Review of Heat and Mass Transfer Enhancement Techniques and Current Advancement for Adsorption Heating/Cooling Systems

Norhayati Mat Wajid, Blaise Mompuouo, Siddig Omer* and Saffa B. Riffat
Institute for Sustainable Energy, Department of Architecture and Built Environment, University of Nottingham, NG7 2RD University Park, Nottingham, UK

Abstract
Adsorption heating/cooling became an alternative to vapour compression system due to low ozone depletion potential (ODP) and global warming potential (GWP). However, more investigation is required due their low efficiency when compared to conventional heating/cooling systems. This review emphasizes on the mathematical modelling simplification and heat transfer enhancement method that applied by many researchers to improve the performance of adsorption heating and cooling technologies. Various techniques investigated by many researchers on solving low thermal conductivity and the different methods for enhancing heat and mass transfer in the adsorbed bed/pipe also discussed. Common techniques used to enhance heat and mass transfer in the adsorbed bed/pipe include the fin type adsorbent tube/ heat exchanger, amalgamated adsorbent bed with a metal foam, consolidated adsorbent, adsorbent coating and adsorbent with multi cooling tubes. Other than that, recent advancements in adsorption cooling/heating systems also discussed in this review.

Keywords: adsorption heating/cooling; heat transfer enhancement

Received 15 April 2015; revised 18 April 2016; editorial decision 21 April 2016

1 INTRODUCTION

Nowadays, CFC (chlorofluorocarbon) has become and debatable and exhaustible problems to solve. Options on adopting adsorption refrigerant or heat pump systems have received more and more attention and develop rapidly as an environmentally-friendly and a kind of efficient means of using low-grade heat sources. Furthermore, these systems would contribute in many advantages such as simple constructions, no moving components, no solutions pump, and would able been driven by lower primary energy without using a source of electricity.

Technically, a major problem with the solid adsorbents used in adsorption heat pumps or refrigeration systems is their poor thermal conductivity. For low capital costs, this system must be physically small and so as the time per cycle. Hence, in turn, requires high rates of heat transfer in and out of the adsorbent. However, most granular beds have low thermal conductivity, mainly due to the high porosity of the material. The fragmented structure of the solid material leads to lower density and lower thermal conductivity [1]. Therefore, many approaches had been developed to improve the global heat transfer within the solid adsorbent. The most common method to increase thermal conductivity in the adsorbent bed is by using consolidated materials and materials with high conductivity such as graphite or metallic foams [1, 2]. This paper also aims to review the heat and mass transfer enhancement of adsorption cooling and heating technologies that currently investigated by many researchers with the emphasis on its compactness, effectiveness and more importantly the economic feasibility.

2 BASIC ADSORPTION PROCESS

Adsorption heating/cooling system based on performing reversible chemical reaction [3]. Adsorption processes are divided
into three phases which consist of; (i) charging, which normally known as an endothermic reaction. The heat source is required for the dissociation process of C. (ii) storing, this stage occurs after the charging process and A and B will be formed and stored, (iii) discharging, where A and B associated with an exothermic reaction and material C are regenerated and the recovered energy released [4, 5] (see Figure 1).

3 HEAT AND MASS TRANSFER ENHANCEMENT TECHNIQUES

Among the three components (adsorber, evaporator and condenser) used in adsorption refrigeration or heating systems, only the adsorber/adsorbent bed is particular by of interest while the others are similar to conventional adsorption systems. The recognized drawback of solid/vapour adsorbent bed is the poor heat transfer. The heat and mass transfers have critical roles in improving the cycle performance, and their optimization is one of the technical challenges to be faced in progressing adsorption refrigeration systems. Hence, to optimize an adsorber, it is essential to control these limiting factors [7]. Some of the enhancement methods that have been studied from previous investigations were fin type adsorbent tube, embedded adsorbent bed with a metal foam, consolidated adsorbent, adsorbent coating and multi-tube adsorbent coating. All these methods and techniques for enhancing the heat and mass transfer in the adsorbent summarizes in Table 1 below;

