International Journal of Heat and Mass Transfer 52 (2009) 1811–1816

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Operational strategy of adsorption desalination systems

Kyaw Thu [a], Kim Choon Ng [a,*], Bidyut B. Saha [b,*], Anutosh Chakraborty [b], Shigeru Koyama [b]

[a] Department of Mechanical Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, Singapore
[b] Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, 6-1 Kasuga-koen, Kasuga-shi, Fukuoka 816-8580, Japan

ARTICLE INFO

Article history:
Received 28 May 2008
Received in revised form 10 September 2008
Available online 6 December 2008

Keywords:
Adsorption desalination
Specific daily water production
Performance ratio
Regeneration temperature

ABSTRACT

This paper presents the performances of an adsorption desalination (AD) system in two-bed and four-bed operational modes. The tested results are calculated in terms of key performance parameters namely, (i) specific daily water production (SDWP), (ii) cycle time, and (iii) performance ratio (PR) for various heat source temperatures, mass flow rates, cycle times along with a fixed heat sink temperature. The optimum input parameters such as driving heat source and cycle time of the AD cycle are also evaluated. It is found from the present experimental data that the maximum potable water production per tonne of adsorbent (silica gel) per day is about 10 m^3 whilst the corresponding performance ratio is 0.61, and a longer cycle time is required to achieve maximum water production at lower heat source temperatures. This paper also provides a useful guideline for the operational strategy of the AD cycle.

1. Introduction

The search for the potable water for quenching global thirst remains a pressing concern throughout many countries of the world, particularly in semi-arid, desert countries and the highly populated city states. Especially, the Arabian Gulf countries have been struggling for many decades to meet fresh water demand with a considerable amount of desalination plants [1]. Although most of the Earth's surface is covered by oceans, the effort of providing fresh water for the world's inhabitants seems insurmountable. According to the World Health Organization (WHO), at least one billion people do not have access to clean and fresh water, and about 41% of Earth's population live in the water-stressed areas, and this deprived population may climb to 3.5 billion by the year 2025. Thus, the demand for new and sustainable sources and the associated technologies for producing fresh water are intrinsically linked for solving potable water availability and hitherto, innovative and energy efficient desalination methods seem to be practical solution.

Desalination processes can be divided into two major groups: the first group is a heat-driven process (distillation) such as multi-stage flashing (MSF), multiple effect distillation (MED) and solar distillation. The second method employs electric power driven processes that include freezing, mechanical vapor compression, electro-dialysis and reverse osmosis [2–10]. All the desalination systems suffer from two heritage drawbacks namely; high energy intensive and/or prone to fouling and corrosion to the evaporation or separation unit of the sea water [11].

Adsorption desalination cycles are aimed to mitigate the shortcomings of the conventional desalination methods [12–14]. The salient features of the AD cycles are (i) the utilization of low temperature waste heat, (ii) no major moving parts, and (iii) utilization of environmental friendly adsorbent/adsorbate pairs (silica gel/water). As compared with other desalination methods, the AD cycle has the unique advantages, namely (i) the utilization of renewable or waste heat sources at temperatures below 90 °C, (ii) low corrosion and fouling rates on the evaporator tube materials due to the evaporation of saline water at low temperatures (typically below 35 °C). It has no major moving parts, which renders low maintenance cost, (iii) the adsorbent–adsorbate pair is silica gel and water, and (iv) it has low electricity usage [8]. In addition, the adsorption cycles offers two important benefits which are not found to the existing desalination technologies; namely, (i) a two-prong phenomenal barrier to eliminate any "Bio-contamination" during the water production process as compared with existing membrane methods, and (ii) the reduction in global warming due to the utilization of low-temperature renewable or waste heat which otherwise would have been purged or dissipated into the atmosphere. Wang and Ng [12] reported that the specific daily water production of the AD plant can be expected approximately about 4.7 kg/kg of silica gel at chilled water temperature 12.5 °C by employing the heat and mass recovery schemes. El-Sharkawy et al. also reported the AD cycle is capable to produce about 8.2 m^3 potable water per tonne of silica gel per day as the chilled water approaches the ambient temperature [8]. The specific daily water production and the performance ratio of the AD cycle vary depending on the regeneration temperatures and cycle times.

