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Effect of Evaporator and Condenser Temperatures on the Performance of Adsorption Desalination Cooling Cycle

P.G. Youssef [a]*, R.K. AL-Dadah[a], S.M. Mahmoud[a], H.J. Dakkama[a], A. Elsayed[a]

[a]School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham, B15-2TT.

Abstract

As world population is growing the need for fresh water is increasing. Many technologies have been investigated for seawater desalination but each one has its own drawbacks. Desalination process with adsorption technology has gained interest in the last few years due to its ability to use waste heat sources leading to minimal energy requirements and reduced CO_2 emissions. This work mathematically investigates the effect of evaporator and condenser temperatures on the adsorption cycle performance for the production of potable water and cooling effect using silica-gel as the adsorbent material. It was found that as condenser temperature decreases, more water is produced and higher specific cooling capacity was achieved. Moreover, as evaporator temperature increases, similar improvements in water production and cooling were achieved. Results showed that for 10 ^{o}C condenser water temperature and 30^{o}C evaporator inlet water temperature, potable water production of 10 m^3/tonne silica-gel/day and specific cooling capacity (SCC) of 77 Rton/tonne silica-gel were achieved highlighting the potential of this cycle.

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Keywords: Desalination; Cooling; Adsorption; Silica-gel.

1. Introduction

Around the world, fresh water sources are limited as 97% of world water is salty. Only 0.3% of the remaining 3% is usable by humans since the remaining fresh water is either underground or in the form of ice covering mountainous regions [1]. Desalination offers the means to provide for some of this increasing fresh water demand. Different technologies can be used, thermal, membrane, chemical or adsorption [2-4]. Regarding energy needs and expected environment pollution, adsorption technology is most suited for desalination as it uses renewable sources like solar energy or low temperatures waste heat (below 85 ^{o}C) [5, 6]. In this adsorption technology the system will consist of two beds, evaporator and condenser. Seawater evaporates at low temperature and pressure in the evaporator and the vapor is adsorbed by the adsorbent material (Silica-gel) packed in the adsorption bed. On the same time, desorption bed regenerates the water vapor as hot water is circulated, and cooling water is used in the condenser to condense the water vapor coming from the desorption bed [7]. In order to further improve the overall cycle efficiency, a cooling effect can be obtained from the evaporator by passing water through a coil. This water losses heat that is gained by seawater which helps in its evaporation [8].

* Corresponding author. Tel.: +44-0121-4143513; fax: +44-0121-4143598.
E-mail address: pgy348@bham.ac.uk.

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Kim Ng et al. [9], have mathematically and experimentally investigated the performance of a silica-gel adsorption system for desalination purposes in addition to cooling. A solar system was used as the heating source at temperatures (65 to 80^{o}C). Results showed that the cycle is capable of producing potable water at a rate of 3-5 m^{3}/tonne silica-gel/day besides cold water (7-10 ^{o}C) at specific cooling capacity (SCC) of 25-35 Rton/tonne silica-gel. Kim Ng et al. [10], have analyzed the performance of a waste heat driven adsorption system using silica-gel as an adsorbent, with mathematical results were validated by experimental measurements. The cycle was assessed by calculating, specific cooling power (SCP), specific daily water production (SDWP), coefficient of performance (COP) and overall conversion ratio (OCR). The results showed that 3.8 m^{3} of fresh water can be produced per tonne silica-gel per day in addition to 23 Rton/tonne silica-gel of cooling at evaporator inlet water temperature of 10^{o}C. S. Mitra et al. [11], have studied the performance of a solar driven single stage adsorption cycle at different cycle times and condenser temperatures. Energy and mass conversion equations as well as adsorption/desorption kinetics equations were solved for the 4-bed system. It was found that the optimum cycle time is 600-900 sec. based on the values of SDWP (2.3 m^{3}/tonne silica-gel/day), SCP (18 Rton/tonne silica-gel) and COP (0.45). Moreover, results showed that as condenser temperature increases, cycle performance degrades because of operating pressure ratio rise. Jun Wu et al. [12], have studied all possible adsorption thermodynamic cycles for silica-gel/water pair. The effect of varying seawater temperature relative to adsorption bed cooling water temperature and condenser water temperature was analyzed according to water production and energy consumption. Analysis indicated that evaporator temperature relative to bed cooling temperature, controls the cycle characteristics either for desalination only or for both cooling and desalination. Furthermore, it was found that maximum water production and minimum energy consumption is obtained when bed and condenser cooling temperatures are lower than evaporator temperature.

In this work, the effect of evaporator inlet water temperature and condenser cooling water temperature are mathematically investigated on a typical 450 kW two bed adsorption chiller with desalination. The cycle operation is assessed in terms of SDWP, SCP, COP and performance ratio (PR).

