THERMODYNAMIC MODELLING OF HYBRID ADSORPTION AND ABSORPTION DESALINATION SYSTEMS

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Keywords: Absorbent, Absorption, Adsorbate, Adsorbent, Adsorption, Bed, Brine, Condenser, Desalination, Desorption, Distillation, Energy, Enthalpy, Entropy, Exergy, Hybrid, Salinity, Solar, Temperature.

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Summary

According to WHO and UNICEF"s Joint Monitoring Programme (JMP) of the Millennium Development Goals (MDG), 663 million people in the world still lacked improved drinking water sources in 2015 (WHO/UNICEF, 2015). As per the report of the World Economic Forum, water scarcity will be the biggest societal and economic risk in the coming years (WBCSD, 2016). The situation can only be tackled if there is an alternative to produce fresh potable water from available resources. This chapter outlines the absorption and adsorption principles employed in desalination for potable water production. It emphasizes the importance of switching over to renewable energy from fossil fuel by introducing the thermodynamic aspects and developments in the field of absorption and adsorption desalination. It also summarizes how a low-temperature heat source such as solar energy can be used for desalination using adsorption and absorption principles. It further describes the ability of adsorption systems to cogenerate cooling effect along with potable water in a hybrid system. Water desalination using adsorption phenomena are not very recent; experimental investigations have been going on over the last 20 years. In addition to single bed adsorption desalination system, various configurations of the adsorption-based systems such as multiple bed, heat recovery systems, and hybrid options are illustrated in this chapter. The basic working of absorption desalination systems and the thermodynamic analysis of the system based on the First and Second law of thermodynamics are also presented. These will help a reader in identifying the quantitative and qualitative degradation of energy in such desalination systems based on these fundamental thermodynamic laws. The fundamental concepts of various desalination systems such as vapor compression, reverse osmosis, multi-effect distillation, and solar still are also outlined in this chapter. The chapter also summarizes some of the recent technological developments in adsorption and absorption desalination systems. Although the commercialization of these developing technologies is still to be attained, a brief outline of market status, cost of water production, economic and technical barriers are also included in the chapter with a view to explore the areas of absorption and adsorption desalination for further progress.

1. Background

According to the World Health Organization (WHO) standards, 97 % of water available on the Earth is saline and only 3 % of water is fresh. Out of the 3 % freshwater, more than 2.5% is locked up in glaciers and ice caps. Therefore, humanity relies only on 0.5 % of the global stock of fresh water for all its needs. Currently, one million people of the world are living in water stressed areas and this number may increase up to 3.5 million by the year 2025. One of the greatest challenges is the production of potable water. Though many techniques are employed, desalination is considered as one of the solutions for the same. The conventional desalination plants (Karagiannis et al, 2008) such as reverse osmosis and multi-effect distillation play an essential role in satisfying the current water demands. But these technologies require huge amounts of energy for their operation and in turn pose environmental issues. Therefore, a practical solution for solving the global water shortage must focus on developing environmentally friendly and energy efficient desalination systems. One of the techniques address the issue is to integrate desalination system with renewable energy sources like solar radiation or biomass. Adsorption and absorption systems are very much significant in these situations because they are capable of utilizing renewable energy such as solar energy, biomass, or waste heat as energy sources. The ability of adsorption based desalination system to cogenerate distilled fresh water and cooling effects attracts increasing attention in the field of desalination. Meanwhile, thermally driven adsorption desalination systems and absorption desalination systems are proven to be eco-friendly and energy saving methods.

In the past few decades, adsorption desalination method has received considerable attention due to its ability to operate under low-grade heat source (solar, waste heat, etc.) at temperatures below 100°C. For large-scale production of potable water to meet global requirements we have to consider alternative configurations, such as desalination systems coupled to solar/biomass energy sources. The application of solar-driven adsorption and absorption systems is a viable option to desalination around the globe.