* Corresponding authors.
E-mail addresses: mpengkc@nus.edu.sg (K.C. Ng), bidyutb@cm.kyushu-u.ac.jp (B.B. Saha).

0017-9310/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2008.10.012

Nomenclature

c_p	specific heat capacity, J/kg K	*Subscripts*	
h_{fg}	latent heat of vaporization, J/kg	*ads*	adsorption
M_sg	mass of adsorbent (silica gel), kg	*cond*	condenser
$\dot{m}$	mass flow rate, kg/s	*cool*	cooling water
P	pressure, Pa	*des*	desorption
Q	power, W	*hot*	hot water
T	temperature, °C	*in*	inlet
t	time, s	load	load surface at the evaporator
t_{cycle}	cycle time, s	*out*	outlet
N	number of cycles operating/day, –		

Nevertheless, the performance of the AD cycle with different heat source temperatures at different cycle times is yet to be reported.

The present paper deals with the operation strategy of an adsorption desalination system in two-bed and four-bed operation modes for assorted heat source temperatures supplied to the sorption elements (SE). The optimal operating cycle times for the AD system in both modes at different available heat source temperatures are also presented.

2. Adsorption desalination system

The adsorption desalination process utilizes the adsorbent–adsorbate characteristics [15] and produces fresh water at the condenser by the amalgamation of "adsorption-triggered-evaporation" and "desorption-resulted-condensation". Fig. 1 shows the schematic layout of the AD system. It comprises with an evaporator, a condenser and four sorption elements (SE) or adsorbent beds. A pilot adsorption desalination (AD) plant has been constructed and operated in the Air Conditioning Laboratory at National University of Singapore (NUS). Fig. 2 shows the pictorial diagram of the adsorption desalination system that can be operated both in two-bed and four-bed modes. The main difference between the four-bed and two-bed operation modes is that the hot water is supplied to the desorption beds in SE I and SE II in series configuration for four-bed mode whilst in two-bed mode, SE 1 and SE II work as a single bed (CV1) and thus the hot water is supplied in parallel to SE 1 and SE II. On the other hand, the coolant is supplied in series to SE III and SE IV in four-bed mode, and in parallel to CV2 (SE III and SE IV) in two-bed operation mode. The evaporator and condenser are connected all the time with at least one adsorber and desorber in four-bed operation mode. However, two sorption elements are connected with evaporator and condenser only in the operation phase for the two-bed operation mode.

The operation of the AD cycle can be summarized as follows:

(i) The pre-treated (e.g., filtering and de-aeration) saline or brackish water is fed into the stainless steel evaporator. The evaporator is the only unit which is built of anti-corrosive material. Purging of brine from the evaporator is periodically conducted for the purpose of salt concentration control.
(ii) An external water circuit provides the heating load for maintaining the evaporator process. This evaporation energy is internally recovered from adsorber beds through plate heat exchanger. The evaporation is further enhanced by using the spray nozzles.
(iii) The sea water level inside the evaporator is regulated to maintain evaporation and control salt concentration. This prevents the fouling and corrosion of the evaporating unit.
(iv) During the adsorption phase, the evaporator is connected with the adsorber beds where the water vapor is adsorbed by the silica gel. The heat of adsorption is removed by coolant from the cooling tower. The adsorption process continues until the preset cycle time is reached.
(v) During the desorption phase, the low temperature hot water typically less than 85 ºC is employed to desorb the water vapors from the sorption element which previously is under adsorption mode.
(vi) The desorbed vapor is condensed in the condenser where the heat of condensation is rejected to the cooling water from the cooling tower.
(vii) The condensate (fresh water) is collected in the collection tank which is either intermittently pumped out to the ambient or extracted via a 10 m high U-bend tube.

Table 1 furnishes the experimental operating parameters of the AD cycle. The switching time is the time period for the pre-heating and pre-cooling of the sorption elements prior they change in their role. The experiments are conducted using different hot water inlet temperatures with assorted cycle times. In the experiments, the load water flow rate is regulated at 1.9 kg/s to enhance the heat transfer of the evaporation process. The tests are conducted under steady state conditions of the hot water and cooling water source temperatures which are accurately conditioned by the rating facility.

