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USE OF CARBON FIBROUS SORBENT IN AN ADSORPTION REFRIGERATOR

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Results of experimental study of heat and mass transfer on a model of a refrigerator adsorber with a carbon fibrous adsorbent–acetone sorption pair are presented.

Sorption devices for heat transformation (like refrigerators and heat pumps) depend for operation on external energy in the form of heat. This makes it possible to regard them as an important element of energy-efficient technologies, since these devices can utilize the heat of industrial plants or can be used along with alternative energy sources. Another circumstance that in the past decade became foremost in evaluating technologies is the problem of conserving the ozone layer of the planet. In the area of refrigeration engineering, the most hazardous chlorine- and fluorine-containing compounds (coolants) are now actively abandoned. The range of potential ecologically safe refrigerants can be extended if the refrigerator is constructed on the basis of a sorption cycle. Additional oportunities arise from creating new types of solid sorbents because, apart from such traditional refrigerants as water and ammonia, a great many other organic and inorganic fluids with appropriate thermophysical and performance characteristics can be brought into consideration.

Adsorption refrigerators do not have moving parts, as is the case with steam compression plants, and do not generate noise and vibrations. They are more resistant to shaking and change of position than absorption devices, which makes it possible to use them in vehicles.

Works on designing adsorption refrigerators are currently underway in France, USA, China, and other countries [1-4]. Use is made of various sorbents and composites based on them, but among other solid sorbents we should note activated carbons owing to their chemical stability, mechanical strength, and high sorption capacity in relation to many materials. The development of new technologies of producing carbon sorbents allows modification of the sorbent properties in the desired direction, specifically, an appreciable increase in their sorption capacity. In this respect, of great interest are carbon fibrous materials [5] whose specific surface can be as large as 2000 m^2/g and more, which allows the creation of sorption-type refrigerators.

At the same time, it should be noted that the set of sufficiently well studied sorption pairs with reference to the problem of designing refrigerators is limited. As refrigerants (the use of coolants should now be excluded), consideration has mainly been given to ammonia, methanol, and water, and as adsorbents, to calcium chloride, granulated activated carbon, some zeolites, and silica gel.

Ammonia has good thermophysical properties and is widely used in refrigerators. However, its employment imposes more stringent requirements on structural strength of the refrigerator. Methanol is toxic. Water can only be used at positive temperatures.

Among advantages of carbon fibrous sorbent the most important for use in refrigerators are the following:

a) the possibility of controlling the sorption properties of adsorbents over a wide range;

b) high rates of adsorption and desorption;

c) the possibility of creating adsorbents of different textile forms (in the form of rope, fabric, felt, etc.), due to which they can be freely included in the structural elements of refrigerators.

This study employs a carbon fibrous adsorbent of the "Busofit" type, produced in the Republic of Belarus, with a specific surface of 2400 m^2/g [6]. Acetone is selected as the refrigerant. This material is used in manufacturing heat pipes and it demonstrated good compatibility with the structural materials.

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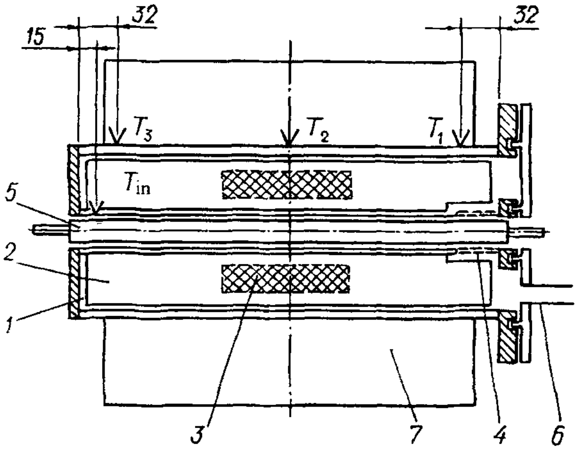

Fig. 1. Schematic of the adsorber model: 1) cavity for the sorbent, 2) fin, 3) sorbent, 4) bellow, 5) electric heater, 6) steam line, 7) fin.

The theory of volume filling of micropores adequately describes adsorption on such sorbents as activated carbons. At the same time, this theory, like others, has limitations of its own. Specifically, this is manifested in that at small values of sorption (for AC35 granulated activated carbon when $a < 0.087$ kg/kg [7]) and at pressures approaching P_s at the sorbent temperature, i.e., at states close to saturation, there are significant deviations of experimental data from theoretical results.

