World Academy of Science, Engineering and Technology
International Journal of Environmental and Ecological Engineering
Vol:9, No:6, 2015

Effect of Evaporator Temperature on the Performance of Water Desalination/Refrigeration Adsorption System Using AQSOA-ZO2

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***Abstract*—**Many water desalination technologies have been developed but in general they are energy intensive and have high cost and adverse environmental impact. Recently, adsorption technology for water desalination has been investigated showing the potential of using low temperature waste heat (50-85°C) thus reducing energy consumption and CO_2 emissions. This work mathematically compares the performance of an adsorption cycle that produces two useful effects namely, fresh water and cooling using two different adsorbents, *silica-gel* and an advanced zeolite material *AQSOA-ZO2*, produced by Mitsubishi plastics. It was found that at low chilled water temperatures, typically below 20°C, the AQSOA-Z02 is more efficient than *silica-gel* as the cycle can produce 5.8 m^3 of fresh water per day and 50.1 Rton of cooling per tonne of *AQSOA-ZO2*. Above 20°C *silica-gel* is still better as the cycle production reaches 8.4 m^3 per day and 62.4 Rton per tonne of *silica-gel*. These results show the potential of using the *AQSOA-Z02* at low chilled water temperature for water desalination and cooling applications.

***Keywords*—**Adsorption, desalination, refrigeration, seawater.

I. Introduction

MANY areas around the world are suffering from high weather temperature in addition to inadequate fresh water resources. Therefore, cooling and fresh water are becoming increasingly needed. Many technologies can be used to provide such needs, but suffer from excessive energy consumption; adverse environmental impact and high cost [1]-[3]. Adsorption technology offers the means to supply cooling [4], [5], desalination [6]-[8] or both [9]-[12]. In this technology, waste heat or solar energy can be used at low temperatures (50 - 85°C) in addition to environmental friendly adsorbents which results in minimized costs and pollution [9]. In an adsorption system, four consecutive processes occur, evaporation, adsorption, desorption and condensation. Firstly, seawater is evaporated in the evaporator as a result of the heat gained from the chilled water passing through the evaporator coil. In addition, evaporation is aided by the uptake of water vapor by the adsorbent. The evaporated water vapor is adsorbed by the adsorber bed while cooling water at ambient temperature is used to absorb the heat of adsorption. Then the adsorbed water vapor is regenerated in the desorber bed via hot water stream which can be supplied by utilizing waste heat or solar energy. Finally, the incoming water vapor is condensed in the condenser as a result of cooling water circuit and the produced fresh water is collected [13]. Cooling effect is utilized from the cold chilled water coming out from the evaporator which is operating as a chiller in this system [14].

Ng et al. [9] have developed a mathematical model for an adsorption system using silica gel and water to produce both cooling and desalinated fresh water. A number of parameters were selected to analyze the cycle performance, which are: specific cooling power (SCP), specific daily water production (SDWP), and overall conversion ratio (OCR). It was found that a silica gel adsorption cycle can produce 8 m3 /day and 51.6 Rton per tonne of silica gel. In addition, the cycle can reach OCR of 1.4. Wu et al. [10] have analyzed all the possible adsorption thermodynamic cycles based on silica gel as an adsorbent. These cycles can co-generate cooling and fresh water and their performance were determined in terms of fresh water productivity and specific energy consumption. From this study it was concluded that the value of cooling water temperature relative to evaporator temperature affects the output of the cycle, which can be used either for desalination, cooling or both. Thu et al. [8] have studied the performance of a silica gel adsorption desalination system that operates on either two or four bed modes. Tested parameters are, water production, cycle time and performance ratio at both different heat source temperatures and constant heat sink temperature. Their experimental results showed that a longer cycle time is required in case of low heat source temperature for the production of maximum amount of fresh water. In addition, the maximum water production achieved was 10 m^3 per day per tonne of silica gel at a performance ratio of 0.61 in the case of operating the cycle at four bed master-slave configuration. Chakraborty et al. [11] have investigated the effects of adsorbent physical characteristics on the performance of adsorption cooling cum desalination (ACCD) cycle. Different types of silica gel that varies in pore widths and pore volumes were used in the study. For verification, a comparison between the findings and experimental data were carried out. It was noticed that optimizing silica gels pore size and volume, can result in an increase in the coefficient of performance (COP) and overall performance ratio (OPR) by an order of 20 to 40%. The best performance of silica gel-water ACCD system is obtained at pore width of 0.9 nm with higher pore volume. Moreover, decreasing evaporator temperature, reduces the COP. Ng et al. [12] have investigated the use of low temperature heat source (65 to 80°C) in the form of solar energy for the applications of cooling and desalination based on adsorption technology using silica gel as

