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## ADSORPTION REFRIGERATION CYCLE APPLICATION IN THE INDUSTRY: A REVIEW

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**Abstract.** *The adsorption refrigeration cycle is being considered as an alternative for the conventional vapor-compression refrigeration cycle commonly used nowadays. The demand for more efficient, sustainable, and alternative energy resources and the high global warming potential (GWP) of conventional refrigeration gases support and justify the application of this system. This work presents a review around the adsorption refrigeration cycle theory, components, improvements, and differences among other very common refrigeration cycles (such as vapor-compression and absorption), as well challenges regarding alternative energy sources, working temperature variations, components size, efficiency, and performance, which are still in discussion around the world. The study presents a discussion around those challenges and compares the adsorption capacity between different substances, such as Metal-Organic Framework, activated carbon, silica gel, zeolites, and new technologies for the adsorbent-adsorbate working pair. At last, due to the increasing improvement of the cycle, this research shows that adsorption refrigeration cycles are being used more frequently in many fields, such as transportation and ice makers, and represent a potential expansion for other industrial areas. Many studies are being developed to pair the technology with solar panels and the research already progressed to test phases for the application of the adsorption cycle in the automotive industry, as the movement and the limited space can affect the results and the performance of the system.*

**Keywords:** *sustainability, heat waste, adsorption refrigeration cycle, industry application potential*

### 1. INTRODUCTION

Since the 1980s, the concept of Sustainable Development has been spread around the world, especially due to worries regarding the environment and economic growth (Emas, 2015). It can be defined as the needed development that doesn't compromise the needs of the future generation. Based on this theory, many researchers realized that it was possible to innovate and turn products into profit, while still caring for the environment. Some scholars, as Michael Porter (Porter and van der Linde, 1999), even theorized that pollution was a clear sign of inefficient use of resources, which could lead to low profits in the industry.

Heating, air conditioning, and refrigeration (Benhadid-Dib and Benzaoui, 2012) contribute, constantly, to the increase of pollution and global warming, as it is intrinsically related to the burning of fossil fuels, such as coal, oil, and natural gas, which produces CO<sub>2</sub>. Another issue faced is the impact of refrigerants: there is a presence of leakage in the cooling systems, which are responsible, to some degree, for the destruction of the ozone layer and the increased greenhouse effect seen in regions all over the world.

The replacement of HCFCs (hydrochlorofluorocarbons) and CFCs (Chlorofluorocarbons) by HFCs (Hydrofluorocarbons) took away the problem of chlorine (Benhadid-Dib and Benzaoui, 2012) in the atmosphere, the great responsible for the destruction of the ozone layer. However, all these molecules still have a high GWP (Global Warming Potential), despite not being as damaging as the HCFCs and the CFCs. The R-134a, a very common type of HFC, used in air-conditioning systems, have GWP for the next 100 years of 1300, which is still very high. That is one of the many reasons, many research institutes and industries started to search for new methods of refrigeration, more environmentally friendly and efficient if compared to the standard method.

Among the new technologies, the thermally driven refrigeration systems (Elsheniti et al., 2018) are a good solution to reduce greenhouse emissions. Those systems are known for having high efficiency, being light and small if compared to other options. Originally, they relied on the energy produced by burning fuels and the use of toxic refrigerants.

However, nowadays, they are being considered to reuse heat wasted in industrial processes or even in the combustion of engines.

One of the thermally driven methods studied, nowadays, is the adsorption refrigeration cycle (Rezk et al, 2010). This cycle consists of two sources, operating at three different temperature levels. The difference in temperature between two of them works as a thermal compressor, substituting the mechanical compressor used in the traditional compression cycle. It works in a wide range of temperatures, even lower ones, as 50 °C, is almost noiseless and there are no special needs for maintenance, being a nice alternative compared to other methods. That is why it has been studied and applied in many fields, all over the industry. This new cycle (Lambert and Jones, 2006) could save the consumption of fuels and utilize waste heat, making the process more efficient and less pollutant, as it avoids the need for a new heat source, which could burn fuel just to make the system work, being able to be paired, even, with solar panels, that use the heat from the sun instead.

