# THERMODYNAMIC MODELING OF HYBRID DESALINATION SYSTEM INTEGRATED WITH HUMIDIFICATION DEHUMIDIFICATION SYSTEM

A PROJECT REPORT

submitted by

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**REG NO: TKM20MEIR14**

to

the APJ Abdul Kalam Technological University
in partial fulfilment of the requirements for the award of the Degree

of

Master of Technology

in

*Industrial Refrigeration and Cryogenic Engineering*

**Department of Mechanical Engineering**

THANGAL KUNJU MUSALIAR COLLEGE OF ENGINEERING

KOLLAM

JULY 2022

## DEPARTMENT OF MECHANICAL ENGINEERING
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## CERTIFICATE

This is to certify that the report entitled '*Thermodynamic Modeling Of Hybrid Desalination System Integrated With Humidification Dehumidification System*' submitted by **ROJINI S R**, **TKM20MEIR14** during **2021-2022** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Industrial Refrigeration and Cryogenic Engineering is a bonafide record of the project work carried out by him under my guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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# DECLARATION

I undersigned hereby declare that the project report "Thermodynamic modeling of hybrid desalination system integrated with humidification dehumidification system", submitted for partial fulfilment of the requirements for the award of degree of Master of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of **Dr. Baiju V.** This submission represents my ideas in my own words and where ideas or words of others have been included, I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

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# ABSTRACT

One of the largest environmental problems facing today is the fresh water scarcity in the world. On earth, 97% of total water is salt water and the remaining 3% is the freshwater. Desalination is the process by which the salt water or the brackish water can be converted into potable water so that the water scarcity can be reduced. Many desalination techniques such as multi-stage flash, multi-effect distillation, and reverse osmosis have been conventionally used but, they have limitations like high energy consumption, low water productivity and cost. The main advantage of this technique is that it can produce cooling along with potable water. The present study focuses on thermodynamic modelling of hybrid solar adsorption desalination and cooling system. Initially, a numerical analysis of the adsorption desalination and the cooling system operating with silicagel-water is carried out to determine its performance. Two modifications are incorporated for the improvement of the system performance. The first method is the use of suitable composite adsorbent made of silicagel as the parent material with combinations of aluminium fumerate and PVC. The second method is the integration of the humidification dehumidification unit to the conventional adsorption desalination system. The system is analysed by varying the operating parameters such as hot water temperature, cooling water temperature, condenser temperature and salinity on the water productivity, coefficient of performance and the energy requirement. The result reveals that the water productivity obtained from adsorption desalination and the cooling system operating with silicagel-water is 1.3kg/cycle, whereas with that of composite adsorbent is 1.54kg/cycle. For the hybrid system integrated with the humidification dehumidification unit the water productivity is found to be 2kg/cycle which is 23%more than the conventional system.

**Keywords**: Desalination; Adsorption; Humidification; Dehumidification; Percentage of yield; Simulink

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# ABBREVIATIONS

| | |
|---|---|
| AD | Adsorption desalination |
| COP | Coefficient of performance |
| DSSS | Double slope solar still |
| HDH | Humidification dehumidification |
| MED | Multi effect distillation |
| MFD | Multi flash distillation |
| MOF | Metal organic framework |
| RO | Reverse osmosis |
| SDWP | Specific daily water production |
| SSSS | Single slope solar still |
| VCD | Vapour compression desalination |
| BET | Brunauer-Emmett-Teller |

# NOTATIONS

| | |
|---|---|
| $C$ | Specific heat capacity (kJ kg$^{-1}$ K$^{-1}$) |
| $E$ | Characteristic energy (kJ mol$^{-1}$) |
| $h$ | Convective heat transfer coefficient (W m$^{-2}$ K$^{-1}$) |
| $\Delta H$ | Isosteric heat of adsorption/desorption (kJ kg$^{-1}$) |
| $K$ | Thermal conductivity (W m$^{-1}$ K$^{-1}$) |
| $m$ | Mass (kg) |
| $P$ | Pressure (kPa) |
| $P_{sor}$ | Sorption Pressure (kPa) |
| $R$ | Gas constant (kJ kg$^{-1}$mol$^{-1}$) |
| $q$ | Concentration ratio (kg kg$^{-1}$) |
| $q_{eq}$ | Maximum concentration ratio (kg kg$^{-1}$) |
| $T$ | Temperature (K) |
| $U$ | Overall heat transfer coefficient (W m$^{-2}$ K$^{-1}$) |

# CHAPTER 1

# INTRODUCTION

Fresh water is one of the fundamental needs for humans and is vital for the economic development of a country. Water scarcity is a very big environmental problem in the world. The total global water reserves are 1.4 billion km$^3$, of which around 97.5% is in the oceans and the remaining 2.5% is fresh water present in the atmosphere, ice-mountains and ground water. Of the total, only 0.014% is directly available for human beings and the other organisms. Many countries have constructed ground reservoirs for storing the rainwater and they are not effective for the countries in the semi-arid and desert region due to lower rainfall. Water shortage is caused mainly due to the rapid increase in the world's population and the economic development which leads to high water consumption of major sectors of industries. So there is a need for finding out a practical solution which is to be eco-friendly and cost-effective. One such solution is the use of desalination technique. It is the process by which fresh water is produced from salt water or brackish water of high dissolved salt.

## 1.1 DESALINTION METHODS

Desalination techniques can be of thermal or non-thermal process. Desalination using thermal process can be broadly classified into direct and indirect methods as shown in Fig.1.1(Chauhan *et.al*, 2020).Thermally driven system uses the thermal energy to split the fresh water by evaporation and condensation whereas non thermal processes use other forms of energy other than thermal energy. Direct method includes solar still, humidification dehumidification and solar chimney. Solar stills can be of active or passive solar desalination. In passive solar desalination system the heat and mass transfer takes place simultaneously. The raw water will be placed in the basin placed below the glass cover of the solar still, where the heat transfer is occurred by convection or radiation heat transfer. The water get evaporated and leaves the brine. Thus the pure water can be produced. Passive solar desalination technique includes single slope solar still (SSSS), double slope solar still (DSSS), wick type solar stills and multi basin solar still. Active solar stills are the solar stills which are integrated with additional accessories like solar flat plate collectors, solar concentrators, reflectors, condensers and mechanical agitators which can provide more surface area for the heat transfer so as to increase the water productivity. Solar chimneys are fabricated to convert solar irradiation to electric power. Solar chimney integrated with solar desalination system is a very effective way to utilize maximum amount of thermal energy to produce fresh water.

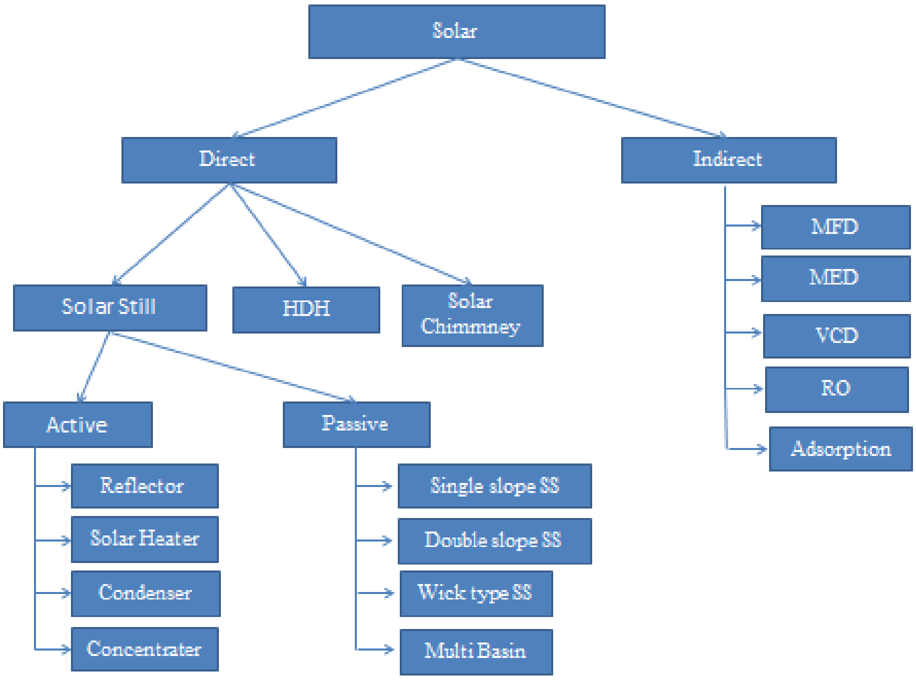

Fig. 1.1. Classification of different techniques of desalination (Chauhan *et.al*, 2020)

The indirect thermal desalination techniques include the multi-effect distillation (MED), multi flash distillation (MFD), vapour compression desalination (VCD), reverse osmosis (RO) and adsorption desalination (AD). MED and MEF can produce high quality distillate but have higher energy consumption and higher cost. VCDs are used in low capacity applications and can produce high quality water but it may corrode the compressor and also costs high. RO process is an energy efficient process which uses membrane technology and the limitation is the use of membrane which gets scaled and fouled making them ineffective to use. Among all of the above desalination processes, MSF, MED and RO accounts for about 95% of global desalination capacity.

## 1.2 ADSORPTION DESALINATION SYSTEM

Many desalination systems have been introduced for the effective fresh water production. But the main limitations of these systems are energy intensiveness and high maintenance cost of membrane replacement and corrosion. So there is a need for other techniques in desalination process with low energy consumption and low running cost. Adsorption desalination is one of the emerging techniques which is energy efficient and environmental friendly. Unlike the other techniques, in the desalination system water and cooling effect can be produced. Adsorption is the process in which the water vapour on the surface of the adsorbent is taken by van der Waal's or polar bonding forces.

## 1.3. PROBLEM FORMULATION

Adsorption desalination is one of the desalination systems which have lower energy consumption when compared with other conventional systems. Many hybrid systems are introduced which combines various types of desalination systems. But only little attention is made in the field of combining other systems with the adsorption system. The researches were focused mainly on the solar powered adsorption systems experimentally and numerically. No researches were concentrated on the analysis of the hybrid system which combines the adsorption system and the humidification system. There are not any published experimental and numerical studies dealing with the adsorption system combined with the humidification dehumidification system. From this motivation, this work is devoted to investigate theoretically and experimentally the operation and performance of an adsorption desalination system coupled with humidification dehumidification system.

## 1.4 THESIS OUTLINE

This thesis consists of six chapters. The first chapter introduces the project topic and its background. The second chapter discusses the various desalination systems which uses the adsorption techniques and infers the performances of the each system. It also includes the objective and the methodology of the work. The third chapter shows the description, working and the results obtained from the numerical simulation. The fourth chapter presents the study on the composite adsorption which includes the preparation, physical property analysis and the selection of the suitable composite. It also includes the performance of the system which uses the selected composite adsorbent and is compared with the existing system. The fifth chapter introduces a new hybrid system, its working and the simulation. The performance of the new system is numerically analysed and is compared with the existing system and the system with the composite adsorbent. Chapter six gives the conclusion of this study and the scope for future work.

# CHAPTER 2

# LITERATURE REVIEW

This chapter presents the literature review on adsorption desalination and the various developments in the field of desalination. The very basic need for all living creatures in the earth is water and the lack causes an obstruction of economic development of an economy. Water is adequate for agriculture, industry, recreation and human consumption. On the earth, three-quarters is covered by water. However, all water is not suitable for human consumption due to salinity. 97.5% of the earth's water includes the oceans or sea and only the remaining 2.5% is the fresh water, and of which 80% of this includes the frozen in the icecaps or which are combined as soil moisture. The best solution for the global water scarcity is the conversion of the saline water into potable water with minimum cost of production. One of the most energy efficient methods for the production of potable water in the desalination technology is the adsorption desalination. The adsorption desalination process diminishes the limitations such as high energy consumption, high maintenance cost etc, of the current desalination technologies are facing. The following section discusses about the developments in the field of desalination technologies.

## 2.1 DESALINATION PROCESSES

From the year 1800, the desalination was practised on ships using single stage stills. Their operation was in batch mode and the energy wasn't recovered from the heat of condensation but supplied from stoves or furnaces (El-Dessouky *et al.*, 2002). Desalination techniques have been developed technically and economically since then. The amount of saline water needed for the production of fresh water increases each year due to the increase in the scarcity of water.

Aly *et al*. (2003) conducted thermal performance analysis of various seawater desalination systems. For the analysis of multi-stage and multi-effect desalination systems, a steady-state mathematical model was developed. The model includes the geometry of the stages, the heat transfer mechanism, variations of the different properties of saline water with salinity and temperature and the fouling and its effect on the plant performance. From this study it is inferred that the performance ratio depends completely on the number of effects and slight dependency on the top brine temperature.

Thermal analysis of vapour compression was conducted by Darwish (1988). The effects of the operating parameters like evaporator temperature, pressure drop across the evaporator, feed temperature to the evaporator etc.

Veza *et al.* (2004) set up an electro dialysis desalination plant and the water flow rate was found to be between 3 and 8.5 $m^3$/hr and the power requirement between 4 and 19kW. The tests were carried out in the frame work at Gran Canaria Island, Spain.

## 2.2. ADSORPTION DESALINATION

Broughton introduced developments in the field of adsorption desalination in the year 1984. In his study, he used thermally driven two bed system and anion retarded resin was used for the uptake of water.

Zejli *et al.* (2004) studied an adsorption system in which the adsorption desalination system and the multi effect distillation were combined. He proposed a heat recovery process which was based on the thermal wave concept.

