Methods of Improving the Performance of Adsorption Thermophysical battery based on the Operating Conditions and Structure: A Review

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Abstract: Methods of improving the performance parameters of the adsorption thermophysical battery (ATB) including, coefficient of performance (COP), specific cooling power (SCP) have been reviewed in this study. Adsorption thermophysical battery has received much attention in the last few decades due to its advantages in utilizing waste heat or solar energy and using environment-friendly refrigerants. This survey reviews 158 papers that propose method and technologies to improve ATB. Structures and operating conditions such as heat exchanger, solar collector, fins, heat and mass transfer, adsorbent-adsorbate working pairs are discussed in this review. It was collected from the review literature: (i) cooling capacity and COP are increased with hot water temperature increasing and with reduction of inlet cooling water temperature, (ii) the condensation temperature is inversely proportional with COP and SCP for single and double stages ATB, (iii) both SCP and COP are increased when the heat source is a relatively high temperature; (iv) operating cycle time is important to achieve the optimal system performance, where the COP increases with cycle time increasing for particular limits. (iv) novel adsorbent materials such as MOF can significantly improve the ATB performance, (v) enhancement in cooling capacity of the ATB can be achieved under high flow rates of hot and cold water, (vi) improving the adsorbent thermal conductivity can enhance the performance. This review can assist in selecting the ATB for future research works with improved COP and reduced cost when this system is driven by waste heat or solar energy.
Keywords: Adsorption thermophysical battery; performance; working pairs; thermal energy storage; structures; operating conditions.

1. Introduction

In the last years, international energy demand increased by approximately 2.3% because of progress in a range of 3.7% in the powerful global economy. Some countries such as the United States, China, and India together represent customers of about 70% of the total energy demand, and most of this energy is consumed in cooling and heating applications [1]. Moreover, a rise in fossil fuel consumption, global energy-related carbon dioxide productions raised an estimated 1.7% through one year [2]. Heating requesting makes up the widely popular, although thermal energy demand for cooling is increasing rapidly [3][4]. Consumption of energy for cooling and heating remains heavily based on fossil fuels approximately 40% of total energy associated CO2 emissions [5]. Thermal energy demanding for cooling has developed more rapidly than any other end custom in buildings [6]. Therefore, environmental wrongs such as ozone depletion, global warming, and growing energy costs can be mitigated by the employ of low-temperature heat sources to provide a cooling effect for air conditioning application. As of the middle 2019, cooling and heating accounted for about 51% of final energy custom, transport for 32%, and electricity demand for around 17%. The building’s energy demand for air-conditioning application has increased from 1.7 GWh in 1990 to 44 GWh in 2010 [7]. The technology that uses low-temperature heat sources is absorption and adsorption systems [8][9][10][11].

The first advantage of ATB is an operation with a thermal heat source and particularly waste heat. Adsorption systems utilize the wasting heat energy of solar energy, hot exhaust gas and geothermal energy to produce a cooling effect without risky environmental influence, with low-temperature source (60°C to 120°C) [12][13]. Indian government building used the solar adsorption system with a cooling capacity equal to 528 kW. As well as in 2018, Fahrenheit successfully installed 7 new sorption cooling systems (ATB) in numerous countries, including Germany, Austria, Netherlands, Spain and Saudi Arabia [1]. The second benefit of adsorption is significant for many applications such as thermal batteries, dehumidification, and delivery of drinking water. The third advantage of this system does not contain the moving part except some valves only which reduces the maintenance costs, additionally the most adsorption system used environmentally friendly materials. Heating and cooling system are attained upon adsorption and desorption of water from adsorbent materials such as silica gel, zeolite, and metal organic frameworks (MOFs). The surveyed statistics showed that many adsorption pairs have been recycled in adsorption systems such as Zeolit-water and silica gel-water are the most working adsorption pairs in adsorption cooling systems [14]. The importance effect in the adsorption system is energy density which is defined as the amount of energy stored in a given system or region of space per unit volume or per unit
mass. It can be calculated based on mass or volume, depending on which measure makes the most sense for each situation. For example, the energy density of the AA/13X zeolite adsorbent and water is 160 kWh m\(^{-3}\) [15]. The most successful adsorbents informed in the survey for energy storage which provides energy densities ranging from 226 to 309 kWh m\(^{-3}\) for water adsorption [16]. For these reasons, improving their performance, reducing the cost of adsorption components system, developing typical adsorption systems for structure and process, and increasing sensibility can all benefit to make ATB more economical compared to other refrigeration systems. The purpose of this paper is to review recent research into the ATB. This research reviews some important strategies and methods required to improve the coefficient of performance, specific cooling capacity and energy density for adsorption systems. Figure 1 shown the operation principle of ATB.

![Figure 1. Operation principle of ATB.](image)

2. Methods of Improvement the Adsorption Thermophysical Battery

In order to enhance the COP, SCP and ED of adsorption thermophysical Battery, researchers investigated and suggested some methods such as structure and operation, thermal energy storage, novel mechanism and cycle and stages as shown in Figure 2. In the current study, the first three methods for improving the ATB will be reviewed because they are more effective methods with relatively low cost and high performance. The cycle and stages were reviewed in details by literature [17] [18] [19] [20] [21] [22] [23] [24].