In this paper, we intend to analyze what is the adsorption cycle, its materials needed, how it works, and what are its benefits. It is going to be examined, also, the uses of the technology in the general industry and what are the prospects in the automotive industry.

## 2. MATERIALS AND METHODS

This paper consists of a literature review around the adsorption cycle and its constant innovation. For that, first and foremost, the cycle was briefly explained, with its components and its functions. Afterward, some coefficients were pointed out, that are important to understand the performance of the refrigeration cycle and how it evolved. It was considered of importance to explain and differentiate the absorption cycle from the adsorption cycle, as both are very similar and are also being studied in the same areas.

Afterward, the major adsorbents and adsorbates pairs were highlighted and what are the main features that a good pair should have. It was preferred to list the major adsorbents in topics (activated carbon, silica gel and zeolites, and metal-organic frameworks and new prepositions), mentioning, right after, the adsorbates mostly paired with them.

After establishing what is the cycle analyzed and how it works, its approach in the industry was the next focus. A brief explanation of the evolution of the adsorption cycle in the industry introduces the topic, while papers regarding the different applications of the technology were used as a base for this work, with the main results found, the challenges that were faced, and the previews for the upcoming studies.

## 3. THE ADSORPTION CYCLE

The adsorption cycle can be divided into two different cycles, due to their characteristics (Elsheniti et al, 2018). One is a type of heat engine, while the other is a heat pump. Although two separate cycles, the work produced in the heat engine is assumed to be used in the refrigeration part. The refrigeration cycle (Wolak, 2016) may be divided into intermittent and continuous cycles, being the single-bed intermittent cycle (explained in the next paragraph) the most basic and earliest type used in the industry.

It is composed of an adsorbent bed, called desorber, in contact with the adsorbate, a condenser, an evaporator, and an expansion valve, very similar to a refrigeration cycle by compression (Elsheniti et al, 2018). The adsorbent bed contains an adsorbent, a very porous material with a large internal surface. The pores can be classified (Knaebel, 2004) as micropores ( $d_p < 20\text{\AA}$ ), mesopores ( $20\text{\AA} \leq d_p < 500\text{\AA}$ ), and macropores ( $d_p \geq 500\text{\AA}$ ), which can affect the adsorption process, as it increases or decreases the area. It is connected to the adsorbate through something called “adsorptive property”, making it work as a refrigerant in this cycle. That is why the adsorbent and adsorbate are studied in pairs and its success and efficiency depend on their interaction.

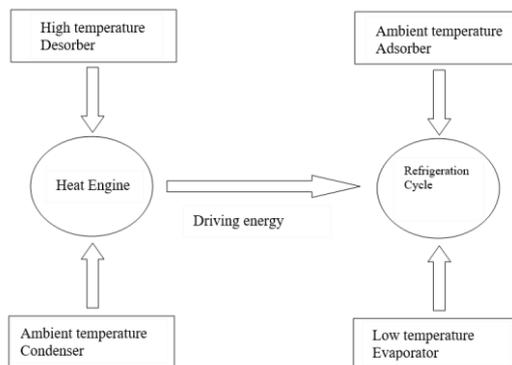


Figure 1. The sorption thermodynamic cycle. Available from: Rezk et al., 2010.

In the cycle, the adsorbent bed is heated to desorb the adsorbate, increasing the local pressure (Rezk et al, 2010). The temperature keeps increasing, until the condenser is connected, allowing the adsorbate, which was desorbed, to condense and travel to the evaporator. Now, with a low concentration of adsorbate, the bed is cooled down and the local temperature of the reactor is reduced. While being cooled down, the bed is connected to the evaporator and adsorbs the adsorbate (working as a refrigerant) back, achieving the cooling effect through evaporation. Figure 1, above, represents the adsorption cycle through a diagram.

The efficiency of adsorption refrigeration systems (Gwadera and Kupiec, 2011) is verified through the coefficient of performance (COP) and the specific cooling capacity, named SCP. The COP is the ratio between the heat cooled taken from the space around them and the sum of heat inserted in the system. Usually, the higher the temperature of the heat source, the higher is the COP value and the efficiency of the process. The SCP is the ratio between the cooling capacity and the mass of adsorbent.