4 CURRENT ADVANCEMENT ON ADSORPTION HEATING/CoolING SYSTEMS

Adsorption heating/cooling system widely investigated due to their advantages such as high energy density, low toxicity, low regeneration temperature and low cost. Veselovskaya et al. [10] synthesized and tested a laboratory scale adsorption chiller using composite adsorbent composed of BaCl2 impregnated into expanded vermiculite. From their investigation, vermiculite chose as the host matrix for the composite sorbent due to its macroporous structure to prevent agglomeration of the salt and improve mass transfer. Other than that, these authors used a flat plate heat exchanger as the generator to enhance the heat and mass transfer (see Figure 2). From their investigation, they found that the theoretical estimation of adsorbent kinetics fitted well with the experimental results giving COP as high as 0.54 and SCP ranging from 300 to 680 W/kg. Thus, they suggested that the proposed methods and composite material could effectively apply to low energy heat regeneration (80°C–90°C) cooling systems. The idea of using plate heat exchanger by these authors is to increase the area of heat transfer in the adsorbent generator. Furthermore, using a metal plate may increase the thermal conductivity, and hence, enhance the performance of the adsorption chiller. Hence, this investigation has proved that using natural resources such as vermiculite will improve the heat and mass transfer in sorption cooling technology. However, this investigation was done based on lab-scale prototype systems. Therefore, more research investigation needs to be entailed to realize the cooling/heating systems application in buildings.

Stitou et al. [29] carried out an experimental investigation of a solar assisted Thermochemical Heat Storage system used for air conditioning in a pilot plant for housing (see Figure 3). The plant, which has a daily cooling capacity of 20 kWh, consists of a solid–gas thermochemical sorption process which assisted at 60–70°C by 20 m² of flat plate solar collectors. The reactive solid BaCl2 and a phase change refrigerant, NH3 were used as the sorption couple. From their studied, they found that within two years, the average efficiency of the solar collectors was found to be at least 40–50% while the process COP was about 30–40%. This investigation has proved that the solid gas thermochemical could be adopted for cooling systems in an actual scale of cooling demand in the building. However, the integration of solid gas thermochemical and Phase change material is technically a complicated system to manufacture and commercialize. Furthermore, technically, optimization is vital importance as the phase change material required more time to melt when compared to the thermochemical reaction.

Another experimental study involving Thermochemical Energy Storage was carried out by Hamdan et al. [30] These authors using a working pair of sodium chloride as sorbent material and water as sorbate media. Few parameters have been identified influence the performance of their systems such as the amount of vaporized water from the evaporator, system initial temperature and type of salt on the increase in temperature of the salt. They had also found that Lithium chloride salt has a higher effect on the performance of the heat pump that of sodium chloride & the pump performance improved with the amount of water vaporized. This experimental study shows that to improve the

