

Experimental study on the adsorption refrigeration device built on a water-silica gel working pair

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Abstract

Due to increasing restriction put on compressor based cooling, adsorption cooling has been increasing its popularity. Abovementioned restrictions forces usage of ecological refrigerants, such as water. Additional advantage of adsorption devices is possibility to use low-grade waste heat source or solar energy as the main driving energy instead of electricity. This trend has lead to significant development of adsorption based branch in cooling industry over past 30 years. The paper presents the results of experimental research for an adsorption refrigeration device built of two deposits. Water-silica gel was chosen as the working pair, because this solution allows to work at the lowest drive temperatures. As a result of the experiment, EER coefficients were obtained at the level of 0.57-0.82 and SCP coefficients in the range from 8 to 21 W/kg. The results allow to conclude that adsorption devices can, in many cases compete with compressor solutions.

Keywords: adsorption refrigeration, adsorption, water-silicagel

1 Introduction

1.1 Sorption process

Adsorption is the process of binding molecules of a substance to a surface or interface of physical phases, resulting in local changes in concentration. It is often mistaken for absorption. The difference is that adsorption occurs on the surface of the adsorbent, and in the absorption process the absorbent is absorbed by the adsorbent in its entire volume. In the further part of the work, the adsorbent will be called a solid, usually loose, in the form of granules or in the form of a porous body, on the surface of which the working refrigerant collects. The factor that is adsorbed on the surface will be called the adsorbate, and the factor in the space of the vapor bed will be called the adsorbent. Due to the bonds formed, two types of adsorption are distinguished: physical (physisorption) and chemical (chemisorption). Physical adsorption occurs due to intermolecular interaction (van der Waals forces) between the adsorbate molecule and the adsorbent surface. During adsorption, heat is released, known as adsorption heat. This is due to a decrease in entropy in the system when the adsorbate molecules bind on the adsorbent surface. To a large extent, this process can be treated as condensation of the refrigerant on the adsorbent surface. It depends on the pressure, temperature and concentration of the adsorbate. For most adsorbents, the heat of adsorption is close to the heat of condensation of the working medium (adsorbate). Due to the nature of the physical adsorption process, the adsorbate particles are not destroyed and if the temperature is increased or the pressure is lowered, the reverse process will occur, i.e. desorption of the factor. In addition to the adsorbent - adsorbate interactions, adsorbate-adsorbate interactions also occur during physisorption, so that the process does not stop forming a monolayer (single layer of molecules / atoms) of the adsorbate on the adsorbent surface, but leads to the emergence of subsequent layers of adsorbate.

Chemical adsorption is significantly different from physical adsorption. During this process, a chemical reaction occurs between the adsorbate and the adsorbent and new chemical compounds will be formed [5]. Usually the process ends when an adsorbate monolayer is formed on the surface with the adsorbent, because the chemical adsorbents cannot adsorb subsequent layers of adsorbate. In the case of chemisorption, the heat of adsorption and desorption will usually be an order of magnitude higher than in the case of physical adsorption. Like physical adsorption, chemisorption is selective. In the case of chemisorption, it is much more important what elements will be able to

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adsorb a particular adsorbate. For example, a hydrogen molecule is adsorbed by tungsten, platinum and nickel, but it is not adsorbed by copper, zinc and silver. It was found that physical adsorption will occur prior to chemisorption, as the range of van der Waals forces is much larger than the effective distance required for chemisorption. Therefore, when the adsorbate molecules approach the adsorbent, physical adsorption will occur first and then it will undergo chemisorption as the distance between the adsorbate particles and the adsorbent decreases. By the appearance of a chemical reaction in chemical adsorption, it will depend not only on the heat and mass exchange in the adsorbent, but also on the kinetic reaction of the molecules and the chemical reaction. In addition, adsorption hysteresis occurs during chemisorption. This is because adsorption energy is different from desorption energy. The latter is always significantly higher because it is the sum of adsorption energy and adsorption heat. This difference leads to the appearance of a significant hysteresis between adsorption and desorption [1-4, 6-8]

1.2 Theoretical cycle of adsorption refrigeration device

The adsorptive refrigeration cycle partly similar to a compressor refrigeration cycle. The refrigerant is condensed at high pressure, then it is expanded and evaporated at low pressure. The refrigerant flows into a system is forced by the pressure difference. Compressor and adsorption devices differ in terms of the pressure differential method. In compressor devices, the low pressure in the evaporator is due to the suction of the refrigerant by the compressor, which, after compressing the refrigerant vapor, injects it into the condenser, maintaining high pressure there. It is different in adsorption devices. As a result of heat supply, the refrigerant desorbs by increasing the pressure. During the operation of the device, the factor from the desorber flows through a condenser connected directly to the bed. An adsorption process takes place in the adsorber, during which the pressure is lowered and the heat selected. The medium flows into the bed from the evaporator, which also has low pressure. The evaporator with condenser are connected to each other by a valve that regulates the flow of refrigerant from the condenser to the evaporator. The main elements of the adsorption system are: adsorbent bed - to carry out adsorption and desorption of the medium, condenser, expansion valve, evaporator. The adsorbent is usually placed in a hermetically sealed container (for simplicity the container and bed will be referred to as bed). Heat can be exchanged with the beds by means of a separate heat transfer medium circulation that flows through the bed just like in finned heat exchangers. The refrigerant (adsorbate) together with the adsorbent are a very important element of the whole system. The parameters of the refrigeration cycle depend on the adsorption / desorption characteristics of the specific sorption unit. The operating conditions of the cooling device, its efficiency factor, the amount of generated cooling and energy consumption in the form of heat depend on the selection of these two elements (adsorbent and adsorbate - sorption unit).

The basic, theoretical adsorptive refrigeration cycle consists of four stages: 1 - heating and pressure increasing - isosteric heating of adsorbent; 2 - heating, desorption and condensation - isobaric desorption (refrigerant release), isobaric liquefaction of the refrigerant; 3 - cooling and pressure reduction - isosteric cooling of the adsorbent; 4 - cooling, adsorption and evaporation - isobaric boiling of the refrigerant in the evaporator, isobaric adsorption of the refrigerant on the adsorbent. These stages are shown in the diagram $l P (-1 / T)$ in Figure 1.

