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Numerical Study of an Adsorption Water Desalination System Utilizing Low-grade Heat Sources

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Abstract

Adsorption desalination technology has gotten a lot of attention in the recent decade. It can be powered by waste heat sources, which means it uses less energy and emits less CO2. This research investigates a two-bed silica-gel/water-based system. The conservation of energy/momentum equations of the current system are modeled using MATLAB SIMULINK software, as a result of which the energy balance equations for the adsorber bed, condenser, and evaporator were solved. The study is carried out with the investigation of many key parameters like heat source, condenser, evaporator temperatures and half-cycle time to find their effect on the SPECIFIC DAILY WATER PRODUCTION (SDWP) and SPECIFIC COOLING POWER (SCP) generated from the system. The simulation model used in this paper was verified using previously published experimental research. The results show that the maximum (SDWP) generated from the system is (19.3221 l/kg_{ads}/day) and (SCP) is (493.183 W/kg_{ads}). A comparison was made to the current research with previously published research, and promising results were obtained.

Keywords: Desalination, Adsorption, Silica-gel, SDWP, SCP, Low grade heat sources.

1. Introduction

Recently worldwide, clean water and a sufficient amount of energy have been re-identified as critical determinants for long-term growth. Desalination (the conversion of saltwater to potable water) is a great example of how these three elements are linked. Seawater is a particularly attractive alternative water supply due to its availability and is less impacted by climate change compared with other water resources[1]. Desalination operations, like thermally-driven, electrically-driven, and pressure-driven processes in general, need a lot of electricity or a lot of heat, and maintenance is tough and expensive[2]. As a result, water desalination has led researchers and engineers to develop new techniques that are both energy efficient and environmentally beneficial. The traditional desalination devices, such as MULTI-STAGE FLASH (MSF), REVERSE OSMOSIS (RO), and MULTI-EFFECT DISTILLATION (MED), are either energy-consuming or expensive to maintain[3]. As a result, a device that uses little energy and requires little maintenance is needed. Low-grade energy (<120°C) silica-gel-water ADSORPTION DESALINATION (AD) device that substitutes the mechanical energy compression mechanism with thermal compression that primarily requires heat as input is one of the effective solutions that needs minimal energy. Furthermore, system operation is low-cost because of the reduction of rotating parts throughout compression and the absence of expensive filters for desalination. The adsorption desalination system can also produce cooling, allowing it to meet the double demands of desalination and cooling, which is advantageous in hot climates[4]. In this paper, a simulation model was created using Simulink Matlab to study a two-bed adsorption desalination system using silica gel as an adsorbent. Silica-gel/water has small adsorption uptake of 00.2 kg/kg $_{ads}$, but some types have higher water [5]. To assess the optimal operating conditions, the simulation analysis compares the efficiency of the adsorption desalination (AD) device for varying cyclic times and condenser, evaporator temperatures, as well as different temperatures of the regeneration water. Researchers have Studied desorption technologies for the past 25 years, looking at applications such as desalination, cooling, and energy generation.

