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# Performance Analysis of Four Bed Adsorption Water Desalination / Refrigeration System, Comparison of AQSOA-Z02 to Silica-gel

Peter G. Youssef*, Saad M. Mahmoud, Raya K. AL-Dadah

***Abstract*—**Although many water desalination techniques have been introduced decades ago, there are still areas around the world suffering from fresh water shortages. The widespread of desalination technologies is limited due to their high energy consumption, cost and adverse environmental impact. Recently, adsorption technology for water desalination has been investigated showing potential of using low temperature waste heat (50-85$^{o}$C) thus reducing energy consumption and $CO_2$ emissions. This work mathematically investigates the performance of 4 bed adsorption cycle using two different adsorbents, *silica-gel* and an advanced zeolite material *AQSOA-Z02*, produced by Mitsubishi-plastics for fresh water production and cooling. The work studied effects of evaporator and heat source temperatures on water production rate and cooling capacity. Results showed that at low chilled water temperatures below 20$^{o}$C, *AQSOA-Z02* outperform *silica-gel* with water production of 6.2 m$^3$ of water/day and cooling of 53.7 Rton/ tonne of *AQSOA-Z02* compared to 3.5 m$^3$ of water/day and 15.0 Rton/tonne of *silica-gel.* While, at chilled water temperatures above 20$^{o}$C, *AQSOA-Z02* and *silica-gel* have comparable performance with around 7m$^3$ of water/day and 60 Rton of cooling. Since cooling applications require chilled water temperature less than 20$^{o}$C, therefore *AQSOA-Z02* is more suitable for applications where cooling and fresh water are needed.

***Keywords*—**Adsorption, AQSOA-Z02, Desalination, Refrigeration, Seawater, Silica-gel.

## 1. INTRODUCTION

Although about 70% of the earth is covered with water, 97% of this water is salty. Also, 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]. Therefore seawater desalination is required to provide part of human needs for water. Different desalination technologies exist like thermal, membrane and chemical [2] but many of these suffer from excessive energy consumption; adverse environmental impact and high cost [3, 4]. Recently, adsorption technology was shown to provide water desalination with minimum energy consumption [5]. It is capable of producing fresh water with low salinity of 10 ppm, running cost of 0.2\$/m$^3$ and $CO_2$ emissions of 0.6 kg/m$^3$ [6]. In this technology, besides water production, cooling can be produced for air conditioning required in many areas around the world [7-11]. A major advantage of adsorption technology is its ability to utilize low grade waste heat sources (50 - 85$^{o}$C) or solar energy and using environmentally friendly refrigerants leading to lower pollution and cost [8, 12]. A comparison between a lumped parameter model and experimental tests has been presented by Ng et al [13]. The comparison covered wide range of operating conditions for basic and hybrid *silica-gel*/water pair adsorption cycles that are able to produce cooling and desalination. In addition the energetic efficiency and life cycle cost (LCC) of adsorption plants have been compared to other conventional desalination technologies. It was found that adsorption desalination plants require electrical energy of 1.38 kWh/m$^3$ and thermal energy of 38.8 kWh/m$^3$. Comparing to other desalination methods, multi effect desalination (MED) and multi stage flash (MSF) needs 43.21 and 57.14 kWh/m$^3$ of thermal energy respectively. Also reverse osmosis (RO) needs 3.5-5 kWh/m$^3$ of electric energy. Moreover, studies showed that adsorption desalination and cooling cycle has the lowest cost of US \$2.7/ MWh compared to

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## Nomenclature

| | | | |
|---|---|---|---|
| $c$ | Uptake (kg.kg$^{-1}$) | $PR$ | Performance ratio (-) |
| $c^*$ | Equilibrium uptake (kg. kg$^{-1}$) | $Q_{st}$ | Isosteric heat of adsorption (kJ/kg) |
| $c_p$ | Specific heat at constant pressure (kg. kg$^{-1}$.K$^{-1}$) | $SCP$ | Specific cooling power (kW.kg$^{-1}$) |
| $COP$ | Coefficient of performance (-) | $SDWP$ | Specific daily water production (m$^3$ t$^{-1}$ day$^{-1}$) |
| $h$ | Enthalpy (kJ.kg$^{-1}$) | $T$ | Temperature (K) |
| $M$ | Mass (kg) | $X$ | Salt concentration (ppm) |
| $\dot{m}$ | Mass flow rate (kg.s$^{-1}$) | $\theta$ | Seawater charging flag (-) |
| $n$ | Adsorption/Desorption phase, flag (-) | $\gamma$ | Brine discharge flag (-) |
| $OCR$ | Overall conversion ratio (-) | $\tau$ | No of cycles per day (-) |
| $P$ | Pressure (kPa) | | |

### *Subscripts*

| | | | |
|---|---|---|---|
| *a* | Adsorbent material | *hw* | Heating Water |
| *ads* | Adsorption | *HX* | Heat exchanger |
| *b* | Brine | *in* | inlet |
| *cond* | Condenser | *Mads* | Master adsorber bed |
| *cw* | Cooling Water | *Mdes* | Master desorber bed |
| *D* | vapor | *out* | outlet |
| *d* | Distillate water | *s* | Seawater |
| *des* | Desorption | *Sads* | Slave adsorber bed |
| *evap* | Evaporator | *Sdes* | Slave desorber bed |
| *f* | Liquid | *t* | Time |

$4.4/MWh for the combined RO and mechanical chiller or $3.4/MWh for RO and absorption chiller.