Nomenclature

c	Uptake (kg.kg^{-1})	*abe*	Adsorbate
c_p	Specific heat at constant pressure (kg. kg^{-1}.K^{-1})	*ads*	Adsorption
COP	Coefficient of performance (-)	*cond*	Condenser
h	Enthalpy (kJ.kg^{-1})	*cw*	Cooling Water
M	Mass (kg)	*D*	vapor
$\dot{m}$	Mass flow rate (kg.s^{-1})	*d*	Distillate water
OCR	Overall conversion ratio (-)	*des*	Desorption
PR	Performance ratio (-)	*evap*	Evaporator
SCP	Specific cooling power (kW.kg^{-1})	*hw*	Heating Water
SDWP	Specific daily water production (m^{3} t^{-1} day^{-1})	*HX*	Heat exchanger
T	Temperature (K)	*in*	inlet
τ	No of cycles per day -()	*out*	outlet
X	Concentration (ppm)	*s*	Seawater
		t	Time

Subscripts

a	Adsorbent material

2. Adsorption Cycle Analysis

A two bed adsorption machine produced by 'Weatherite Manufacturing LTD' has been modeled using Simulink software to achieve potable water production and cooling effect. This machine is originally a 450 kW chiller but modified to include water desalination. Each bed is packed by 890 kg of silica gel and connected to evaporator and condenser by flap valves which are opened and closed by pressure difference between bed and either condenser or evaporator. Beds are cooled and heated by cold and hot water respectively while there are 12 pneumatic valves controlling the flow of water through beds, evaporator and condenser, as shown schematically in Fig 2.

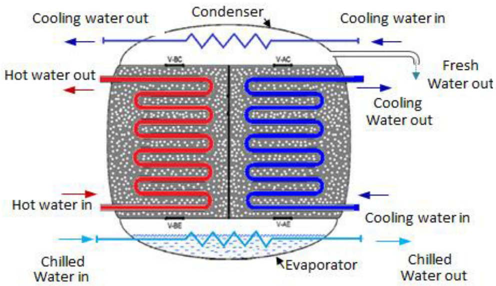

Fig. 1. Schematic diagram of the system

2.1. Material Characteristics

In order to predict amount of water vapor uptake by the silica-gel at different pressure ratios, isotherms should be calculated. In addition, adsorption kinetics is calculated to take into account the effect of the time. For silica gel, isotherms can be predicted by the modified Freundlich model (Eq. 1 - 3) with the constants given in table 1 [13].

$$w^* = A(T_{ads})[P_{sat}(T_{ref})/P_{sat}(T_{ads})]^{B(T_{ads})} \quad (1)$$

$$A(T_{ads}) = A_0 + A_1 T_{ads} + A_2 T_{ads}^2 + A_3 T_{ads}^3 \quad (2)$$

$$B(T_{ads}) = B_0 + B_1 T_{ads} + B_2 T_{ads}^2 + B_3 T_{ads}^3 \quad (3)$$

Table 1. Modified Freundlich equation constants

Constant	*Value*	*Unit*	*Constant*	*Value*	*Unit*
A_0	-6.5314	Kg/kg	B_0	-15.587	K
A_1	0.72452E-1	Kg/kg.K	B_1	0.15915	K^{-1}
A_2	-0.23951E-3	Kg/kg.K^2	B_2	-0.50612E-3	K^{-2}
A_3	0.25493E-6	Kg/kg.K^3	B_3	0.53290E-6	K^{-3}

For kinetics modelling, linear driving force (LDF) model is used as in equations 4 and 5 where the values of D_{so}, R_p and E_a are 2.54E-4 [$m^2.s^{-1}$], 0.16E-3 [m] and 42000 [J/mol] respectively [14].

$$\frac{dw}{dt} = k(w^* - w) \quad (4) \qquad k = \left(15\, D_{so}/R_p^2\right) e^{\left(\frac{-Ea}{RT}\right)} \quad (5)$$

2.2. Cycle performance

Mass and salt balance equations are solved for the evaporator. In addition, energy equation is solved for adsorber, desorber, condenser and evaporator. The balance equations are solved for all cycle phases i.e. adsorption/desorption, mass recovery and heat recovery. For cycle performance assessment, several parameters are calculated which are (SDWP), (SCP), (COP), (PR) which is the ratio between energy needed for condensation of desalinated water and desorption energy and overall conversion ratio (OCR).

A lumped model is used in the simulation which means that temperature is the same for all points within the desorber, adsorber, evaporator or condenser, with the assumption that no heat losses occur.. All used equations are given below [15] and solved with a tolerance of 1 x 10^{-6} .