Wang *et.al* (2005) introduced a four-bed AD system. Specific daily water production (SDWP) was measured by varying different operating parameters. The adsorbent used were silica gel. The maximum SDWP obtained was 4.7 kg per kilogram of silica gel when operating at a cycle time of 180s. It is observed that SDWP could be increased by 10% when the cooling water temperature is dropped by $1.6^0$C or raising the chilled water temperature by $1.8^0$C. As the source temperature increases, the COP and SDWP also get increased.

Thu *et al.* (2009) presented the performance of an AD system with two beds and four beds which uses silica gel as the adsorbent. SWDP, performance ratio was found for various heat sources. From the experiment the result obtained as the maximum potable water production per tonne of adsorbent per day is about $10m^3$ and the performance ratio is 0.61. Longer cycle time is needed for the production of maximum water at lower source temperature.

Thu *et al*. (2010) investigated the efficiency of silica gel-water based advanced AD system. This system produced SDWP of 9.24 $m^3$/tonne of silica gel per day at hot water temperature of $70^0$C and the performance ratio of 0.77. While comparing the conventional and advanced AD systems, the SWDP of advanced AD system is twice that of the conventional AD system.

Wu *et al.* (2010) introduced a thermodynamic model of water adsorption system which uses silica gel as the adsorbent using Langmuir isotherm. From this he inferred that there is an optimum temperature at which the fresh water is produced at minimum energy consumption and it depends on various operating parameters of the system and the cooling water temperature. Water productivity and the energy consumption are mainly affected by the temperature of cooling water entering the bed. Thus the system performance and the cost required mainly depend on the cooling water temperature. From this, it can be inferred that an air cooled condenser may be suitable for the cooling water that enters the condenser.

Thu *et al*. (2011) investigated the performance of an adsorption desalination system which has internal heat recovery between the condenser and the evaporator. For the evaporation of the saline water, the energy which is rejected from the condenser is recovered in the evaporator. This advanced system produced SDWP of 9.24 $m^3$/tonne of silica gel per day at hot inlet temperature of $70^0$C and the performance ratio was 0.77 which was comparatively higher.

Ng *et al.* (2012) studied the performance of a 4-bed adsorption system driven by waste heat which can produce both potable water and cooling. The system produced SDWP of 8 $m^3$ per kilogram of silica gel per day and the cooling power of 51.6 TR per ton of silica gel per day.

Thu *et al.* (2012) presented the development of an adsorption system having internal heat recovery between the condenser and the evaporator which uses an encapsulated evaporator-condenser unit for effective heat transfer. The temperature in the evaporator and the vapour pressurization of the adsorber are raised due to the direct heat recovery from the condenser, resulting in the higher water production rates, typically improved by as much as three folds of the conventional AD cycle in the integrated system. Corresponding to the heat source temperature of $50^0$C TO $85^0$C, the SDWP was improved from $8.1m^3$ to 26 $m^3$ respectively.

Thu *et al.* (2013) investigated the improvement in the adsorption desalination system having internal heat recovery between the condenser and the evaporator. In the advanced system, the heat was recovered either by using an integrate evaporator-condenser unit or providing a water circulating loop between them. The SDWP was increased to 15 m$^3$ per ton of silica gel. For the source temperature of 50$^0$C, the water productivity was found to be 4.3 m$^3$ per ton of silica gel.

Hamed *et al.*(2014) proposed a desalination system based on air humidification-dehumidification (HDH) unit to evaluate the performance and productivity by developing a theoretical model by considering the energy equations of the each component. The result shows that that when the system is operated 4 hours, the water productivity was found to be 22 L/day.

Kim *et al.* (2014) investigated the possibility of using adsorption characteristics of microporous ferroaluminophosphate adsorbent in the adsorption desalination and cooling cycles. The surface characteristics of the adsorbent was find out using the $N_2$ gas followed with water vapour uptake for the temperature ranging 20$^0$C to 80$^0$C. The equilibrium adsorption capacity of the ferroaluminophosphate is five times that of the silica gel.

Mitra *et al.*(2014) made a simulation study in a single-stage AD system and evaluated the performance for various cycle time and condenser temperature. The simulation shows that for maximum desalination the optimum cycle time ranges from 600-900s and the COP increase with the cycle time. The performance of the system decreases as the condenser temperature increases due to the increased operating pressure.

Youssef *et al.* (2015) conducted mathematical investigation on the effect of evaporator and condenser temperature on the performance of the system, the potable water productivity and the cooling effect when using the silica gel as the adsorbent. When the condenser temperature and the evaporator temperature is increased, more will be the water produced and the cooling rate achieved. For condenser water temperature of 10$^0$C and evaporator inlet water temperature of 30$^0$C, the potable water production of 10m$^3$/tonne of silica gel per day and the specific cooling capacity of 77 ton/tonnes of silica gel were obtained.

Youssef *et al.* (2015) investigated the performance of a four bed adsorption desalination system using two different adsorbents (silica gel and advanced zeolite material AQSOA-Z02). The investigation showed that AQSOA-Z02 gave 6.2 m$^3$ SDWP and 53.7 TR per ton of AQSOA-Z02 compared with silica gel which gave 3.5 m$^3$ SDWP and 15TR per ton of silica gel at low chilled water temperature below 20$^0$C. For the chilled water temperature above $20^0$C AQSOA-Z02 and silica gel gave comparable SDWP about 7 $m^3$ and specific cooling rate about 60 TR.

Ali *et al*. (2016) modelled a double stage cooling cum desalination system in which the first stage is the adsorption cooling system and the second stage is the adsorption desalination system. Due to the heat recovery between the condenser and the evaporator, the performance of the system was increased. The system produced 26% more water and 45% more cooling capacity when comparing with the conventional adsorption desalination and cooling systems.

Thu *et al*. (2016) introduced an advanced adsorption desalination cum cooling system consist of 3 beds and 2 evaporators. Different levels of chilled water temperatures were produced. One evaporator is at $7\text{-}9^0$C and the other at $18\text{-}20^0$C, that are suitable for latent and sensible cooling. The water production was 6.5 $m^3$ per ton of silica gel per day and the COP was found to be 0.84. The performance of the low pressure evaporator in terms of COP is sensitive to the operating conditions such as heat source temperature and the cycle times but the high-pressure evaporator performs steady.

Askalany *et al*. (2016) proposed a desalination system combining mechanical vapour compression and adsorption desalination systems. The system was simulated in different operating conditions. It was observed that the daily water production was increased in a range of 10-45% according to the source temperature.

Youssef *et al*. (2016) introduced a multi-cycle adsorption desalination and cooling system which uses AQSOA-Z02 for higher water production and cooling rates using renewable and waste water source. There are two 2-adsorber bed cycles linked with the integrated evaporator/condenser, in which one cycle uses the integrated evaporator/condenser as the evaporator (upper) and the other uses it as a condenser (lower). The low condensing temperatures are achieved by using the cooling effect from the evaporator of the lower cycle and the integrated evaporator/condenser so that increasing the system performance. The adsorber beds of the upper and the lower cycles are heated using the same heat source during the desorption process. The result showed that the specific water production of the system was 6.64 to 15.4$m^3$/tonne of adsorbent/day and the cooling capacity reached up to 46.6 ton/tonne adsorbent at the evaporator temperature of $10^0$C. The new cycle have the potential to produce large amount of desalinated water and cooling capacity (at $10^0$C) compared with other cycles.

Thu *et al.* (2017) modelled and simulated adsorption desalination system having mass recovery which is achieved by pressure equalization. It is found that for optimum mass recovery, there is a specific equalization time or otherwise the reverse phenomena occur. The results showed that the optimum mass recovery time is about 15 to 20s which depend on the temperature sources. The SDWP was increased by 5% by the mass recovery scheme rather than using any additional hardware and heat source.

Qu *et.al* (2018) proposed a hybrid reverse osmosis and humidification dehumidification system which is analysed for the use with a concentrating photovoltaic/thermal solar collector that produces both thermal and electrical energy. This system utilizes both thermal and electrical energy and can produce 38% more fresh water at steady state conditions than reverse osmosis system alone.

Deng *et al.* (2018) explains the use of metal organic frameworks (MOFs) in the membrane desalination and in the water treatment. Several methods are introduced for the preparation of the MOFs which contributes to the water filtration applications such as desalination, nanofiltration, microfiltration and ultrafiltration. MOFs enhance the performance of the membrane performance due to their structure and properties.

Chan *et al.* (2018) introduced new composite adsorbent MWCNT (multi-wall carbon nano tube) embedded zeolite 13X/$CaCl_2$ in the adsorbent bed of the desalination system. The results show that the desalination system using this composite adsorbent gives higher SDWP than the other conventional adsorbents and the enhancement by 40%.

Naef *et al.* (2019) modelled a novel hybrid desalination system comprising HDH and AD in two distinct schemes. Scheme 1 is used only for the desalination of seawater which is precooled by AD evaporator and the scheme 2 is used for both desalination and for producing cooling effect. For the hybrid HDH-AD system, the HDH unit contributes more in the water productivity and the performance than the AD system.

Ali *et al.* (2020) introduced as novel hybrid system which combines the adsorption system with two ejectors and used silica gel as the adsorbent. The numerical results showed that the optimal half cycle time is 400s and the SDWP IS 23.0$m^3$ per ton of silica gel at a COP of 1.64 at a regeneration temperature of $85^0$C.

Naeimi *et al.* (2020) modelled an adsorption desalination system with double-cycle multi-bed dual-evaporator with internal heat recovery. It is observed that this proposed system has 20% more SDWP when comparing with a single-cycle multi-bed dual evaporator system. The system produced 9.6$m^3$ SDWP and is suitable to be replaced with the conventional desalination system.

Yassin *et al.*(2021) proposed a hybrid multi-effect distillation adsorption desalination system powered with solar thermal energy. It is observed that the fresh water production rate was increased by the 2.68 times and achieved 57.78% lower specific energy consumption by adding the adsorption desalinations stage.

Albaik *et al.* (2021) introduced a scaled-up adsorption system using multiple heat exchanger modules packed with commercially available metal-organic framework material which operates at low desorption temperature. The MOF used was aluminium fumarate which as pocked in 16 modules. The results show that the water productivity is 201L/day and the cooling capacity of 5.25kW.

## 2.3. OBJECTIVES

The main aim of this project is to carry out the theoretical studies on the hybrid adsorption desalination system with humidification dehumidification unit. This includes the thermodynamic modelling of the hybrid desalination system. This thesis also includes the numerical analysis of an existing desalination system and the selection of composite adsorption. Theoretical analysis of the adsorption system using new composite adsorbents is also done. The objective of this research is as follows:

1. To conduct numerical study on the existing adsorption desalination system.
2. Selection and characterisation of composite adsorbent
3. Simulink modeling of the adsorption system with composite adsorbent
4. Analysis of system incorporating humidification dehumidification unit

## 2.4. METHODOLOGY

The detailed methodology of the above work is described:

1. **Numerical study on the existing adsorption desalination system**

    - Study on the adsorption desalination system
    - Analyze the numerical output
    - Analyze the performance and yield of the system under various conditions

2. **Selection and characterisation of composite adsorbent**
    - Preparation of composite adsorbents
    - Characterisation of the composite adsorbents
    - Selection of the composite adsorbent
3. **Simulink modeling of the new adsorbent system**
    - Selection of composite adsorbent
    - Numerical simulation of the system with the selected composite adsorbent using SIMULINK.
    - Performance of the adsorption system in terms of percentage of yield and water productivity.
4. **Analysis of system incorporating HDH unit**
    - Thermodynamic modeling of the system by introducing governing equations on each component.
    - Numerical simulation of the hybrid system operating with silica gel adsorbent.
    - Performance evaluation of the system based on varying water temperature, cycle time etc.

## 2.5 CONCEPTUAL FRAMEWORK

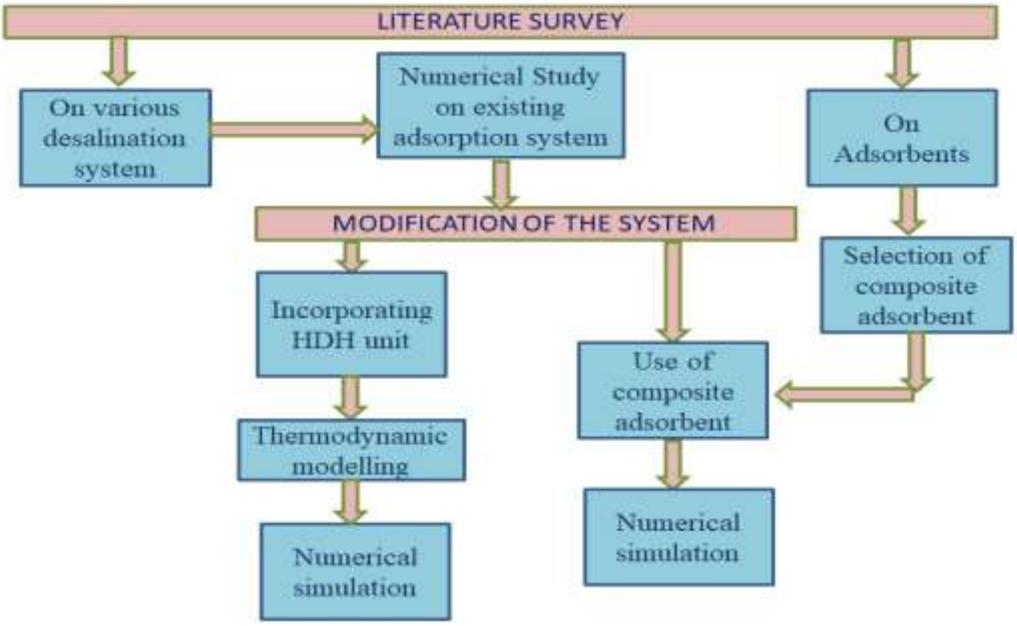

Fig.2. Methodology of work

# CHAPTER 3

# NUMERICAL MODELING OF ADSORPTION DESALINATION AND COOLING SYSTEM

Adsorption desalination cycle is a desalination system method by which produces potable water from the sea or the brackish water. It uses hot water from the renewable energy such as process exhaust and solar energy. A typical adsorption desalination plant consist of the components namely (1) the evaporator, (2) single or multi adsorbent bed and (3) the condenser. The working principle, various components, the thermodynamic cycle and the numerical simulation of the adsorption desalination system are discussed in this chapter.