The desalination/refrigeration adsorption system consists of four consecutive processes namely evaporation, adsorption, desorption and condensation. In the evaporator, seawater is evaporated due to the effect of adsorption by the dry adsorbent material while extracting heat from the chilled water passing through the evaporator coil thus producing cooling effect [14]. In the adsorption process, water vapour is adsorbed by the adsorbent material while in the desorption process the water vapour is regenerated by the waste heat. The desorbed water vapour is then condensed in the condenser producing fresh water [8, 15].

Various researchers have investigated the use of adsorption technology for water desalination and cooling using silica gel with various cycle configurations. Wang et al. [12], experimentally investigated the performance of a four bed *silica-gel* adsorption desalination system, studying the effects of cycle time, hot, cold and chilled water temperatures on water production rates and cycle coefficient of performance. They found that at chilled water temperature of 12.2$^o$C, a maximum specific daily water production (SDWP) of 4.7 m$^3$/day per tonne of silica gel was obtained using cycle time of 150 seconds, switching time of 40 seconds and low heat source temperature of 85$^o$C. In addition, they have reported that this method of desalination produced potable water without any means of bio-contamination.

Thu et al. [16] studied experimentally the performance of a four bed silica gel adsorption desalination system that operates on either two or four bed configuration. In the two bed operation, each two beds are heated or cooled jointly while in the four bed operation mode, each two beds are heated or cooled sequentially in a master and slave arrangement. Water production and performance ratio were studied at different heat source temperatures with constant heat sink temperature using cycle time ranging from 950 to 2400 seconds for two bed operation or from 480 to 1920 seconds for four bed operation. Experimental results showed that in four bed operation at low heat source temperature (<65°C), a longer cycle time (1560 sec.) is required for the production of maximum amount of fresh water of 6.28 $m^3$ of water per day per tonne of silica gel. At the maximum heat source temperature of 85°C, the two bed configuration produced 8.79 $m^3$/day per tonne of silica gel while the four bed master-slave configuration produced 10 $m^3$ of water per day per tonne of silica gel with performance ratio of 0.61.

Mitra et al. [17], have analyzed a four bed single stage silica gel/water adsorption desalination system that used solar energy for the desorption process. Effects of condenser temperature and cycle time were studied to find the optimum operating conditions for maximum water production and cooling outputs. Simulation results showed that 600-900 seconds is the optimum half cycle time for producing maximum SDWP and specific cooling power (SCP) of 2.3$m^3$/day and 18 Rton per tonne of silica gel respectively at condenser temperature of 25°C. They concluded that compromise is needed between desalination and cooling capacities as COP increases with increasing in cycle time while increasing condenser temperature degrades the cycle performance.

Ng et al. [8], have developed a mathematical model for a 4 bed adsorption system using silica gel/water pair to produce both cooling and desalinated fresh water. At different hot and chilled water temperatures, cycle performance was analyzed by calculating SCP, SDWP, and overall conversion ratio (OCR). It was found that a silica gel adsorption cycle can produce 8 $m^3$/day and 51.6 Rton per tonne of silica gel when optimized for water production at evaporator temperature of 30°C or 3.8 $m^3$/day and 22 Rton per tonne of silica gel at evaporator temperature of 10°C. In addition, the cycle can reach a maximum OCR of 1.4.

Ng et al. [10], have investigated experimentally and mathematically a 4 bed adsorption cycle that uses *silica-gel*/water pair. The cycle is capable of producing two useful effects which are desalination and cooling using solar energy at low temperature namely (65 to 80°C). Measurements indicated that chilled water at 7 to 10°C with a SCP of 25-35 Rton/tonne of silica gel can be produced in addition to a SDWP of 3-5 $m^3$ per tonne of silica gel per day while the OCR ranging from 0.8-1.1.

Youssef et al. [18], compared numerically the performance of an adsorption, two bed cycle using *AQSOA-Z02*/water with the same two bed cycle using *Silica-gel*/water. Different heating source temperatures and evaporator water inlet temperatures were applied to study their effect on cycle performance. It was found that at all heating temperatures, and evaporator water inlet temperatures above 25°C, *Silica-gel* cycle produces more water and cooling. *Silica-gel* cycle produces maximum SDWP of 8.4 $m^3$ and 62.4 Rton of cooling at 30°C evaporator water inlet temperature. However, as evaporator inlet water temperature decreases, *AQSOA-Z02* outperforms *Silica-gel*. At 10°C evaporator inlet water temperature, *AQSOA-Z02* cycle produced 5.8 $m^3$ of fresh water per day and 50.1 Rton of cooling while *Silica-gel* cycle generated only SDWP of 2.8 $m^3$ and SCP of 17.2 Rton.

*AQSOA-Z02* was studied as an adsorbent but in other applications like cooling [19] and dehumidification [20]. Verdi et al. [19] have developed a numerical model for a truck air conditioning system using *AQSOA-Z02*/ water adsorption system that utilizes waste heat from truck engine at temperature (80-90°C). Experimental tests were also performed using a lab-based adsorption chiller prototype. The specific cooling power produced at the laboratory reached 600 W/kg of AQSOA-Z02 which is 180% higher than the amount of cooling produced by *Silica-gel* system which is 334 W/kg [21].

