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REFRIGERATION SYSTEMS WITH ONE ADSORPTION BED

Key words: adsorption, desorption, adsorbent, adsorbate.

Abstract: In the article, solutions of devices, using the process described by the Clapeyron diagram are analysed. The diagram characterizes the individual operation phases of a single adsorption bed. Those types of the device solutions are used, among others, for heat receiving. The basic principles describing thermal energy transfer in the single bed adsorption refrigeration system are presented. Multiple adsorption refrigeration solutions with a single adsorption bed are discussed. The solutions use different pairs, e.g., an adsorbent-adsorbate pair. The presented case study includes devices using the cyclical heat exchange during the adsorption and desorption process which are applied in the following: adsorption ice maker, adsorption air conditioning and energy storage systems, as well as solutions for heat receiving and adsorption air-heating systems. Moreover, advantages and disadvantages of the adsorption systems mentioned above are reported. Our own solution of a system with a single adsorption bed is presented. The author's system is characterized by the possibility of using adsorption systems for both air conditioning and adsorption ice makers. The directions and tendencies of further development of the adsorption solutions for refrigeration systems are discussed.

Układy chłodnicze z pojedynczym złożem adsorpcyjnym

Słowa kluczowe: adsorpcja, desorpcja, adsorbent, adsorbat.

Streszczenie: W artykule dokonano analizy rozwiązań urządzeń wykorzystujących proces opisany wykresem Clapeyrona, który charakteryzuje poszczególne fazy pracy pojedynczego złoża adsorpcyjnego. Rozwiązania tego typu są wykorzystywane między innymi do odbierania ciepła. Przedstawiono podstawowe zależności charakteryzujące przepływ energii cieplnej w jednozłożowym adsorpcyjnym układzie chłodniczym. Omówiono szereg rozwiązań adsorpcyjnych układów chłodniczych z pojedynczym złożem adsorpcyjnym, wykorzystujących różne pary jako adsorbent-adsorbat. Prezentowane studium przypadku obejmuje rozwiązania, które wykorzystują adsorpcyjny obieg wymiany ciepła w następujących urządzeniach: wytwornicach lodu, układach klimatyzacji i magazynowania energii oraz rozwiązaniach odbierania ciepła i podgrzewania powietrza. Przedyskutowano wady i zalety przytoczonych przykładowych układów adsorpcyjnych. Przedstawiono własne rozwiązanie układu z pojedynczym złożem adsorpcyjnym, które charakteryzuje się możliwością zastosowania zarówno w układach klimatyzacji, jak i w wytwornicach lodu. Omówiono kierunki i tendencje dalszego rozwoju adsorpcyjnych układów chłodniczych.

Introduction

The development of techniques and technology and the increased demand for electricity prompts search for new methods of reducing the electricity consumption in devices and technical objects. Currently, heating and cooling processes absorb approximately *50%* of the primary energy consumed [1]. A substitute for electricity could be solar energy or thermal energy from low temperature sources [2], including the following: waste heat from operating fluids, heat of exhaust gases from industrial processes [3], together with heat of drain water from the heating plants or geothermal waters heat. As an example of a device which does not use any electricity or requires a minimum electric power supply for refrigeration process is an adsorptive refrigeration system [4]. However, this system needs low temperature thermal energy for its work. This solution for heat receiving process involves an adhesion phenomenon of adsorbate to a surface (adsorption). In order to perform the regeneration of an adsorption bed, external thermal energy needs to be supplied, causing the process of removing adsorbed particles from a surface of the adsorbent (desorption). This type of refrigeration devices utilize sorption processes and require external thermal energy to accomplish the refrigeration cycle. Moreover, in these systems, the refrigerant undergoes phase conversions. The main elements of the adsorption refrigeration systems are the adsorbent and the adsorbate, which are a pair of cooperating substances. The adsorbent-adsorbate pair consists of different substances that can form various combinations of substances within the pair. Generally, adsorbents are divided into physical, chemical, and composite, depending on the abilities of adsorption interactions [5]. Examples of adsorbents could be activated carbon, zeolites, silica gel, or metal chlorides. Examples of adsorbates are water, methanol, ethanol, or ammonia [6–8].

