Productivity Improvements of Adsorption Desalination Systems

Ramy H. Mohammed and Ahmed A. Askalany

Abstract Addressing the water energy cooling environment nexus in an integrated and proactive way is an insistent motivation for research, development, and innovation. This combination is highly valued as renewable energy is used to drive plants to produce electrical power, provide cooling or heating, and extract clean water. Such plants significantly reduce the greenhouse gases and air pollutant emissions generated by combustion of fossil fuels. Adsorption-based desalination (AD) system has been proposed to produce both fresh/potable water and cooling effect for rural and remote coastal communities. The system is powered by low-grade heat or solar energy. Desalination feature has been added to adsorption cooling system to distinguish it and improve its performance. However, the performance of this hybrid system is still relatively low comparing to the other cooling and desalination technologies. Accordingly, the AD systems are being evolved steadily over the past decades to enhance their performance. In this chapter, the working principle of the AD cycle is demonstrated, and the characteristics of the recommended working pairs are discussed. Productivity progress of different arrangements of AD plant in terms of specific daily water production (SDWP) is presented in chronological order. The effect of the operating conditions and the system cycle time on the system performance is shown. Predicting the technology performance is also exhibited. Until now, the cycle could produce a SDWP up to 25 kg/kg of adsorbent per day. Moreover, this work summarizes the improvement that has been achieved in the last decades and the trend of this technology in the near future.

Keywords Adsorption-based desalination · Specific daily water production · Operating conditions · Future technology

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1 Introduction

Fossil fuels are still one of the major sources of energy, where oil, coal, and natural gas are the predominant fossil fuels consumed by most developing and industrialized nations. The rapid and huge rise in the cost of the fossil fuels is unavoidable in the world market due to the growth of world population and economically fast-developing countries. In addition, greenhouse gases (carbon dioxide (CO_2) of 82%, methane (CH_4) of 10%, nitrous oxide (N_2O) of 10%, and fluorinated gases of 3%) through burning fossil fuels intensify dramatically. In turn, the finite amount of fossil fuels starts to minimize because the world population keep growing, and it will not be affordable to produce the amount of power required by the world. This successively reveals that the price of the desalinated water from traditional thermal systems [multiple effect distillation (MED), multistage flash (MSF), reverse osmosis (RO)] will steadily augment. Moreover, the expected desertification process in many temperate regions, such as Southern Europe, South USA, and the Mediterranean Sea area, will cause an additional boost in water requirement. So, using renewable energy such as solar energy to product energy and freshwater will be more and more economically viable in the near future and seems to be a compulsory choice. Nowadays, water, cooling, energy, and environment are tightly intertwined. As a result, there is a motivation for research, development, and innovation to handle the water energy cooling environment nexus in an integrated and proactive way. This integration is highly valued as it reduces and limits greenhouse gases and air pollutant emissions generated by combustion of fossil fuels.

Desalination processes are categorized into two major techniques: a heat-driven process (distillation) and electric power-driven process or in other words thermal and non-thermal technologies as categorized in Fig. 1. The heat-driven process is a solar distillation, multistage flashing (MSF), and multiple effect distillation (MED). The electric power-driven process includes mechanical vapor compression cycle, freezing, reverse osmosis, and electrodialysis. These desalination systems suffer from high energy consumption, corrosion, and fouling because of the seawater evaporation. On the other hand, since the AD system has no moving parts, it proposed to overcome the deficiencies of the conventional desalination techniques.

Hybrid adsorption cooling and desalination cycles driven by renewable energy have received much interest owing to its capability of producing freshwater with zero emissions as well as a cooling effect. This system is able to treat highly concentrated feedwater, ranging from chemically laden waste to water seawater. Also, heat sources with a temperature of less than 100 °C can power this system. However, this technology suffers from low cooling power capacity and freshwater production. The distinguished features of the adsorption-based desalination cycles compared with the other desalination methods are [1, 11, 39, 40, 47, 19–21]:

(i) utilization of low-grade waste energy below 100°C or solar heat,
(ii) no moving parts, which render low maintenance cost,
(iii) employing environmental friendly working pairs such as silica gel/water,
(iv) zero greenhouse gases emissions,

(v) limited fouling and corrosion rates on the material of the evaporator tubes because the seawater evaporation occurs at relatively low temperature (typically below 35 °C),
(vi) the capability of cogenerating cooling power along with freshwater,
(vii) low electricity usage, about 1.2–5.6 kW/m^3 compared to 6–9 kW/m^3 for MED, and
(viii) unwanted aerosol-entrained microbes from the evaporator are killed, and any biocontamination is eliminated by using a desorption temperature of 65 °C or more.

This chapter reports in details the progress in productivity of different arrangements of adsorption-based desalination (AD) system in terms of cooling power and specific daily water production (SDWP). It also predicts the future of the technology. The working principle of the AD system is demonstrated, and the characteristics of the recommended working pairs are discussed. The influence of the cycle duration and operating conditions on the system performance is presented. Moreover, it presents and summarizes the improvement that has been achieved in the last decades and the trend of this technology in the near future.

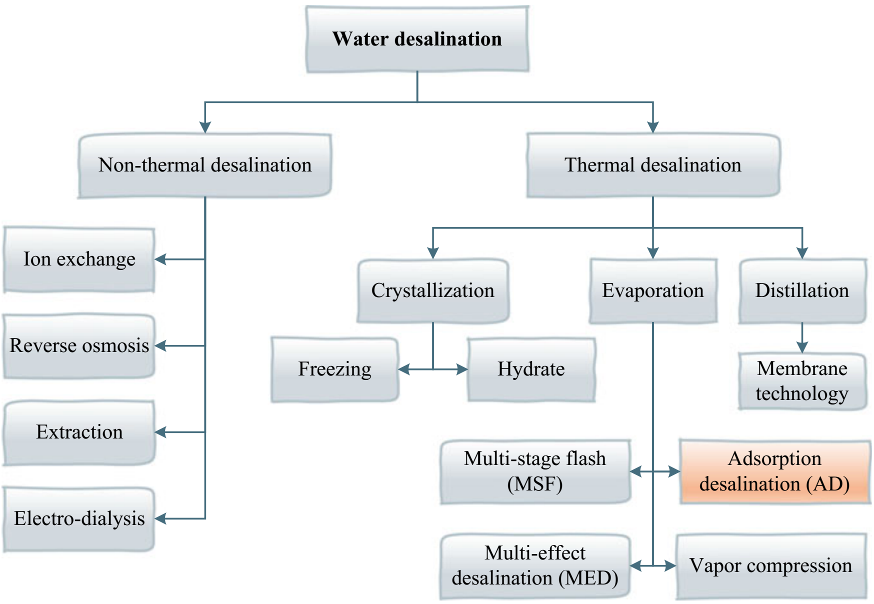


Fig. 1 Categories of desalination processes

2 Working Principle

Adsorption (AD) cycle has two main processes: (1) adsorption–evaporation process and (2) desorption–condensation process [3, 5, 27, 19–21]. In the first process, the surface area of adsorbent in the adsorption bed adsorbs by the vapor generated in evaporator. Heat of adsorption is released during this adsorption process. A cooling fluid is used to remove the heat generated in the bed to facilitate a continuous adsorption process. In the evaporator, chilled refrigerant is circulated through tubes, while seawater is sprayed over the external surfaces of tube bundle as shown in Fig. 2a. Initially, the evaporation is occurred by a heat source that ranges from 2 to 25 °C, but during the adsorption process, the evaporator pressure drops due to the adsorption and contributes in the evaporation. The adsorption process ends when the adsorber bed reaches an equilibrium state. In the second process, low-grade waste energy or solar energy is used to generate the adsorbent. The desorbed vapor is circulated to a condenser to condense and stored as pure water in a collection tank. Obviously, cooling power during the adsorption period and potable water during the desorption period are the two beneficial outputs produced by the adsorption cooling and desalination cycle. These two outputs are produced simultaneously by using a multi-bed arrangement [36, 47] as presented in Fig. 2b. Each bed comprises a thermodynamic cycle during the desorption and adsorption stage as shown in Fig. 3.

2.1 Adsorption Working Pairs

The performance of adsorption desalination systems critically relies on the solid adsorbent ability to adsorb vapor and on the adsorption and desorption rate. Therefore, the selection of an appropriate adsorbate/adsorbent pair is a key parameter for designing an efficient adsorption system. The adsorbent surface characteristics and the working pair thermo-physical properties are the main features in making a decision. Working pairs control the operating pressure of the adsorption system as:

- *Low-pressure systems*: These systems use working pairs such as silica gel/water, activated carbon/methanol, or zeolite/water.
- *High-pressure system*: The working pairs used in these systems could be silica gel/sulfur dioxide, activated carbon/ammonia, zeolite/fluorocarbon, or activated carbon/fluorocarbon.

In low-pressure systems, good design and manufacturing are required to avoid leakage that seriously affects the system performance, whereas higher generation (desorption) temperature is required in the high-pressure systems.

