Thermal performance of a vapour adsorption refrigeration system: an overview

Sohan Singh, Sunil Dhingra

Department of Mechanical engineering, University Institute of Engineering & Technology (UIET), Kurukshetra, Haryana, India (136119)

E-mail address: harisohan007@gmail.com, pecdhingra@gmail.com

Abstract: The paper gives the latest review on the thermodynamics modeling and the COP of vapour adsorption refrigeration system operating with one bed or double bed intermittent cycle. A detailed literature review has been carried on the principle of adsorption, properties of adsorbent-adsorbate materials, and this adsorbent-adsorbate work with vapour adsorption cycle. It was observed that the technology is very attractive, but it has limitations relating to its low coefficient of performance. A survey of new research techniques for the improvement is also shown in this paper. It showed that there were adsorption systems which can be useful for ice-making, air-conditioning, refrigeration, as stand alone or hybrids systems, but also cater to environmental protection and energy conservation.

Keywords: - Adsorbate, Adsorbent, Adsorption, solar energy and solar refrigeration.

Contents

1. Introduction
2. Schematic process
   2.1 Principle of adsorption
   2.2 Single bed vapour adsorption refrigeration cycle
   2.3 Selection of the working pair
3. Thermodynamic modeling
   3.1 Mathematical model
   3.2 Thermodynamic analysis approach
4. Choice of adsorbent-adsorbate pairs
   4.1 Zeolites-water systems
   4.2 Activated carbon / methanol systems
   4.3 Activated carbon / ammonia systems
   4.4 Silica gel-water and silica gel / methanol systems
   4.5 Other working pairs
5. Conclusions

Reference

1. Introduction

The conventional cooling systems give rise to pollution in the environment such as greenhouse gas emissions and global warming by the utilization of fossil fuels. In the 21st century is an important need to change those renewable fast heat systems by solar energy based good energy change systems for generating refrigeration effect. Adsorption refrigeration systems are environmentally good natured and based on the low grade heat sources. The benefits of adsorption cooling systems based on the not availability of moving parts, mobile application suitability maintain free and no rusting problems. The
adsorption chiller quality is affected remarkable by the change in the temperature, which make them useful for various solar applications [1]. Other useful qualities of vapour adsorption cooling systems are given by [2, 3]:

i. Adsorption system can hold high temperature (520°C) with no corrosion while corrosion produces in absorption system above 210°C.

ii. Adsorption technology can be run on 55°C temperature, but to drive the absorption system at least 75°C is required.

iii. Adsorption cooling systems are useful for the application with less vibration as compared to absorption technology because in adsorption system uses the liquid absorbent.

iv. A significant amount of electrical power is saved in vapour adsorption refrigeration system. It causes less pollution. Since solar energy is available in every part of the world, it is available in abundance and thus can be used constantly.

v. The solar refrigerator can be useful where there is no electricity continuous supply. It has low maintenance cost as compared to the conventional system.

The main limitations of adsorption systems are; (i) In the container m tightness is necessary; (ii) the solar power vapour adsorption refrigeration system cannot be used in those places where there is no solar radiation. (iii) It needs a larger space for the collector; (iv) The adsorption system have low COP value as compared to other absorption system; (v) Adsorption system has higher specific volume and mass than absorption system; (vi) Due to the limited no. of suppliers the commercial adsorption machine are expensive [4,5].

2. **Schematic process**

The schematic process is classified into various parts and the various parts are principle of adsorption, single bed vapour adsorption cooling system and the selection of working pairs for the vapour adsorption refrigeration system.

2.1 **Principle of adsorption**

The schematic of adsorption is the phenomena of the interaction of a fluid (refrigerant) and solid which depends upon a chemical or physical adsorption. Then the molecules of adsorbate make a mixed layer of adsorbate porous solid element on the outer adsorbent surface to the Vander Waal force is known as physical adsorption. Therefore ahead to the total collection of the substance on the outer surface. Heat is given to the adsorbent then adsorbate evaporates particles. However this process in adsorption or desorption is possible again and again. The results in chemical adsorption due to covalent or ionic bond produced midway of the adsorbent/adsorbate substance. In chemical adsorption bonding forces more heat is released as compared to the physical adsorption. Whereby in this process reversing is not easily possible similarly the chemical bonding advances the chemical reaction of adsorbed particles, according the adsorbent/adsorbate particles never hold unique state after adsorption. Along these lines, the greater parts of the adsorption cooling system for the most part take physical adsorption [6]. At the point when settled adsorption beds of adsorbent are used the procedure can work with moving parts. This process is simplicity, high reliability, long life and silent operations. The other position on, it manual discontinuous activity with adsorption bed common between in desorption / adsorption process. The heat of adsorption is experimentally determined by calorimetric method. The adsorbents performance utilized in physical adsorption is determined by the area of surface, surface properties, and size of granules in powders, macro-pores, micro-pores and crystals. Adsorbs having exceptional closeness with polar substance relating water are known as “hydrophobic”. These include zeolites, active alumina and silica gel known as ‘hydrophobic’ has closeness for gases and oils than for water. These particles together form copolymer adsorbents, silicalites and activated carbons. The common term “sorption” is utilized when both absorption and adsorption happen at the same time. Desiccant materials are special adsorbent having unique closeness for water and have been utilized extensively for drying or dehumidification in air conditioning application. Adsorbents are portrayed by the surface property for instance surface area. A particular region utilized for giving vast adsorption limit, However the production of huge inward
surface area. Large specific areas in a constrained volume fundamental offer ascend to substantial number of little estimated pores between adsorption.