3. Performance analysis

The performance modelling of any adsorption system for cooling [15–17] and desalination [12–14] is based on adsorption isotherms, kinetics and energy balances between sorption elements and evaporator/condenser. The type-RD silica gel is employed as the adsorbent in the experiment. The physical properties of the type-RD silica gel are listed in Table 2.

The uptake of water vapor by the silica gel can be accurately estimated using Tóth isotherm equation given below

$$q^* = \frac{K_0 \cdot \exp\{\Delta_{ads}H/(R\cdot T)\}\cdot p}{\left[1+\{K_0/q_m \cdot \exp(\Delta_{ads}H/(R\cdot T))\cdot P\}^t\right]^{1/t}} \tag{1}$$

here q_m is denotes the monolayer capacity, $\Delta_{ads}H$ is the enthalpy of adsorption, R is the gas constant, T is the adsorption temperature in Kelvin, K_0 is the pre-exponential constant and t is the dimensionless Tóth constant.

The transient uptake of water vapor by the silica gel at specific temperature and pressure is given by kinetic equation as below

$$\frac{dq}{dt} = \frac{15D_{s0}\exp\left(\frac{-E_a}{RT}\right)}{R_p^2}(q^* - q) \tag{2}$$

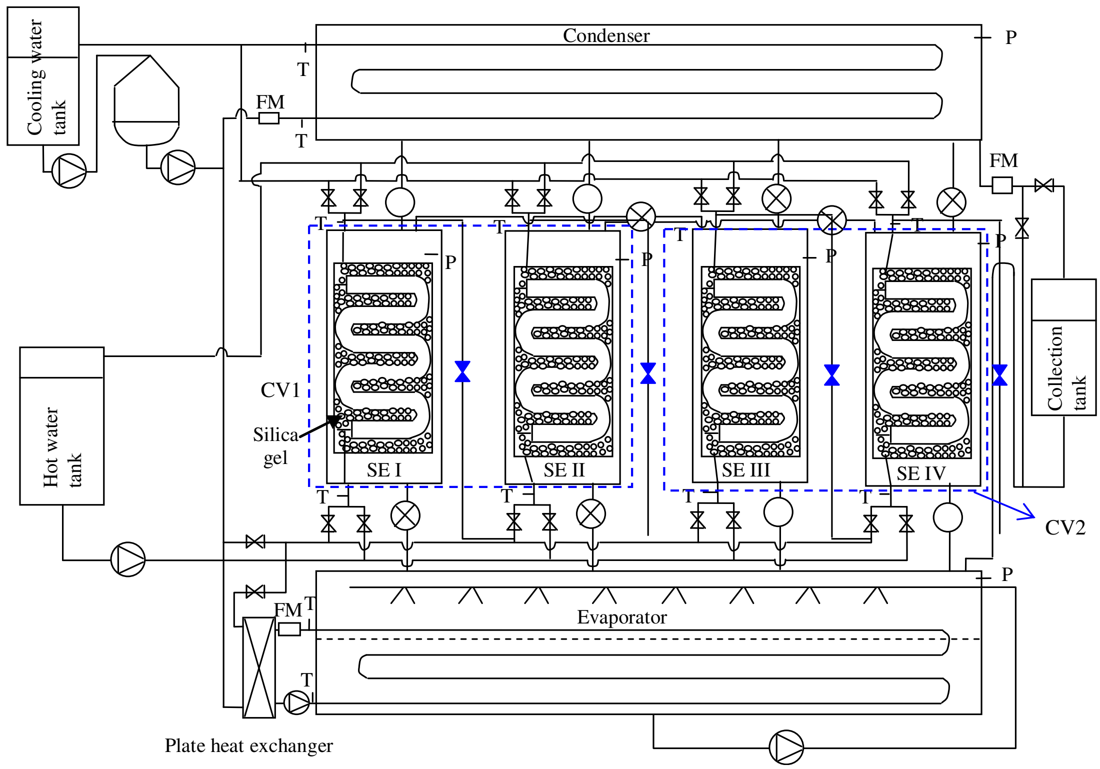

Fig. 1. Skeletal diagram of AD system in two-bed and four-bed modes (blue-colored valves that they are idle in two-bed operation). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