2. Literature Review

Kyaw et al.(2013)[6] used a numerical simulation of an advanced adsorption desalination cycle with two beds to examine an internal heat recovery between the evaporator and the condenser. The advanced adsorption desalination AD cycle has the benefits of lower parasitic electrical power consumption (1.38 kWh m^3) and a higher silica-gel adsorption capability (40 % of the mass of the adsorbent). Mitra et al. (2014)[4] studied a numerical analysis of a 4-bed single-stage silica-gel/ water solar-driven adsorption desalination system. According to the simulation results, the single-stage adsorption desalination AD device had an optimal half-cycle time of 600-900s and a condenser temperature of 25ºC for maximum desalination of (2.4 m^3 per day per ton of silica-gel).The results showed that hybridizing multi-effect desalination and adsorption desalination plants improve yield by more than three times (6.2 LPM) with the same parameters as conventional multi-effect desalination plants. Shahzad et al. (2014)[7] provided a numerical analysis on a novel desalination cycle that combined a classical multi-effect distillation (MED) technology with a contemporary, low-energy adsorption desalination technique (AD). The proposed MEDAD cycle was statistically analyzed and compared to classic and hybridised MED water output rates. The MED and adsorption desalination AD modeling equations were constructed in FORTRAN using a user-defined subroutine. The results revealed that hybridising MED + AD plants enhances output by more than three times (6.2 LPM) with the same parameters as classic MED plants. A numerical simulation of a combined adsorption desalination cycle with joined evaporator/condenser had been proposed by Youssef et al. (2016)[8]. It was made up of two cycles of two adsorber beds joined by a combined evaporator/condenser. The first cycle used the built-in evaporator/condenser as a condenser, while the second cycle utilized it as an evaporator (lower). The cooling effect of the lower cycle evaporator and the combined evaporator/condenser may be used to produce low condensing temperatures in this system, enhancing system efficiency. Simulink was used to model a full-scale adsorption system with the setup shown. The daily water output fluctuated between 6.64 and 0015.4 m^3per ton adsorbent per day. Adsorption-assisted cooling and desalination were proposed by Syed (2016)[9], who used zeolites and silica-gel as adsorbents and water as an adsorbate. They developed a cooling and desalination system that integrates the adsorption cooling (stage-1) technology with the adsorption desalination system (stage-2). In both cycles, heat recovery between the condensers and evaporators enhanced overall efficiency. The results showed that the system's cooling capacity is 44% and SDWP 45% higher than the traditional two-bed cum desalination adsorption, the SDWP of phase-2 is 18% more than a classic 2 beds adsorption desalination AD, the system is 26% more water and 45% more cooling than a classic two-bed desalination system of the same scale. Thu et al. (2016)[6] investigated the efficiency of a waste heat-driven three-beds, two-evaporators adsorption cycle for cooling and desalination numerically. The adsorbent material was A++ silica-gel with a surface area of 0863.6 m^2 per g and a pores volume of 00.446 cm^3 per g. The findings showed that at a rate of (6.5 m^3 / ton of silica-gel / day), the cycle yielded high-quality potable water. Ali et al. (2017)[10] used a theoretical simulation to look at the impact of RO brine recycling with adsorption desalination on total desalinated water productivity in a system. Engineering equation solver (EES) was used to simulate reverse osmosis desalination, while MATLAB is used to simulate the adsorption desalination method. The RO-AD findings indicated that, as compared to a single-stage RO system, system recovery increased by about 25%, resulting in a maximum achieved water productivity of 7.8 m^3/ ton of silica-gel. Eman et al.(2017)[11] used Simulink software to simulate the thermodynamic cycle performance of a two-bed adsorption device in order to establish the aptitude and performance under different operating conditions of such MOFs for the desalination by adsorption. When adsorption temperature (505°C) and desorption temperature (110°C) are presented, the CPO-27(Ni) was found to be more suited, with an SDWP of 4.61 m^3. $(ton.day)^{-1}$. With SDWP of 6.3 m^3. $(ton.day)^{-1}$, the aluminium fumarate worked effectively at high evaporator temperatures (20°C). At increased evaporator temperatures (20°C), the aluminum fumarate beat the other materials with an

SDWP of 6.3 m^3 $(ton.day)^{-1}$. It was also revealed that aluminum fumarate had a low desorption temperature (70 °C). The MIL -101 (Cr) adsorbent outperformed all other adsorbents, yielding 11 m^3. $(ton.day)^{-1}$. Rezk et al. (2019)[12] published a numerical analysis to determine the best operating conditions for a solar-driven adsorption desalination cooling (SADC) device in order to improve its performance. A mathematical model based on silica-gels has been suggested for the SADC technique. The radial movement optimizer is an optimization method that is used to identify the optimal operational parameters for the SADC mechanism. It is a robust, simple, and quick algorithm. The ideal operating circumstances resulted in a 70% increase in SDWP and SCP with no changes to the device setup or components utilized. The intended SADC system may produce 6.9 m^3/day/ton desalinated water and 191 W/kg cooling capacity, among other things. Ali et al. (2020)[13] proposed a theoretical mathematical structure based on novel innovative adsorption desalination and cooling device consisting of a two-cycle multi-bed, tow-evaporator with internal heat recovery and silica-gel as the adsorbent substance. The findings revealed that not only can the proposed configuration's SDWP benefit by 20% as compared to a single-cycle multi-bed, two- evaporator design, but it can also supply large volumes of two different results of cooling water, with 9.6 m^3 of SDWP and 24 and 25 Rton/ton. Using silica-gel as an adsorbent, Amirhossein et al. (2020)[14] explained a modern double-bed ADS with the recovery of heat and mass between cycle parts. In the recovery phase, cold water was utilized to remove heat and transmit it to the evaporator from the beds and condenser. The daily water production (SDWP) for these 2-bed ADS was 009.5 m^3/ton of silica gel.day^{-1}. The SDWP was therefore 66 percent greater than the normal 2-bed ADS for the innovative 2-bed ADS. Ahmed et al. (2020)[15] proposed a novel hybridization of two ejectors and an adsorption desalination system. This integration used a working pair of silica gel and water. AD2EJ contained two sorbent beds, two evaporators, two condensers, and two ejectors, as well as a hybrid design. The AD2EJ process took an optimum half cycle time of around 400 s with a silica gel SDWP of 23.0 m^3 per ton, and a desorption temperature of 85 °C. The volume of a typical desalination adsorption device was three times the volume (ADS). The AD2EJ condenser and evaporator were connected to the internal heat recovery circuit to improve its performance even further. Elbassoussi et al. (2020)[16] proposed a novel hybrid AD based on a silica-gel-based humidification-dehumidification desalination unit HDH system that produced potable water and cooling capacity at the same time. Photovoltaic (PV) panels were needed to fuel extra components. The system was turned on largely by a low-grade energy source (natural gas) (65–80°C). A robust thermo-economic model was developed and solved using MATLAB software to investigate the effect of different parameters on unit performance and product cost. The freshwater per hour was 21.75 kg, and the cooling power was 2.53, kW according to the data. This research is the first of its kind in Iraq, and we hope that it will become the basis for researchers in the field of water desalination and clean energy in Iraq.