Table 1 . Adsorption of heat for different working pairs

| S. No. | Adsorbent         | Adsorbate          | Heat of adsorption (KJ/kg) |
|-------|-------------------|--------------------|----------------------------|
| 1     | Zeolites          | Water              | 3250-4150                  |
|       |                   | Ammonia            | 3900-5900                  |
|       |                   | Carbon dioxide     | 800-1100                   |
|       |                   | Methanol           | 2300-2540                  |
| 2     | Silica gel        | Methyl alcohol     | 1000-1490                  |
|       |                   | Water              | 2800                       |
| 3     | Activated alumina | Water              | 2998                       |
| 4     | Charcoal          | Ammonia            | 2400                       |
|       |                   | Water              | 2550                       |
|       |                   | Methanol           | 1900-2050                  |

Vapour adsorption system is approximating the same to vapour compression system in which compressor is changed by adsorption bed. The adsorption bed works with a different collector and contains a porous adsorbent (low grade Activated carbon) or another adsorbent material.

Refrigerant used is methanol as it has greater affinity towards charcoal. This cycle consists of two phases;

1. Daytime: During this phase adsorption bed gets heated due to solar heat and its pressure increases. The refrigerant present on the surface of the bed gets evaporated at a constant pressure which is known as desorption. Vapour refrigerant is passed thorough condenser where it gets after which it is passed through expansion valve where its pressure come down to evaporator pressure. This condensed refrigerant is stored in refrigerant storage tank.
2. Night time: During this phase, cooled refrigerant come to the evaporator where it takes heat from the cold cylinder and get vaporized, after that giving the cooling effect. This vapour adsorbate gets adsorbed in the adsorption bed which is known as adsorption. So the actual cooling effect is achieved during night time only.

2.2 Single bed vapour adsorption refrigeration cycle

Solar oriented heat is the origin of most adsorption cooling systems running with the single bed. In another system, like vapour absorption system condenser, evaporator etc. are not changed but the only difference is that of heat gained method. A vapour adsorption refrigeration system assisted on the single bed adsorption does not need any electrical or mechanical energy, but only heat energy; it runs from time to time under the condition to the everyday cycle. Like a
simple vapour absorption cooling system, this cooling system is closed, comprising a generator, a condenser and an evaporator. Notwithstanding, the generator is controlled by the heat energy as an adsorber, and evaporte of an adsorbate to the cooling effect is produced while the vapour is adsorbed in the adsorber by the adsorbate layer.

![Fig. 2 Simplified scheme of the solar adsorption refrigeration device](image_url)

The adsorbed adsorbate content varies cyclically, according to the condition of pressure and temperature. The pressure in the condenser should be higher than in the adsorption bed. The vapour adsorption cooling system devices is shown in figure 2. The hot pipe of the evaporator end is produced at the engaged of the PTC collector, while the adsorber bed in condenser is inserted [7]. At the evaporator section, the sun energy is changed into the heat energy. The solar direct radiation is reflected to the reflective surface of PTC collector and then focused on the absorber tube. Then, the sun energy is changed into heat energy, which is adsorbed on the heat evaporation section. These solar heat vaporize the adsorbate in the adsorption-desorption bed. The pressure of refrigerant in the condenser should be higher than in the adsorption bed, where it is condensed and then cooling box to the latent heat of refrigerant released. The theoretical thermodynamics cycles of the solar adsorption cooling system is based on clausius clapeyron equation and is depend of four phase is shown in fig. 2 [8]. In this process cooling produced is directly proportional to the cycle mass in this machine. The continuous cooling effect is needed; more than two adsorption bed must be operating out of phase [9]. Abu-Hamdeh et. Al. [10] developed vapour adsorption system working with the olive waste-methanol pair. This paper in the temperature gained in the cooled space 4°C; with a coefficient of performance 0.03 with sun radiation in this system are 56.2 MJ/m². M.Zainal ismail [11] find an experimental result to prove that increasing the air flow in the desiccant bed decreases the COP of the system. M.Li [12] obtained that the machine can produced 5 kg ice with 14-16MJ of sun energy.

2.3 Selection of the working pair

The working fluid selection of adsorbent-adsorbate plays an good role in the system operation. Different pairs of adsorbent-adsorbate give different working temperatures and it affects the rate of heat transfer. The selections of adsorbent-adsorbate pair for cooling application depend on some valuable features.

2.3.1 Choice of adsorbate. The flowing ideal properties used in working pair of the solar refrigeration system is as follow [13]: The properties of ideal adsorbate used in solar adsorption system are as follows:-
1. Vapour adsorption refrigeration system in evaporate temperature above 0°C (for air conditioning it can be lower in the refrigeration application).
2. Low specific volume and high latent heat of vaporization when in the liquid state.
3. Low viscosity and high thermal conductivity.
4. Temperature range of adsorbent are thermally and chemically stable.
5. Low saturation pressure at normal operating temperature.

The adsorbates used in the vapour adsorption cooling systems generally have zero effect. The mostly used adsorbates are methanol, water and ammonia, which have latent heat (1160, 2258, and 1368 KJ/Kg respectively). Water and methanol run at atmospheric pressure sat the temperature needed. In ammonia pressure of 1.05 bar at condensate temperature of 34°C is needed for some times small leakage can be tolerated. Ammonia is corrosive and toxic, while methanol and water are not, but the later is flammable. Water is the high value of latent heat, closely followed by ammonia and methanol. The Water is the cheapest adsorbate but it cannot be used for refrigeration system below 0°C [14]. Mohamed M. Younis [15] studied the review paper on the different pairs for cooling applications. It can be resulted that the adsorption was cooling system still in need to useful development and commercial adsorption cooling systems.