![Figure 1. Basic adsorption process [5, 6].](https://academic.oup.com/ijlct/advance-article-abstract/doi/10.1093/ijlct/ctw010/5601411)
| Reference | Nature | Regeneration temperature (°C) | Techniques | Application/results/comments |
|-----------|--------|-----------------------------|------------|-------------------------------|
| [8] close | Silica gel/water | (59.85–79.85) | Fin type silica gels tube module | Cooling improved more than two times cooling output per unit absorber. Maximum cooling output 3.12 kW achieved under the operation conditions. |
| [9] Close | Zeolite/Water | 100 | Consolidate zeolite layer with heat exchanger | Cell wall heat transfer coefficient (κw) of 230 W m⁻² K⁻¹, micropore diffusion coefficient at infinite temperature (Do) of 1.58 X 10⁻⁴ m² s⁻¹ and an activation energy (Ea) of 32.41 kJ mol⁻¹. |
| [10] Close | Composite BaCl₂/vermiculite/NH₃ | 90 | Composite adsorbent material slotted in the heat exchanger fin/plate | Low potential heat source (80–90°C) giving COP as high as 0.54 and SCP ranging from 300 to 680 W/kg. |
| [11] close | Silica gel/water, zeolite/water | 80°C | Fin type heat exchanger embedded with silica gel/zeolite | The conductivity (λ) of zeolite is higher than silica gel which were 0.4 & 0.3 W/m.K respectively. Heat transfer coefficient of silica gel is higher that zeolite (h) (330 & 269.3 W/m² K). |
| [12] | Silica gel/water | Experimental | Layers of loose grains (with n layer) (n = 1, 2, 4, and 8) located on a heat transfer metal support | Cycle powers of prototypes are 2–6 times lower than those measured in LTJ (Large Temperature Jump) test. |
| [13] Open | Silica gel/water | Experimental | Cooling composite silica gel coated heat exchanger (CCHE) | CCHC has better dehumidification performance compared with SGCHC (silica gel coated heat exchanger) |
| [14] close | BaCl₂/NH₃ | 75 to 90 | Expanded graphite composite consolidated with BaCl₂ | COP between 0.50 and 0.53 when the evaporation temperature ranged from 0 to 15°C and at a generation temperature of 80°C the density of 250 kg m⁻³ (composite block) could incorporate 0.61 kg of ammonia per kg of the reactive salt. |
| [15] close | MnCl₂/NH₃ | Experimental | Expanded graphite composite consolidated with MnCl₂ | SCP varied between 200 Wkg⁻¹ and 700 Wkg⁻¹ when the evaporation temperature ranged from −35°C to 0°C. COP employing a basic sorption thermodynamic cycle was as high as 0.34 at the generation temperature; 180°C, heat sink temperature of 25°C and evaporation temperature of 30°C. |
| [16] Close | Zeolite/H₂O/NaCl | - | Zeolite embedded with aluminium foams with NaCl distributed in between the zeolite | Zeolite/foam, aluminium thickness 5 mm and cycle time 8 min, the SCP reaches the maximum value 641 W/kg with the COP 0.24. Automobile air-conditioning application. |
| [17] Close | Zeolite/water | - | Zeolite embedded with aluminium foams | Synthesizing using Microwave was much faster compared to the hydrothermal method. The thermal conductivity of a graphite foam of 85% porosity was 24 W/m K. |
| [18] Close | Zeolite/water | - | Zeolite embedded with graphite foams | The SCP varied between 200 Wkg⁻¹ and 700 Wkg⁻¹ when the evaporation temperature ranged from −35°C to 0°C. COP employing a basic sorption thermodynamic cycle was as high as 0.34 at the generation temperature; 180°C, heat sink temperature of 25°C and evaporation temperature of 30°C. |
| [19] open | CaCl₂/Water | - | CaCl₂ coated the fibre membrane and LiCl₂ filming the fibre membrane | Improve the energy (enthalpy) exchange efficiency, particularly moisture transfer efficiency of the exchanger. |
| [20] close | Zeolite A&X/water | 95 | zeolite coatings directly crystallized on metal supports | Directly crystallized sample exhibited a better performance at least up to 85% of final loading and heat rejection, compared to the reference sample consisting of a polymer-zeolite structure glued on the metal support. |
| [21] open | Silica gel/polymer | 60 | the fin-tube heat exchanging devices coated with silica gel and polymer materials | Moisture removal of both methods (silica gel/polymer) increases significantly with the increasing of regeneration temperature, and silica coating obtains the highest COP thermal when regeneration temperature equal to 70 °C. |
| [22] close | Zeolite/water | - | In situ direct growth coating of zeolite on heat exchanger fins | Surface coverage, adhesion, and mechanical properties, should be considered for a valuable coating. |
| [23] Open | Zeolite/water | 90 | adsorber heat exchanger coating with zeolite | 500µm gives the effective of 7% enhancement in the adsorption speed on the small scale, and COP of the heat pump module has increased almost linearly with increasing the zeolite layer thickness for the full-scale experiment. |
performance of thermochemical energy storage, the water that vaporized is of vital importance. Therefore, more investigation needs to be entailed mainly involving the kinetic of vapor transport and factor influence the amount of water to vaporize.

Hasan et al. [31] investigated an integrated concept using solar thermal energy with sorption storage systems. On utilizing the availability of solar energy in the hot and humid country, these authors develop a solar adsorption cooling system as shown in Figure 4. As can be seen that, the construction involved of using a rotating flat plate solar collector and the adsorbent material (Activated carbon/Methanol) placed on the flat plate. From this experiment, these authors found that the chiller produced a daily mass of 2.63 kg of 0°C cold water with the respective COP of 0.66. This investigation shows that hot-humid or hot-arid countries could utilize the surplus of solar energy by integrating with thermochemical energy storage system. Furthermore, by using this concept, the COP of systems will increase the energy required to desorb/dehydrate the material alleviated by free energy sources from solar.

