*Review Article*

# Adsorption heat storage: state of the art and future perspectives

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**Abstract:** Thermal energy storage (TES) is a key technology to enhance the efficiency of energy systems as well as to increase the share of renewable energies. In this context, the present paper reports a literature review of the recent advancement in the field of adsorption TES systems. After a first introduction about different heat storage technologies, the adsorption TES working principle is explained and compared to the other technologies. Subsequently, promising features and critical issues at material, component and system levels are deeply analyzed and the ongoing activities to make this technology ready for marketing are introduced.

**Keywords:** adsorption, heat storage, thermo-chemical, zeolite, silica gel, adsorbent materials.

## 1. Introduction

One of the key technologies for boosting the diffusion of renewable energies and for developing efficient energy systems is the Thermal Energy Storage (TES). Indeed, the employment of TES can allow to overcome the existing mismatch between energy production and demand for intermittent energy sources (e.g. solar thermal) and/or variable loads (e.g. thermal energy demand in buildings). It is therefore evident that this component is gaining a crucial role in the development of highly efficient thermal energy systems [1]. The three main technologies for thermal energy storage are (Figure 1): sensible, latent and thermo-chemical heat storage.

For sensible heat storage, thermal energy is stored as a function of temperature difference only and the amount of stored energy depends on the specific heat and on the temperature difference between charge and discharge phase. The heat storage media can be either liquid or solid. The most common example of sensible heat storage media is water. Indeed, it represents the typical media employed for heat storage at temperature below 100°C, since it couples its abundancy, cost effectiveness and not polluting features to good thermodynamic characteristics, such as the high specific heat and good heat transfer efficiency in the operating ranges. Nevertheless, its working temperature range is limited between 0 and 100°C, and it presents corrosive behavior.

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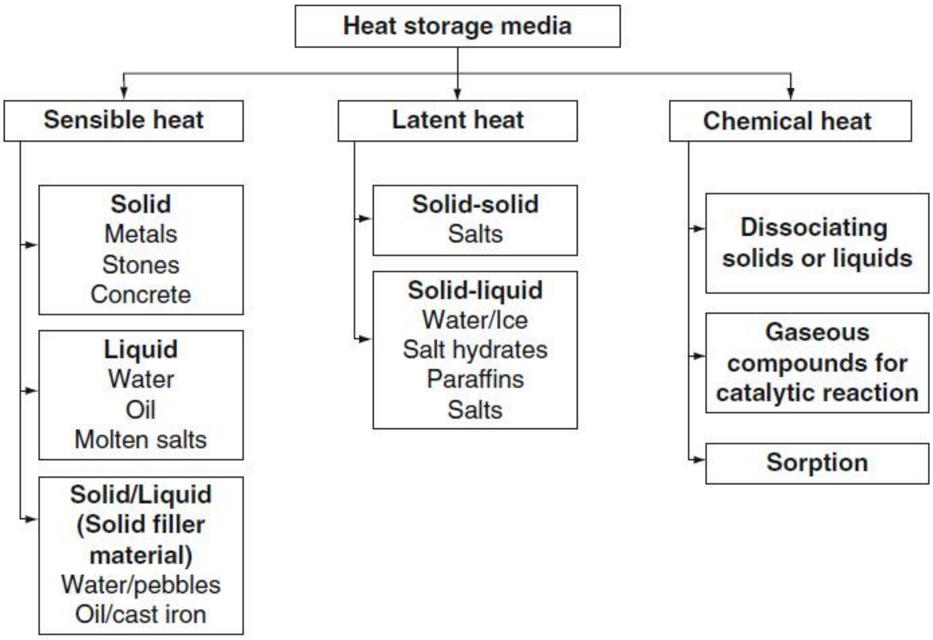

**Figure 1**. Thermal energy storage technologies [5].

Main advantages of sensible heat storages are related to the simple design, cost effectiveness and wide temperature range of applications. Nevertheless, they are characterized by low heat storage density and degradation of energy stored due to heat dissipation through the environment. This means that they cannot be efficiently used for medium/long-term periods [2].

In the latent heat technology storage, thermal energy is mainly stored exploiting the latent heat of phase transition of the heat storage media. The phase change can involve either a solid/liquid transition (i.e. melting /solidification process) or a solid/solid transition (i.e. transition from a crystal structure to another one). The most common class of materials employed as latent heat storage media are: salts, water, hydrated salts and paraffins, which usually undergo a solid/liquid transition. The advantages of such a technology are higher heat storage density if compared to sensible systems, possibility to store energy in a narrow temperature range, possibility to employ the phase transition to smooth temperature fluctuations (e.g. in building envelope applications). Main disadvantages are related to the slow kinetic of phase transition, which limits charging/discharging power, instability of materials undergoing several melting/solidification processes, presence of a volume variation passing from solid to liquid phase, which needs to be carefully taken into account during design process. Furthermore, also latent heat storage suffers of heat dissipation through the environment, which limits its application for long-term heat storage [3].