A single-bed cycle (Gwadera and Kupiec, 2011), as shown above, has low efficiency and works in an intermittent way, which could prolong the process. For these reasons, different cycles were created, to increase the efficiency of the process and make it faster. The heat recovery cycle uses the heat that would be lost in the cooling phase in the desorber, to help heat the adsorber, which can increase the efficiency by 25%. The heat and mass recovery cycles usually have two steps. The mass recovery uses maximum temperature and pressure in the desorber and minimal temperature and pressure in the adsorber, both connected, to allow an additional adsorbate to be adsorbed. The heat recovery follows as explained before, due to the wide range of temperatures in the system, improving not only the efficiency but also the specific cooling capacity.

The adsorption cycle is often confused with the absorption cycle (Pang et al., 2013), which is also very used in the industry, with mainly three differences: materials, state of the substances, and the circuit layout. In the absorption cycle, a solution known as “base” is used to dilute the refrigerant vapor, getting it weaker by doing that. This base is, then, regenerated when the refrigerant starts to evaporate from the solution due to the heat provided to the system. In the adsorption process, the refrigerant adsorbed stays on the surface of the solid adsorbent and only needs heating to evaporate.

The absorber and generator (Pang et al., 2013) in the absorption cycle are, often, in two different compartments, between a heat exchanger. In the adsorption cycle, the adsorption and desorption area are together in the same bed. The absorption cycle has, mainly, the same functions as the adsorption cycle: provide refrigeration, heat, and/or dehumidification, working in low temperatures as well (80-150°C).

It could be said that absorption cycles were more studied and researched the last few years (Ji et al., 2015) due to the fact that it produced more cooling capacity from waste heat recovery if compared to the adsorbent cycle, being, also, a more mature type of technology. That is one of the reasons (Dilshad et al., 2019) 59% of the solar refrigeration systems located in Europe uses the absorption cycle, achieving a COP (Alahmer & Ajib, 2020) of 0.6 to 0.8 and requiring low supply temperatures. There is also a lot of studies (Venkataraman et al., 2020) focused on applying this technology to vehicles coupled to the engine exhaust or harnessing the heat from new sources of energy, such as fuel cells. However (Ji et al., 2015), the whole system, with all its parts, is huge and more complex if compared to the adsorption system, making it more difficult to fit in small spaces, such as vehicles and vessels.

For Wang et al. (2014), the adsorption cycle for refrigeration, especially using solid adsorption, is very simply constructed and has a low cost. Besides that, it is interesting the use in vehicles and vessels, as the technology is more compact and works fine with vibrations, as it has few moving parts (not requiring a distillation device or a solution pump) and strong anti-bumps resilience (Ji et al., 2015).

Despite its simplicity, one of the most important parts regarding the study of the adsorption cycle, is, still, the appropriate choice of the adsorbents and adsorbates working pair. Those materials and innovation in the field will be analyzed in the next section.

#### **4. ADSORBATES AND ADSORBENTS**

The working pair in the refrigeration cycle (also known as the duo of adsorbents and adsorbates) is extremely important, as its results depend on the chemical, physical and thermodynamic properties of the pair (Younes et al., 2016). The materials will be used in new technologies built by a growing industry, whose main goal is to have increased profits and market shares, it's, also, very important to take into account the availability of the pair and its cost.

For refrigeration by adsorption cycle (Younes et al., 2016), a large amount of adsorbate (refrigerant) must be exchanged during the sequence, needing a large latent heat of vaporization to rise the refrigeration capacity, it mustn't transform into solid in the temperature and pressure range used in the cycle and it can't be flammable or toxic.

Another property (Giraldo et al., 2019) that often substitutes or adds to the latent heat of vaporization is the isosteric heat, which is measured with an indirect method and helps to present other surface properties of the adsorbents, determining the homogeneity or heterogeneity and the adsorption energy distribution.

Elsheniti et al. (2018) highlight that good adsorbents should be identified as having a wide range of adsorption capacity (considering the variation of temperature) and high heat and mass transfer properties. Other properties should be checked, such as thermal conductivity, boiling point, and working pressures. A good or high thermal conductivity

can reduce the cycle time of the process (Abullah et al., 2011), while very close boiling points among the working pair consumes a lot of energy (Dabrowski, 2001) and high working pressures allow the working pair to be applied in sub-atmospheric conditions (Elsheniti et al., 2018).