3. Structure and Operation

This section includes a discussion about technologies currently available for improving the ATB. The literature was review to examine available methods that could be used to select the suitable ATB based on structure and operation conditions. Here, we discuss the six major areas of relevance to this study. These are explained, together with their advantages and disadvantages of ATB. An overview of the limitations of the different methods is presented.
4. Physical working pairs development

In general, the adsorbent and adsorbate working pairs can be classified into three kinds (physical, chemical and composite adsorbents) based on the forces implicated in the adsorption process. The physical working pairs (PWP) are used in ATB [25], which depend on van der Waal’s forces to surround the adsorbate. Public examples of physical working pairs are, (zeolite, silica gel, MOF-water), (activated carbon-methanol, ethanol, ammonia), (activated carbon fiber-methanol, alcohol, ammonia) and (composite, polymers). This PWP can be measured by two methods specifically, the volumetric and gravimetric methods [26]. The specification of working pairs must be taken at selective physical adsorbent and adsorbate as illustrated in Table 1 [27]. While the important characteristics of the most commonly used adsorption pairs are described in Table 2 [28]. Figure 3. Math between adsorbent and adsorber PWP. Chan [29] studied the performance of the ATB using the composite adsorbent of the zeolite 13X/CaCl2. The results indicated that the COP and SCP were increased by 81% and 34% respectively at utilized composite adsorbent compared to using pure zeolite 13X under the same desorption temperature 75°C. The relation between adsorption capacities of the water with their structural properties of zeolites was studied by Tatlier et al. [30]. It was found that the enhancement in water
adsorption capacities depends on the fractal dimension of zeolite as well as providing a large ratio between surface area and volume. And moreover, the large size of sensitivity and surface asymmetry of zeolites. Sharafian et al. [31] investigated the effects of adsorbent mass on the COP and SCP of a FAMZ02/water. The experimental results indicated that at a cycle time of 20 min and the reduction of the mass of FAM-Z02 from 1.9 to 0.5 kg, the COP reduces by 37% and SCP increases by 82% from 65.8 to 119.4 W kg⁻¹. Due to the need of increasing uptake rate for ATB, Sharafian et al. [32] experimentally investigated novel composite of the adsorbent Silica gel mixed with polyvinylpyrrolidone (0.2–0.69 mm in thickness) to obtain high thermal conductivity (0.26 W m⁻¹K⁻¹) with 78.6% higher than that of dry silica gel. Rouhani et al. [33] demonstrated an improvement for thermal conductivity to FAM-Z02 SC of uniformly size filled bed adsorber. The result shows water uptake is 2.2 times higher than the originality (0.1031 W m⁻¹K⁻¹) compared to (0.0474 W m⁻¹K⁻¹). Sapienza et al. [34] recommended a database that can be used for predicting the performance of ATB based on the water–silica, which enables to reaching of the cooling power equal to 6-8 kW kg⁻¹. Screening of the best working pair used to improve the performance of the ATB by reduction both of absorbent vaporization enthalpy and refrigerant acentric factor due to a low molecular weight ratio between refrigerant and absorbent was done by Chatzitakis and Dawoud [35]. Dzigbor and Chimphango [36] compared COP and SCP by using two refrigerants, the first refrigerant was low-grade ethanol (60% ethanol+ 40% water) and the second was high purity ethanol (99.7%) and paired with 10-35.7% w/v (activated carbon and sodium chloride) composite adsorbents. The experimental results indicted COP and SCP equal to 0.146 and 150 Wkg⁻¹ for the first refrigerant, and equal to 0.091 and 79 Wkg⁻¹ for the second refrigerant. The energy required for the evaporation of refrigerants decreased from 27 to 20 MJ per cycle when matching composite adsorbents with the first refrigerant. The importance conditions in the selection of adsorber materials were crystallinity, binder type, and content, these particular parameters were documented for various zeolite by Kraus et al. [37]. Emrah et al. [38] presented a synthesis of adsorbent materials called MIL-160 (which can be derived from renewable biomass) to be an alternative for silica, increased heat transformation enthalpies and uptake refrigerant. Elsayed et al. [39] synthesized, MIL-101(Cr)/calcium chloride composites to enhance adsorption cooling capacity and water adsorption characteristics. It was found that vapor uptake increased from 0.1 g H₂O g⁻¹ to 0.65 g H₂O g⁻¹ at a relative pressure equal to 0.3. Moreover, improving the performance of ATB must provide high thermal diffusivity. Bauer et al. [40] suggested new zeolite/aluminum composite adsorbents, the results indicated the greatest performance combined with high mechanical stability by measurements of thermal capacities and kinetics for planar samples. Solovyeva et al. [41] examined the Large Temperature Jump technique in the study of water adsorption on adsorbent material NH2-MIL-125 with grains size range 0.2-1.8 mm. This technique depends on the adsorption rate determined by the ratio S m⁻¹ of the heat transfer area to the adsorbent mass regardless of the grain size. The results show that, SCP equal to 0.4 - 2.8 kW kg⁻¹ at (S m⁻¹) of 1.6 to 6.9 m² kg⁻¹ respectively. Pal et al. [42] investigated the synthesis of porous material that qualities high,
surface area, pore volume, and microporous nature. This synthesis consists of activated carbon composite employing graphene nanoplatelets namely, H-grade and C-grade and polyvinyl alcohol. The results compared between thermal conductivity for H-grade and C-grade, the highest thermal conductivity was found equal 1.55 Wm⁻¹K⁻¹ for H-grade (40 wt%). Younes et al. [43] examined synthesis and composite of polymer binders with silica gel powder namely, Polyvinyl pyrrolidone, Polyvinyl alcohol, Hydroxyethylcellulose, and gelatin. The results indicated that the volumetric uptake increased by 12.5% and there was no variation in water uptake between silica gel powder and Polyvinyl pyrrolidone (2 wt%).

Brancato and Frazzica [44] experimentally studied, tested water as a refrigerant with three zeotype materials, namely, FAPO-34, Alpo-18, and SAPO-34. Experimental results show that, maximum COP value was 0.8 at using adsorbent SAPO-34 with water in ATB.