2.3.2 Choice of adsorbent. The properties of ideal adsorbent used in solar adsorption system are as follows:
1. Adsorbent capability to adsorb a huge amount of adsorbate to produced a high cooling effect.
2. When heat source is heated to desorption most of the adsorbate.
3. It has low specific heat and good thermal conductivity.
4. The adsorption capacity and non-deterioration losses with usage.
5. Non-corrosive and non-toxic.

The most approximate adsorbent materials sufficiently permeable with particular demand of the surface of 600m²/g higher to consider adsorption of extensive cooling amounts, yet this outcome in thermal conductivity is low, which confines the execution of the cooling system. In this way, there must be exchange between the high densities needed for good thermal conductivity [16]. A survey on the condition of state for the adsorbent-adsorbate utilized as a part for the adsorbent-adsorbate used in adsorption refrigeration system [17]. The various formulas and models show the adsorption match condition of state for various blends of pairs can be seen in the report. Moreover, these state conditions incorporate a few coefficients which are resolved tentatively for every mix of the adsorption match. The utilized adsorbent are Zeolites, silica-gel and activated carbon. Adsorption and desorption powers of activated carbon offer a good compromise. Thus, regular Zeolites available in expensive amount since just a little measure of adsorbate are desorbed with the increment temperature. Conversely, Silica gel and activated carbon get show short pressure dependence isothermal. Silica gel fulfills a large portion recorded above; anyway it is costly and not available in most nations. Some of the following working pair are used in the vapour adsorption system discussed in the next chapter of this review paper.

3. Thermodynamic Modeling

The thermodynamic modeling is basically studied the physical description, mathematical modeling and the thermodynamic analysis approach. The physical description of this system is shown in figure 2. The following assumption and the thermodynamic modeling is used to obtain the COP of the system and the mass of ice produced at evaporation temperature.

3.1 Mathematical Modeling

A rearranged mathematical model of adsorption bed to heat and mass transfer was developed in view of the accompanying presumptions. Few presumptions investigated in last studies [18, 19] are:-
1. The thermodynamic balance of the pairs system is confirmed at each time and each adsorption point.
2. The pressure of adsorbate in the adsorption bed is uniform.
3. The convectional heat losses are neglected.
4. In the adsorption bed mass transfer occurs only in the vapour phase.
5. Both a condenser and an evaporator work ideally.
6. The mass fluid of the adsorbate is considered as specific heat of the adsorbate.
7. The adsorbate works as ideal gas.

3.2 Thermodynamic analysis approach

A thermodynamic operating cycle consist of mainly four phase for adsorption. It may be given as follow are:

3.2.1 Isosteric heating phase. The mass of adsorbent preheated at a changeless mass of adsorbate, \( x_{\text{max}} \). The sensible heat \( Q_r^{1-2} \) given as:

\[
Q_r^{1-2} = Q_w^{1-2} + Q_{\text{AC}}^{1-2} + Q_m^{1-2}
\]

(1)

Where \( Q_{\text{AC}}^{1-2} \), \( Q_m^{1-2} \) and \( Q_w^{1-2} \) are sensible heat of the adsorbent, adsorbate and metallic wall respectively.

These equations are given in derived form:

\[
Q_w^{1-2} = m_w C_{pw} \left( T_{ad} - T_{ad} \right)
\]

(2)

\[
Q_{AC}^{1-2} = m_{AC} C_{PAC} \left( T_{ad} - T_{ad} \right)
\]

(3)

\[
Q_m^{1-2} = m_{AC} x_{\text{max}} \int_{T_a}^{T_{pl}} C_p dT
\]

(4)

3.2.2 Isobaric desorption phase. In desorption phase mass of adsorbate reached at minimum value in the adsorbent. The total heat \( Q_r^{2-3} \) are given as:

\[
Q_r^{2-3} = Q_w^{2-3} + Q_{AC}^{2-3} + Q_m^{2-3} + Q_{\text{des}}
\]

(5)

The sensible heat of the adsorption ate calculate:

\[
Q_w^{2-3} = m_w C_{pw} \left( T_g - T_{ad} \right)
\]

(6)

\[
Q_{AC}^{2-3} = m_{AC} C_{PAC} \left( T_g - T_{ad} \right)
\]

(7)

\[
Q_m^{2-3} = m_{AC} x_{\text{min}} \int_{T_a}^{T_{pl}} C_p dT
\]

(8)

\[
Q_{\text{des}} = m_{AC} \int_{T_a}^{T_{pl}} \Delta H \left( \frac{\partial x}{\partial T} \right)_{T_a} dT
\]

\[
= m_{AC} \int_{T_a}^{T_{pl}} C_p dT
\]

(9)

The input heat is the total of the isobaric adsorption and desorption heat from the sun radiation and written as:-

\[
Q_\text{in} = Q_r^{1-2} + Q_r^{2-3}
\]

(10)

3.2.3 Isosteric cooling phase. The heat losses in the environment to the adsorption bed at constant adsorbate mass, \( x_{\text{min}} \). The sensible heat in this phase \( Q_r^{3-4} \) given as:

\[
Q_r^{3-4} = Q_w^{3-4} + Q_{AC}^{3-4} + Q_m^{3-4}
\]