Additionally, Abdullah et al. (2011) mention that it is very important the adsorbent-adsorbate pair cannot react chemically between each other and should be, preferably, of easy access and considerably cheap.

The activated carbon (Dabrowski, 2001) can be considered the first type of adsorbent widely used in history. The Egyptians used charcoal, as it could be seen in papyrus, considered to be used since 3750 B.C. Until World War I, the adsorption technique relied, mostly, on carbon adsorbents, transferring to active carbon, silica acid gels, and aluminum oxides in the period between the wars and, after World War II, great progress was made using synthetic zeolites.

Below, there are some of the pairs more used nowadays.

#### 4.1 Activated Carbon

A varied range of carbon-based materials can be defined as activated carbon, being very porous and having large internal surface areas (Abdullah et al., 2011). To produce it, usually, is necessary to carbonize a material in high temperature and an inert atmosphere. After that, the product is activated through a physical or chemical method. The physical process is the most popular, where the carbonized product is activated using oxidizing gases (steam or carbon dioxide) in high temperatures, allowing the pores to grow and creating the large surface needed in the adsorbents. During the chemical process, a chemical agent is inserted before the carbonization.

The activated carbon has a large specific area (Elsheniti et al., 2018) around 800 to 1500 m<sup>2</sup>/g. It has a low adsorption heat if compared to the other pairs, around 1800 to 2000 kJ/kg, which is good for the COP of the system, as most of the heat consumption in the regeneration phase is due to the adsorption heat value. It has a higher surface reactivity, a good size of pores, and a large surface area. However, it has poor thermal conductivity.

The activated carbon is one of the most used substances for adsorbent applications, as its porosity and surface area can be controlled with success (Dabrowski, 2001). Some of the pairs are, as followed: activated carbon/methanol, activated carbon/ethanol, activated carbon/R134a, activated carbon/ammonia, activated carbon/CO<sub>2</sub>, among others.

The activated carbon/ammonia pair (Elsheniti et al., 2018) has a high working pressure, around 1600 kPa, making the permeability of the sorbent non-critical, making it easier to apply than sub-atmospheric systems. One of the biggest problems with this pair is the toxicity factor and the strong ammonia smell. The activated carbon/methanol pair has a large adsorption capacity, around 0.45 kg/kg ads. It can be used with low regeneration temperatures, such as 100 °C. However, it should not be used for temperatures over 120 °C, in which the activated carbon will catalyze the methanol, decomposing it in dimethyl ether.

It's interesting to notice that the use of alcohol as working fluid (such as ethanol and methanol) is a good alternative, as it can be used in low-temperature applications, which, with more unstable adsorbents (as HKUST-1 or MIL-101) could be dangerous to the process (Elsheniti et al., 2018).

The preferable adsorbent-adsorbate working pair for air conditioning systems (Ramji et al., 2014) was determined, through simulation, to be activated carbon-water. Compared to methanol and ammonia, it conquered the optimal cooling effect, with a COP of 0.58 and reaching a temperature of 12°C and a cooling power of 1kW, while methanol reached a COP of 0.37 and a temperature of 15°C, and ammonia reached a COP of 0.4 and a temperature of 19°C.

#### 4.2 Silica Gel and Zeolites

One of the most common pairs is the silica gel/water (Elsheniti et al., 2018). The silica gel is a synthetic amorphous silicon dioxide, having a very granular and porous surface. Its regeneration temperature is quite low (85°C), making it one of the best alternatives when using it in the adsorption cycle for solar energy or waste heat sources. However, the silica gel will be dissolved over 120°C (Rezk et al., 2010). The adsorption heat is around 2500 to 2800 kJ/kg, higher if compared to the activated carbon. Considering the same comparison, its porosity is lower, around 100 to 1000 m<sup>2</sup>/g. Its maximum adsorption capacity is around 0.35 to 0.4 kg/kg silica gel. The freezing point of the water can be considered a drawback, making it better for this pair to be used in systems with larger chilled water flow rates.