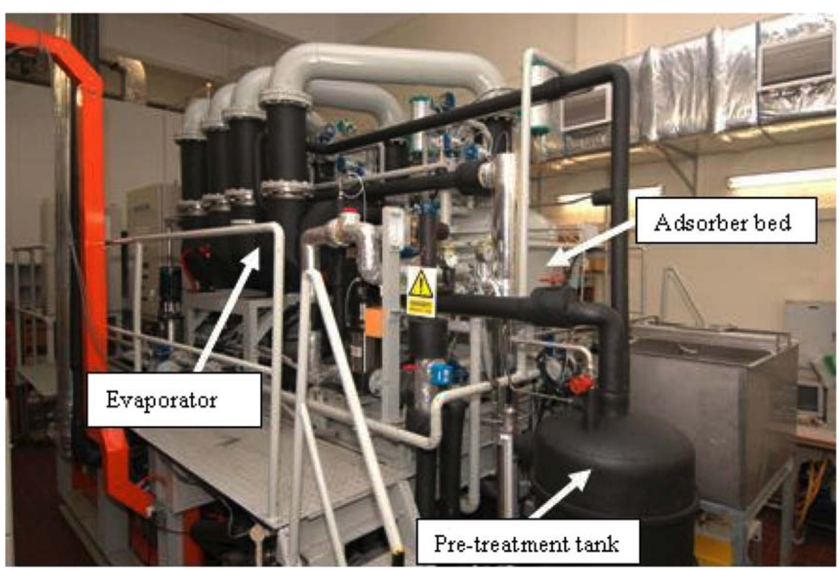

Fig. 2. Pictorial view of AD plant showing evaporator and pre-treatment tank.

Table 1
Experimental operating parameters.

	Temperature (°C)	Flow rate (kg/s)
Hot water inlet (desorber)	65–85	0.8
Cooling water inlet (adsorber)	29.5	0.8
Cooling water inlet (condenser)	30	2
Load water inlet (evaporator)	30	1.9
Pressure equalization time (s)	10	
Mass of silica gel per bed (kg)	36	
Switching time (s)	40	

Table 2
Properties of type-RD silica gel.

Property	Value
Pore size (nm)	0.8–7.5
Porous volume ($cm^3\ g^{-1}$)	0.37
Surface area ($m^2\ g^{-1}$)	720
Average pore diameter (nm)	2.2
Apparent density ($kg\ m^{-3}$)	700
pH	4.0
Specific heat capacity ($kJ\ kg^{-1}\ k^{-1}$)	0.921
Thermal conductivity ($W\ m^{-1}\ k^{-1}$)	0.198

where D_{s0} is the kinetic constant for the silica gel–water system, E_a is the activation energy, R_p is the particle radius and q denotes the instantaneous uptake.

The energy required (Q_{des}) to remove water vapors from silica gels of sorption element can be calculated by using the inlet ($T_{hot,in}$) and outlet ($T_{hot,out}$) temperatures of the heat source, and this is given by

$$Q_{des} = \dot{m}_{hot} c_p(T_{des})(T_{hot,in} - T_{hot,out}) \tag{3}$$

where $\dot{m}_{hot}$ indicates the mass flow rate and $c_p(T_{des})$ defines the specific heat capacity of heating fluid. On the other hand, the energy rejected (Q_{ads}) to adsorb water vapor into silica gel is estimated by measuring inlet ($T_{cool,in}$) and outlet ($T_{cool,out}$) temperatures of cooling fluid and this is written as

$$Q_{ads} = \dot{m}_{cool} c_p(T_{ads})(T_{cool,out} - T_{cool,in}), \tag{4}$$

where $\dot{m}_{cool}$ and $c_p(T_{ads})$ indicate the mass flow rate and the specific heat capacity of cooling fluid. The heat of evaporation (Q_{evap}) and the condensation energy (Q_{cond}) rejected at the condenser are given by

$$Q_{evap} = \dot{m}_{load} c_p(T_{evap})(T_{load,in} - T_{load,out}) \tag{5}$$
$$Q_{cond} = \dot{m}_{cond} c_p(T_{cond})(T_{cond,out} - T_{cond,in}) \tag{6}$$

