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ADSORPTION COOLING AS AN EFFECTIVE METHOD OF WASTE HEAT UTILIZATION

CHŁODZENIE ADSORPCYJNE JAKO EFEKTYWNA METODA WYKORZYSTANIA CIEPŁA ODPADOWEGO

A b s t r a c t

The principle of operation of adsorption cooling systems, a review of adsorbent-adsorbate working pairs as well as basic information on modelling and methods for improvement of their efficiency are presented. Possible applications and perspectives for development of adsorption cooling devices are also analysed.

Keywords: adsorption, cooling, waste heat, solar energy

S t r e s z c z e n i e

W artykule przedstawiono zasadę działania adsorpcyjnych urządzeń chłodniczych, stosowane układy adsorbent-adsorbat, podstawowe informacje o modelowaniu oraz rozwiązania służące poprawie ich efektywności. Przeanalizowano możliwości praktycznych zastosowań i perpektywy rozwoju chłodziarek adsorpcyjnych.

Słowa kluczowe: adsorpcja, chłodzenie, ciepło odpadowe, energia słoneczna

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Nomenclature

COP	– coefficient of performance [–]
M_a	– adsorbent mass [kg]
Q	– heat [J]
SCP	– specific cooling capacity [W/kg]
T	– adsorbent temperature [K]
T_{sat}	– saturation temperature [K]
W_L	– cooling power [W]
x_0	– saturated adsorption capacity [kg/kg]

1. Introduction

Cooling is used in many aspects of human life. It is necessary for food storage or air conditioning. The use of conventional compression cooling systems contradicts the concept of sustainable development because of environmental pollution and considerable energy consumption. Freons used in these systems cause ozone layer depletion and are currently being withdrawn from production and marketing under the Montreal Protocol and UE regulations [1]. Moreover, large amounts of energy are supplied to compressor refrigerators. It was estimated that 15% of the total World electricity production and 45% of energy consumed in households, workplaces and public buildings is used for refrigeration and air conditioning [2]. The electricity consumption for these purposes is particularly significant in industrialized countries with warm climate, where increased energy demand for air conditioning in the summer can cause electric grid overloads and blackouts (Table 1).

Table 1

Large electric grid failures [3–7]

Date	Duration	Place	Number of people affected
August 1996	several dozen hours	western states of USA	15 million
July 2006	9 days	USA (New York)	174 thousand
July 2006	4 hours	England (London)	3 thousand
June 2007	several days	Greece	several million
January 2009	several dozen hours	Australia (Victoria)	350 thousand

In recent years there has been a considerable interest is adsorption cooling systems [8, 9]. Refrigerants used in these systems, such as water or methanol, are environmentally friendly. What is more, these devices can be driven by low-temperature sources such as solar energy or waste heat.

Except from the need for waste material management, problems with thermal waste management also exist. A large quantity of waste heat is produced in energy conversion processes, e.g. in automobile engines, power or steel plants. Only a small part of this heat is used and it reduces the efficiency of primary energy utilization. Waste heat usually constitutes 50–70% of the energy supplied as a fuel in thermal power plants and 50–60% of the energy used in internal combustion engines [10]. The part of waste heat which is utilized is about 15% of the gross calorific value of the fuel [10]. Also in solar collectors excessive heat is produced during the summer and can be utilized by adsorption cooling devices. The use of solar energy allows for using these devices in underdeveloped regions with warm climate, where the intensity of solar radiation is often large, while electricity grids are usually not sufficiently developed, so traditional refrigeration systems cannot be used. An advantage of solar powered cooling devices is that the greatest need for cooling coincides with the highest performance of the system.

In addition to environmental benefits and energy saving, adsorption cooling systems have many other advantages [11–13]: simplicity of construction, lack of moving parts, simple control, no vibration, quiet operation and low operating costs. Furthermore, compared with absorption cooling devices, the adsorption systems do not require pumps or rectification columns, they show no problems with corrosion and crystallization, and are less sensitive to shocks.

Disadvantages of adsorption cooling systems include: lack of continuity of operation, high design requirements for the maintenance of high vacuum, large size and mass when compared to conventional cooling systems and low values of the coefficient of performance COP [2, 14]. The low values of COP are the reason why this type of systems should be driven by waste heat or solar energy.

The need for efficiency improvement encourages scientists to search for the possibilities of improving heat and mass transfer during the adsorption-desorption cycle [11]. Most of works focus on adsorption and physicochemical properties of different adsorbent-adsorbate pairs [14, 15], different types of adsorption-desorption cycles, such as heat and mass recovery cycle [13, 16] and mathematical modelling of the process [17–19].
Basic information about adsorption cooling systems, the operating principle, characteristic of adsorbent-adsorbate pairs, improvements in their operation such as heat or mass recovery and principles of modelling of these systems are presented in this work.