Wang et al. [45] summarized the most important parameters effects on the COP when using silica gel–water in ATB. It was found that the weakness in heat and mass transfer between the working pairs decreasing the COP and SCP, a mixed refrigerant with water can be used in reducing the high vacuum condition determined by water vapor. Zheng et al. [46] experimentally investigated a new composite from combining silica gel with graphite treated and sulfuric acid. The results show a relatively high thermal conductivity (19.1Wm⁻¹K⁻¹) which was more than 270 times as compared to that of unmixed silica gel. Mohammed et al. [47] mixed silica-gel particles in a high-porosity aluminum foam, the results recorded for both COP and SCP were 0.75 and 827W kg⁻¹ respectively. Chan et al. [48] examined the synthesis of zeolite 13X and CaCl2 for applications in ATB. The results were recorded for water uptake at temperature range 25-75°C equal to 0.4 g g⁻¹, with high improvement in COP and SCP from 0.42 – 0.76 and 13.7 – 18.4W kg⁻¹ respectively as compared with pure zeolite 13X. Table 3 summarizes the value of COP, SCP and uptake for PWP. Based on customary PWP can achieve high adsorption capacity, better thermal conductivity as well as high permeability that leads to improved heat and mass transfer in the adsorbent. Useful PWP research could produce novel combined adsorbent or adsorber in order to succeed a higher SCP for ATB.
Table 1. Specification of Physical Adsorbent and Adsorbate.

| Physical adsorbent and adsorbate specification |
|-----------------------------------------------|
| Large change in adsorbate content             |
| High thermal conductivity                     |
| Great latent heat of vaporization             |
| Little specific volume                        |
| Suitable refrigerant evaporating temperature, |
| Nontoxic, nonflammable, noncorrosive, stable  |
| for repeated cycle                            |
| low intra and inter-particle mass transfer    |
| resistances                                   |

Table 2. Important characteristics of some commonly used adsorption pairs [49]

| Properties                             | Zeolite -water | silica gel -water | MOF-water     |
|----------------------------------------|----------------|-------------------|---------------|
| The uptake (kg<sub>ref</sub> kg<sub>ads</sub><sup>-1</sup>) | 0.17           | 0.25              | 0.3-1.4 cm<sup>3</sup> g<sup>-1</sup> |
| Heat of evaporation (kJ kg<sup>-1</sup>)<sub>ref</sub> | 2270           | 2270              | 2270          |
| Iso-steric heat (kJ kg<sup>-1</sup>)     | 3200-4200      | 2500-2800         | 46-48 kJ mol<sup>-1</sup> |
| Specific heat capacity (kJ kg<sup>-1</sup>K<sup>-1</sup>) | 0.2-0.7        | 0.9               | -             |
| Heat conductivity (W m<sup>-1</sup>K<sup>-1</sup>) | 0.15-0.2       | 0.17-0.2          | -             |
| Regeneration temperature °C             | 75-200         | 50-100            | 50-80         |

ref=refrigerant, ads=adsorbent
Table 3. Values of COP, SCP and uptake for some working pairs.

| Adsorbent       | Refrigerant | Uptake (kg_ads kg<sup>-1</sup>_ref) | COP  | SCP W kg<sup>-1</sup> | Reference |
|-----------------|-------------|------------------------------------|------|-----------------------|-----------|
| Zeolite 13x     | water       | 0.4                                | -    | 0.25                  | [50]      |
| Active carbon   | methanol    | 0.45                               | -    | -                     | [51]      |
| Silica gel      | water       | 0.3                                | 0.53 | 176                   | [52]      |
| Active carbon   | Ammonia     | -                                  | 0.43 | 104                   | [53]      |
| Silica gel      | water       | 0.3                                | 0.25 | 7                     | [54]      |
| Active carbon   | methanol    | 0.25                               | 0.385| -                     | [55]      |
| Active carbon   | methanol    | 0.2565                             | -    | -                     | [56]      |
| Silica gel      | water       | 0.3                                | 0.3  | 198.4                 | [57]      |
| MIL-101-3       | ethanol     | 0.74                               | -    | 283                   | [58]      |
| zeolite13X/CaCl<sub>2</sub> | water       | 0.5                                | -    | 1113.4                | [59]      |
| MIL-101-3       | water       | 0.95                               | -    | -                     | [60]      |
| MIL-101(Cr)     | water       | 0.45                               | -    | -                     | [61]      |

4.1 Novel adsorbent porous materials (MOF)

In this section new adsorbent materials, metal organic framework (MOFs) with high importance specifications will be discussed. The ratio of adsorbate refrigerant (gram)/ adsorbent material (kilogram) over cycle time or the cycle COP, is very small compared to the total capacity of ATB. New adsorbent materials (MOF) are generated from metal ions, clusters bridging with organic linkers [62], have great promising adsorbents to change the currently used adsorbent materials. The MOF properties are shown in Table 4 [63][64][65]. Additionally, the applications of MOF including heat storage, heating and cooling, power generation, water desalination and desiccant [66][67]. Also, the MOF-801 can be used in the separation of CO2 gas by mixed with polyether-block-amide [49][68]. Furukawa et al. [69] [70] studied and examined the adsorption capacity of water with 23 type materials of MOF. The results show that MOF-801-P and MOF-841 have the highest performance parameters, uptake water and surface area as illustrated in Table 5. Also, the Solovyeva et al. [71] [72] prepared and tested the working pairs, water-MOF and MIL-101(Cr)–methanol for ATB. It was found that at the evaporation temperature 5°C, adsorption temperature 30 °C and regenerated temperature in rang 80–85°C, the uptake water and SCP values were 0.21 g g<sup>-1</sup> and 2 kW kg<sup>-1</sup> respectively at S m<sup>-1</sup> ratio equal to 6 m<sup>2</sup>kg<sup>-1</sup>. Lenzen et al. [73] evaluated the water adsorption capacity of nanoscale Aluminum hydroxide isophthalate MOF (CAU-23) at cycling stability of 5000 cycles, pressure ratio P<sub>P0</sub>= 0.3 and driving temperature 60 °C. It was found that water adsorption capacity (0.37 g<sub>H2O</sub> g<sup>-1</sup> CAU-23) is related to unique crystal structure properties of nanoscale MOF. Kim et al.[74] suggested two experiments technique for estimating the enthalpy as a function of both temperature and uptake for MOF-801 and zeolites with water by using the thermogravimetric analyzer and differential scanning calorimetry. The results indicated that enthalpies of MOF-801 are approximately constant for a varied range of vapor uptakes, while the zeolites can be increased to greater than two times the latent heat (latent heat as a function of temperature 30 °C and 100 °C for MOF-801 and 30 °C, 100 °C, and 200 °C for zeolites). Cui et al. [75] investigated, using coated heat exchangers with MOF-MIL-100(Fe) for removing both latent and sensible heat loads. The power
density of $82 \, \text{W} \, \text{L}^{-1}$ for the working cycle with a temperature difference between the evaporator and the condenser lower than 30 °C. Teo et al. [76] prepared and tested three modules of formic acid modulated-aluminum fumarate MOF with 5 ml, 10 ml, and 15 ml. It was found that the particles extending with add up of formic acid and the mixture period is reduced. Water adsorption of MOF was improved by 12.5% as compared with the original aluminum fumarate at the addition of 10 ml formic acid. Wöllner et al. [77] tested the adsorption water from MOF using calorimetry broadband IR-detection of the released heat of adsorption at a given relative humidity. This method allows for describing small amounts of materials for usage in water adsorption applications and hence to accelerate research and development processes. Jiang et al. [78] compared using MOF-801 and Zeolite 13X in ATB for heating applications. The results indicated that the COP at a regeneration temperature of 76 °C was 1.6 for MOF-801 and 1.5 for Zeolite 13X with a regeneration temperature of 120 °C. Jun An et al. [79] successfully improved the water adsorption for both isotherms and dynamic water adsorption/desorption by using MOF like UiO-66 and MIL-125 and reformed to introduce aminoterephthalic acid groups ($–\text{NH}_2$ and $–\text{NH}_3^+\text{Cl}^-$). Xia et al. [67] reported the effect of structure-property for MOF materials such as, Zr-MOFs, UiO-66, UiO-67 and NU-1000 with water and ethanol refrigerants. It was found that UiO-66/water with small pores gives high COP and SCP, while NU-1000 with large pores and ethanol gives greater uptake ethanol but low COP and SCP.