The whole work cycle can be divided into two stages - semi-cycles. The first will include isosteric heating and isobaric desorption, while the second will include isosteric cooling and isobaric adsorption. The adsorption cycle requires heat supply in the first phase (first half cycle), and heat dissipation in the second phase (second half cycle). The heat needed for work can be waste heat or heat obtained from solar energy. This excludes the need to supply electricity to the system and allows it to be used in areas where no electrical network has been built. Unfortunately, some devices need small amounts of electricity to power the circulation pumps, but they do not require connection to the electricity network, because we can provide it, for example, with power generators powered by energy from fuel combustion, which may be oil.

1.2.1 Isosteric heating and isobaric desorption

This stage begins with isosteric heating. Heat is supplied to the bed to raise the temperature of both the adsorbent and adsorbate adsorbed on it, as well as the adsorbent, i.e. the non-adsorbed phase. The temperature rises from T_{a2} to T_{g1} . As the temperature increases and the volume of the bed has not changed, the pressure increases. When the condensation pressure (P_c) is reached in the bed, desorption of the adsorbate from the adsorbent surface begins. During desorption, heat is constantly supplied to the bed and the bed temperature increases to T_{g2} at constant pressure. The desorbed refrigerant in the form of an adsorptive flows to the condenser where the superheated vapors are cooled. Then the refrigerant in the condenser is condensed and the refrigerant condensate is cooled. Condensing itself is analogous to condensing in a compressor-steam refrigeration circuit. The first phase ends when the bed is depleted.

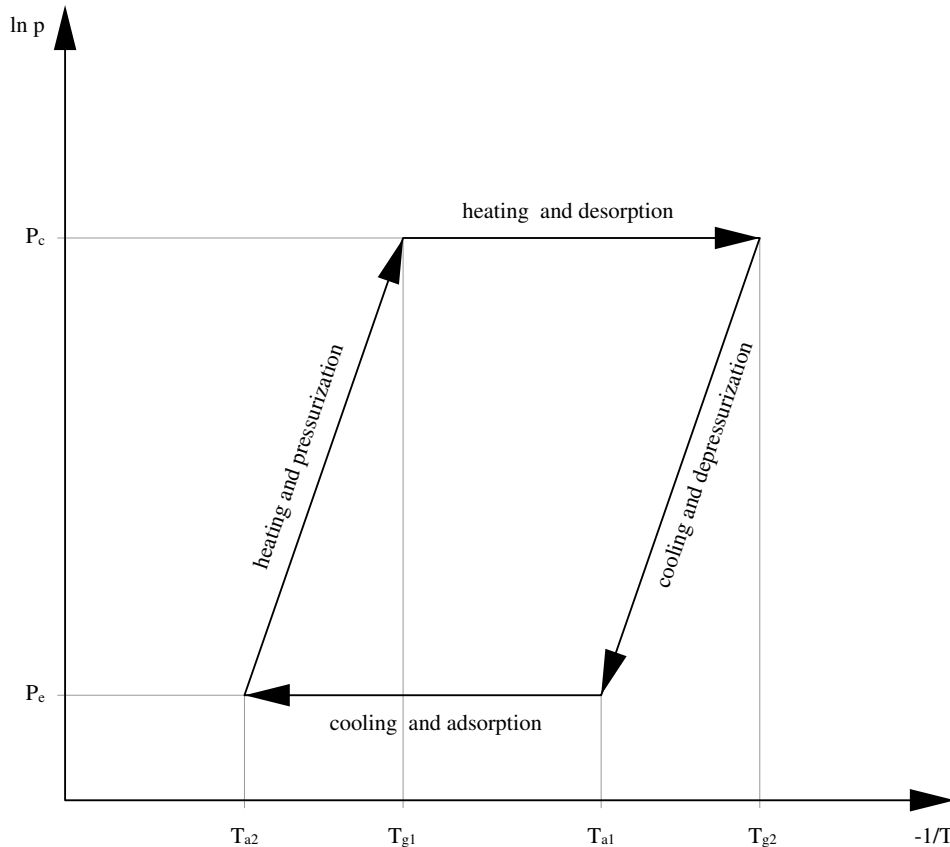


Figure 1. Pressure dependence on the temperature of the adsorption refrigeration cycle.

1.2.2 Isostatic cooling and isobaric adsorption

At the end of the first phase of the cycle, a change occurs. Now the bed is cooled. During heat removal from the bed, the temperature of the adsorbent and adsorbate as well as the adsorbent decreases. As a result of the temperature drop, the adsorption capacity increases and the pressure in the bed decreases. The bed temperature drops to T_{a1} and the pressure drops to evaporation pressure (P_e). It is followed by isobaric adsorption of factor vapors. The refrigerant previously evaporated in the evaporator during the boiling process is introduced into the bed. The boiling process itself is analogous to boiling in compressor-steam refrigeration cycles. During adsorption, heat is further removed from the bed and the temperature drops to T_{a2} .

1.3 Real adsorption cycle

The actual course of processes in the adsorption cycle differs from the theoretical cycle described. At the beginning of the first half-cycle, the system is under low pressure and at a low temperature, and a high degree of adsorption of the refrigerant on the adsorbent surface. The adsorbate vapor is in equilibrium with the adsorbed refrigerant on the adsorbent. When we start to provide heat, the bed temperature increases. As a result of this change, the equilibrium is disturbed and the refrigerant begins to desorb from the adsorbent, increasing the pressure in the bed. You cannot distinguish isosteric heating because desorption immediately occurs. When the pressure reaches the condensing pressure, the valves separating the bed from the condenser are opened. There, the desorbed medium condenses and is discharged into the liquid medium tank. Due to the pressure drop, the condensing pressure is slightly lower than the pressure in the bed. Continuously supplied heat no longer causes the pressure in the system to increase because the refrigerant is simultaneously condensed. When the maximum operating temperature is reached, the medium stops desorbing and the first half cycle is completed by closing the valves. Then the bed is cooled, as a result of which the temperature inside begins to decrease. At a lower temperature, the adsorbent can adsorb more of the medium, so it begins to absorb it, reducing the pressure in the bed. When the pressure reaches the evaporating pressure, the valves separating the bed from the evaporator are opened. The expansion valve upstream of the evaporator regulates the flow of medium from the storage tank to the evaporator. In the evaporator, the refrigerant evaporates and then

flows to the bed where it is adsorbed by the adsorbent. The pressure in the bed stops dropping, because during the adsorption factor continues to flow into the bed. Due to the flow resistance, this pressure is slightly lower than the evaporation pressure. The adsorption process will continue until the initial temperature is reached. Then the valves will close and the second half cycle will end.