Silica gel (Rezk et al., 2010) can be divided into two different groups, solely on the size of its pores: regular density, when the pore has 2 nm of diameter and low density, when the pore has a 15 to 20 nm diameter. Nowadays, super-microporous or silica gel of high density can be observed, with pore sizes of around 1 to 2 nm. This type of material allows the operation of the adsorption cycle in lower temperature differences, adsorbing almost 3 times more if comparing to regular density silica gel.

The zeolite is an alumina silicate crystal with microporous formed by alkali (Elsheniti et al., 2018). They are considered the main category of microporous sorbents, together with aluminosilicates and different types of interrupted frameworks of materials similar to zeolites, like aluminophosphates. They are considered the only crystalline material with a very well-defined pore, with strong acidic regions in its surface, which allows it to be a superior type of cracking catalyst. The material has high selectivity and can separate materials based on the size and shape of its molecules,

working like a sieve. Adsorption processes that use the sieving method are, usually, reversible, which makes it possible to reuse the zeolite all over again until it wears off.

Its hydrophilicity (Rezk et al., 2010) is associated with the silicon/aluminum ratio. With the lower ratio, the higher the hydrophilicity.

As the silica gel (Elsheniti et al., 2018), the pair with zeolite (usually zeolite/water) has a wide range of desorption temperatures, with low regeneration temperatures as well (70°C – 250°C). As it keeps stable in high temperatures, the zeolite can be directly heated by the exhaust gases in an engine. The adsorption heat is higher if compared to the silica gel/water pair, being around 3300 to 4200 kJ/kg, allowing the COP to be low.

Usually, zeolites are produced on a micro-scale (Machado and Bergmann, 2011), uniform crystals of zeolites in the nano-scale are also possible (dimensions around 10 to 500 nm). They have a great mechanical and chemical resistance, high surface area, around 400 to 1000 m<sup>2</sup>/g, and high density of adsorption areas. It was noticed in multiple researches that the adsorption capacity of nano-zeolites is higher if compared to micro-zeolites.

According to Dabrowski (2001), the research of zeolites, nowadays, had been focused on catalysis. The material is a great promise in catalysis for the production of special chemical products and could be used as synthetic enzymes.

### 4.3 Metal – Organic Framework and new prepositions

The metal – organic frameworks (also known as MOF's) are a new type of structure, as its structure can be seen in "Fig. 2", very promising for catalysis, gas separation or storage, a very porous crystalline material (Elsheniti et al., 2018). MOF's have a more flexible architecture and more control over their pores if compared to inorganic materials such as zeolites and silica gels, being more stable and porous. Additionally, they are less hydrophilic compared to silica gel and zeolite, making them release more water vapor under the same pressures (Rezk et al., 2010).

As it is a new material, and considering all their properties, many studies researching adsorption heat pumping for cooling applications have been using the MOF's as adsorbents, opening a field that has been very limited due to the limited adsorption capacity of silica gel, zeolites, and activated carbon (Elsheniti et al., 2018). Some of the MOF's used are MIL-101 or MIL-101(Cr), CPO-27(Ni), SAPO-34, and other variations. They can be paired with water, ethanol, methanol, among others.

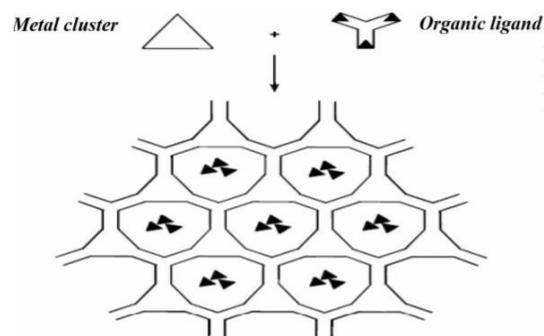


Figure 2. Sketch of the framework structure. Available from: Elsheniti et al., 2018.

When paired with water (Elsheniti et al., 2018), the MOF's allow an improvement in the performance, due to its high-water uptake and the fact it can use low-temperature waste heat or solar panels as energy sources. CPO-27(Ni) was used for air conditioning systems in cars, producing a specific cooling power of 440 W.kg<sup>-1</sup> at low temperatures, higher than the value reached using SAPO 34/zeolite in the same conditions.

R134a (Rezk et al., 2010) is a very common refrigerant, used in the compression cycle, in which its application in the adsorption cycle is currently being researched.

