An Advance Adsorbent Coated Adsorption Cycle Performance

Muhammad Wakil Shahzad[1*], Li Ang[2], Muhammad Burhan[1] and Kim Choon Ng[1]

[1]Water Desalination and Reuse Centre,
King Abdullah University of Science & Technology, Saudi Arabia.
[2]MEDAD Technologies Pte Ltd., National University of Singapore.
*Muhammad.shahzad@kaust.edu.sa

ABSTRACT

Waste heat driven adsorption (AD) cycle has been employed in the industries for cooling and desalination because of their simple operation and low OPEX. In conventional AD cycle, the granular adsorbent are packed in the form of cake in heat exchangers, results larger foot print and lower performance due to poor heat transfer from heat source to adsorbent. The heat transfer rate of an adsorbent embedded heat exchanger can be significantly improved by using powder adsorbent coated by binder on the fin surfaces of exchangers. This work will evaluate the performance of adsorbent coated heat exchanger adsorption cycle. We focuses on a common adsorbent-adsorbate pair utilized in the AD cycle, i.e. silica gel-water and hydroxyethyl cellulose (HEC) binder. We presented that overall heat transfer coefficient can be improved to almost two folds by coating techniques as calculated experimentally. We also showed that binder have minimal effect on pore surface area of adsorbent. We developed detailed mathematical model to simulate, using FORTRAN, adsorbent coated heat exchanger AD cycle performance and to compare it with conventional cycle. The results showed that, advance adsorbent coating technique can improve AD cycle performance to two folds as compared to conventional granular packed bed technology. With coated bed AD cycle, system can produce double the amount of desalinated water or cooling effect with same amount of waste heat available.

NOMENCLATURE

Abbreviations

AD	Adsorption cycle
OPEX	Operational expenditure
HEC	hydroxyethyl cellulose
PVA	Polyvinyl alcohol
U	Overall heat transfer coefficient
A	Area of heat transfer
T	Temperature

Subscripts

In	Inlet
Cw	Cooling water
Ads	Adsorption

INTRODUCTION

To increase the volume-specific cooling or heating power of adsorption cycle is a persistent goal since last decades for a compact unit design and heat exchangers improvement continues to take a central place in this effort. In conventional adsorption cycle, the granular adsorbent are usually packed in the form of cake in finned tubes heat exchangers to facilitate the water vapor adsorption and desorption processes for cooling and desalination as shown in Figure 1 [1-3]. The conventional heat exchanger cakes involve six resistance during heat transfer namely; (i) radial convective thermal resistance from the secondary fluid stream to the internal tube wall, (ii) radial conduction thermal resistance through tube wall, (iii, iv) two contact thermal resistances between silica gel granules and tube outside surface and fins surface in both radial and axial directions respectively and (v, vi) two conduction thermal resistances through silica gel granules in radial and axial directions. The poor heat transfer due to limited point-contacts of granular adsorbent to the fins is the major hindrance in efficient design of AD cycle [4]. Many heat transfer improvement approaches has been suggested for compact and efficient adsorbent bed design such as (i) mixing adsorbent granules with metal additives to improve the thermal conductivity, (ii) covering adsorbent granules by polyaniline net and (iii) adsorbent deposition over metallic foam.

Figure 1 (a) Single module for adsorption bed and (b) stack of modules for adsorption bed construction.

Mixing adsorbent granules with metal additives such as metallic foam, thermal conductive polymers and natural expandable graphite have been investigated by many researchers [5-9] to improve heat transfer between adsorbent and heat exchanger and they reported up to two fold heat transfer improvement but at expense of increase in mass transfer resistance. Demir et al [10] mixed copper, aluminum, stainless steel and brass with silica gel, as shown in Figure 2, using different weight ratios (5, 10 and

15wt %). They concluded that using different metal additives improves the heat transfer performance up to 58.2%.

Figure 2 Metal additives tested to improve adsorbent performance.