The thermo-chemical technology is based on the reversible reaction occurring between two components and it is associated with high amount of energy. These reactions can be either chemical or physical. Main limits are related to the very slow reaction kinetics, due to the high energy associated to the process as well as to the heat and mass transfer diffusion resistance within the material. Physical reaction are typical of sorption applications, where a refrigerant (e.g. water, ammonia) reacts with a sorbent, which can be either liquid (absorption systems), or solid (adsorption systems). Since this technology is based on physical reaction, it generally needs lower charging temperatures (i.e. 70-150°C) and is characterized by lower reaction enthalpies if compared to the chemical reactions. Accordingly, they are characterized by faster kinetics but lower heat storage densities [4].

The present paper will focus on the analysis of the state of the art and the future perspectives of the adsorption heat storage systems, mainly for domestic and tertiary sectors.

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## 2. Principles of adsorption heat storage

Adsorption heat storage belongs to the wider class of thermo-chemical heat storage. The principle on which this technology is based is the interaction between a liquid sorbate, usually water, and a solid sorbent (e.g. zeolites, silica gels, activated carbons). This interaction occurs between the sorbate molecules and the available surface of the solid, as represented in Figure 2.

In order to explain the working principle of an adsorption heat storage, it is necessary to distinguish between direct and indirect heat storage methodologies [6]. The direct heat storage, as represented in Figure 3, is the typical technology employed to store heat in sensible and latent form.

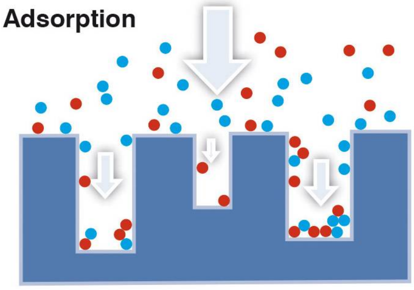

**Figure 2.** Adsorption of refrigerant over the external surface of an adsorbent solid material (courtesy of Klingenburg GmbH).

In this case, there is a coupled heat and entropy flux from the heat source to the storage, at temperature T. Accordingly, since heat and entropy are closely related, Q = T-S, this means that the heat storage capacity depends on the temperature level and on the entropy content. Due to the temperature difference between TES (either hot or cold storage) and ambient, there is a continuous loss of heat storage capacity during time, due to the reduction of the ΔT between stored heat and ambient. Accordingly, it may happen that below certain levels of ΔT, the stored heat is not anymore useful for practical applications (e.g. domestic hot water, space heating).

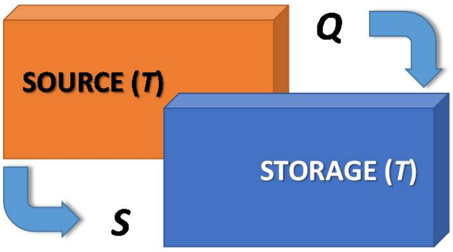

**Figure 3.** Direct heat storage, charging phase.

On the contrary, an indirect TES, as represented in Figure 4 for the charging process, can overcome this limitation, converting heat into a different form of energy (e.g. mechanical, chemical), which is stored without any limitation (i.e. no heat losses to the ambient). Since this technology is based on an energy conversion process, the converter needs to be connected to an external sink (e.g. ambient) to which the produced waste heat and entropy, due to irreversibility, must be dissipated. The reverse phenomena, which exploits heat and entropy flux from the ambient to convert again the stored energy in useful heat, represents the discharging phase. It is therefore evident that this technology needs to be connected to two different source/sink, which makes the TES an indirect process, like a heat pump.

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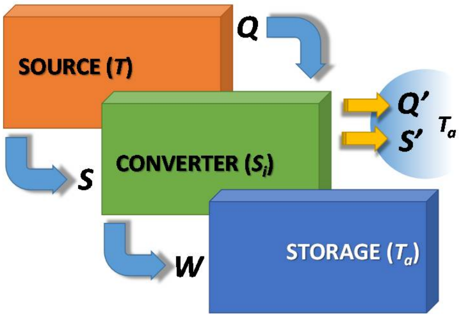

**Figure 4.** Indirect heat storage, charging phase.

Adsorption heat storages belong to the indirect TES class. Indeed, in this case, heat is employed to drive a desorption process, which means that energy is stored in the form of adsorption potential energy. Actually, heat is stored without any loss until the refrigerant fluid (adsorbate) is kept separated from the adsorbent.

Generally, there are two system configurations for adsorption TES: closed and open cycle.

Figure 5 reports the working phases of a closed adsorption TES. During the charging phase (Figure 5 a), the adsorber, in which the adsorbent material is saturated of adsorbate, is regenerated exploiting heat coming from the heat source, $Q_{des}$. The desorbed vapour is then condensed in the condenser, and the heat of condensation, $Q_{cond}$, is either dissipated in the ambient or delivered to the load, if the temperature level is adequate. Once the charging process is completed and the adsorbent material is dry, the connection between condenser and adsorber is closed. In this condition, the system can keep the stored energy for indefinite time, since the thermal energy is stored as adsorption potential between adsorbate and adsorbent material. To recover the stored thermal energy (Figure 5 b), the connection between liquid adsorbate reservoir, which in this phase acts as evaporator, and adsorber is again opened. During this discharging phase, the adsorbate is evaporated adsorbing heat from the ambient, $Q_{evap}$, then the vapour fluxes to the adsorber, since the adsorption process is exothermic, heat is released to the load, $Q_{ads}$.