Table 1. (Continued)

| Ref | Open/ close Sorption | TCM working pairs | Nature | Regeneration temperature (°C) | Techniques | Application/results/comments |
|-----|----------------------|------------------|--------|-------------------------------|------------|-------------------------------|
| [24] | close | Zeolite/water | Experimental | - | adsorber heat exchanger coating with zeolite directly crystallized on fibrous plates | Directly crystallized zeolite coating on fibrous plates will stabilize the coating and heat transfer properties. |
| [25] | close | Zeolite/water | Experimental | - | Zeolite coated graphite heat exchanger plate | The direct-grown coatings showed a mechanical resistance of 0.78 MPa while the dip coated plates of 0.82 MPa. |
| Adsorbent with multi cooling tubes | | | | | | |
| [26] | Close | Silica gel/water | Experimental & theoretical | 85 | Silica gel filled inside the multiples cooling tubes | The COP and the SCP of the designed AHP are more than 0.5 and 85 W/kg adsorbent, temperature (hot water; 85°C, cooling water; 30°C, the chilled water; 15°C) and the heating/cooling time is about 630 s. Summer days, (7 kg/m² ice formed), cloudy winter days about 4 kg/m² of ice formed. |
| [27] | Close | Carbon/methanol | Experimental | ≤110°C | Solar Tube filled with carbon | |

Figure 2. A photo of a Plate heat exchanger generator (4 mm adsorbent layers) [28].

Figure 3. Illustration of the solar sorption pilot plant for air-conditioning, flat plate solar collectors and the thermochemical reactor design [29].

Figure 4. Schematic representation of the proposed CO-SAR system [31].

Finck et al. [32] experimentally investigated a 3kWh of heat storage module for a space heating application. The heat storage module was consolidated with zeolite coating on the fin.
type heat exchanger-adsorber as illustrates in Figure 5a. Then, this adsorber placed in a cylindrical stainless steel vessel. By using 41 kg of zeolite this system could generated heating power range of 730–1600 W and a maximum energy content of 14.3 MJ. However, further investigation is needed as the decreasing temperature between desorption and condensation will lower the energy content. This experiments proved that a larger scale of 3kWh of heating storage could realize the actual performance of space heating system. Other than that, the operating condition in this study will become as a reference to other researchers on looking alternative methods to improve the performance of thermochemical heat storage system.

![Figure 5](image)

**Figure 5.** (a) adsorber/desorber unit; (b) evaporator/condenser unit front view; (c) evaporator/condenser unit back view [32].