3. System Diagram, Simulation Model and Governing Equations

The schematic diagram of the system that was simulated is shown in Figure 1.
The system consists of two adsorbent beds, an evaporator and a condenser. The specifications of the adsorption bed, evaporator and condenser are listed in Table 1. Figure 2 shows a flow-chart for the Simulink model of the 2-bed adsorption desalination cycle. This Simulink model uses an ordinary equation solver (ODE) to perform numerical integration based on an explicit Runge-Kutta process proposed by 'Dormand and Prince' with a configurable time step and relative tolerance of 10^{-3}.
To model any adsorption unit, a range of equations are needed, including an adsorption material description on the simulation software, an energy balance for the adsorber bed, evaporator, condenser, and secondary heating/refrigeration water circuits.

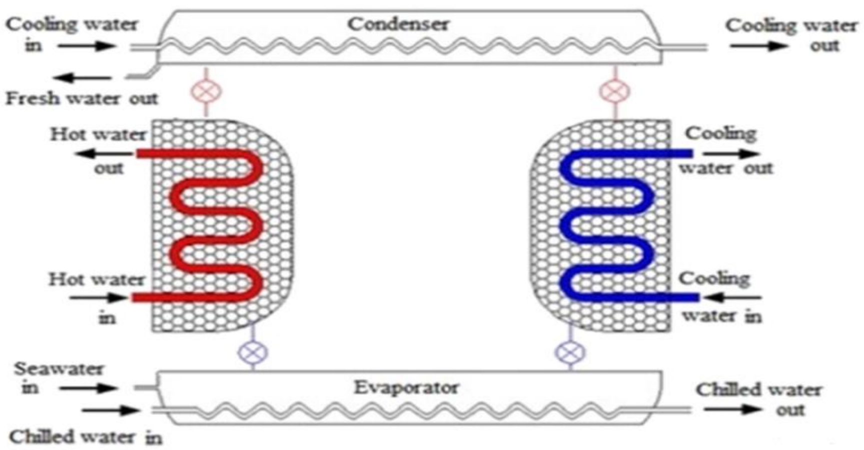

Figure 1 Schematic diagram of AD system[1].

The Dubinini-Astakhovi (D-A) model (Equation.1) is used to model silica-gel isotherms. [1]

Table 1 Dimensions of the simulated system

ADSORPTION BED		EVAPORATOR		CONDENSER	
Bed fin long	172 mm	Coil outer dia.	15.87 mm	Coil outer dia.	15.87 mm
Bed fin height	30 mm	Coil thickness	0.8 mm	Coil thickness	0.8 mm
Fin Pitch	1.2 mm	No. of tube	4	No. of tube	4
Fin width	0.12 mm	Coil long	10 m	Coil long	5.5 mm
Module long	800 mm	Fin long	40 mm	---	---
Module tube number	6	Fin height	40 mm	---	---