Evaporator mass balance equation:

$$\frac{dM_{s,evap}}{dt} = \theta \dot{m}_{s,in} - \gamma \dot{m}_{brine} - n.\frac{dc_{ads}}{dt} M_a \tag{6}$$

Evaporator salt balance equation:

$$M_{s,evap}\frac{dX_{s,evap}}{dt} = \theta X_{s,in}\, \dot{m}_{s,in} - \gamma X_{s,evap}\, \dot{m}_{brine} - n.X_D \frac{dc_{ads}}{dt} M_a \tag{7}$$

Evaporator energy balance equation:

$$\left[M_{s,evap}c_{p,s}\left(T_{evap},X_{s,evap}\right) + M_{HX,Evap}c_{p,HX}\right]\frac{dT_{evap}}{dt} = \theta.h_f\left(T_{evap},X_{s,evap}\right)\, \dot{m}_{s,in} - n.h_{fg}\left(T_{evap}\right)\frac{dc_{ads}}{dt} M_a + \dot{m}_{chilled}c_p\left(T_{evap}\right)\left(T_{chilled,in} - T_{chilled,out}\right) - \gamma h_f\left(T_{evap},X_{s,evap}\right)\dot{m}_{brine} \tag{8}$$

Adsorption /Desorption bed, energy balance equation:

$$\left[M_a c_{p,a} + M_{HX}c_{p,HX} + M_{abe}c_{p,abe}\right]\frac{dT_{\frac{ads}{des}}}{dt} = \pm n.Q_{st}M_a\frac{dc_{ads/des}}{dt} \pm \dot{m}_{cw/hw}c_p\left(T_{cw/hw,in} - T_{cw/hw,out}\right) \tag{9}$$

Condenser energy balance equation:

$$\left[M_{cond}c_p(T_{cond}) + M_{HX,Cond}c_{p,HX}\right]\frac{dT_{cond}}{dt} = h_f\frac{dM_d}{dt} + n.h_{fg}(T_{cond})\frac{dc_{des}}{dt}M_a + \dot{m}_{cond}c_p(T_{cond})\left(T_{cond,in} - T_{cond,out}\right) \tag{10}$$

Cycle performance parameters:

$$SDWP = \int_0^{t_{cycle}}\frac{Q_{cond}}{h_{fg}M_a}dt \tag{11}$$

$$PR = \frac{1}{t_{cycle}}\int_0^{t_{cycle}}\frac{m_d h_{fg}}{Q_{des}}dt \tag{12}$$

$$SCP = \frac{Q_{evap}}{M_a} \tag{13}$$

$$COP = \frac{Q_{evap}}{Q_{des}} \tag{14}$$

$$OCR = \int_0^{t_{cycle}}\frac{Q_{evap}+Q_{cond}}{Q_{des}}dt \tag{15}$$

Where:

$$Q_{cond} = \dot{m}_{cond}c_p(T_{cond})\left(T_{cond,out} - T_{cond,in}\right) \tag{16}$$

$$Q_{des} = \dot{m}_{hw}c_p\left(T_{hw,in} - T_{hw,out}\right) \tag{17}$$

$$Q_{evap} = \dot{m}_{chilled}c_p\left(T_{evap}\right)\left(T_{chilled,in} - T_{chilled,out}\right) \tag{18}$$

3. Results and Discussion

The numerical model is validated against the measured experimental results from an adsorption plant operating in a 2-Bed mode for desalination application [16]. Fig. 2 shows the comparison between the simulation results and experimental measurements for the basic components of an adsorption cycle. These results show that the current model can predict the cycle performance within ±10% error margin.

The performance of the adsorption cycle is investigated at different condenser and evaporator water temperatures, typically (10 - 30^{o}C). Hot water and cold water temperatures are 85^{o}C and 30^{o}C respectively in all conditions while cycle time is kept at 425 second.

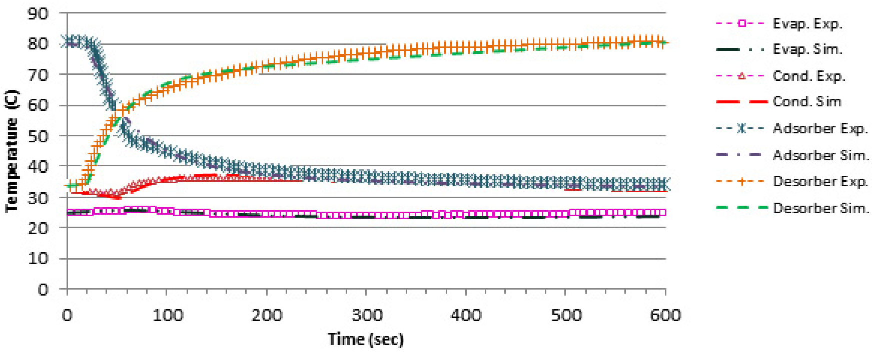

Fig. 2 Comparison of numerical results and experimental measurements for 2-Bed adsorption desalination cycle.