The article presents systems with a single adsorbent bed, using sorption processes as well as varied substances as an adsorbent-adsorbate pair. The number of adsorption refrigeration systems for the heat transfer which include devices of various constructions and applications are described. Furthermore, the author's solution of an adsorption system is briefly discussed.

1. The cycle of work of a single bed

The typical structure of the adsorptive refrigeration system with a single bed consists of the following elements: an evaporator, one adsorber bed, a condenser, and a throttling valve (Fig. 1). This kind of system is powered by thermal energy which generates the cyclical heat receiving process in the evaporator. The work cycle of this type of refrigeration system is comprised of four phases: the adsorbent bed heating phase, the bed regeneration (desorption), the adsorbent bed cooling phase, and the adsorbate adsorption. Furthermore, the periodic run of individual phases in the *Clapeyron* diagram is shown (Fig. 2). During the first phase *(1-2)*, the adsorbent bed is heated in the isochoric process causing the pressure and temperature to increase simultaneously. When the pressure reaches the value p_s at the Point *2*, then the desorption process takes place. During the second phase *(2-3)*, there is further heating of the bed over the isobaric process and desorption is carried out at that time. The end of this phase occurs after reaching Point *3*, when the adsorbent bed is completely regenerated. The next stage of the process is the *3-4* phase, when heat is given back.

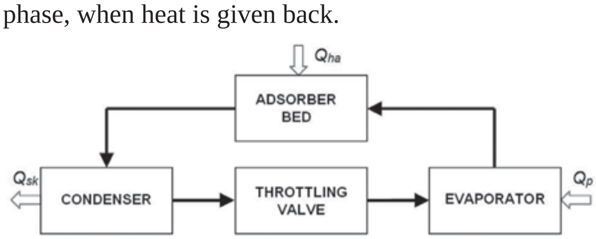

Fig. 1. Block diagram of a single bed adsorption refrigeration system

During this phase, which is the isochoric cooling of a single bed, a decrease in temperature and pressure occurs. At the moment of the p_p pressure of adsorbate evaporation, when Point *4* is reached, the adsorption process starts on the surface of the adsorbent bed. This process is performed during the *4-1* phase while heat is received from the system. At Point *2*, when the desorption process in a single adsorber bed is started in parallel, evaporated refrigerant flows from the adsorber bed to the condenser (Point *3'*). Under the *3'-4'* step, condensation of the refrigerant in the condenser happens.

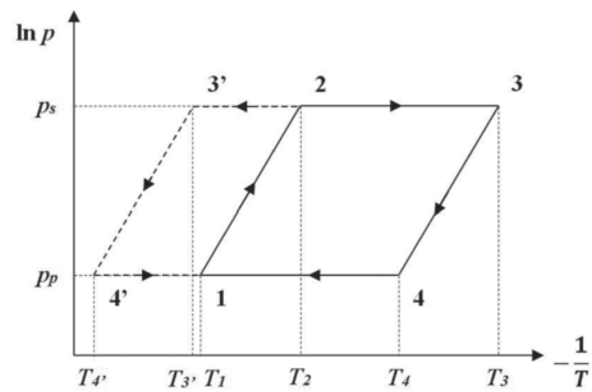

Fig. 2. Diagram of the ideal adsorption cycle running in a single bed of an adsorption refrigeration device [9, 10]

In a further stage, the liquid phase of the adsorbate via the throttling valve into the evaporator space is dosed (Point *4'*). In the evaporator space, the evaporation of the refrigerant takes place whose steam goes to the adsorber bed, where it is re-adsorbed. Moreover, evaporation of the adsorbate in the evaporator causes a decrease of the temperature in the evaporator space under the influence of receiving heat. As a result, a cooling effect in the adsorption refrigeration system is created.

2. The basic principles of energy transfer in a single bed

The above adsorption refrigeration device is powered by thermal energy, which is supplied to the system. Furthermore, the total thermal energy, Q_{ha}, provided to the system comes into a single bed of the adsorber for its heating (Fig. 1). The presented graph (Fig. 2) of the ideal cycle of the adsorption heat exchange shows that the total thermal energy Q_{ha} supplied to the system is equal to the sum of energy Q_{1-2} and energy Q_{2-3} [11, 12]. Whereas, the Q_{1-2} is the energy required to increase the adsorbent temperature of a single bed and the adsorbate (from Point *1* to Point *2*). On the other hand, the Q_{2-3} is the energy needed to continue the heating and desorption process of the adsorbate (from