Tube outer diameter	15.87 mm	Fin width	0.12 mm	---	---
Tube thickness	0.8 mm	Fin pitch	0.12 mm	---	---

$$C^* = C_o exp\left[-\left(\frac{RT}{E} ln\left(\frac{p}{p_o}\right)\right)^n\right] \tag{1}$$

$$\frac{dc}{dt} = (C^* - C) \tag{2}$$

$$k = k_o\left(\frac{-E_a}{RT}\right) \tag{3}$$

Adsorber /Desorber Bed Energy Balance Equation [1]

$$\left[M_a C_{p,a} + M_{HX} C_{p,HX} + M_{abe} C_{p,abc}\right]\frac{dT_{ads/des}}{dt} = ZQ_{st} M_a \frac{dc_{ads/des}}{dt} + m^{\cdot}_{cw/hw} C_p\left(T_{cw/hw,in} - T_{cw/hw,out}\right) \tag{4}$$

Evaporator Energy Balance Equation [1]

$$\left[M_{s,evap} C_{p,s}\left(T_{evap}, X_{s,evap}\right) + M_{HX,Evap} C_{p,HX}\right]\frac{dT_{evap}}{dt} = \theta . h_f\left(T_{evap}, X_{s,evap}\right) m^{\cdot}_{s,in} - z. h_{fg}\left(T_{evap}\right)\frac{dc_{ads}}{dt} M_a - \gamma h_f\left(T_{evap}, X_{s,evap}\right) m^{\cdot}_{brine} + m^{\cdot}_{chilled} C_p(T_{evap})(T_{chilled,in} - T_{chilled,out}) \tag{5}$$

Condenser Energy Balance Equation [1]

$$\left[M_{cond} C_p(T_{cond}) + M_{HX,Cond}\, C_{p,HX}\right]\frac{dT_{cond}}{dt} = z. h_{fg}(T_{cond}) M_a . \frac{dc_{des}}{dt} - h_f(T_{cond})\frac{dM_d}{dt} + m^{\cdot}_{cond} C_p(T_{cond})(T_{cond,in} - T_{cond,out}) \tag{6}$$

Evaporator Mass Balance Equation [1]

$$\frac{dM_{s,evap}}{dt} = \theta m^{\cdot}_{s,in} - \gamma m^{\cdot}_{brine} - M_a \frac{dc_{ads}}{dt} \tag{7}$$

Cycle Performance Indicator Equations [1]

$$SDWP = \int_0^{t_{cycle}} \frac{Q_{cond}}{h_{fg} M_a} dt \tag{8}$$

$$Q_{cond} = m^{\cdot}_{cond} C_p(T_{cond,out} - T_{cond,in}) \tag{9}$$

$$Specific\ cooling\ power = \int_0^{t_{cycle}} \frac{Q_{evap}}{M_a} dt \tag{10}$$

$$Q_{evap} = \dot{m}_{evap} C_p\ (T_{evap,in} - T_{evap,out}) \tag{11}$$

The range of variables used in the simulation T_b (80 – 110ºC), T_c (22 – 38ºC), T_{ch} (12 – 24ºC) half cycle time (220 – 520 s). The simulation process is carried out by entering the inputs for each part of the system, including entering the mass flow rate for each of the hot and cold water entering the adsorption bed, evaporator and condenser water, and the temperature of each water line. The material properties are identified through equations (1 to 4) for each bed. The energy balance and mass balance of the evaporator are calculated using rates (5 and 7), and the energy balance of the condenser is calculated using equation (6). In the event of desorption, the code is transmitted to the condenser to calculate its output through equation (9), which is entered into the calculation of equation (8). In the event of adsorption, the code is transmitted to the evaporator to calculate its output through equation (11) which is entered into the calculation of equation (10).

The fundamental two-bed adsorption cycle illustrated in Figure 1 has been validated using experimental data from a two-bed adsorption cooling system previously published [17]. The predicted output temperature profile of heat transfer fluids shows a less than 12% divergence from the experimental data of the bed, condenser, and evaporator.