| References | Nature       | Material                          | Concept                | Application            | COP | Heating/cooling storage density |
|------------|--------------|-----------------------------------|------------------------|------------------------|-----|--------------------------------|
| [33]       | Experimental | MgSO₄ hydrate                      | Close sorption         | Heat storage           | -   | 2.2 GJ/m³                      |
| [34]       | Experimental | Expanded graphite (EXG) and carbon fibres (CF) | Close sorption         | Refrigeration          | 0.48–0.96 | -                      |
| [35]       | Experimental | Zeolite/water                      | Open sorption          | Dishwasher             | -   | 1.05kWh to 0.80kWh per washing cycle daily ice production (DIP) of 20 kg/m² |
| [36]       | Numerical    | Lithium chloride – silica gel      | Close sorption         | Ice-maker              | 0.33 | -                      |
| [10]       | Experimental | BaCl₂/vermiculite                  | Close sorption         | Air-conditioning       | 0.54 ± 0.01 | 300 to 680 W/kg Cooling |
| [29]       | Experimental | BaCl₂/NH₃                          | Phase change & close sorption | Air-conditioning       | 1.5–2.3 | 0.8–1.2 kWh cooling |
| [37]       | Experimental | Lithium chloride – silica gel      | Close sorption         | Air-conditioning       | 0.41 | 4.99 kW cooling              |
| [38]       | Numerical & Experimental | Silica gel/water                  | Close sorption         | Refrigeration          | 0.66 | -                      |
| [39]       | Numerical & Experimental | MgCl₂·6H₂O                        | Open sorption          | Heat storage           | 12  | 50 W                      |
| [40]       | Numerical & Experimental | CaCl₂/NH₃                         | Solid–gas sorption     | Seasonal Storage       | 0.60–heat recovery | 1043 kJ/kgsalt |
| [41]       | Numerical    | Silica gel/water                   | Close sorption         | Solar adsorption       | 0.3  | 10 kW cooling              |
| [30]       | Experimental | Lithium chloride & sodium chloride | Close sorption         | Chemical heat pump     | -   | -                      |
| [42]       | Experimental | Lithium chloride/silica gel        | Close sorption         | Thermal-energy storage | -   | 108 kWh/m³ cooling 163.6 kW/m³ Heating |
| [31]       | Numerical    | Activated carbon–methanol          | Solar adsorption       | Refrigeration          | 0.66 | 2.63 kg cold water at 0°C |
| [43]       | Numerical    | Zeolite 13X/CaCl₂                  | Close sorption         | Refrigeration          | 0.5  | 517 w/kg cooling          |
| [44]       | Experimental | Zeolite/activated carbon           | Close sorption         | Refrigeration          | 0.25–0.35 | 0.2 kW/L (Volumetric cooling power) |
| [45]       | Experimental | Activated carbon – CaCl₂/NH₃       | Close sorption         | Refrigeration          | 0.197 | 205.2 W kg specific cooling power/1.64 kW cooling capacity |
| [32]       | Experimental | Zeolite/water                      | Close sorption         | Heat storage           | -   | 730 – 1600 W heating       |
| [46]       | Experimental | Zeolite-LiCl/MgSO₄ & MgCl₂/MgSO₄ | Open sorption          | Heat storage           | -   | 5kWh – heating (70 kg composite material) |
There are several other studies into both open and closed Adsorption systems used for various purposes with some of these are listed in Table 2. The materials used, storage type, method and analysis results are shown. It is evident from the widespread usage that adsorption heat storage can be used in wide range of applications, including heat storage, air conditioning and ice making systems.

5 CONCLUSION

Adsorption cooling or heating is the most promising technology that will alleviate high dependency of energy use by adopting the conventional vapor compression systems. Nevertheless, the uptake of adsorption systems is still at the laboratory scale due to few drawback of low heat transfers in the adsorbent bed. The most common enhancement method that this reviewed revealed is embedding the adsorbent material in the heat exchanger fins. Indeed, this approach is considered as the most efficient compared to coating the adsorbent onto the heat exchanger fins. Technically, most of the researchers have chosen on insertion of metal inside the adsorbent bed or adsorber. This method may increase the thermal conductivity of the adsorbent bed which are relatively lower than metal.

The relevant parameters on investigating the heat and mass transfer enhancement of the adsorption cooling are the COP (Coefficient of performance), SCP (specific cooling power) and the adsorption and desorption time and maximum power (W) per mass (kg) of adsorbent material. The most desirable effectiveness from most of the researchers in the adsorption systems is to attain 1 kW per kg of adsorbent mass. On the other hand, apart from enhancing the heat and mass transfer in the adsorbent bed, the working pairs are also becoming an important factor to be considered. Furthermore, the regeneration temperature for desorption process should not be higher than the heat extracted through the adsorption process. It would suggest that the regeneration temperature would be in the range of the temperature that could be utilized from waste heat such as nuclear plants, various heat engines, fuel cells, and motor vehicles. This would be more economical and sustainable technology to be adopted in the long-term run.