**Table 4. Summary of MOF specifications. [63-65]**

| Specifications of MOF                                                                 |
|--------------------------------------------------------------------------------------|
| High potential for heat and mass transfer due to their high ability to adsorb the molecules. |
| Thermal stability                                                                     |
| Non-restricted water uptake at high value of the relative pressure                    |
| Great energy storage for heating, cooling applications.                              |
| Easy of synthesis and selectivity of the adsorption process.                         |
| Ultra-high porosity and boundless chemical tenability                                 |
| High thermal conductivity for some MOF such as UiO-66, UiO-67 and Cu-BTC, are 0.11 W m$^{-1}$K$^{-1}$, 0.19 W m$^{-1}$K$^{-1}$, and 0.39 W m$^{-1}$K$^{-1}$. [80] |

**Table 5. Surface area and uptake water for some types of MOF. [69-70]**

| material | surface area, m$^2$ g$^{-1}$ | water uptake, cm$^3$ g$^{-1}$ |
|----------|-----------------------------|--------------------------------|
|          | $P_{P_0} = 0.1$         | $P_{P_0} = 0.3$ | $P_{P_0} = 0.9$ |
| MOF-801-P | 1070                        | 280                | 380                | 450            |
| MOF-801-SC | 770                        | 170                | 270                | 350            |
| MOF-802   | < 20                       | 35                 | 70                 | 110            |
| UiO-66    | 1390                       | 20                 | 125                | 535            |
| MOF-808   | 2390                       | 55                 | 160                | 735            |
| MOF-841   | 1540                       | 10                 | 550                | 640            |
| DUT-67    | 1720                       | 100                | 390                | 625            |
| PIZOF-2   | 2490                       | 4                  | 7                  | 850            |
| MOF-804   | 1260                       | 160                | 235                | 290            |
| MOF-805   | 1370                       | 25                 | 160                | 415            |
| MOF-806   | 2390                       | 30                 | 60                 | 425            |
5. Heat exchanger improvement

5.1 Development of adsorber bed

Many researchers investigated using an efficient adsorption bed to improve the performance of ATB [81][82]. For example, Sharafian and Bahrami [83] summarized the adsorption bed geometry types as illustrated in Table 6. The relationship between the honeycomb geometry adsorption bed and the performance of ATB (silica gel-water) was investigated by Shi et al. [84]. The results indicated that water uptake decreased with the cell height of honeycomb increasing, as well as increasing the Reynolds number above 5000 has no important effect on the water uptake. The common specifications of adsorber bed such as lightweight, cost, area and volume, and thermal conductivity considered a good choice for adsorber bed in ATB applications. Zhu et al. [57] compared and examined four types of adsorption beds to evaluate the performance of ATB working with Silica gel-water. The results indicated that the smaller bed size had a positive effect on improving SCP, and the smaller bed geometry has a higher SCP and COP, 198.4 W kg\(^{-1}\) and 0.30 respectively. Sharafian et al. [85] demonstrated an improvement on COP and SCP for ATB by design adsorber bed working with AQSOA FAM-Z02 and water. The tested parameters COP and SCP were 0.34 and 112.9 W kg\(^{-1}\) respectively at time cycle 10min, adsorption temperatures 30°C, desorption temperatures 90 °C and supplied water vapor at 20 °C.

The heat transfer surface area was strongly depends on the main specifications of the calculated adsorber bed. Pan et al. [86] experimentally studied the adsorber bed design working at silica gel/water and under cycle time 720, 40 and 24 sec respectively to estimate the COP and SCP. The results have shown a rise of 0.51 and 125.0 W kg\(^{-1}\) in COP and SCP respectively under characteristic conditions of inlet hot water 86°C, inlet cooling water 30°C and the outlet chilled water temperatures 11°C. Mohammed et al. [87] analytically evaluated the performance of ATB by a new bed arrangement consists of two layers of packed beads separated by vapor p. The results showed that enhancing the bed thermal conductivity can lead to improving SCP at reducing of adsorbent bed thickness and particle diameter. Reaching the maximum performance of ATB will require determining the thermal and geometrical parameters of a flat tube fin adsorber bed as analyzed by Verde et al. [88]. The results showed that SCP increased with a reduction in tube thickness and fin pitch in the flat tube as well as to reduce the channel pitch with improvement in specific thermal conductance by 2.5%. Schaefer and Thess [89] numerically examined honeycomb adsorber bed working with Zeolite 13X/water. The results show that the internal and external mass transfer resistance inversely depends on the channel size and also it was found that, the thermal power can depend on the inlet pressure. Bahrehmand and Bahrami [90] analytically studied the effect of ATB performance with adsorber bed geometric and cycle time. It was indicated that the geometrical and heat transfer features of adsorber beds such as fin height and thickness, adsorber thickness, refrigerant channel height and cycle time, have counteraction effects on SCP and
COP. Improving or developing adsorber bed modules was applying by previous research for innovative ATB is attractive to make system with flexible capacity for heating or cooling applications.