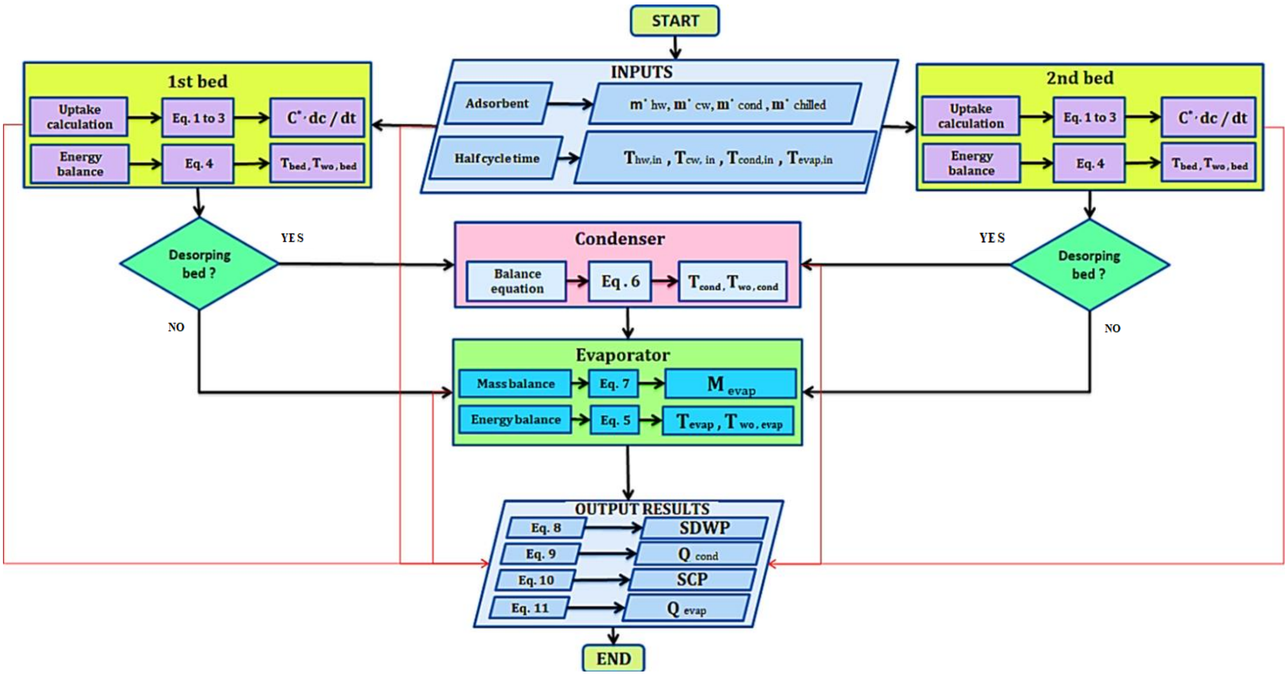

Figure 2 Flow chart for the SIMULINK model

4. Results and Discussion

The adsorption desalination system was modelled to decide the best operating parameters for achieving the maximum possible values of the two outputs, specific daily water production (SDWP) and specific cooling power. The simulated system consists of two adsorption beds and exploits silica gel as an adsorbent. The two beds system is a standard system for comparison with other, more advanced systems. Silica gel is a standard material used for comparison with modern materials, as it is the first substance used in adsorption desalination technology. Figure 3 and Figure 4 discusses numerically the relationship between the specific daily water production with the hot water temperature of the adsorption bed and the relationship between specific cooling power and hot water temperature of the adsorption bed, respectively. In these figures, the temperature was increased from 80 to 110^{o}C, with the rest of the operating conditions stable. With increasing temperature, an increase in SDWP and SCP was observed.

High heating water temperatures lead to more desorbed water vapor because of increased silica-gel uptake due to the increase in relative pressure and temperature, as shown in Figure 5, and a large amount of refrigerant vapor is produced from the adsorber bed to the condenser as the desorption temperature increases.