Clearly, this process is defined closed since the adsorbate is continuously condensed/evaporated in a closed system without any mass exchange with the ambient.

Differently, the open adsorption TES system, represented in Figure 6, continuously exchanges mass (adsorbate) with the ambient. Actually, the two charging/discharging phases are similar to the ones already described for the closed cycle. Main difference is that, in this case, heat is provided and extracted by fluxing air through the adsorbent bed. Particularly, during charging/desorption phase, a hot and dry air flux enters the storage, causing the desorption of adsorbed water, and exiting at lower temperature and higher humidity content.

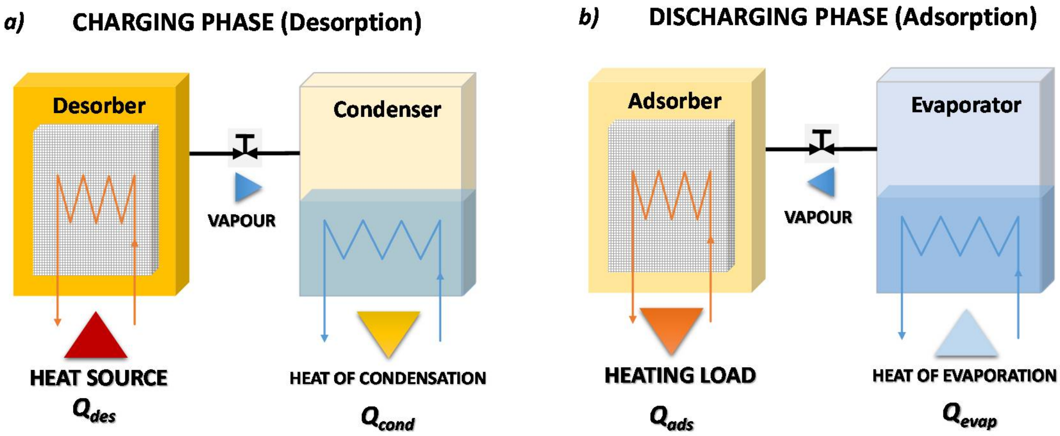

**Figure 5.** Closed adsorption heat storage cycle: a) charging phase; b) discharging phase.

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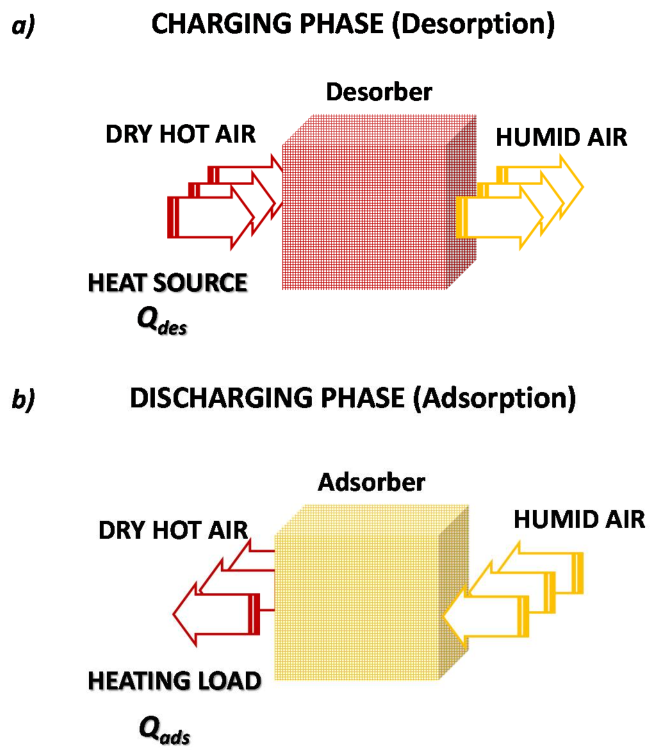

**Figure 6.** Open adsorption heat storage cycle: a) charging phase; b) discharging phase.

During discharging/adsorption phase, the humid and cooled air flux is provided to the dry adsorbent, which triggers the adsorption and the consequent release of stored heat, which reflects on the exiting hot and dry air flux. Some clear differences must be highlighted between closed and open adsorption TES.

- Open adsorption TES can employ only water as adsorbate, since they exploit the moisture of the ambient air as working fluid. On the contrary, closed adsorption TES can use different adsorbate, even if the most widely employed is water, thanks to its high latent heat as well as its reduced environmental impact.
- Open adsorption TES strongly depends on the external ambient conditions. This means that the higher is the moisture content of the external air the higher can be the achievable heat storage density.
- Closed adsorption TES, if employed for short-term heat storage, can exploit also the heat pumping effect, related to the energy recovered from the condensation of water vapour during charging phase. In this way, the energy storage density is enhanced. On the contrary, for the open adsorption TES, the heat of condensation is dumped to the ambient and not recovered.
- Closed adsorption TES are usually more complex systems, since they employ different heat exchangers to provide/extract heat in the adsorber and in the evaporator/condenser. Furthermore, working in a closed cycle, they need to keep a saturated adsorbate atmosphere, which means that any air leakage must be prevented, making system more complex and expensive. On the contrary, open adsorption TES are less complex and expensive systems, which seem more suitable for long-term heat storage.