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an adsorbent. The cycle was modelled mathematically in addition to the experimental tests where the assessment was performed in terms of (SDWP) and specific cooling capacity (SCC). Measurements indicated that this cycle can produce chilled water at 7 to 10°C at SCC of 25-35 Rton/ton of silica gel in addition to a SDWP of 3-5 m^3 per ton of silica gel per day while the OCR is about 0.8-1.1. All reviewed work showed that *silica-gel/* water were the only adsorption working pair used in water desalination.

In this work, an advanced zeolite adsorbent material, (*AQSOA FAM-ZO2*, produced by Mitsubishi plastics), is investigated in adsorption cycle for production of both cooling and fresh water at various evaporator and hot water source temperatures. The adsorption characteristics and cycle performance are compared to those for a silica gel desalination system.

TABLE I
MODIFIED FREUNDLITCH EQUATION CONSTANTS

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

[a]Units are; kg = kilogram, K = Kelvin.

TABLE II
LINEAR DRIVING FORCE, LDF EQUATION CONSTANTS

Symbol	SILICA GEL	AQSOA-ZO2		Unit [a]
		Pr [b] >0.1	Pr <0.1	
D_{so}	2.54 E-4	4.85 E-9	2.77 E-5	m^2/s
R_p	0.16 E-3	0.15 E-3	0.15 E-3	m
E_a	42000	17709.8	44423.5	J/mol

[a]Units are; m = meter, s = second, J = Joule, mol = mole.
[b]Pr is the pressure ratio between bed and heat exchanger

II. MATERIAL CHARACTERISTICS

A. Adsorption Isotherms

One of the adsorbent characteristics is the amount of adsorbate that can be adsorbed per unit mass of dry material at a specific vapor pressure. Adsorption isotherms represent this feature.

For *silica gel*, isotherms can be predicted by the modified Freundlich model (1) to (3) with the constants given in Table I [15].

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

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

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

where, c^* is the equilibrium uptake [kg_w/kg_{ads}], T, is temperature [°C] and P, is pressure [kPa].

Sun et al. [16] have developed a model that describes the water vapor uptake on *AQSOA-ZO2*. The formulation of their model is shown in (4) and (5):

$$\frac{c}{c_{max}} = \frac{K(P/P_s)^m}{1+(K-1)(P/P_s)^m} \quad (4)$$

where,

$$K = \alpha\, exp\left[m\left(Q_{st} - h_{fg}\right)/RT\right] \quad (5)$$

$$\alpha = 9 * 10^{-7}\ ,\ m = 3.18 \text{ and } Q_{st} = 3600\ kJ/kg$$

c_{max}, is maximum uptake, m, is heterogeneity factor, h_{fg}, is the latent heat [kJ/kg], R, is universal gas constant [J/mol.K] and Q_{st} is isosteric heat of adsorption.

B. Adsorption Kinetics

Another important parameter is the adsorption kinetics which determines the rate of adsorption or desorption. Linear driving force (LDF) model is used (6) and (7) [17] to determine the adsorption kinetics of both adsorbents with the constants given in Table II.

$$\frac{dw}{dt} = k(w^* - w) \quad (6)$$

$$k = \left(15\, D_{so}/R_p^2\right) e^{\left(\frac{-Ea}{RT}\right)} \quad (7)$$

The constants of the LDF model for *AQSOA-ZO2*, were determined by applying the model on the results obtained from the dynamic vapor sorption (DVS) gravimetric analyzer tests which were done at University of Birmingham. The test results at temperature of 36°C and at different vapor partial pressures (0.1 to 0.95) for both *silica gel* and *AQSOA-ZO2* are shown in Fig. 1.