Another circumstance to be taken into account when designing adsorption refrigerators is that total adsorption equilibrium is usually unattainable because the process is very long. At the same time, a full account of kinetic effects over the entire range of adsorption values is also very complicated.

In this connection, of great practical interest is an experimental study of the characteristics of heat and mass transfer in an adsorber model complying in its parameters with the requirements of a real refrigerator.

The experimental setup includes a sorbent-containing adsorber, an evaporator, a condenser, and vacuumizing and cooling systems.

The amount of the adsorbed working fluid (refrigerant) was determined using a glass evaporator in the form of a measuring flask placed in a temperature-controlling glass vessel with hollow walls. The evaporator surface is provided with a scale that allows recording of the volume of the fluid residing in the evaporator. The circulation of the refrigerating fluid through a coiled heat exchanger, also immersed in a temperature-controlling vessel, maintains the evaporator temperature below the ambient temperature.

Figure 1 shows the structure of the adsorber model used in this study.

The adsorber cavity is 400 mm long, the larger diameter of coaxial clearance is equal to 60 mm, and the smaller, to 18 mm. The sorbent mass is 217 g.

A strip of the carbon fibrous adsorber is wound on thin copper plates and afterward is fitted tightly between fins 2 and the coaxial cylindrical tubes of the adsorber frame. The thermal conductivity of the sorbent is about 0.13 W/(m·K) [8]. The thermal resistance of the copper plates and fins is much smaller than that of a tricot strip.

The adsorber is heated via tubular electric heater 5 located in the inside tube. Finning is also imparted to the outer surface of the adsorber to ensure its efficient cooling.

Near the steam inlet to the cavity of the adsorber model a free space is left for a more uniform distribution of the vapor phase of the refrigerant over the sorbent placed between the fins.

The arrangement of the thermocouples is shown in Fig. 1. The temperatures T_1, T_2, and T_3 are recorded by the thermocouples located on the outer surface of the adsorber. The thermocouple T_2 is placed in the midsection of the adsorber. The experiments determine time dependences for the temperature at the points indicated in Fig. 1, for the pressure in the adsorber cavity, and for the amount of adsorbed refrigerant.

Figure 2 presents experimental data for adsorber heating and cooling.

Figure 2a displays a time dependence for acetone sorption during adsorption. Prior to measurements the working fluid is withdrawn from the sorbent with the aid of a vacuum pump. This figure also illustrates the

