lowers its irreversibility.

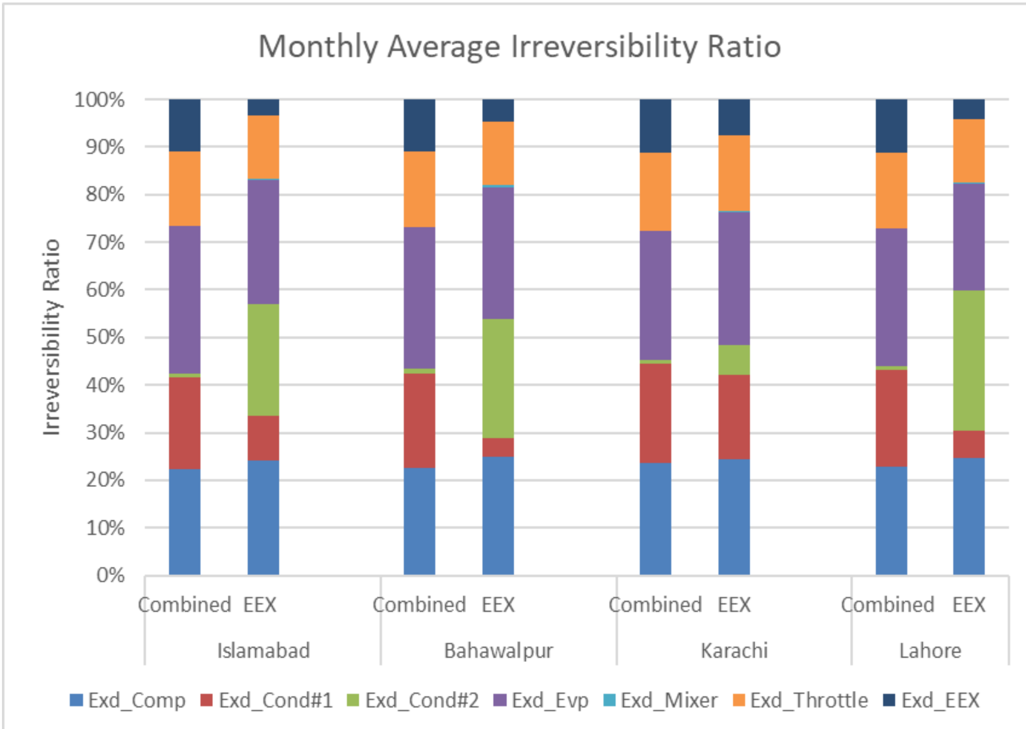

Figure 4.24: Comparison of irreversibility ratios

Summary:

This chapters presents the major results and finds when Humidification Dehumidification (HDH) System work in combination with vapor compression system. Results includes closed system analysis of HDH system and Vapor Compression system modeling and verification. HDH open system results to check if there is any performance decrement or not. After it proves that HDH open system in fact work better in terms of thermal optimization than closed system a comparison for required input power for single vapor compression system and combined system has been drawn. From input power comparison we can conclude that combined system results in power savings for hot and humid areas. Chapter also includes freshwater production rate to meet demands of fresh water along with providing air conditioning at lower cost.

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Chapter 5 : Conclusions and Recommendations

5.1 Conclusions

HDH systems have been in use at lab scale for low production of freshwater using low grade heat source which provide higher efficiency and higher production rate as compared to conventional solar stills all other technologies like RO plants and Multistage Flash Desalination for water production mostly uses electricity or steam which can be used for remote locations and moreover, they are high grade energy and thus causing more exergy destruction during their work. Along with water crisis energy crisis is another major issue which the world is currently facing. And air conditioning devices fall into the category of most energy consumption devise the building consumes. Therefore, a lot of efforts have been made to make vapor compression system energy efficient and to make them suitable for less exergy destruction so that the energy can be recovered as much as possible. Employing a desiccant with vapor compression system, using an enthalpy exchanger with vapor compression system are among the efforts which have been made to make VCS energy efficient. There some studies in which vapor compression system has been coupled with another system in the form of a hybrid air conditioning to provide conditioned space and freshwater or might be some other products as well.