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## 3. State of the art

Adsorption TES is considered quite a promising technology both for seasonal and daily storage applications, nevertheless, its commercial diffusion is still not completely developed, mainly for its cost as well as lack of technical knowledge at system level. This means that there is still need for development and research, in order to make the technology commercially competitive. The research activities in the field can be divided in three levels: materials, components and systems.

### *3.1. Adsorbent materials*

Development of adsorbent materials for adsorption TES is strongly related to the adsorbate to be employed. Since the most common adsorbates are water and ammonia, in the following sections the research activities on adsorbents developed for these kind of adsorbates are summarized.

#### *3.1.1.* Silica gels

Silica gels historically represent one of the most employed adsorbent material for water vapour adsorption. Actually, they represent the less expensive option for adsorption TES applications and they can be easily employed for heat sources at temperature lower than 100°C (e.g. flat plate solar thermal collectors). It is important to highlight that the porous structure of silica gels for closed adsorption TES must be completely different from the one employed for open adsorption TES. Indeed, since in a closed system the adsorption/desorption process usually occurs in a limited partial pressure range (e.g. between 0.1 and 0.3 p/p0), it is necessary to have silica gels with highly microporous structure, able to exchange high quantity of water vapour. On the contrary, in an open adsorption TES, since the working partial pressures are usually higher, a mesoporous silica gel can be also employed, due to the capillary condensation phenomena occurring in this working range.

As will be described afterwards, despite their competitive cost and wide availability, silica gels showed too low heat storage capacity, which often lead to experimental heat storage density even lower than water [7, 8]. Nevertheless, they still represent a possible option if employed for long-term heat storage applications, since for these applications, the cost can become the main selection criteria. At the same time, their application as a support matrix for composites is considered an interesting alternative.

#### 3.1.2. Classical zeolites

Zeolites are crystalline alumino-silicates, characterized by high specific surface area (i.e. about 800 m2/g) and wide microporous volume, which make these materials perfectly suitable for water vapour adsorption. Thanks to their porous structure, they are usually highly hydrophilic, which allows to obtain high adsorption capacities already at low partial pressures. This high affinity with water, of course, reflects also on strong bonding that needs higher temperatures to be broken, if compared to silica gels (i.e. more than 150°C). The most common synthetic classical zeolites employed for adsorption heat storage are zeolites type A, 13X and Y. These materials are mostly used for open adsorption TES, since, in order to get enough energy storage density, they must be regenerated at high temperatures, which make air the most effective heat transfer media. Clearly, due to the required high temperature of operation, they are usually employed for industrial waste heat recovery and storage [9].

Thanks to their crystalline structure, differently from the amorphous structure of silica gels, they can guarantee higher long-term hydrothermal stability, offering a more reliable option for applications where several adsorption and desorption phases are expected.

#### *3.1.3.* Zeo-like materials

More recently, several new microporous adsorbents have been proposed as adsorbents for TES applications. They are often referred as zeo-like materials, since their crystalline structure is somehow similar to the classical zeolites. The two classes that showed the most promising features are the aluminophosphates (AlPOs) and the silico-aluminophosphates (SAPOs). Indeed, differently from other classical adsorbents, these materials show a partially hydrophobic behavior, that reflects in an S-shaped adsorption isotherm. This is an advantageous characteristic, that allows obtaining high amount of water vapour exchange in a narrow range of partial pressure. Accordingly, since the overall heat storage capacity is highly dependent on the water vapour exchange, these materials can guarantee really high heat storage capacities.

Among these two classes, the most attractive materials are known as AlPO-18 and SAPO-34 as reported by several authors [10]. Particularly, the research on these materials brought to the first commercial adsorbent specifically developed for closed adsorption systems (e.g. for heating, cooling and storage applications). It is known as AQSOA Z02, and is produced and commercialized by Mitsubishi Plastic Inc. [11]

#### *3.1.4.* Metal Organic Frameworks

Metal Organic-Frameworks (MOFs) represent a new emerging class of adsorbent materials [12]. These materials, still in an early stage of development, are considered the future of adsorption TES, since, thanks to their structure, made up of metal ions interconnected each other by organic macro-molecules, it is possible to select several different compositions, giving an infinite possibility adjusting the synthesis procedure, to obtain the ideal adsorbent material. Indeed, they are usually characterized by high specific surface area (i.e. higher than 2000 m2/g) which guarantees to reach higher adsorption capacities, if compared to other adsorbent classes, thanks also to the possibility of tuning the pore sizes, according to the adsorbate and the working range. Nevertheless, as already pointed out, this class is still far from practical application, due to two main reasons: their high cost, related both to the small amount currently produced and to the cost of raw materials. Moreover, their hydrothermal stability must be deeply investigated.