2. An Overview of Conventional Desalination Systems

One of the most age old ways of desalination is by distillation. Desalination is based on boiling and evaporation of saline or brackish water followed by condensation. Earlier, solar energy was used as the heat source and in modern times, the required thermal energy is obtained from industrial waste heat, solar collector, or steam generator. Solar still, multi-effect distillation (MED), multi-stage flash (MSF), reverse osmosis (RO) and vapor compression desalination are commonly used thermal desalination methods. The qualitative and quantitative information on various desalination systems is required and is covered in various textbooks and elsewhere in the EOLSS. Therefore, a very detailed description of these systems is avoided here. Here the essential information and some insights into conventional desalination systems as required in the context of this topic are provided. Other publications in this area are recommended for further reading in the bibliography.

2.1. Solar Still

The schematic diagram of a simple solar still (Setoodeh et al, 2011) is shown in Figure 1. The system consists of a basin with a black liner (for good absorption of the incoming solar radiation) and covered by an inclined glass roof to form an enclosure. The basin is filled with saline water up to a certain depth. The glass cover permits solar energy into the basin as shown in Figure 1. The solar radiation entering the solar still heats the basin liner and saline water. This heating process causes the evaporation of saline water. The evaporated water vapor rises and condenses below the glass roof due to temperature difference and partial pressure difference. The condensate slides down along the inner surface and is collected in a tray at the bottom of the glass cover. The remaining salt solution in the basin is known as brine and is collected in the brine water tank. Solar stills are cheap but they require a large area for the solar energy collection, so they are not viable for large quantities of water production.