Two factors are used to assess the effectiveness of adsorption refrigeration cycles: EER and SCP. The first of these, EER (Energy Efficiency Ratio) is expressed for refrigeration devices as the ratio of the generated cooling power to the driving power consumed by the refrigeration device needed for its operation. Its record for adsorption devices is presented in a slightly different way:

$$EER = \frac{Q_E}{Q_H} \quad (1)$$

That is, as the ratio of the amount of cold delivered during the entire QE cycle to the amount of heat throughout the entire Q_H cycle (3, 7).

Unit cooling power, or SCP (Specific cooling power), is the second indicator for assessing refrigeration equipment. It is calculated as the ratio of the amount of heat to the product of the adsorbent mass and the cycle time and expressed in W / kg.

$$SCP = \frac{Q_H}{m_{ads} \cdot \tau} \quad (2)$$

This value quickly shows how large the adsorbent deposits must be to obtain the average (i.e. nominal cooling power).

1.4 Cycle description

To describe the thermodynamics of the adsorption cycle, you can use the Clapeyron chart in the $\ln P$ ($-1/T$) system with the adsorbate constant concentration lines plotted in Figure 2. During the cycle operation, heat is released due to different binding energy of the molecules during adsorption. The adsorbate particles binding to the adsorbent surface reduce the degree of disorder in the system, and thus the entropy of the system. This change in entropy increases the heat generated by the system, making the entire adsorption process exothermic. The reverse process occurs during refrigerant desorption. The adsorbate particles, being released from the adsorbent surface, increase entropy in the system and this process is endothermic. Desorption absorbs more energy than adsorption generates, leaving the entire endothermic cycle.

2 Sorption pairs

The most important element of any adsorption device is the sorption unit consisting of adsorbent and adsorbate (adsorbent). The choice of assembly usually depends on the desired characteristics of the operation of the device, the properties of the sorption unit, the temperature of the heat source and their cost, availability and environmental impact. It should be remembered that for any application of the working medium, the adsorbent must have low adsorption at high temperatures and high pressure or high adsorption at room temperatures and low pressure.

Adsorbent properties that are important in the context of use in adsorption refrigeration circuits include:

- high adsorption and desorption capacity,
- low specific heat,
- good thermal conductivity,
- non-toxic,
- indifference to structural metals (not metal corrosion),
- chemically and physically compatible with the selected adsorbate (refrigerant),
- low price and high availability

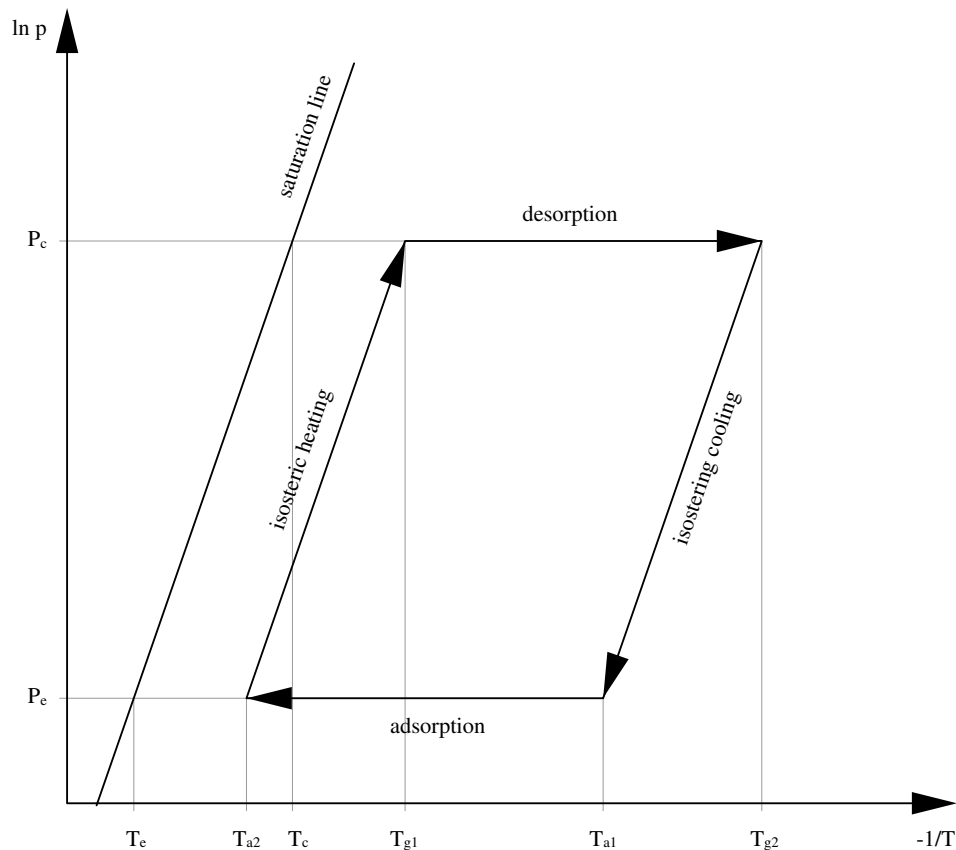


Figure 2. The basic adsorption cycle as a function of P ($-1/T$).

The heat-conducting material for the adsorbent should optimize the high porosity for absorbing adsorbate vapors relative to the high density, since high porosity leads to reduced thermal conductivity. When the bed conducts heat worse, it requires more time to carry out the same processes or to bring more heat to the system (for example, by heating the bed with water at a higher temperature). This affects the component of the thermal efficiency coefficient responsible for the energy supplied to the system, thereby reducing the efficiency of the entire cycle. The most commonly used adsorbents include activated carbon, silica gel and zeolite.

Adsorption systems do not consider adsorbents and adsorbates (working factors) separately, but their connections are called sorption units. Despite this, the working factors themselves also have their own properties important in their selection. These are:

- small particle size, for better adsorption,
- high heat of liquid-vapor phase transition,
- high thermal conductivity,
- stability in working conditions,
- low viscosity,
- low specific heat,
- non-toxic,
- non-flammable and non-corrosive structural metals,
- low saturation pressure,
- environmental performance.

Among the available factors, the most promising are ammonia, methanol and water, which is distinguished by high specific heat and good performance. Ammonia, due to its flammability and corrosivity towards copper alloys, is a factor

of difficult application. Research work is still underway on sorption assemblies for adsorption systems. Unfortunately, no sorption syndrome has been found that meets all the selection criteria, but assemblies that meet most of them are commonly used. The most commonly used sorption units are silica gel - water, zeolite - water, activated carbon - methanol, activated carbon - ammonia and activated carbon - methanol. The capacity of the adsorption refrigeration system depends mainly on the capacity of the adsorbent-refrigerant assembly. We characterize sorption assemblies by means of operating temperatures and pressure, thermal capacity, heat of adsorption, thermal conductivity [(1, 8)].