## 3.1 WORKING PRINCIPLE OF ADSORPTION DESALINATION AND COOLING SYSTEM

The major components of the adsorption desalination and cooling system are the evaporator, adsorbent bed and the condenser. The schematic diagram of the system is shown in the Fig.3.1.

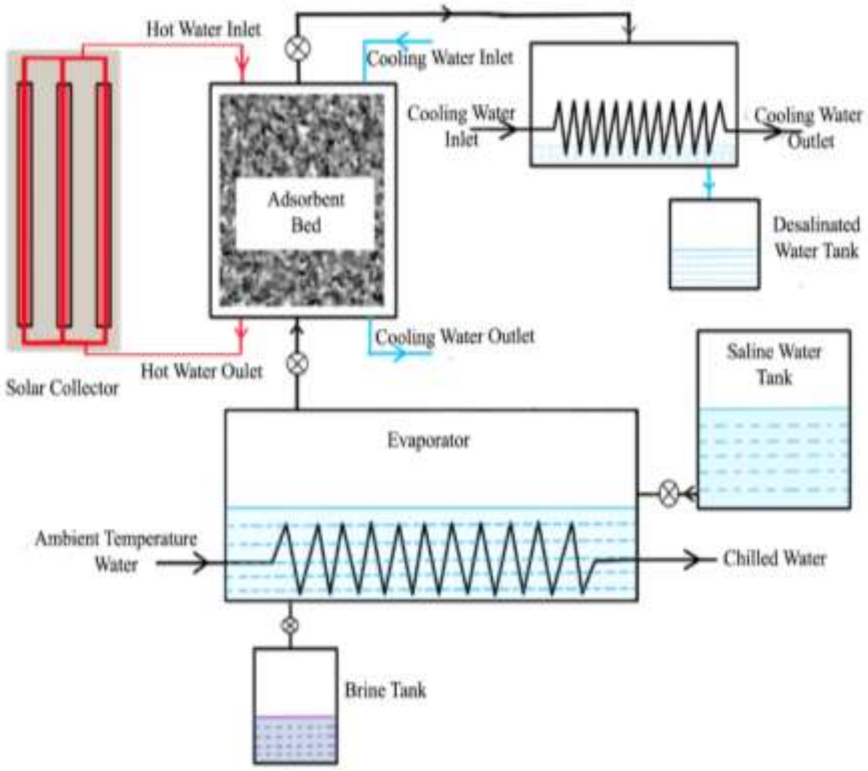

Fig.3.1 Schematic diagram of an adsorption desalination and cooling system

Initially in the evaporator, the saline or the brackish water is charged. The water is flash evaporated at lower pressure in the evaporator. In order to maintain the evaporation process, the chilled water is circulated which can be used for the cooling purposes. The brine solution in the evaporator is discharged periodically for regulating the sea water level and the salt concentration. Water evaporates and travels from the evaporator into the adsorbent bed where it is adsorbed by the silica gel when the valve between the evaporator and the adsorption bed is opened. The cooling water is circulating in the adsorption bed which removes the heat of adsorption during the adsorption process. The adsorption process continues till the silica gel gets saturated with water and then the valve between the evaporator and the adsorption bed get opened. The regeneration of the silica gel done using the hot water circulating through the bed and this process is known as the desorption process. Now the valve between the adsorbent bed and the condenser is opened, the hot water which flows through the adsorption bed drives off the regenerated water into the condenser. The heat of condensation is rejected to the cooling water circulating through the condenser and the condensate can be collected as the pure water in the condenser. Now the desalinated water can be collected. The details about the components are discussed in the following sections.

### 3.1.1 Evaporator

Evaporator is the component in which the evaporation of the water vapour and the cooling taking place. Through the sea water inlet valve, the saline water is charged into the evaporator. Inside the evaporator, the sea water is vaporized. The evaporation should take place at lower temperature so that low pressure is needed for the evaporator. In the evaporator, the heat is observed from cooling space while the phase change of water takes place from liquid to vapour. Chilled water can also be circulated in the evaporator for the evaporation process and for the cooling purposes. Due to the evaporation of water, high concentration of salt will be left in the evaporator. This concentrated salt solution or the brine has to be removed periodically.

### 3.1.2 Adsorbent Bed

The main component in as adsorption desalination and cooling system is the adsorbent bed which has influences the performance of the system. It is similar to the compressor in a conventional vapour compression system, but here it is driven by the thermal energy.

The adsorbent material used must be a hydrophilic porous material with higher surface area which has transient bonding to water molecules via hydrogen bonds. The most popular adsorbent is the silica gel as it is able to take-up significant level of water (up to 40% by mass) without any change in its structure and volume and can release in mild heating. Regeneration at lower temperature is possible for the silica gel so it is the best adsorbent that can be used.

Adsorbent bed adsorbs a low temperature and low pressure water vapour from the evaporator during the adsorption phase. The water will get vaporized as it produces the refrigerating effect. Since the adsorption process is exothermic process, the heat of adsorption will be removed by circulating the cooling water through the adsorption bed. During the desorption process, hot water is circulated through the bed so as to increase the temperature and the pressure. Desorption start when the regeneration temperature is reached. In the desorption process, the bed will desorb the high temperature and high pressure vapour to the condenser. The adsorption also contains the flow control valves at the evaporator and condenser side.

### 3.1.3 Condenser

Condensers used in the adsorption refrigeration system are of primarily two types: air-cooling and water-cooling. The vapour at higher temperature and pressure after desorption, reaches the condenser from the adsorbent bed. Cooling water is circulated through the condenser which absorbs the latent heat from the vapour and thus it gets condensed. The condenser temperature is a main parameter which affects the water productivity rate and the COP of the system. The potable water produced is collected in the condenser.

## 3.2 THERMODYNAMIC CYCLE OF ADSORPTION DESALINATION AND COOLING SYSTEM

The thermodynamic cycle of an adsorption desalination system consists of two isosters and two isobars as shown in Fig. 3.2. For the convenient way to describe the thermodynamic cycle of the adsorption desalination system, the P-T-X diagram on lnP vs -1/T coordinates (Where X is the amount of adsorbate adsorbed by the adsorbent at equilibrium conditions, kg of adsorbate/kg of adsorbent).

Process 1-2

The process starts at point 1, where the silica gel gets saturated with water (i.e, the concentration of water in silica gel reaches maximum), the valve between the adsorption bed and the evaporator is closed and the cooling water which is circulating through the adsorption bed is stopped. To increase its temperature and pressure along the constant concentration line, hot water is circulated through bed. This process continues until it reaches the point 2. The pressure is determined by the saturation pressure of water at the condenser temperature (slightly greater than the cooling water temperature).

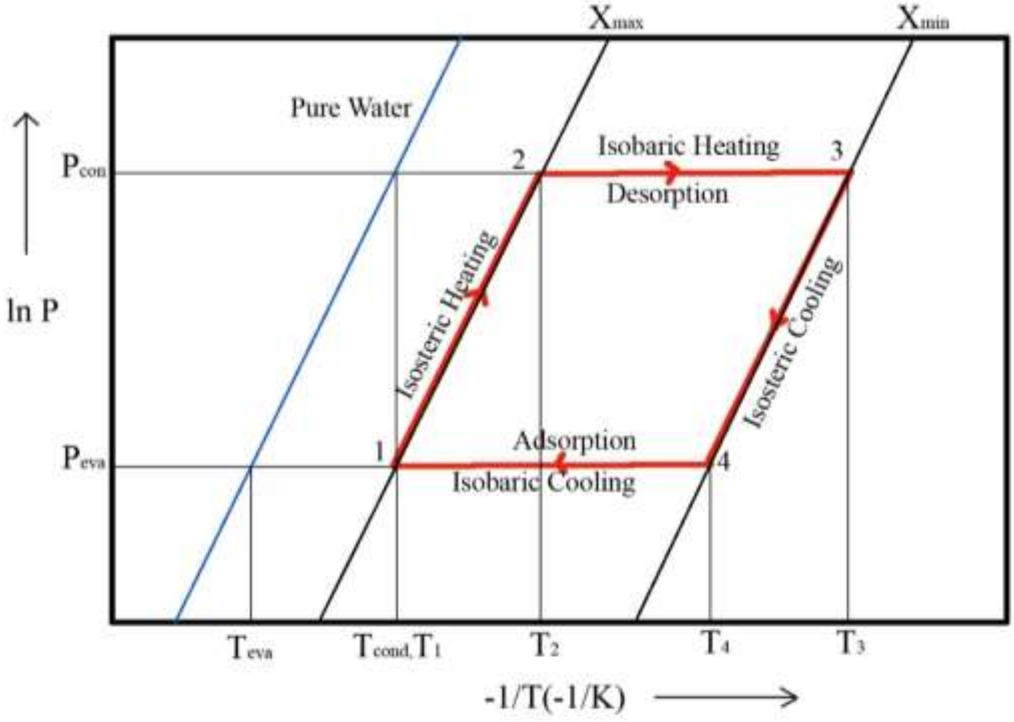

Fig.3.2 Adsorption desalination cycle

Process 2-3

At point 2, the water vapour starts to desorb from the silica gel when the valve between the adsorbent bed and the condenser is opened. The desorption takes place due to the hot water circulating through the adsorbent bed. The vapour condenses in the condenser as the cooling water is circulated through the condenser. The condenser is fixed until the bed reaches its maximum temperature and the adsorbed water a minimum. This process can be called as the silica gel regeneration or condensing process and also as the fresh water production process.

Process 3-4

At point 3, the adsorbent silica gel is at the maximum temperature of $90^0$C and the water adsorbed water is at a minimum. When cold water is circulated through the bed, silica gel temperature decreases at fixed concentration until point 4 where the bed pressure is the saturated pressure of the pure water at the evaporated temperature. At this point, the bed temperature will be 60-$70^0$C.

Process 4-1

At the point 4, the valve between the bed and the evaporator is opened. The cooling water continues to circulate through the adsorbent bed. The water in the evaporator starts vaporizing and moves to the adsorbent bed where it gets adsorbed by the silica gel. The pressure in the bed and the evaporator remains constant but the temperature will be decreasing and it is determined by the cooling water supply temperature. At the initial point, the concentration of silica gel will reach the maximum.

## 3.3 ADSORPTION EQUILIBRIUM MODEL

The modelling is done based on the following assumptions:

1. The temperature across the silica gel is uniform
2. The adsorption rate of water in the silica gel inside the adsorbent bed is uniform
3. The adsorbent (silica gel) and the adsorbate gas phase are in equilibrium condition
4. Heat losses from evaporator, condenser and adsorbent bed are neglected
5. The specific heat capacities of water, adsorbent, metallic wall are constant

The uptake of water vapour by the silica gel at temperature (T) and pressure (P) can be obtained from the Dubinin-Astakov (D-A) equation as (Ng et.al, 2012).

$$q_{eq} = q_{max} \exp[-[\frac{RT}{E} \ln(\frac{P}{Psor})]^n] \qquad (3.1)$$

The adsorption is an exothermic process where the heat is rejected whereas the desorption process is an endothermic process where the heat is absorbed. The amount of heat needed to adsorb or desorb a unit mass of adsorbate is known as the latent heat, or isosteric heat, of adsorption or desorption.

## 3.4 THERMODYNAMIC MODELLING OF THE SYSTEM

Mass balance and energy balance are applied to the each component of the adsorption desalination and cooling system.

(a) Evaporator

The evaporator is a vital component in an adsorption desalination system due to its participation in the desalination mechanism and in the production of cooling effect. Thus, the mass balance and the energy balance equations are important. The equations are:

$$m_{sw} = m_{pw} + m_b \tag{3.2}$$

$$((mc_p)_{tube}+(mc_p)_{fin}+(mc_p)_{sw})\,\frac{dTevp}{dt} = m_{sw}h_fT_{evp} - m_bh_fT_{evp} + (mc_p)_{ch}(T_{in} - T_{out}) - m_{sw}h_{fg}T_{evp}\left(\frac{dq}{dt}\right) \tag{3.3}$$

(b) Condenser

The condenser is used to condense the desorbed water vapour from the adsorption bed. The mass and energy balance of the condenser input and output is given as:

$$\left(\frac{dm}{dt}\right)_{cond} = m_s\left(\frac{dq}{dt}\right)_{des} \tag{3.4}$$

$$m_{pw} = \left(\frac{dm}{dt}\right)_{cond} \tag{3.5}$$

$$((mc_p)_{tube} + (mc_p)_{fin} + (mc_p)_w)\,\frac{dTcond}{dt} = m_sc_{pwv}(T_{des} - T_{cond})\left(\frac{dq}{dt}\right)_{des} + m_sh_{fg}T_{cond}\left(\frac{dq}{dt}\right)_{des} + m_a(h_{out} - h_{in}) \tag{3.6}$$

(c) Sorption Bed

The energy conservation of sorption (adsorption and desorption) involves the heat stored into the bed, heat transfer between the bed and the heating or cooling water, and adsorption or desorption heat. The mass and energy balance equations are:

$$((mc_p)_{tube} + (mc_p)_{fin} + (mc_p)_s + m_sc_vq)_{bed}\,\frac{dTbed}{dt} = m_s\Delta H\frac{dq}{dt} + (mc_p)_w(T_{wi} - T_{wo}) \tag{3.7}$$

$$\Delta H = h_{fg} + E\ln\left(\frac{qmax}{qeq}\right)\frac{1}{n} + E\,T_\alpha\ln\left(\frac{qmax}{qeq}\right)\frac{1-n}{n} \tag{3.8}$$

Dubnin-Ashtackov (D-A) model for water vapor sorption

$$q_{eq} = q_{max} \exp[-[\frac{RT}{E} \ln(\frac{Pbed\,sat}{Psor})]^n] \quad (3.9)$$

$$(\frac{dq}{dt}) = K_L(q_{eq} - q) \quad (3.10)$$

$$K_L = \frac{Ao\,Dc}{(rp)2} \exp[\frac{-Ea}{RT}] \quad (3.11)$$

In the adsorption bed most commonly used adsorbent is the silica gel and the regular density type silica gel is used. The unknown values in the Dubinin-Astakhov equation for the regular density type silica gel are taken from the literature (Ali et al., 2016) is shown in the table 3.1. The mathematical modeling equations of the adsorption desalination system are solved using MATLAB 2019.