On the other hand, adsorbents for adsorption cooling applications can also be classified into two main categories: classical and composite/consolidated adsorbent. Classical adsorbents are zeolite, silicagel, and activated carbon. Composite/consolidated adsorbents like FAM-Z02 (silicoaluminophosphate), LiCl/silica, salt

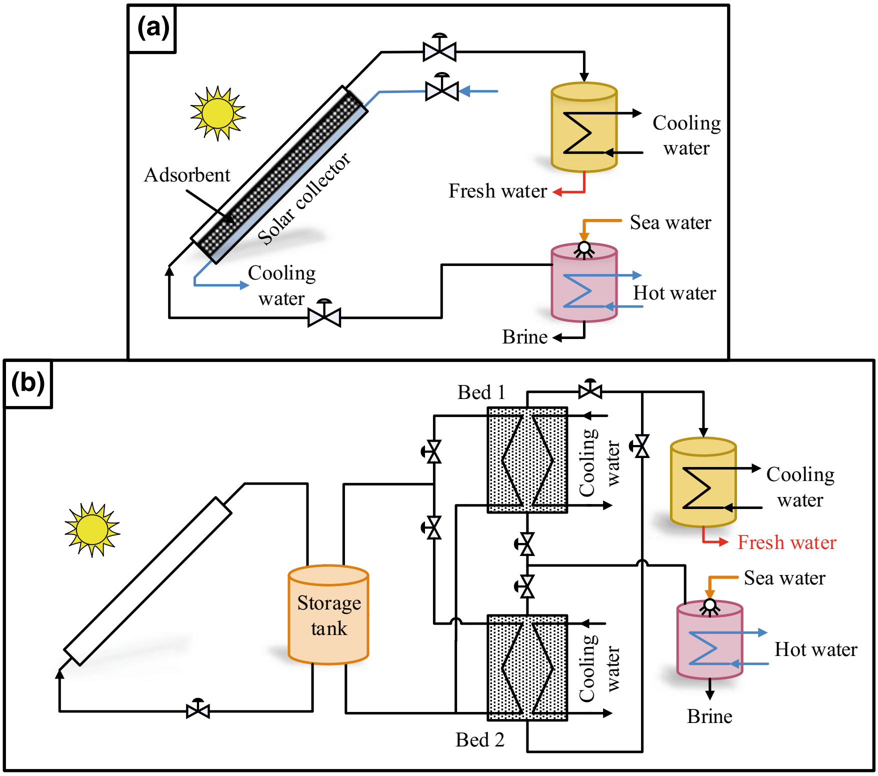


Fig. 2 **a** One-bed and **b** two-bed configuration of adsorption desalination unit powered by solar energy

Fig. 3 P-T-X diagram of an adsorption bed operation

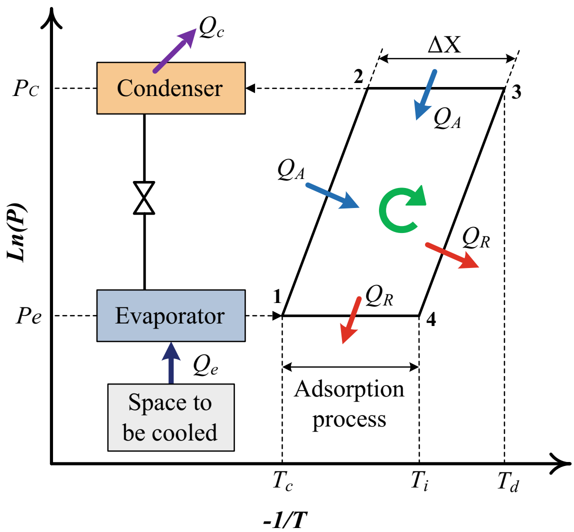


Table 1 Thermo-physical properties of common adsorption working pairs

Working pair	Pore diameter (nm)	Pore volume (m^3/kg)	BET surface area (m^2/g)	Maximum capacity (kg/kg of solid)
Silica gel RD/water [41]	2.20	4.0×10^{-4}	838	0.30
Fuji silica gel RD/water [21]	2.24	4.4×10^{-4}	780	0.48
Fuji silica gel 2060/water [21]	1.92	3.4×10^{-4}	707	0.37
Silica gel 2560/water [33]	1.32	3.27×10^{-4}	636.4	0.32
Silica gel A^{++}/water [33]	1.38	4.89×10^{-4}	863.6	0.48
Zeolite/water [28]	1.78	3.1×10^{-4}	643	0.25
AQSOA-Z01/water [31]	1.178	0.712×10^{-4}	189.6	0.215
AQSOA-Z02/Water [31]	1.184	2.69×10^{-4}	717.8	0.29
AQSOA-Z05/water [31]	1.176	0.7×10^{-4}	187.1	0.22

in porous matrix composite sorbents, and metal aluminophosphates (metal–organic framework oxides synthesized without silica).

Although plenty of materials have the adsorption ability, silica gel and zeolite are the recommended adsorbent materials for adsorption desalination application because [6, 18]:

- Their high water uptake capacity under the operating conditions.
- Their capability of desorbing most of the adsorbed vapor when it is exposed to a heating source.
- They have a relatively high heat of adsorption compared to sensible heat.
- Their chemical stability.
- They are non-corrosive and non-toxic.
- Their availability at low cost.

The maximum equilibrium uptake and the thermo-physical properties of different kinds of zeolite/water as well as silica gel/water are summarized in Table 1.

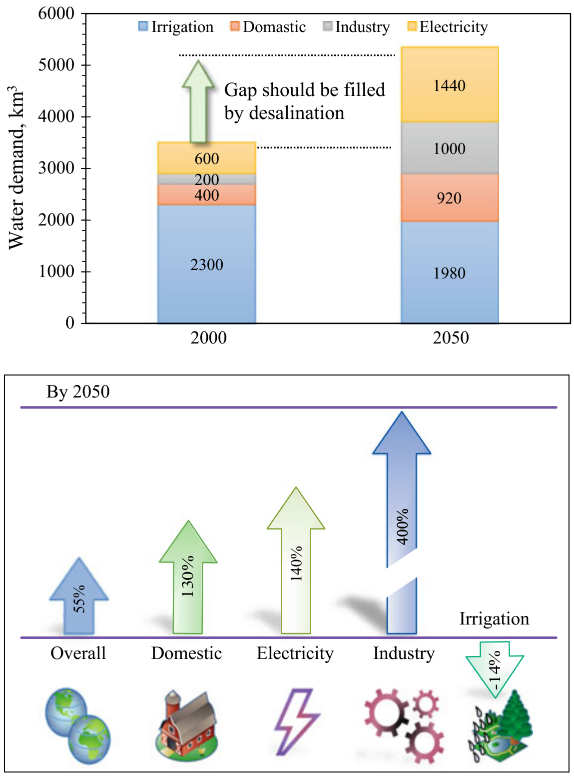


Fig. 4 Growing water demand from manufacturing, electricity, irrigation, and domestic use by 2050

3 Development of Adsorption Desalination System

World population continuously grows, and it is anticipated to rise from a present value of 7.3–9.7 billion in 2050 and 11.2 billion in 2100, according to UN DESA report (NU). Accordingly, water demand is projected to increase by 2050 by 55% as illustrated in Fig. 4 (Helen). Accordingly, technical and scientific communities focus on optimizing current adsorption desalination systems as well as proposing new ones. The recent research interests are dealing with the use of renewable energies to produce freshwater from the seawater as well as cooling power.

In 1984, Broughton [7] reported the earliest unit of adsorption cycle for desalination purpose. Simulation for a thermally driven two-bed configuration was conducted. Further developments later have been carried out to enhance the systems performance. Zejli et al. [47] described a multi-effect desalination (MED) unit hooked to an adsorption heat pump using zeolite/water as shown in Fig. 5. This is a combination of MED unit and adsorption heat pump cycle using internal heat recovery and supplying the MED unit with seawater and steam. The desalination system comprises an evaporator set between two adsorption beds and three-effect desalination system (see Fig. 5). The heat recovery process suggested in this configuration was according

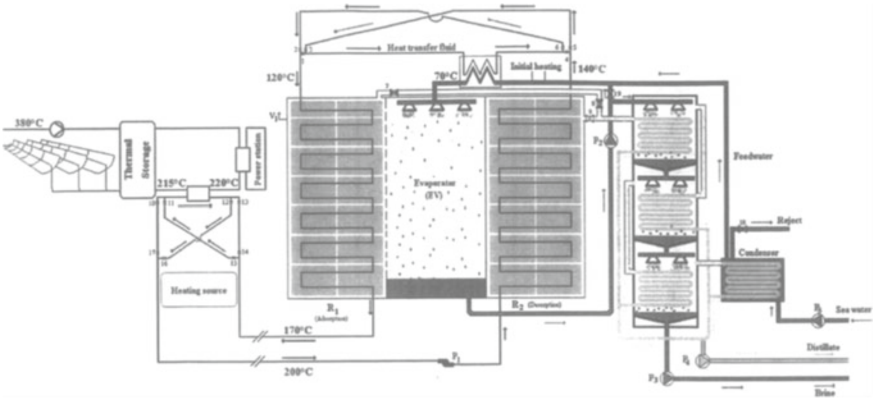


Fig. 5 Scheme of the adsorption desalination plant

to the thermal wave concept. In this proposed approach, the heat rejected from one bed is directly used on the second one that needs high-temperature thermal energy. In the 1950s, the initial experiments conducted and produced an SDWP of 0.12 m^3 desalinated water per ton of adsorbent. This innovative thermally driven distillation technique opened the door for promising possibilities for developments.

Wang and Ng [39] and Wang et al. [40] presented an experimental investigation of a four-bed adsorption desalination plant using silica gel/water as shown in Figs. 6 and 7. It has two major sections: cooling tower and heat source, and adsorption water output unit as shown in Fig. 7. The operating procedure of the system is similar to the adsorption cycle, while the condensed water is collected as distilled water. The inlet temperature of fluid supplied to the adsorptive beds, condenser, and evaporator are set as 29.4, 85, and 12.2 °C, respectively. This plant provided SDWP of 4.7 kg/kg of silica gel. El-Sharkawy et al. [8] also concluded that the AD plant could deliver about 8.2 kg of freshwater per kg of silica gel per day when the chilled water is set to be equal to the ambient temperature. Further, it was reported that this cycle could produce an SDWP of 7.8 kg/kg of silica gel at 30 °C evaporator temperature [23].