SDWP and SCP are shown in figures (3-a & 3-b) respectively. As shown in figure 3, cycle performance is enhanced by decreasing condenser cooling water temperature and in contrast it gets worse by decreasing evaporator inlet water temperature. In best cases, cycle can produce 10 m^3/tonne silica-gel/day of potable water besides a specific cooling capacity (SCC) of 77 Rton/tonne silica-gel at 10 ^oC condenser water temperature and 30^oC evaporator inlet water temperature.

By the same manner coefficient of performance and performance ratio are affected by condenser and evaporator water temperatures. Figures (4-a, 4-b & 4-c) presents PR, COP and OCR with the same legend of fig. 3. As shown, the cycle has a maximum PR, COP and OCR of 0.55, 0.52 and 1.07 respectively at the minimum and maximum condenser and evaporator water temperatures respectively. The reason for this attitude is the pressure ratio between beds and heat exchangers. As condenser cooling water temperature decrease, desorber pressure ratio decrease while adsorber pressure ratio increase with the increase of evaporator inlet water temperature.

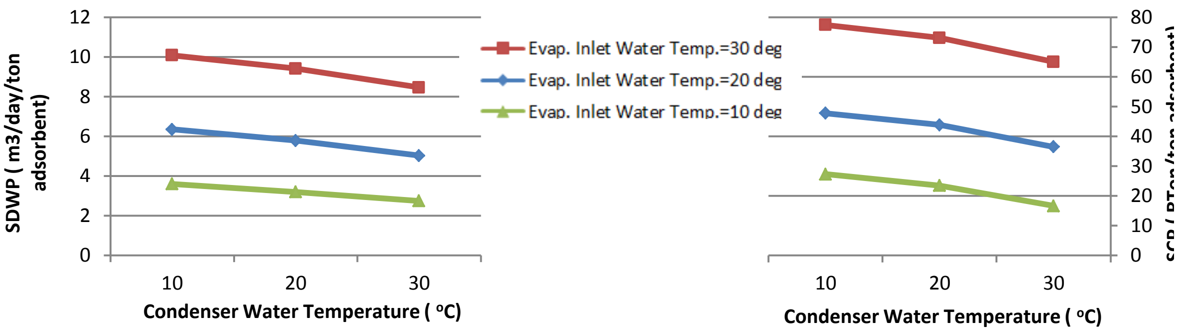

Fig. 3. Effect of condenser and evaporator temperature on (a) SDWP; (b) SCP

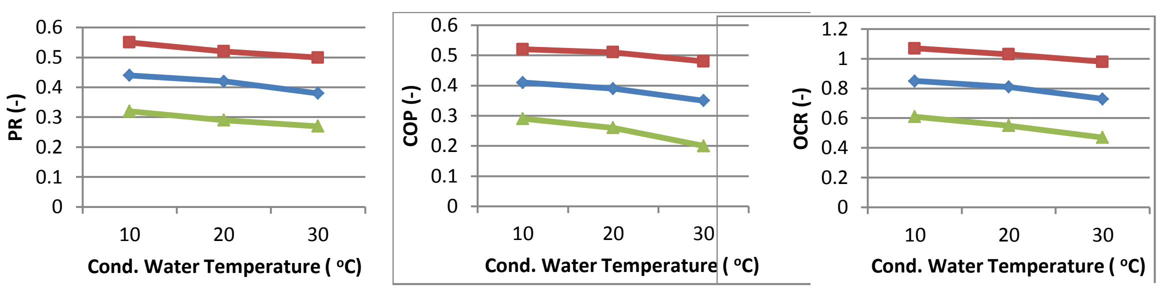

Fig. 4. Effect of condenser and evaporator temperature on (a) PR; (b) COP; (C) OCR

Conclusion

The performance of adsorption silica-gel cycle was investigated for different evaporator and condenser water temperatures typically (10 - 30^{o}C). The cycle was assessed by number of key performance parameters which are specific daily water production (SDWP), specific cooling power (SCP), performance ratio (PR), coefficient of performance (COP) and overall conversion ratio (OCR). It was found that decreasing condenser cooling water temperature and increasing evaporator water temperature can improve the cycle COP by 260%, PR by 200% and OCR by 227% with condenser cooling water temperature of 10^{o}C instead of 30^{o}C and evaporator water temperature of 30^{o}C instead of 10^{o}C.

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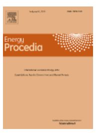

Biography

Peter Youssef, was graduated from Alexandria University, Egypt, class of 2007. He got his MSc degree in Thermal engineering, 2011. Currently doing a PhD in adsorption system for desalination applications.