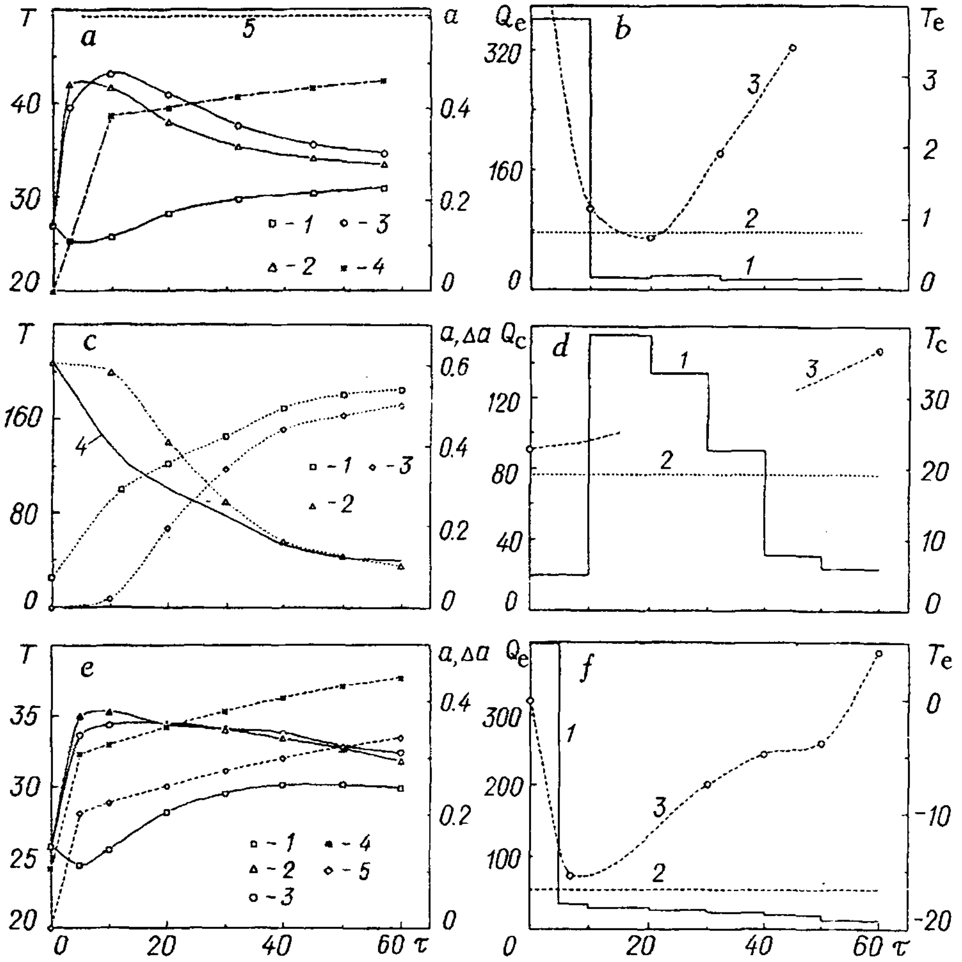

Fig. 2. Time dependences of the characteristics of heat and mass transfer in adsorption-desorption: a) adsorption: 1) T_1 (see Fig. 1), 2) T_2, 3) T_3, 4) sorption, 5) ultimate sorption at $T_{\text{sorb}} = 21^{\circ}\text{C}$; b) the same: 1) specific heat flux, 2) mean specific heat flux over the adsorption period, 3) temperature in the evaporator; c) desorption: 1) sorbent temperature, 2) sorption, 3) sorption variation, 4) equilibrium sorption at $T_c = 21^{\circ}\text{C}$; d) the same: 1) specific heat flux, 2) mean specific heat flux, 3) condensation temperature; e) adsorption: 1) T_1, 2) T_2, 3) T_3, 4) sorption, 5) sorption variation; f) the same: 1) specific heat flux, 2) mean specific heat flux, 3) temperature in the evaporator. τ, min.

temperature variation for the adsorber surface at the points indicated in Fig. 1. Initially, the sorbent temperature was equal to room temperature. The specific heat flux (per kg of sorbent) in the evaporator and the fluid temperature therein, corresponding to the data of Fig. 2a, are shown in Fig. 2b. The specific heat flux and the mean specific heat flux are obtained from the expression

$$Q_e = \Delta a_a r_e / \Delta \tau_a \,, \tag{1}$$

where Q_e is the specific heat flux in the evaporator (per unit mass of sorbent).

Figure 2b shows the maximal amount of heat removed from the evaporator for the given adsorber. The mean specific heat flux is 76.4 W/kg. The major part of the heat energy is withdrawn from the evaporator during the initial 10 min. In 57 min the value of sorption amounts to 0.46 kg/kg, which corresponds to 261 kJ/kg of heat energy withdrawn from the evaporator. The presented temperature dependences also indicate that the sorbent is cooled by a steam flow arriving from the evaporator. This is attested by a significant stratification of the temperature

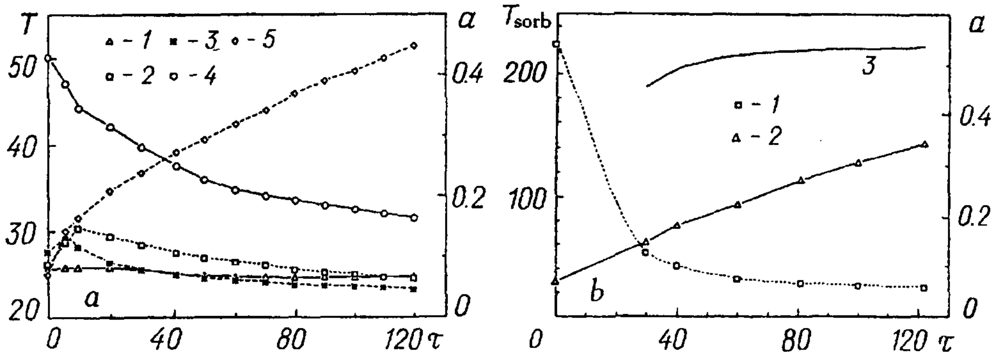

Fig. 3. Time dependence of the surface temperature of the adsorber and sorption (a) and of the sorbent temperature and sorption (b) in adsorption ($T_e \leq 0^oC$): 1) T_1, 2) T_2, 3) T_3, 4) T_{in}, 5) sorption (a); 1) temperature, 2) sorption, 3) equilibrium sorption at $T_e = 0^oC$ (b).

curves. Heat transfer in the sorbent layer proceeds in two ways: a) by heat conduction through the sorbent and b) by forced convection from the sorbent to the steam.