(11)
Where,  
\[ Q_{w}^{3-4} = m_{w} C_{pw} (T_{w} - T_{sa}) \]  
(12) 
\[ Q_{AC}^{3-4} = m_{AC} C_{pAC} (T_{g} - T_{sa}) \]  
(13) 
\[ Q_{m}^{3-4} = m_{AC} x_{\min} \int_{T_{sa}}^{T_{g}} C_{p}dT \]  
(14) 

3.2.4 Isobaric adsorption phase. In the phase, mass of adsorbate reached at maximum value in the adsorption bed. The \( Q_{T}^{4-1} \) is given as:- 
\[ Q_{T}^{4-1} = Q_{w}^{4-1} + Q_{AC}^{4-1} + Q_{m}^{4-1} + Q_{ads} \]  
(15) 
Where,  
\[ Q_{w}^{4-1} = m_{w} C_{pw} (T_{sa} - T_{ad}) \]  
(16) 
\[ Q_{AC}^{4-1} = m_{AC} C_{pAC} (T_{sa} - T_{ad}) \]  
(17) 
\[ Q_{m}^{4-1} = m_{AC} \int_{T_{ad}}^{T_{g}} x C_{p}dT \]  
(18) 
\[ Q_{ads} = m_{AC} \frac{\tau_{g}}{\tau_{ad}} \Delta H \left[ \frac{\partial x}{\partial T} \right] \int_{p_{ev}}^{p_{ad}} dT \]  
(19) 

The two limit point is completed in the thermodynamic cycle (At point 4, starting adsorption and at point 2, starting desorption) was written as:- 
\[ T_{sd} = T_{con} T_{ad} / T_{ev} \]  
(20) 
\[ T_{sa} = T_{g} T_{ev} / T_{con} \]  
(21) 

3.2.5 The condenser. In this phase, the adsorbate vapour phase begins to condense and lost heat energy to the surrounding, after that vapour condensed to liquid. The heat lost to the surrounding is given as:- 
\[ Q_{con} = m_{AC} \Delta x L_{m} (T_{con}) + m_{AC} C_{p} \int_{T_{ad}}^{T_{con}} (T_{con} - T) \left[ \frac{\partial x}{\partial T} \right] \int_{p_{con}}^{p_{ev}} dT \]  
(22) 

3.2.6 The evaporator. In this phase, cooling produces by evaporate of the adsorbate in the liquid phase. The cooling produced at the evaporator is written as:- 
\[ Q_{ev} = m_{AC} \Delta x \left[ L_{m} (T_{ev}) + \int_{T_{con}}^{T_{ev}} C_{p}dT \right] \]  
(23) 

3.2.7 Energy balance for the whole system. The input and output energy of the system is determined from: 
\[ Q_{add} = Q_{T}^{1-2} + Q_{T}^{2-3} + Q_{ev} \]  
(24) 
\[ Q_{rej} = Q_{T}^{3-4} + Q_{T}^{4-1} + Q_{con} \]  
(25)
3.2.8 The performance indices. The performance terms used in vapour adsorption cooling systems are the COP of the cycle and total mass of the ice produced. These terms are given (i) and (ii) in the following formulas.

1. The COP is the ratio of total cooling produced to the total input heat given in the equations are:-

\[
COP_{\text{cycle}} = \frac{Q_{\text{ev}}}{Q_{\text{in}}}
\]

(26)

2. The mass of ice produced at evaporating temperature is given in kg/cycle by:-

\[
m_{\text{ice}} = \frac{Q_{\text{ev}}}{C_w(\text{ice} - 273) + C_{\text{ice}}(273 - T_{\text{ev}}) + L_{\text{ice, fus}}}
\]

(27)

In writing, theoretical systems of adsorption cooling framework with their numerical clarification have been generally discussed. Douss et al. created a theoretical model for basic recovery of heat cycles with zeolites NaX-water pair [22]. In this forecast, the recovery of heat and mass cycle and basic cycle achieved the COP 1.56 and 1.38, respectively. The author expressed the evaporation and condensation pressures and the biggest impact on the coefficient of performance values among temperatures of adsorption bed and other parameter heat and mass cycle. Alam et al. [23] a description of the two-arrange adsorption refrigeration cycle was created. Silica gel-water pair was used in the study, and impact of cycle process, maximum condensation temperature and adsorption bed performance were investigated. The cooling capacity is increased with diminishing cycle time while with longer process duration, better COP achieved. At last as the decreased condensation temperature, both increased cooling capacity and coefficient of performance. Wang et al. [24] built up and theoretical model for two-bed adsorption refrigeration system with silica gel-water pair. The total effect of temperature, and mass and heat recovery on the system outcome were examined. The maximum adsorption temperature was 65-85°C on highest COP obtained. The condenser temperature is 20 °C on the most extreme COP value 0.65. M.Li. et al. [25] theoretically announced that the solar ice created can produce 5 Kg ice on an each day time under the condition that sun radiation is approximate 18-22 MJ/m² with no valve solar ice maker. N.M. khattab [26] obtained experimentally that reflector type D heated four types of adsorption bed technique in cold environment to increased maximum adsorption temperature between 13% and 60% then solar energy to plain bed heated. F. Aghbalou et. Al. [27] result the experimental result to show that COP and different temperatures of the adsorption system. As a result COP=14.3%, with adsorption of ammonia in cylindrical adsorption bed. Ramesh P. Sah [28] studied the review of modeling technique utilized for simulation of low-grade heat run into the adsorption refrigeration system. It was result the adsorption chiller have not been yet commercial and are in the stage of prototyping and demonstration. The performance of adsorption chiller increased by few research works is needed. The advanced and simulated model should be developed for optimal design of adsorption chiller based on low grade energy sources.