In this study analysis one similar system has been performed. HDH system combined with vapor compression system through an enthalpy exchanger has been performed for different climate regions. A global analysis has also been performed to find out the exact value to temperature and humidity above which combined system shows significant power savings. Power savings shows in the forms of bar plots and percentage power savings has also been calculated for the regions. Besides providing power savings water production rate has also been calculated. Along with energy exergy analysis has also been performed for the components of vapor compression system in combined system. Detailed conclusions are as follows.

- Both open and closed air HDH systems have an optimum value MR at which HDH system shows maximum performance, which changes subjected to any change in the conditions.
- GOR increases with increase in sea water temperature or with decrease in maximum water temperature showing a greater effect of heat parameter on GOR as compared to freshwater production rate.
- Open air HDH system shows higher value of GOR for almost all climate condition providing the same maximum water temperature.
- For water heated cycles for maximum performance of HDH system mass flow rate of water should be higher than mass flow rate air all conditions.
- For air heated cycle mass flow rate of air should be greater than mass flow rate of water at all conditions for maximum performance.
- For satisfactory performance rather than changing the mass flow rate with a minimum changer in conditions it a good approximation for maximum that mass flow rate of water should b 2 times than the mass flow rate of air.
- Open air HDH system shows higher value GOR for dry regions since dry carry more water from the sea water.
- Open air HDH system shows less GOR for hot regions for same maximum water temperature due to less driving force in the humidifier.
- Combined system shows a maximum power savings of 20% for Lahore region and thus can be effectively used for hot and humid regions.
- Combined system results in power savings along with freshwater production for the region where average summer temperature is greater than $35℃$ and average humidity is greater than 50%.
- At a temperature less than $35℃$ humidity should be higher and at the humidity less than 50% temperature should be higher for savings as also shown in global analysis.
- Combined system shows an average freshwater production of about $10\ L/h$ which is 30% higher than conventional HDH systems. This production rate is at maximum water temperature.

- When air from combined system is used for air conditioning purposes then all components in the vapor compression system shows average less exergy destruction and less irreversibility ratio.

5.2 Recommendations

- Since HDH systems runs at very low mass flow rate of air and vapor compression systems runs at higher mass flow rate of air, there is a need to study when 2 or 3 HDH systems couples with single vapor compression system.
- In this study heat required for water is provided by any external low-grade source, but since, condenser of vapor compression system is also emitting a lot of heat form the building that heat will be used to water heating that could eliminate the heating requirement of HDH system and in such a way HDH coupling with vapor compression will result in maximum savings.
- In present study pumping power for air and water has been ignored being small as compared to heating required. But at large or industrial scale it can not be ignored specially when mass flow rate is high.
- Cost has been ignored at this point because for small flow rates both the systems are running individually and just by couple them would not affect the cost much, but cost analysis would be required for its implementation at large scale.
- Present study is theoretical study of proposed idea future experimental study would also be required for its proper implementation.

Appendix

Conference Extended Abstract

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New Campus, University of Engineering and Technology Lahore
31st March 2021, Lahore, Pakistan

PERFORMANCE ANALYSIS OF COMBINED HUMIDIFICATION DEHUMIDIFICATION(HDH) SYSTEM COUPLED WITH AIR CONDITIONING SYSTEM

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- **ABSTRACT**

Performance analysis of Humidification Dehumidification (HDH) system coupled with vapor compression system through an enthalpy exchanger has been performed to provide conditioned space and fresh water as a product. Results shows up to 20% reduction in input power for hot regions and 30% increased freshwater productivity at an average production rate of $10l/h$.