The results of determining the amount of desorbed working fluid are plotted in Fig. 2c, which shows the variation in two characteristic mean temperatures: T_{surf} and $T_{sorb} = (T_{surf} + T_{in})/2$.

Figure 2d presents the heat flux in the condenser and the condensation temperature corresponding to the data of Fig. 2c. The specific heat flux in the condenser and the mean specific heat flux are obtained from the expression

$$Q_c = \Delta a_d r_c / \Delta \tau_d , \tag{2}$$

where Q_c is the specific heat flux in the condenser (per unit mass of sorbent).

Over the desorption period, the maximal specific heat flux in the refrigerant condensation is about 156 W/kg, which is more than twice as large as the mean specific heat flux for the same period, equal to 76 W/kg.

Figure 2e shows the time dependence for the amount of adsorbed refrigerant in adsorption carried out after desorption in accordance with Fig. 2c. The temperature and the specific heat flux in the evaporator are presented in Fig. 2f. The initial temperature was 0°C. Transition to the region of subzero temperatures in the evaporator, from 0 to −15°C, is accomplished in 7 min.

Figure 3 gives experimental data for a 600 mm long adsorber model with the larger diameter of the cavity equal to 74 mm and the smaller diameter, to 16 mm. The sorbent mass is 500 g. Copper plates were not used in laying the sorbent in this case; the sorbent was placed in a disorderly manner.

Figure 3a shows time dependences for the temperatures on the adsorber surface and the value of sorption. In the initial state, the temperatures of the outer surface of the adsorber are close to room temperature. On the inner surface adjoining the electric heater the temperature is about 50°C. Increase in the adsorber dimensions and the sorbent mass does not lead to qualitative changes during sorption in comparison with Fig. 2. The results presented in Fig. 3a support the conclusion that heat transfer inside the adsorber proceeds in two ways. Comparing the data of Figs. 2 and 3a reveals that a regular arrangement of the sorbent is more efficient.

Figure 3b plots time dependences for sorption and sorbent temperature in the case where the sorbent was initially heated. Adsorption occurs simultaneously with sorbent cooling with the aid of a ventilator. In this case, the time dependence for sorption is close to linear. This implies that the heat flux in the evaporator varies little. This result demonstrates the possibility of efficient temperature control of the rate of heat removal in the evaporator, specifically, of ensuring cooling steadiness during sorbent saturation. At the same time, cooling variation over the considered period (120 min) is here more than 25% lower than during sorption by a precooled sorbent. Accordingly, the amount of removed heat will decrease.

However, if adsorption is carried out simultaneously with sorbent cooling, its rate is governed by the rate of variation in the thermal state of the sorbent, the steam flow dynamics, and the adsorption kinetics. The thermal state of the sorbent (the temperature) determines the parameters of equilibrium adsorption. From Fig. 3b, which also includes a curve describing an equilibrium state of the sorbent, it can be seen that, for a real adsorber, the steam flow dynamics in the sorbent layer and the adsorption kinetics restrict the adsorption rate to a greater extent than the rate of thermal processes.

NOTATION

P_s, saturation pressure at the sorbent temperature, N/m^2; T, temperature, ^{o}C; a, sorption, kg/kg; Q, specific heat flux (per unit mass of sorbent), W/kg; r, evaporation heat, J/kg; $\Delta\tau$, sorption (desorption) period, sec; T_{surf}, mean surface temperature, ^{o}C; T_{sorb}, mean temperature of the sorbent, ^{o}C; T_{in}, temperature of the inner cylindrical surface of the adsorber, ^{0}C. Subscripts: s, saturation; surf, surface; sorb, sorbent; in, inner; e, evaporator; a, adsorption; c, condenser; d, desorption.

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