2.1 Water-silica gel working pair

Silica gel is a type of amorphous, synthetic silica formed from sodium silicate. This gel is a rigid, continuous colloidal silica network attached to very small grains of hydrated silicate tetrahedron (SiO_4). It is a porous material with pore diameters from 0.7 nm to 3 nm and its specific surface is in the range 100 - 1000 m^2 / g . The heat of adsorption of the silica-gel assembly is about 2800 kJ / kg. The desorption temperature for the gel silicon may not exceed 120°C, because above this temperature the gel silicon decomposes. Water itself as a refrigerant is ecological, non-flammable, non-toxic, has a high boiling point of 335 kJ / kg, conducts heat well, has low saturation pressure and is stable during operation. An additional advantage is its high availability and practical lack of acquisition costs. Unfortunately, it has a high specific heat of 4.2 kJ / kg in atmospheric conditions. This sorption unit requires a low temperature source supplying the refrigeration circuit between 60 °C and 85 °C at a low pressure of approx. 5 kPa. The disadvantage of this unit is the low adsorption concentration at 0.2 g / g. In addition, water could be a very good refrigerant if it was not possible to obtain a boiling point below 0 °C. The expected EER values for silica gel - water working pair are 0.45 - 0.75 [(3, 8-10)]. Similar refrigeration devices to the one tested in this work (adsorption devices with two beds using silica gel and water as a sorption unit) generated an SCP index of 132 W / kg [(7)].

2.2 Water- zeolite working pair

Zeolite is a type of aluminosilicate crystal. Pore diameters in aluminosilicates range from 0.2 nm to 0.5 nm. There are about 40 types of natural zeolites in nature, and chabazite, sodium chabazite, faujasite and cowlesite are mainly used for adsorption. In addition, you can artificially synthesize about 150 types of zeolites, which are called single letters or groups of letters, for example type A, type X, type Y, type ZSM, etc. Molecular sieves in synthetic zeolites have pores of uniform sizes and using various methods of synthesis we can achieve various specific sizes. The main types of zeolites used in adsorption refrigeration are 4A, 5A, 10X and 13X. For zeolite sorption assemblies, the adsorption temperature is about 250 - 300°C, and the heat of adsorption is in the range 330 - 4200 kJ / kg, where natural zeolites have lower heat of adsorption than synthetic ones. An example of the maximum adsorption concentration in 13X zeolite is 0.12 g / g.

2.3 Ammonia - AC working pair

Activated carbon is mainly elemental carbon most often produced by the so-called physical activation. It involves carbonization of the source material, followed by gasification of coal with a gaseous refrigerant. Activated carbon materials can be coal, wood, nut shells and synthetic polymers. In fluid adsorption, it is usually used in the form of powder (particle sizes from 15 to 25 mm). Carbon is not toxic and is also used in air purifying filters. The disadvantage of this sorption syndrome is ammonia. It is toxic, harmful to the environment, especially water. In addition, it is flammable and strongly corrodes structural metals. Its specific heat at -30°C is 1365 kJ / kg. The advantage of ammonia, however, is its freezing point below 0°C, which makes it possible to produce ice. For this unit, the heat of adsorption is from 2000 to 2700 kJ / kg, and the maximum concentration of adsorption is 0.29 g / g. The desorption pressure for this unit is 1.6 MPa. Relatively high supports mass flow during the cycle, thanks to which the cooling power of the whole system increases [(8)].

2.4 Methanol-AC working pair

This sorption system is similar to a system using ammonia. It is characterized by lower adsorption heat ranging from 1800 to 2000 kJ / kg. Methanol, like ammonia, has a freezing point below 0°C. For this sorption unit, the maximum desorption temperature is 120 °C. Above this temperature, as with gel silicon, methanol will decompose. In addition, methanol is flammable and highly toxic to humans. The maximum adsorption concentration for this unit is 0.45 g / g, and at 30°C the specific heat is 1229.1 kJ / (kgK). A significant disadvantage of systems using this sorption unit is the need to work under vacuum [(6, 8)].

3 Experimental research

3.1 Description of the experimental apparatus

The design of the tested adsorption refrigeration device is based on two circuits: water circulation as a cooling medium and water as a medium supplying and receiving heat from deposits. In addition, both mass and heat recovery are possible during operation.

The first circuit is shown in Figure 3. The A1 and A2 deposits are tanks with solid silicone gel used in the process of water adsorption on its surface. ZC1 - ZC4 valves are mechanical valves manually adjusted to close or open the flow. The condenser and evaporator are countercurrent plate heat exchangers that are responsible for the liquefaction and evaporation of the medium, as well as exchanging heat with water supplied from the plumbing. ZR is an expansion valve regulating the flow of medium between heat exchangers. There is also a sight glass in this circuit to observe the flow of liquid medium from the condenser to the evaporator. During operation, the flow of medium through the system is controlled by means of valves ZC1 - ZC4. They allow both the flow of the medium from the desorbing bed to the adsorbing bed and for mass recovery after the end of the cycle work phase. For example, when the bed A1 desorbs and the bed A2 adsorbs, the valves ZC1 and ZC3 are open, allowing the flow of medium from the first bed to the condenser and the flow of refrigerant vapor from the evaporator to the second bed. Similarly, when the bed A1 adsorbs and the bed A2 desorbs, the valves ZC2 and ZC3 are open. To recover mass between beds, the ZC1 - ZC4 valves are opened, allowing the medium to flow freely between the beds, bypassing the condenser, evaporator and expansion valve.