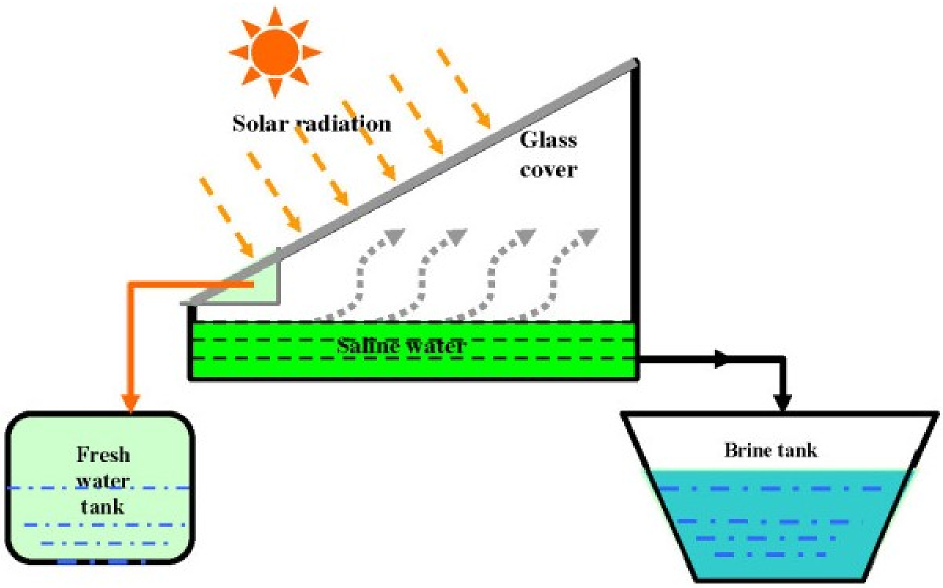

Figure 1. The schematic of a simple solar still

2.2. Multi-Effect Distillation (MED) System

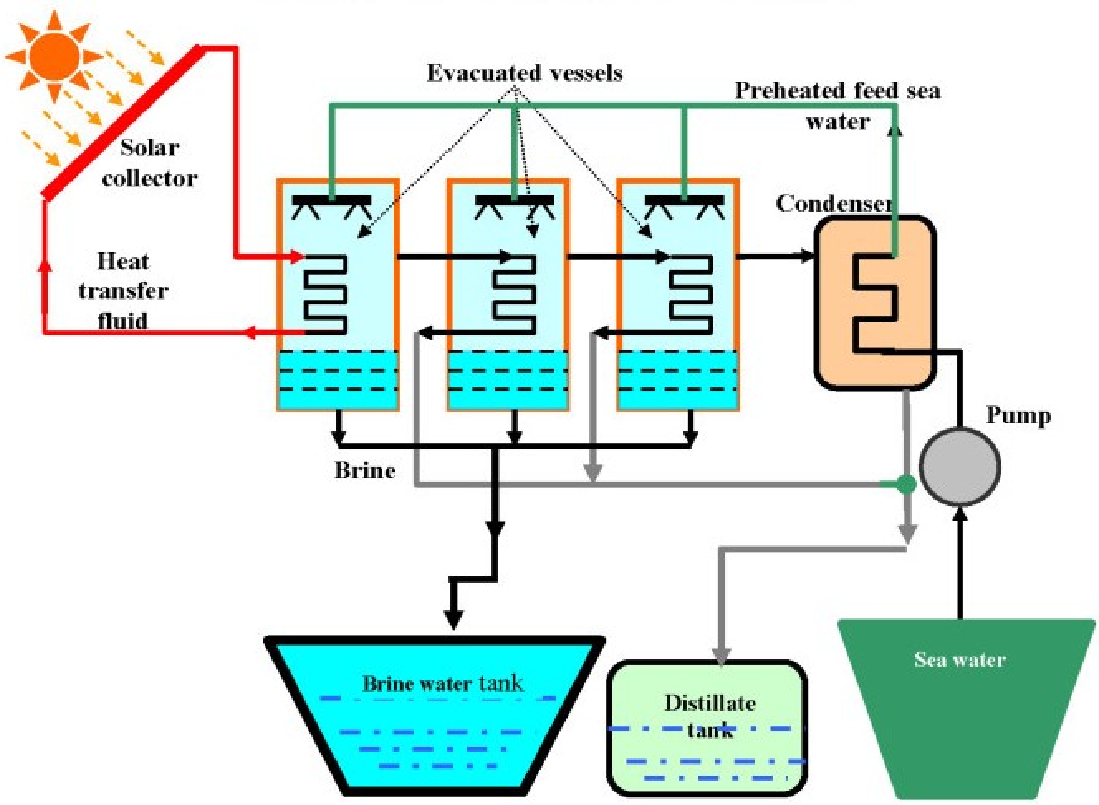

Figure 2. Solar powered multi-effect distillation unit

Multi-effect distillation (MED) (Sharaf et al, 2011) is one of the large scale conventional thermal desalination systems used for potable water generation. The system consists of a sequence of evacuated vessels for the evaporation process. A three-effect distillation unit is illustrated in Figure 2. In each vessel, the saline water is sprayed over the tubes carrying a hot medium. The heat energy required for evaporation in the first vessel is supplied through the hot thermal fluid from the solar collector. The water vapor formed due to evaporation in the first vessel is supplied to the next stage for heating the feed saline water.

The feed water sprayed over the surface of the evaporator tube gets evaporated by receiving heat energy from previous effect circulate (water vapor). The water vapor flowing through the evaporator tube and the distilled water is collected in the distillate tank. This process of evaporation and condensation is repeated from stage to stage.

2.3. Multi-Stage Flash Distillation (MSF) System

The multi-stage flash unit mainly consists of a saline water heater unit, where the feed saline water is heated. Each vessel of MSF consists of a heat exchanger and a condensate collector. A solar collector and thermal energy storage unit are attached to the heater for supplying heat energy as shown in Figure 3.