Intini et al. [20] have analyzed numerically and experimentally the performance of an AQSOA-based desiccant wheel. Performance of the system was assessed by determining the effect of area ratio, process inlet temperature, humidity and air force velocity. It was found that maximum moisture removal capacity is achieved at equal area split. In addition, inlet humidity ratio was found to be important in determining moisture removal efficiency while process inlet temperature is not that much effective.

All reviewed work on water adsorption desalination, showed that *silica-gel* / water was the only adsorption working pair investigated in a 4 bed cycle. This work, investigates the use of an advanced zeolite adsorbent material, (*AQSOA FAM-Z02*, produced by Mitsubishi plastics) in a 4 beds adsorption cycle for production of both cooling and fresh water. The effect of operating conditions in terms of evaporator and hot water temperatures were studied and compared to those for a silica gel 4 beds adsorption desalination system.

## 2. SYSTEM MODELLING

A full scale four bed adsorption machine is simulated by Simulink to study its ability to produce both cooling and fresh water. It comprises of four beds with the capacity of 890 kg of silica gel per bed in addition to an evaporator and a condenser (Fig. 1).

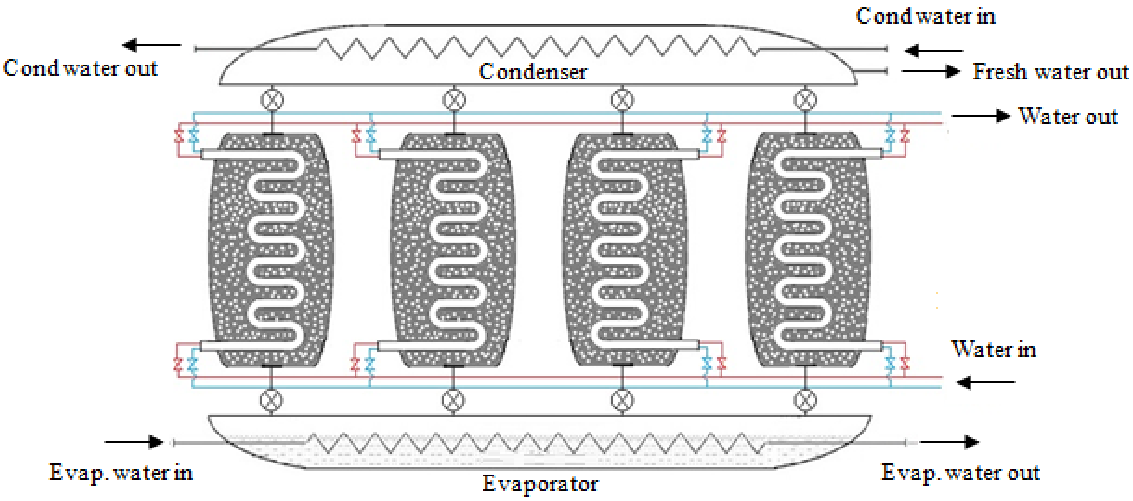

Fig. 1 Schematic diagram of the adsorption system

In this system, cooling water is passed through first adsorbing bed (master bed) and the outlet stream continues the cooling process in the second adsorber bed (slave bed). This cooling is to absorb the heat of adsorption. For desorption, hot water is passed through desorbing beds (master then slave bed). Fresh water is obtained from the condenser by condensing water vapour via external cooling water passing through cooling coil while cooling is achieved at the evaporator.

In order to study the cycle, energy equations are solved for evaporator, condenser, adsorber and desorber beds in addition to mass and salt balance equations for the evaporator [8] as shown in equations 1-6:

*Evaporator mass balance equation:*

$$\frac{dM_{s,evap}}{dt} = \theta \dot{m}_{s,in} - \gamma \dot{m}_b - \frac{dc_{Mads}}{dt} M_a - n.\frac{dc_{Sads}}{dt} M_a \qquad (1)$$

*Evaporator salt balance equation:*

$$M_{s,evap}\frac{dX_{s,evap}}{dt} = \theta X_{s,in}\, \dot{m}_{s,in} - \gamma X_{s,evap}\, \dot{m}_{brine} - X_D \frac{dcM_{ads}}{dt} M_a - n.X_D \frac{dc_{Sads}}{dt} M_a \qquad (2)$$

*Evaporator energy balance equation:*

$$\left[M_{s,evap} c_{p,s}\left(T_{evap}, X_{s,evap}\right) + M_{HX,Evap} c_{p,HX}\right] \frac{dT_{evap}}{dt} =$$

$$\theta . h_f\left(T_{evap}, X_{s,evap}\right)\ \dot{m}_{s,in} - h_{fg}\left(T_{evap}\right)\frac{dc_{Mads}}{dt}\ M_a$$
$$-n\ .\ h_{fg}\left(T_{evap}\right)\frac{dc_{Sads}}{dt}\ M_a - \gamma h_f\ \left(T_{evap}, X_{s,evap}\right)\dot{m}_b$$
$$+\dot{m}_{chilled}c_p\left(T_{evap}\right)\left(T_{chilled,in} - T_{chilled,out}\right) \tag{3}$$