John et al. (2017) studied the use of other commercial refrigerants such as R1234yf, R1234ze (E), R450A, R290, R600a, R744, and R717, commonly used in vapor compression cycles as adsorbates for solar refrigeration through the adsorption cycle. They noticed that those refrigerants had great potential, especially considering the adsorption capacity. For the usual working pairs (activated carbon-methanol, activated carbon-ethanol, activated carbon-ammonia, silica gel-water, and zeolite water), the adsorption capacity was measured to be around 0.26 kg/kg, while for the activated carbon-R134a, the capacity was of 2 kg/kg. Despite the good results and the continuous research, the refrigerants are not yet being applied commercially (Rezk et al., 2010).

Shabir et al. (2020) tested many new adsorbent and adsorbate working pairs, primarily using refrigerants as adsorbates. They noticed that the maximum adsorption uptake was with activated carbon (phenol resin-based)-R32 working pair, around 2.23 and 2.34 kg/kg at 30°C and 1670 KPa. Activated carbons were paired with types of butanes and CO<sub>2</sub> as well, showing promising results.

However, as noticed by John et al. (2017), commercial refrigerants usually have high GWP (global warming potential) levels. They could be replaced for new refrigerants, as mentioned above, which would present similar results, when paired with common adsorbents, increasing the options and variety for adsorption refrigerants and reducing the number of problems related to compatibility, as it is normally seen between ammonia and copper systems.

Machado and Bergmann (2011) focused on the use of nanotechnology for adsorbents, citing dendrimers, and carbon nanotubes as novelties. Dendrimers are formed by the union of polymer molecules. It has a core, where other molecules can be trapped, and branches. They are very small (10 to 20 nm), which made them ideal for water purification. The carbon nanotubes can be considered one dimension only due to their small diameter and large length/diameter ratio, usually being insoluble in many liquids. They can form a single wall or multiple walls, which can determine some pore characteristics.

Below, in “Tab. 1”, it is possible to see a small summary of the main adsorbents, the adsorbates they are paired with and their characteristics.

Table 1. Summary of the working pairs used in adsorption

Adsorbents	Characteristics	Common Pairs
Activated-Carbon	A large specific area, low adsorption heat (which is good for COP), high surface reactivity, good pore size, large surface area, and poor thermal conductivity. When paired with refrigerants, presented the higher adsorption capacity seen.	Activated-Carbon/Methanol, Activated-Carbon/Ethanol, Activated-Carbon/R-134a, Activated-Carbon/CO <sub>2</sub> , Activated-Carbon/Ammonia, Activated-Carbon/Refrigerants
Silica-Gel	Very granular, less porous than Activated-Carbon, low regeneration temperatures, and higher adsorption heat, if compared to Activated-Carbon	Silica-Gel/Water
Zeolite	High selectivity, hydrophilic, low regeneration temperatures, keeps stable at high temperatures, adsorption heat is higher than silica-gel (which provides a very low COP), has great mechanical and chemical resistance, high surface area	Zeolite/water
Metal – Organic Frameworks	Extremely porous, has more control over pores, less hydrophilic, incredibly efficient when paired with water (due to its high water up-take), work well with low temperatures	MIL-101, MIL-101(Cr), CPO-27(Ni), SAPO-34, etc., all can be paired with water, ethanol, methanol, and others

## 5. USE IN INDUSTRY AND FUTURE TRENDS

The use of adsorption (Dobrowski, 2001) can be traced back to Ancient Greece: Hippocrates used charcoal on open wounds, to remove the stench of decay. The use in the industry started along with the Industrial Revolution, at the end of the 18th century, by the use of charcoal in the adsorption of gases, followed by the use of the same material to adsorb contaminants, being used in the sugar industry. In 1903, adsorption was first used in a selectivity process. During World War I, activated carbon was used to protect the human respiratory system. Since then, the studies revolving adsorption in the industry have expanded so much that it would be impossible to focus on everything in only one book or even a series of texts. Adsorption can be used for industrial processes, such as separation of liquids and gases, purification, and removal of impurities and recovery of chemicals used in the processes. Adsorption can also be used in environmental applications, through heat pumps and refrigeration cycles.