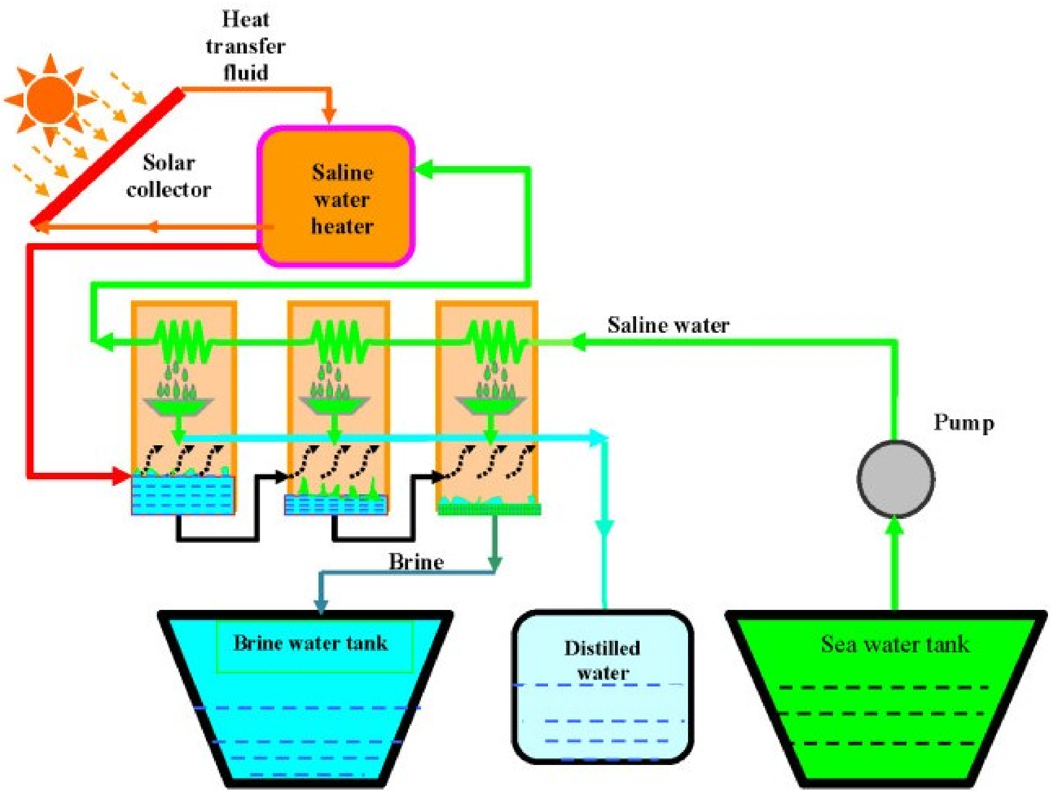

Figure 3. Solar powered multi-stage flash system

The saline water is pumped to the heat exchangers of each vessel. When it reaches the heat exchanger unit, heat energy is added to the saline water in the flash chambers, i.e., preheated. The saline water is further heated in the heater and from there it flows through a series of vessels maintained at pressures reducing successively. In the vessels which are at successively reduced pressures below the atmosphere, the sea water boils and evaporates. This process of boiling below atmospheric pressure is called flashing.

The water vapor generated by the flashing process is converted into freshwater by condensation on the tubes of heat exchangers that run through each stage from the feed end towards to the heater. Thus the feed saline water is pre-heated by the latent heat of condensation of vapor, and each stage is maintained thus maintained at low temperature.

2.4. Vapor Compression Desalination System

The vapor compression desalination system (Farbod et al, 2020) utilizes a mechanical vapor compressor to increase the pressure of water vapor. Figure 4 shows the schematic diagram of a vapor compression desalination system. Horizontal evaporator tube, water spray nozzle, steam compressor, pump, and preheating unit are the main components of the system. The saline water is sprayed over the tubes in the evaporator. The incoming saline water is preheated in two heat exchangers as shown in Figure 4. The water vapor formed in the evaporator is compressed by means of a compressor and is supplied to the evaporator tubes. The compressed vapor from the evaporator tube is led into two heat exchangers in which it condenses into desalinated water, thereby preheating the incoming feed saline water.