Table 6. Types of adsorber bed geometry. [83]

| Adsorber bed geometry                           | COP  | SCP  | Working pair                      |
|------------------------------------------------|------|------|-----------------------------------|
| Multi tube copper hairpin, 3*118kg              | 0.65 | 23   | Zeolite/water,                    |
| Aluminum finned tube,4.6kgga                    | 0.061| 33   | Consolidated act. carbon/ ammonia |
| Stainless steel Finned tube                     | -    | 30   | Silica gel/methanol               |
| Stainless steel cylindrical finned tube,31kg    | 0.38 | 22.8 | Zeolite 13X/water                 |
| Finned tube, 260 kg                             | 0.25 | 28.5 | Zeolite 13X/water                 |
| Stainless steel finned tube, 3.3 kg             | 0.43 | 23.5 | Silica gelZCaCl2(SWS-1L)/ water   |
| Two Aluminum finned tube,15kg/bed               | 0.27 | 131.5| AQS0A-FAM-Z02/water              |
| Two Finned tube, 32.7 kg/bed                    | 0.43 | 48   | Silica gel/water                  |
| Stainless steel Finned tube                     | 0.11 | 25   | Coated hydrophobic Y zeolite (CBV-901)/ methanol |
| 2 Finned tube                                   | 0.29 | 35   | Silica gel/water                  |
| 2 Finned tube                                   | 0.19 | 70.8 | Act. carbon2CaCl2 (1:4)/ ammonia  |
| Aluminum finned tube, 6,08kg                    | 0.15 | 137  | Silica gelZCaCl2(SWS-1L)/ water   |
| Finned tube 2                                   | 0.23 | 43   | Silica gelZCaCl2/water            |
| Aluminum finned tube,13.6kg/bed                 | 0.29 | 158  | Silica gel/water                  |
| Stainless steel 304annulustube, 5.18kg         | 0.28 | 38   | Consolidated graphite zeolite 13X/ water |
| 2 Annullus tube                                 | 0.41 | 97   | Consolidated zeolite/water        |
| 2 spiral plate, 80 kg/bed                       | 0.2  | 2.63 | Act. carbon/methanol              |
| 2 Plate-tube, 90 kg/bed                         | 0.37 | 152  | Act. carbon/ammonia               |
| 2 Shell and tube, 184.8 kg/bed                  | 0.08 | 7.6  | Act. carbon/methanol              |
| 4 Shell and tube, 73kg/bed                      | 0.06 | -    | Act. carbon/ammonia               |
| Plate, 9 kg                                     | 0.22 | 200  | Consolidated act. carbon/ ammonia |
| 2 Plate                                         | 0.33 | 118  | Silica gel/water                  |
| 4 Plate fin, 115kg/bed                          | 0.51 | 57   | Silica gel/water                  |
| 2 Plate fin, 180kg/bed                          | 0.21 | 26.5 | Silica gel/water                  |
| 2 Plate fin, 115kg/bed                          | 0.36 | 132  | Silica gel/water                  |
| Flat tube with corrugated fins,                 | 0.45 | 87.8 | Silica gel/water                  |
| 2 heat exchanger, 129 kg/bed                    | 0.5  | 26   | Silica gel/water                  |

5.2 Evaporator and condenser bed modification

Most of ATB working with evaporation pressure and temperature in range (0.76-2.34kPa) and (3-20°C) respectively. Some authors studied the effects of enhancing the heat transfer from the surface of the evaporator and thermal resistances in the heat flow. Sharafiana and Bahrami [91] investigated the effects of the temperature variation of the evaporator and condenser in the ATB working with zeolite 13X/water. The results showed that increasing evaporation and regeneration temperatures will lead to a rise in COP while increasing condensation temperature has an undesirable effect on COP and entropy generation. Thimmaiah et al.[92][93] compared three tubes with different fin geometries using capillary assisted tubes in the evaporator of ATB, for an acceleration of refrigerant evaporation and enhancement of COP and SCP. The thermal resistance in fin tubes was 89% of the internal convective resistance. As well, Thimmaiah et al. [94] showed that the capillary assisted tubes provide a greater heat transfer rate of about 1.6-2.2 times compared to a plain tube.
5.3 Coated heat exchangers

In order to improve the performance of ATB, the thermal resistance in the adsorbent layers must be reduced. Coated heat exchangers with adsorbent materials such as AlCu5 fibers which are coated with SAPO-34 [95] were the best alternative solution for the enhancement of heat and mass transfer. Kim et al. [96] presented the study to improve heat and mass transfer for ATB by coating heat exchangers with a polymer. It was found that the SCP increased by 13%. Wang et al. [97] examined the effect of the coated heat exchanger with AQSOA employed as adsorber. The results showed that improvement in COP and SCP was 0.37 and 410.625W kg\(^{-1}\) respectively. Grabowska et al. [98] proposed numerical relations by computational fluid dynamics method to determine the essential input parameters of a coated adsorption bed geometry. The results were compatible with Wang results [97]. Seol et al. [99] experimentally studied the coated plates with Wakkanai Siliceous Shale saturated with lithium chloride of 20 wt% with different thicknesses 27 μm, 65 μm, 0.19mm, 0.38mm, and 0.71mm, for separating the effects of interfacial and inner mass transfers from a total mass transfer.

New adsorber design was developed by Engel et al. [100], which is consist of conjoining fin-coating and filling of granules between the fins. The COP of the new design was compared with plain design (without filling of granules) at the conditions of the same parameters. The novel design indicated a higher peak power and a higher performance over a longer cycle time 30min. Tsujiguchi et al. [101] investigated the adsorption-desorption behavior of a fin-tube heat exchanger coated with Zeolite for examinations of heat flow, cycle time and hot water circulation. The results indicated that, increasing water temperature from 50 to 60°C results in improvement in the dehumidification performance. Applying of lumped-parameter model (LPM) method for (1-D) and (2-D) to give information on how many dimensions required for providing accurate results of ATB with a coated tube adsorber was analyzed by Dias and Costa [102]. The results showed that the LPM method was able to predict the COP with minimized deviations from the original model.