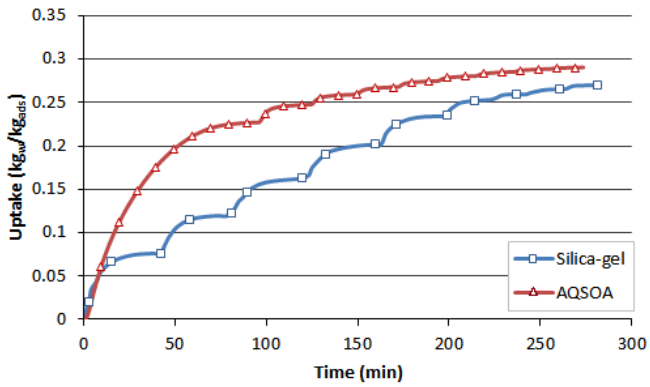

Fig. 1 DVS test results at 36°C for *Silica-gel RD-2060* and *AQSOA-ZO2*

III. CYCLE ANALYSIS

A two bed adsorption machine produced by 'Weatherite Manufacturing LTD' is simulated by Matlab to study its ability to produce both cooling and fresh water. Originally this machine is a 450 kW chiller but modified to include water desalination. It comprises of two beds with the capacity of 890 kg of silica gel per bed which are connected either to the

condenser or to the evaporator by flap valves. The pressure difference between heat exchangers results in the opening and closing of these valves. Besides, there are 12 pneumatic valves that control the flow of cooling and heating water through adsorbent / desorbent beds in addition to the flowing chilled water in the evaporator and cooling water in the condenser (Fig. 2).

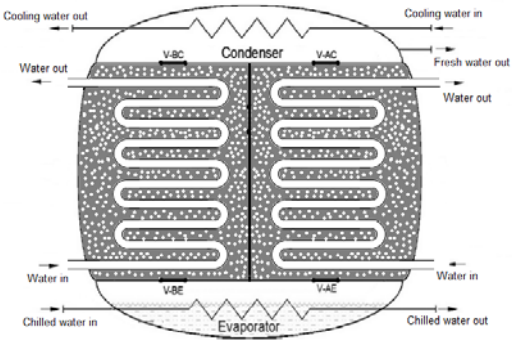

Fig. 2 Schematic diagram of the adsorption system

In order to study the cycle, energy equations are solved for evaporator, condenser, adsorber and desorber beds in addition to the mass and salt balance equations for the evaporator [18] as shown in (8)-(12):

Evaporator mass balance equation:

$$\frac{dM_{s,evap}}{dt} = \theta \dot{m}_{s,in} - \gamma \dot{m}_{brine} - n.\frac{dc_{ads}}{dt} M_a \tag{8}$$

Evaporator salt balance equation:

$$M_{s,evap}\frac{dX_{s,evap}}{dt} = \theta X_{s,in}\, \dot{m}_{s,in} - \gamma X_{s,evap}\, \dot{m}_{brine} - n.X_D \frac{dc_{ads}}{dt} M_a \tag{9}$$

Evaporator energy balance equation:

$$\left[M_{s,evap}c_{p,s}(T_{evap},X_{s,evap}) + M_{HX,Evap}c_{p,HX}\right]\frac{dT_{evap}}{dt} = \theta . h_f(T_{evap},X_{s,evap})\ \dot{m}_{s,in} - n\,.\,h_{fg}(T_{evap})\frac{dc_{ads}}{dt} M_a + \dot{m}_{chilled}c_p(T_{evap})(T_{chilled,in} - T_{chilled,out}) - \gamma h_f\,(T_{evap},X_{s,evap})\,\dot{m}_{brine} \tag{10}$$

where, M, is mass [kg], θ, is flag for seawater charging, γ, is flag for brine discharging, $\dot{m}$, is mass flow rate [kg/s], X, is salt concentration [ppm], h_f, is enthalpy of liquid [kJ/kg]. c_p, is specific heat at constant pressure [kJ/kg.K].