The application of the adsorption cycle for refrigeration (Shabir et al., 2020) is propelled by studies around efficiency and the need to find new working pairs of adsorbents and adsorbates which have a larger adsorbing capacity if compared to the pre-existing types. To enhance furthermore the performance of the systems, multi-bed and multi-stage cycles were used by researchers, along with new pairs, improving its efficiency and allowing the products to enter with renewed strength in the market.

The technology of refrigeration through an adsorption cycle found applications in many different industries, such as transportation (Rezk et al., 2010), ice makers, energy management in buildings, electronic cooling, food (Gwadera and Kupiec, 2011), vaccines, and medicines storage, among others.

Most of the time, the technology is related to solar panels, especially when the focus is on air-conditioning (Gwadera and Kupiec, 2011). In the case of solar panels, the compressor is replaced by the solar heat-driven adsorption bed, integrated with a solar collector (Dusane and Guge, 2016). Although it is still needed a lot of work, especially in the heat transfer aspect and it has a high dependency on the environmental conditions, the technology already has prototypes, focused on trade, services, and industrial buildings, as well, depots (Gwadera and Kupiec, 2011). Adsorption coolers based in solar energy are already being used in commercial buildings, mainly in the United States and Japan.

In a research done by Barreto et al. (2018) in Brazil, the system was considered effective, capable of maintaining the temperature in a condition known as “thermal comfort”, with only some small temperature spikes during the mornings, when the water was not heated enough by sunlight to help the proper work of the adsorption system and a COP of 0.63. However, there were some small difficulties throughout the research, such as the high cost of the solar chillers, the high tax rate for the import of some machines and components, and the lack of skilled labor to deal with the solar components, etc.

Considering ice makers, in which the temperatures achieved must be below 0°C, the heat sources must have higher temperatures than the used in the air-conditioning application (Gwadera and Kupiec, 2011). They are dependent on shifts between night and day (Rezk et al., 2010): during the day, the adsorbent bed absorbs solar energy, raising the temperature and pressure of the bed, making the refrigerant evaporate and desorbing from the bed. The vapor will, then, be condensed, flowing directly to the evaporator. At night, as the temperature reduces, the refrigerant goes back to the adsorbent bed. During this process, the cooling effect is initiated, and the ice is formed inside of an insulated water box.

There is also a need to preserve food and medication, making it possible by using the adsorption cycle with solar energy, especially in places where there is no electricity available, where the conventional systems of refrigeration would not work (Gwadera and Kupiec, 2011).

Adsorption (Pang et al., 2013) can also work as a desiccant, paired together with chillers and solar-driven heaters, helping to provide air, hot or cold, with comfortable levels of humidity. The desiccant wheel can work as a humidifier/dehumidifier, depending on when it is used in the refrigeration/heating cycle.

Besides solar energy, the cycle of refrigeration through adsorption can be achieved, also, by using waste heat. This is a smart use of resources especially for transportation, considering that around 40% to 50% of the fuel energy is rejected in the exhaust gases during combustion in the form of heat (Rezk et al., 2010). This waste heat could, then, be used to drive the chillers and reduce fuel consumption and CO<sub>2</sub> emissions, not only for air-conditioning systems, but also for heat pumps.

In transportation (Abdullah et al., 2011), the differences and similarities between adsorption and vapor compression systems had made the new cycle a good alternative to be used in automobiles. The mechanical compressor in the traditional system is changed by a thermally driven compressor, the compressor that can be driven by heat waste, as seen in previous sections. The traditional air conditioning system uses the shaft work to drive the mechanical compressor, which can increase engine load, temperature, and fuel consumption, which is not seen in the adsorption cycle. The vapor compression system also mainly uses HCFCs (hydrochlorofluorocarbon) and HFCs (hydrofluorocarbons, such as the R-134a) refrigerants, which are attributed as one of the primary agents of global warming. As seen before, the adsorption system also has high reliability, due to the few moving parts, which provides simplicity and a long lifetime, fit for the needs of a vehicle.