*Master adsorption /desorption bed, energy balance equation:*

$$\left[M_a c_{p,a} + M_{HX}c_{p,HX} + M_{abe}c_{p,abe}\right]\frac{dT_{Mads/Mdes}}{dt} =$$
$$\pm\ \dot{m}_{cw/hw}c_p\left(T_{cw/hw,in} - T"_{cw/hw,out}\right)$$
$$\pm\ Q_{st}M_a\frac{dc_{Mads/Mdes}}{dt} \tag{4}$$

*Slave adsorption /desorption bed, energy balance equation:*

$$\left[M_a c_{p,a} + M_{HX}c_{p,HX} + M_{abe}c_{p,abe}\right]\frac{dT_{Sads/Sdes}}{dt} =$$
$$\pm\ \dot{m}_{cw/hw}c_p\left(T"_{cw/hw,in} - T_{cw/hw,out}\right)$$
$$\pm z\ .\ Q_{st}M_a\frac{dc_{ads/des}}{dt} \tag{5}$$

Where, z is a flag equals 0 in heat recovery phase and 1 in all other cases.

*Condenser energy balance equation:*

$$\left[M_{cond}c_p(T_{cond}) + M_{HX,Cond}c_{p,HX}\right]\frac{dT_{cond}}{dt} =$$
$$h_f\frac{dM_d}{dt} + h_{fg}(T_{cond})\ M_a\left(\frac{dc_{Mdes}}{dt} + n.\frac{dc_{Sdes}}{dt}\right)$$
$$+\dot{m}_{cond}c_p(T_{cond})\left(T_{cond,in} - T_{cond,out}\right) \tag{6}$$

For assessment of cycle performance, different parameters are calculated which are specific daily water production (SDWP), performance ratio (PR) which is the ratio between heat of condensation to the heat of desorption, specific cooling power (SCP) and coefficient of performance (COP). For the determination of the overall cycle performance where two useful effects are obtained from the same heat source, overall conversion ratio (OCR) is calculated. OCR is the ratio between useful effects produced (summation of heat of condensation and heat of evaporation) over the input which is heat of desorption [8]. These parameters are calculated using equations 7-14:

$$SDWP = \int_0^{t_{cycle}}\frac{Q_{cond}}{h_{fg}M_a}dt \tag{7}$$

$$PR = \frac{1}{t_{cycle}}\int_0^{t_{cycle}}\frac{m_d h_{fg}}{Q_{Mdes}+Q_{Sdes}}dt \tag{8}$$

$$SCP = \int_0^{t_{cycle}}\frac{Q_{evap}}{M_a}dt \tag{9}$$

$$COP = \int_0^{t_{cycle}}\frac{Q_{evap}}{Q_{Mdes}+Q_{Sdes}}dt \tag{10}$$

$$OCR = \int_0^{t_{cycle}}\frac{Q_{evap}+Q_{cond}}{Q_{Mdes}+Q_{Sdes}}dt \tag{11}$$

*Where,*

$$Q_{cond} = \dot{m}_{cond}c_p(T_{cond})\left(T_{cond,out} - T_{cond,in}\right) \tag{12}$$

$$Q_{Mdes/Sdes} = \dot{m}_{hw}c_p\left(T_{hw,in} - T_{hw,out}\right) \tag{13}$$

$$Q_{evap} = \dot{m}_{chilled}c_p\left(T_{evap}\right)\left(T_{chilled,in} - T_{chilled,out}\right) \tag{14}$$

These set of energy and mass balance equations are solved by Simulink 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.

## 3. ADSORBENT MATERIAL CHARACTERISTICS

Two materials are compared in this work, *Silica-gel*-RD and *AQSOA-Z02*. Figure 2 (a –b), shows SEM images for both materials and their physical properties are listed in table I [19, 22, 23].

To investigate the performance of any adsorbent material, adsorption isotherms and adsorption kinetics are required.

Adsorption isotherms represent the maximum amount of adsorbate that can be adsorbed per unit mass of dry material at a specific vapor pressure.

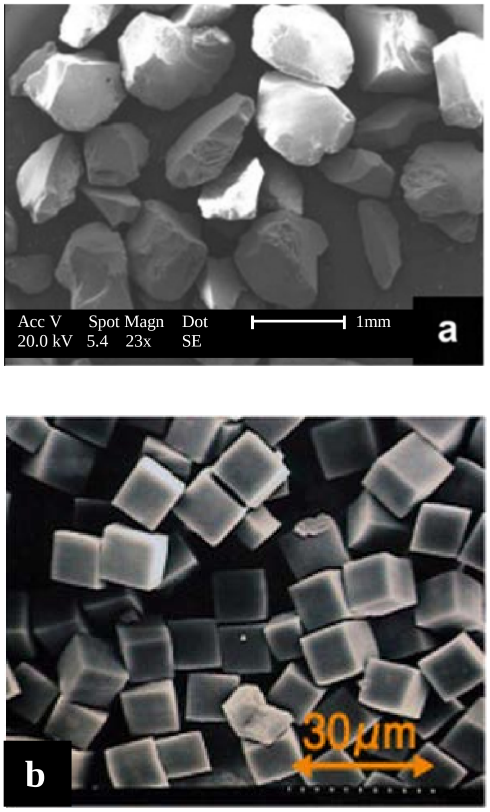

Fig. 2 SEM images for (a) RD Silica-gel

(b) AQSOA-Z02

TABLE I
PHYSICAL PROPERTIES OF ADSORBENT MATERIALS

| Property | SILICA GEL | AQSOA-Z02 |
|---|---|---|
| *Granules size* | 0.18-1 mm | 0.25-0.4 mm |
| *BET surface area* | 840 m$^2$/g | 650-770 m$^2$/g |
| *Bulk Density* | 1 g/cm$^3$ | 0.5-0.7 g/cm$^3$ |