4. Choices of adsorbent – adsorbate pairs

Adsorption cooling system is accomplished utilizing a mix of adsorbent and adsorbate. The useful upgrade of such performances of system may be acknowledged by utilizing of various pairs. The choice of any match mix relies on certain attractive qualities of the substance. Various investigations have been completed theoretically and experimentally with choice of pair’s material. Yet the costs for choice of pair’s material still make them non –feasible. In the way few investigation are focused on increasing efficiency and cost reduction of the systems. The outline of the most widely utilized working pairs sets are also the performance of working pairs combine is reviewed based on heat source temperature.
4.1 Zeolites-water system

Since the late 1970s, significant efforts were made by Grenier et al. [29] who built a system utilizing a area of collector 20 m² containing Na-X zeolite360 kg for cold storage. When the sun radiation was 17.8 MJ/m² with cold generation during evaporation was 1.93 MJ/m². The cooling condition was set to evaporating, condensation and regeneration temperature at 1°C, 32°C and 105°C respectively. This system to COP value of solar 0.105 and the cycle COP was 0.38. Meunier [30] theoretically studied the zeolites/water pair and found that the net in 1984, they created a machine which worked at various temperatures and the system couple 0.14 COP was attained. E.E.Anyanwu et. Al. [31] theoretically concluded that in air conditioning systems Zeolites/water is preferred but in refrigeration systems other applications in activated carbon/ammonia is preferred as the working fluids.

4.2 Activated carbon-Methanol systems

Activated carbon / methanol are a standout amongst the broadly utilized pair in adsorption cooling system as a result of high latent heat, low adsorption temperature and with large adsorption capacity. It is being utilized for the past thirty two years. Ponset et. Al. [32] studied a experimental solar assisted ice maker with an AC/methanol pair. The area of collector 6 m² contained 130 kg of AC produced 0.12 net COP for the regeneration temperature of 95°C, a stand point amongst the most proficient solar ice maker in 1986. Himsar ambarita et. Al. [33] and experimentally result concluded that for the flat plate collector, the pair of AC / methanol is good than activated alumina. M.A. Hadji Ammar et. Al. [34] was theoretically analysis that the optimal COP was equal to 0.73 with total ice produced of 13.65 kg at -3°C with flat plate collector. S.K. Henninger et. Al. [35] found that the wetted tests showed an effective heat capacity of 1.41/gk at 40°C and 1.7 l/gk at 60°C. In this paper yunfeng Wang et. Al. [36] proposed an adsorption system in enhancing mass transfer method work with the basis cycle. The results showed that the system has high COP, faster desorption rate, and more desorbed adsorbate mass due to the enhanced mass transfer technologies and the application of reducing pressure. The desorbed refrigerant in to one and half hour can be saved with same adsorbate mass. Yunfeng Wang et. Al [37] studied a new experimental SAR system was built enhanced mass transfer and to increase performance. The result showed that the SAR system with enhanced mass transfer of higher refrigeration capacity and the COP value. Due to the application of increasing mass transfer method and the application of reducing pressure to maximum ice produced and the maximum COP value in the enhanced refrigeration system were 7 kg and 0.142 respectively. Additionally the micro vacuum pump help to increase the COP of the SAR system. Jaimin k patel [38] studied the ice production system based on the adsorption cooling system has been designed depending on the heat transfer and thermodynamics principle. The parameter used in the adsorption cooling system has been analyzed using (D–A) model. The experimental system is scaled up and developed keeping needs of rural area in mind.

4.3 Activated carbon-ammonia system

The AC/ ammonia working pair was an important pair for adsorption cooling system during the period 1986s. Miles and Shelton [39] achieved a coefficient of performance 1.21 for heating and 0.76 for cooling, using a two bed adsorption cooling system with duration of 2.6 minutes with half cycle. Critoph [40] developed a model of another regenerative cycle in which heat transfer was refrigerant. A model is showed by this author finds 0.95 COP value. Q.W.fan [41] developed a performance of adsorption system with AC/methanol pair with double bed adsorption refrigeration system. Al Mersetal. [42] Developed a model explaining the heat transfer processes in the solar adsorption refrigeration with finned reactor. The result showed that adsorption bed with a 6 fins and without fins, the adsorption bed of COP value 45% higher than that to without fin.

4.4 Silica –gel methanol and Silica –gel/water systems

Since mid 1981, the works on silica-gel/water has been carried out in Japan and popular. With an end goal to use sun radiation, Suzuki and Sakoda [43] created a adsorption system with COP value of
approximate 0.2 with collector volume 500×500×50 mm³ depth, with 1.5 kg refined in evaporator and 1 kg of silica gel. On a crisp morning with added sun radiation of 19.3 MJ/m² days, it was assessed that coefficient of performance of around 0.4 with 0.4 m² collector can be possible. X. Zheng et al. [44] experimentally concluded that the composite silica gel covered sheet showed better mass and heat transfer performance than pure silica gel. Elab S. et al. [45] has been theoretically investigated the Hybrid adsorption desalination cooling system showing adsorbent silica gel material with use software. The hybrid cooling system is driven by sun radiation. An adsorption desalination-cooling system acclenting silica gel 13.5 kg used in the two adsorption bed used in this study for producing the result. The average COP, SCP and SDWP values are 0.5, 13.4 W/kg, and 10.5 m³ton respectively.