2. Operating principle

The operating principle of adsorption cooling devices is analogous to the case of absorption devices: the refrigerant is adsorbed and desorbed. However, because the adsorbent is stationary (a solid), adsorption system is built differently than adsorption system. Usage of stationary adsorbents leads to an intermittent operation of adsorption systems. Continuous cooling requires two or more adsorbents, in which adsorption and desorption processes occur alternately [20].

Main elements of an adsorption cooling system are: an adsorbent bed, a condenser and an evaporator (Fig. 1). The adsorbent plays a similar role to the compressor in traditional cooling systems. The principle of operation of adsorption system may be illustrated using the Clapeyron diagram (Fig. 2). A complete cycle of work consists of four steps: heating of the bed, desorption (regeneration), cooling and adsorption. At point A the adsorbent bed is saturated with adsorbate. Heating leads to an increase in temperature and pressure in the system. At point B condensation pressure is reached and endothermic process of desorption starts, during which the adsorbate is removed from the adsorbent surface and flows into

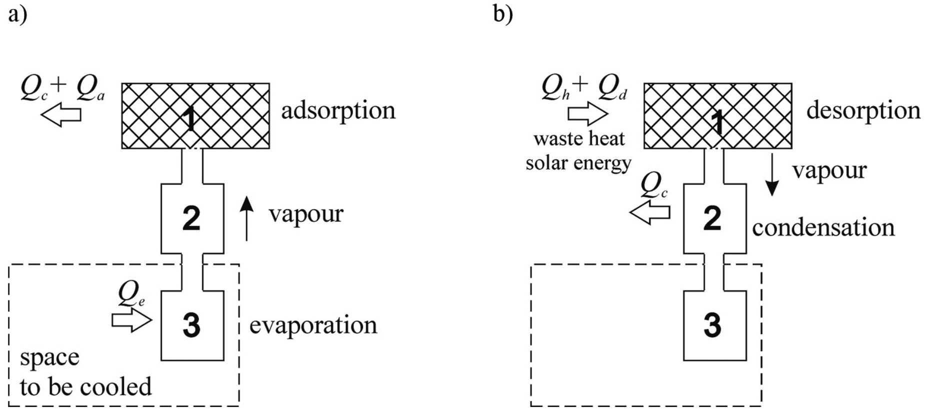

Fig. 1. Adsorption cooling system [21]:1 – adsorber/desorber, 2 – condenser, 3 – evaporator; a) adsorption step, b) desorption step

Rys. 1. Adsorpcyjny układ chłodniczy [21]: 1 – adsorber/desorber, 2 – skraplacz, 3 – parownik; a) etap adsorpcji, b) etap desorpcji

a reservoir or directly into a condenser. The pressure remains approximately constant, while the temperature rises. At point C the temperature reaches the highest value and the bed is theoretically completely regenerated. From this moment cooling of the bed begins and the pressure decreases. When the pressure drops to the evaporation pressure (point D), the adsorbate begins to boil. The heat necessary for this process is taken from the space to be cooled and the cooling effect is produced. Adsorbate molecules are adsorbed on the surface of the adsorbent (section D-A) and the cycle is closed. Because of the exothermic nature of adsorption, the heat Q_a is emitted to the environment. Adsorption of large amounts of adsorbate requires additional cooling of the adsorbent bed [21].

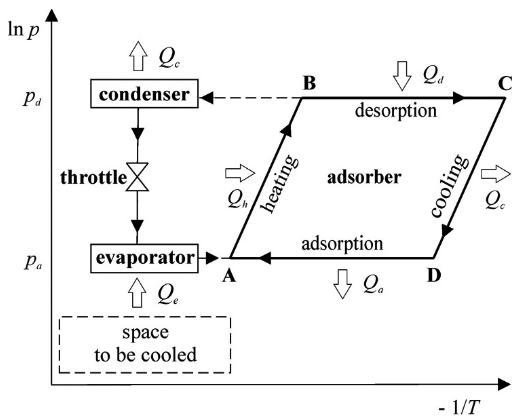

Fig. 2. Adsorption cooling cycle [13, 14, 21, 22]

Rys. 2. Cykl chłodzenia adsorpcyjnego [13, 14, 21, 22]

3. System efficiency evaluation

The efficiency of the system can be determined using two factors: the coefficient of performance COP and the specific cooling capacity SCP. COP is the ratio of heat taken from the space to be cooled during evaporation of the refrigerant to the amount of heat delivered to the system for heating and desorption [2, 23]

$$\mathrm{COP} = \frac{Q_p}{Q_d + Q_o} \tag{1}$$

COP is highly dependent on the temperature of a heat source: the higher the temperature, the greater the COP value. However, above a certain temperature changes are small.