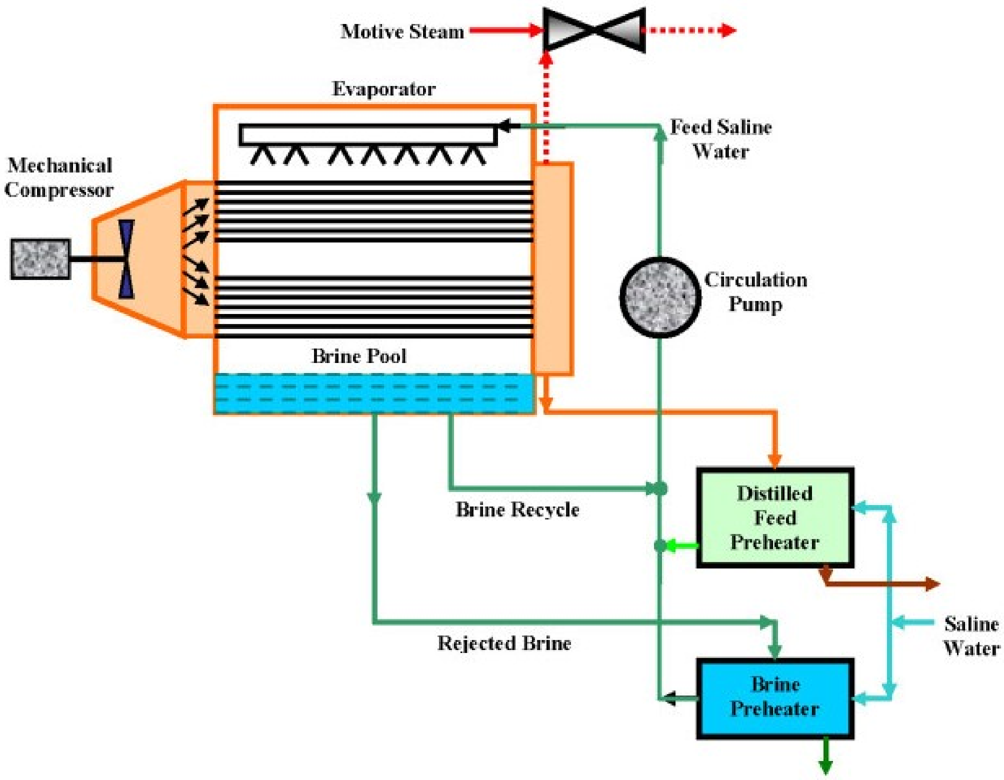

Figure 4. Vapor compression desalination system

2.5. Reverse Osmosis

The basic working principle of reverse osmosis (Farbod et al, 2020) is overcoming the natural osmotic pressure between two solutions at different concentrations separated by a semi permeable membrane. Osmotic pressure depends on the difference in concentration and flow of water is from dilute solution to concentrated solution.

Naturally, in forward osmosis (FO) or just osmosis the solvents in water move from a region of low solute concentration to the region of high solute concentration, whenever these two regions are separated by a membrane as shown in Figure 5(a). This process continues until the concentrations come into balance between the two solutions. During “reverse” osmosis which is shown in Figure 5(b), an external pressure is applied for reversing the water flow through the semi permeable membrane, that is, from the high concentration side to the low concentration side of the membrane. Thus, by applying an external pressure higher than the osmotic pressure desalination process is carried out in reverse osmosis (RO) pushing the solvent from the high concentration side to the low concentration side.

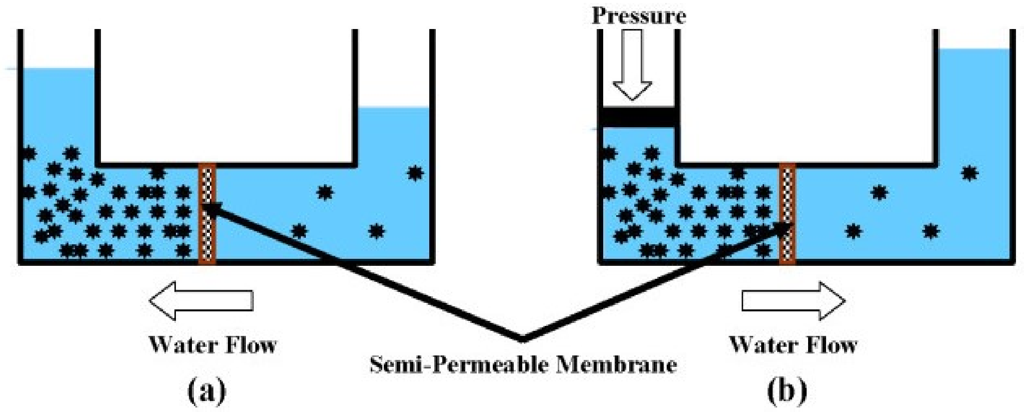

Figure 5. (a) Working principle of osmosis; (b) Working principle of reverse osmosis

RO desalination processes account for 95% of global desalination capacity. A comparison of various conventional desalination methods is shown in Table 1.