All improvement methods can enhance the heat transfer performance of adsorbent material but they reduce its mass transfer performance due to additives resistance. To overcome this limitation, adsorbent coated heat exchanger were introduced [11-20] by concluding that the adsorption kinetics depends on the thickness of coating. In this paper we evaluated the adsorbent coated heat exchanger performance. The powder silica-gel (type 3A) was mixed with suitable binder to coat on finned tube heat exchanger, eliminating wire mesh used as in conventional system to hold granular silica-gel. The heat transfer improvement of coated silica-gel heat exchanger was compared with conventional meshed fin-tube heat exchangers experimentally and as well as theoretically.

EXPERIMENTATION

The uptake of water vapor onto silica gel is depend on pore surface area as adsorption is known as surface phenomenon between solid and gas interface. Mixing of binder with silica-gel powder to cover inter-particle spaces may effect pore surface area of silica-gel. A suitable binder selection depends on number of parameters such as (i) durability, (ii) no or minimal influence on uptake, (iii) chemically inert to the adsorbent-adsorbate pair, (iv) good adhesive ability and (v) enhance heat transfer between absorbent and heat exchanger. To investigate suitable binder with required properties, seven different kind of binders were selected for experimentation. The five organic-based binder namely, epoxy, polyvinyl alcohol (PVA), corn-flour, hydroxyethyl cellulose (HEC) and gelatin and two inorganic type namely bentonite and sepiolite were mixed with silica-gel sample with adsorbent–binder mass ratio of 1:10. The Figure 3 shows the field emission scanning electron microscopic (FESEM) photos of silica-gel powder and mixture with binder and Figure 4 shows the absorbent coated heat exchanger.

Figure 5 shows the experimental apparatus where the temperature and pressure measurements was taken by OMEGA themistors and GEMS™ pressure transducer with accuracy ± 0.15 ºC and ± 0.25 kPa respectively.

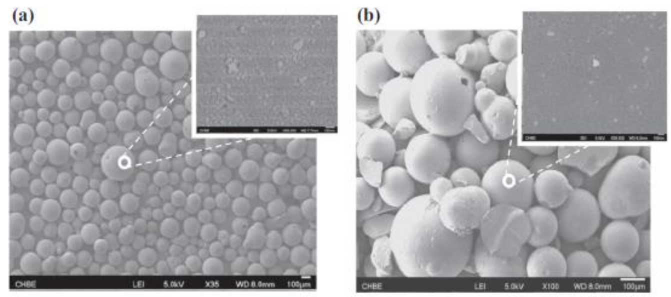

Figure 3 Field emission scanning electron microscopic (FESEM) photos for (a) silica-gel 3A and (b) Silica gel with 3.3 wt% HEC binder.

.

Figure 4 Silica gel type 3A with 3.3 wt% HEC binder coated heat exchanger.

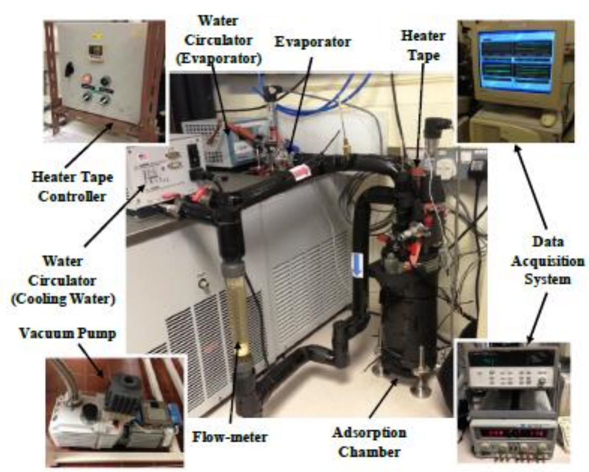

Figure 5 Adsorption heat transfer measurement apparatus.

Water circulators are used to maintain evaporator temperature and adsorption coolant temperature. Saturation pressure is maintained by vacuum pump. Agilent data logger used to log temperature, pressure and flow rate data. Adsorbent chamber and all pipes are insulated to prevent any condensation due to low temperature.