Points *2* to *3*). The energies can be calculated using the following relations:

$$Q_{ha} = Q_{1-2} + Q_{2-3} \tag{1}$$

$$Q_{1-2} = \left(m_s Cp_s + m_{w1} Cp_w\right)\left(T_2 - T_1\right) \tag{2}$$

$$Q_{2-3} = \left(m_s Cp_s + Cp_w[(m_{w1} + m_{w3})/2]\right) \left(T_3 - T_2\right) + (m_{w1} - m_{w3}) H_{aw} \tag{3}$$

where: m_s – mass of a single bed of the adsorbent, *kg*; m_{w1}, m_{w3} – adsorbate mass, *kg,* (*1,3* – the points on the *Clapeyron* diagram (Fig. 2)); T_1, T_2, T_3 – temperature, *K, (1,2,3* – the points on the *Clapeyron* diagram (Fig. 2)); Cp_s – specific heat of the adsorbent, *kJ/kgK*; Cp_w – specific heat of the adsorbate, *kJ/kgK*; H_{aw} – heat adsorption of the adsorbate, *kJ/kg*; *Q* – thermal energy, *kJ*.

A calculation of the entire evaporative energy of the adsorbate (Q_p) generated in the heat receiving process in the evaporator is shown below:

$$Q_p = \left(m_{w1} - m_{w3}\right) H_{pw} \tag{4}$$

where: H_{pw} is the heat of the evaporation of the adsorbate, *kJ/kg*.

The total Q_{sk} energy dissipated as a result of the refrigerant condensation in the condenser is represented as follows:

$$Q_{sk} = \left(m_{w1} - m_{w3}\right) Cp_w \left(T_{3'} - T_{4'}\right) \tag{5}$$

where: $T_{3'}$, $T_{4'}$ – temperature, *K, (3',4'* – the points on the *Clapeyron* diagram (Fig. 2)).

Performance of an adsorption refrigeration cycle for an adsorber with a single bed, defined as *the Coefficient of the Performance (COP),* is calculated by the following equation:

$$COP = \frac{Q_p}{Q_{ha}} \tag{6}$$

3. Case study of adsorption systems with a single bed

3.1. Adsorptive Ice Makers with a Cylindrical Adsorber

A series of adsorption refrigeration systems are devices powered by solar thermal energy. One of these solutions is a system used to produce ice [13] in which a single adsorber bed consists of a set of parallel tubes (Fig. 3). The basic elements of the system construction are a solar collector-adsorber, a condenser, a condensate tank, a valve, a cold cabinet with evaporator, and ice storage. The solar collector-adsorber in the device is one element. However, they play different roles. On the one hand, the solar collector collects energy from the sun using its thermal exchange area (*2 m*^{2}). Whereas, sorption processes take place in the adsorber. The adsorber is built

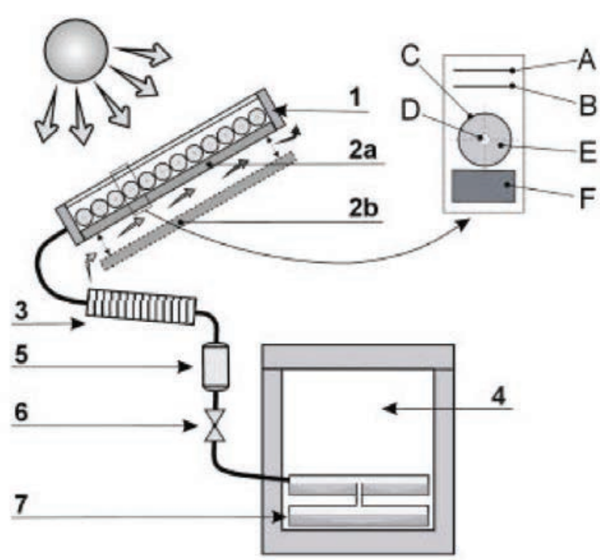

Fig. 3. View and draft of adsorptive solar refrigerator: 1 – solar collector-adsorber with detail: A – glass cover, B – Teflon film, C – tube covered with selective surface and internally layered with Papyex, D – central tube for vapour transport, E – silicagel bed, F – thermal insulation around the collector; 2 – ventilation dampers: 2a – closed and 2b – open, 3 – condenser, 4 – cold cabinet, 5 – graduated tank, 6 – check valve, 7 – evaporator and ice storage [13]