4.5 Other working pair

Notwithstanding the various common adsorbent-adsorbate pairs, different pair has also been researched. Erhanrd et al. (46) addition to utilize the strontium chloride/ammonia pair used in an adsorption cooling device. Nonetheless, a worldwide 0.08 COP value resulted in evaporator temperature -5°C. Maggio et al. [47] developed a scientific model to find COP of the adsorption cooling system with the composite material and the COP produced was 0.33. Q. F. Chen et al. [48] made an experimental adsorption cooling system with the working pair. This SAR system has provided a support for the verification of the optimization possibility. S. W. Du et al. [49] studied the experimental performance of the SAR system. The COP and the SCP for any cooling mode ZSM-5 zeolite is less than that of SAPO-34 zeolite. Ahmed S. Alsaman [50] developed SAC system which is designed and tested in Egypt. The result showed that the COP 0.45 and SCP is 112 w/kg and per ton of silica gel in 4 m³ water production. Mahammad et al. [51] presented a simulated study of a SAR. The results showed that linear PTC collector has lower performance as compared to wing type PTC collector. The performance increased 2% in winter and 6% in summer with the wing type collector. The ice produced increased up to 13% with wing type PTC collector. IIEI Sharkawy et al. [52] studied the experimental results that 1.2 kg ethanol adsorbed by the per kg of adsorbent and calculation showed that regeneration temperature 80°C to achieved cooling effect 420 KJ/kg at an evaporator 7°C temperature and this pair is useful for solar cooling. IIEI Sharkawy et al. [53] developed a adsorption system in activated carbon fiber (A-15) and (A-20) with ethanol. The Dubinin-Radusndevich equation is used for experimental data. It was observed that activated carbon fiber (A-15)/ethanol has lower adsorption capacity than the ACF (-20). The paper shows that adsorption capacity increases per unit volume of the absorber with higher density.

5. Conclusions

The paper exhibits the latest review on the thermodynamics modeling and the COP of vapour adsorption refrigeration systems working with single or double bed intermittent cycle. The principle of adsorption, basic solar adsorption cycle covering its main components, thermodynamics modeling and the properties of adsorbent-adsorbate for SAR system is explained. The most regularly utilized pair working sets are also explained with different solar collectors for SAR system. The solar adsorption system has various advantages over the vapour compression system. The ecological advantages of this technology and for further its-independence on non-renewable sources make sit increasingly popular development Moreover, because of the year-round accessibility of sunlight, solar radiation can be effectively caught all over the world. The technology keeps on advancing and the cost of delivering power with SAR system is falling. On the off chances that the expenses of transportation, fossil fuels, electricity transmission, energy conversion and system maintained are considered, the cost of energy created SAR systems would be much lower than that for traditional cooling systems. The paper introduces a general survey on the major compensation on the various SAR cycles and the applicability of solar adsorption both in refrigeration and cooling with the increased COP. The literature shows that SAR devices can supply, among others, the need for ice making, air conditioning, and for refrigeration applications with extraordinary potential in the protection of some goods (e.g. medicines, food supplies) in remote areas. The most commonly utilized working pair is AC/ammonia-methanol. By the way, the option of every system (e.g. ice
making, air conditioning) and the ambient conditions direct its arrangement and working pair, and along these line its performance. Various experimental papers are presented in this paper. It is possible to consider that adsorption systems can be other option of decreasing the CO₂ emissions and the electricity demand when they are powered by sun radiation. For further extensive usage, the investigator should keep going for improvement in the efficiency of the system such that the system results in enhanced adsorption capacity with minimum manufacturing costs and the other inputs.

### Nomenclature

**Symbols**

- C: Specific heat (J/kgK)
- C_p: Specific heat at constant pressure (J/kgK)
- Q: Heat energy (kJ)
- L: Latent heat (kJg⁻¹)
- U: Overall heat transfer coefficient
- h: Convective coefficient [W/m²K]
- x: Adsorbed mass (kg)
- T: Temperature (°C)
- P: Pressure (Pa)
- m: Mass (kg)
- R: Gas constant (J/molK)
- ΔH: Isosteric heat of adsorption (kJ/kg)

**Greek letters**

- ρ: Density (kg/m³)

**Subscripts**

- AC: Activated carbon
- me: Methanol
- I: Liquid
- so: Starting adsorption
- ad: Adsorption
- Cond: Condensation
- ev: Evaporation
- v: Vapor
- w: Wall
- am: Ambient
- g: Generation
- des: Desorption
- max: Maximum
- dey: Dehydration
- ref: Reference
- ice: Ice
- fus: Fusion
- m: Mass
- cycle: Cycle

**Abbreviations**

- SAR: Solar adsorption system
- COP: Coefficient of performance
- PTR: Parabolic trough collector

### References

[1] Choudhury, B.B. Saha, P.K. Chatterjee and J.P. Sarkar (2013), “An overview of developments in adsorption refrigeration systems towards a sustainable way of cooling” Applied Energy, vol. 104, pp.554-567.