Ng et al. [24] built and evaluated a laboratory-scale two-bed solar-powered AD cycle. Solar collector with a surface area of 215 m^2 was used to provide the heat required for the regeneration. The experimental results indicated that the adsorption-based desalination unit could produce freshwater of 3–5 kg/kg of silica gel per day. In the same way, an experimental adsorption desalination unit was designed and constructed with the flexibility to operate either four-bed or two-bed operation mode as shown in Fig. 8 [24, 36]. It consists of four sorption adsorbent beds (SE), evaporator, and condenser as presented in Fig. 9. This plant has been built at the National University of Singapore (NUS) in the Air Conditioning Laboratory. In the four-bed mode, the hot water is fed in series to the adsorption beds, while water is supplied in parallel in case of the two-bed mode; thus, they behave as a single bed. The effectiveness of the heat source temperature, flow rate, and cycle time on the efficacy

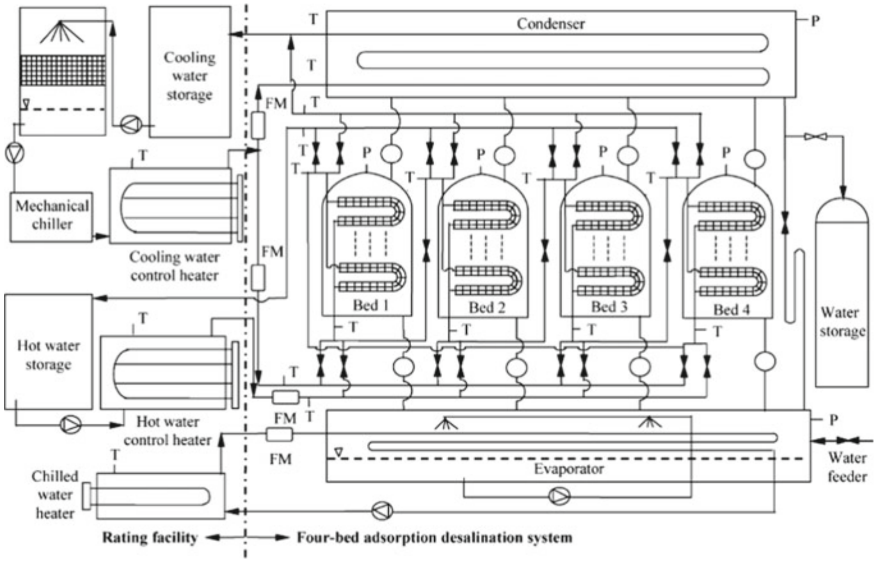


Fig. 6 Schematic of a four-bed AD plant [39, 40]

of AD system was studied. Optimum operating conditions of the AD cycle were experimentally investigated. Figure 10 shows the SDWP for various regeneration temperatures at the optimum time cycle. The experimental measurements highlighted that the four-bed operation mode delivers higher potable water than the two-bed operation mode. In addition, noticeable improvement can be achieved using hot water inlet temperature higher than 70 °C. The four-bed mode and two-bed mode could deliver a SWDP of 10 and 9 kg/kg of silica gel, respectively, using a hot water inlet temperature of 85 °C. This experimental study pointed out the prominence of suitable convenient cycle duration and hot water inlet temperature in the operation and design of adsorption desalination systems.

SDWP produced from a conventional two-bed AD system was enhanced by incorporating internal heat recovery approach between the condenser and the evaporator [37]. In this developed AD cycle, heat rejected from the condenser is used (recovered) to evaporate the saline water in the evaporator. From another point of view, it can be said that the condenser has been cooled down by the evaporator. This internal heat recovery is implemented using a heat transfer cycle running through the condenser and the evaporator of the cycle. The advantages of this suggested arrangement over the conventional one are as follows: (i) The condensation heat is reused to evaporate seawater, (ii) eliminating the pumping power required for running the cooling water through the condenser, and (iii) recovery of the condensation heat increases the evaporator temperature and hence increases the amount of vapor uptake during the adsorption period. For this two-bed configuration, the numerical outcomes and experimental measurements indicated that the maximum freshwater produced by the

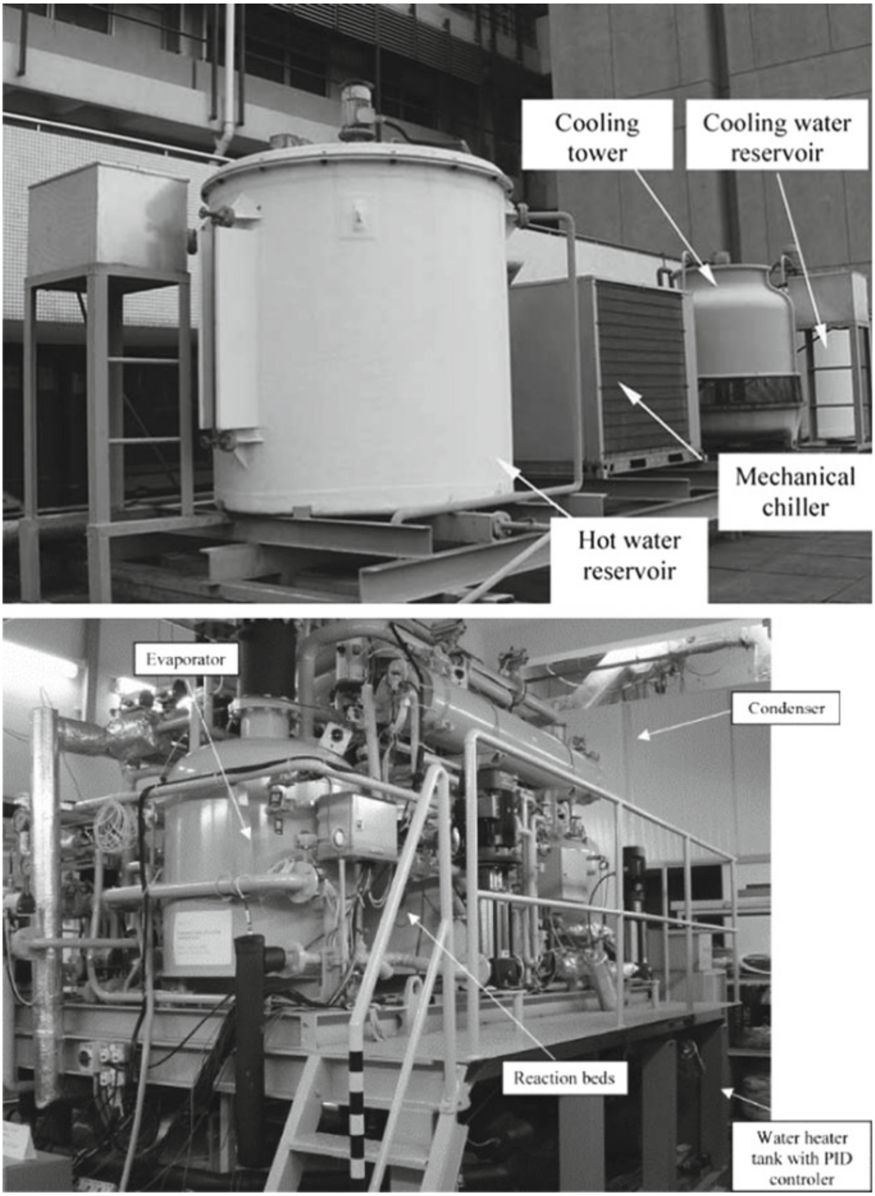


Fig. 7 A pictorial view of the four-bed AD plant [39]

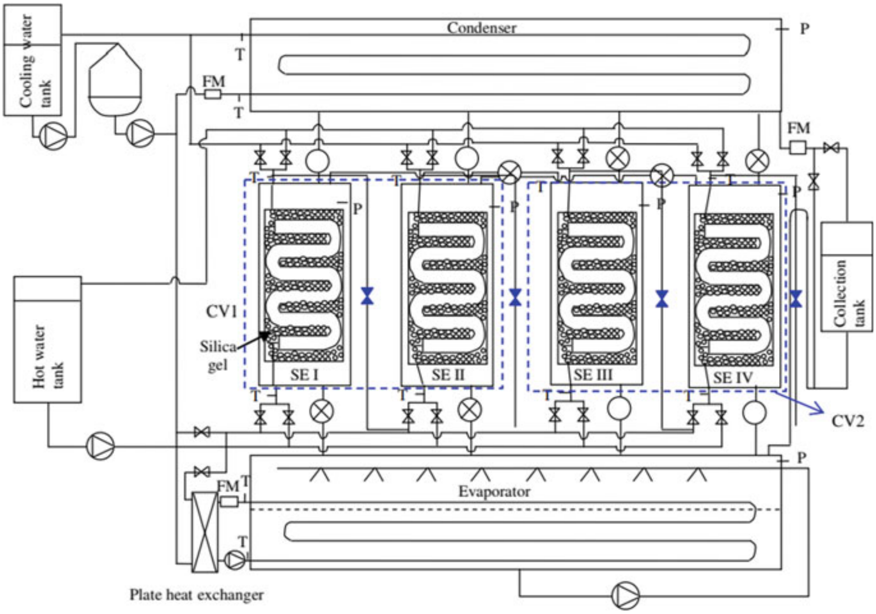


Fig. 8 Schematic drawing of AD unit in four-bed and two-bed mode. (blue valves are active in four-bed mode) [36]

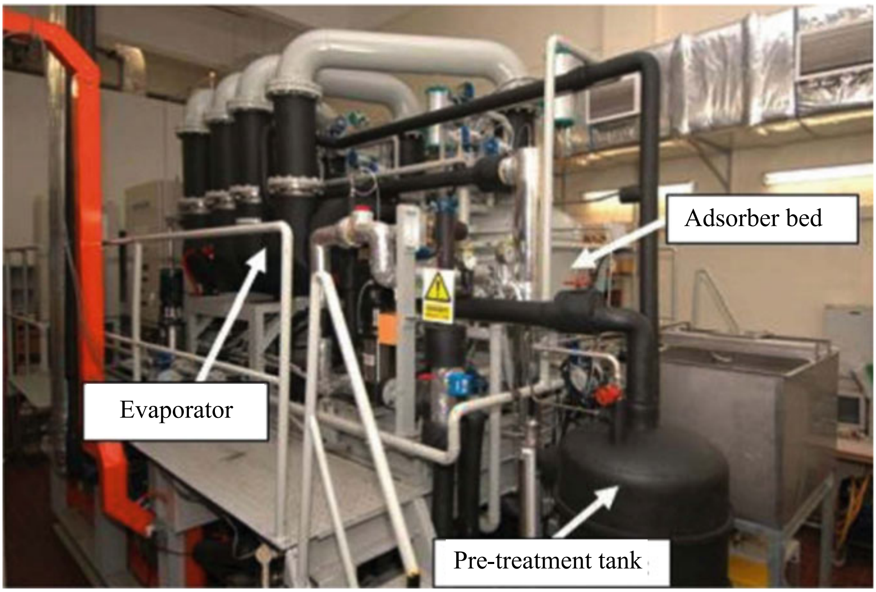
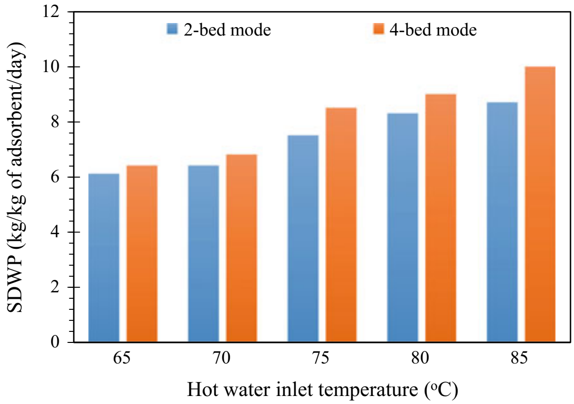