Key words: *Humidification-Dehumidification, Enthalpy Exchanger, Air Conditioning*

- **Introduction**

HDH system is being used for freshwater production using low grade heat source and vapor compression system is widely used for air conditioning which consumes most of the electricity produced. Air at the exit of HDH system is at lower temperature and higher humidity when this air is used in vapor compression system instead of ambient air it results in significant power savings in hot and humid regions where decrease in sensible load dominates the increase in latent load. Along with power savings fresh water is also collected through HDH system and in evaporator coil as well thus productivity of HDH system also enhanced. A combined system schematic diagram is shown in *Figure 25*.
Ambient air enters into humidifier gets hot and humid by incoming hot water then enters

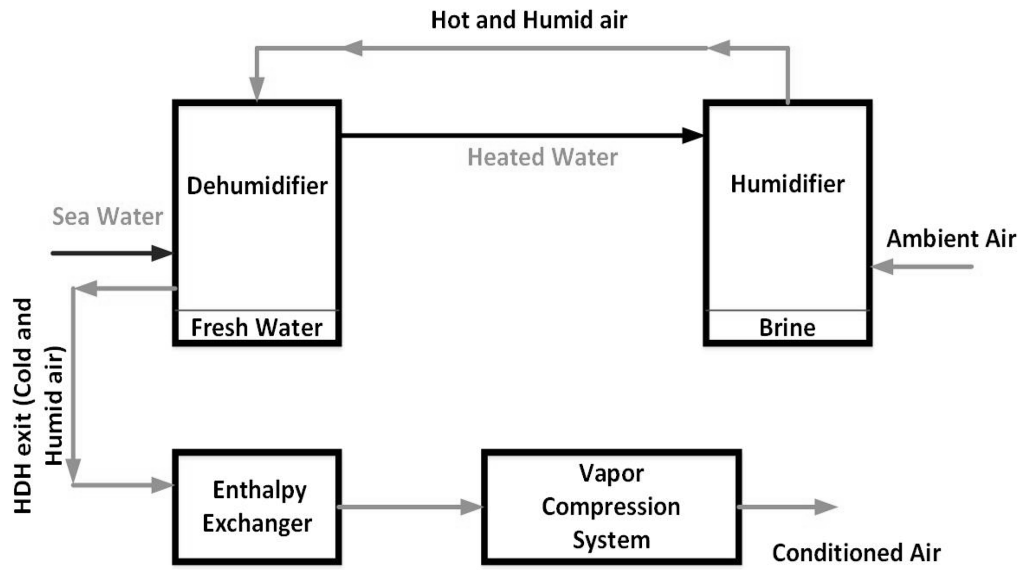

Figure 25: HDH System combined with Vapor Compression System through an Enthalpy Exchanger

into dehumidifier where it interacts with cold sea water, condensate or fresh water is collected in dehumidifier and then air enters into enthalpy exchanger where it temperature and humidity decreases by its interaction with return air from the room. Then air enters into evaporator for further cooling to a lower temperature of comfort zone.

- **Methodology**

Key modeling equations are based upon energy and mass balance analysis of components. Model used for vapor compression system is based upon the modeling equations of vapor compression system [1]. While modeling equations for enthalpy exchanger are used which gave best results in agreement with experimental data [2]. These equations have been solved iteratively using F-Chart Software. Different performance parameters of HDH system have been studied to optimize the performance and effect of different climate conditions has also been studied.

- **Results and Analysis:**

Results shows that there exist optimum mass flow rates for both air and water which depends upon the ambient conditions i.e., temperature and humidity of air and maximum and minimum temperature of water. HDH system shows better performance in dry regions. Dry regions show high Gain Output Ratio (GOR) while increasing ambient air temperature decreases GOR. Optimum Mass Flow Rate Ratio of water to air is always greater than 1 in case of water heated HDH system. HDH closed air open water cycle results are in exact agreement with the results present in literature [3].
Combined system shows significant power savings in hot and humid regions where average temperature is greater than 35 degrees Celsius, and average humidity is greater than 50%. With a constant maximum water temperature average freshwater productivity

is about $10l/h$. Exergy Destruction and Irreversibility Ratio of components also improves when a combined system is used.

