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

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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

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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

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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 $BaCl_2$ 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 m^2 of flat plate solar collectors. The reactive solid $BaCl_2$ and a phase change refrigerant, NH_3 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

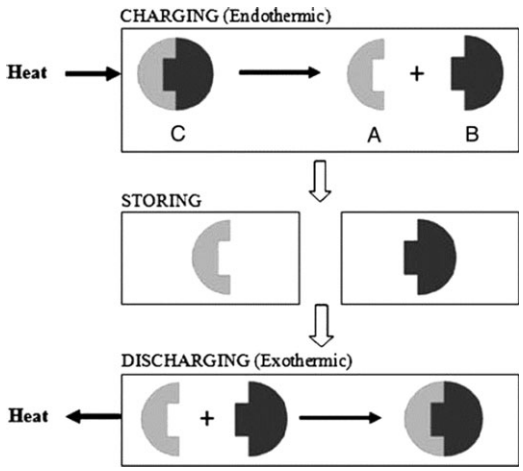

Figure 1. *Basic adsorption process [5, 6].*

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Table 1. *Summary of heat transfer enhancement.*

Ref	Open/ close Sorption	TCM working pairs	Nature	Regeneration temperature (°C)	Techniques	Application/results/comments
Fin type adsorbent tube Module/heat exchanger						
[8]	close	Silica gel/ water	Experimental & theoretical	(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	Experimental & theoretical	100	Consolidate zeolite layer with heat exchanger	Cell wall heat transfer coefficient ($\propto_w$) of 230 W m^{-2} K^{-1}, micropore diffusion coefficient at infinite temperature (D∞) of 1.58 X 10^{-4} m^2 s^{-1} and an activation energy (Ea) of 32.41 kJ mol-1
[10]	Close	Composite $BaCl_2$/ vermiculite/ NH_3	Experimental	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 was ranging from 300 to 680 W/kg.
[11]	close	Silica gel/ water& zeolite/water	Experimental & theoretical	Silica gel (65–90) Zeolite (70–90)	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/m^2 K)
[12]		Silica gel/ water	Experimental	80°C	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 & theoretical	Cooling	composite silica gel coated heat exchanger (CCHE)	CCHE has better dehumidification performance compared with SGCHE (silica gel coated heat exchanger
Consolidated Adsorbent						
[14]	close	$BaCl_2/NH_3$	Experimental	75 to 90	Expanded graphite composite consolidated with $BaCl_2$	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	$MnCl/NH_3$	Experimental	180	Expanded graphite composite consolidated with $MnCl_2$	SCP varied between 200Wkg^{-1} and 700Wkg^{-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
Adsorbent material embedded in metal foams						
[16]	Close	Zeolite/H_20/ NaCl	Experimental & theoretical	-	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	Experimental	-	Zeolite embedded with aluminium foams	Synthesizing using Microwave was much faster compared to the hydrothermal method.
[18]	Close	Zeolite/water	Experimental	-	Zeolite embedded with graphite foams	The thermal conductivity of a graphite foam of 85% porosity was 24 W/m K.
Adsorbent Coating						
[19]	open	$CaCl_2$/Water	Experimental & theoretical	-	$CaCl_2$ coated the fibre membrane and $LiCl_2$ filming the fibre membrane	Improve the energy (enthalpy) exchange efficiency, particularly moisture transfer efficiency of the exchanger.
[20]	close	Zeolite A& X/water	Experimental & theoretical	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	Experimental & theoretical	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	Experimental	-	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	Experimental	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.

(*Continued*)

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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.
[27]	Close	Carbon/ methanol	Experimental	≤110°C	Solar Tube filled with carbon	Summer days, (7 kg/m^2 ice formed), cloudy winter days about 4 kg/m^2 of ice formed.

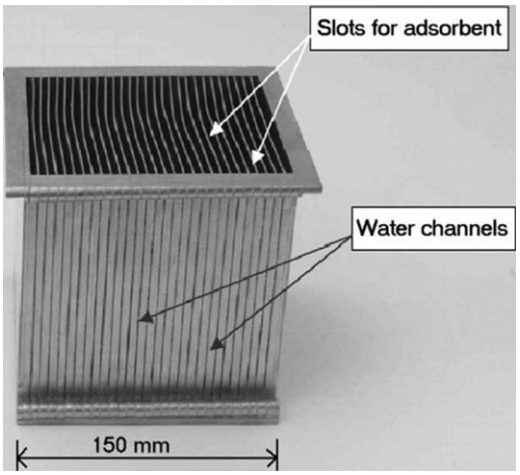

Figure 2. *A photo of a Plate heat exchanger generator (4 mm adsorbent layers) [28].*