#### *3.1.5.* Activated carbons

Activated carbons are carbonaceous adsorbent materials, obtained from different possible precursors (e.g. coconut shells, wood, coal), characterized by wide specific surface area and microporous volume. These adsorbent materials are typically employed as ammonia and alcohols adsorbent for adsorption TES, thanks to the good affinity showed towards these adsorbates. Thanks to the competitive cost and wide commercial availability they are considered as a promising option for TES applications. Nevertheless, they can be employed only for closed adsorption TES, since their affinity towards water vapour is quite limited. However, there are no examples in the literature of the use of these materials in TES so far. As for the case of silica gels, they have been mainly investigated as possible substrates and matrices for composite adsorbents, mainly exploitable to increase the otherwise poor thermal conductivity of adsorption materials.

#### *3.1.6.* Composite sorbents

Composite sorbents represent a hybrid way to enhance sorption ability of materials under typical working boundary conditions of adsorption TES [13]. Indeed, they are based on the embedding of inorganic salt (e.g. LiCl, LiBr) inside a host porous structure (e.g. silica gel, vermiculite). This concept was invented by Boreskov Institute of Catalysis, trying to exploit the absorption ability of some kinds of salts, avoiding one of their main limitation, which is the excessive mass transfer limitation induced by the agglomeration of the salt when it is employed in bulk. Indeed, as depicted by the working principle reported in Figure 7, the reaction between salt and adsorbate is always confined inside the pores of the host matrix, this makes the adsorption/desorption more stable and less affected by the adsorbate diffusion phenomena. Furthermore, the proper selection of the salt and the pore size of the host matrix allows to nano-tailor the achievable adsorption properties of the synthesized material. Thanks to the wide availability of inorganic salts, able to react with different adsorbate, it is possible to tailor and synthesize composite sorbents to be employed with a large number of adsorbates. Typical examples are the well know Selective Water Sorbents, SWSs, which represent the wider class of composite materials, specifically developed for water adsorption.

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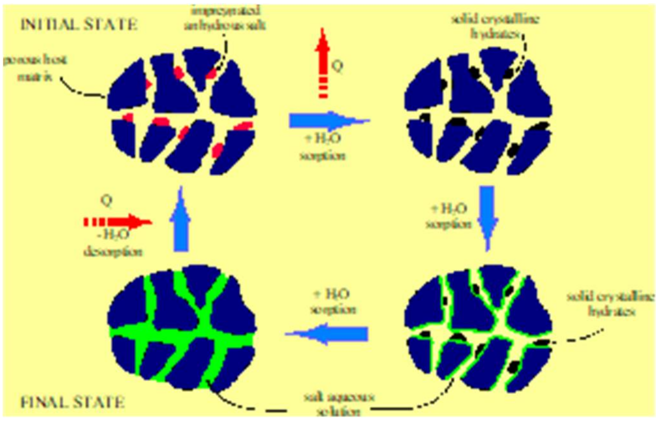

**Figure 7**. Working principle of a composite adsorbent [13].

The literature is full of several different developed composite sorbents for TES applications. They often showed attractive performance, in terms of heat storage density, especially on thermodynamic basis. Main issues showed by these materials are related to possible salt leakage from pores and slow kinetic behavior, due to the chemical reaction occurring between salt and adsorbate.

*Adsorption material heat storage calculations*

An interesting comparison among several adsorbent materials introduced above is reported in [14]. The calculations are performed only for closed systems with water as adsorbate, since they are still the most widely employed adsorption TES under investigation. In the present paragraph some of the main obtained outcomes are summarized. Generally, in order to calculate the most effective adsorbent material for TES, the main parameter to be investigated is represented by the integral enthalpy of adsorption, which can be easily calculated as reported by the following equation:

$$H_{ads} = \Delta H_{ads}\,(w_{max} - w_{min})\ [J/g_{ads}]$$

Where:

- $H_{ads}$ [J/$g_{ads}$] is the enthalpy of adsorption, which can be considered as the achievable heat storage density at material level;
- $\Delta H_{ads}$ [J/$g_{water}$] is the differential enthalpy of adsorption referred to the adsorbed amount of water;
- $w_{max}$ and $w_{min}$ [$g_{water}$/$g_{ads}$] are the maximum and minimum adsorption amount of water over the adsorbent material, at the given working boundary conditions.

The value of the differential enthalpy of adsorption. Is generally calculated thought the measurement of the equilibrium adsorption curves according to the well-known Clausius-Clapeyron equation [15],

Authors in [14] demonstrated that SAPO-34 and SWS generally show the highest heat storage capacities regardless the boundary conditions. Nevertheless, classical zeolites whose integral heat of adsorption is very limited at 90°C of regeneration temperature, become very attractive when higher temperatures (i.e. 160°C) are available instead. Silica gels, as already pointed out before, maintain quite limited TES density, which makes this class of adsorbents not so attractive for this application.