Table 3.1 Values of the parameters used in simulation

| **Parameter** | **Numerical Value** | **Unit** |
|---|---|---|
| $q_{eq}$ | 0.592 | kg/kg of silica gel |
| E | 3.105 | kJ/mole |
| n | 1.1 | - |
| R | 8.314 | J/mole. K |
| $m_{bed}$ | 10 | kg |
| $m_{wall}$ | 12 | kg |
| ΔH | 2800 | kJ/kg |
| $C_{wall}$ | 0.510 | kJ/kg |
| $C_{bed}$ | 0.92 | kJ/kg |
| $C_{water}$ | 4.18 | kJ/kg |

## 3.5 RESULT AND DISCUSSIONS

The simulation of the adsorption desalination system and the hybrid system was done using MATLAB 2019. The parametric analysis has been done to see the effect of different parameters on the performance of the system. The parameters used to simulate the system performance are water produced per cycle, energy required per cycle and the coefficient of performance.

The variation of the water productivity with various operating parameters is discussed below:

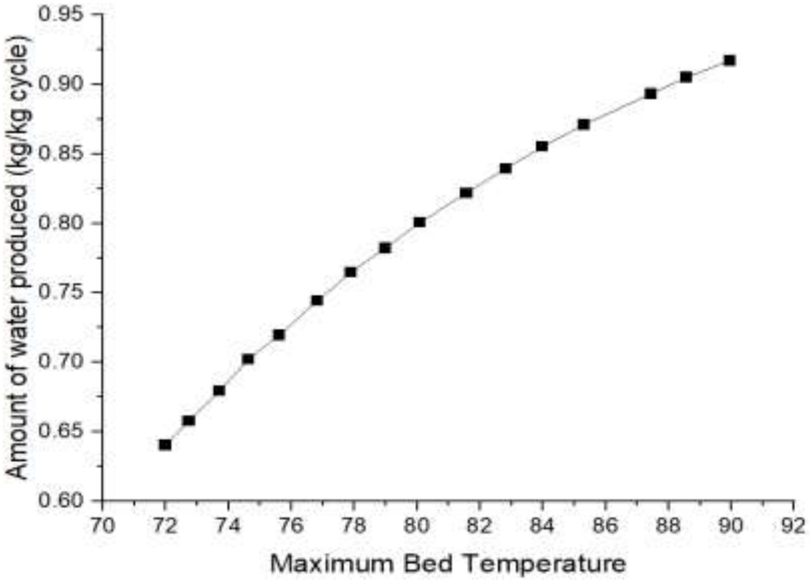

Fig.3.3 Effect of varying bed temperature on the water production

In the Fig.3.3, the bed temperature is varied between the range of 72ºC to 92ºC. The water production rate increases with increase in bed temperature and gradually flat out at the higher temperatures. This increasing tendency of water production with temperature is because of the increase in desorbed amount of water from the adsorbent with the increase in adsorbent bed temperature. The water production reaches maximum when adsorbed water completely removed from the adsorbent. At this stage the adsorbate concentration is minimum in adsorbent. It can be observed that desorption takes place at lower temperature of about $72^0$C itself.

Fig.3.4 shows the variation of amount of water produced with the cooling water temperature for the different bed temperatures. For the lower cooling water temperature, the water productivity is higher since the more heat of adsorption is removed so that the adsorption rate can be increased. The water productivity will be more for the higher bed temperature. It is shown for the bed temperatures $80^0$C and $90^0$C. Desorption will be more for the higher bed temperature and thereby increasing the water productivity rate.

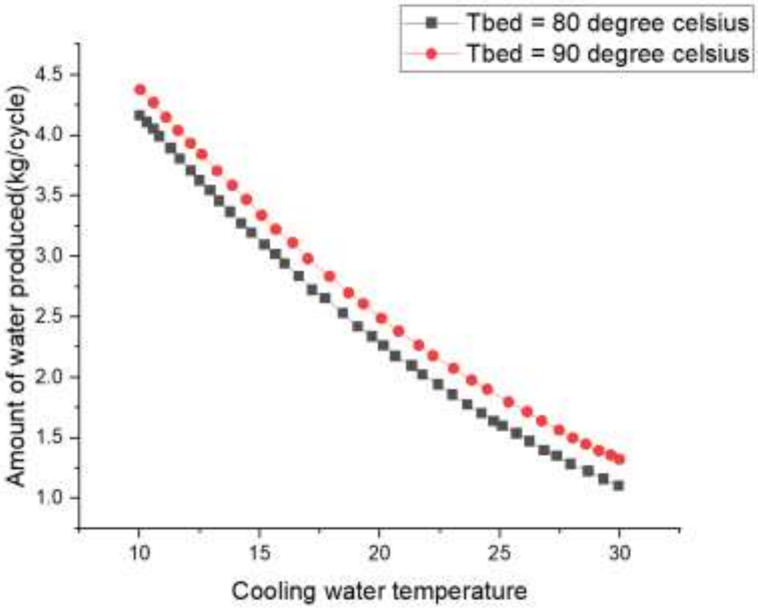

Fig.3.4 Effect of water productivity on cooling water temperature for different bed temperatures

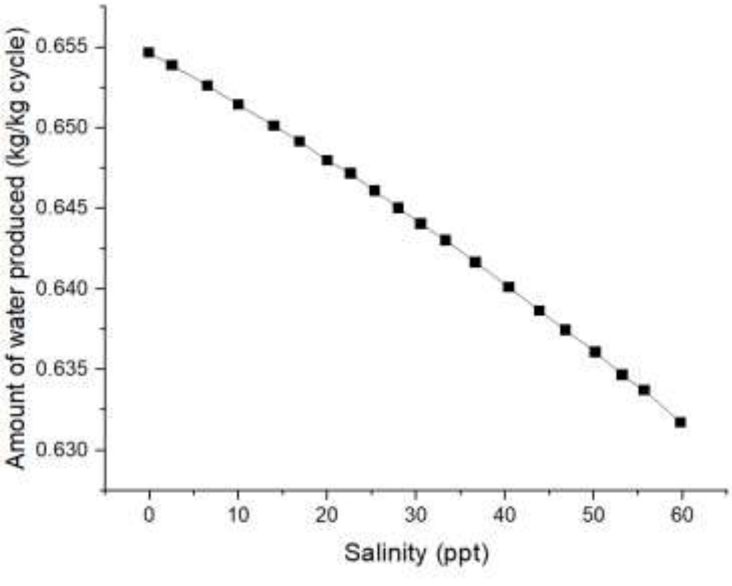

Fig.3.5 Variation of water productivity with salinity

Fig. 3.5 shows the variation of water production with salinity. Water production decreases with increase in salinity of seawater. This is because of the decrease in vapour pressure of the saline water at the evaporator with the increase in salinity. When the vapour pressure is decreased, the adsorbed amount of water vapour decreases and thus results in reduced water production.

The coefficient of performance depends on the operating parameters such as hot water temperature, cooling water temperature and the condenser temperature. The effects in COP are discussed below:

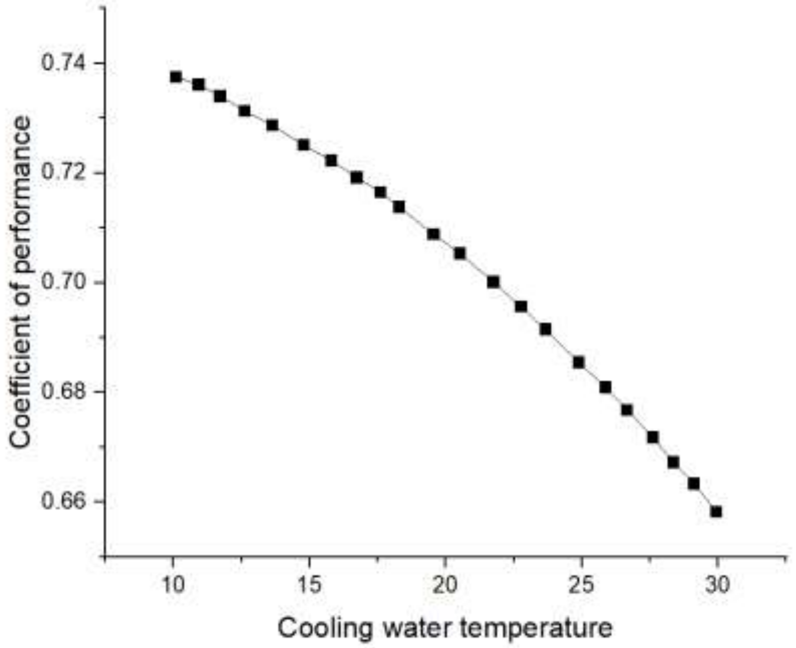

Fig.3.6 Effect of COP on cooling water temperature

The COP of the system increases with decreasing cooling water temperature (in Fig. 3.6). It is because of the increased adsorbed amount of water vapour at low adsorbent temperature increases the refrigeration effect. The dependence of the COP of the system on hot water temperature plotted in Fig.3.7. There is a certain temperature at which there exists a maximum COP for a fixed cooling water and condenser temperatures. COP is increasing rapidly with the bed temperature and attains a maximum value at 85˚C then decreasing slowly. It is because initially, the increase of refrigeration effect is more than the increase of heat input. After 85˚C the heat input required is very high.

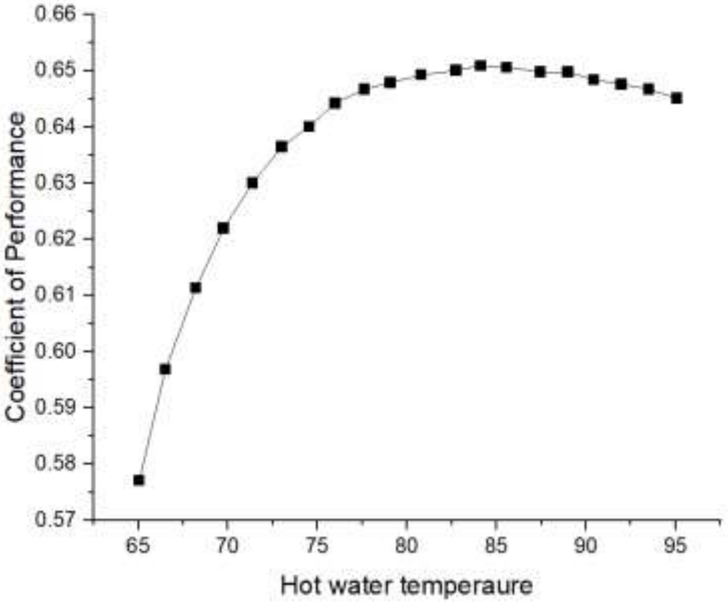

Fig.3.7 Effect of COP with the hot water temperature

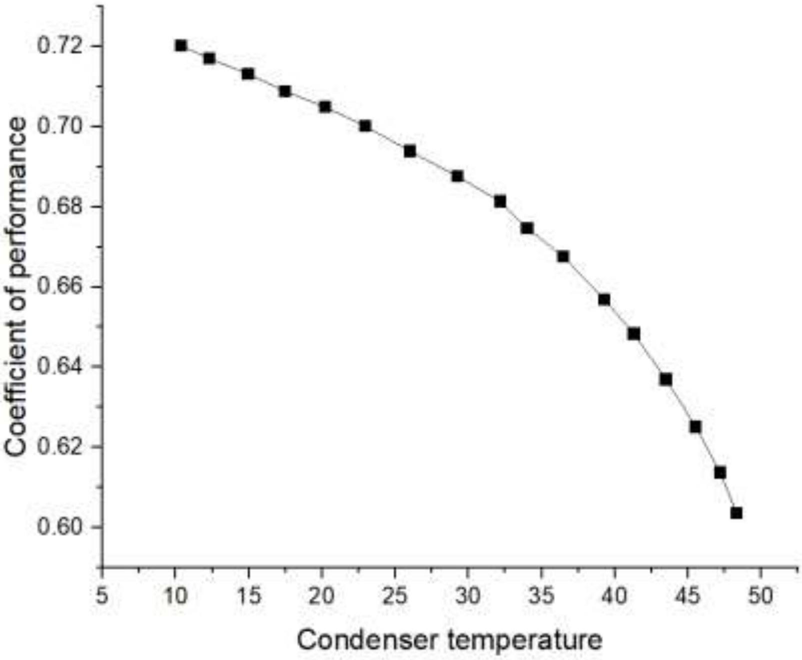

Fig.3.8 Effect of COP with the condenser temperature

The COP of the system decreases with increasing condenser temperature as shown in Fig. 3.8. It is due to the reduced desorbed amount and high heat input at higher condenser pressures that reduces the refrigeration effect and the heat input is high.