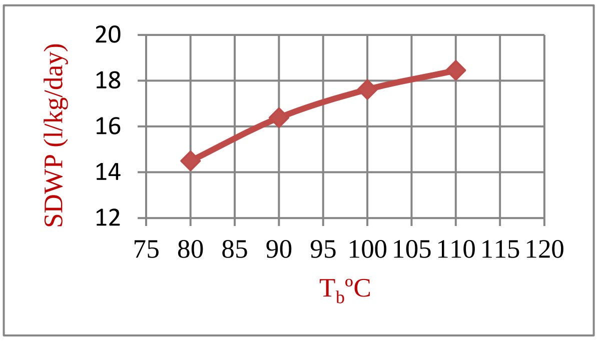

Figure 3 Temperature of bed hot water effect on SDWP

T_c=30°C, T_{ch}= 20°C, $t_{half\text{-}cycle}$ = 320 s

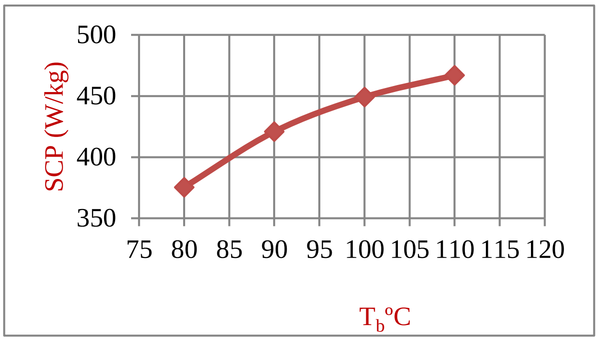

Figure 4 Temperature of bed hot water effect on SCP

T_c=30°C, T_{ch}= 20°C, $t_{half\text{-}cycle}$ = 320 s

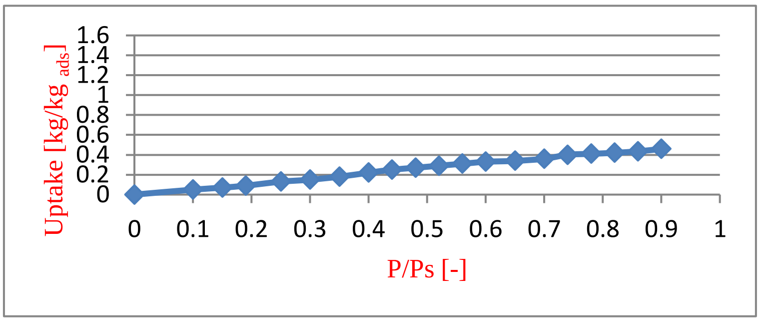

Figure 5 Isotherms of Silica - gel at 25°C.

Figures 6 and 7 discuss the effect of evaporator water temperature on SDWP and SCP, respectively. The evaporator temperature increases gradually from 12°C to 24°C with the stability of the rest of the operating conditions. The output of the system increases with the increase in the temperature of the evaporator water. The rationale for this behaviour is related to the quantity of water vapour created in the evaporator, which increases with the temperature of the evaporator water as a result of increased water absorption owing to a relative pressure increase and linear form of silica-gel isotherms.

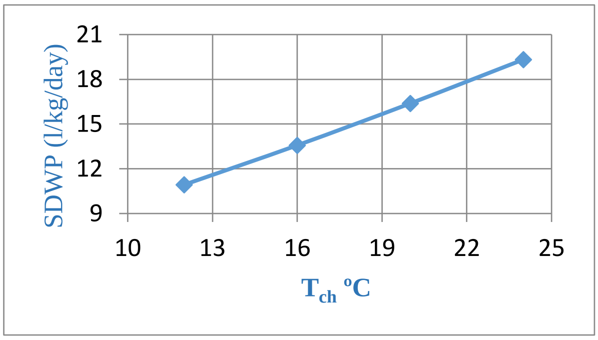

Figure 6 Effect of evaporator water temperature on SDWP

T_c=30°C, T_b= 90°C, $t_{half\text{-}cycle}$ = 320 s

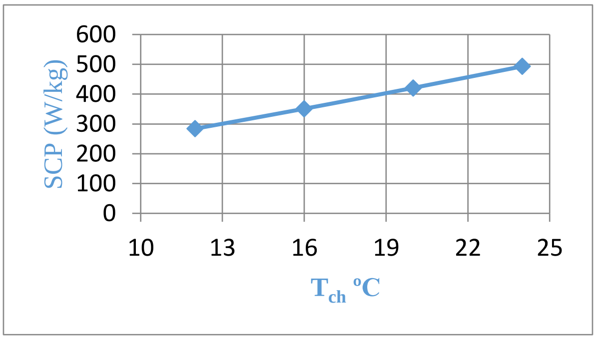

Figure 7 Effect of evaporator water temperature on SCP

T_c=30°C, T_b= 90°C, $t_{half\text{-}cycle}$ = 320 s

Figures 8 and 9 discuss the effect of condensate water temperature on SDWP and SCP. The condenser water temperature is gradually increased from 22°C to 38°C, with the remaining operating conditions fixed. The outputs of the system are inversely proportional to the temperature of the condenser water, as it was observed that these outputs decreased with the increase in the temperature of the evaporator water. The rationale for the significant fall in SDWP is that the condensation rate is quite low at high condensing temperatures due to limited water absorption under these conditions.