RESULTS AND DISCUSSION

Adsorbent properties are investigated using Hydrosorb and Autosorb machines and presented in Table 1. All binder were tested for their adhesive abilities to select suitable candidate for heat transfer experiment. It is found that inorganic binder have poor bonding abilities as compared to organic binders. In organic binders list, epoxy shows a low BET surface area and gelatin and PVA have peel-off tendency. Only HEC showed good adhesive properties and it has softening temperature 140°C while desorption process only require 85-90°C temperature. HEC properties are summarised in Table 2.

Table 1 Thermophysical properties of silica-gel

Properties	Type 3A	Type RD powder
Particle size (mm)	0.2	0.07
BET surface area (m^2/g)	680	573
Porous volume (ml/g)	0.47	0.39
Specific heat capacity (J/kg-k)	921	921

Table 2 Properties of hydroxyethyl cellulose (HEC)

Properties	Value
BET surface area (m^2/g)	1.76
Porous volume (ml/g)	0.031
Specific heat capacity (J/kg-k)	4
Apparent density (kg/m^3)	600
Softening temperature (C)	140C

Pressure, temperature and flow rats were measured using highly accurate instruments. Pressure and temperatures at different locations was logged by Yokogawa pressure transducers (accuracy ±0.1 kPa) and OMEGA thermistors (accuracy ±0.1°C). Krohne flow meters was installed for flow measurements. They are accurate at the level of ±1% of full scale measurement.

Figure 6 shows the effect of different binder percentage on the silica-gel and binder mixture. It can be noticed that at 3.3% of binder weight, maximum BET surface area and porous volume observed are 507 m^2/g and 0.334 mg/l. There is negligible effect on adsorbent physical properties. The proposed 3.3% of binder weight was selected after many iterations starting from 10%.

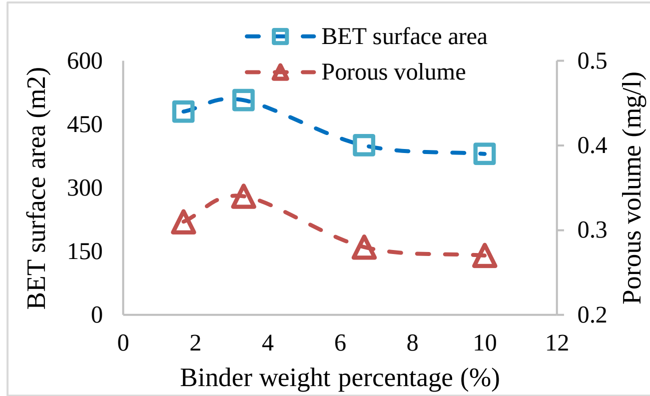

Figure 6 BET surface area and porous volume of mixture at different binder percentage.

Figure 7 shows the temperature difference between average adsorption and cooling water inlet for conventional RD granular type and 3A mixed with HEC binder. Significantly lower heat accumulation can be clearly observed for coated heat exchanger that lower temperature rise up to 50% as compared to conventional packed heat exchanger. This lower accumulation heat will reduce pre-heating and pre-cooling energy as well as time as compared to conventional cycle. It shows that the switching time can be reduced to almost few seconds as compared to minute in conventional adsorbent packed systems.

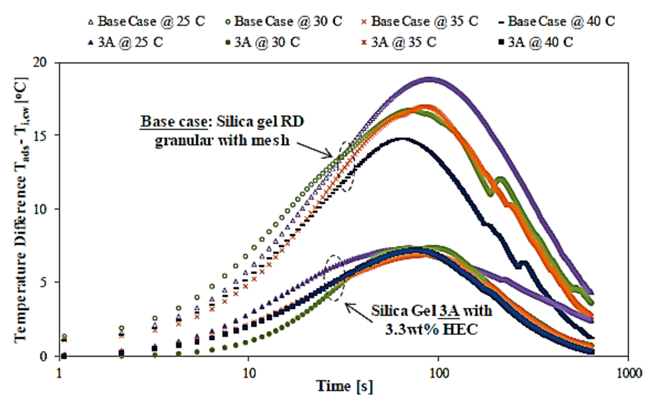

Figure 7 Heat accumulation for conventional granular type silica-gel and 3A mixed with HEC binder.