6. Solar energy utilization in ATB

The ATB combined within a solar collector is called a solar adsorption thermal system (SATB). Yu et al. [103] and Goyal et al. [104] reviewed utilizing solar energy in the sorption thermal storage and refrigeration technology respectively. The SATB can be classified into intermittent and continuous cycles depending on solar radiation’s daily time and intensity [105]. The intermittent cycle undergoes with the limitation of dis-continuity in cycle time operation (single bed ATB). However, continuous cycles could be achieved with the employment of multi-bed for providing adsorption and desorption cycle. Many authors working on SATB combined with solar energy to reduce collector area and cost, simple designs and to enhance the performance. The SATB performance strongly depends on the solar collector area and size[106]. Omisanya et al. [107] used a concentrating parabolic collector with an area of 1.029m\(^2\), the
concentration ratio of 1.8 and height aperture ratio 1.19 for the production of solar energy. The cylindrical adsorber was constructed with diameter 42mm working with Zeolite 4A/water. The COP recorded was 0.838 at evaporator temperature 11°C and maximum adsorber temperature 110°C. Hasan [108] evaluated the performance of SATB working with silica gel and water. The results indicated that COP, SCP and cooling capacity were 0.402, 1.82 W kg⁻¹ and 363.8 W respectively at solar collector thermal efficiency of 62.96%. The results show as well that, 1 kg of silica gel could produce every day about 3 kg of cooled water at temperature 10 °C. Najeh et al. [109] developed SATB with a solar flat plate collector working with silica gel and water at COP of 0.62. Fadar [110] made variations for solar parabolic through concentrator for enhancement of a continuous SATB. It was found that the number of refrigeration cycles achieved per day was increased. Cherrad et al. [111] [112] used activated carbon AC35-methanol to develop a numerical study of heat transfer inside the adsorber-collector and predicting operating temperatures of SATB. The results indicated that the heating time is a very important factor affecting the amount of energy loss. Chen et al. [113] developed an experimental study to investigate the change of COP with a time of SATB (SAPO-34 zeolite and water). The results indicated that the overlong time of adsorption did not assist in improving the performance of the SATB. The COP and the SCP did not share the same adsorption time for their maximum values. The exergy based performance of SATB was analyzed by Ogueke et al. [114] to improve the exergetic efficiency as well as enhancement of the desorption process. Wang et al. [115] experimentally studied the SATB prototype working with activated carbon-methanol. The experimental results showed that, the system employing an active enhancing mass transfer method increased the mass of desorbed refrigerant by about 20% if compared with a natural desorption refrigeration system. Yaici and Entchev [116] suggested a model for optimal design and performance of SATB working with adsorbents Silica gel and zeolite 13X - water. The results indicated that the heat exchanger tube thickness was relatively unimportant changes in the performance of SATB. Lattieff et al. [117] developed an experimental study for SATB (Silica gel and water) using two solar evacuated tube collectors (4m²) with multi-flow rates of hot water (10, 20, 30, and 40 L min⁻¹). It was found that the best COP and SCP were 0.55 and 39 W kg⁻¹ respectively at evaporator temperature 6.6°C and flow rate 30 L min⁻¹. Table 7 shows the temperature range of common solar collectors [118].

| Solar collectors type | Temperature range |
|-----------------------|-------------------|
| Evacuated tube U-pipe | 60–85 °C          |
| Compounded parabolic concentrating | 85–125 °C         |
| Parabolic trough      | 125–150 °C        |

7. Enhancement of heat and mass transfer by fins

To improve the heat and mass transfer performance for ATB, many authors used a finned-tube heat exchanger for the adsorber bed [119] [120]. Heat transfer enhancement by finned tube adsorber beds has
shown higher COP and SCP with low adsorbent mass ratio. Sharafian et al. [121][122] presented experimental analysis to study the effects of fin pitch on temperature distribution over the finned -tube in the adsorber bed. The experimental results indicated that decreasing the fin pitch from 9.5 to 6.35 mm would reduce 110% from the temperature difference between the fin and adsorbent (silica gel) and reduce the cycle time from 1400 to 600 sec. Golparvar et al. [123] studied the effects of fin height and pitch on the operating parameters to find the optimum fin geometry. The results indicated that the decrease in fin pitch leads to decreasing the COP and an increase in SCP. It was found as well that, the optimum averaged fin spacing was 5.4-6.8 mm for the adsorber beds with 10-20 mm fin heights. Zhao et al.[124] compared between 2-D of the two adsorbent tubes, finned tube, and smooth tube. The results showed that fins had a large effect on COP of ATB, and the radial heat loss of the finned tube was less than that of the smooth tube. Therefore, the fin geometry should be optimized before the design and construction heat exchanger in the adsorber bed for providing high COP and SCP [125].