The performance of the adsorption desalination system is expressed in terms of specific daily water production (SDWP) and the performance ratio (PR) and these are defined by

$$SDWP = N \int_0^{t_{cycle}} \frac{Q_{cond}}{h_{fg}(T_{cond}) M_{sg}} dt \tag{7}$$
$$PR = \frac{\dot{m}_{water} h_{fg}(T_{cond})}{Q_{des}} \tag{8}$$

where $\dot{m}_{water}$ is the fresh water production rate in kg/s and N is the number of cycles per day. The SDWP can be expressed as kg of potable water produced per kg of silica gel per day or can also be presented using equivalent expression of m^3 of potable water per tonne of silica gel per day. The performance ratio of the AD cycle is the ratio of the condensation heat to the heat input for desorption.

4. Results and discussion

The performance parameters of the AD system include the specific daily water production and the performance ratio, and these are calculated as a function of cycle time and the driving heat source temperature (hot water), from the experimental data in steady state conditions. The transient water production rate (LPM-time profile) of the AD system in four-bed operation mode for different cycle times at the inlet hot water temperature of 85 °C is presented in Fig. 3. The maximum SDWP is achieved at 600 s as shown in the bottom left-side corner of Fig. 3.

Figs. 4 and 5 show the SDWP against cycle times for two-bed and four-bed operation modes of the AD cycle at different hot water inlet temperatures. These results denote the existence of optimal cycle times at the specific hot water inlet temperature as the SDWP varies with cycle time. The SDWP is obtained lower at relatively shorter cycle times, and this is due to the fact that the regeneration process during desorption is not completed and the water vapors from silica gels are not fully emitted for condensation

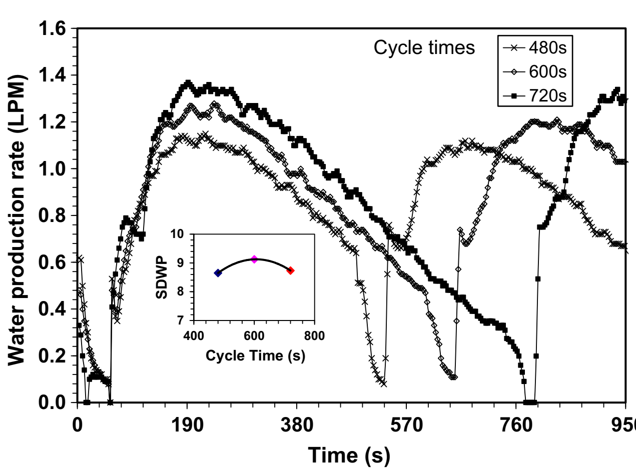

Fig. 3. SDWP–cycle time profile for four-bed operation mode at the hot water inlet temperature of 85 °C.

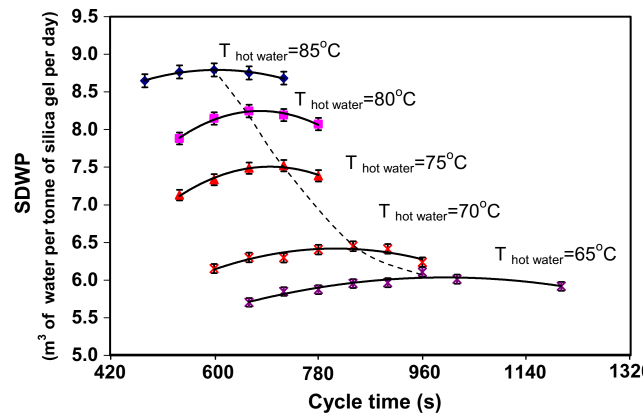

Fig. 4. SDWP at different cycle times for two-bed mode.