Figure 8 shows the overall heat transfer coefficient (U) for similar two cases calculated by equation 1. Two important point can be noted from U plot. Firstly, the overall heat transfer coefficient value for coated heat exchanger is 2-3 fold higher as compared to conventional silica-gel packed heat exchanger and it drop to 1.5 times at the last stages of cycle.

$$U = \frac{\dot{m} C_p \left(T_{in,cw} - T_{out,cw}\right)}{A\left(T_{ads} - T_{in,cw}\right)} \qquad (1)$$

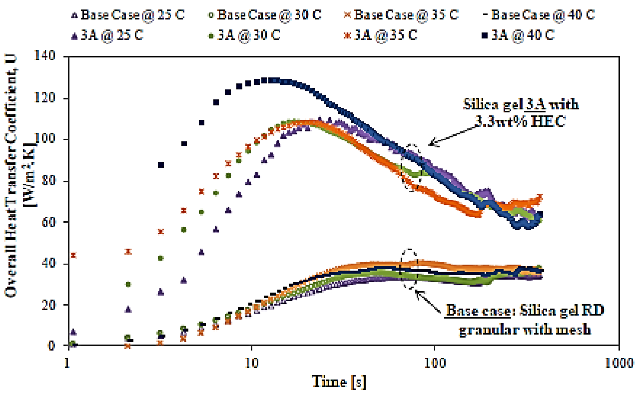

Figure 8 Overall heat transfer coefficient for conventional granular type silica-gel and 3A mixed with HEC binder.

Secondly, time to reach to highest U value is very fast, 10-12 seconds as compared to 70-80 seconds of conventional cycle. This highest U and shortest cycle time can lead to compact and efficient AD cycle for future applications. This fast response to approach highest U values will help to save a large fraction of energy that were wasted for thermal mass heating in conventional systems.

Figure 9 summarized the overall heat transfer coefficient improvement by proposed adsorbent coated heat exchangers. It can be clearly seen that coating method can improve overall heat transfer coefficient 2-3 times as compared to conventional packed beds systems. This improvement can help to reduce size of system 2-3 times for same capacity or can produce 2-3 times more output with same design parameters.

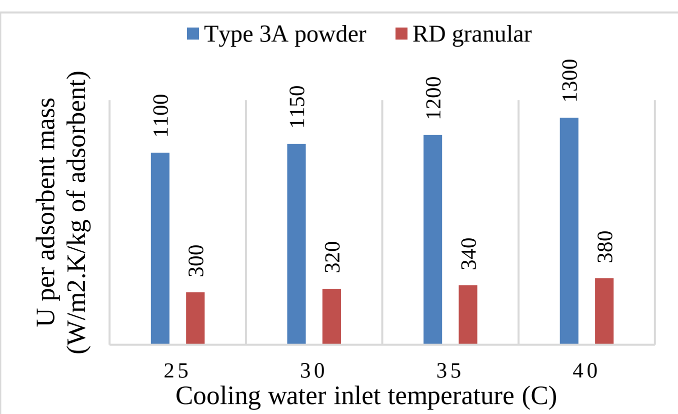

Figure 9 U value normalized with adsorbent mass for conventional granular type silica-gel and 3A mixed with HEC binder.

The uncertainty of all experimental data was measured as ±2%.

THEORATICAL MODEL AND SIMULATION

Conventional AD cycle theoretical model published in the literature [21-25] is modified according to improved overall heat transfer coefficient for adsorbent coated heat exchanger and simulation is conducted in FORTRAN. Figure 10 shows the cycle time for conventional packed bed and improved coated heat exchangers.