of twelve parallel cylindrical tubes with a diameter of *72.5 mm*. A tube with a smaller diameter (15 mm) runs inside each of the pipes. The central pipes are made of a grid with a mesh of *1 mm* (wire *0.45 mm*). A single adsorber bed contains the adsorbent, which is silicagel (*78.8 kg*), and water is used as an adsorbate in the system. The solar collector-adsorber works in such a way that it is heated by solar radiation during the day and cooled at night by natural convection. The next element of the system is the condenser. It is constructed by eight parallel finned tubes, which are air-cooled as well as through natural convection. Moreover, the total heat transfer surface of the finned condenser is $6.9\ m^2$. The next component of the system is the evaporator, which is made from square pipe in the form of three rings. Furthermore, the entire area of heat exchange in it is $3.4\ m^2$. The evaporator is placed in an insulated chamber with a volume of *320 l*, and the evaporator contains *40 litres* of water, which is converted into ice.

In the presented system, after performing numerous verification tests and improvements, a *COP* from *0.10* to *0.25* was obtained. The distinguishing features of the presented solution are the following: simple construction, the possibility of using solar thermal energy, utilizing ecological substances as the adsorbent-adsorbate pair, and dispensing refrigerant from the graduated tank. The challenges of the system are cyclical operation and the low value of the coefficient of the performance.

Another analysed adsorption refrigeration system is a device for ice production in which the adsorber is designed in a shape of a flat cylindrical container (Fig. 4). In this solution, as in the previous one, solar energy is used as a supply source of the thermal energy. Charcoal with small pieces of blackened steel and methanol are utilized as an adsorbent-adsorbate pair. The charcoal is in the form of granules with a diameter of *5* to *7 mm*. The analysed system is built of an adsorbent bed located in the adsorber, condenser, and evaporator. The adsorbent bed is placed in a flat glass circular container with a diameter of *20 cm* and a thickness of *5 cm*. The thickness of the cylindrical glass of the bed is *3 mm*. The amount of charcoal grains found in the deposit is *0.6 kg,* and the weight of the small pieces of steel is *0.2 kg*. The next element of the system, the condenser, is constructed of a glass tube with a *15 mm* diameter and a *50 cm* length. Another component of the device is the evaporator, which is designed in a shape of a cylinder with a *5 cm* diameter and is also made of glass, and it contains *0.2 kg* of methanol. The operation of the presented solution consists of adsorption and desorption of methanol by the adsorbent bed. During the day, the adsorbent bed is heated by the solar radiation, and the evaporated adsorbate flows to the condenser. In order to condense the evaporated refrigerant in the condenser, the refrigerant in the liquid phase then runs to the evaporator where it is stored. During the night, since there is no supply by the solar energy, the adsorbent bed is cooled through natural convection of the ambient air.