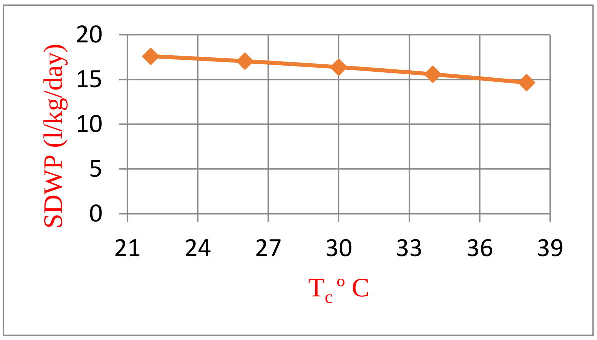

Figure 8 Effect of condenser water temperature on SDWP
T_{ch}=20°C, T_b= 90°C, t $_{half\text{-}cycle}$ = 320 s

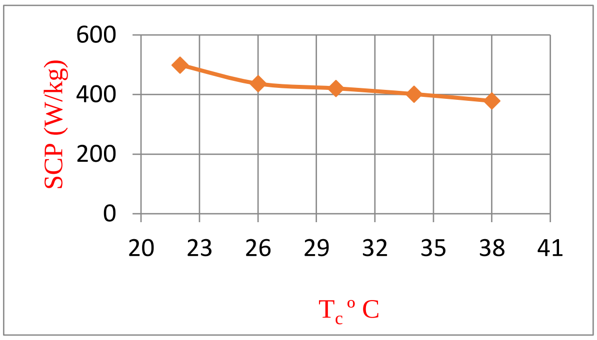

Figure 9 Effect of condenser water temperature on SCP
T_{ch}=20°C, T_b= 90°C, t $_{half\text{-}cycle}$ = 320 s

In Figures 10 and 11, the effect of half-cycle time on system outputs is discussed. The half-cycle time is increased from 220 s to 520 s with the remaining operating conditions fixed. At the beginning of the operation, the outputs of the cycle increase with the passage of time, up to a certain time (220 seconds), in which the outputs of the system are as high as possible. After this time, the outputs of the cycle gradually decrease with the passage of the operating time. That referred to a greater quantity of desorbed vapour from the silica gel, and then begins to decrease with the remainder of the cycle time. This indicates that just a small amount of vapour is desorbed throughout this time period. The action in Figure 11 is due to the evaporator temperature profile, which declines at a faster rate at the start than at the conclusion of the adsorption period, resulting in a lower average evaporator temperature for shorter cycle durations, which improves SCP.

The optimum parameters that give the system maximum throughput were checked and found as follows T_b= 90 ºC, T_c= 30 ºC, T_{ch}= 24 ºC and half-cycle time= 320 s. The maximum outputs of the system are SDWP= 19.322 (l / kg $_{ads}$/ day) and SCP= (493.18 W/kg $_{ads}$). Figure 12 shows effect of t $_{half\text{-}cycle\ time}$ on SDWP and SCP. The optimal results were compared with the optimal results of a previously published research [17], where he obtained a maximum output from the system estimated at (11 l/ kg $_{ads}$ /day) SDWP and SCP (281.7 W/kg).