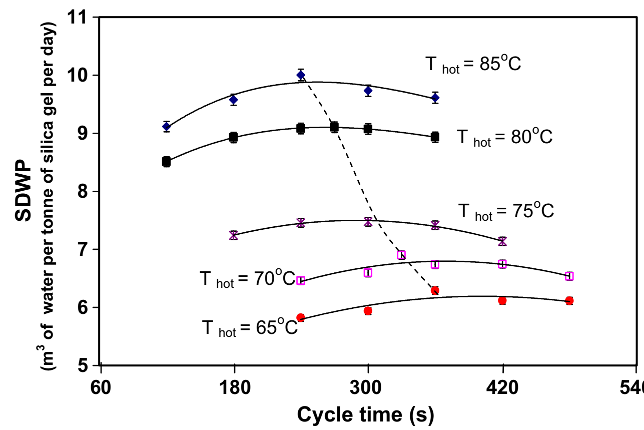

Fig. 5. SDWP at different cycle times for four-bed mode.

Table 3
Specific daily water production and optimal cycle times at different regeneration temperatures.

$T_{hot\ water}$ (°C)	Four-bed mode			Two-bed mode		
	t_{cycle} (s)	SDWP	PR	t_{cycle} (s)	SDWP	PR
85	1080	10.0023	0.6065	1240	8.7932	0.5731
80	1200	9.1036	0.6195	1360	8.2462	0.5997
75	1320	8.5218	0.6409	1480	7.5213	0.6231
70	1440	6.9012	0.6441	1720	6.4510	0.6380
65	1560	6.2895	0.6795	1960	6.1076	0.6830

and producing water in the condenser. This means that the affinity of the adsorbent (silica gel) for the uptake of water vapor in the next cycle will be damped due to the incomplete regeneration. On the other hand, the lower SDWP at longer cycle time is due to the waste of thermal energy resulting from the excessively longer supply of the hot water to the sorption elements during desorption process. As a result, the additional energy supplied by the hot water has no effect for desorption but just heating the adsorbents and the heat exchanging components. In addition, the total numbers of operation cycles per day is also significantly reduced.

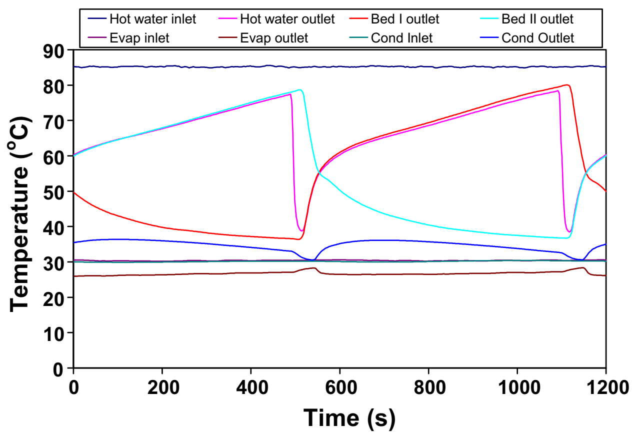

Fig. 6. Temperature profile of adsorption desalination plant at hot water inlet 85 °C.

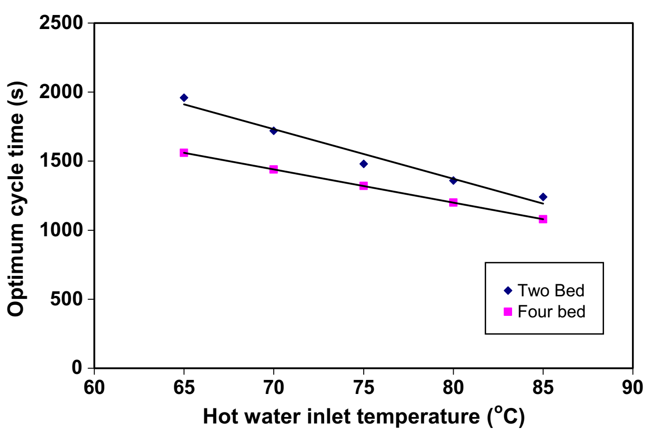

Fig. 7. Optimum cycle time at different hot water inlet temperatures.