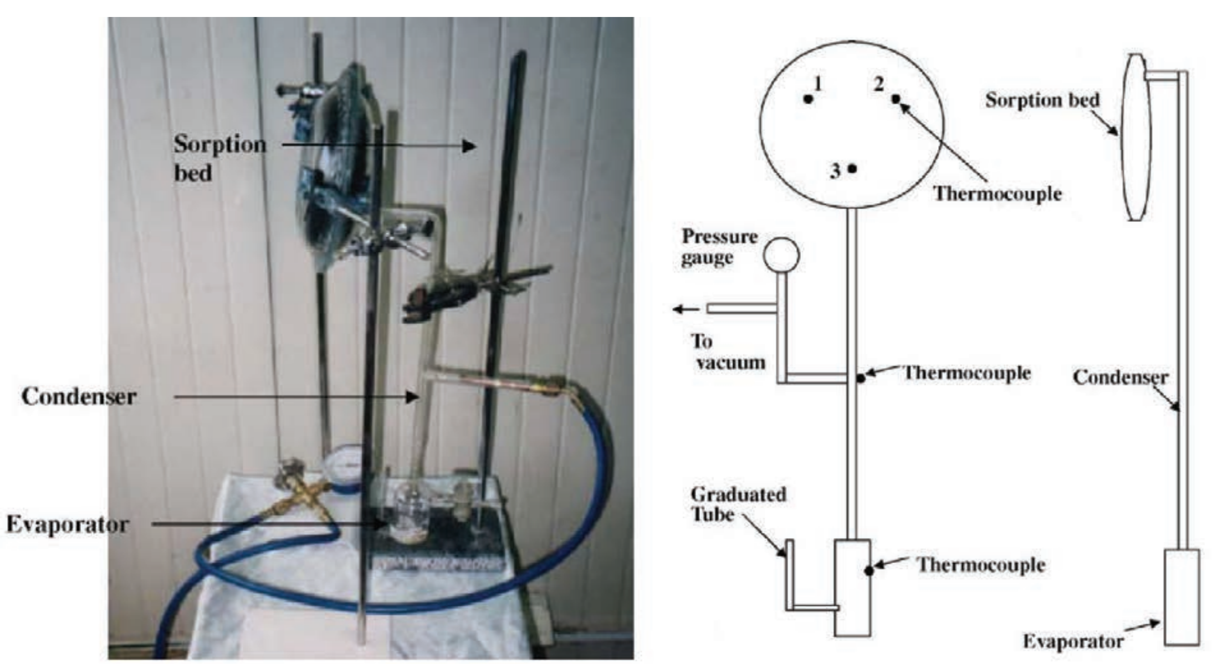

Fig. 4. Photograph and scheme of the adsorption refrigeration system with adsorber in a form of flat cylindrical container [12]

Afterwards, the methanol stored in the evaporator evaporates, resulting in a heat receiving process and ice production. Then, the vapour of the refrigerant is adsorbed by the adsorbent bed during the adsorption process. Operation parameters of the system are as follows: the lowest temperature in the evaporator is *-1°C* by *4 mbar* pressure; *24* to *33°C* is average temperature in the condenser by *125* to *220 mbar* pressure; *114* to *130°C* is maximum temperature of the adsorbent bed; *120* to *162 g* is amount of methanol obtained in the desorption process; and, the gained value of the coefficient of the performance is from *0.136* to *0.159*. The presented solution is characterized by the possibility of utilizing solar energy, simple construction, and the use of ecological substances as the working pair. An unfavourable aspect of the system is storing the liquid refrigerant directly in the evaporator, since it can evaporate in an uncontrolled way. Other unfavourable aspects include the low value of the coefficient of the performance and the periodical work of the device.

3.2. Adsorption Refrigeration System for Air Conditioning with Energy Storage

A different solution using the adsorption refrigeration system with a single bed is a device for the storage of thermal energy in the adsorbent bed. This device is utilized for the heat receiving in the evaporator (generating cold), in this way, air cooling is realized in a connected room. Moreover, the received thermal energy can be directly transferred to this room as well (Fig. 5). The system is dedicated to the cyclical storage of thermal energy from hot exhaust gas of a combustion engine during the daytime and cold generation from the stored heat during the night. The presented solution consists of the two main components: the adsorber and the evaporator/condenser as one element. Furthermore, in this system, *13XBF* zeolite and water is exploited as an adsorbent-adsorbate pair. A single bed is placed inside a finned copper adsorber, which consists of an inner and outer layer, and it is in the shape of a rectangle. The construction of the finned copper adsorber has its benefits, i.e. better heat transfer to the bed. However, this effect is a weak spot of the solution, because it prevents maintaining a low temperature in the bed. Moreover, the internal volume of the adsorber in which the bed is located is *35 l*. The second main component of the system is the evaporator/condenser as one unit, which contains a vessel for a refrigerant.