Finally, it has to be pointed out that these calculations have been performed for unit mass. Usually, TES density is calculated on volumetric basis, since the occupied volume can be an issue, for instance, in the domestic sector. Nevertheless, to calculate the volumetric adsorption storage is quite complicated, since the bulk adsorbent material density strongly depends on grain size and composition. For this reason, in order to compare different adsorbent materials, the gravimetric TES density is taken as reference parameter. Main features of the introduced sorption material classes are shown in Table 1.

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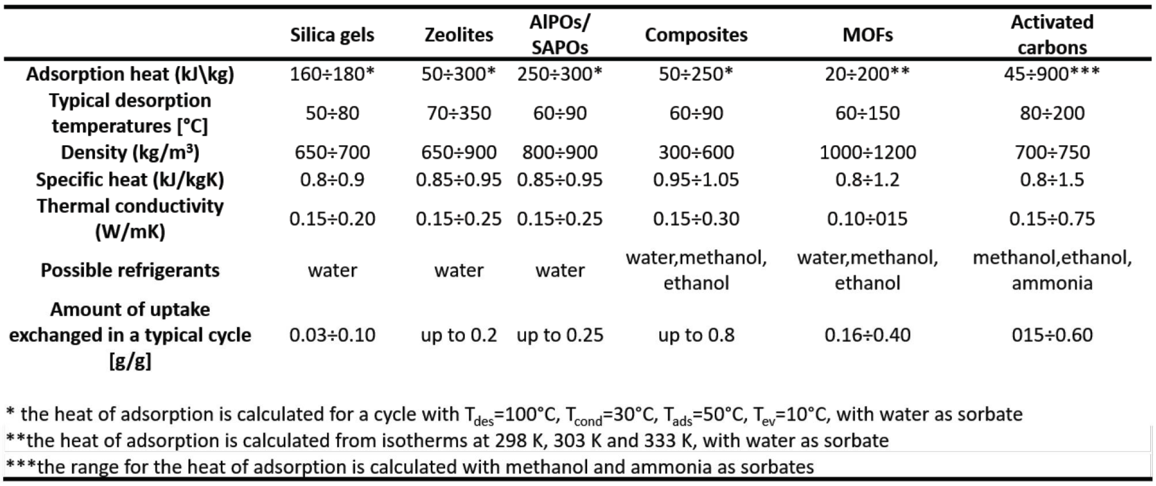
**Table 1**. Main properties of sorbent material classes.



| | Silica gels | Zeolites | AlPOs/ SAPOs | Composites | MOFs | Activated carbons |
|---|---|---|---|---|---|---|
| **Adsorption heat (kJ\kg)** | 160÷180* | 50÷300* | 250÷300* | 50÷250* | 20÷200** | 45÷900*** |
| **Typical desorption temperatures [°C]** | 50÷80 | 70÷350 | 60÷90 | 60÷90 | 60÷150 | 80÷200 |
| **Density (kg/m³)** | 650÷700 | 650÷900 | 800÷900 | 300÷600 | 1000÷1200 | 700÷750 |
| **Specific heat (kJ/kgK)** | 0.8÷0.9 | 0.85÷0.95 | 0.85÷0.95 | 0.95÷1.05 | 0.8÷1.2 | 0.8÷1.5 |
| **Thermal conductivity (W/mK)** | 0.15÷0.20 | 0.15÷0.25 | 0.15÷0.25 | 0.15÷0.30 | 0.10÷015 | 0.15÷0.75 |
| **Possible refrigerants** | water | water | water | water,methanol, ethanol | water,methanol, ethanol | methanol,ethanol, ammonia |
| **Amount of uptake exchanged in a typical cycle [g/g]** | 0.03÷0.10 | up to 0.2 | up to 0.25 | up to 0.8 | 0.16÷0.40 | 015÷0.60 |

* the heat of adsorption is calculated for a cycle with $T_{des}$=100°C, $T_{cond}$=30°C, $T_{ads}$=50°C, $T_{ev}$=10°C, with water as sorbate

**the heat of adsorption is calculated from isotherms at 298 K, 303 K and 333 K, with water as sorbate

***the range for the heat of adsorption is calculated with methanol and ammonia as sorbates

### *3.2. Adsorption TES components*

Development of closed adsorption TES components is mainly focused on the core component represented by the adsorber unit, realized by putting in contact the adsorbent material with an efficient heat exchanger. Indeed, since the adsorbent materials present a very low thermal conductivity, their inertia towards thermal cycles is quite high. This behavior reflects in limited dynamic performance which causes reduced achievable specific power (both in terms of mass and volume) leading to bulky components. With this regards, several activities have been carried out in the past to optimized the thermal conductivity of adsorbent materials, either adding pieces of highly conductive materials [16]. More recently, the research activity has been mainly oriented towards the optimization of the adsorber unit itself, which means to reduce the heat and mass transfer resistance between the heat exchanger and the adsorbent material. So far, three main technologies have been identified to realize effective adsorbers: loose grains, binder-based coating and in-situ crystallization coating technique.