For Lambert and Jones (2006), adsorption heat pumps are smaller and lighter than absorption heat pumps and could be used in the automotive field as a substitute for traditional air conditioners. The system could reduce fuel consumption around 12 to 17% when in use, with a performance similar to compression systems, while eliminating the extra consumption of power due to the mechanical parts of the system. The shape and volume of the parts are not a problem, as it is believed that they would fit comfortably in a passenger vehicle: the adsorbers would be placed underneath the driver’s seat and the heater would be under the front passenger seat, while the cooler would be placed next to the radiator.

Critoph et al. (2010) analyzed the use of adsorption cycle for refrigeration in vehicles, using the exhaust gas of a 4-stroke gasoline engine as the energy source and an *activated-carbon/ammonia* working pair. It was noticed that the system worked fine with driving temperatures around 80°C and 90°C, presenting a SCP of 800 W/kg and a COP of 0.22. Sharafian and Bharani (2014) managed to study which design for a vehicle air conditioning system was best, based on former experiments. It was observed that the best COP achieved was of 0.43 was with *silica gel/water* working pairs and the best design chosen was the finned tube, working with silica gel solutions. Those values slightly match the prediction given by Abdullah et al. (2011), of a COP ranging from 0.5 to 0.8 and SCP above 1 kW/kg. However, this application still faces some limitations (Abdullah et al., 2011):

1. Nowadays, most of the adsorbents available in the market have low adsorptive-desorptive capacity. This could lead to a necessity of huge systems, which could not be feasible in a small area, such as the ones available inside of vehicles.
2. The heat transfer is slow, compared to other systems, increasing the time needed for the cycle.
3. Adsorbates commonly used in this application often have low latent heat and a high boiling point, which means that the cooling effect is low, compared to other systems.

The SCP (Maeda et al., 2018) of the adsorption cycle for refrigeration purposes is still very poor, even with developments in the industry, such as the creation of compact vapor ducts, valve designs, adsorber heat exchanger, the use of expansion valves in the place of u-bends and the introduction of composite adsorbents. The cost is still pretty high, although the cost breakdown of the system over the price of the vehicle is considered a trade secret.

Additionally, the systems face a new problem, as they are placed in vehicles: the motricity. With it, problems such as vibrations, impacts, and high-temperature surroundings may appear as well, which may affect the reliability of the process (Maeda et al., 2018).

Still, the researchers have high hopes for the technology and its use in future trends. Maeda et al., (2018) believes that with the technological progress and the correct incentives from the government, the future of adsorption chillers in vehicles are realistically possible. It is interesting to notice, as well, that despite the tendency of changing the conventional internal combustion engines for electric engines in vehicles, studies around adsorption refrigeration in E-vehicles (Electric) are being launched every day with nice results. Haas et al., (2019), for example, installed an auxiliary heating system in a Renault Zoe, run by bio-ethanol, to improve the range in winter months, which could be converted in an adsorption refrigeration system to improve the range of the vehicle in the summer months as well.

The prospects of adsorption chillers with fuel cells are also being studied (Hassan et al., 2020). They are considered to be more environmentally friendly, if compared to internal combustion engines, and have greater electric efficiency, while producing heat, as well. Some of the results achieved are optimistic, showing a higher efficiency of the system while saving fuels and reducing emissions. At the same time, the use of hybrid cooling systems is also a possibility in the closer future. The system consists of using, paired together, a conventional vapor-compression chiller and adsorption chiller, to magnify the efficiency of the combined system.

An example of the benefits achieved with this hybrid system can be seen while pairing an adsorption chiller in a conventional power plant (Sztekler et al., 2019). Electricity production often has several losses when it is dependent on combustion, such as in the form of heat. When pairing an adsorption chiller with the power plant, producing cold that can be used in other processes in the plant, making it more energy-efficient.

John et al. (2020) even highlight the importance the adsorption refrigeration systems could have for off-grid areas, as it is a system that can cool down the temperature enough to store vaccines and medicines, produce ice and air-condition a room, without many resources, like what was seen with solar collectors or use even the heat generated by burning agricultural waste or biomass in general, attending faraway places and islands where is more difficult to attach villages and farms to the electrical grid of the country.

In conclusion, is important to keep the work related to the refrigeration through the adsorption cycle, as, despite some challenges faced currently by the researchers, the technology has an optimistic prospect to be applied in the future, saving fuels, increasing efficiency, helping the environment and the people that are in need.

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