- **Conclusions**

Performance analysis of Humidification Dehumidification (HDH) system combined with air conditioning system has been performed to assess its performance for different climate conditions its terms of thermal optimization of HDH system, water productivity and power savings for air conditioning. Following conclusions have been drawn from the study.

- Open air Open water HDH cycle has high GOR as compared to closed air open water cycle.
- Combined system shows a reduction in compressor input power for hotter regions up to 20%, with a water production of 10 liters per hour.
- Combines system shows average less exergy destruction for hotter region.

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Combined System EES Code:

```
"!Enthalpy Exchanger"
"Given Conditions"
//m_dot_r=0.2 [kg/s]
m_dot_air=1.12 [kg/s]
T_6a =20 [C]
Pratio=4
eta_s=0.75
Ref$='R134a'
epsilon_s=0.8
epsilon_l=0.9
R_air=287 [J/kg-K]
C_pair=1005 [J/kg-K]
C_pvpr=1996 [J/kg-K]
w=1.6081
"Ambient Referecne"
h[0]=ENTHALPY(Ref$,T=Tair[1],P=P_3a)
s[0]=ENTROPY(Ref$,T=Tair[1],P=P_3a)
T_0_k=CONVERTTEMP('C','K',Tair[1])
omega_0=omega[1]
"Stage 1 Before Compressor"
P[1]=300 [kpa]
T[1]=TEMPERATURE(Ref$,P=P[1],x=1)
h[1]=ENTHALPY(Ref$,x=1,T=T[1])
s[1]=ENTROPY(Ref$,x=1,T=T[1])
ex[1]=(m_dot_r*((h[1]-h[0])-((T_3a_k*(s[1]-s[0]))))))*CONVERT(kw,W)



"Stage 2 After Compressor"
P[2]=Pratio*P[1]
h_2_s=ENTHALPY(Ref$,P=P[2],s=s[1])
eta_s=(h_2_s-h[1])/(h[2]-h[1])
T[2]=TEMPERATURE(Ref$,h=h[2],p=P[2])
s[2]=ENTROPY(Ref$,h=h[2],p=P[2])
ex[2]=(m_dot_r*((h[2]-h[0])-((T_3a_k)*(s[2]-s[0])))))*CONVERT(kw,W)
"Stage 3 After Condenser 1"
P[3]=P[2]
h[3]=ENTHALPY(Ref$,p=P[3],x=0)
T[3]=TEMPERATURE(Ref$,p=P[3],x=0)
s[3]=ENTROPY(Ref$,p=P[3],x=0)
ex[3]=((1-y)*m_dot_r*((h[3]-h[0])-((T_3a_k)*(s[3]-s[0]))))*CONVERT(kw,W)
"Stage 6 after Condensor 2"
T[6]=30 [C]
P[6]=P[3]
h[6]=ENTHALPY(Ref$,T=T[6],P=P[6])
s[6]=ENTROPY(Ref$,T=T[6],P=P[6])
ex[6]=((y)*m_dot_r*((h[6]-h[0])-((T_3a_k)*(s[6]-s[0]))))*CONVERT(kw,W)
"stage 4  mixer"
P[4]=P[2]
h[4]=(h[6]*(y)*m_dot_r+h[3]*(1-y)*m_dot_r)/m_dot_r