Different isotherm models can predict adsorbent materials performance such as Dubinin-Astakhov (D-A), Sips, Toth, Freundlich, Modified Freundlich and Langmuir. Isotherms of *Silica-gel*-RD, can be predicted by the Dubinin-Astakhov (D-A) model (equation 15) with the constants given in table II [8].

$$c^* = c_0\, exp\left[-\left(\frac{RT}{E}\, ln\left(\frac{P}{P_o}\right)\right)^n\right] \qquad (15)$$

TABLE II
DUBININ-ASTAKHOV EQUATION CONSTANTS

| Symbol | Value | Unit [a] |
|---|---|---|
| $c_0$ | 0.592 | kg/kg of adsorbent |
| $E$ | 3.105 | kJ/mole |
| $n$ | 1.1 | (-) |
| $R$ | 8314 | J/mole.K |

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

For *AQSOA-Z02*, water vapor uptake is calculated via the model developed by Sun et al. [24] as shown in equations (16-17).

$$\frac{c}{c_{max}} = \frac{K(P/P_S)^m}{1+(K-1)(P/P_S)^m} \qquad (16)$$

*Where,*

$$K = \alpha\, exp\lfloor m\left(Q_{st} - h_{fg}\right)/RT\rfloor \qquad (17)$$

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

*Where,* $c_{max}$ is maximum uptake, $m$, is heterogeneity factor, $h_{fg}$, is the latent heat [kJ/kg], $R$, is universal gas constant [J/mol.K].

As adsorption process is time dependent, adsorption kinetics are needed to determine the rate of adsorption or desorption at the specified operating conditions. Adsorption kinetics are modeled by Linear Driving Force (LDF) model for both materials, (equations 18-19) [8] with all constants given in table III.

$$\frac{dc}{dt} = k(c^* - c) \qquad (18)$$

$$k = \left(15\, D_{so}/R_p^2\right) e^{\left(\frac{-Ea}{RT}\right)} \qquad (19)$$

For Silica-gel, LDF model constants are obtained from Ng et al [8] while for AQSOA-Z02, tests by a dynamic vapor sorption (DVS) gravimetric analyzer, fig. 3, were carried out at University of Birmingham to determine the constants.

This DVS analyser consists of a temperature controlled chamber that contains a sensitive recording microbalance (Cahn D200).

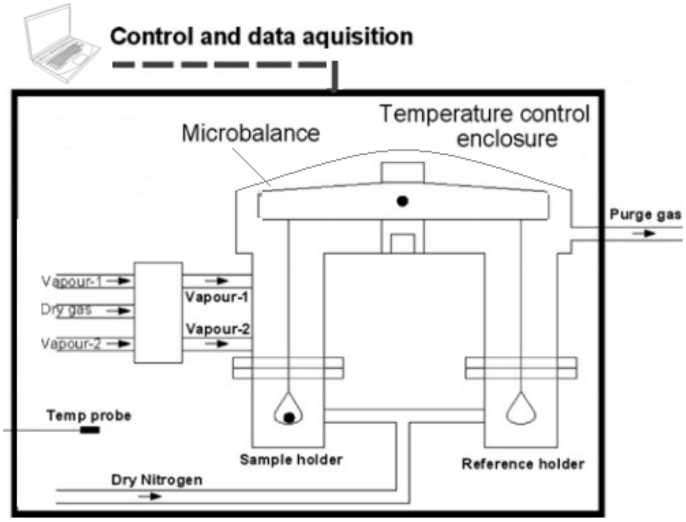

Fig. 3 Schematic diagram of the used DVS instrument

A dry Nitrogen purge system is applied before sample loading to ensure accurate uptake measurements by preventing vapor condensation on the balance head. The vapor pressure in the chamber is regulated by mass flow controller which determines the amount of dry and saturated vapor gas. A PC microcomputer is connected to the microbalance to record mass readings every 4 seconds while vapor pressure sensor and RTD temperature sensor are used to measure testing conditions. The accuracy of the DVS analyser microbalance Cahn is verified by using 100 mg standard calibration mass, where the expected mass accuracy of the tested sample is ±0.05 mg.

To measure adsorption kinetics, firstly a sample of 10 mg (±0.05 mg) is placed in the sample pan and then dried at certain temperature until no change in the mass is recorded. Secondly, adsorption process is started at various partial pressures starting from 0.1-0.95. During that time, change of the mass is calculated every 4 seconds. This test is repeated at different temperatures starting from 20$^o$C to 52$^o$C.