Fig. 9 Pictorial view of evaporator and pretreatment tank of adsorption desalination plant [36]

Fig. 10 Water production rate at various hot water inlet temperatures for four-bed and two-bed modes



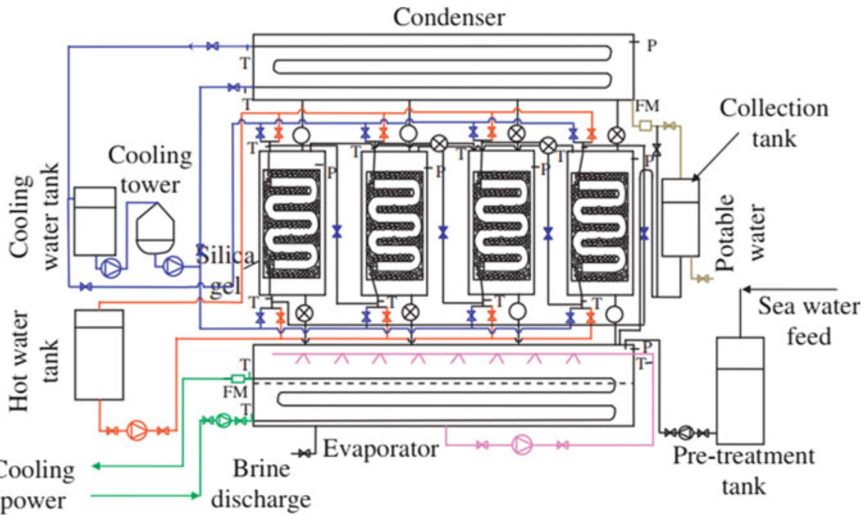


Fig. 11 Schematic drawing of a four-bed AD system [26]

developed cycle is 9.34 kg/kg of silica gel per day using regeneration temperature (i.e., hot water inlet temperature) of 70 °C. The optimal cycle time of this advanced cycle was found to be shorter than that of a traditional cycle. Ng et al. [26] presented a theoretical study of adsorption cycle operated in a four-bed mode driven by waste heat (see Fig. 11) that simultaneously produces a cooling power and potable/freshwater. The parametric analysis reported the effect of various chilled water temperatures on the SDWP produced by the AD system as presented in Fig. 12. This AD unit is able to deliver a freshwater of 8 kg/kg of silica gel/day using a 30 °C fluid temperature (T_{ch}) and 85 °C hot water inlet temperature.

At the King Abdullah University of Science and Technology (KAUST), KSA, adsorption desalination-cooling pilot plant was designed and built as presented in

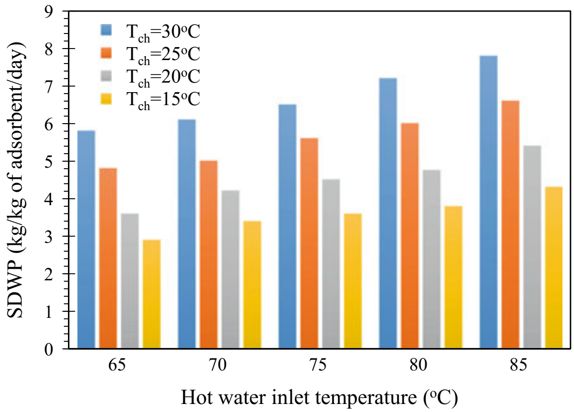


Fig. 12 SDWP of AD system at different chilled water hot water inlet temperatures

Fig. 13 [25]. The plant consists of four silica gel packed beds, one evaporator, and one condenser. 485-m^2 flat-plate collectors are utilized to provide solar heat to the plant, while water storage tanks are used to store the excess energy. The nominal water production capacity of the plant is about 12.5 kg/kg of silica gel per day with a cooling power of 84 kW (i.e., 24 refrigeration tons) using 85 °C hot source temperature and 30 °C cooling water temperature. A new arrangement for this plant was proposed and studied numerically [32, 34]. The proposed AD cycle used an internal heat recovery scheme between the condenser and evaporator and utilizes an encapsulated evaporator–condenser unit for efficient heat transfer as shown in Fig. 14. The integrated evaporator–condenser unit is made of a shell-and-tube heat exchanger. For this integration, the use of working fluid circuits to heat the evaporator and to cool down the condenser is one of the advantages which results in a significant decrease in the cost of the pumping power. Also, this configuration declines the heat transfer resistances and improves the seawater evaporation rates. The analysis of the theoretical results indicated that this advanced arrangement is able to deliver a SDWP of 26 kg/kg of silica gel per day using a hot water temperature of 85 °C, which is twofold higher than the basic plant. Further, the performance of an alternative arrangement, which is similar to the existing pilot adsorption desalination plant in NUS, was studied numerically. This alternative arrangement with internal heat recovery is a fully integrated condenser–evaporator design using a cooling fluid circuit for supplying the condensation heat of condenser to the evaporator as shown in Fig. 15. Figure 16 presents a comparison between two advanced AD systems using internal heat recovery and integrated evaporator–condenser device. Advanced AD system using integrated evaporator–condenser device produces a SDWP of two times higher than that delivered from AD system using internal heat recovery.

A laboratory two-stage AD system was designed and built as presented in Fig. 17 [12, 14]. The system consists of four beds in each stage, evaporator, and air-cooled condenser. The system was designed to operate in three different modes: two-bed/two-stage, three-bed/three-stage, and four-bed/four-stage. Figure 18 presents

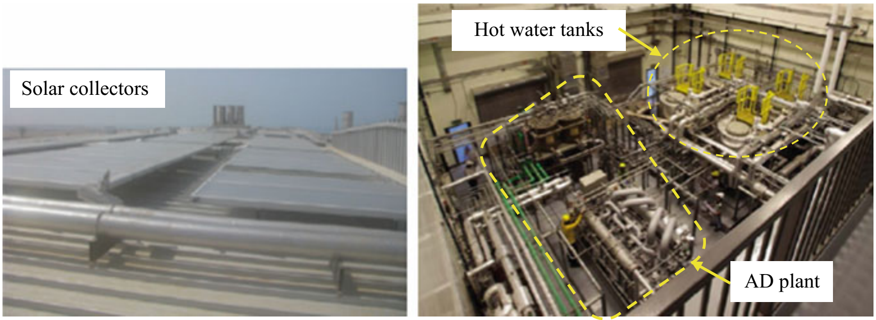


Fig. 13 Pictures of the solar-powered adsorption desalination plant at KAUST, KSA [25]

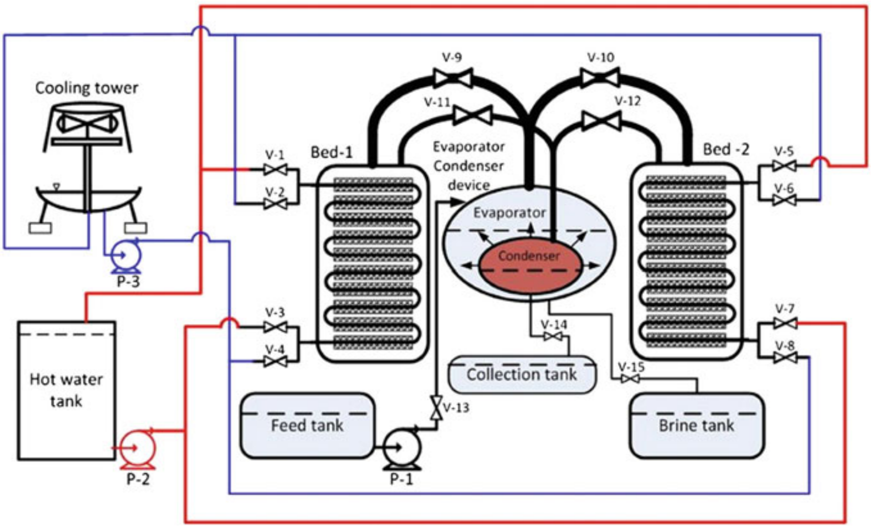


Fig. 14 AD plant with integrated evaporator–condenser unit [25]

the timing scheme for two-bed/two-stage and three-bed/three-stage modes. Brackish water evaporates in the evaporator and enters the first stage to be thermally compressed to the pressure of the interstage. The vapor of intermediate pressure goes to the second stage through a plenum to the condenser. Any pressure fluctuations arising during the adsorption and desorption period are damped in the plenum. The steam desorbed from the second-stage beds condenses in an air-cooled condenser and then collects in a tank as freshwater. The adsorption beds of this system were shell-and-tube heat exchangers packed with silica gel whose diameter of 1.6 mm on the shell side and heat transfer fluid, which is water in this case, in the tube as shown in Fig. 19. The absence of fins makes the packing of the silica gel easy by pouring it from the top, and it becomes easier for vapor to penetrate through the bed. Results indicated that an SDWP of 0.94 kg/kg of silica gel and cooling capacity of 26 W/kg of

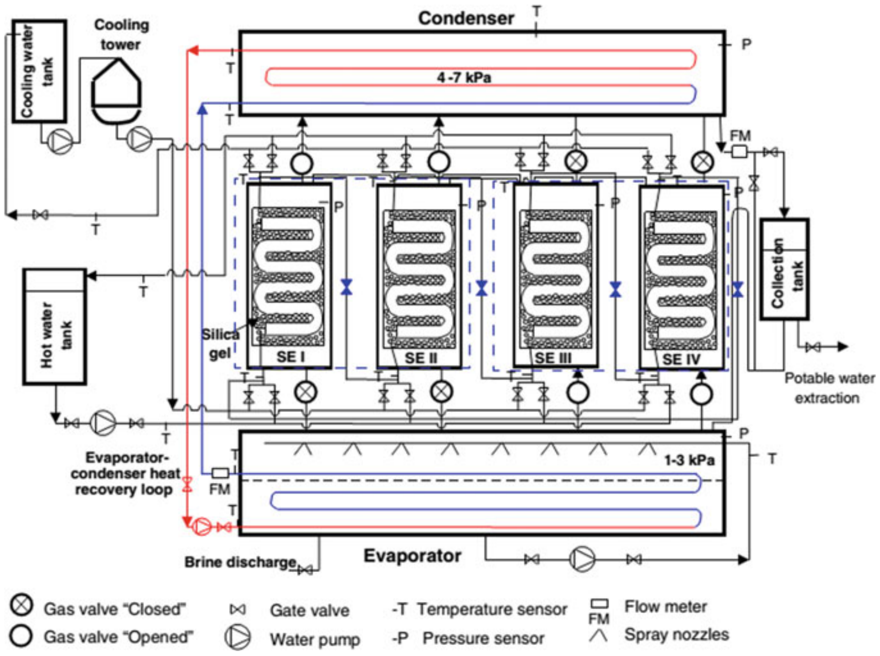
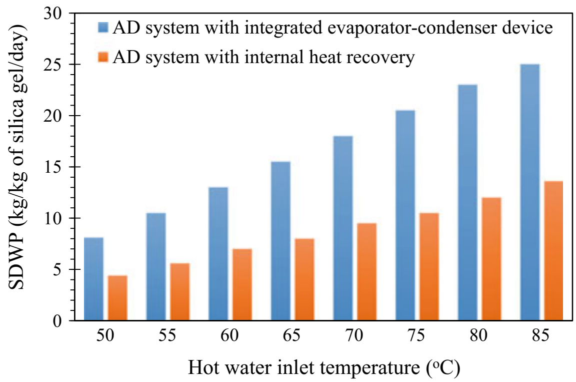