The specific cooling capacity SCP is defined as cooling capacity per kg of the adsorbent [14]

$$\mathrm{SCP} = \frac{W_L}{m_a} \tag{2}$$

SCP takes the mass of the adsorbent and the cooling power of the device into account, so it indicates the compactness of the system [24]. The greater the SCP value, the more compact the device. The value of SCP may be increased by the enhancement of external and internal heat transfer in the adsorber [11].

4. Advanced adsorption cooling cycles

Due to the low efficiency and intermittent work of the basic or single-bed cycle [10, 16] shown in Fig. 2, many more advanced cycles have been developed. These are primarily heat recovery cycle and heat and mass recovery cycle, in which the system of two or more beds is used. Other advanced cycles are thermal wave cycle, convective thermal wave cycle, cascading cycle etc. [10, 16].

In the heat recovery cycle [10, 16], heat from the desorber to be cooled is passed by the heating medium to the adsorber to be heated. With the heat recovery COP can be increased by 25% [16].

The heat and mass recovery cycle [10, 16] is comprised of two steps: mass recovery and heat recovery. In the mass recovery step, when temperature and pressure in a desorber are maximal (point C in Fig. 2) and temperature and pressure in the adsorber are minimal (point A) the desorber and adsorber are connected by the valve. Adsorbate vapour flows from the desorber to the adsorber. Pressure in the desorber decreases and further desorption occurs, while pressure in the adsorber rises, which enables more adsorbate to be adsorbed. The mass recovery is maintained until pressures in the two beds are equal. After mass recovery, the heat recovery process can be applied because of a large temperature difference between the adsorber and desorber. The mass and heat recovery cycle is expected to improve not only COP but also SCP [10]. When this advanced cycle is implemented, the ability of an adsorption cooling system to use low-temperature heat sources increases [10].

5. Adsorbent-adsorbate pairs

Work of an adsorption cooling device depends heavily on the adsorbent-adsorbate working pair [10, 13, 14]. A well-designed system should have large adsorption capacity and large capacity changes with temperature variations. The choice of the adsorbent-adsorbate pair is also influenced by costs and availability on the market.

An adsorbent [21] must have the ability to adsorb large quantities of an adsorbate at low temperatures and to effective desorption when temperature rises. Its properties should not change with age and use. Adsorbents can be divided into physical, chemical and composite [14]. Physical adsorbents include activated carbon, activated carbon fibre, silica gel and zeolite, while metal chlorides or oxides, salts and metal hydrides are chemical adsorbents. Composite adsorbents are usually obtained by combining a chemical adsorbent with a porous material with high thermal conductivity, which may or may not exhibit adsorption properties. Metal chlorides with activated carbon, activated carbon fibres, expanded graphite, silica gel or zeolite are the most common combinations [14].

An adsorbate [2, 10, 14] should have the evaporation temperature below 0°C, low saturation pressure (1–5 atm) at normal operating temperature, high latent heat of vaporization and small size of molecules. It should also be chemically and thermally stable, non-flammable, non-toxic and non-corrosive. Ammonia, water and methanol are the substances most commonly used as adsorbents. Ammonia has an advantage of a low normal boiling point of −34°C. However, its saturation pressure of 13 atm at 35°C is high and moreover it is toxic and corrosive. Methanol has the normal boiling point of 65°C. Its low saturation pressure may be used for leakage detection, which must cause an abnormal increase in the system pressure and efficiency drop. The disadvantage of this alcohol is its flammability. Water has much higher heat of vaporization (2258 kJ/kg) than ammonia (1368 kJ/kg) and methanol (1102 kJ/kg) and is the most thermally stable and ecological refrigerant. Nevertheless, it has an extremely low saturation pressure and cannot be used for freezing purposes.

The most common working pairs used in the adsorption cooling systems are: activated carbon–methanol, activated carbon fibres–methanol, activated carbon–ammonia, zeolite–water, silica gel–water, calcium chloride–ammonia, composite adsorbent–ammonia. From a practical point of view none of these pair is ideal. The main limitation is the poor mass and heat transport within the adsorbent bed. Adsorbents which are currently used have low thermal conductivity and low porosity [2]. This results in a large scale of apparatus and excessive energy consumption, which in consequence leads to low values of the COP.