The energy required for the water production also varies according to the various operating parameters and they are discussed below:

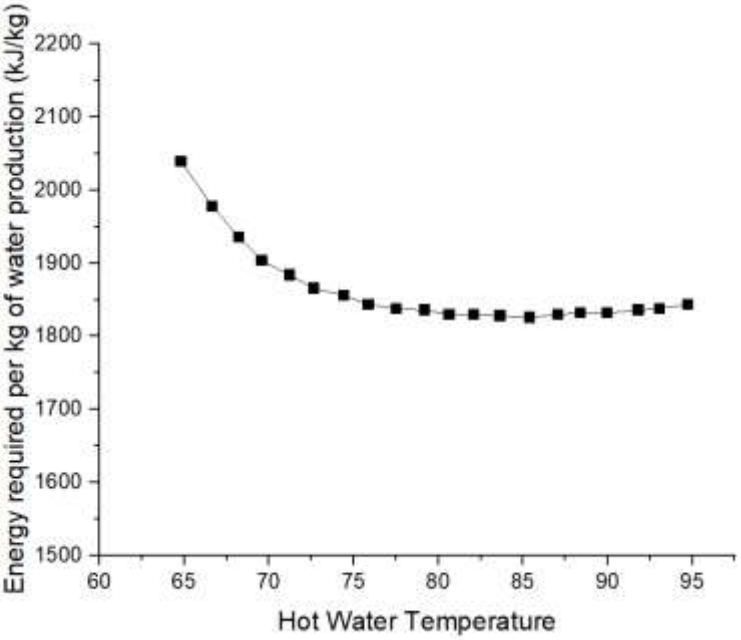

Fig.3.9 Effect of energy required per kg of water produced with hot water temperature

Fig. 3.9 shows the variation of energy required per kg of water produced with hot water temperature. Energy required per kg of water produced is the ratio between the heat energy requirement of the system and the amount of water produced during a cycle. The energy consumption per kg of water production firstly decreases up to a maximum be hot water temperature of 80˚C then increases. The decreasing tendency is due to the increase of water production is more, while the  total heating requirement does not vary much in the range of 60˚C - 80˚C. Above 80˚C, the water production is low compared with the heating requirement, which decreases the energy required per kg of water produced.

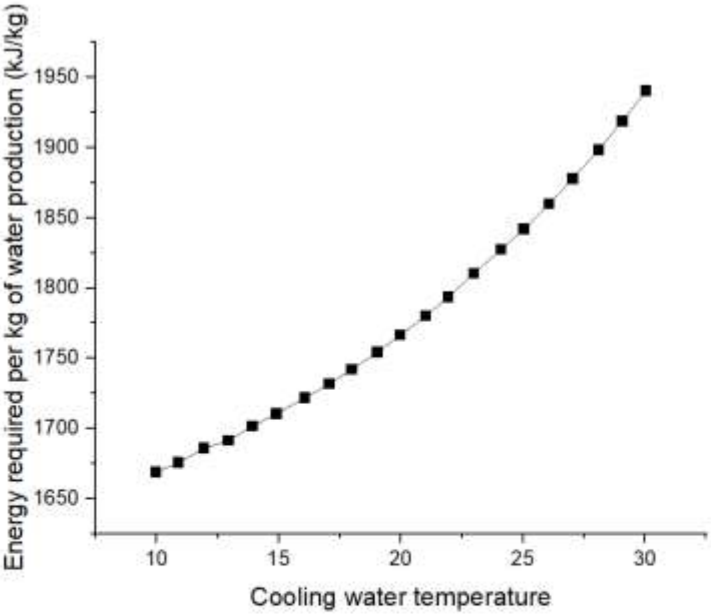

Fig. 3.10 Effect of energy required per kg of water production with cooling water temperature.

Energy consumption per kg of water production is decreasing with decreasing cooling water temperature, shown in Fig. 3.10. It is because of the more water production occurring at low cooling water temperature. Hence for unit amount of water production, the heat requirements are low.

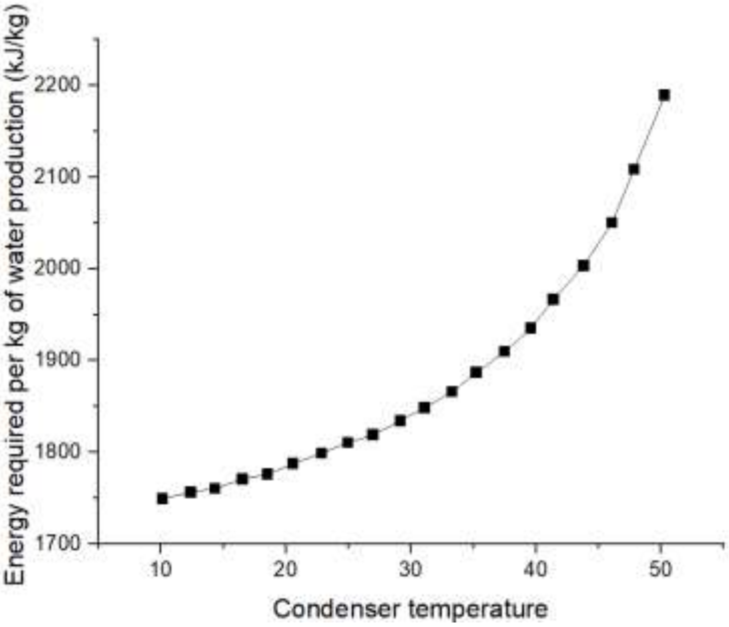

Fig.3.11 Effect of energy required per kg of water production with condenser temperature

The energy consumption per kg of water production increases more rapidly with condenser temperature shown in Fig.3.11. It is because of the very high heat input and low water production at the higher condenser temperature.

## 3.6 SUMMARY

The numerical simulation of the existing desalination system infers that the maximum productivity of water is 1.3kg/cycle for a cycle time of 30 minutes which use silica gel as the adsorbent and the COP is 0.75. The parameters such as the cooling water temperature, hot water temperature and the condenser temperatures play major role in the performance of the system which was explained on the above sections. It is clear that the water productivity of the existing system as per the numerical simulation done is lower. So there is a need for some modification of the system. The two modifications that can be done are:

(d) Replacing the adsorbent (silica gel) of the existing system with a suitable composite adsorbent.

(e) Integrating humidification dehumidification unit with the existing desalination system.

# CHAPTER 4

# SELECTION OF COMPOSITE ADSORBENT AND PERFORMANCE ANALYSIS

Physical adsorbents are porous materials having different topologies and pore sizes which can adsorb gases through Vander Waals forces and can retain their original properties during the regeneration process. The main criteria for the selection of adsorbents are affinity of the pair for each other, pore size, surface area, thermal and chemical stability, toxicity, diffusivity, heat of adsorption, heat of evaporation, corrosiveness, availability and costs. Most commonly used adsorbents are activated carbon, zeolite, silica gel etc.

Metal organic frameworks (MOFs) are organic-inorganic hybrid crystalline porous materials which consist of regular array of positively charged metal ions surrounded by organic molecules. These metal ions form nodes which can bind s the arms of the linker molecules to form a cage like structure. MOFs have very large surface area due to this hollow structure. These MOFs can be used along with the parent adsorbent so that composite adsorbent with increased adsorbent capacity can be produced. The preparation of composite adsorbents by combining the parent adsorbent and the MOFs are discussed in this chapter.

## 4.1 COMPOSITE ADSORBENT PREPERATION

In the preparation of composite adsorbents, silica gel is used as the parent adsorbent due to its good adsorption properties and easy availability. Three distinct composites are prepared.  Metal organic frameworks (MOFs) are combined with the silica gel. MOFs used are aluminium fumarate and CPO-27(Ni). The physical properties of silica gel, aluminium fumarate and CPO-27(Ni) are shown in the Table.4.1. Binder is needed for preparing the composite and the binder used is the polyvinyl pyrrolidine (PVP).

Three combinations are prepared and in all three, the weight percentage of silica gel is retained at 90%, while the weight percentage of MOFs is kept at less than 10%. This is because when the weight percentage of MOFs increases, more binder has to be added to the mixture. The surface area, pore volume, pore size of the adsorbent will be lowered when binder is used. Due to this reason, only lower amount of MOFs are used.

Table.4.1 Physical Properties of adsorbents

| **Adsorbent** | **Surface Area ($m^2/g$)** | **Pore Volume($cm^3/g$)** |
|---|---|---|
| Silica gel | 601 | 0.284 |
| Aluminium fumarate | 1021 | 0.436 |
| CPO-27(Ni) | 1218 | 0.520 |

### 4.1.1 Steps involved in preparation

Fig.4.1 shows the steps involved in the preparation of consolidated composite adsorbent. In the preparation of consolidated composite adsorbent, the silica gel powder (SGP) and the MOF material is initially heated for 3 hours at a temperature of $100^0$C for the removal of moisture content. Now the PVP binder is mixed with water to make the binder solution. The dried silica gel powder and the MOF are mixed along with the binder solution and stirred for its uniform mixing. This sample is compressed and then dried at $100^0$C for 3 hours for the removal of moisture content. Multiple samples are prepared by adding different MOFs. The composition of composite adsorbents is shown in the Table.4.2.

Table.4.2 Composition of Composite adsorbent

| **Adsorbent** | **Silica gel powder (SGP)** | **CPO-27(Ni)** | **Aluminium fumarate** |
|---|---|---|---|
| Composite-1 | 90% wt | 10% wt | - |
| Composite-2 | 90% wt | - | 10% wt |
| Composite-3 | 90% wt | 5% wt | 5% wt |

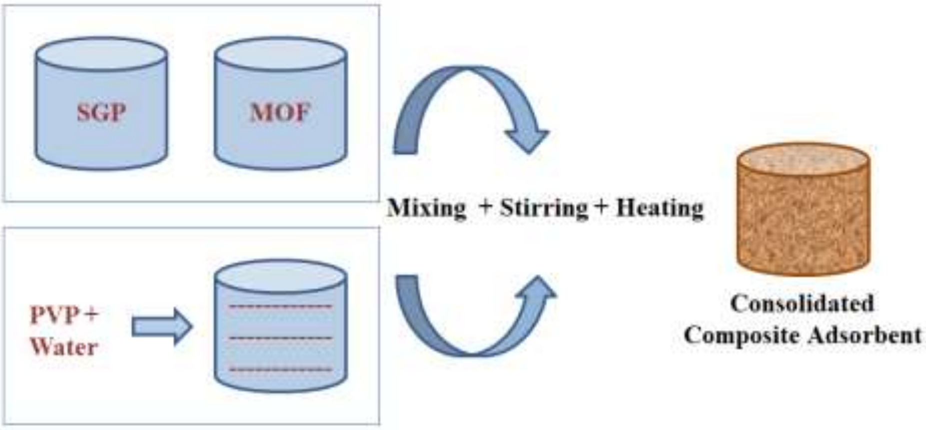

Fig.4.1 Preparation of Composite Adsorption

## 4.2 RESULT AND DISCUSSIONS

The results include the variations of the properties of the composite adsorbents and the improvement in the performance of the system while using the composite adsorbent.

### 4.2.1 Surface area and pore volume measured by BET surface analyser

Table 4.3 Physical properties of the composite adsorbents

| Adsorbent | Surface area ($m^2/g$) | Pore volume ($m^3/g$) |
|---|---|---|
| Composite-1 | 578 | $275 * 10^{-6}$ |
| Composite-2 | 590 | $279* 10^{-6}$ |
| Composite-3 | 540 | $263* 10^{-6}$ |

Table.4.3 shows the surface area and the pore volume of the different composites. Composite adsorbents possess different surface area and pore volume while using different MOFs depending on their nature. . It can be seen that composite 2 possess the highest surface area of $590m^2/g$ with a pore volume of 0.279cc/g, whereas composite 1 and 3 have a surface area of $578m^2/g$ and $540m^2/g$, respectively. Pore volume is found to be 0.275cc/g and 0.263cc/g, respectively, for composite 1 and 3. Composite 2 composed of silica gel, aluminium fumarate, and PVP binder can be inferred to be a

good option for adsorption desalination due to its microporous structure, large surface area and pore volume.

### 4.2.2 Thermal stability obtained from thermo gravimetric analyser

The thermogravimetric analysis assesses the thermal stability of composite adsorbents, which measures weight loss at various temperatures. Fig.4.2 shows the percentage weight reduction of composite adsorbents at different temperatures. It can be seen that all composite adsorbents lost 5-20% of their weight at a temperature less than $80^0$C. This emphasizes the low desorption temperature of composite adsorbent in driving off the physically adsorbed water vapour from the adsorbent's surface. At temperature of $80^0$C, composite 1 and composite 3 both lost 7% of their weight, whereas composite 2 lost approximately 20% of their weight. This could be because free water which is trapped in their pores is being removed. Composite 2 losses relatively little weight when the temperature increases from $80^0$ to $200^0$ C, whereas composites 1 and 3 lose weight at varying levels. It can be concluded that composite 2 is more thermally stable than the other two composite adsorbents within the temperature limit ranges from $80^0$C to $200^0$C. The weight reduction of composite 2 happens beyond a heating value of $210^0$C, as shown in Fig.7.1. At temperatures above $180^0$C, gradually, weight loss is noticed in composite 1 and 3. This reflects the low thermal stability of composite 1 and composite 3. TGA results show that the weight loss in composite adsorbents 1 and 3 is most apparent at $180^0$C, while in composite 2 it is found to be $200^0$C.