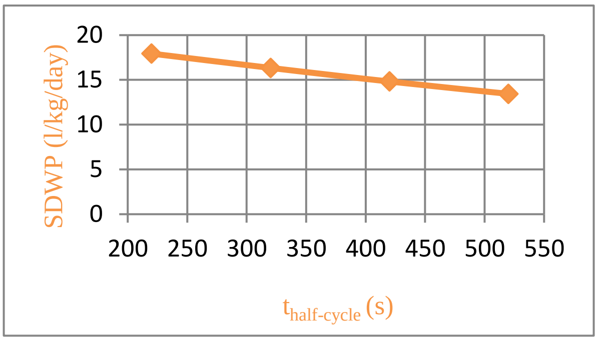

Figure 10 Effect of half cycle time on SDWP
T_{ch}=20°C, T_b= 90°C, T_c=30°C

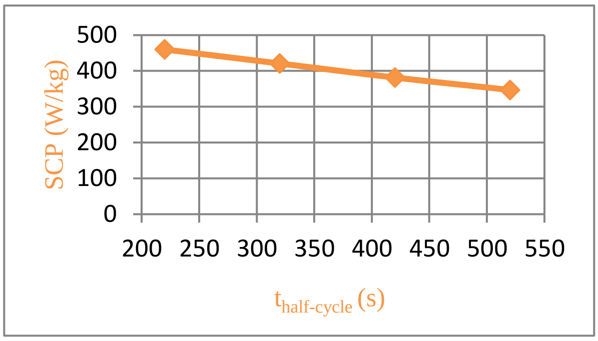

Figure 11 Effect of half cycle time on SCP
T_{ch}=20°C, T_b= 90°C, T_c=30°C

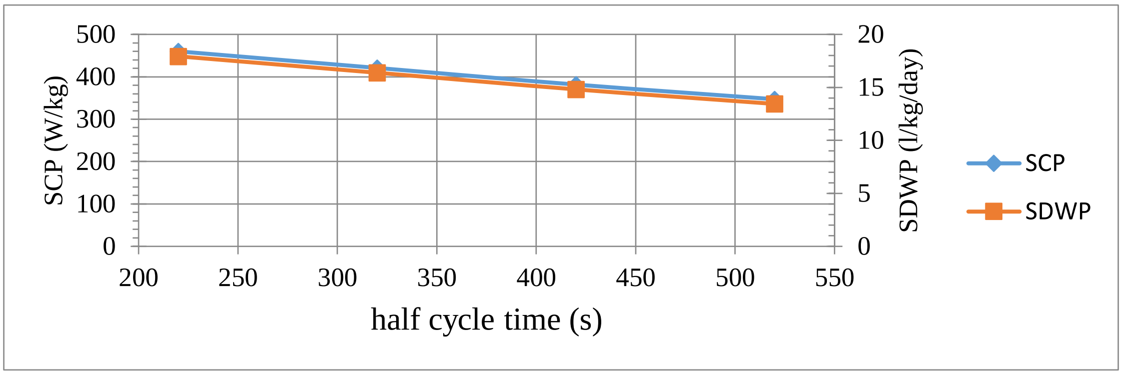

Figure 12 SDWP & SCP of 2-beds cycle utilize silica-gel/water pair. T_b=90°C, Tc=30°C, Tch=20°C

5. Conclusions

This study numerically investigates a two-bed adsorption system for desalination using silica-gel. The simulation model used in the study was validated against experimental data from previous work. Four key parameters were studied including heat source temperature, evaporator temperature, condenser temperature and half-cycle time to find their effect on SDWP and SCP generated from the system. Maximum SDWP (19.322 l / kg $_{ads}$/ day) using T_b= 90 ºC, T_c= 30 ºC, T_{ch}= 24 ºC and half cycle time= 320 s and SCP (493.183 W/kg) using T_b= 90 ºC, T_c= 30 ºC, T_{ch}= 24 ºC and half cycle time= 320 s. As heating temperature increases, SDWP increase by 27% and SCP by 19.6%. As evaporator temperature increases, SDWP and SCP increase by 43% and 42% respectively. As condenser temperature increases, SDWP and SCP decrease by 16.7% and 14.9% respectively. As half cycle time increases, SDWP and SCP decrease by 25% and 24.5%.

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دراسة عددية لمنظومة تحلية امتزازية تعمل بمصادر الطاقة الواطئة

الخلاصة: *حظيت تقنية تحلية المياه باستخدام الامتزاز باهتمام كبير في العقد الأخير. يمكن تشغيله بمصادر الحرارة المهدرة، مما يعني أنه يستخدم طاقة أقل ويصدر انبعاثات أقل من ثاني أكسيد الكربون. يبحث هذا البحث في نظام مكون من سريرين من هلام السليكا / الماء. تم تصميم معادلات حفظ الطاقة / الزخم للنظام الحالي باستخدام برنامج MATLAB SIMULINK، ونتيجة لذلك تم حل معادلات توازن الطاقة لسرير الممتز والمكثف والمبخر. يتم إجراء الدراسة من خلال التحقيق في العديد من المعلمات الرئيسية مثل مصدر الحرارة والمكثف ودرجات حرارة المبخر ووقت نصف الدورة لمعرفة تأثيرها على الإنتاج اليومي المحدد للمياه SDWP وقوة التبريد المحدد SCP المتولدة من النظام. تم التحقق من نموذج المحاكاة المستخدم في هذه الورقة باستخدام البحوث التجريبية المنشورة سابقا. بينت النتائج أن الحد الأقصى SDWP الناتج من النظام هو (19.3224 لتر / كجم. هلام السليكا / يوم) و SCP هو (493.183 واط / كجم). تم إجراء مقارنة مع البحث الحالي مع الأبحاث المنشورة سابقًا، وتم الحصول على نتائج واعدة.*