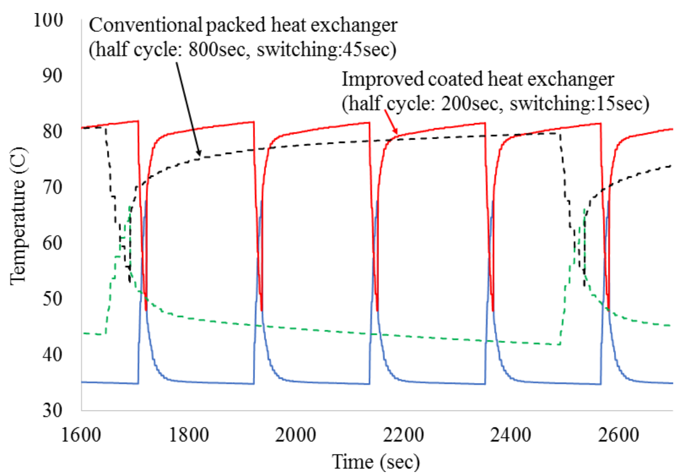

Figure 10 AD cycle simulated water temperature profiles comparison.

It can be seen that the adsorbent coated system can complete 3 cycle in the same time when conventional system can only complete one cycle only. This huge improvement is due to reduction in thermal mass resistance and increase in U value. The overall performance improvement 2-3 folds was observed.

Similarly, Adsorption cooling cycle was simulated for coated beds and found 2-3 times performance improvement. In addition, adsorption desalination simulation was also performed and it shows good agreement with experimental data, 2-3 times performance improvement. The overall heat transfer improvement with loosing physical properties of adsorbent is the key for this performance boost.

CONCLUSION

Adsorbent heat exchanger heat transfer improvement have been investigated in this paper. It is proved experimentally that adsorbent coated heat exchanger can improve adsorption cycle performance to 2-3 fold as compared to conventional packed bed cycle. Different kind of organic and inorganic binders are also investigated and found that HEC have best adhesive capabilities with minimal effect on pore surface area of adsorbent. The improved adsorption cycle simulation showed that coated bed heat exchanger can lead to compact and efficient adsorption cycle design for future desalination and cooling applications.

ACKNOWLEDGEMENT

Author would like to thank to King Abdullah University of Science and Technology, Saudi Arabia.

REFERENCES

[1] K.C. Ng, K. Thu, S.J. Oh, A. Li, M.W. Shahzad, A.B. Ismail, Recent developments in thermally-driven seawater desalination: energy efficiency improvement by hybridization of the MED and AD cycles, Desalination, Vol. 356, 2015, pp. 255–270.

[2] K.C. Ng, K. Thu, Y. Kim, A. Chakraborty, G. Amy, Adsorption desalination: an emerging low-cost thermal desalination method, Desalination, Vol. 308, 2013, pp.161–179.

[3] K.C. Ng, K. Thu, B.B. Saha, A. Chakraborty, Study on a waste heat-driven adsorption cooling cum desalination cycle, Int. J. Refrig. Vol. 35, 2012, pp.685–693.

[4] Ang Li, Kyaw Thu, Azhar Bin Ismail, Muhammad Wakil Shahzad, Kim Choon Ng, Performance of adsorbent-embedded heat exchangers using binder-coating method, International Journal of Heat and Mass Transfer, Vol. 92, 2016, pp.149–157.

[5] J. Guilleminot, A. Choisier, J. Chalfen, S. Nicolas, J. Reymoney, Heat transfer intensification in fixed bed adsorbers, Heat Recovery Syst. CHP, Vol. 13, 1993, pp. 297–300.

[6] M. TatlIer, A. Erdem-Senatalar, The effects of thermal and mass diffusivities on the performance of adsorption heat pumps employing zeolite synthesized on metal supports, Microporous Mesoporous Mater, Vol. 28, 1999, pp. 195–203.

[7] E. Hu, D.-S. Zhu, X.-Y. Sang, L. Wang, Y.-K. Tan, Enhancement of thermal conductivity by using polymer-zeolite in solid adsorption heat pumps, J. Heat Transfer, Vol. 119, 1997, pp.627–629.