Table 2

Comparison of adsorbent-adsorbate pairs [2, 14]

Adsorbent-adsorbate pair	Evaporation temperature	COP
silica gel–water	10°C	0.4
activated carbon fibres–calcium chloride–ammonia (composite adsorbent)	1°C	0.6
activated carbon–ammonia	3°C	0.67
zeolite–water	5°C	0.9

6. Modelling

A mathematical model must include each part of the system, i.e. an adsorber, condenser and evaporator [22]. The model describes heat transfer between these devices and mass transfer inside the adsorber. In the case of the adsorber, heat balance for the adsorbent, the wall of the apparatus and the heat transport medium, as well as mass balance and momentum balance for gas phase must be written separately for an adsorption and desorption phase [17, 19, 22, 24]. The condenser and evaporator are described by the heat balance [22]. If an impact of the heat source on the work of the cooling system is to be determined, efficiency and temperature changes of an external heat source must also be described using appropriate relations [17, 19].

Due to the fact that mass transfer rate must be implemented in the balance equations, it is necessary to determine the kinetics model describing the rate of the refrigerant transfer between the gas phase and the surface of the adsorbent. The Linear Driving Force model (LDF) may be used for this purpose [23].

7. Application

Depending on the desired temperature, the use of adsorption cooling systems can be divided into three categories [2]: air conditioning (8–15°C), refrigeration for food, vaccines and medicines storage (0–8°C), freezing and ice making (< 0°C).

There is a heavy demand for air conditioning in industrialized countries, particularly in big cities in the summer. Solar collectors connected with an adsorption cooling device may be used for air conditioning purposes. Prototypes of such systems already exist. They are designed for the use in trade, servicing and industrial buildings and also in vegetable, fruit and grain depots [11, 16, 25, 26]. Besides these prototypes described in the literature, there are also adsorption coolers driven by solar energy which are used in commercial buildings. Japan and the USA are the leaders in this area [11], however, in Europe the market of these devices is also developing and they can be found in real buildings like hospitals or factories [11]. To a large extent it is a result of such programmes as Climasol or Solair [26, 27]. The adsorption air conditioning systems driven by waste heat which comes from e.g. automobile exhaust gases or industrial processes, are also under development. Because adsorption cooling devices have large volume and mass, nowadays they can be used only in locomotives, boats, buses and trucks [11, 12] or in industrial buildings in which a lot of waste heat is produced, e.g. in chemical, steel or power plants [10].

The need for preservation of food products such as vegetables, fruit, milk and meat, in order to extend their availability on the periods in which they are not produced, opens another field for the application of adsorption cooling systems, especially those which are driven by solar energy [25, 28]. Such systems can also be used for medicines and vaccines storage [28]. Their work can be based on blowing the cold dry air produced by the device into the space to be cooled when the temperature inside rises [26]. The product which is cooled plays the role of a cold storage material.

Another promising way of application of adsorption chillers is freezing and ice making. In this case the temperature must be below 0°C, so heat sources must have higher temperatures than in the case of cooling or air conditioning [2]. Many prototypes of ice making adsorption devices driven by solar energy exist in the world [11, 23, 29]. Its work corresponds to the natural diurnal and nocturnal solar periods. Desorption occurs during the day, adsorption and ice making – during the night. These systems are usually built as well-insulated containers which are cooled by the produced ice. Medicines, vaccines and food can be kept in them in those regions of the globe, in which there is no access to electricity, and thus the application of conventional refrigerators is not possible. Another possibility is to use waste heat as an energy source. Prototypes of such devices are also known [15]. The produced ice can be used e.g. for fish preservation on fishing boats.

Adsorption heat pumps are devices based on a similar principle as adsorption cooling systems [30] but they can be used for both heating and cooling. In this case solar energy, geothermal energy or waste heat can be used as a source of driving energy.

8. Conclusions

Cooling (heating) systems based on adsorption-desorption cycles are environmentally friendly and have many advantages which allow them to compete with absorption and compression devices. A great advantage is a possibility of using waste heat or solar energy as an energy source.

Studies on adsorption cooling are conducted in many countries of the world. However, these studies have not led yet to a state that allows researchers to model, design and apply these systems commercially. Tests are conducted for specific cases and there are no generalizations, which are necessary for predicting how the process will run under different conditions. Nowadays, the coefficients of performance are unacceptably low, adsorption-desorption cycles are too long and volume and mass of adsorption devices are too large for the commercial use. Further research, concerning for example heat and mass transfer enhancement, is necessary. A numerical simulation can play an important role in this field. Moreover, adsorption cooling seems to be a prospective field for research as there are few studies on their work under the central European climatic zone conditions.

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