8. Thermal energy storage and densities with ATB

Thermal energy can be stored as a conversion in the internal energy of physical materials such as sensible heat and latent heat. There are four types of energy storage mechanisms as illustrated in Figure 4 [126][127]. The specific process considered for thermal energy storage is adsorption. Adsorption energy storage systems can be named (thermophysical battery) are capable of providing a high energy density and can work in a continuous cycle to store thermal energy. The limitations of energy storage are due to the low transport characteristics of adsorbent materials used in the thermo-adsorptive battery [128]. The details of thermophysical battery was studied and developed by Kim et al. [129]. He combined the zeolite 13X with the aluminum hydroxide to enhance the transport characteristics and thermal conductivity. The author used four technique methods, surface sorption analyzer, x-ray scattering, thermogravimetric analyzer, and laser flash to determine the adsorption storage capacity. The storage capacity for some working pairs is summarized in Table 8 [130]. Narayanan et al. [131][132] developed a thermal battery accomplished of supplying both heating and cooling for electric vehicles (water- zeolite 13X). The thermal energy storage for ATB is strongly depending on the thermal conductivity of adsorbents of pure zeolite 13X which is about 0.1W m\(^{-1}\)K\(^{-1}\). A lower thermal conductivity can lead to limitations in the performance. The porosity of the bed must below to get a higher thermal storage capacity. Enhancement in the porosity in the range 50% will reduce the cooling rate by 30%. Lefebvre et al. [133] developed a study for the prediction of thermal energy storage for ATB. It was found that the best thermal energy performance was at operating conditions, flow rate 24 L min\(^{-1}\) (water- zeolite 13X), column diameter ratio 1.4 and a void fraction 0.4, column diameter to particle diameter ratio 14.7 and column volume 6.275 × 10\(^{-5}\) m\(^3\). Narayanan et al.[134] examined the thermophysical battery in detail to detect important parameters governing the performance of ATB working with NaX-zeolite and water. It was found that cooling and heating powers were 650W and 900W respectively. Power densities and specific powers
observed were 103 W L⁻¹ and 65 W kg⁻¹ for heating, and 78 W L⁻¹ and 49 W kg⁻¹ for cooling respectively. The Palomba et al. [135] experimentally studied the scale heat storage capacity for three types of the adsorbent materials, Mitsubishi AQSOA FAM-Z02, silica gel, and composite LiCl/silica. For the silica gel and FAM Z02, the maximum heat storage was 450 kJ kg⁻¹ at the evaporation temperature of 25°C. Table 9 shows a summary of the energy densities in the variety of 86-309 kWh m⁻³ for water adsorption under various adsorbents [136].

On the other hand, research stays to be executed to improve the steadiness of the salt addition to the adsorbent material for repeated regular long-term uses with high energy densities.

Table 8. Storage capacity for some PWP. [130]

| Refrigerant | Adsorbent | Heating temperature | Storage capacity (Wh kg⁻¹) |
|-------------|-----------|---------------------|---------------------------|
| water       | Zeolite 4A| 80, 90, 120         | 3, 8, 10                  |
| water       | Silica gel| 80 °C               | 4                         |
| water       | NaI       | 120 °C              | 122                       |
| water       | K₂CO₃     | 120 °C              | 125                       |
| water       | LiCl      | 120 °C              | 180                       |
| water       | MgCl₂     | 120 °C              | 220                       |
| water       | CaCl₂     | 120 °C              | 260                       |
| water       | NaOH      | 120 °C              | 265                       |
| water       | Na₂S      | 120 °C              | 360                       |
| water       | LiBr      | 80, 90 °C           | 55, 85                    |
| water       | H₂SO₄     | 80, 90 °C           | 50, 80                    |

Table 9 Summary of energy densities for water adsorption for various adsorbents. [136]

| Adsorbent                                                                 | Energy Density (kWh m⁻³) |
|--------------------------------------------------------------------------|--------------------------|
| Hybrid of zeolite 13X and AA impregnated with LiCl                          | 309                      |
| Silica gel impregnated with CaCl2                                         | 228                      |
| Activated alumina with high alkaline addition                              | 226                      |
| AA/13X (activated alumina and zeolite 13X hybrid)                         | 200                      |
| Zeolite 13X                                                               | 180                      |
| AS/CaCl2 (Impregnated aluminosilicate)                                    | 172                      |
9. Other improvement strategies/simulation and modeling

Many researchers performed simulation and modeling studies to examine the operating parameters (temperature and pressure for adsorbent and adsorbate, heat exchanging design and materials, fins and tubes, adsorber geometry, working pairs, thermal conductivity, density, cycle time, evaporator and condenser design) and to evaluate COP, SCP and cooling capacity for ATB. Several methods were used to analyse the system such as CFD, lump-parameter model, transient analysis, instantaneous equilibrium and linear driving force [137-139].

A mathematical model was developed by Verde et al. [139] to simulate the dynamic behavior and improve the performance of ATB (silica gel-water) driven by waste heat source with temperature range 80-90°C and cooling temperature at 33°C. The heat recovery system was found to have a significant effect on the chiller’s COP, and a slight effect on the cooling power. Solmus et al. [140] numerically studied internal and external mass transfer resistances using a transient 2-D non-equilibrium model working with silica gel-water. Two important parameters, transient temperature, and thickness of the adsorbent bed were simulated to find the effect of the adsorbent bed thickness on transient distributions of the solid phase temperature and adsorbate concentration. Two simulation methods based on the lumped parameter approach and computational fluid technique were used to analyse the adsorption process (silica gel-water) [141]. The results showed that decreasing of fin pitch can increase the water uptake by up to 8%, and there were deviations in water uptake, bed temperature and water outlet temperature in the range of 8.2%, 0.9%, and 0.2% respectively. Narayanan et al [142] develop a computational model to optimize both intermittent and continuously operating of ATB (zeolite 13X-water). The scaling analysis has been identified to determine the geometry of the optimum parameters of the adsorbent particles. Santori and Santis [143] used trial and error methods for the optimization of working pairs for 258 refrigerants on 16 adsorption materials. The results reflected a high performance of ATB can be achieved depending on the critical temperature of the refrigerant and thermodynamic properties. Gao et al. [144] investigated the heat and mass transfer in the adsorption process (silica gel-water) using 2-D numerical simulation. At cycle time 400 sec, the bed temperature and heat generation were significantly increased.
Mohammed et al. [138] used to scale and numerical analyses of heat and mass transfer processes in ATB, and the results showed that the best ratio between the particle diameter to adsorbent layer thickness was less 0.1.