T[4]=TEMPERATURE(Ref$,h=h[4],p=P[4])
s[4]=ENTROPY(Ref$,h=h[4],p=P[4])
```

```
ex[4]=(m_dot_r*((h[4]-h[0])-((T_3a_k)*(s[4]-s[0]))))*CONVERT(kw,W)
"stage 5 throttle"
h[5]=h[4]
P[5]=P[1]
T[5]=TEMPERATURE(Ref$,h=h[5],P=P[5])
s[5]=ENTROPY(Ref$,h=h[5],P=P[5])
ex[5]=(m_dot_r*((h[5]-h[0])-((T_3a_k)*(s[5]-s[0]))))*CONVERT(kw,W)
"at inlet of Enthalpy exchagner"
T_3a_k=CONVERTTEMP('C','K',T_3a)
omega_3a=HUMRAT(AIRH2O,P=P_3a,r=RH_3a,T=T_3a)
h_3a=ENTHALPY(AIRH2O,P=P_3a,r=RH_3a,T=T_3a)
s_3a=ENTROPY(AIRH2O,P=P_3a,r=RH_3a,T=T_3a)
"air entry in room at D"
RH_6a=0.55
omega_6a=HUMRAT(AIRH2O,r=RH_6a,T=T_6a,P=P_3a)
h_6a=ENTHALPY(AIRH2O,r=RH_6a,T=T_6a,P=P_3a)
s_6a=ENTROPY(AIRH2O,r=RH_6a,T=T_6a,P=P_3a)
"air exit properties from room "
T_7a=22[C]
omega_7a=0.0088
RH_7a=RELHUM(AIRH2O,w=omega_7a,T=T_7a,P=P_3a)
h_7a=ENTHALPY(AIRH2O,w=omega_7a,T=T_7a,P=P_3a)
s_7a=ENTROPY(AIRH2O,w=omega_7a,T=T_7a,P=P_3a)
"mixer equation for calculation of y"
m_dot_r*(h[4])=(1-y)*m_dot_r*h[3]+(y)*m_dot_r*h[6]
Omega_5a=Omega_6a
m_dot_r*y*(h[2]-h[6])=m_dot_air*(h_6a-h_5a)
T_5a=TEMPERATURE(AIRH2O,h=h_5a,w=omega_5a,P=P_3a)
s_5a=ENTROPY(AIRH2O,h=h_5a,w=omega_5a,P=P_3a)
"enthalpy exchanger"
epsilon_s=(T_3a-T_4a)/(T_3a-T_7a)
epsilon_l*epsilon_s=(omega_3a-omega_4a)/(omega_3a-omega_7a)

h_4a=ENTHALPY(AIRH2O,T=T_4a,w=omega_4a,P=P_3a)
s_4a=ENTROPY(AIRH2O,T=T_4a,w=omega_4a,P=P_3a)
omega_8a=omega_7a+(omega_3a-omega_4a)
T_8a=T_7a+(T_3a-T_4a)
h_8a=ENTHALPY(AIRH2O,T=T_8a,w=omega_8a,P=P_3a)
s_8a=ENTROPY(AIRH2O,T=T_8a,w=omega_8a,P=P_3a)
"evaporator equation to calculate m_dot_air"
m_dot_r*(h[1]-h[5])+m_dot_wev*h_fwev=m_dot_air*(h_4a-h_5a)
T_4a_dp=DEWPOINT(AIRH2O,w=omega_4a,T=T_4a,P=P_3a)
h_fwev=ENTHALPY(WATER,T=T_4a_dp,P=P_3a)   "fresh water produces at dewpoint temperature"
"exergy calculation of moist air"
P_r_a=P_3a/P_3a
T_r_a=((T_3a_k)/T_0_k)
Ex_3a=m_dot_air*(T_0_k*(C_pair+omega_3a*C_pvpr)*(T_r_a-1-
LN(T_r_a))+R_air*T_0_k*(1+w*omega_3a)*LN(P_r_a)+R_air*T_0_k*((1+w*omega_3a)*LN((1+w*omega_0)/(1+w*o
mega_3a))+(w*omega_3a)*(ln(omega_3a/omega_0))))
T_4a_k=CONVERTTEMP('C','K',T_4a)
T_r_b=(T_4a_k)/T_0_k