[8] L. Wang, D. Zhu, Y. Tan, Heat transfer enhancement on the adsorber of adsorption heat pump, Adsorption, Vol. 5, 1999, pp.279–286.

[9] T.-H. Eun, H.-K. Song, J. Hun Han, K.-H. Lee, J.-N. Kim, Enhancement of heat and mass transfer in silica-expanded graphite composite blocks for adsorption heat pumps: Part I. Characterization of the composite blocks, Int. J. Refrig. Vol. 23, 2000, pp.64–73.

[10] H. Demir, M. Mobedi and S. Ulkü, The use of metal piece additives to enhance heat transfer rate through an unconsolidated adsorbent bed, International Journal of Refrigeration, Vol. 33-4, 2010, pp. 714-720.

[11] H. Yanagi, N. Ino, Heat and mass transfer characteristics in consolidated silica gel–water adsorption-cooling system, in: presented at the ASME ASIA'97, 1997.

[12] H. van Heyden, G. Munz, L. Schnabel, F. Schmidt, S. Mintova, T. Bein, Kinetics of water adsorption in microporous aluminophosphate layers for regenerative heat exchangers, Appl. Therm. Eng. Vol. 29, 2009, pp.1514–1522.

[13] K.-S. Chang, M.-T. Chen, T.-W. Chung, Effects of the thickness and particle size of silica gel on the heat and mass transfer performance of a silica gel-coated bed for air-conditioning adsorption systems, Appl. Therm. Eng. Vol. 25, 2005, pp.2330–2340.

[14] A. Basile, G. Cacciola, C. Colella, L. Mercadante, M. Pansini, Thermal conductivity of natural zeolite-PTFE composites, Heat Recovery Syst. CHP. Vol. 12, 1992, pp.497–503.

[15] L. Pino, Y. Aristov, G. Cacciola, G. Restuccia, Composite materials based on zeolite 4A for adsorption heat pumps, Adsorption, Vol. 3, 1997, pp.33–40.

[16] K.C. Ng, H.T. Chua, C.Y. Chung, C.H. Loke, T. Kashiwagi, A. Akisawa, et al., Experimental investigation of the silica gel–water adsorption isotherm characteristics, Appl. Therm. Eng. Vol. 21, 2001, pp.1631–1642.

[17] V. Ponec, Z. Knor, S. Cerny, Adsorption on Solids, Butterworths and Co., London,1974.

[18] J. Oscik, Adsorption, Ellis Horwood Ltd./John Wiley and Sons, 1982.

[19] D.M. Ruthven, Principles of Adsorption and Adsorption Process, John Wiley & Sons, New York, 1984

[20] A. Li, A.B. Ismail, K. Thu, M.W. Shahzad, K.C. Ng, B.B. Saha, Formulation of water equilibrium uptakes on silica gel and ferroaluminophosphate zeolite for adsorption cooling and desalination applications, Evergreen, Vol. 1, 2014, pp.37–45.

[21] M. W Shahzad and K. C. Ng, On the road to water sustainability in the gulf, Nature Middle East (2016).

[22]M. W. Shahzad, K. C. Ng and K. Thu, A Waste Heat Driven hybrid ME+AD Cycle for Desalination, Environmental Science, Water Research Technology, Vol. 2, 2016, pp.206-212.

[23]M. W. Shahzad, K. Thu, Y. D. Kim and K. C. Ng, An Experimental Investigation on MEDAD Hybrid Desalination Cycle, Applied Energy, Vol. 148, 2015, pp.273-281.

[24]M. W. Shahzad, K. C. Ng, K. Thu, B. B. Saha and C. W. Gee, Multi Effect Desalination and Adsorption Desalination (MEDAD): A Hybrid Desalination Method, Applied Thermal Engineering, Vol. 72, 2014, 289-297.

[25]M. W. Shahzad, A. Myat, C. W. Gee and K. C. Ng, Bubble-assisted film evaporation correlation for saline water at subatmospheric pressures in horizontal-tube evaporator,Applied thermal Engineering, Vol. 50, 2013, pp. 670–676.