REFERENCES

[1] Tamainot-Telto Z, Critoph RE. Monolithic carbon for sorption refrigeration and heat pump applications. Appl Therm Eng 2001;21:37–52.
[2] Critoph RE, Zhong Y. Review of trends in solid sorption refrigeration and heat pumping technology. Proc Inst Mech Eng Part E J Process Eng 2005;219:285–300.
[3] Shkatulov A, Ryu J, Kato Y, et al. Composite material ‘Mg(OH)2/vermiculite’: a promising new candidate for storage of middle temperature heat. Energy 2012;44:1028–34.
[4] Yuktaka K. Chemic al energy conversion technologies for efficient energy use. In Paksoy H (ed). Thermal Energy Storage for Sustainable Energy Consumption. Springer, 2007.
[5] Ding Y, Riffat SB. Thermochemical energy storage technologies for building applications: a state-of-the-art review. Int J Low-Carbon Technol 2012; 8:106–16.
[6] Abedin A, Rosen M. A critical review of thermochemical energy storage systems. Open Renew Energy J 2011;4:42–6.
[7] Wang SG, Wang RZ, Li XR. Research and development of consolidated adsorbent for adsorption systems. Renew Energy 2005;30:1423–41.
[8] Kubota M, Ueda T, Fujiwara R, et al. Cooling output performance of a prototype adsorption heat pump with fin-type silica gel tube module. Appl Therm Eng 2008;28:87–93.
[9] Dawoud B, Vedder U, Amer E-H, et al. Non-isothermal adsorption kinetics of water vapour into a consolidated zeolite layer. Int J Heat Mass Transf 2007;50:2190–9.
[10] Veselovskaya JV, Critoph RE, Thorpe RN, et al. Novel ammonia sorbents ‘porous matrix modified by active salt’ for adsorptive heat transformation: 3. Testing of BaCl2/vermiculite composite in a lab-scale adsorption chiller. Appl Therm Eng 2010;30:1188–92.
[11] Riffel DB, Wittstadt U, Schmidt FP, et al. Transient modeling of an adsorber using finned-tube heat exchanger. Int J Heat Mass Transf 2010;53:1473–82.
[12] Aristov YI, Glaznev IS, Girkis IS. Optimization of adsorption dynamics in adsorptive chillers: Loose grains configuration. Energy 2012;46:484–92.
[13] Jiang Y, Ge TS, Wang RZ, et al. Experimental investigation and analysis of composite silica-gel coated fin-tube heat exchangers. Int J Refrig 2015;51:169–79.
[14] Li TX, Wang RZ, Wang LW, et al. Study on the heat transfer and sorption characteristics of a consolidated composite sorbent for solar-powered thermochemical cooling systems. Sol Energy 2009;83:1742–55.
[15] Li TX, Wang RZ, Kiplagat JK, et al. Performance study of a consolidated manganese chloride-expanded graphite compound for sorption deep-freezing processes. Appl Energy 2009;86:1201–9.
[16] Hu P, Yao J-J, Chen Z-S. Analysis for composite zeolite/foam aluminum-water mass recovery adsorption refrigeration system driven by engine exhaust heat. Energy Convers Manag 2009;50:255–61.
[17] Bonaccorsi L, Calabrese L, Freni A, et al. Hydrothermal and microwave synthesis of SAPO (CHA) zeolites on aluminium foams for heat pumping applications. Microporous Mesoporous Mater 2013;167:30–7.
[18] Bonaccorsi L, Bruzzaniti P, Calabrese L, et al. Synthesis of SAPO-34 on graphite-foams for adsorber heat exchangers. Appl Therm Eng 2013;61:848–52.
[19] Liu S, Riffat S, Zhao X, et al. Impact of adsorbent finishing and absorbent filming on energy exchange efficiency of an air-to-air cellulose fibre heat & mass exchanger. Build Environ 2009;44:1803–9.
[20] Schnabel L, Tatlier M, Schmidt F, et al. Adsorption kinetics of zeolite coatings directly crystallized on metal supports for heat pump applications (adsorption kinetics of zeolite coatings). Appl Therm Eng 2010;30:1409–16.

ACKNOWLEDGEMENTS

The first author wish to express her acknowledgements to Public Works Departments (PWD) and Public Services Departments of Malaysia (PSD) for their scholarship support associated with this study.

FUNDING

The work of this paper supported by the Department of Energy & Climate Change (DECC) (RGS: 109613).
[21] Ge TS, Dai YJ, Wang RZ, et al. Experimental comparison and analysis on silica gel and polymer coated fin-tube heat exchangers. *Energy* 2010;35:2893–2900.

[22] Bonaccorsi L, Calabrese L, Freni A, et al. Zeolites direct synthesis on heat exchangers for adsorption heat pumps. *Appl Therm Eng* 2013;50:1590–5.

[23] Dawoud B. Water vapor adsorption kinetics on small and full scale zeolite coated adsorbers; a comparison. *Appl Therm Eng* 2013;50:1645–51.

[24] Atakan A, Fueldner G, Munz G, et al. Adsorption kinetics and isotherms of zeolite coatings directly crystallized on fibrous plates for heat pump applications. *Appl Therm Eng* 2013;58:273–80.