Many studies used Clausius-Clayperon equation for calculation of isosteric heat of adsorption with two assumptions, perfect gas and negligible adsorbed phase volume. Azahar et al. [145] developed a thermodynamic model based on new conditions, non-ideal gas and there is a change in the adsorbed phase density. A reduction in COP by 13% and higher rate of isosteric heat 3.8% to 8.6% were achieved at these assumptions. Mohammed et al. [147,148] suggested two numerical methods, the first coupled heat and mass transfer, and the second lumped parameter to find SCP and optimal cycle time for ATB (silica gel-water). The results show that, at the negligible effect of the evaporator pressure drop, the SCP value obtained from the first method was higher at comparative experiment results, and the cycle time can be optimized by using the second method. Pártl and Mikyška [148] proposed a mathematical and numerical model for non-isothermal compositional style compressible humid air flow in a zeolite bed. The results show that, the sizes of the time steps must be well selected due to the changes in the adsorption effects. Vivekh et al. [149] demonstrated a new mathematical model to simulate the heat and mass transfer process in the coated heat exchanger (silica gel and composite polymer). The performance enhancement in the moisture removal capacity was 7% and 40% for tube fin and annular fin shapes respectively. Elsheniti et al. [150] developed a numerical model of a two-bed ATB to study the relationship between overall performance and operating parameters. The COP and SCP were increased by 68% and 42% respectively at the cycle time of 840 sec when the heat transfer fluid flow changed from the laminar to the turbulent flow. Dishing Lu [151] successfully built a combined adsorption system driven by 80–95°C of the solar hot water. The cooling exergy efficiency in refrigeration, air conditioning, and heat pump heating were about 0.13, 0.18 and 0.24 respectively. Duong et al. [152] conducted a numerical analysis to determine the system performance of an adsorption cooling chiller composed of multi modules in a serial and parallel arrangement. The highest COP and SCP were 0.47 and 295.19 W kg⁻¹ respectively. Papakokkino et al. [153] presented a 3-D simulation model of five reactor geometries and a comparison between copper and aluminum heat exchanger materials for improving the design of ATB was conducted. The maximum value of SCP was for the highest solid volume fraction and for the lowest fin thickness and length. A simulation model based on the conditions, the flow rate of 21 m³ hr⁻¹, bed volume of 5.09×10⁻⁴ m³ and regeneration temperature of 95 °C and solved using COMSOL Multi-physics software was developed by Helaly et al. [154]. The results described the effects of increasing relative humidity with storage density. Schaefer and Thess [155] studied the effects of change in the configuration of adsorbent zeolite 13X (powder, granules, honeycomb). The results show that, the limitations by inter and intra-particle mass transfer resistances. The discharging degree depends on the discharging conditions and it decreases with increase in discharging temperature and heat transfer fluid volume flow rate. Yeung and Sumathy [156] suggested thermodynamic analysis for ATB combined from heating and cooling cycle
(activated carbon fiber and methanol) with heat supplied from an evacuated vacuum tube collector (2 m²). The value of COP was 0.56 based on theoretical results. Sharafian and Bahrami [157] analysed the thermodynamic cycle of ATB used in the vehicle’s air conditioning applications to produce 2 kW cooling power depending on exhaust heat. It was found that the engine coolant cannot supply enough heat for the desorption process under different operating conditions. Jiang et al. [158] investigated the thermodynamic limits of the ATB using non-ideal adsorbents with more and fewer steps such as (MOF 801 and Zeolite 13X). The COP was 1.6 and 1.5 for MOF 801 and Zeolite 13X respectively with a regeneration temperature of 76 °C and 120°C.

10. Conclusion

Though many different ATB have been studied, some of these advanced systems demonstration promise, and they should be considered so that the weaknesses that avoid them from employed can be corrected. Decreasing the cost of the ATB by developing low cost adsorbent material, eco-friendly refrigerant, and higher COP adsorber bed are still important research area. From the reviewed literature, the available improving methods of the adsorption thermal systems can be concluded as follows:

Working pairs:
(i) The important factors affecting the enhancement of water adsorption capacity are fractal dimension and adsorbent material properties.
(ii) Both COP and SCP can be improved by utilizing some composite adsorbents such as Silica gel mixed with polyvinylpyrroledone and zeolite 13X mixed with CaCl2.
(iii) High thermal conductivity and diffusivity of the adsorbent have significant effects on improving the ATB performance.
(iv) To provide the best performance of ATB, the absorbent vaporization enthalpy and refrigerant acentric factor must be minimized.
(v) The energy required for refrigerant evaporation can be decreased by change the refrigerant concentration.
(vi) Low heat and mass transfer between adsorbent and refrigerant can significantly reduce the values of COP and SCP.

Adsorption and desorption in MOF
(i) The range of uptake water for MOF with different pressure ratios (0.1-0.9) was about (4-850 cm³ g⁻¹).
(ii) The enthalpy of MOF-801 is approximately constant for various ranges of vapor uptake.
(iii) The MOF-Uio-66/water with small pores volume can provide high COP and SCP.

Adsorber bed and heat exchanger
(i) The common specifications of adsorber bed such as lightweight, cost, area and volume, and thermal conductivity are considered a good choices for adsorber bed in ATB applications.
(ii) Smaller dead volume has a positive effect on improving SCP, and the smaller bed geometry has a higher SCP and COP.
(iii) Enhancing the bed thermal conductivity can lead to improving SCP by reducing the adsorbent bed thickness and particle diameter.
(iv) The adsorber bed geometry such as fin height, thickness, refrigerant channel height and cycle time, have importance influence effects on SCP and COP.
(v) Increasing evaporation temperature will provide a high COP, while the increase in condensation temperature has an undesirable effect on COP and entropy generation.
(vi) Using capillary assisted tubes in the evaporator can provide a greater heat transfer rate between refrigerant and adsorbent.
(vii) Utilizing coated heat exchangers with adsorbent layers will improve COP and SCP.

**Solar energy as a heat source**
(i) The SATB performance strongly depends on the solar collector area and size.
(ii) The heating time is a very important factor affecting on amount of energy loss, while the overlong time of adsorption does not influence on the performance of the SATB.

**Fins area**
(i) The decrease in fin pitch leads to a reduction in COP and an enhancement in SCP.
(ii) The fin spacing in the heat exchanger must be increased to accelerate the heat and mass transfer between the refrigerant and adsorbent.

**Thermal energy storage**
(i) The storage capacity is depending on the rise in heating temperature.
(ii) The thermal energy storage for ATB is depended on the thermal conductivity of adsorbents.

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