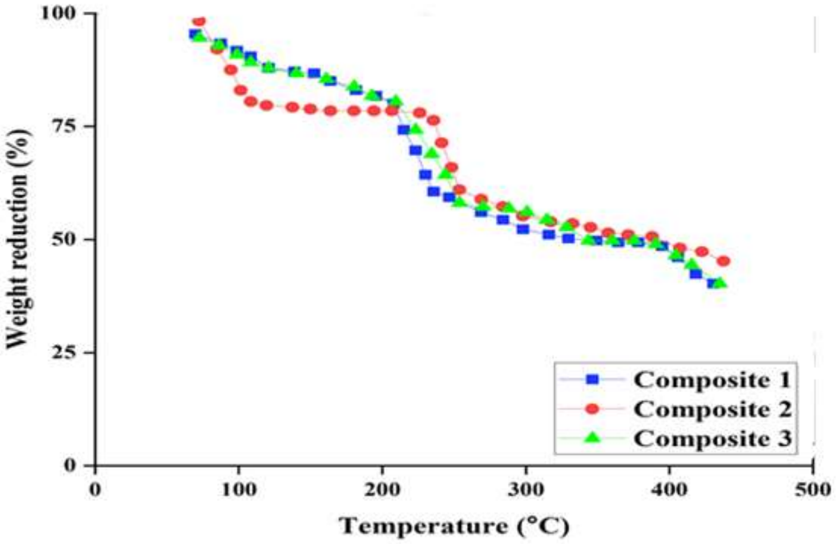

Figure.4.2 Thermo gravimetric analysis of composite adsorbents

### 4.2.2 Pore size distribution

The pore size distributions of composite adsorbents are shown in fig 4.3. All composite adsorbents show their highest peaks at less than 2nm pore width. Among the three composites, composite 2 offers the largest pore size at a pore width of 1.85nm. Since composite adsorbents' maximum pore size distribution lies at less than 2nm pore width, they can be considered microporous adsorbents.

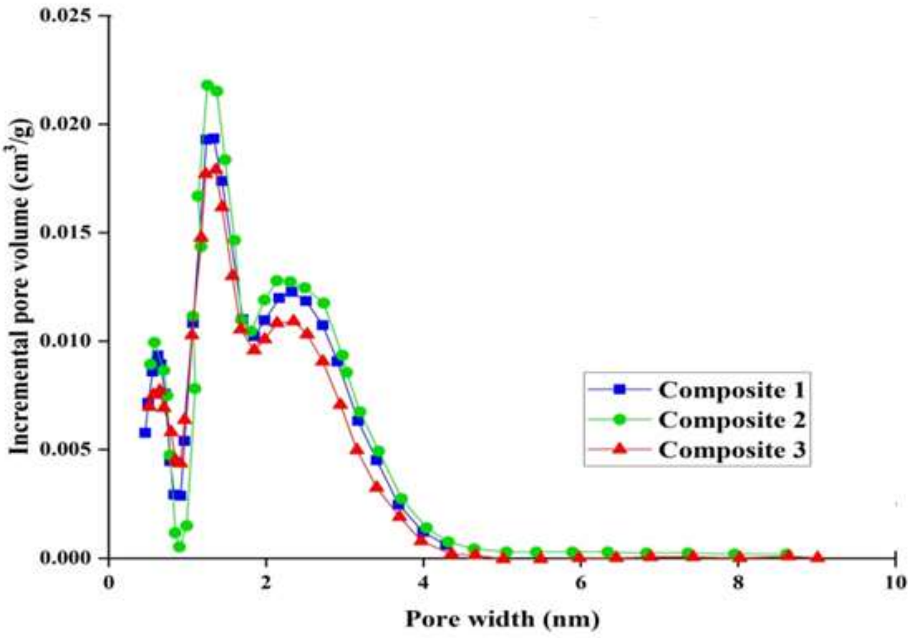

Fig.4.3 Pore size distribution of composite adsorbents

### 4.2.3 Adsorption isotherm and D-A equation curve fitting

The adsorption isotherm determines the amount of adsorbed water vapour onto the composite adsorbent as a function of its vapour pressure at a constant temperature. The adsorption isotherms for the investigated composite adsorbents at temperatures of 30°C, 40°C, 50°C, and 60°C are shown in Fig.4.4.

It is seen that the composite 2 adsorbs more water vapour than other composite adsorbents at all temperatures tested, with a maximum uptake value of 0.32kg/kg of adsorbent.

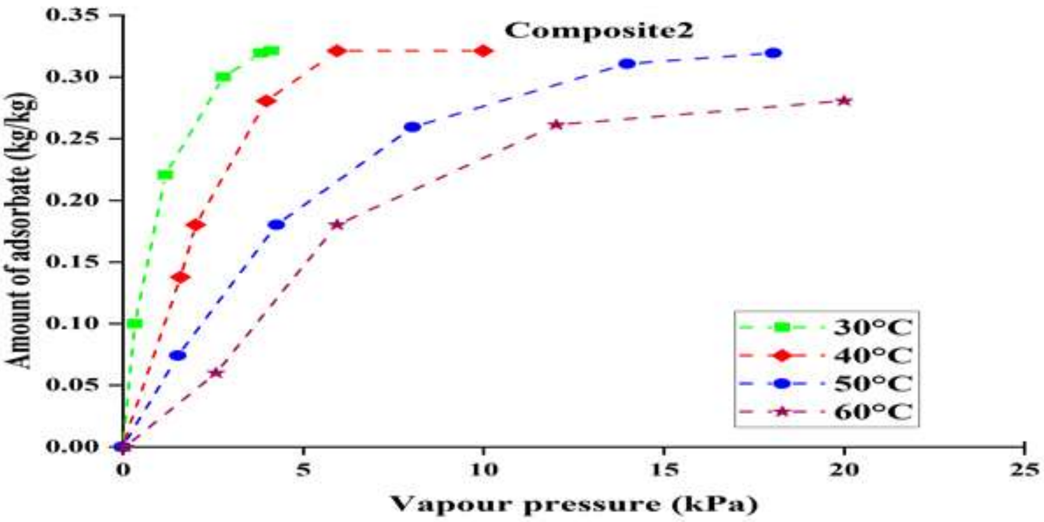

Fig.4.4 Amount of adsorbate v/s vapour pressure

D-A equation fitting

D-A model is given by the equation,

$$X = X_0 \exp(-(\frac{RT}{E}\ln(\frac{P_0}{P}))^n) \tag{3.1}$$

The D-A equation for the composite 2 is fitted on the adsorbate v/s vapour pressure. The experimental data is also find out and it is observed that the D-A curve and the experimental data coincides and thus the D-A equation can be chosen for the composite adsorbent. Fig.4.5 shows the D-A curve.

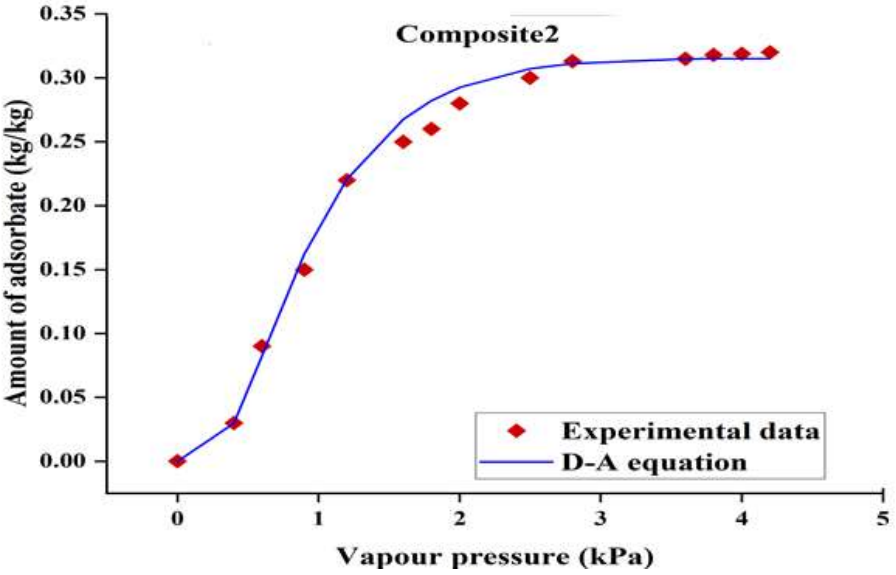

Fig.4.5 D-A equation curve fitting

The maximum uptake of adsorbate by the composite 2 is 0.315kg/kg and the activation energy (E) is 4.45kJ/mol.

## 4.3 COMPARITIVE STUDY

Figure.4.6 shows the percentage variation in relative water uptake values for each composite adsorbent and silica gel adsorbent. Relative water uptake is defined as the ratio of instantaneous water uptake at each relative pressure to the highest adsorption equilibrium value.

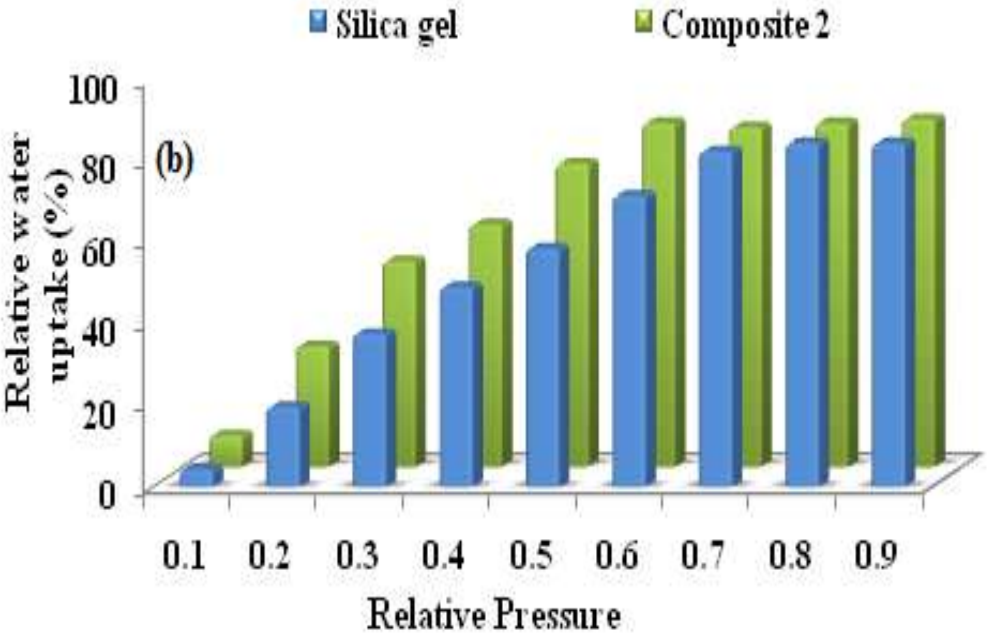

Fig.4.6. Variation in water uptake by silica gel and composite 2

At a fairly low relative pressure of 0.1, all of the composite adsorbents give about 15-20% relative uptake, as shown in the Fig.8.16. Silica gel, on the other hand, only consumes 15% of the relative water absorption uptake at low relative pressure. All the three composite adsorbents achieve 50% relative uptake at a relative pressure of 0.3. The performance of all composite adsorbents is more than that of silica gel at all relative pressures. Fig.8.14 Adsorption uptake value of composite adsorbent and silica gel at an adsorption temperature of $30^0$C and desorption temperatures of $80^0$C.

Figure 4.7 represents the adsorption uptake value of each composite adsorbent and silica gel at an adsorption temperature of $30^0$C and desorption temperatures of $80^0$C. Here, ideal adsorption cycle of composite adsorbent (1-2-3-4-1) is compared to that of silica gel (1sg-2sg-3sg-4sg-1sg) between $30^0$C and $80^0$C. It is seen that the silica gel provides higher water uptake than that of composite 1 and composite 3.The water uptake of silica gel differs from composite 1 and composite 3 by 0.02kg/kg and 0.05kg/kg, respectively. In composite2, there is a water enhancement of 0.06kg/kg. Results infer that the composite adsorbent 2 can be selected as an adsorbent for desalination cycle with performance higher to silica gel.