Ex_4a=m_dot_air*(T_0_k*(C_pair+omega_4a*C_pvpr)*(T_r_b-1-
LN(T_r_b))+R_air*T_0_k*(1+w*omega_4a)*LN(P_r_a)+R_air*T_0_k*((1+w*omega_4a)*LN((1+w*omega_0)/(1+w*o
mega_4a))+(w*omega_4a)*(ln(omega_4a/omega_0))))
```

```
T_5a_k=CONVERTTEMP('C','K',T_5a)
T_r_c=(T_5a_k)/T_0_k
Ex_5a=m_dot_air*(T_0_k*(C_pair+omega_5a*C_pvpr)*(T_r_c-1-
LN(T_r_c))+R_air*T_0_k*(1+w*omega_5a)*LN(P_r_a)+R_air*T_0_k*((1+w*omega_5a)*LN((1+w*omega_0)/(1+w*o
mega_5a))+(w*omega_5a)*(ln(omega_5a/omega_0))))
T_6a_k=CONVERTTEMP('C','K',T_6a)
T_r_d=(T_6a_k)/T_0_k
Ex_6a=m_dot_air*(T_0_k*(C_pair+omega_6a*C_pvpr)*(T_r_d-1-
LN(T_r_d))+R_air*T_0_k*(1+w*omega_6a)*LN(P_r_a)+R_air*T_0_k*((1+w*omega_6a)*LN((1+w*omega_0)/(1+w*o
mega_6a))+(w*omega_6a)*(ln(omega_6a/omega_0))))
T_7a_k=CONVERTTEMP('C','K',T_7a)
T_r_e=(T_7a_k)/T_0_k
Ex_7a=m_dot_air*(T_0_k*(C_pair+omega_7a*C_pvpr)*(T_r_e-1-
LN(T_r_e))+R_air*T_0_k*(1+w*omega_7a)*LN(P_r_a)+R_air*T_0_k*((1+w*omega_7a)*LN((1+w*omega_0)/(1+w*o
mega_7a))+(w*omega_7a)*(ln(omega_7a/omega_0))))
T_8a_k=CONVERTTEMP('C','K',T_8a)
T_r_f=(T_8a_k)/T_0_k
Ex_8a=m_dot_air*(T_0_k*(C_pair+omega_8a*C_pvpr)*(T_r_f-1-
LN(T_r_f))+R_air*T_0_k*(1+w*omega_8a)*LN(P_r_a)+R_air*T_0_k*((1+w*omega_8a)*LN((1+w*omega_0)/(1+w*o
mega_8a))+(w*omega_8a)*(ln(omega_8a/omega_0))))
"Exergy destruction rates of components"
W_c=m_dot_r*(h[2]-h[1])*CONVERT(kw,W)
Exd_com=ex[1]-ex[2]+W_c
Exd_con_1=(1-y)*(ex[2])-ex[3]
Exd_con_2=y*(ex[2])-ex[6]+(ex_5a-ex_6a)
Exd_throt=ex[4]-ex[5]
Exd_ev=ex[5]-ex[1]+ex_4a-ex_5a
//Exd_mix=y*ex[6]+((1-y)*(ex[3]))-ex[4]
Exd_mix=ex[6]+ex[3]-ex[4]
Exd_memb=ex_3a-ex_4a+ex_7a-ex_8a
Q_dot_ev=m_dot_r*(h[1]-h[5])*CONVERT(kw,W)
m_dot_wev=m_dot_air*(omega_4a-omega_5a)
COP=Q_dot_ev/W_c
"irreversiblity Ratio"
Exd_to=Exd_com+Exd_con_1+Exd_con_2+Exd_throt+Exd_ev+Exd_mix+Exd_memb
X_com[1]=Exd_com/Exd_to
X_con_1[1]=Exd_con_1/Exd_to
X_con_2[1]=Exd_con_2/Exd_to
X_throt[1]=Exd_throt/Exd_to
X_ev[1]=Exd_ev/Exd_to
X_mix[1]=Exd_mix/Exd_to
X_memb[1]=Exd_memb/Exd_to
"!Required Inputs="
Tair[1] = 41 [C]
RH_hdh[1] = 0.5
T_3a=Tair[3]
RH_3a=RH_hdh[3]
P_3a=P
T_min_sea = 30 [C]  "minimum water temp"