Fig. 15 Schematic view of advanced AD system using an evaporator–condenser water circulating circuit and internal heat recovery [25]

Fig. 16 SDWP of advanced AD systems at various hot water inlet temperatures



silica gel with COP of 0.25 are produced from four-bed/four-stage AD system [12]. These results were achieved at 1.7 kPa evaporator pressure and 1800 s half-cycle time. Moreover, simulations and experiments were conducted at various cycle times and evaporator pressures to predict the desalinated water output. Figure 20 depicts the effect of evaporator pressure on SDWP produced from two-bed/two-stage (see Fig. 21) and three-bed/three-stage AD system at a half-cycle time of 1800 s [13, 14]. SDWP obtained from three-bed/three-stage AD system is about 50% higher than two-bed/two-stage mode because of the existence of an extra bed/stage, thereby increasing the vapor uptake. Furthermore, the influence of the chilled water inlet temperature and air temperature on SDWP of two-bed/two-stage was studied experimentally and numerically at 85 °C hot water inlet temperature [16, 17]. Figure 22 summarizes that this system produces an SDWP around 0.9 kg/kg of silica gel per day at 1800 s optimal half-cycle time of using a chilled water inlet temperature and an air temperature of 20 and 39 °C, respectively.

A developed zeolite material, namely as AQSOA-Z02, was proposed to be used in adsorption cooling and desalination applications [46]. A differentiation between the silica gel and AQSOA-Z02 was carried out when the adsorption cycle operates in two-bed mode producing desalinated water as well as cooling effect. AQSOA-Z02 was found to be not sensitive to the variations of chilled water temperature like silica gel. AQSOAZ02 cycle delivered a SDWP of 5800 L of water per day and a SCP of 176 kW at 10 °C evaporator temperature. In turn, silica gel cycle generated only SDWP of 2800 L and SCP of 60.5 kW at the same evaporation temperature. Results addressed that cycle using a silica gel could produce a maximal SDWP of 8400 L and SCP of 219.5 kW at a regeneration temperature of 85 °C and evaporator temperature of 30 °C. Youssef et al. [46] conducted a numerical study to investigate the implementing of AQSOA-Z02 in a new four-bed AD system. It consists of an integrated evaporator–condenser device, evaporator, and condenser. Results showed that production rate of the freshwater could reach 12.4 kg/kg of adsorbent per day and a cooling capacity of 114 W/kg of adsorbent at 10 °C evaporator temperature by using a heat recovery scheme between the components of the system. In addition, results indicated that the system could produce a desalinated water of 15.4 kg/kg of adsorbent per day in the absence of the cooling effect. Ali et al. [2] presented a numerical study for a double-stage system to provide a potable/freshwater from condensers of both stages and cooling effect through stage 1 as shown in Fig. 23. AQSOA-Z02 (i.e., advanced zeolite material) and silica gel utilized as a solid adsorbent in stages 1 and 2, respectively. The system was equipped with a heat recovery between evaporators and condensers of the cycle to increase evaporator pressure and decrease the condenser pressure. This approach resulted in increasing the system outputs. The SDWP from stage 2 was calculated to be 10 kg/kg of silica gel per day for 600 s cycle time. This new configuration produces a more cooling effect and freshwater than the conventional adsorption cooling and desalination systems by 45 and 26%, respectively.

Askalany [5] proposed and studied an innovative integration of adsorption technique and mechanical vapor compression (MVC) cycle as shown in Fig. 24. The performance of the proposed cycle was evaluated theoretically at various operating

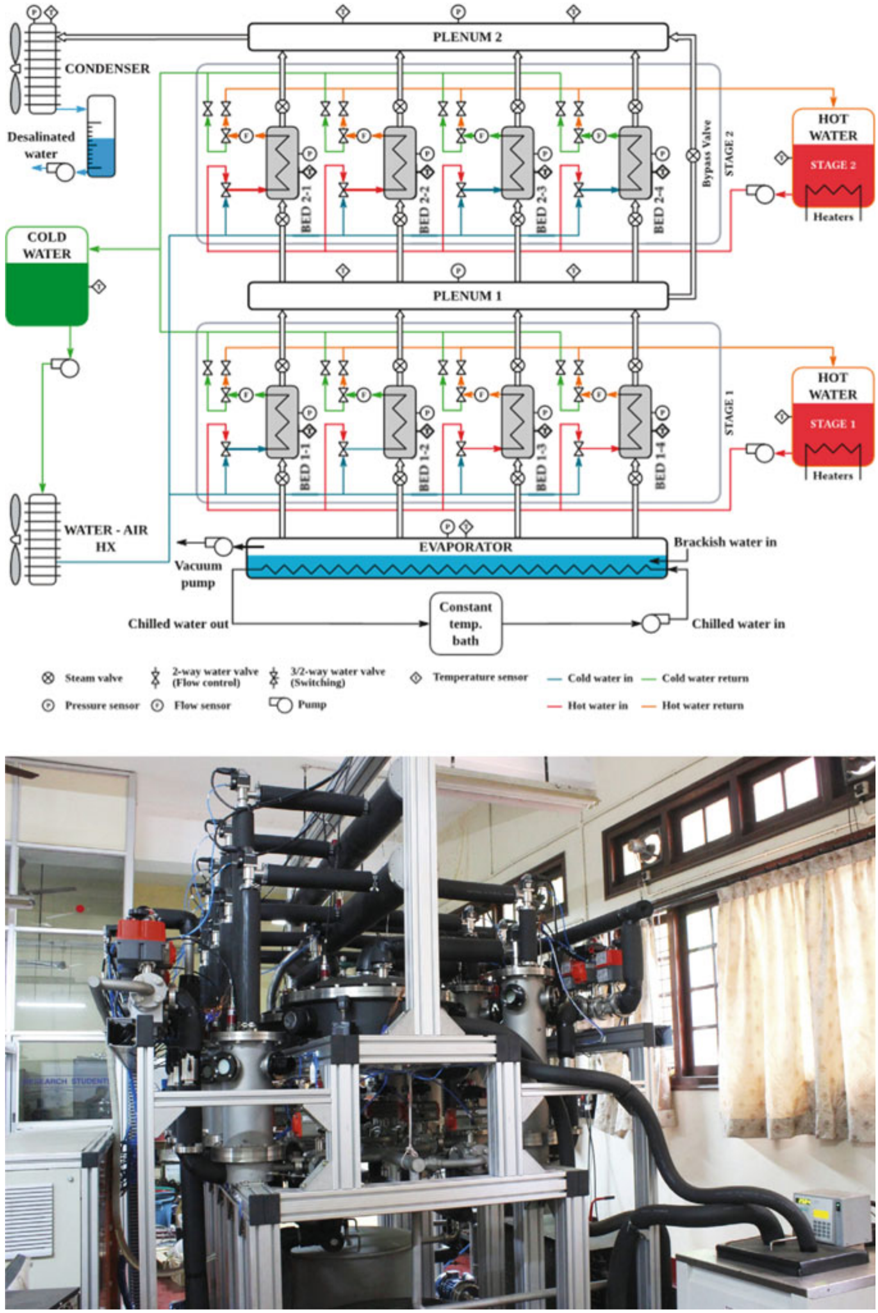


Fig. 17 Schematic and photograph of two-stage, four-bed/four-stage AD system [14]

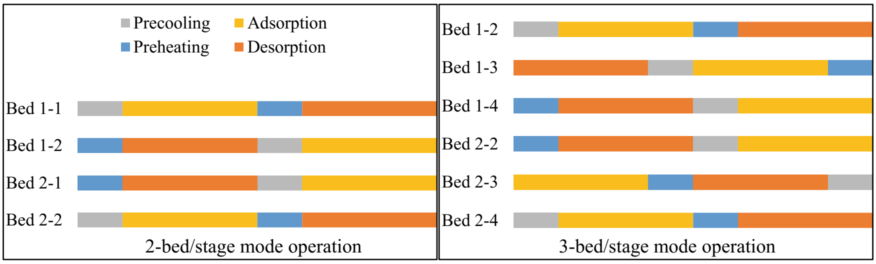


Fig. 18 Timing scheme for two-bed/two-stage and three-bed/three-stage mode operation of AD system