Adsorption /Desorption bed, energy balance equation:

$$\left[M_a c_{p,a} + M_{HX}c_{p,HX} + M_{abe}c_{p,abe}\right]\frac{dT_{ads/des}}{dt} = \pm n\,.\,Q_{st}M_a\frac{dc_{ads/des}}{dt} \pm \dot{m}_{\frac{cw}{hw}}c_p\left(T_{\frac{cw}{hw},in} - T_{\frac{cw}{hw},out}\right) \tag{11}$$

Condenser energy balance equation:

$$\left[M_{cond}c_p(T_{cond}) + M_{HX,Cond}c_{p,HX}\right]\frac{dT_{cond}}{dt} = h_f\frac{dM_d}{dt} + n\,.\,h_{fg}(T_{cond})\frac{dc_{des}}{dt} M_a + \dot{m}_{cond}c_p(T_{cond})(T_{cond,in} - T_{cond,out}) \tag{12}$$

For assessment of cycle performance, different parameters are calculated which are specific daily water production (SDWP), performance ratio (PR), specific cooling power (SCP), coefficient of performance (COP) and overall conversion ratio (OCR) for the determination of the overall cycle performance where two useful effects are obtained from the same heat source. Equations (13)-(20) are used to calculate these parameters.

$$SDWP = \int_0^{t_{cycle}} \frac{Q_{cond}}{h_{fg}M_a}dt \tag{13}$$

$$PR = \frac{1}{t_{cycle}}\int_0^{t_{cycle}} \frac{m_d h_{fg}}{Q_{des}}dt \tag{14}$$

$$SCP = \int_0^{t_{cycle}} \frac{Q_{evap}}{M_a}dt \tag{15}$$

$$COP = \int_0^{t_{cycle}} \frac{Q_{evap}}{Q_{des}}dt \tag{16}$$

$$OCR = \int_0^{t_{cycle}} \frac{Q_{evap}+Q_{cond}}{Q_{des}}dt \tag{17}$$

where,

$$Q_{cond} = \dot{m}_{cond}c_p(T_{cond})(T_{cond,out} - T_{cond,in}) \tag{18}$$

$$Q_{des} = \dot{m}_{hw}c_p(T_{hw,in} - T_{hw,out}) \tag{19}$$

$$Q_{evap} = \dot{m}_{chilled}c_p(T_{evap})(T_{chilled,in} - T_{chilled,out}) \tag{20}$$

These set of energy and mass balance equations are solved by Matlab with tolerance value of 1 x 10^{-6}. A lumped simulation model was used where the adsorbent, adsorbate and heat exchangers are assumed to be momentarily at the same temperature. Also perfect heat insulation is assumed for all parts.

IV. 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 [19]. Fig. 3 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 (Fig 4).

To investigate the performance of the *AQSOA FAM-ZO2*, a parametric study was carried out to compare the SDWP and SCP with *Silica-gel* at different inlet hot water temperatures and chilled water temperatures typically (85-65°C) and (30-10°C) respectively. Bed cooling water and condenser cooling water temperatures are kept constant at 30°C with cycle time of 400 sec and switching time of 25 sec.