[2] K.R. Ullah, R. Saidur, H.W. Ping, R.K. Akikur and N.H. Shuvo (2013), “A review of solar thermal refrigeration and cooling methods” Renewable and Sustainable Energy Reviews, vol. 24, pp.499-513.

[3] L.W. Wang, R.Z. Wang and R.G. Oliveira (2009), “A review on adsorption working pairs for refrigeration” Renewable and Sustainable Energy Reviews, vol. 13, pp.518-534.

[4] J. White(2013), “Literature review on adsorption cooling systems” American and Caribbean Journal of Engineering Education 378–884–1 RV.

[5] A.A. Askalanay, S.K. Henninger, M. Ghazy and B.B. Saha (2016), “Effect of improving thermal conductivity of the adsorbent on performance of adsorption cooling system” Applied Thermal Engineering, Accepted manuscript.

[6] Sumathy K, Yeung KH and Yong L(2003), “Technology development in the solar adsorption refrigeration systems” Progress Energy Combustion Science, vol. 29, pp.301–327.

[7] A. El Fadar, A. Mimet and M. Pe’ rez-Garca’s (2009), “Study of an adsorption refrigeration system powered by parabolic trough collector and coupled with a heat pipe” Renewable Energy, vol.34, pp.2271–2279.

[8] M.A. Hadj Ammar, B. Benhendaou and F. Bourras(2016), “Thermodynamic analysis and performance of an adsorption refrigeration system driven by solar collector” Applied Thermal Engineering, accepted manuscript.

[9] Choudhury B, Chatterjee PK and Sarkar JP (2010), “Review paper on solar-powered air conditioning through adsorption route” Renew Sustain Energy Rev, vol.14, pp.2189–2195.

[10] Nidal H. Abu-Hamdeh, Khaled A. Almefai and Khalid H. Almaitan (2016), “Design and performance characteristics of solar adsorption refrigeration system using parabolic trough collector: Experimental and statistical optimization technique” Energy Conversion and Management, vol.74, pp.162–170.

[11] M. Zaimal ismail, D. E. Angus and G. R. Thorpe (1991), “The performance of a solar-regenerated open cycle desiccant bed grain cooling system” Solar Energy, Vol. 46, pp. 63-70.

[12] M. Li, R.Z. Wang, X.Y. Xu, J.Y. Wu and A.O. Dieng (2002), “Experimental study on dynamic performance analysis of a flat-plate solar solid-adsorption refrigeration for ice maker” Renewable Energy, vol. 27, pp.211-221.

[13] R.Z. Wang and R.G. Oliveira (2006), “Adsorption refrigeration—An efficient way to make good use of waste heat and solar energy” Progress in Energy and Combustion Science, vol.32, pp.424–458.

[14] M.S. Fernandes, G.J.V.N.Brites, J.J.Costa, A.R.Gaspar and V.A.F.Costa (2014), “Review and future trends of solar adsorption refrigeration systems” Renewable and Sustainable Energy Reviews, vol.39, pp.102–123.

[15] M.M. Younes, L.L. El-Sharkawy, A.E. Kabeel, B. Barun Saha (2016), “A review on adsorptive adsorbate pairs for cooling applications” Applied Thermal Engineering, Accepted manuscript.
[16] Tather M, Tantekin-Erolsozlu B and Erdem-Senatalara L (1999), “A novel approach to enhance heat and mass transfer in adsorption heat pumps using the zeolite– water pair” Micropor Mesopor Mater, vol.27(1), pp.1–10.

[17] H.Z. Hassan, A.A.Mohamed, Y.Alyousef and H.A.Al-Ansary (2015), “A review on the equations of state for the working pairs used in adsorption cooling systems” Renewable and Sustainable Energy Reviews, vol.45, pp.600–609.

[18] Guillenminot JJ and Meunier F (1987), “Heat and mass transfer in a non-isothermal fixed bed solid adsorbent reactor: a uniform pressure on- uniform temperature case” In: J. Heat Mass Transfer, vol. 30, pp.1595–1606.

[19] Luo L and Tondeur D (2000), “Transient thermal study of an adsorption refrigeration machine” Adsorption, vol. 6, pp.93–104.

[20] Dahlim M S Jalal and Antakov VA (1971), “Development of the concept of volume filling of micropores in the adsorption of gases and vapors by microporous adsorbents” Washington, DC, USA: American Chemical Society, vol.1, pp.17-21.

[21] El Fadar A, Minet A and Pérez-Garcia M (2009), “Modeling and performance study of a continuous adsorption refrigeration system driven by parabolic trough solar collector” Sol Energy, vol. 83, pp.850–861.

[22] N. Douss, F. E. Meunier and L.M. Sun (1988), “Predictive model and experimental results for a two-adsorbor solid adsorption heat pump” Ind. Eng. Chem., vol. 27, pp.310-316.

[23] K. C. A. Alam, B. Saha, A. Akisawa and T. Kashihara (2004), “Influence of design and operating conditions on the system performance of a two-stage adsorption chiller”. Chemical Engng. Commun., vol.191, pp.981-997.

[24] D. C. Wang, Z. Z. Xia, J. Y. Wu, R. Z. Wang, H. Zhai and W. D. Dou (2005), “Study of a novel silica gel– water adsorption chiller. Part I. Design and performance prediction” Int. J. Refrig., vol. 28, pp.1073-1083.

[25] Manuel I Gonzalez and Luis R. Rodriguez (2004), “Solar powered adsorption refrigerator with CPC collection system: Collector design and experimental test” Energy Conversion and Management, vol. 46, pp.2587-2594.