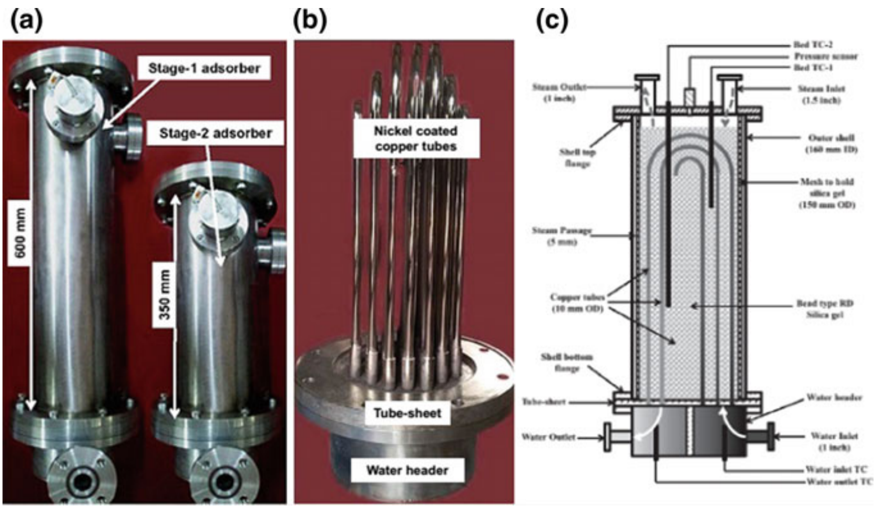
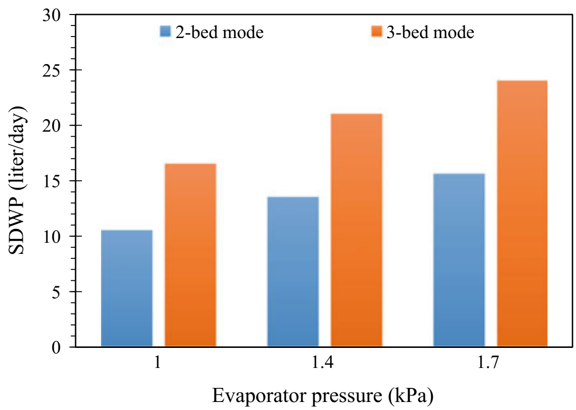


Fig. 19 Construction details of adsorber **a** beds of stage 1 and stage 2, **b** assembly of copper tubes, and **c** schematic view of adsorber [14]

Fig. 20 SDWP of two-bed/two-stage and three-bed/three-stage AD system



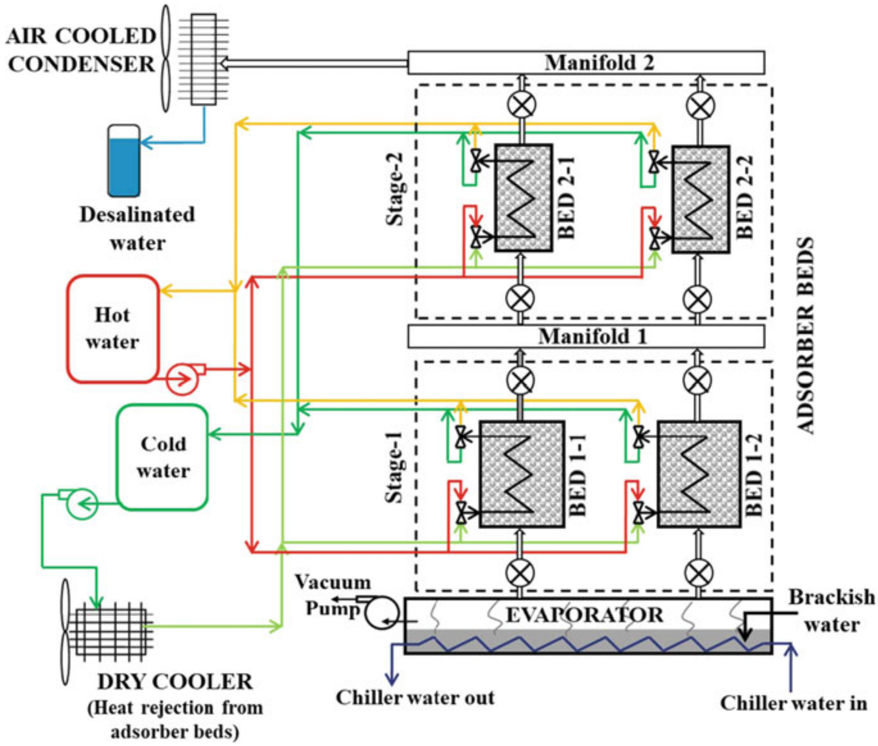


Fig. 21 Drawing of two-stage adsorption cooling desalination system using air-cooled condenser [13, 14]

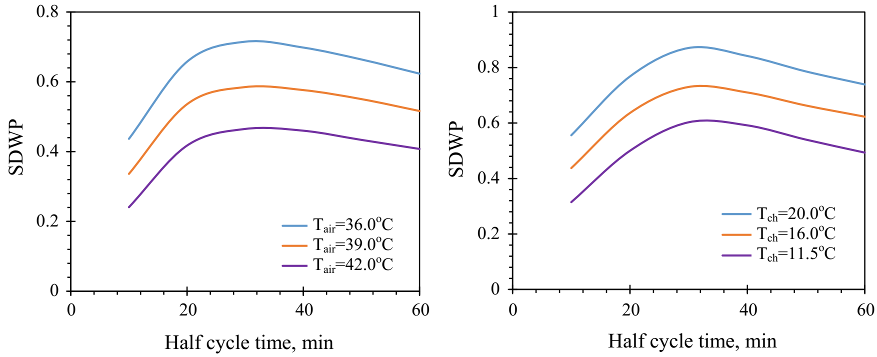
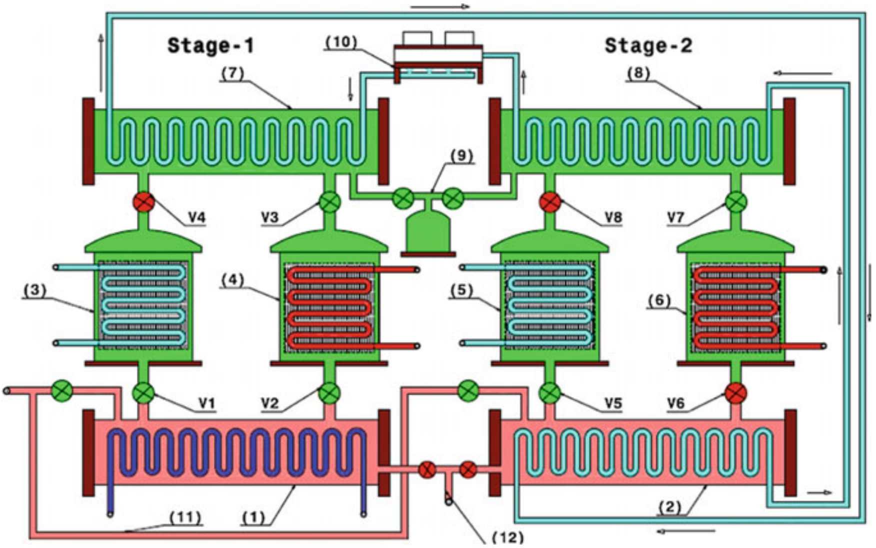


Fig. 22 SDWP of two-bed/two-stage AD system at various air temperatures and chilled water temperature and 85 °C of hot water inlet temperature



Cooling cycle **Desalination cycle**

1,2	Evaporator	3,4,5,6	Adsorber bed	7,8	Condenser
9	Water tank	10	Cooling tower	11	Feed water line
12	Brine discharge line	V1-V8	Electromagnetic valves		

Fig. 23 Schematic drawing of multistage AD system [2]

conditions using FORTRAN code. It was decelerated that SDWP of 14 kg/kg of silica gel and SCP of 0.21 kW/kg of silica gel may be delivered, respectively. Compared with a conventional AD cycle, the daily desalinated water was increased by 10–45% according to the driving temperature. Alsaman et al. [4] designed, built, and tested a new proposed solar adsorption cooling and desalination unit that operates under Egypt's climate conditions. Figures 25 and 26 show solar hybrid AD system using silica gel as a solid adsorbent material. The system was designed and built on Sohag University, Egypt, and driven by 4.5-m^2 evacuated tube solar collector. The solar collector was connected to a thermal storage water tank driving the system. The experimental measurements showed that the system is able to produce a SDWP of 4 L per kg of silica gel and 5.3 L per kg of silica gel using cooling water inlet temperature of 30 and 25 °C, respectively. Simulation results showed that SDWP of 8 kg/kg of silica gel every day could be produced at a cooling water temperature of 15 °C.

Thu et al. [38] investigated a multi-bed adsorption unit using internal heat recovery approach between evaporator and condenser for desalination purposes. Schematic diagram and photographic views of a four-bed AD cycle are given in Figs. 27 and 28. This configuration has three significant advantages:

(i) maximal use of the heat source,

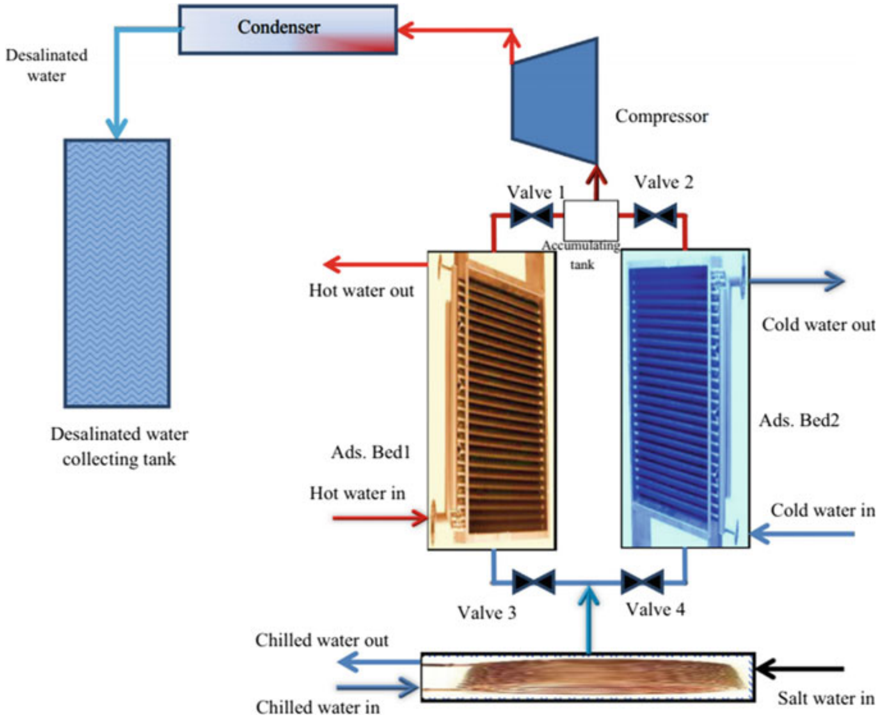


Fig. 24 Schematic diagram of MVC-AD system [5]

(ii) less variation in the evaporation and condensation temperatures,
(iii) saving in the pumping power because of the decreasing in the flow rate of the heat transfer fluids.