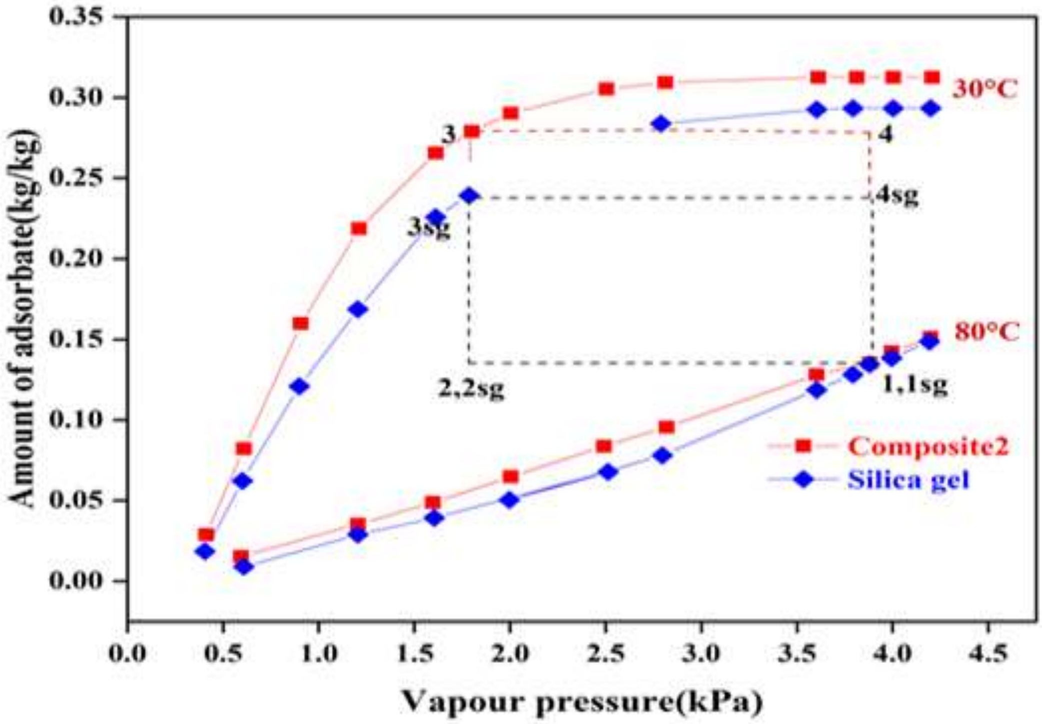

Fig.4.7 Adsorption uptake value of composite adsorbent and silica gel at an adsorption temperature of $30^0$C and desorption temperatures of $80^0$C.

## 4.4 SUMMARY

Three composites are prepared and the properties are found out. It is observed that the physical properties such as surface area, pore volume and thermal stability are more for the composite two with is the combination of silica gel and aluminium fumarate which is the composite 2. The water productivity enhancement is about 0.06kg/kg of the adsorbent. The productivity of water is increased by using the composite adsorbent.

Table.4.4 Comparison of relative water uptake between silica gel and composite 2

| Parameter | Silica gel | Composite 2 (Aluminium fumarate) |
|---|---|---|
| Relative uptake of water at relative pressure of 0.5 | 59% | 68% |
| Relative uptake of water at relative pressure of 0.6 | 78% | 89% |

From the table.4.4, it is observed that the relative uptake of water is more for the composite adsorbent than the silica gel while comparing at the relative pressure of 0.5 and 0.6. Thus the productivity is increased by using the composite adsorbent.

# CHAPTER 5

# NUMERICAL ANALYSIS OF ADSORPTION DESLINATION SYSTEM INTEGRATED WITH HUMIDIFICATION DEHUMIDIFICATION UNIT

The adsorption desalination systems used today gives only very lower water productivity. Productivity can be improved by making the system hybrid by integrating with any system. One such unit is the humidification dehumidification system which can be combined along with the adsorption desalination system. The working, various components and the performance of the hybrid adsorption desalination system integrated with HDH unit is discussed in this chapter.

## 5.1 WORKING OF THE HYBRID SYSTEM

The major components of the adsorption desalination and cooling system are the evaporator, the adsorbent bed, the condenser, the humidifier and the dehumidifier. The schematic diagram of the system is shown in the Fig.5.1.

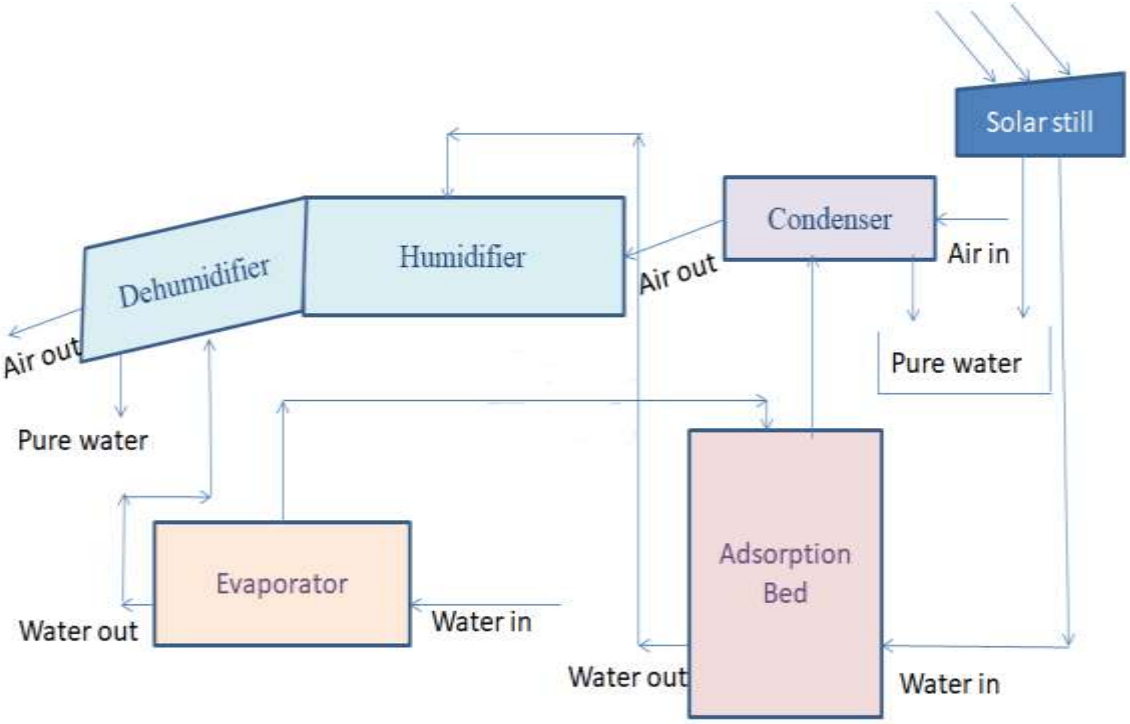

Fig.5.1 Schematic diagram of the hybrid system

Initially the evaporator is charged with the saline water. The water is flash evaporated in the evaporator. The chilled water is circulated through the evaporator in order to maintain the evaporation process and can be used for the cooling purpose. The concentrated brine is to be removed periodically for the regulation of saline water level and the salt concentration. The water evaporates and travels to the adsorption bed when the valve between the evaporator and the adsorbent bed is opened. The water vapour reaches the adsorbent bed and get adsorbed by the silica gel which is the adsorbent used in the bed. Heat of adsorption is evolved during the adsorption process and can be reduced by circulating the cold water through the bed. When the silica gel reaches its saturation level, the valve between the adsorbent bed and the evaporator is closed. Now the hot water is circulated through the bed which enables the desorption process. This can be also called as the regeneration process of the silica gel. The valve between the adsorbent bed and the condenser is opened so that the desorbed water vapour will flow into the air-cooled condenser. In the condenser, the heat of condensation is rejected into the air which is passed through the condenser, thus condensation takes place. The condensate is collected as the pure water. The air which moves to the humidifier is humidified by waste water from the adsorption bed which is sprayed on the top of the humidifier. This humidified air flows in to the dehumidifier where the chilled water from the evaporator is circulated through it. When the humidified air comers in contact with the circulating chilled water, the heat is absorbed by the chilled water and thus makes the humidified air to get condensed. Thus the pure water can be produced from the dehumidifier along with the dehumidified air. More pure water, cooling effect and dehumidified air can be produced from this system. The components evaporator, adsorbent bed and condenser have the same function as that of the adsorption desalination system explained earlier. The working of the humidification and the dehumidification systems are discussed below:

### 5.1.1 Humidifier

Humidifier is used to increase the moisture content in the air. The air from the air cooled condenser is humidified by using the water which is circulated through the adsorption bed. The water is sprayed from the top of the humidifier. When the air flows into the humidifier, the water droplets and the air comes in contact with each other. The moisture will be added to the gases and thus the humidified air is produced. Thus humidification process takes place.

### 5.1.2 Dehumidifier

Dehumidifier is the system in which the moisture content in the air is removed. The humidified air from the humidified air flows into the dehumidifier unit. The moisture content in the humid air can be removed by condensing the moisture. In order to condense it, the chilled water from the evaporator is used. The chilled water causes the moisture content in the air to get condensed so that the moisture is removed. Thus the air becomes dehumidified air. The condensate can be collected as the pure water.

## 5.2 ADSORPTION DESALINATION MODEL

For the modelling of the AD system, following assumptions are considered:

1. The adsorbent material is homogenous.
2. All the system components are well insulated
3. The thermal resistance between the adsorbent tubes and the adjacent adsorbent is neglected.
4. Pumping energy of the heating and the cooling water is neglected when compared with the amount of energy provided for heating

The uptake of water vapour by the adsorbent can be obtained by the Dubinin-Astakov (D-A) equation which was used earlier in the adsorption desalination system.

## 5.3. THERMODYNAMIC MODELLING OF HYBRID SYSTEM

Energy balance is applied for all the components in the hybrid desalination system. The energy balance for the evaporator, the condenser and the adsorbent bed are same as in the adsorption desalination system.

Some assumptions are made for the simulation of the HDH system. They are:

1. The HDH components and the connecting tubes are well insulated
2. Outlet air from the humidifier and dehumidifier is saturated
3. The energy consumption for the air blower and the sea water pump is neglected.

The energy balance for the humidification and dehumidification system is as follows:

a) Humidifier

For the humidifier, the water from the adsorption bed which is sprayed exchanges heat with the air from the condenser. Therefore, mass and energy transfer takes place. The mass and energy balance equations are given as:

$m_{ai} + m_{wi} = m_{ao} + m_{wo}$ (5.1)

$m_a h_{ai} + m_w c_{pw} T_{wi} = m_a h_{ao} + m_w c_{pw} T_{wo}$ (5.2)

b) Dehumidifier

The mass and energy equations of the dehumidifier include the mass and heat transfer between the chilled water from the evaporator and the humid air. These can be expressed as:

$m_a(w_o - w_i) = m_{cond\ water}$ (5.3)

$m_a(h_{in} - h_{out}) - m_a w(h_{v1} - h_{v2}) = m_w h_{fg}$ (5.4)

The numerical simulation of the hybrid system is done in the SIMULINK software. Using the energy equations, subsystems are created. The subsystems are connected to form the algorithm of the hybrid system as shown Fig.5.2.

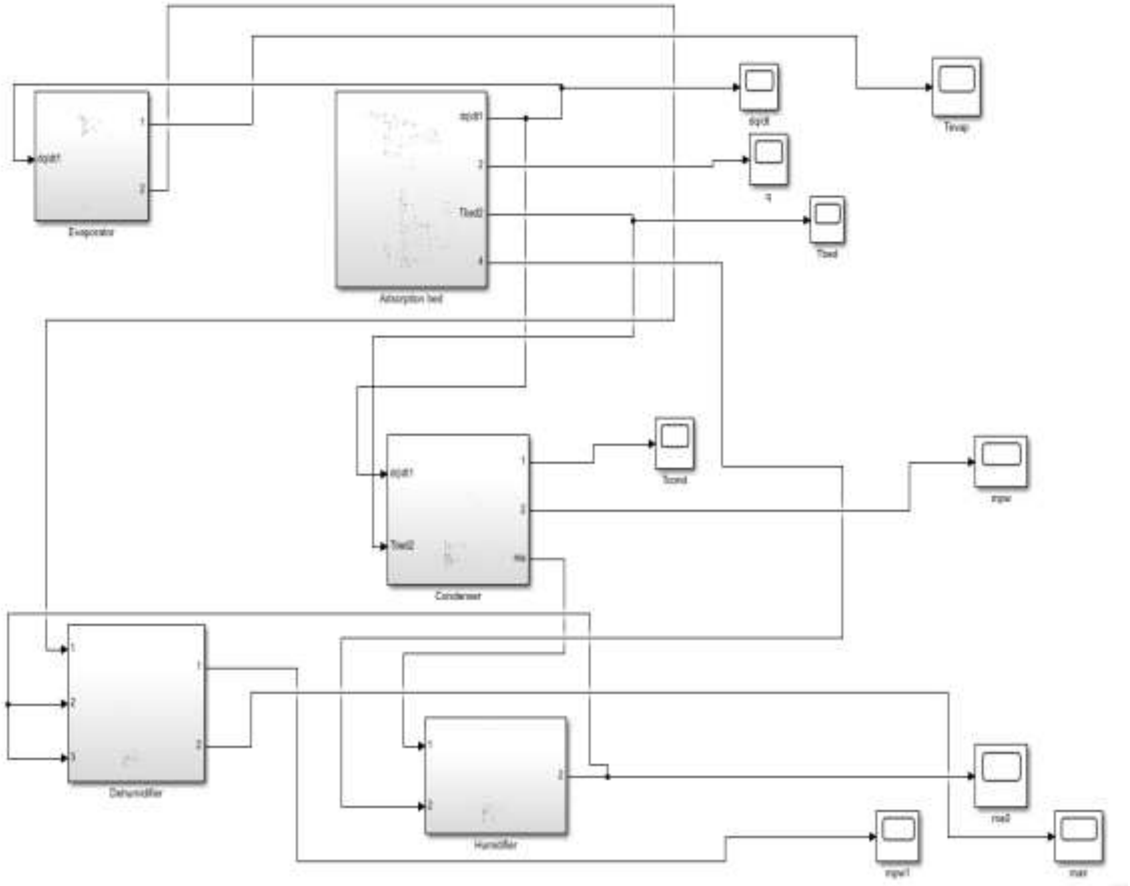

Fig.5.2 Simulink algorithm of the hybrid system

## 5.4 RESULT AND DISCUSSIONS

The HDH system is integrated with the adsorption desalination and cooling system with an aim to increase the water productivity, where the water productivity was increased in the HDH unit. The system was operated for a cycle time of 30 seconds where the first half cycle is the desorption period and the remaining is the adsorption period.