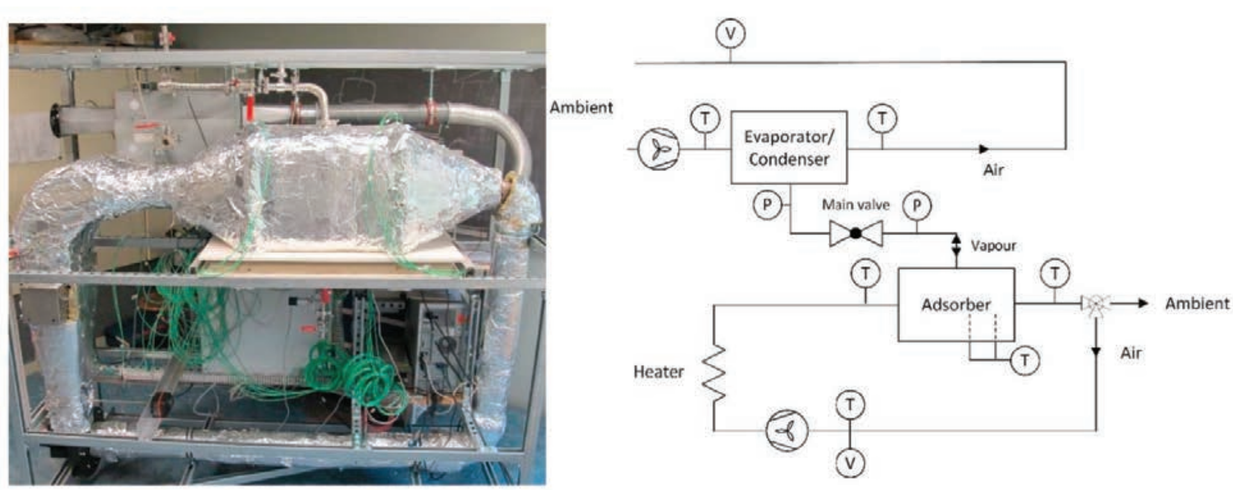

Fig. 5. View and diagram of the adsorption refrigeration setup for air conditioning with energy storage [14]

This element plays the role of the condenser and a refrigerant storage place in the liquid phase during the desorption process. When hot exhaust gas flows by the adsorber, heat transfer to the bed occurs. During this time, the desorption process takes place and thermal energy storage in the adsorbent bed happens. When the desorption process stops and the adsorption starts, the component of the system changes its function from the condenser to the evaporator. Afterwards, the refrigerant stored in the liquid phase evaporates and generates cooling in the evaporator space. During the adsorption process, ambient air flows through the evaporator where is cooled down and flows into the room to be cooled. An additional component of the system is the main valve connecting the adsorber and the unit of the evaporator/ condenser. It works periodically by its cyclic opening and closing. Values of the main parameters of the work of the system are as follows:

- The minimum pressure in the adsorber is *0.1– 10 Pa*.
- The maximum temperature of exhaust gas that flows throughout the adsorber is under *300°C*.

- *12–20°C* is the air temperature in a cooled room.
- The entire amount of stored energy for several hours of cooling is *3 kWh*.
- *20–100 mbar* is the range of pressure change during the desorption process in the adsorber and the condenser.
- *24–40°C* is the temperature in the condenser.
- The pressure change during the adsorption process in the evaporator is *10–24 mbar* when the temperature in the evaporator is below *20°C*.

The interesting features of this system are the possibility of utilizing energy from the heat of exhaust waste gas, using the adsorbent bed as an innovative thermal energy store and applying ecological substances as the adsorbent-adsorbate pair. Furthermore, in the solution, there are some aspects to take into consideration, such as the following: using medium-temperature sources as heat sources, a complicated construction of the device, cyclical operation of the system, and the lack of possibility of long-term maintenance of the low temperature in the adsorbent bed.

3.3. Adsorption System for Heat Receiving and Ambient Air Warming

Another analysed system using the adsorption process is a solution in which the device is utilized to increase the ambient air temperature (Fig. 6). A characteristic feature of this solution is the low temperature of *2–25*°C applied as a heat source. The main components of the presented prototype are the adsorber and the evaporator/condenser as one element. The adsorber is made of two commercial heat exchangers, which are constructed in the form of finned flat tubes. The heat exchange surface of each is *1.24* m^2. Moreover, the volume of the adsorber is *110 ml*, and it is filled with the adsorbent in the form of a $CaClBr/SiO_2$ composite (a grain size of *0.2–0.5 mm* and a mass of *700 g*). The next component of the system is the evaporator/condenser, which is built as a single exchanger, which is the same as mentioned above. In this unit, the refrigerant is stored in the liquid phase.