T_max_heater= 55 [C]
P=100 [kpa]
                    "!==== HDH ====="
MR = m_water/m_air          "mass flow rate of air"
MR = 2.2
```

```
m_water = 0.06
Q_hdh_system=m_water*(ENTHALPY(WATER,T=T_max_heater,x=0)-ENTHALPY(WATER,T=Twater[2],x=0))
eff_Hum = 0.90                                   "effectivness of the humidifier"
eff_Dehum = 0.90                                 "effectivness of the dehumidifier"
eff_H_air = (ha[2] - ha[1])/(ENTHALPY(AIRH2O,T=Twater[3],r=1,P=P)-ha[1])
eff_H_water = (hw[3] - hw[4])/(hw[3] - ENTHALPY(WATER,T=T_wb_hum, P=P))
eff_Hum = MAX(eff_H_air,eff_H_water)
eff_D_air = (ha[2] - ha[3])/(ha[2]-ENTHALPY(AIRH2O,T=Twater[1],r=1,P=P))
eff_D_water = (hw[2] - hw[1])/(ENTHALPY(WATER,T=Tair[2], P=P)-hw[1])
eff_Dehum = MAX(eff_D_air,eff_D_water)

"!==== Properties ====="
"Air"
ha[1]=ENTHALPY(AIRH2O,T=Tair[1],r=RH_hdh[1],P=P)
omega[1]=HUMRAT(AIRH2O,T=Tair[1],r=RH_hdh[1],P=P)
rho_a[1]=DENSITY(AIRH2O,T=Tair[1],r=RH_hdh[1],P=P)
T_wb_hum = WETBULB(AIRH2O,T=Tair[1],r=RH_hdh[1],P=P)
RH_hdh[2] = 0.9
ha[2]=ENTHALPY(AIRH2O,T=Tair[2],r=RH_hdh[2],P=P)
omega[2]=HUMRAT(AIRH2O,T=Tair[2],r=RH_hdh[2],P=P)
rho_a[2] = DENSITY(AIRH2O,T=Tair[2],r=RH_hdh[2],P=P)
RH_hdh[3] = 0.9
ha[3]=ENTHALPY(AIRH2O,T=Tair[3],r=RH_hdh[3],P=P)
omega[3]=HUMRAT(AIRH2O,T=Tair[3],r=RH_hdh[3],P=P)
rho_a[3] = DENSITY(AIRH2O,T=Tair[3],r=RH_hdh[3],P=P)
"water"
Twater[1] = T_min_sea
Twater[3] = T_max_heater
Duplicate i=1,4
hw[i]=ENTHALPY(WATER,T=Twater[i],x=0)
rho_w[i] = DENSITY(WATER,T=Twater[i], P=P)
end
"!==== Energy and mass balances ======="
"Humidifier"
m_water*hw[3]+m_air*ha[1]=m_b*hw[4]+m_air*ha[2]
"Dehumidifier"
m_water*hw[1]+m_air*ha[2]=m_water*hw[2]+m_air*ha[3]+m_air*(omega[2]-omega[3])*((hw[1]+hw[2])/2)
h_fw_hdh=(hw[1]+hw[2])/2
"!==== Performance ======="
hfg = ENTHALPY(WATER,T=Twater[1],x=1) - ENTHALPY(WATER,T=Twater[1],x=0)
m_fw_hdh = m_air*(omega[2]-omega[3])
m_b = m_water - m_fw_hdh
GOR = (m_fw_hdh*hfg)/(Q_hdh_system)
rho_fw=DENSITY(WATER,h=h_fw_hdh,x=0)
LPH = (m_fw_hdh/rho_fw)*CONVERT('m3/s','l/h')
RR=m_fw_hdh/m_water
```