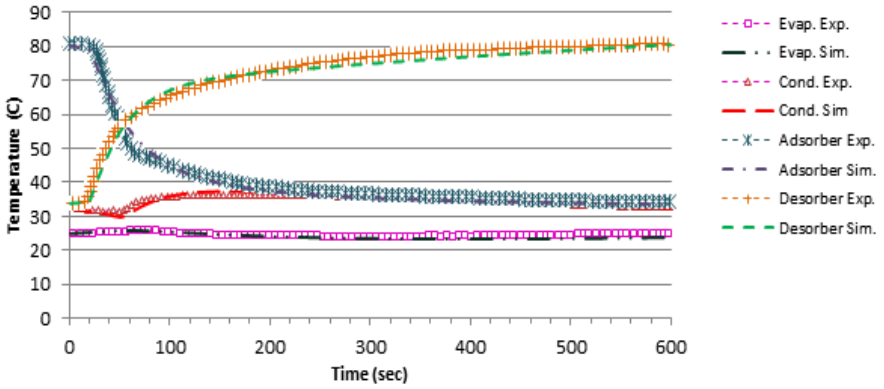

Fig. 3 Comparison of numerical results and experimental measurements for 2-Bed adsorption desalination cycle

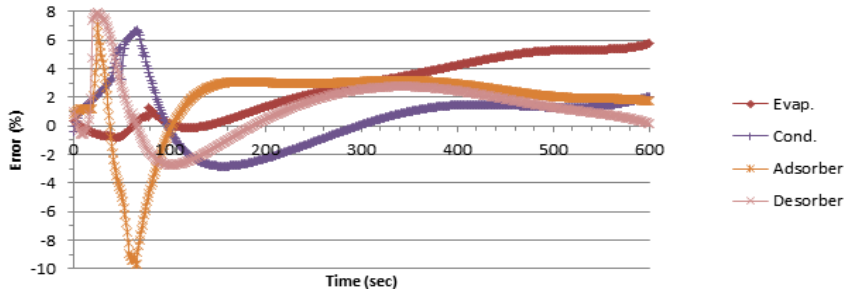

Fig. 4 Error between numerical results and experimental measurements for 2-Bed adsorption desalination cycle

In Figs. 5-9, SDWP is presented by continuous line while SCP by dotted line. As shown in Figs. 5, 6, for chilled water temperatures over 20°C, *silica-gel* is better than *AQSOA-ZO2* as the SDWP and SCP reach up to 8.4 m^3 per day and 62.4 Rton per tonne of *silica-gel*, respectively. At chilled water temperature of 20°C, and at hot water temperatures over 80°C, *AQSOA-ZO2* begins to be more efficient than *silica-gel*, Fig. 7. *AQSOA-ZO2* can result in a SDWP and SCP of 6.3 m^3 per day and 52.9 Rton per tonne of *AQSOA-ZO2*, respectively while *silica-gel* is capable only of producing 5.1 m^3 per day of fresh water and 36.1 Rton of cooling per tonne of *silica-gel*. If the hot water source temperature is below 80°C, use of silica-gel is recommended.

For space cooling applications where lower chilled water temperatures are needed, typically (20-10°C), *AQSOA-ZO2* offers better performance, (Figs. 8, 9). At low chilled water temperature of 10°C, while *silica-gel* can produce only 2.8 m^3 per day of fresh water and 17.2 Rton of cooling per tonne of *silica-gel*, it is found that *AQSOA-ZO2* can produce 5.8 m^3 of fresh water per day and 50.1 Rton of cooling per tonne.