Test results at temperature of 36$^o$C and at different vapor partial pressures (0.1 to 0.95) are shown in Fig. 4. The kinetics of *AQSOA-Z02* were then fitted using equations 18, 19 and the constants are tabulated in table III.

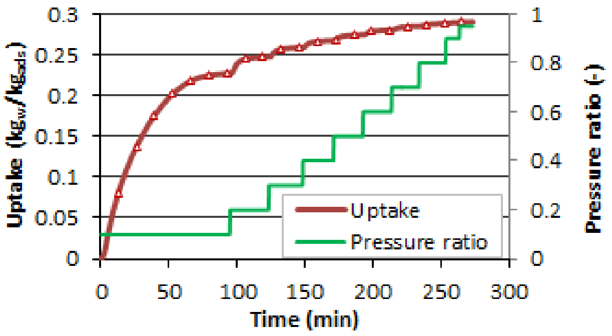

Fig. 4 DVS test results at 36$^o$C for *AQSOA-Z02*

TABLE III

LINEAR DRIVING FORCE, LDF EQUATION CONSTANTS

| Symbol | SILICA GEL | AQSOA-Z02 |  | Unit [a] |
|---|---|---|---|---|
|  |  | Pr [b] >0.1 | Pr <0.1 |  |
| $D_{so}$ | 2.54 E-4 | 4.85 E-9 | 2.77 E-5 | $m^2/s$ |
| $R_p$ | 0.4 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

Figure 5, compares the LDF predicted temporal uptake to the experimental ones showing deviation of less than ±15%.

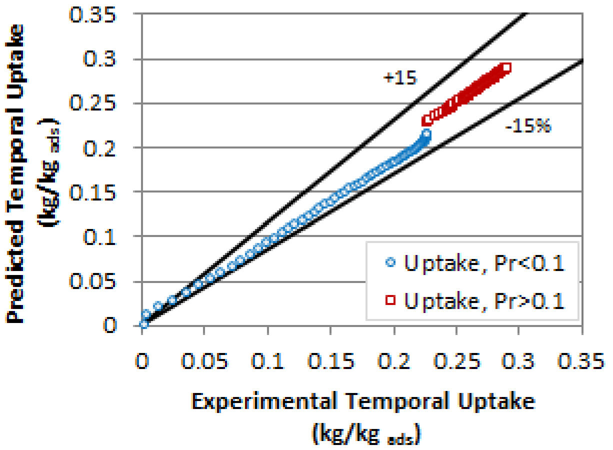

Fig. 5 Comparison between the measured water uptake for *AQSOA-Z02* and those predicted by the LDF model

## 4. METHODOLOGY

The developed numerical model of the 4 bed adsorption system shown in fig 1 is validated against the measured experimental results from a *silica-gel/water* adsorption plant operating in a 4-Bed mode for desalination application and cooling production [25]. Fig.6 shows the comparison between the simulation results and experimental measurements for the basic components of an adsorption desalination cycle.

TABLE IV
ERROR RANGE FOR THE VALIDATION OF ADSORPTION DESALINATION CYCLE

| | Maximum (%) | Minimum (%) |
|---|---|---|
| *Bed 1* | 4.05 | -8.34 |
| *Bed 2* | 4.6 | -8.48 |
| *Bed 3* | 2.79 | -9.89 |
| *Bed 4* | 3.67 | -3.08 |
| *Condenser* | 5.59 | -3.98 |
| *Evaporator* | 4.25 | -1.37 |

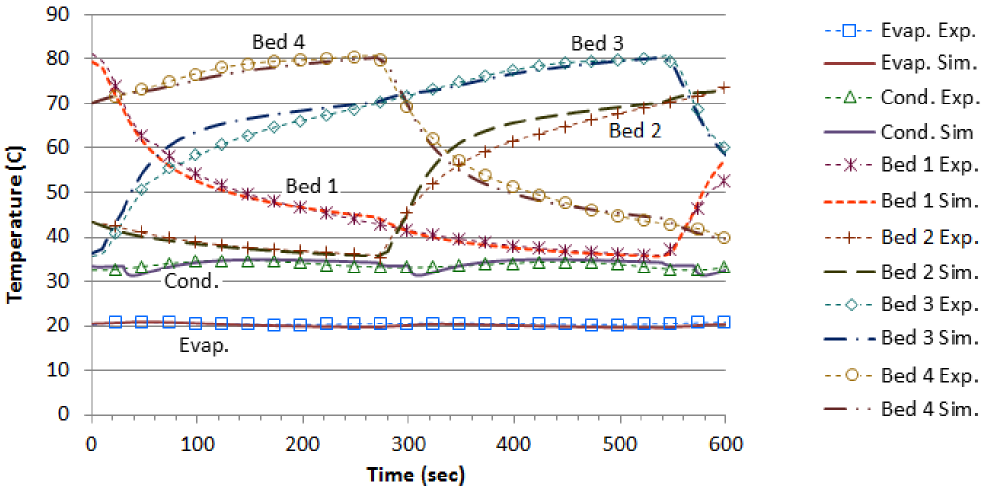

Fig. 6 Comparison of Basic components temperatures for numerical and experimental results for 4-Bed adsorption desalination cycle using silica-gel.