The Fig.5.3, 5.4, 5.5 show the temperature variation of the adsorbent bed for different hot water temperatures $70^0$C, $80^0$C and $90^0$C. In the desorption period hot water is circulated through the bed for desorbing the water vapour. At the end of the half cycle, the bed temperature reaches the maximum .. After the time of 15s adsorption is taking place so that cooling water is circulated through the bed. Thus the bed temperature is decreased.

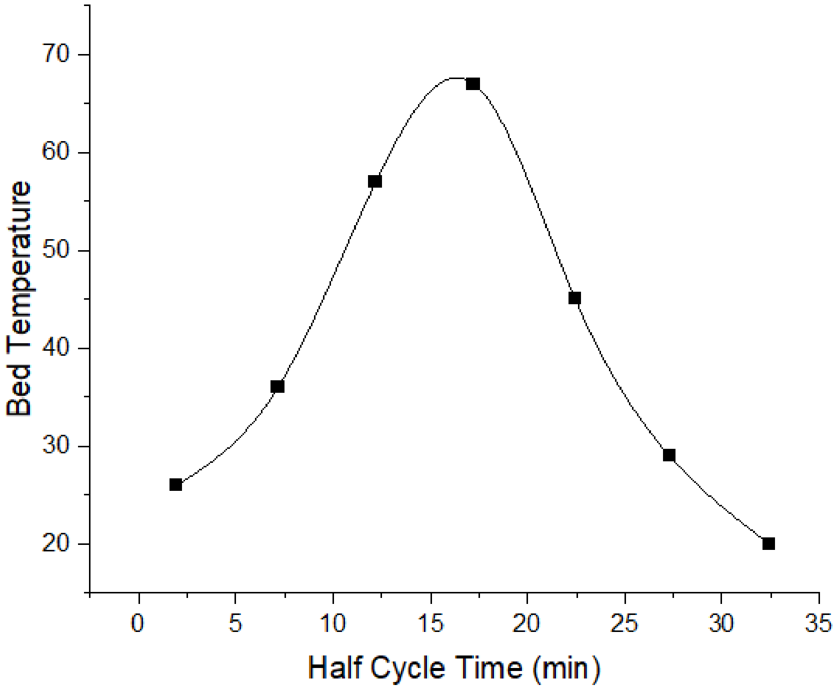

Fig.5.3 Variation of bed temperature with the cycle time for hot water temperature of $70^0$C

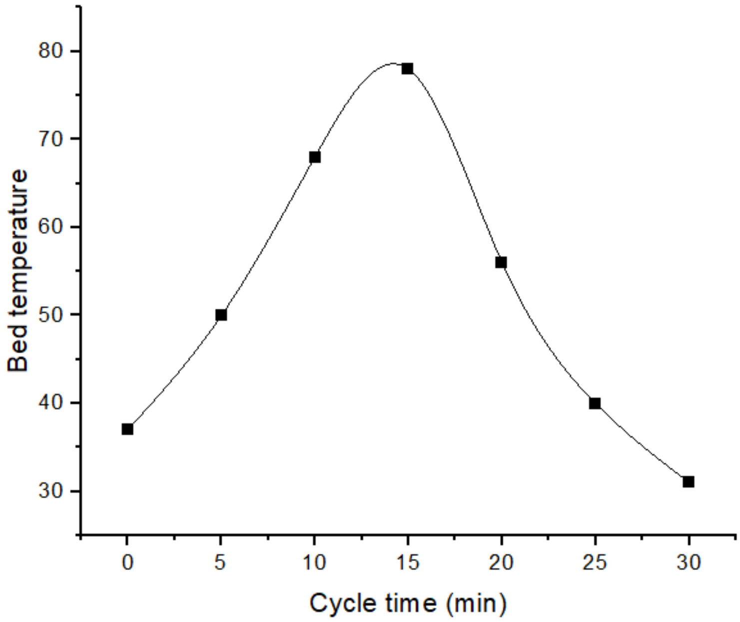

Fig.5.4 Variation of bed temperature with the cycle time for hot water temperature of $80^0$C

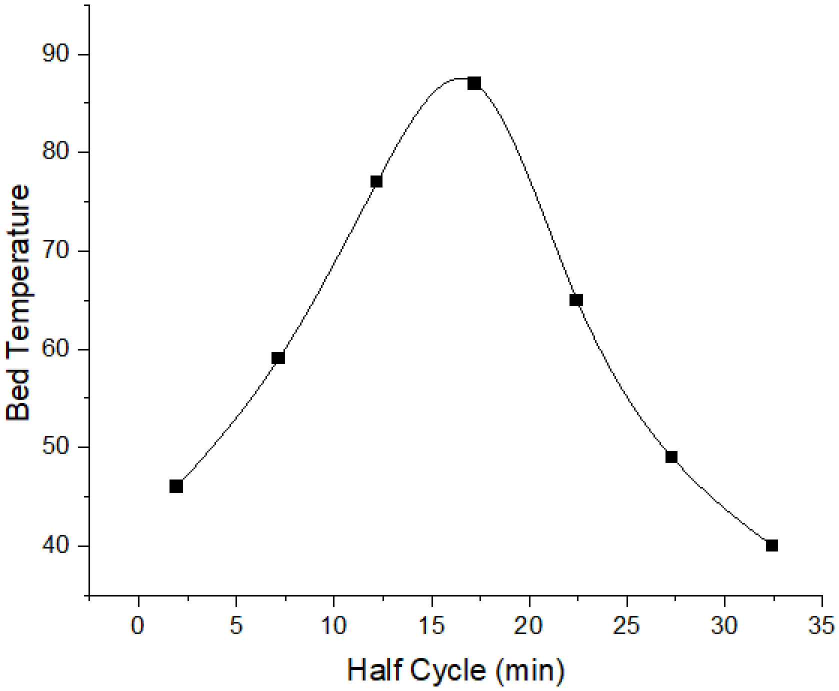

Fig.5.5 Variation of bed temperature with the cycle time for hot water temperature of $90^0$C

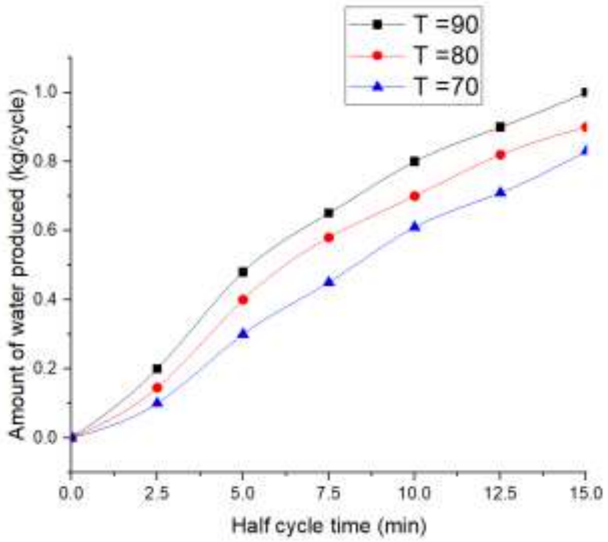

Fig.5.6 Variation of amount of water produced per cycle for hot water temperature

The maximum amount of water that can be produced in the adsorption bed is obtained as about 1kg/cycle at a hot water temperature of $90^0$C. More adsorption takes place at higher hot water temperature which increases the desorption rate. So higher the desorption temperature, higher will be the water production. Fig.5.6 shows the variation of water productivity with half cycle time (desorption period) for different hot water temperature.

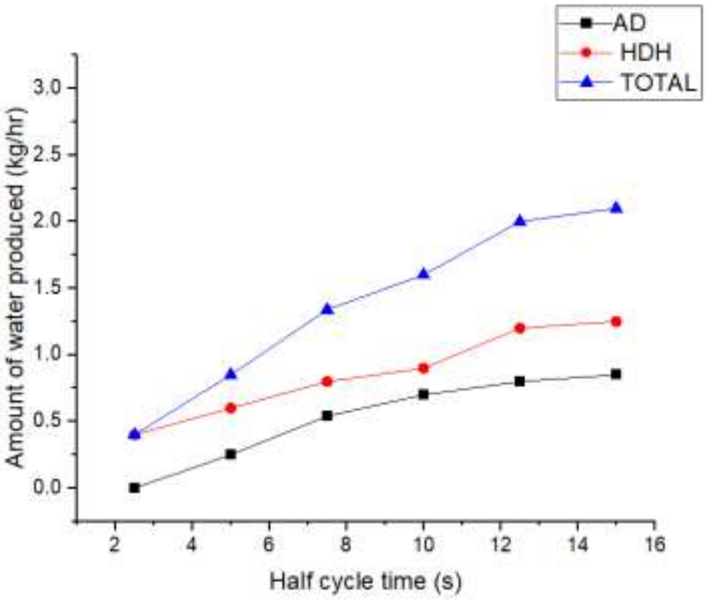

Fig.5.7 Variation in water production with the cycle time for the AD and HDH system

From the Fig.5.7 it can be observed that the HDH system produces more water than the AD system thus the combined effect can produce higher productivity of water. The new hybrid desalination system can produce water about 2kg/hr.

## 5.5 COMPARATIVE STUDY

c) Comparison between the adsorption desalination system with the hybrid system.

The variation in the water production for the existing adsorption system and the hybrid adsorption system with half cycle time is given in the Fig 5.8. The maximum water production for the adsorption system is 1.3 kg/cycle. When HDH unit is integrated with the existing system, the water production was obtained from the HDH unit also, which increased the total water production of the system and the water production was increase to 2kg/cycle.

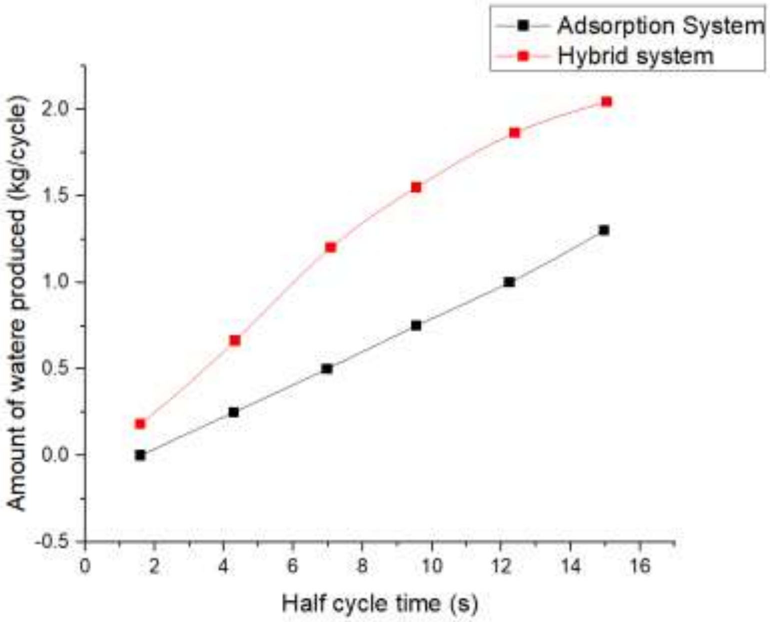

Fig.5.8 Amount of water produced in the existing system and the hybrid system with cycle time.

## 5.6 SUMMARY

The existing system is integrated with the humidification dehumidification unit in order to increase the water productivity. The adsorbent used in this system is the silica gel and so that the water production from the adsorbent bed and the COP are same as that of the existing system. The waste water from the adsorbent bed and the chilled water from the evaporator are made use in the humidification dehumidification unit and thus the fresh water is produced separately in this unit which add upon the total productivity of the system for saline water of 3kg. No additional energy is consumed for the new integrated system which makes it more efficient.

Table 5.1 Comparison of system performance

| System | Water productivity (kg/cycle) | Percentage of yield |
|---|---|---|
| Existing system with silica gel | 1.3 | 43% |
| Existing system with composite 2 | 1.54 | 51% |
| Hybrid system | 2 | 66% |

The table 5.1 shows the comparative study of the existing system with the modified systems. The yield percentage of the existing system was 43%. The improved yield percentage is 51% and 66% for the system with the composite adsorbent and the new hybrid system respectively.

# CHAPTER 6

# CONCLUSION AND SCOPE FOR FUTURE WORK

## 6.1 CONCLUSIONS

In this study, performance analysis of an adsorption desalination and cooling system is done. Variations of various parameters like water productivity, COP and the energy requirement etc with the operating parameters are studied. The main operating parameters are the hot water temperature, cooling water temperature, condenser temperature, cycle time etc. It is observed that the performance of this system is lower. In order to improve the performance and also to reduce the energy requirement, two solutions are introduced. First one is the use of composite adsorbent and the other one is the integration of HDH system with the existing system.

a) The water productivity of the existing system is obtained as 1.3kg/cycle with silica gel as the adsorbent.
b) Study on various adsorbent is done, new composites are prepared and its properties are analysed
c) Composite adsorbent selected is the silica gel with aluminium fumarate which has higher surface area, pore volume and thermal stability.
d) The adsorption –isotherm is selected for the composite 2 is Dubinin-Astakov equation.
e) The productivity while using the composite adsorbent is increased by 0.06kg/cycle and the percentage of yield is 51%.
f) The percentage of yield is obtained as 66% and the water productivity is 2kg/cycle for the hybrid system with humidification dehumidification unit.

## 6.2 SCOPE FOR FUTURE WORK

- Experimental studies on the hybrid desalination system integrated with HDH unit.
- Analysis on the hybrid system by using composite adsorbents.

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