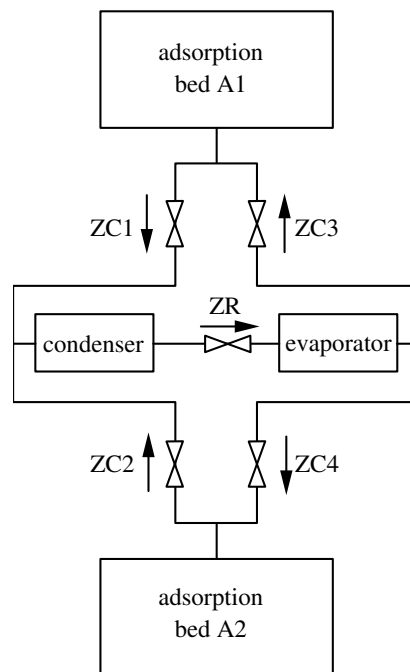


Figure 3. Diagram of the refrigeration circuit of the device

The second circuit is shown in Figure 4. It is the circuit responsible for the flow of water between hot and cold water tanks and adsorbent beds, and thus their heating and cooling. It consists of two beds of adsorbent A1 and A2, expansion vessel 1 with a built-in 2 kW electric heater, expansion vessel 2, water cooler in the form of a counter-current plate heat exchanger fed with water from a water supply system, three circulation pumps and ten electric valves ZW1 - ZW10. The A1 and A2 deposits play the role of heat exchangers in this circuit, and the electric valves are responsible for controlling the water flow in the circuit. At the beginning and end of heating and cooling of the beds, the ZW1 - ZW8 valves are adjusted. After setting the valves, the P1 and P2 pumps start working. The heater is designed to maintain the bed heating water temperature in the range of 79 - 80°C. For example, when we want to heat the A1 bed and cool the A2 bed, the ZW1 - ZW4 valves are opened, while the ZW5 - ZW8 valves remain closed. The heating water then flows through the P1 circulation pump, valve ZW1, bed A1, valve ZW3 and returns to the expansion vessel for reheating. Cooling water flows through the circulation pump P2, valve ZW2, bed A2 and valve ZW4 and returns to the expansion vessel. In the case of heating the A2 bed and cooling the A1 bed, the valves

ZW1 - ZW4 remain closed and the valves ZW5 - ZW8 are opened. In addition, the P3 pump and ZW9 and ZW10 valves in this circuit allow heat recovery between beds. During this phase of the cycle, both valves are open and the pump is running, while the other pumps are off and the ZW1 - ZW8 valves remain closed. At each of the circulation pumps there is a water meter that allows you to measure the amount of water flowing through the pumps, and thus throughout the entire circuit, during operation.

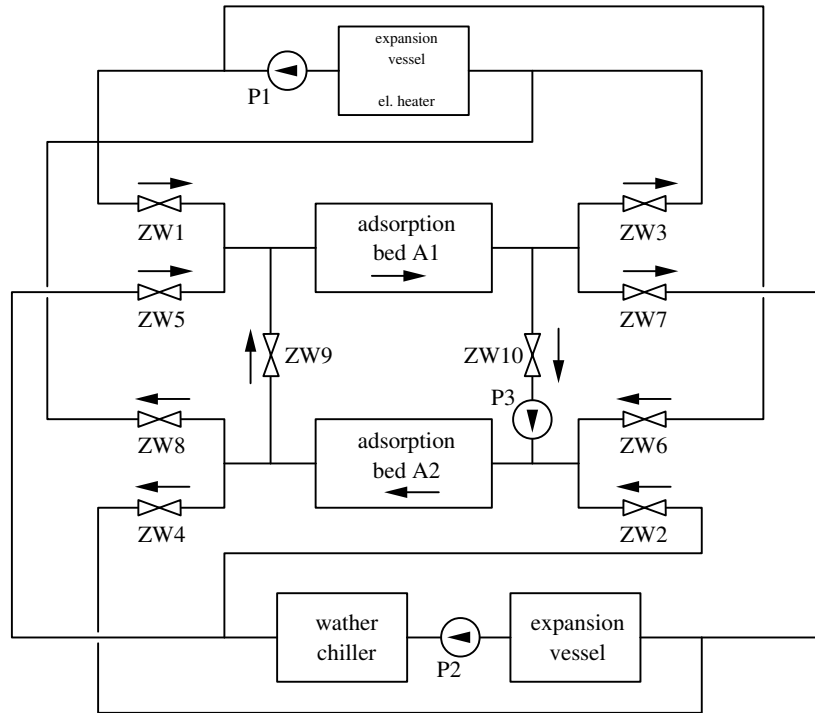


Figure 4. Diagram of the system for heating and cooling the bed

The whole device is also equipped with 4 pressure sensors measuring the pressure in the A1 and A2 deposits, condenser and evaporator, 5 water flow meters counting the water flow through the pumps P1, P2 and P3 and by countercurrent plate heat exchangers in the refrigerant circuit. In addition, the device has 11 temperature sensors. Two pairs measure water inlet and outlet temperatures from the cooling and heating bed circuit. The next two pairs measure water inlet and outlet temperatures from plate heat exchangers in the refrigeration system. One sensor is located in the expansion vessels, and the last one is located behind the water cooler in the cooling system of the adsorbing bed.

Not taking into account the mechanical valves in the working medium circuit, the device is controlled by a measuring and control system using Siemens programmable controllers. The system allows the device to work according to a program uploaded by the operator, or using manual control. During the tests, the system was manually controlled by the author of the work. This control method resulted from the continuous modernization of the device during the tests, which did not allow for fully automatic operation. The device is equipped with a control panel, which is also a monitor. The panel displays the values measured by pressure and temperature sensors in the system and it is possible to switch sets of valves and turn on and off both the heater in the hot water tank and circulation water pumps. Measured quantities are simultaneously saved to a file, which allows further processing. The expansion valve upstream of the evaporator is also controlled by the electronics based on the pressure in the evaporator. In the case of a water heater, the controller also functions as a thermostat, maintaining the temperature of the bed heating water in the range of 79 - 80°C.

During the research, the device underwent a number of modernizations aimed at increasing the device's efficiency. The first elements of the system responsible for heat recovery were added - the originally present P3 pump and ZW9 and ZW10 valves were properly combined in the system. Another change was the reduction of heat loss from deposits to the environment. First, heaters with a power of 150 W were installed with thermostats maintaining a temperature of 45°C on the surface of the reservoirs. Another element that reduced heat loss was a 1 cm thick insulating rubber layer. It was glued on each side of the tank, so that electric heaters were between it and the bed. Another change was the replacement of countercurrent plate heat exchangers that act as a condenser and evaporator for shell and tube

heat exchangers. Trial measurements after this change showed no effect. Because, in addition, there was a suspicion that these heat exchangers were not tight, they were eventually replaced with counter-current plate heat exchangers. Another modernization was the replacement of the expansion valve, because the valve originally installed in the device was damaged. The originally installed valve was a simple solenoid valve that was pulse-opened. It showed a fairly large flow of refrigerant during a single opening, making its work imprecise and the pressure parameters on the condenser and evaporator were highly unstable. The valve has been replaced by Danfoss AKV impulse expansion valve. It shows less flow during opening. After its installation, the pressure parameters on the exchangers were stable, the operation of the valve itself became more even. During the tests, 3 temperature sensors and a condenser pressure sensor were also damaged, which were replaced with new ones.