Comparison of cycle outputs i.e. SDWP and SCP are presented in fig.7, where results show that the current model can predict the performance of desalination and cooling cycles within ±10% error margin (table IV).

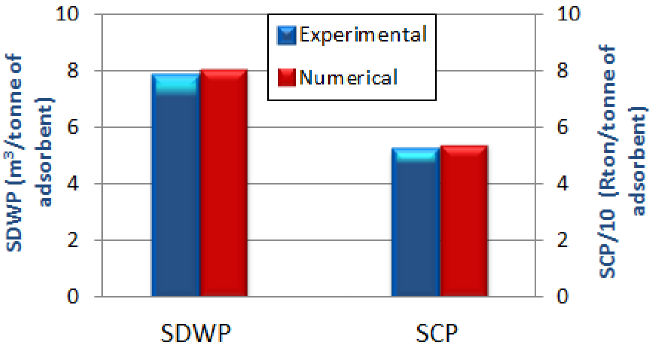

Fig. 7 Comparison of SDWP and SCP for numerical and experimental results for 4-Bed adsorption desalination cycle

To investigate the performance of the *AQSOA-Z02*, a parametric study was carried out to compare the SDWP and SCP of *AQSOA-Z02* against *Silica-gel* at different inlet hot water temperatures and evaporator water temperatures ranging from (65-85$^{o}$C) and (10-30$^{o}$C) respectively.

Bed cooling water and condenser cooling water temperatures are kept constant at 30$^{o}$C with quarter cycle time of 150 sec and switching time of 30 sec.

## 5. RESULTS AND DISCUSSION

Figures 8 to 13 present SDWP and SCP for different evaporator and hot water temperatures. As shown in Figs 8 to 11, at low hot water temperatures, less than 75$^{o}$C, *silica-gel* is better than *AQSOA-Z02* at high evaporator temperatures of more than 20°C. At evaporator water temperature of 30°C, and at hot water temperatures of 65°C, *silica-gel* can result in a SDWP and SCP of 5.4 m$^3$ per day and 38.1 Rton per tonne of *silica-gel*, respectively while *AQSOA-Z02* is capable only of producing 1.1 m$^3$ per day of fresh water and 6.2 Rton of cooling per tonne of *AQSOA-Z02*. However, as evaporator water temperature decreases below 18 °C and hot water temperature increases above 75°C, *AQSOA-Z02* outperforms *silica-gel* as shown in fig. 10 to 10. At evaporator water temperature of 10°C, and at hot water temperatures of 85°C, *AQSOA-Z02* can produce 6.2 m$^3$ per day and 53.7 Rton per tonne of *AQSOA-Z02* while *silica-gel* is capable only of producing 3.39 m$^3$ per day of fresh water and 15.7 Rton of cooling per tonne of *silica-gel.*

Another parameter which indicates the cycle performance is the overall conversion ratio, Figs 14 - 15. It is clear that OCR for *silica gel* is highly affected by varying chilled water temperature (Fig. 14), while it is not the case for *AQSOA-Z02* as shown in Fig. 15 which is a result of the “S” shaped isotherm of *AQSOA-Z02*. Moreover, Figs 15, proves that hot water temperature highly affects the performance of *AQSOA-Z02* cycle where OCR varies from 0.3 to 0.8 as hot source temperature increases from 65 to 85 °C. However, silica gel cycle performance is only better than *AQSOA-Z02* at high evaporator water temperature, above 20°C as it reaches 1.1 at 30°C.

According to these results, where heat source temperatures are available at temperatures above 75°C for the applications of space cooling, typically evaporator temperature (10-20°C), *AQSOA-Z02* is recommended. For applications where evaporator temperature above 20 °C is needed, *silica-gel* becomes more effective.

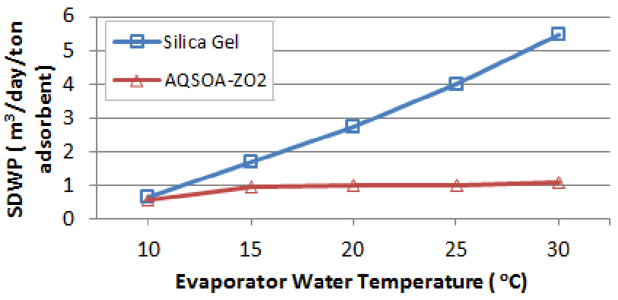

Fig. 8 SDWP at 65°C hot water temperature.

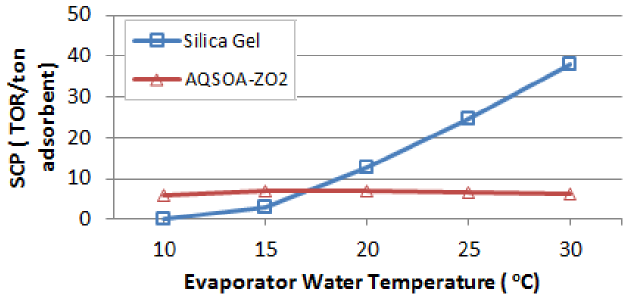

Fig. 9 SCP at 65°C hot water temperature.