Table 3 summarizes the SDWP and PR of the AD plant for both four-bed and two-bed operation modes with the corresponding optimal cycle times at different hot water inlet temperatures. On the basis of optimal conditions (the hot water temperature of 85 °C, operating cycle time 600 s, and the cooling water temperature of 30 °C), the maximum SDWP and PR are obtained as 10 m^3 per tonne of silica gel and 0.61, respectively, which are shown in Fig. 5. During the above mentioned optimum condition, the load water flow rate is 1.9 kg/s that corresponds to the flow velocity of 1 m/s.

Fig. 6 depicts the temperature profile of AD cycle for (i) the hot water inlet and outlet temperatures, (ii) the adsorber/desorber bed outlet temperatures, (iii) the condenser inlet and outlet temperatures, and (iv) the evaporator inlet and outlet temperatures.

Fig. 7 shows the effects of cycle time on heating fluid inlet temperature, and it is found that the optimum cycle time varies linearly with the hot water inlet temperature in both operation modes. The longer cycle time is observed at lower hot water inlet temperatures as a result of slower regeneration process in the desorption bed(s). It should be noted here that it may be possible to make a multi-stage desalination plant which could be operated with a very low heat source temperature of 40 °C [18] that possess a very long cycle time.

Fig. 8 shows the comparison on the specific daily water production and performance ratio of AD cycles operating with four-bed and two-bed operation modes at respective optimal cycle times with assorted hot water inlet temperatures. It is noticed that the AD cycle in four-bed operation mode produces higher SDWP compared with two-bed operation mode and the significant improvement can be realized at higher hot water inlet temperatures typically above 70 °C. This is because of the "master-slave" configuration in the four-bed mode which results in the better energy utilization of the hot water. This is a heat recovery operation in which the outlet hot water from the master desorber is channeled to the slave desorber where it is utilized further for the desorption process. For the lower hot water inlet temperatures, the "master-slave" configuration becomes less effective because the outlet hot water temperature from the master bed is not high enough to perform further desorption in the salve desorber. Thus, the advantage of four-bed operation mode diminishes at lower heat source temperatures. The PR of the AD cycle for both modes is decreased with the increase of hot water inlet temperature.

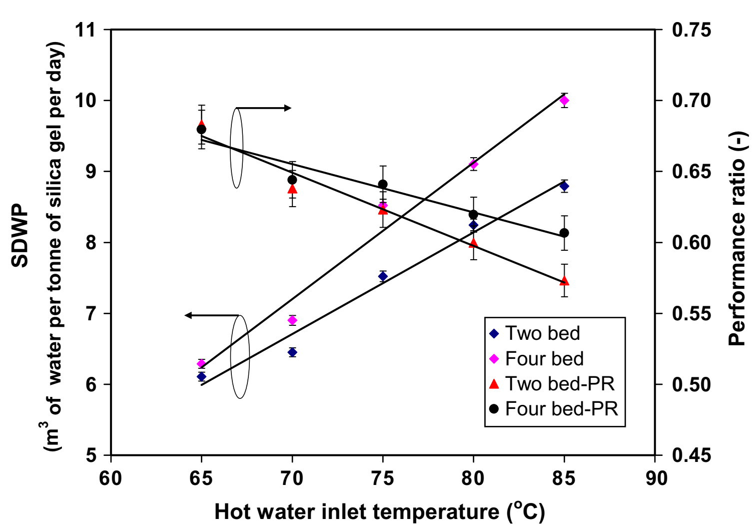

Fig. 8. SDWP at different hot water temperatures for two-bed and four-bed modes.

5. Conclusions

The optimum operating cycle times at different hot water inlet temperatures for the AD cycle have been experimentally investigated. It is noted that the optimum cycle times varies with hot water inlet temperatures. A longer cycle time is required for lower hot water inlet temperature. It is also noted that significant improvement in SDWP is achieved by four-bed operation mode as compared to two-bed mode at high hot water inlet temperatures. The experimental results which highlight the importance of suitable operation cycle time at different hot water inlet temperatures play a pivotal role in the design and operation of AD plants.