3.2 Working pair

The device uses a gel - water silicon working assembly. Each of the beds was filled with 29 kg of gel silicon. The entire system contains 2700 g of demineralized water. The heat of adsorption for this unit is 2693 kJ / kg. The planned operating conditions are heat removal by the medium at 13°C and heat supply by the medium at 35°C. Water condensing pressures at these temperatures are 1.5 kPa and 5.6 kPa, respectively. In practice, the heat supply temperature was higher. It was caused by the fact that the beds unevenly heated and cooled, as a result of which the heated bed first reached the intended value of 5.6 kPa and was further heated while the cooled bed did not lower its pressure yet to 1.5 kPa.

3.3 Measurement methodology

3.3.1 The course of the experiment

The research was conducted as follows. After starting the device, the electric heater in the hot water tank was first switched on. After reaching 80°C, the initial half cycle was started, which was to prepare the system for proper operation, during which the phases of mass and heat recovery were skipped. It was a boot half cycle. Without this cycle, there was a risk that the system might not be able to reach a sufficiently low bed pressure before the next cycle that will adsorb the refrigerant. It could be caused by too even adsorption on both beds. For proper operation before the next half-cycles one of the deposits must have a low and the other a high degree of adsorption. Before the initial half cycle began, the control system began recording temperature and pressure measurement data. Data from the sensors are saved with a frequency of 1 Hz in the internal memory of the controller. The data was saved in csv (comma-separated values) format every hour by a computer on the hard disk of a computer connected with an Ethernet cable to the refrigeration device. After initial processing, the data in Microsoft Excel looked as shown in Table 5 Charts of temperature and pressure dependence as a function of time in the further part of the work were made directly on the basis of these data, and charts of temperature difference based on simple calculations from these data. During the operation of the counter-current device, counter-current plate heat exchangers were constantly supplied with water from the water supply system.

The activities performed during each half-cycle were the same. First of all, with the ZC1 - ZC4 valves closed, the heating and cooling water circulation of the A1 and A2 beds was started by starting the P1 and P2 pumps and opening the appropriate valves. The bed to be desorbed was heated and the other cooled. If in the previous half cycle the bed A2 was desorbing, then in the next half cycle the valves ZW1 - ZW4 were opened to heat the A1 bed and cool the A2 bed. The time needed to heat and cool the beds varied and ranged from 10 to 35 minutes. This could be due to the different content of the factor in the bed in both adsorbed and gaseous state. As a result of these differences, heat is transferred differently inside the bed, but we also need more heat to pick up from the bed. In addition, after completing one half-cycle with a greater degree of bed heating in the next bed, more heat had to be taken away from that bed in order to cool more adsorbent.

When the pressure in the heated bed reached a pressure of at least 5 kPa, and in the cooled bed the pressure drop below 1.5 kPa was opened. If bed A1 was desorbing, valves ZC1 and ZC4 were opened. Otherwise, the valves ZC2 and ZC3 were opened. With this setting of valves, the device performed a half-cycle work phase, i.e. the medium flowing through the evaporator received heat from it, generating cold. This phase of the half cycle had a predefined duration of 20 or 25 minutes. During this phase, measurements of water flow through the bed heating and cooling water system were made. This was done by measuring with a stopwatch the time between two readings of water meters placed at the expansion vessels and measuring the amount of water flowing into these vessels. An example of these measurements is shown in Table 4. These measurements were aimed at determining the mass flow of water through the beds. In combination with measurements of the inlet and outlet water temperature made by the computer, it

Table 1. Sample data collected by the device driver after initial processing.

Record	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	p1	p2	p3	p4
1	27.6	24.4	25.7	24.2	23.9	24.3	22.4	22.0	21.5	79.1	16.6	2.1	1.3	4.2	4.2
2	27.6	24.4	25.7	24.2	23.9	24.3	22.4	22.0	21.5	79.1	16.6	2.1	1.3	4.2	4.2
3	27.6	24.4	25.7	24.2	23.9	24.3	22.4	22.0	21.5	79.2	16.6	2.2	1.2	4.2	4.2
4	27.6	24.4	25.7	24.2	23.9	24.3	22.4	22.0	21.5	79.2	16.6	2.1	1.3	4.2	4.1
5	27.6	24.4	25.7	24.2	23.9	24.3	22.4	22.0	21.5	79.2	16.6	2.1	1.2	4.2	4.2
6	27.6	24.4	25.7	24.2	23.9	24.3	22.4	22.0	21.5	79.2	16.6	2.1	1.2	4.2	4.2
7	27.6	24.4	25.7	24.2	23.9	24.3	22.4	22.0	21.5	79.2	16.6	2.1	1.2	4.2	4.2
8	27.6	24.4	25.7	24.2	23.9	24.3	22.4	22.0	21.5	79.2	16.6	2.1	1.2	4.2	4.2
9	27.6	24.4	25.7	24.2	23.9	24.3	22.4	22.0	21.5	79.2	16.6	2.1	1.3	4.2	4.2
10	27.6	24.4	25.7	24.2	23.9	24.3	22.4	22.0	21.5	79.2	16.6	2.1	1.3	4.2	4.2

allowed to determine the amount of heat supplied or received from the deposit.

Table 2. Sample data collected by the device driver after initial processing.

Lp	hot water loop				cold water loop				secondary fluid loop			
	initial value	final value	difference	time	initial value	final value	difference	time	initial value	final value	difference	time
	l	l	l	s	l	l	l	s	l	l	l	s
1st halfcycle	7225	7231	6	137	6420	6431	11	221	351	360	9	188
2nd halfcycle	7290	7300	10	219	6517	6527	10	210	380	392	12	241
3rd halfcycle	7386	7396	10	216	6634	6645	11	225	407	419	12	242
4th halfcycle	7503	7512	9	190	6795	6807	12	233	435	447	12	301
5th halfcycle	7636	7647	11	228	6973	6984	11	209	457	476	19	388

After the cycle work phase, the mass recovery phase was started. To this end, the ZC valves that were previously closed were opened (in this case, they are ZC2 and ZC3). With this valve setting, refrigerant could flow from the desorbing bed to the adsorbent bed bypassing the condenser and evaporator. No cooling power is generated during mass recovery. It is aimed at depleting the adsorbing bed from the refrigerant and adsorbing it in the adsorption bed, which during the next half-cycle should facilitate adsorbent in the bed adsorption and desorption of the refrigerant, respectively. This phase lasted 5, 10 or 15 minutes and only the pressure and temperature in the system were measured. The mass recovery phase was terminated by switching off the P1 and P2 circulation pumps and closing all ZW and ZC valves.