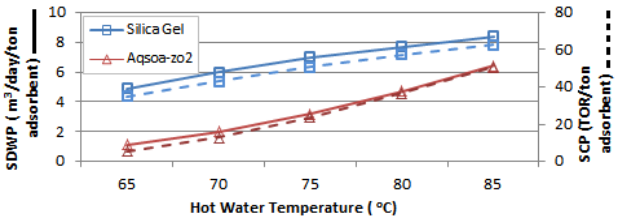

Fig. 5 SDWP & SCP at 30°C chilled water temperature

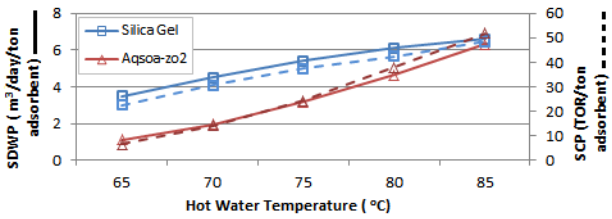

Fig. 6 SDWP & SCP at 25°C chilled water temperature

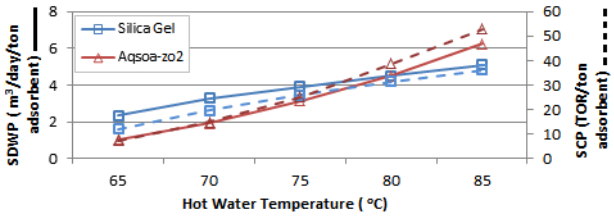

Fig. 7 SDWP & SCP at 20°C chilled water temperature

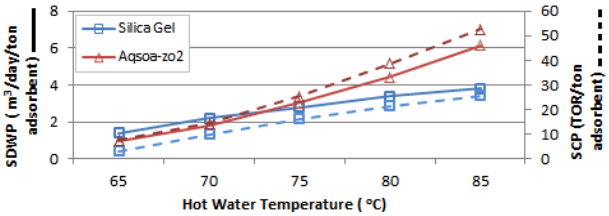

Fig. 8 SDWP & SCP at 15°C chilled water temperature

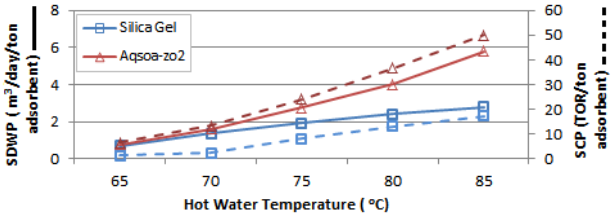

Fig. 9 SDWP & SCP at 10°C chilled water temperature

Another parameter which indicates the cycle performance is the overall conversion ratio, Figs 10, 11. It is clear that OCR for *silica gel* is affected by varying chilled water temperature (Fig. 10), while it is not the case for *AQSOA-ZO2* as shown in Fig. 11. Moreover, OCR for silica gel seems to be higher than *AQSOA-ZO2* in all cases except at low chilled water temperatures (15-10°C) which is the recommended range for operation with *AQSOA-ZO2*. At 10°C, OCR is 0.49 for silica gel compared to 0.74 for *AQSOA-ZO2*.

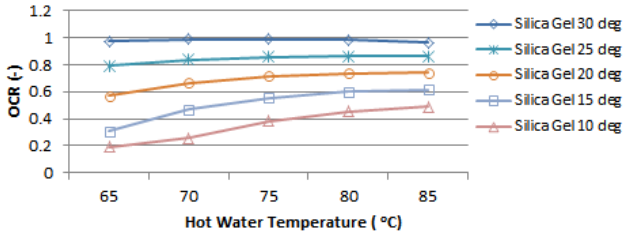

Fig. 10 Overall conversion ratio for *Silica-Gel*

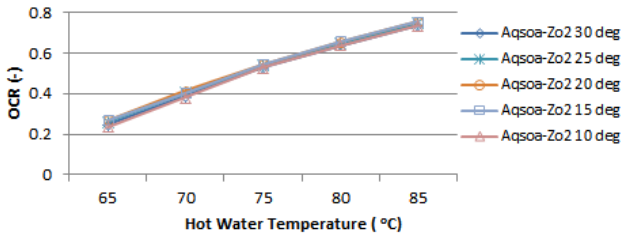

Fig. 11 Overall conversion ratio for *AQSOA-ZO2*

V. Conclusions

The performance of an adsorption desalination cycle for the purposes of fresh water production and cooling has been investigated using both *silica gel* and advanced zeolite material *AQSOA-ZO2*. For the *AQSOA-ZO2* the predicted SDWP, SCP and OCR at low chilled water temperature, (below 15°C) were higher than those of *silica gel* which highlights the potential of such material. Also, it can be concluded that the use of combined system of silica gel and zeolites can cover wide evaporation temperature range.

References

[1] A. Chakraborty, K. Thu, B. B. Saha, and K. C. Ng, "Adsorption - desalination cycle," in Advances in water desalination, N. Lior, Ed. WILEY, 2013, pp. 377-451.