[26] N.M. Khattach (2004), “A novel solar-powered adsorption refrigeration module” Applied Thermal Engineering, vol.24, pp.2747-2760.

[27] Agghbalou A, Minet M, F. Badia J, I Ila A. El Bouardi D and J. Bougard (2004), “Heat and mass transfer during adsorption of ammonia in a cylindrical adsorbent bed: thermal performance study of a combined parabolic solar collector, water heat pipe and adsorber generator assembly” Applied Thermal Engineering, vol. 24, pp.2537-2555.

[28] Ramesh P. Sah, Bislap Choudhury, Ranadip K. Das, Anirban Sur (2017), “An overview of modeling techniques employed for performance simulation of low-grade heat operated adsorption cooling systems” Renewable and Sustainable Energy Reviews, vol.74, pp.364-376.

[29] Grenier PH, Guillenminot JJ, Meunier F and Pons M (1988), “Solar powered solid adsorption cold store” ASME J Solar Energy Eng., vol.110, pp.192–197.

[30] Meunier F (1998), “Solid sorption heat powered cycles for cooling and heat pumping applications” Applied Thermal Engg., vol.18, pp.715–729.

[31] E.E. Anyanwu and N.V. Ogurke(2003), “Thermodynamic design procedure for solid Adsorption solar refrigerator” Renewable Energy, vol. 30, pp.81–96.

[32] M. Pons and J. J. Guillenminot (1986), “Design of an Experimental Solar-Powered, Solid-Adsorption Ice Maker” ASME J. Sol. Energy, vol.108, pp.332-337.

[33] Himansar Ambarita and Hideki Kawai (2016), “Experimental study on solar-powered adsorption refrigeration cycle with activated alumina and activated carbon as adsorbent” Case Studies in Thermal Engineering, vol. 7, pp.36–46.

[34] M.A. Hadij Ammar, B. Benhaoua and F. Bouras(2016), “Thermodynamic analysis and performance of an adsorption refrigeration system using a composite adsorbent” Applied Thermal Engineering, Accepted manuscript.

[35] S.K. Henninger, M. Schicklantz, P.P.C. Hu’genell, H. Sievers and H.M. Henning (2012), “Evaluation of methanol adsorption on activated carbons for thermally driven chillers part I: Thermo-physical characterization” international journal of refrigeration, vol.35, pp.543–553.

[36] Yunfeng Wang, Ming Li, Wenping Du, Xu Ji and Lin Xu (2018), “Experimental investigation of a solar-powered adsorption refrigeration system with the enhancing desorption” Energy Conversion and Management, vol.155, pp. 253–261.

[37] Yunfeng Wang, Ming Li, Xu Ji, Qingfeng Yu, Guoliang Li and Xum Ma (2018), “Experimental study of the effect of enhanced mass transfer on the performance improvement of a solar-driven adsorption refrigeration system” Applied Energy, vol.224, pp.417–425.

[38] Jaimin K. Patel, Nirvesh Mehta and Jaspal Dubhal (2017), “ICEMS 2016 Adsorption Refrigeration System: Design and Analysis” International Journal of Refrigeration, Accepted manuscript.

[39] E.S. Ali, K. Harby, A.A. Askalany, M.R. Diab and A.S. Alsaman (2017), “Weather effect on a solar powered hybrid adsorption desalination cooling system: A Case Study of Egypt’s Climate” Climate, Accepted manuscript.

[40] Erhard A, Spindler R and Ihmeke F (1990), “Test and simulation of a solar powered solid sorption cooling machine” Int J Refrig, vol.21, pp.133–41.

[41] Maggiolo G, Gordeeva L, Frenk A, Aristoy VY, Santoro F and Polonara F (2009), “Simulation of a solid sorption ice-maker based on the novel composite sorbent lithium chloride in silica gel pores” Applied Thermal Engg, vol.29, pp.1714–1720.

[42] Chen S.W. Du, Z.X. Yuan, T.B. Sun, Y.X. Li (2018), “Experimental Study on Performance Change with Time of Solar Adsorption Refrigeration System” Applied Thermal Engineering, Accepted manuscript.

[43] S.W. Du, X.I. Li, Z.X. Yuan, C.X. Du, W.C. Wang and Z.B. Liu (2016), “Performance of solar adsorption refrigeration system for industrial application” International Journal of Refrigeration, vol.31, pp.98–104.

[44] Alsaman AS, Askalany AA, Harby K, Ahmed MS(2017), “Performance evaluation of a solar-driven adsorption desalination-cooling system” Energy, Accepted manuscript.

[45] Muhammad Umair, Atsushi Akisawa and Yuki Ueda (2014), “Performance Evaluation of a Solar Adsorption Refrigeration System with a Wing Type Compound Parabolic Concentrator” Energies, vol.7, pp.1488-1466.

[46] Li. E. Sharikawy, B.B. Saha, S. Koyama, J. He, K.C. Ng and C. Yapt C 0 0 0 5), “Experimental investigation on activated carbon– ethanol pair for solar powered adsorption cooling applications”, International journal of refrigeration vol.3 1, pp.1 4 0 7 – 1 4 1 3.
[53] I.I. El-Sharkawy, K. Kuwahara, B.B. Saha, S. Koyama and K.C. Ng (2006), “Experimental investigation of activated carbon fibers/ethanol pairs for adsorption cooling system application” Applied Thermal Engineering, vol. 26, pp. 859–865.