During some tests, a heat recovery phase was carried out after the mass recovery phase. To carry out heat recovery, the ZW9 and ZW10 valves were opened and the P3 circulation pump was started. During this cycle, the heating and cooling water of the bed was transferred only between the beds, which allowed heat to be transferred from the hot bed to the cold bed with circulating water as the only heat transfer medium. During this phase, the water flow in this circuit was measured. The measurement was made similarly to the work phase by measuring the time between two readings on a water meter mounted on the P3 pump. During the tests, the heat recovery phase lasted 10 minutes. Heat recovery was completed by switching off the P3 pump and closing the ZW9 and ZW10 valves. The heat recovery phase in later tests was omitted because to examine its effect on EER and SCP coefficients, it was necessary to carry out tests for cycles with identical duration of the work phase and mass recovery phase during the half-cycle for different lengths of the heat recovery phase, e.g. for its lack and for a 10 minute heat recovery phase.

After the recovery, the heat recovery phase was completed, and when there was no mass recovery phase, the half cycle ended and the device was switched to the second half cycle in which the roles of adsorber and desorber were exchanged between deposits.

4 Results

In Figure 5. the measurements were carried out at the 20 min operating phase and the 5 min mass recovery, while in Figure 6. the 25 min work phase and the mass recovery 5 min. The difference in the length of the work phase is clearly visible in the graphs below. These measurements were aimed at comparing the length of the cycle work phase by examining its impact on the efficiency of the entire half cycle.

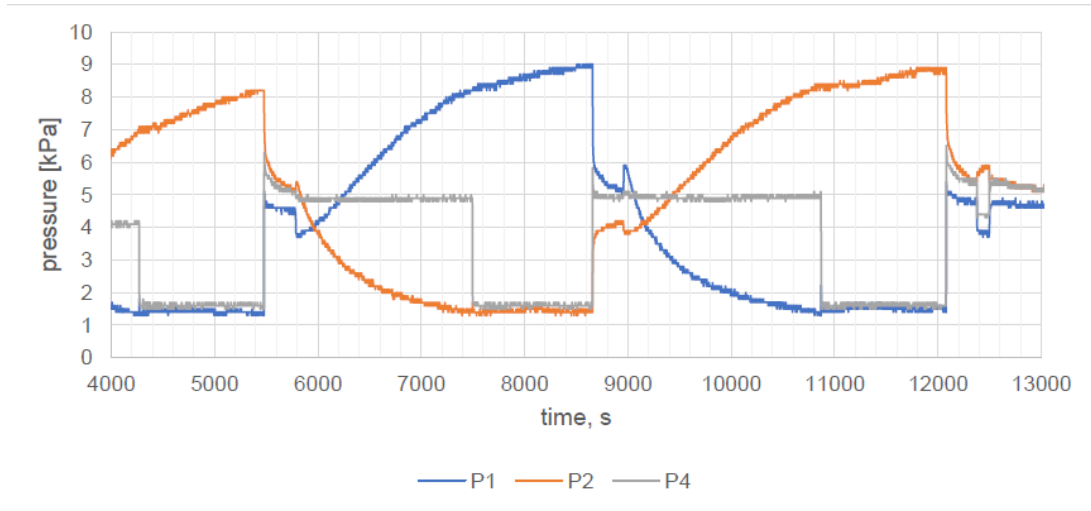


Figure 5. Data for 20 min cycle, (5 min for mass recovery)

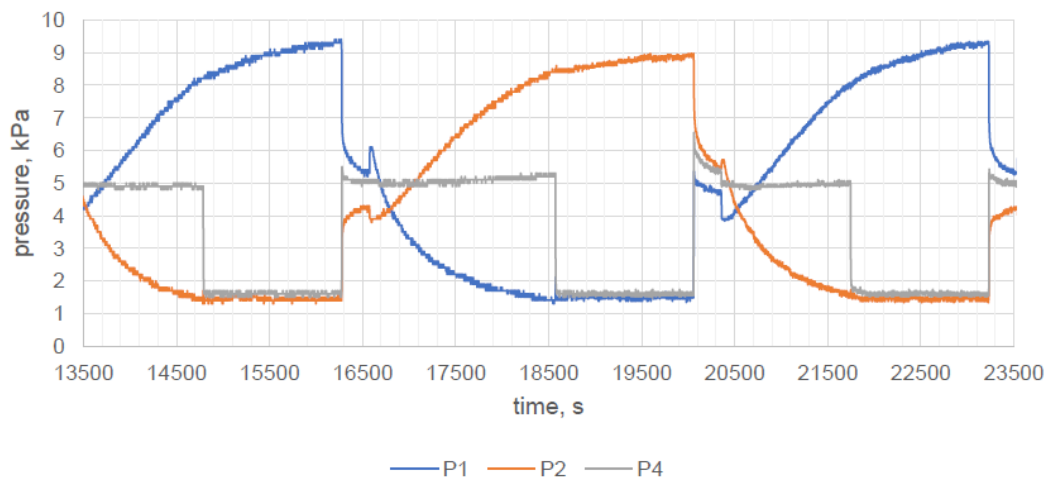


Figure 6. Data for 25 min cycle, (5 min for mass recovery)

EER and SCP were determined based on the measurements. Table 3 presents the summary of calculation results for all half-cycles.

The determined EER coefficients for the tested device can be divided in two ways. The first in terms of the duration of the work phase. The first three semi-cycles operated at a 20- minute work phase and a 5-minute weight recovery, and the EER coefficients for them were 0.68, 0.60 and 0.82 respectively. The half-cycles in the second half of the tests were measured for the 25-minute work phase and the 5-minute mass recovery, and the EER coefficients for them were respectively 0.63, 0.80 and 0.57. These results can also be divided according to the bed that worked as adsorbing. With this division, the A1 deposit adsorbed for semicycles 1, 3 and 5, and the EER coefficients for these semicycles were 0.68, 0.82 and 0.80, respectively. When the bed A2 was adsorbing, i.e. for semicycles 2, 4 and 6, the coefficients were 0.60 0.63 and 0.57, respectively. The average EER for the tested device was 0.68.