[2] J. Cotruvo, N. Voutchkov, J. Fawell, P. Payment, D. Cunliffe, and S. Lattemann, Desalination technology health and environmental impacts: Taylor and Francis Group, 2010.

[3] T. Mezher, H. Fath, Z. Abbas, and A. Khaled, "Techno-economic assessment and environmental impacts of desalination technologies," Desalination, vol. 266, pp. 263-273, 2011.

[4] I. I. El-Sharkawy, H. AbdelMeguid, and B. B. Saha, "Potential application of solar powered adsorption cooling systems in the Middle East," Applied Energy, vol. 126, pp. 235-245, 2014.

[5] A. Rezk, R. Al-Dadah, S. Mahmoud, and A. Elsayed, "Effects of contact resistance and metal additives in finned-tube adsorbent beds on the performance of silica gel/water adsorption chiller," Applied Thermal Engineering, vol. 53, pp. 278-284, 2013.

[6] K. Thu, A. Chakraborty, Y.-D. Kim, A. Myat, B. B. Saha, and K. C. Ng, "Numerical simulation and performance investigation of an advanced adsorption desalination cycle," Desalination, vol. 308, pp. 209-218, 2013.

[7] X. Wang and K. C. Ng, "Experimental investigation of an adsorption desalination plant using low-temperature waste heat," Applied Thermal Engineering, vol. 25, pp. 2780-2789, 2005.

[8] K. Thu, K. C. Ng, B. B. Saha, A. Chakraborty, and S. Koyama, "Operational strategy of adsorption desalination systems," International Journal of Heat and Mass Transfer, vol. 52, pp. 1811-1816, 2009.

[9] K. C. Ng, K. Thu, B. B. Saha, and A. Chakraborty, "Study on a waste heat-driven adsorption cooling cum desalination cycle," International Journal of Refrigeration, vol. 35, pp. 685-693, 2012.

[10] J. W. Wu, E. J. Hu, and M. J. Biggs, "Thermodynamic cycles of adsorption desalination system," Applied Energy, vol. 90, pp. 316-322, 2012.

[11] A. Chakraborty, K. Thu, and K. C. Ng, "Advanced adsorption cooling cum desalination cycle- a thermodynamic framework," in Proc. ASME 2011 International Mechanical Engineering Congress & Exposition IMECE2011, Denver, Colorado, USA, 2011.

[12] K. C. Ng, K. Thu, A. Chakraborty, B. B. Saha, and W. G. Chun, "Solar-assisted dual-effect adsorption cycle for the production of cooling effect and potable water," International Journal of Low-Carbon Technologies, vol. 4, pp. 61-67, 2009.

[13] K. C. Ng, X.-L. Wang, L. Gao, A. Chakraborty, B. B. Saha, S. Koyama, et al., "Apparatus and method for desalination," US 2010/0258426 A1, 2010.

[14] T. X. Li, R. Z. Wang, and H. Li, "Progress in the development of solid–gas sorption refrigeration thermodynamic cycle driven by low-grade thermal energy," Progress in Energy and Combustion Science, vol. 40, pp. 1-58, 2014.

[15] A. Rezk, R. Al-Dadah, S. Mahmoud, and A. Elsayed, "Characterisation of metal organic frameworks for adsorption cooling," International Journal of Heat and Mass Transfer, vol. 55, pp. 7366-7374, 2012.

[16] B. Sun and A. Chakraborty, "Thermodynamic formalism of water uptakes on solid porous adsorbents for adsorption cooling applications," Applied Physics Letters, vol. 104, p. 201901, 2014.

[17] A. Rezk and R. Al-Dadah, "Physical and operating conditions effects on silica gel/water adsorption chiller performance," Applied Energy, vol. 89, pp. 142-149, 2012.

[18] K. C. Ng, K. Thu, Y. Kim, A. Chakraborty, and G. Amy, "Adsorption desalination: An emerging low-cost thermal desalination method," Desalination, vol. 308, pp. 161-179, 2013.

[19] K. Thu, "Adsorption desalination Theory and experiment," PhD, National University of Singapore, 2010.