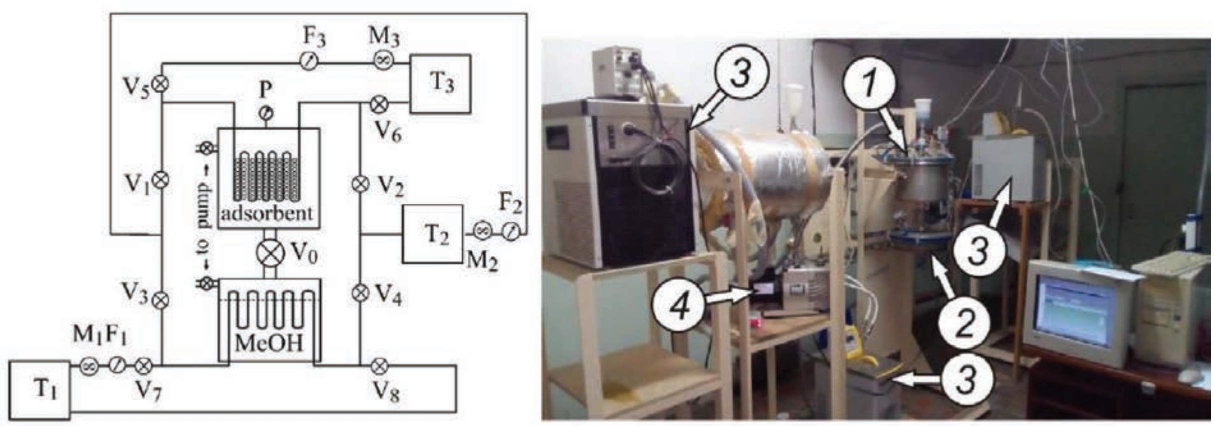

Fig. 6. Photography and diagram of the adsorption system for air heating; 1 – adsorber; 2 – condenser/evaporator; 3 – thermocryostats; 4 – vacuum pump; F1-F3 – flowmeters; V0 – vacuum valve; V1-V8 – valves; P – pressure gauge [15]

The composite and methanol are used as the adsorbent-adsorbate pair. In this device, the methanol is adsorbed at the level of *0.48 g/g*. The subsequent components of the system are the following: the vacuum valve, the vacuum pump, the flow meters, and the pressure and temperature sensors. The system operation depends on the heat received in the evaporator during the adsorption process. In this case, a fluid of the low temperature heat source with a temperature of *2 to 30°C* runs through the evaporator. This kind of energy source can be the waste heat of the domestic sector or the heat of natural water basins. Then, the received heat from the evaporator is transferred to the single adsorbent bed from where the heat is transmitted outside the system as useful heat. The temperature of the thermal energy generated in this way is in the range of *32–49°C*. Thus, the energy at this temperature can be utilized, for example, for warm floor systems. During the desorption process, the external circulation in the adsorber is replaced from a higher temperature circuit to the lower temperature cycle at the range of *2–30°C*. The evaporator switches into the condenser function by changing the outer circulation of the fluid. The circulation is changed from the lower temperature circuit (*2–30°C*) to the very low temperature cycle, which is in the range of *-10 to -60°C*). Therefore, this very low temperature energy source can be, for instance, natural ambient air in cold regions. The desorption process runs in the adsorber at a stable temperature of the low-temperature source, after achieving in the condenser of low pressure in the range of *10–100 mbar*. The presented solution allows the generation of the maximum heating power at the level of *1.0–2.5 kW* with the temperature of the released heat in the range of *32 to 49°C*. A fascinating property of this solution is the innovative application of the adsorption system for the generation of thermal energy using low and very low-temperature heat sources with extreme temperatures from *-60°C* to *30°C*. Furthermore, the challenges of the prototype can be cyclic work, the complexity of the structure, the necessity of mechanical switching of the individual circulations to trigger another sorption process, and no refrigerant container.

3.4. The Author Adsorption Refrigeration System

The major components of the developed proprietary adsorption refrigeration system are the following: adsorber, condenser, throttling valve, and evaporator (Fig. 7). In the prototype, there is a single adsorbent bed which is placed in the adsorber, where the adsorption and desorption process alternate runs. In the device, silica gel and water is exploited as the adsorbent-adsorbate pair, and the amount of silica gel loaded is *4.85 kg*. The adsorber is made of copper in the shape of a cylinder. The condenser is built of copper tubes connected with single flat elements performed with a copper sheet. The adsorber is made of copper in the shape of a cylinder.