Similarly, you can split the results for the SCP indicator. The division according to the length of the cycle work

Table 3. Measurements results

Half cycle		1		2		3		4		5		6	
bed		des.	ads.	des.	ads.	des.	ads.	des.	ads.	des.	ads.e	des.	ads.
m_{wody}	kg/s	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06
Q_{dos}	kJ	741.99	-788.83	2698.95	-2048.31	1621.91	-1856.73	2845.85	-2290.07	1602.96	-2115.95	2968.15	-2147.41
Q_{pw}	kJ	0.77	7.94	2.76	-38.09	0.63	19.70	2.32	30.36	0.67	23.80	2.92	27.30
Q_{aiw}	kJ	243.69	-243.69	212.62	-205.80	297.84	-460.30	308.67	-243.69	297.84	-460.30	243.69	-243.69
Q_{zb}	kJ	118.72	-118.72	86.34	-86.34	145.11	-224.25	150.38	-118.72	145.11	-224.25	118.72	-118.72
Q_{strat}	kJ	78.83	78.8	129.20	129.20	135.68	154.61	106.60	116.86	150.32	171.30	99.14	-116.13
Q_{des}/Q_{das}	kJ	574.94	-507.56	2248.74	-1832.65	1420.34	-1333.22	2628.16	-2058.53	1401.48	-1611.38	2783.05	-1913.10
Δm	kg/s	0.21	-0.19	0.84	-0.68	0.53	-0.50	0.98	-0.76	0.52	-0.60	1.03	-0.71
EER	-	0.55		0.60		0.72		0.60		0.87		54	
SCP	W/kg _{ads}	6.98		18.27		12.13		19.86		13.15		18.53	

Table 4. Measurements results

Halfcycle	bed	m_{wody}	Q_{dos}	Q_{odz}	Q_{pw}	Q_{aiw}	Q_{zb}	Q_{strat}	Q_{des} / Q_{ads}	Δm	EER	SCP
		kg/s	kJ	kJ	kJ	kJ	kJ	kJ	kJ	kJ	kg/s	-
1	des.	0.068	736.7	89.1	0.8	9.0	86.3	91.0	609.1	0.226	0.68	8.61
	ads.	0.070	-783.2	-93.2	8.8	-194.5	-86.3	91.0	-602.2	-0.224		
2	des.	0.066	2679.7	214.2	2.8	226.7	85.4	126.8	2238.0	0.831	0.60	19.33
	ads.	0.071	-2033.7	-108.4	27.9	-194.5	-86.3	127.1	-1907.8	-0.708		
3	des.	0.068	1747.4	46.1	0.7	10.4	99.8	144.4	1603.8	0.596	0.82	14.80
	ads.	0.069	-1913.5	-60.7	26.4	-192.4	-85.4	139.2	-1801.3	-0.669		
4	des.	0.065	2825.5	231.0	2.3	11.4	109.4	118.3	2670.4	0.992	0.63	20.99
	ads.	0.071	-2273.7	-126.4	30.9	-224.8	-99.8	134.1	-2114.2	-0.785		
5	des.	0.067	1591.5	59.5	0.7	10.8	103.6	160.1	1443.8	0.536	0.80	12.13
	ads.	0.070	-2100.8	-93.2	28.3	-246.4	-109.4	162.3	-1935.7	-0.719		
6	des.	0.065	2946.9	220.1	2.9	11.4	109.4	110.3	2791.5	1.037	0.57	19.53
	ads.	0.065	-2132.1	-117.7	28.7	-233.4	-103.6	134.8	-1958.5	-0.727		

phase for the 20 minute work phase was successively received 8.61 W / kg, 19.33 W / kg and 14.80 W / kg, and for the 25 minute work phase 20.99 W / kg, 12.13 W / kg and 19.53 W / kg. If we divide this result by the bed that was adsorbed in a given half cycle for the A1 deposit as adsorbent, 8.61 W / kg, 14.80 W / kg and 12.13 W / kg were obtained, and for the deposit A2 as adsorbing, 19 , 33 W / kg, 20.99 W / kg and 19.53 W / kg. The mean SCP for the 20 minute cycle phase was 14.25 W / kg, and the mean SCP for the 25 minute cycle phase was 17.55 W / kg.

5 Conclusions

As part of the work, a two-bed refrigeration adsorption device was built. The deposits were made of silica gel, and the working medium was water. As a result of experimental studies, EER ratios of 0.57 to 0.82 were obtained.

It turns out that the efficiency of adsorption devices is influenced not only by the supply temperature but also by the temperature that will prevail in the condenser. It is important that adsorption devices usually work with a secondary cooling system.

On the other hand, a relatively low SCP ratio was also obtained - between 8 and 21 W / kg. This means that the 3 kW device requires a bed with a mass of 143 kg at best, i.e. for a silica gel with a density of 500 kg / m³, this means a volume of close to 0.3 m³. These are not the sizes that compressor refrigeration has accustomed us to - so this fact should always be taken into account at project level.

References

1. AHMED, M. S. & kader SHEHATA, A. A. E. *A review: future of the adsorption working pairs in cooling* (2007).
2. DEMIR, H., MOBEDI, M. & ÜLKÜ, S. A review on adsorption heat pump: Problems and solutions. *Renewable and Sustainable Energy Reviews* **12**, 2381–2403 (9 2008).
3. GOYAL, P., BARENDAR, P., MITTAL, A. & SIDDIQUI, A. R. Adsorption refrigeration technology - An overview of theory and its solar energy applications. *Renewable and Sustainable Energy Reviews* **53**, 1389–1410 (2016).

4. GRISEL, R. J., SMEDING, S. F. & BOER, R. Waste heat driven silica gel/water adsorption cooling in trigeneration. *Applied Thermal Engineering* **30**, 1039–1046. <http://dx.doi.org/10.1016/j.applthermaleng.2010.01.020> (8-9 2010).
5. GRZEBIELEC, A. & SZELAĞOWSKI, A. Use of the water-silicagel sorption set in a refrigeration unit. *Przemysł Chemiczny* **96**, 321–323 (2 2017).
6. LI, T., WANG, R. & LI, H. Progress in the development of solid-gas sorption refrigeration thermodynamic cycle driven by low-grade thermal energy. *Progress in Energy and Combustion Science* **40**, 1–58 (1 2014).
7. SHARA, A. & BAHRAMI, M. Critical analysis of thermodynamic cycle modeling of adsorption cooling systems for light-duty vehicle air conditioning applications. **48**, 857–869 (2015).
8. WANG, R., WANG, L. & WU, J. *Adsorption Refrigeration Technology: Theory and Application*. 1st ed. (John Wiley and Sons Singapore Pte Ltd, 2014).