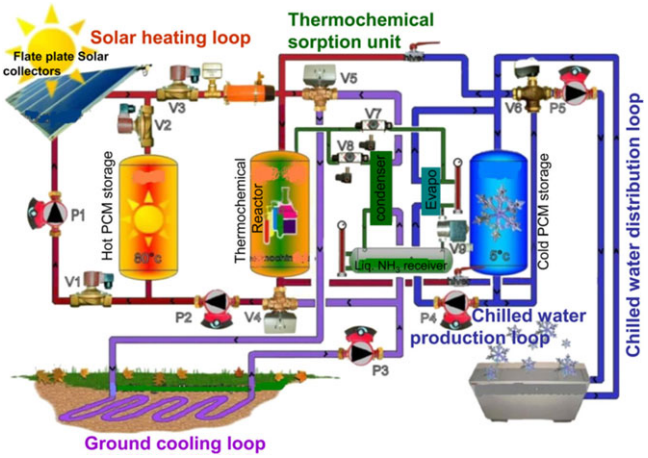

Figure 3. *Illustration of the solar sorption pilot plant for air-conditioning, flat plate solar collectors and the thermochemical reactor design [29].*

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.

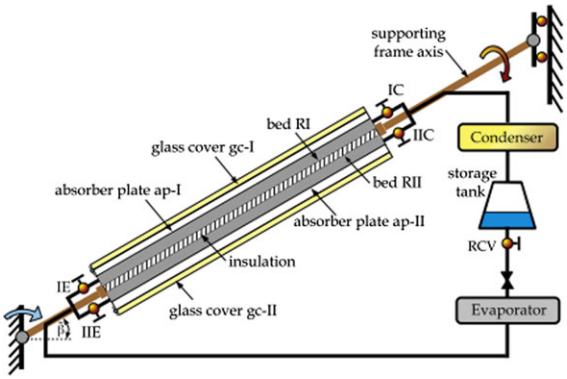

Figure 4. *Schematic representation of the proposed CO-SAR system [31].*

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

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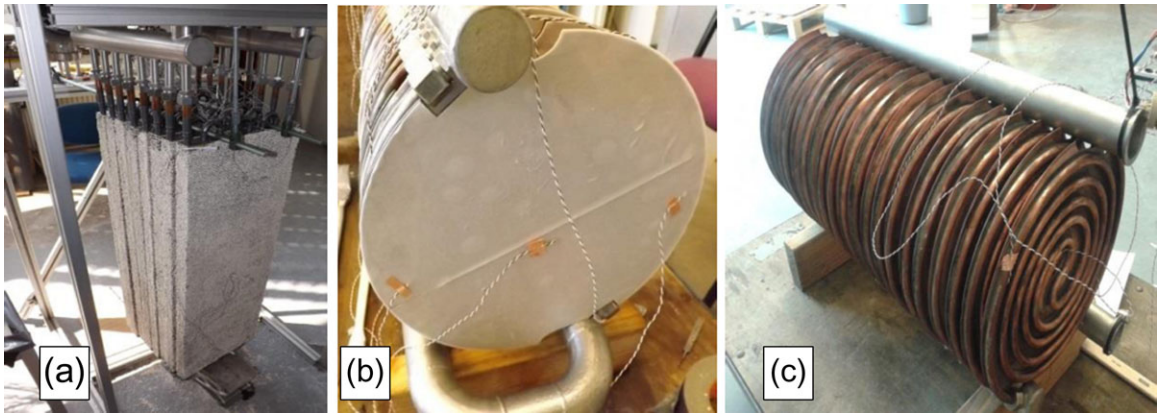

Figure 5. *(a) adsorber/desorber unit; (b) evaporator/condenser unit front view; (c) evaporator/condenser unit back view [32].*

Table 2. *Summary of adsorption heating/cooling systems.*

References	Nature	Material	Concept	Application	COP	Heating/cooling storage density
[33]	Experimental	$MgSO_4$ hydrate	Close sorption	Heat storage	-	2.2 GJ/m^3
[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
[36]	Numerical	Lithium chloride – silica gel	Close sorption	Ice-maker	0.33	daily ice production (DIP) of 20 kgm^2
[10]	Experimental	$BaCl_2$/vermiculite	Close sorption	Air-conditioning	0.54 ± 0.01	300 to 680 W/kg Cooling
[29]	Experimental	$BaCl_2/NH_3$	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]	Experimental	$MgCl_2$•$6H_2O$	Open sorption	Heat storage	12	50 W
[40]	Numerical & Experimental	$CaCl_2/NH_3$	Solid–gas sorption	Seasonal Storage	0.60-heat recovery 0.34-winter	1043 kJ/kgsalt 579 kJ/kgsalt,
[41]	Numerical	Silica gel/water	Close sorption	Solar adsorption cooling	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/m^3 cooling 163.6 kWh/m^3 Heating
[31]	Numerical	Activated carbon-methanol	Solar adsorption	Refrigeration	0.66	2.63 kg cold water at 0°C
[43]	Numerical	Zeolite 13X/$CaCl_2$	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 – $CaCl_2/NH_3$	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/$MgSO_4$ & $MgCl_2$/$MgSO_4$	Open sorption	Heat storage	-	5kWh – heating (70 kg composite material)

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.

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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 of 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 to 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.

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