The less expensive and widely employed technique for adsorption TES is the one based on loose grains embedded in the HEX. In this case, the main issue to be solved is to find the best compromise, in terms of grain size, which allows to have a good heat transfer efficiency without affecting too much the vapour diffusion through the adsorber.

Binder-based coating technique, is based on the reduction of contact resistance between heat exchanger and adsorbent material by distributing a thin and homogeneous layer over the wide heat transfer area of the HEX itself. In this way, heat transfer is enhanced, since the contact between adsorbent and HEX is uniform and not punctual, as in the loose grains configuration. Recently, potentialities of coatings on advanced HEX supports (graphite plates) have been also investigated [17]. Experimental results demonstrated that actually, this approach could enhance the kinetic performance of the components, thus increasing the power of the developed units. Nevertheless, some parameters need to be carefully investigated in order to optimize the binder-based coating technique. Indeed, the thickness needs to be carefully controlled, to avoid excessive mass transfer resistance and to reach high mechanical stability level. Furthermore, despite their good mechanical properties, organic binders can release small quantities of non-condensable gases, which can affect the performance of the adsorber itself.

The last option, currently under development, is the in-situ crystallization technique. This is mainly oriented towards zeolite and zeo-like materials, which are crystalline and can be directly synthesized over the metallic substrate of the HEX, leading to a perfect thermal contact, dramatically reducing the heat transfer resistance. This technique has been already applied to full-scale adsorbers, and confirmed to be really promising from dynamic point of view [18]. Main limitation, still under investigation, are related to the long duration and high energy consumption of the crystallization

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process and to the low amount of adsorbent that can be deposited over the HEX, which can affect the achievable volumetric power.

### 3.3. Adsorption TES systems

Adsorption TES systems are still in an early stage of development and not completely commercialized. Nevertheless, some particular applications have been already put on the market, since they perfectly fit some needs. In this paragraph a brief collections of recently developed adsorption TES applications is reported.

A classic example is the self-cooling portable beer barrel developed by ZeoTech company [19]. This system perfectly exploits the peculiarity of the adsorption TES. Indeed, it consists of a zeolite embedded inside the external shell of the barrel, kept separated from the evaporator (Figure 8). Once that the beer needs to be cooled down, the connection between the anhydrous zeolite and the evaporator is opened through a manual valve, and the heat of evaporation is subtracted from the beer, which is cooled down to the desired temperature. When the barrel is empty, the saturated zeolite is regenerated in the oven, thus performing the charging phase. This process perfectly applies adsorption heat storage to small scale apparatuses.

**Figure 8.** Small beer barrel with embedded adsorption TES for cooling (courtesy of Cool-System).

A different application of adsorption TES is the one recently developed and commercialized by Bosch in collaboration with ZAE Bayern, when an open adsorption TES has been optimized to enhance energetic performance of a dishwasher (Figure 9). The working principle can be found elsewhere [20]. Basically, in this application, the thermal energy is reversibly stored in a zeolite cartridge, which is regenerated (charged) in the first phase of the washing process and discharged, with releasing of high amount of heat, during the drying phase of the dishes. In such a way, it becomes possible to reduce the amount of electric energy consumed to perform the entire washing cycle, enhancing a lot the energetic class of the appliance.

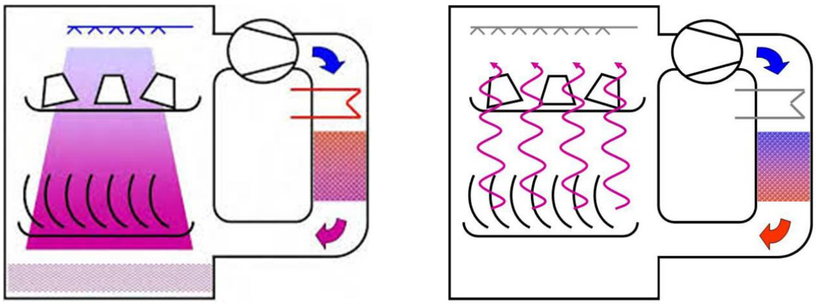

**Figure 9.** Adsorption based dishwasher. Washing phase (left); drying phase (right).

Another reported example of adsorption TES, is a large scale system for industrial heat recovery, storage and transportation, based on an open adsorption cycle. Figure 10 summarizes the concept, developed at ZAE Bayern laboratories [21]. It consists in recovering heat from an industrial site, by flowing hot air through a zeolite 13X bed. Once the adsorbent material is regenerated, the reactor full of dried zeolite (charged TES) is transported to the site where it is discharged, by flowing humid air through the zeolite bed, thus releasing heat to drive another industrial process. This system proved to be quite promising where the demand and the user side are quite close each other, since it is well known that industrial sites are one of the major sources of waste heat worldwide [22]. Clearly, to increase the share of this kind of applications it is mandatory to carefully analyze the boundary conditions, in order to make the process economically feasible.