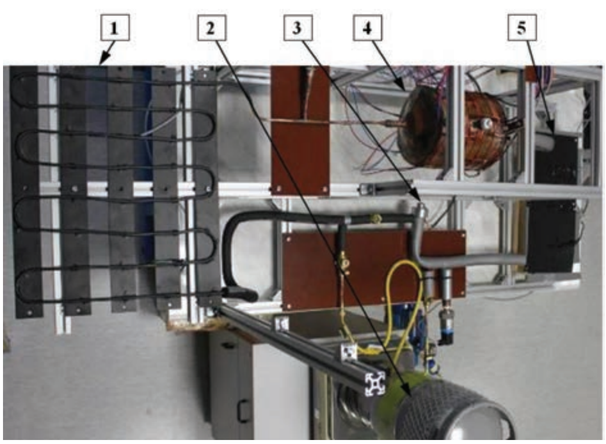

Fig. 7. View of the model adsorption refrigeration system; 1 – condenser; 2 – refrigerant tank; 3 – expansion valve; 4 – adsorber; 5 – evaporator

The condenser is built of copper tubes connected with single flat elements formed from copper sheets. A commercial electronic expansion valve (*LNE* type, *Saginomiya Seisakusho INC*) is used. Another component of the system is the evaporator which is made in the form of a copper plate with copper tubes attached. The system works by forcing the desorption process on the adsorbent bed, and heating the adsorber to a temperature of *70–100*°C. As a result, the evaporated adsorbate passes to the condenser, where the condensation of it takes place. Afterwards, the refrigerant is storage in its tank. From the reservoir, the refrigerant is dosed into the evaporator space via the expansion valve. Evaporated refrigerant in the evaporator flows to the single bed of the adsorbent where it is adsorbed. The evaporation process of the refrigerant in the evaporator causes heat receiving, which results in many hours of temperature drop in the evaporator. The decrease is to the average minimum temperature of *11°C* [16]. As an effect of the multi-day investigations of the device, the average value of the coefficient of the performance is *0.44*.

Conclusions

The analysis shows that the great benefit of the adsorption refrigeration systems is the prospect of their utilization for various applications. In the article, solutions used for ice production, the storage of thermal energy and its use in air-conditioning systems and useful thermal energy generation are presented. The author's solution that can be applied in both air-conditioning systems and ice-maker devices is also described. Other examples of applications of the adsorption refrigeration systems are the following: adsorption chillers [17], sorption heat pumps [18], trigeneration systems [19], and desalination systems [20].

The constructions of the adsorption refrigeration systems are being widely develop due to their advantages, particularly their ecological aspects. This type of solutions have plenty of strengths, e.g., the following [10, 21]: simplicity of construction, low costs of exploitation, noiseless work, immunity to thermal shocks, the possibility of using low-temperature heat sources, corrosion resistance, environmental friendliness (among others due to implementing of environmentally friendly refrigerants), low electricity consumption, no vibration generated during working, and vibration tolerance and insensitivity to deviations and rotation of the system. However, the principal direction of the amelioration of such solutions is the eliminating their drawbacks. Therefore, the challenges include the following [5,11]: low adsorption ability, weak efficiency, discontinuity in operation (cyclic work), insufficient identification of the adsorption and desorption process, low heat transfer coefficients between the adsorber wall and the adsorbent layer, relatively large dimensions and weight in relation to traditional systems, and economic competitiveness in relation to the compressor driven systems. Thus, adsorption refrigeration systems are expected to be widely developed due to their advantages, which will lead to the mitigation or elimination of their disadvantages. The general conclusions resulting from the performed analysis lead to statements about the necessity of the further development of the adsorption systems. This action can be carry on through the following: the development of substances used for the adsorbent-adsorbate pair; improvement of the adsorber construction (as cylindrical, flat or with a complex shape); ameliorating and lengthening the time of refrigerant dosing to the evaporator working space; the development of the construction and operation of the condenser; and, the improvement of other components of this type of systems, e.g.,shut-off valves, expansion valves, reservoirs, and an appropriate location of these subsystems in the installation.

The tendency of investigations of the adsorption refrigeration systems is currently focused on the following issues: increasing the coefficient of the performance, the constructing of systems with a minor cubature, and improving reliability. Furthermore, there should be design solutions that guarantee more effective cooling and heating of the adsorbent, which can be supported by applying modern technologies, such as infrared thermography [22] or innovative coatings of heat exchange elements [23, 24].

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