[25] Vasta S, Giacoppo G, Barbera O, et al. Innovative zeolite coatings on graphite plates for advanced adsorbers. *Appl Therm Eng* 2014;72:153–9.

[26] Wang DC, Zhang JF. Design and performance prediction of an adsorption heat pump with multi-cooling tubes. *Energy Convers Manag* 2009;50:1157–62.

[27] Khattab NM, Sharawy H, Helmy M. Development of novel solar adsorption cooling tube. *Energy Procedia* 2012;18:709–14.

[28] Veselovskaya JV, Critoph RE, Thorpe RN, et al. Novel ammonia sorbents 'porous matrix modified by active salt' for adsorptive heat transformation: 3. Testing of 'BaCl2/vermiculite' composite in a lab-scale adsorption chiller. *J Appl Therm Eng* 2010;30:1188–92.

[29] Stitou D, Mazet N, Mauran S. Experimental investigation of a solid/gas thermochemical storage process for solar air-conditioning. *Energy* 2012;41:261–70.

[30] Hamdan M, Rossides SD, Haj Khalil R. Thermal energy storage using thermo-chemical heat pump. *Energy Convers Manag* 2013;65:721–4.

[31] Hassan HZ, Mohamad AA. Thermodynamic analysis and theoretical study of a continuous operation solar-powered adsorption refrigeration system. *Energy* 2013;61:167–78.

[32] Finck C, Henquet E, van Soest C, et al. Experimental results of a 3 kWh thermochemical heat storage module for space heating application. *Energy Procedia* 2014;48:320–6.

[33] van Essen VM, Zondag HA, Goeres JC, et al. Characterization of MgSO4 Hydrate for Thermochemical Seasonal Heat Storage. *J Sol Energy Eng* 2009;131:041014.

[34] Zająckowski B, Królicki Z, Jezowski A. New type of sorption composite for chemical heat pump and refrigeration systems. *Appl Therm Eng* 2010;30:1455–60.

[35] Hauer A, Fischer F. Open adsorption system for an energy efficient dish-washer. *Chemie Ing Tech* 2011;83:61–6.

[36] Maggio G, Gordeeva LG, Freni A, et al. Simulation of a solid sorption ice-maker based on the novel composite sorbent ‘lithium chloride in silica gel pores’. *Appl Therm Eng* 2009;29:1714–20.

[37] Gong LX, Wang RZ, Xia ZZ, et al. Experimental study on an adsorption chiller employing lithium chloride in silica gel and methanol. *Int J Refrig* 2012;35:1950–7.

[38] Ahmed R. ‘Theoretical and experimental investigation of silica gel/water for adsorption refrigeration systems,’ PhD Thesis. University of Birmingham, 2012.

[39] Zondag H, Kikkert B, Smeding S, et al. Prototype thermochemical heat storage with open reactor system. *Appl Energy* 2013;109:360–5.

[40] Li T, Wang R, Kiplagat JK, et al. Performance analysis of an integrated energy storage and energy upgrade thermochemical solid–gas sorption system for seasonal storage of solar thermal energy. *Energy* 2013;50:454–67.

[41] Alam KCA, Saha BB, Akisawa A. Adsorption cooling driven by solar collector: A case study for Tokyo solar data. *Appl Therm Eng* 2013;50:1603–9.

[42] Yu N, Wang RZZ, Lu ZSS, et al. Development and characterization of silica gel-LiCl composite sorbents for thermal energy storage. *Chem Eng Sci* 2014;111:73–84.

[43] Sadeghlu A, Yari M, Mahmoudi SMS, et al. Performance evaluation of Zeolite 13X/CaCl2 two-bed adsorption refrigeration system. *Int J Therm Sci* 2014;80:76–82.

[44] He ZH, Huang HY, Deng LS, et al. Development of novel type of two-stage adsorption chiller with different adsorbents. *Energy Procedia* 2014;61:1996–9.

[45] Pan QW, Wang RZ, Lu ZS, et al. Experimental investigation of an adsorption refrigeration prototype with the working pair of composite adsorbent-ammonia. *Appl Therm Eng* 2014;72:275–82.

[46] Zettl B, Englmaier G, Sommer W. An open sorption heat storage concept and materials for building heat supply. *Energy Procedia* 2015;73:297–304.