Acknowledgements

The authors wish to thank King Abdullah University of Science & Technology (KAUST) for the generous financial support through the project (WBS R265-000-286-597). The authors would like to thank NUS final year students Mr. K. Maqsood and Ms. A.A.M. Tan for their help in experimental investigations, and also to Dr. H. Yanagi for the valuable advice on the operation of the AD plant.

References

[1] H.E.I. Dessouky, H. Ettouney, Single-effect thermal vapor-compression desalination process: thermal analysis, Heat Transfer Eng. 20 (2) (1999) 52–68.
[2] A.I. Wazzan, F. Al-Modaf, Seawater desalination in Kuwait using multistage flash evaporation technology – historical overview, Desalination 134 (2001) 257–267.
[3] M. Al-Shammiri, M. Safar, Multi-effect distillation plants: state of the art, Desalination 126 (1999) 45–59.
[4] H. Mosry, D. Larger, K. Genther, A new multiple–effect distiller system with compact heat exchangers, Desalination 96 (1994) 59–70.
[5] Z. Amjad, Reverse Osmosis: Membrane Technology Water Chemistry, and Industrial Applications Chapman & Hall, International Thomson Publishing, New York, 1993.
[6] Bart Van der Bruggen, Carlo Vandecasteele, Distillation vs. membrane filtration: overview of process evolutions in seawater desalination, Desalination 143 (2002) 207–218.
[7] R.L. Hummel, Solar distillation with economies of scale, innovation and optimization, Desalination 134 (2001) 159–171.
[8] I.I. El-Sharkawy, K. Thu, K.C. Ng, B.B. Saha, A. Chakraborty, S. Koyama, Performance improvement of adsorption desalination plant: experimental investigation, Int. Rev. Mech. Eng. 1 (1) (2007) 25–31.
[9] L. Awerbuch, S. May, R. Soo-Hoo, V. Van dermast, Hybrid desalting systems, Desalination 76 (1989) 189–197.
[10] D. Zejli, R. Benchrifa, A. Bennouna, O.K. Bouhelal, A solar adsorption desalination device: first simulation results, Desalination 168 (2004) 127–135.
[11] G. Ehrenman, From sea to sink, Mech. Eng. 126 (10) (2004) 38–43.
[12] X.L. Wang, K.C. Ng, Experimental investigation of an adsorption desalination plant using low-temperature waste heat, Appl. Therm. Eng. 25 (2005) 2780–2789.
[13] X.L. Wang, A. Chakraborty, K.C. Ng, B.B. Saha, How heat and mass recovery strategies impact the performance of adsorption desalination plant: theory and experiments, Heat Transfer Eng. 28 (2) (2007) 147–153.
[14] K.C. Ng, X.L. Wang, L.Z. Gao, A. Chakraborty, B.B. Saha, S. Koyama, A. Akisawa, T. Kashiwagi, Apparatus and method for desalination, WO Patent Number 121414 (2006).
[15] K.C. Ng, X. Wang, Y.S. Lim, B.B. Saha, A. Chakraborty, S. Koyama, A. Akisawa, T. Kashiwagi, Experimental study on performance improvement of a four-bed adsorption chiller by using heat and mass recovery, Int. J. Heat Mass Transfer 49 (19–20) (2006) 3343–3348.
[16] B.B. Saha, K.C.A. Alam, A. Akisawa, T. Kashiwagi, K.C. Ng, H.T. Chua, Two-stage non-regenerative silica gel–water adsorption refrigeration, cycle, ASME Adv Energy Syst Division Orlando 40 (2000) 65–69.
[17] B.B. Saha, I.I. El-Sharkawy, A. Chakraborty, S. Koyama, Study on an activated carbon fiber-ethanol adsorption chiller: part I – system description and modelling, Int. J. Refrig. 30 (1) (2007) 86–95.
[18] B.B. Saha, A. Chakraborty, S. Koyama, K. Srinivasan, K.C. Ng, T. Kashiwagi, P. Dutta, Thermodynamic formalism of minimum heat source temperature for driving advanced adsorption cooling device, Appl. Phys. Lett. 91 (2007) 111902.