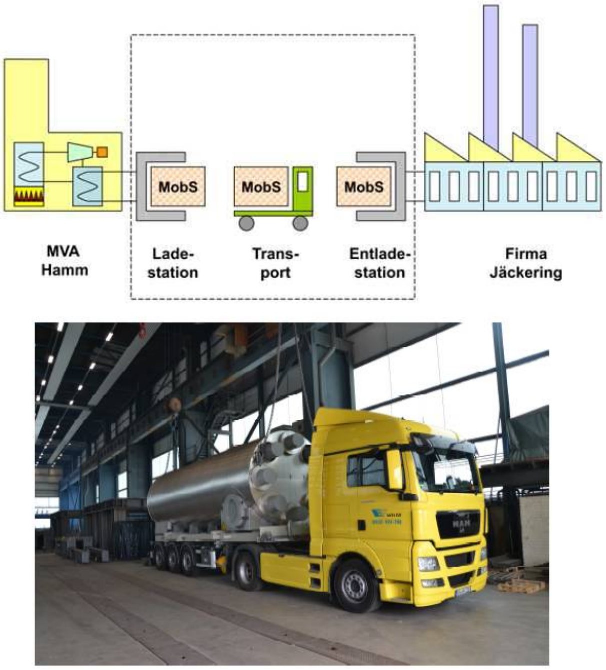

**Figure 10.** Mobile adsorption TES for industrial applications.

The last example is a prototype af a compact TES for mobile applications [23]. The sorption storage system has been realised and tested at CNR-ITAE. It consists of two vacuum chambers, for the adsorber and the phase changer (Figure 11). Some flanges allow the connection to the sensors for the monitoring of the most relevant parameters (pressure, temperature) and the other components of the device. The exchanger used for the adsorber is a flat-tube and fins type with exchange area of 1.75 $m^2$. The exchanger has been filled with 4.3 kg of AQSOA™-Z02 grains, in the range 1÷2 mm. The material has then been contained by means of a metallic net. The connection between the adsorber and the phase changer is realised through an electrically actuated pneumatic valve.

The phase changer consists of a welded chamber, containing 4 high efficency fin-and-tube heat exchangers with copper fins and stainless steel tube connected in parallel through an external tubular steel manifold. Each one has an exchange surface of 1.33 $m^2$. Vacuum flanges allow the connections to the adsorber and to some sensors.

The test set-up is completed by a hydraulic circuit realised with copper $\Phi$12 mm tubes, thermally insulated by a polyurethane foam with thickness of 1.5 cm. The hydraulic circuits includes four 3-way valves.

The results obtained with the system showed good performance and efficiency. In particular, storage capacities up to 263 Wh/kg of adsorbent were obtained, corresponding to 40% more than the storage capacity of water under the same boundary conditions. A peculiarity of the investigated system is the possibility to use low-temperature waste heat (T<100°C) both for heat and cold storage

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purposes: the measurements carried out highlighted that even with a heat source temperature of 85°C, cold at 5-10°C can be efficiently produced.

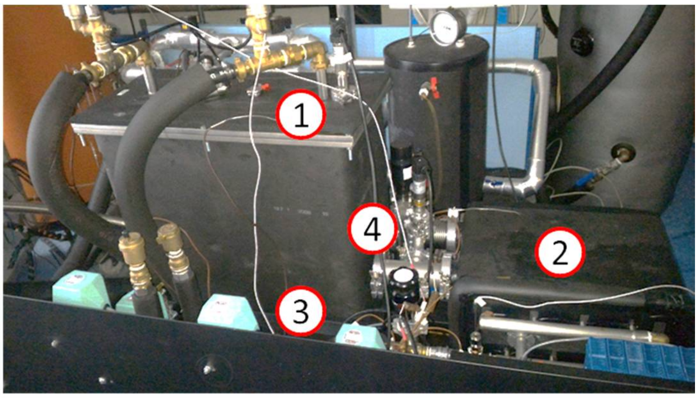

**Figure 11.** The TES prototype system realised at CNR-ITAE. 1: adsorber, 2: phase changer, 3: hydraulics.4: vacuum valve.

## 4. Conclusions and future perspectives

The present paper has summarized some of the main features of the adsorption TES, analyzing its state of development from different point of views, from the material up to the system applications. Research activity is still ongoing, trying to solve the main issues of this technology. Particularly, the following ways seem to be quite promising in order to reach a commercial diffusion during next years:

- At material level, the main challenge is to reduce costs of available materials, in order to make the adsorption TES systems more competitive. In this context, a lot of efforts are put in the employment of less expensive raw materials for zeo-like adsorbents and to reduce the hydrophilicity of classical zeolites, in order to keep down the required regeneration temperature. Furthermore, MOFs are continuously under development, thanks to their promising features.

- At component level, the main task is the realization of efficient adsorbers, based either on adsorbent coating or on loose grains technique, which can allow to limit the size of the storage systems, enhancing the kinetic performance. Furthermore, particular attention is also put on the reliability of these components, in terms of corrosion and hydro-thermal stability issues.

- At system level, small scale adsorption TES units are under development for domestic applications. Indeed, if properly coupled to the distribution system, they can not only store thermal energy, but also provide heat pumping effect during winter season and cooling energy during summer season, thus making this component as a fully integrated heat and cold storage, throughout the year.

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