SDWP of this cycle was estimated to be around 10 L per kg of silica gel using a generation temperature of 70 °C. Figure 29 presents a comparison of various kinds of adsorption cooling desalination systems. One advantage of this AD cycle with this proposed configuration is its ability to provide good performance using a low heat source temperature of 50 °C.

Metal–organic frameworks (MOFs), such as CPO-27(Ni), were proposed to be used as adsorbent instead of silica gel due to its low water uptake capacity. MOFs are porous substances with high internal surface area and hence providing high adsorption uptake. Utilizing of CPO-27(Ni) experimentally as an adsorbent material in an adsorption system using only one bed for cooling and water desalination applications was investigated [44]. In adsorption desalination cycle, it is not necessary for the evaporator pressure to be less than condenser pressure, because the cycle is an open loop in which evaporator is fed by seawater and desalinated freshwater extraction from the condenser. The experimental results presented the SDWP at various condenser and evaporator temperatures as indicated in Fig. 30. Lowering the condenser

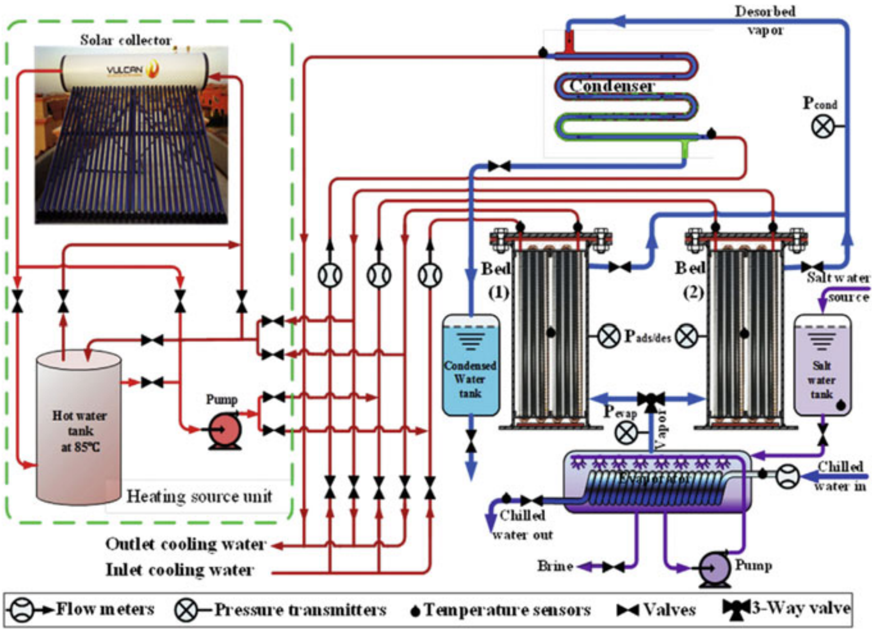


Fig. 25 Schematic diagram of the hybrid ADC system [4]

temperature decreases the operating relative pressure ratio and allows the bed uptake to reach a low amount. This leads to a remarkable increase in the cycle outputs. In turn, increasing the evaporator temperature from 10 to 40 °C increases the freshwater production rate from 6.8 to 20.6 L per kg of adsorbent/day when the cycle is operated at 10 °C condenser temperature. A SDWP of 22.8 L per kg of adsorbent/day was produced using evaporator temperature of 40 °C, condenser temperature of 5 °C, and regeneration temperature of 95 °C.

4 Multi-effect Desalination/Adsorption (MEDAD) Cycle

Selecting the right technology for the desalination depends on many parameters such as site location for brine discharge and feed intake, sort of energy source, and the quality of produced water. Most of the thermal-activated desalination plants have two main issues: (1) boiling of the seawater consumes high energy and (2) fouling and scaling of the condensing/evaporating units. From the point of view of energy efficiency, the adsorption desalination cycle is incompetent for water production in the basic cycle arrangement due to the large latent heat of evaporation. It typically depletes around 640 kWh/m^3 of electrical power or more. Less than 15 kWh/m^3 energy efficiency could be achieved by cycling the latent heat of evapo-

Fig. 26 Photographs of the ADC system built at Sohag University, Egypt [4]

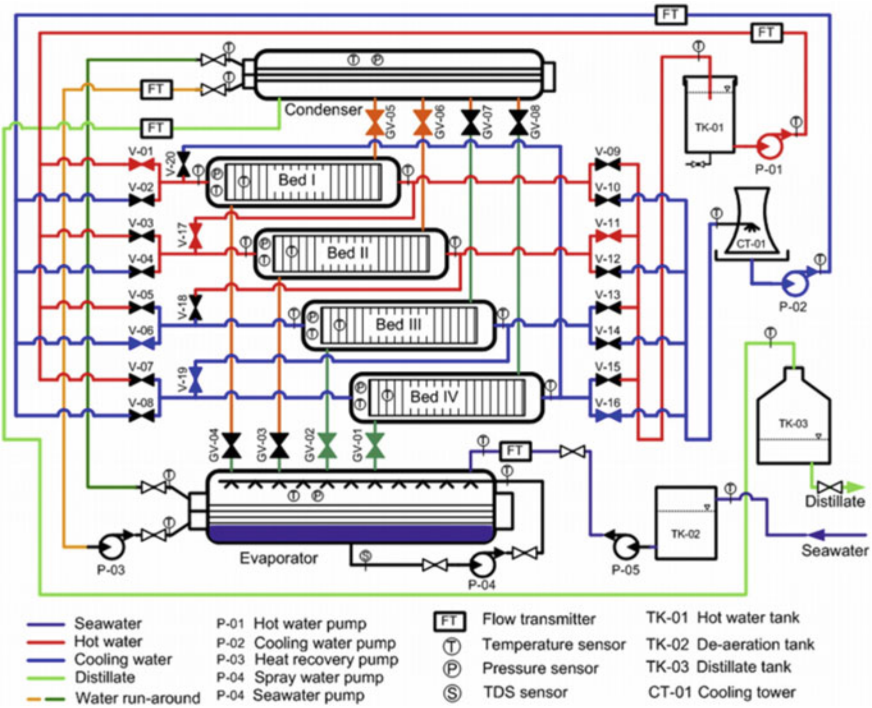


Fig. 27 Schematic diagram of a master-and-slave configuration of four-bed adsorption cooling desalination cycle [38]

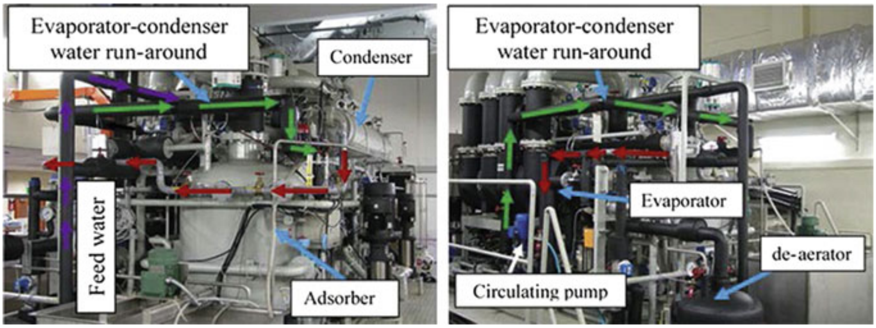


Fig. 28 Photographs of the four-bed adsorption desalination (AD) system [38]

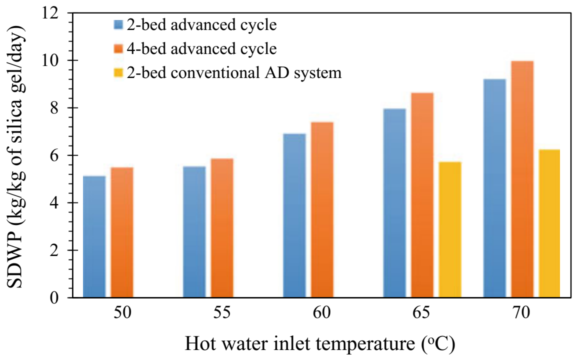


Fig. 29 SDWP of several AD system configurations at various hot water inlet temperatures

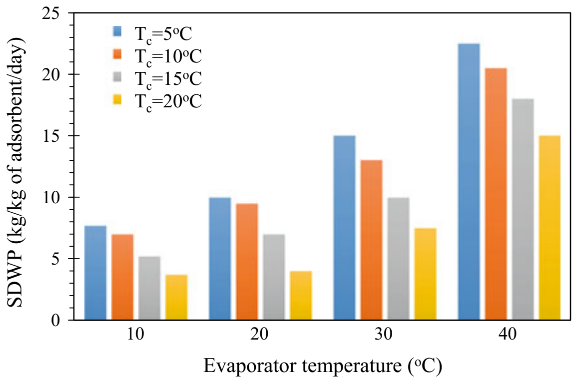


Fig. 30 SDWP produced from one-bed AD system at different condenser and evaporator temperatures

ration/condensation many times [27]. To achieve this objective, the adsorption desalination technology is integrated into thermally driven desalination cycles like MSF or MED cycle. The adsorption desalination cycle treats highly concentrated feedwater, ranging from chemically laden wastewater to groundwater and to seawater.