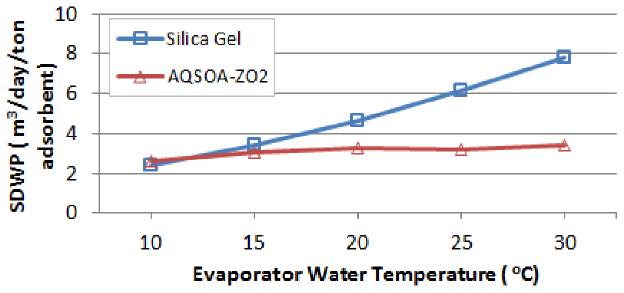

Fig. 10 SDWP at 75°C hot water temperature.

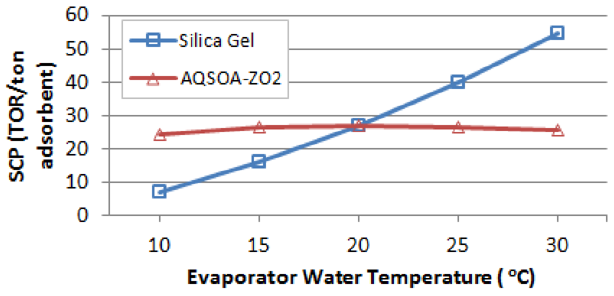

Fig. 11 SCP at 75°C hot water temperature.

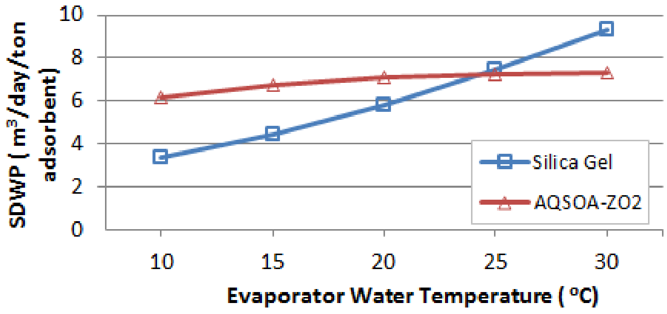

Fig. 12 SDWP at 85$^{o}$C hot water temperature.

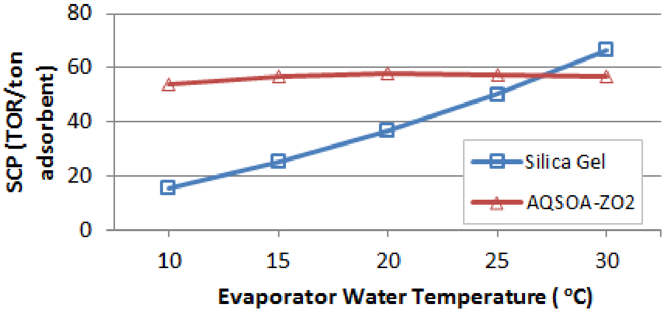

Fig. 13 SCP at 85$^{o}$C hot water temperature.

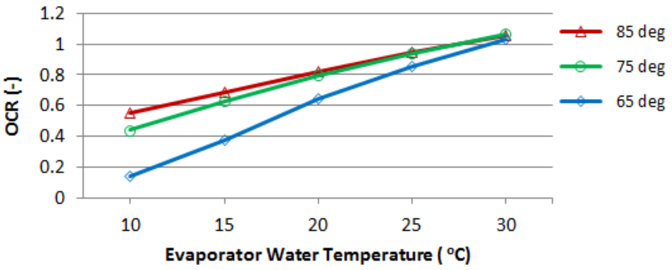

Fig. 14 Overall conversion ratio for *Silica-gel* at hot water temperatures (65-85$^{o}$C).

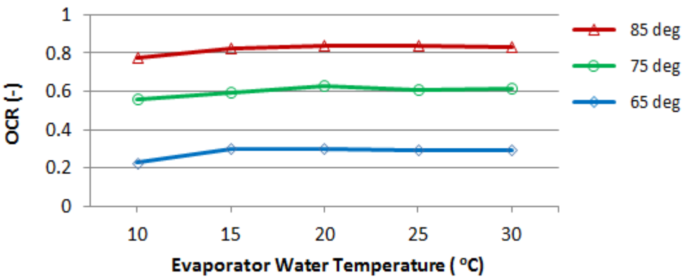

Fig. 15 Overall conversion ratio for *AQSOA-Z02* at hot water temperatures (65-85$^{o}$C).

## 6. CONCLUSIONS

Adsorption based desalination technology outperform other desalination technologies in terms of its ability to use waste heat to produce potable water and simultaneously produce useful cooling effect. However, silica gel adsorbent material was the only material reported in the literature, this work investigates the use of advanced zeolite material *AQSOA-Z02* in a full scale four bed adsorption system for the purposes of fresh water production and cooling and compared the results to silica gel.

Results showed that for heat source temperatures above 75$^{o}$C and evaporator temperature below 20$^{o}$C suitable for cooling applications, *AQSOA-Z02* outperforms silica gel in terms of higher SDWP and SCP. While for application where evaporator temperature above 20$^{o}$C is needed, *silica-gel* becomes more effective. Also, such results indicate that the use of combined system of silica gel and zeolites can cover wide range of evaporation temperature to achieve best combination of cooling and water desalination.

## 7. ACKNOWLEDGEMENT

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