Desalination method	Features
Solar still	▪ Minimum maintenance and operation cost ▪ Product water is of High quality ▪ Low distillate yield ▪ Requires large area ▪ Low overall performance
Solar humidification–dehumidification	▪ Low installation and operation costs ▪ Requires large number of stages for efficient operation ▪ Water production cost is higher
Multi stage flash desalination/ Multi-effect distillation	▪ Suitable for large scale production of distilled water ▪ Plant can feed water of any quality ▪ High quality distillate is produced ▪ No feed water pre treatment is required ▪ High energy consumption ▪ Corrosion takes place due to high temperature operation ▪ The plant is heavy and costly

Vapour compression desalination	▪ High energy consumption ▪ Suitable for low capacity applications ▪ Feed requires less pre-treatment ▪ Product water is of high quality ▪ Compressor may get corrode ▪ High water production cost
Reverse Osmosis	▪ Operation in ambient temperature ▪ High power consumption ▪ Membranes usually have short life time ▪ Pre-treatment of feed water is required

Table 1. Comparison of various desalination methods

Theoretical and experimental investigations of adsorption and absorption systems substantiate that, they are energy-efficient and environmentally friendly. Unlike the conventional systems, adsorption and absorption produce cooling along with desalination. The ability to provide a cooling effect indicates that these systems are suitable for refrigeration and air conditioning applications as well. Therefore, a detailed investigation that deals with the working principles, components, types, and performance of adsorption and absorption desalination systems, needs to be explored. The features of working fluid used in vapor adsorption desalination system are explained in Section 3.

3. Features of Adsorption: Adsorption Principle, Adsorbents and Refrigerants

Adsorption is a surface phenomenon in which the accumulation or concentration of a substance occurs at the surface interface. The process of adsorption mainly involves adhesion, of atoms, molecules or, ions from a gas, liquid, or dissolved solids, to the surface of another substance. In the adsorption process the adsorbate adheres on to the surface of the adsorbent.

Figure 6 illustrates the adsorption of gas particles on a solid surface. Here the gas is the adsorbate and the solid surface is the adsorbent. The selection of proper adsorbent-adsorbate pair for the desired application is the preliminary step in the design of an adsorption system.

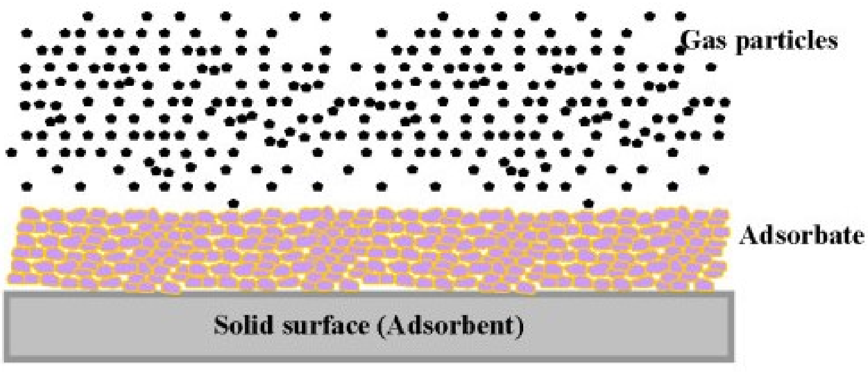

Figure 6. Adsorption process

The selection of adsorbent depends on the following factors (Daou et al, 2007)

- Thermal conductivity
- Specific heat
- High adsorption capacity when cooled to ambient temperature
- Ability to desorb most of the adsorbate when heated with available heat source
- It should be chemically stable
- Non-toxic and non-corrosive

There are several possible adsorbent-adsorbate (the latter is water vapor in the present context of desalination) working pairs for the adsorption desalination system. The proper selection of adsorbent depends on the temperature of the heat source and the thermo physical characteristics of adsorbent which affect the affinity towards water vapor.