A three-stages MED system was engineered and built in the National University of Singapore (NUS) and then coupled to four-bed AD system as presented in Figs. 31 and 32 [27, 30]. Multi-effect desalination adsorption (MEDAD) system is an integration of traditional MED and AD cycle. MED comprises of a brine storage tank and four evaporating/condensing effects, while the AD plant consists of four adsorption beds and one condenser. Seawater (i.e., feed water) is evaporated by falling film evaporation process in the four effects of MED cycle. Evaporation heat is recovered by reusing of the vapor condensation heat in the MED stages. The energy recovery by vapor condensation and vapor production process continue till the last stage of the desalination cycle. The vapor generated in the last stage goes to adsorption beds to be adsorbed on the surface of adsorbent pores. As long as the adsorbent adsorbs the vapor, the pressure drops and allows the saturation temperature of the last stages to be less than the ambient temperature. Hooking the AD to the last stage of MED helps to expand the temperature operation range that helps to add more numbers of MED

Fig. 31 A three-stages MEDAD experimental unit built in NUS [27, 35]

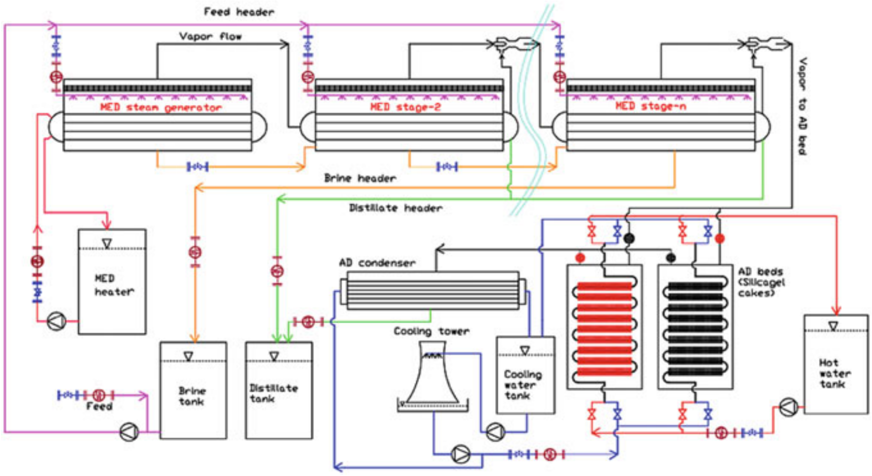


Fig. 32 A schematic of the hybrid MEDAD pilot [27, 35]

stages, resulting in higher system performance ratio. The hybrid plant was tested at assorted heat source temperatures ranging from 15 to 70 °C [30]. It was observed that the hybrid MEDAD cycle has a noticeable rise in freshwater production, up to 2.5 to threefold compared with a traditional MED at similar operating conditions. Later, it was reported that MEAD cycle with seven intermediate stages produced an SDWP of 24 kg/kg of silica gel with a performance ratio of 6.3 [35].

5 Trend of AD System in the Near Future

Adsorption-based desalination plants powered by solar energy have been built and installed at KAUST in Saudi Arabia and at NUS in Singapore. Different systems have been installed in Singapore that use waste heat. In Saudi Arabia, three large-scale systems will be implemented in the near future for desalination purposes. Specific electrical energy consumption of less than 1.5 kW/m^3 has been reported for AD technology, which is substantially less than seawater desalination using traditional thermal-based and membrane-based technologies [22]. Although the theoretical invented and developed cycles of water desalination using adsorption/desorption phenomena are not so recent, the experimental investigations are still in the cradle with age less than 20 years. During this short period, specific daily water production from experimental AD systems is still under 10 kg/kg of silica gel/day with an ascending increase in the last few years. This may lead to an expectation of intensive researches that might be conducted in the next few years in this field.

Based on the above-figured state of the art, one could extract some beneficial data that could help in predicting the near future of the adsorption desalination technology. The presented data could be summarized in Table 2 and Fig. 33. It can be seen that silica gel comes first undisputed adsorbent of the applied materials in AD experimental systems. The maximum SDWP could be achieved until now is less than 25 kg/kg of adsorbent per day.

6 Conclusion

The efficient use of the renewable energy is the prime mover of the future sustainable development of desalination plants. Energy and water systems are interconnected as energy is required to produce clean water and provide cooling power. Brackish or seawater is used in the adsorption cycle to produce potable water and cooling power as well. This hybridization has been proposed for energy efficiency improvement and system performance enhancement. Recent developments in the working pairs used in different arrangements of hybrid adsorption-based desalination (AD) system are reviewed in this chapter. It is shown that the water production and cooling power mainly depend on the ability of the adsorbent materials to adsorb vapor and the adsorption rate of the bed. Therefore, the picking up an appropriate working pair is a key parameter for designing an efficient hybrid adsorption-based desalination plant. It is highlighted that the operating conditions and cycle time of the system significantly affect the water production. Reviewing the developments of this system in the last decades reveals that the adsorption system could produce potable water of 25 kg/kg of adsorbent when it is integrated with multi-effect desalination (MED) cycle. This integration also reduces the corrosion in the MED system and increases its production by twofold compared with traditional MED systems. The low water production rate produced by hybrid adsorption-based desalination system

Table 2 Summary of experimental and simulated adsorption desalination systems

Adsorbent	System configuration	Approach	T_{source} (°C)	Cycle time (s)	SDWP (kg/kg adsorbent/day) SCP (TR/ton of adsorbent)
Zeolite 13X [47]	MEDAD	Exp. and sim.	120–195	NA	0.12 N/A
Silica gel [39]	Four beds, single stage	Exp.	85	180	4.7 N/A
Silica gel [23]	Four beds, single stage	Exp.	84	NA	7.8 N/A
Silica gel RD [24, 36]	Two beds, single stage	Exp./sim.	85	1240	9 N/A
	Four beds, single stage			1080	10 N/A
Silica gel RD [24]	Four beds, single stage	Exp. and sim.	85	1200	3–5 25–35
Silica gel RD [37]	Two beds with internal heat recovery	Exp.	70	600	9.34 N/A
Silica gel RD [37]	Two beds with internal heat recovery	Sim.	85	600	13.7 N/A
Silica gel [26]	Four beds, single stage using 30 °C chilled water temperature	Sim.	85	960	8 52
Silica gel [25]	Four beds, single stage	Exp.	85	NA	12.5 N/A
Silica gel A++ [34]	advanced two beds with internal heat recovery	Exp.	85	1440	13.46 N/A
Silica gel A++ [32]	Two beds with internal heat recovery and encapsulated evaporator—condenser	Sim.	85	600	26 N/A
Silica gel RD [15]	Four beds, single stage	Exp.	85	1200–1800	2.3 18
Silica gel [29]	MEDAD two beds using 100 kg of silica gel	Sim.	50	NA	5 LPM

(continued)

Table 2 (continued)

Adsorbent	System configuration	Approach	T_{source} (°C)	Cycle time (s)	SDWP (kg/kg adsorbent/day) SCP (TR/ton of adsorbent)
Silica gel [42]	Two beds	Exp. and sim.	80	NA	SDWP of 0.315 during 10^5 s
Silica gel RD [10]	advanced four beds T_{cond} = 30 °C and T_{evap} = 7 °C	Exp.	85	200–700	SDWP 12 SCP 25
Silica gel RD [13]	Two beds, two stages, P_{evap} of 1.7 kPa.	Exp.	85	3600	15.8 L/day 460 W
Silica gel RD [43]	Two beds T_{cond} = 10 °C and T_{evap} = 30 °C	Sim.	85	425	10 77
AQSOA-Z02 [45]	Four beds, T_{evap} = 10 °C	Sim.	85	600	6.2 53.7
	Four beds, T_{evap} = 30 °C				7.2 55
Silica gel [45]	Four beds, T_{evap} = 10 °C	Sim.	85	600	3.5 18
	Four beds, T_{evap} = 30 °C				9.3 66
Silica gel [5]	Two beds, single stage	Sim.	85	500	14 60
Silica gel RD [14]	Two beds, two stages at P_{evap} = 1.7 kPa	Exp.	85	3600	15.6 7.4
	Three beds, two stages at P_{evap} = 1.7 kPa				24 7.4
	Four beds, two stages at P_{evap} = 1.7 kPa				N/A 5.5
Silica gel RD [17]	Two beds, two stages at P_{evap} = 1.7 kPa	Sim.	85	3800	0.9 6.8
Silica gel [4]	Two beds, single stage	Exp. and sim.	95–75	650	4 33

(continued)

Table 2 (continued)

Adsorbent	System configuration	Approach	T_{source} (°C)	Cycle time (s)	SDWP (kg/kg adsorbent/day) SCP (TR/ton of adsorbent)
CPO-27(Ni) [9]	Two beds, single stage	Sim.	150	700	4.3 35.3
Aluminum fumarate [9]	Two beds, single stage	Sim.	150	700	6.5 22
CPO-27(Ni) [44]	One bed at $T_{cond} = 5$ °C and $T_{evap} =$ 40 °C	Exp. and sim.	95	600	22.8 65

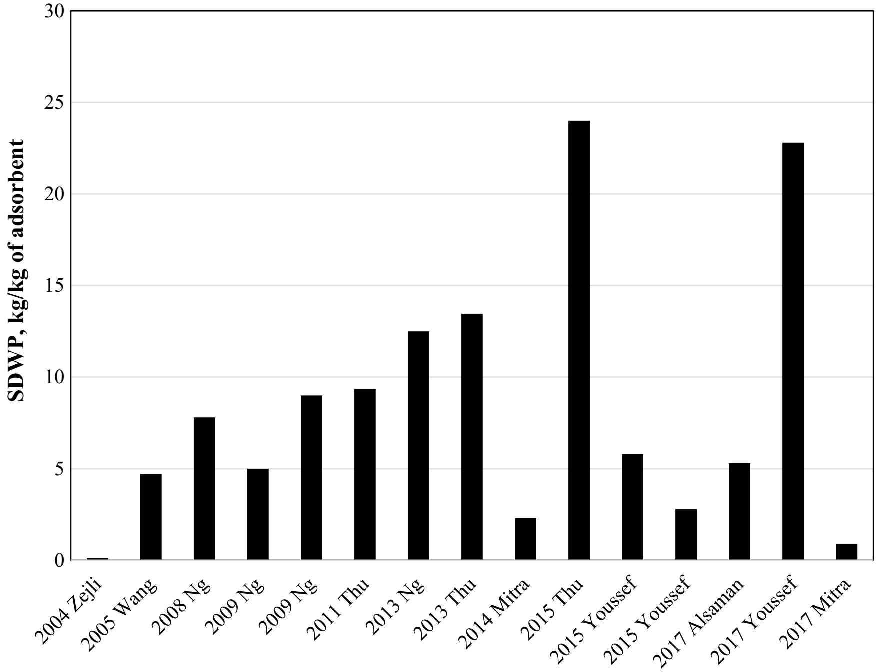


Fig. 33 SDWP of established experimental AD systems in a chronological order

is controlled by thermal response of the adsorption bed and mass transfer inside the adsorbent material. Therefore, more research and developments are inevitable to design adsorption beds with low thermal resistance and high adsorption rate to be able to achieve more folds in water production. Lowering the cost to be less than US$0.5/m^3 of potable water will be an additional challenge that needs to be overcome. Achieving these goals will help in designing a new generation of AD system that will be able to compete with the other desalination technologies and meet the increasing demand of clean water especially in rural and remote coastal areas.

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