The adsorbents that are compatible with an adsorption desalination system can be classified into the three groups such as:

a) *Physical adsorbents:* Adsorbate particles are adhered to the surface by weak Vander Waals forces, hydrogen bonding, and electrostatic forces.

b) *Chemical adsorbents:* Adsorbate particles are adhered to the surface by a chemical reaction between adsorbate and adsorbent surface.

c) *Composite or consolidate adsorbents:* A combination of the different physical, or chemical, or physical and chemical, adsorbents. High adsorption capacity and higher adsorption rate can be achieved by a combination of these adsorbents-called composite adsorbents.

Table 2 represents commonly used physical, chemical, and possible composite adsorbents in cooling and desalination systems.

	Adsorbent	**Remark**
Commonly Used Physical Adsorbents	Silica gel	• Comparatively low regeneration temperature. • Adsorb only average amount of water at a particular operating pressure.
	Zeolite	• Excellent adsorption capacity. • More than 100^{0}C is required for the desorption process.
	Activated carbon	• Large internal surface area due to the very high porosity. This will increase adsorption capacity. • High thermal conductivity as compared to the other physical adsorbents.
Commonly Used Chemical Adsorbents	$CaCl_2$, $SrCl_2$, $BaCl_2$, LiH,CaH_2, metal oxides	• Requires certain level for energy activation. • Adsorption rate is more at high pressure. • Rate of adsorption also depends on the surface area.

Possible Combinations of Consolidated adsorbents	Silicagel+$CaCl_2$, Silica gel + NaCl, Zeolite+$CaCl_2$, Activated carbon + silica gel + $CaCl_2$	• Nature of modifying agent and its content open up new opportunities for improving the adsorption properties. • Better thermal conductivity • Better surface diffusivity.

Table 2. Types of adsorbents

Most of the traditional adsorbents are porous enough to adsorb more amounts of water vapor, but these have low thermal conductivity which in turn reduces the performance of the desalination system. Therefore, there must be a compromise between density required for good thermal conductivity and porosity for good diffusion of water vapor as far as the selection of adsorbent is concerned. It is proved by various studies that composite adsorbents have good thermal conductivity and adsorption characteristics. For a two-component composite adsorbent such as porous host material modified by an active material, it is possible to change more than two parameters. Silicagel+$CaCl_2$, Zeolite+$CaCl_2$, Activated carbon + silica gel + $CaCl_2$ are the major types of composite adsorbents. The first substances used as modifying agents are hygroscopic inorganic salts such as $CaCl_2$. The thermal conductivity of activated carbon is the best among all the common adsorbents, silica gel and zeolite. Higher thermal conductivity will lead to a higher performance of heat and mass transfer in the adsorber during the adsorption/desorption process.

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Biographical Sketches

Dr. Baiju V. is currently an Assistant Professor in the Department of Mechanical Engineering, TKM College of Engineering, Kollam, Kerala, India. He has more than ten years of teaching and research experience. He established an Energy Research Centre at TKMCE recently. His expertise is in the area of solar cooling systems, vapor adsorption cooling and desalination systems in particular. He did his PhD and Post-Doctoral studies in design, fabrication and performance studies of Solar vapor adsorption refrigeration systems, desalination and hybrid atmospheric water generators. His research group at Sreechithra Thirunal College of Engineering and TKM College of Engineering, Kollam has developed a number of lab scale models of solar adsorption refrigeration, desalination and cooling systems in recent years. His research area includes solar cooling, vapor absorption and adsorption desalination systems, exergy analysis, biomass and its utilization in cooling and desalination systems, heat transfer in energy systems, solar thermal collectors, wind and solar thermal hybrid, energy storage systems in desalination and cooling systems.

P Abhishek is currently pursuing his research work in the area of solar hybrid adsorption desalination system in TKM Engineering College, Kollam affiliated to APJ Abdul Kalam Technological University, Kerala, India. His main research interests are focused on desalination systems driven by renewable energy sources, adsorption systems and air water generation. His research activities encompass thermodynamic aspects of desalination system based on energy and exergy analysis. His research work is currently focused on developing a hybrid system that integrates adsorption desalination system with any of the other thermal desalination system for improving water productivity using a composite adsorbent. He is also working as Assistant Professor, in the Department of Mechanical Engineering, Bishop Jerome Institute, Kollam, Kerala.