

COOLERS BASED ON SOLID SORBENTS

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A cooler based on solid sorbents, in which an activated carbon fiber (pure) and an activated carbon fiber impregnated with CaCl_2 are used, has been designed. Results of an experimental investigation of the time dependence of the change in the heat flux are presented.

Coolers based on solid sorbents are of interest to a number of industries and agriculture [1–3]. At the present time, they are also used in the space programs of the USA and Western Europe [4, 5].

Self-contained, portable coolers are necessary for storage of food products or different medications and as elements of conditioning systems in transport and private life. Coolers with a steam-compression cycle, which are popular today, have a number of disadvantages: they necessitate electric power, freons — environmentally hazardous substances — are used in them, and their rotating members produce noise and reduce the reliability of the cooling systems (especially in transport).

As an alternative, one can use coolers based on solid and liquid sorbents, in which heat energy is converted directly into refrigeration owing to the sorption cycle [6]. In this case, it becomes possible to utilize low-potential heat energy (waste heat, solar radiation, etc.) for production of refrigeration. Coolers based on solid sorbents are noiseless, free of moving members, insensitive to vibrations and rotation, and what is most important they use environmentally safe coolants (water, ammonia, alcohol, etc.). At present, the problem of improving their efficiency is posed. It is desirable that the efficiency of the sorption cycles cooling/heating be comparable to the efficiency of the analogous steam-compression cycles.

The aim of the present investigation is to develop and design a self-contained compact cooler, in which an activated carbon fiber (sample No. 1) or an activated carbon fiber saturated with CaCl_2 salts (sample No. 2) are used as the sorbent and ammonia is used as the coolant (sorbate). The cooler can serve as a consumable accumulator of cold (heat) and can be used in conditioning and ventilation systems or in systems of two-phase temperature control [5, 6].

Adsorption Refrigeration Cycles with the Use of Solid Sorbents. A cooler based on solid sorbents is a thermodynamic system of periodic action, in which a porous material is heated and cooled. The higher the rate of change of the heating–cooling cycles, the closer the given experimental setup in parameters to the systems of continuous operation (adsorption or steam-compression refrigerating machines and thermocompressors). This can be attained by decreasing the heat capacity of the system and increasing the heat conduction of the sorbent or through the use of at least two adsorbers operating in antiphase [3, 4].

Let us consider an elementary refrigeration cycle with the use of sorbents. The refrigeration cycle (adsorption–desorption) consists of four stages, a_1 – a_2 – g_1 – g_2 (Fig. 1) [7].

The heating of the adsorber (a_2 – g_1) is accompanied by the heating of the sorbent from a high-temperature energy source. In this case, we have the desorption of the gas with absorption of heat and increase in the pressure in the *gaseous space of the adsorber*. The gas released from the sorbent in the process of desorption condenses in the condenser/evaporator at a low pressure and gives up its heat.

A high-temperature medium (liquid, gas, waste vapor, etc.) can be used as the external energy source. The heat exchange occurring in the process of condensation in the condenser with liberation of heat is described by the process (g_1 – g_2) (Fig. 1). As the temperature in the condenser increases at a constant pressure, the process becomes isobaric. Once the vapor of the working fluid has completely been condensed, it is cooled in the condenser to the ambient temperature (g_2 – a_1) and, accordingly, the pressure in the system decreases. Since in this case the sorbent is also

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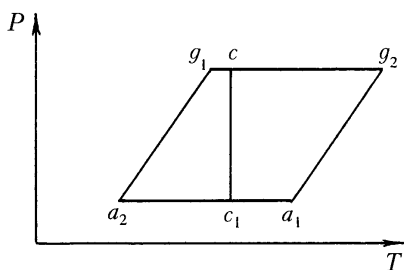


Fig. 1. Diagram of a refrigeration cycle.

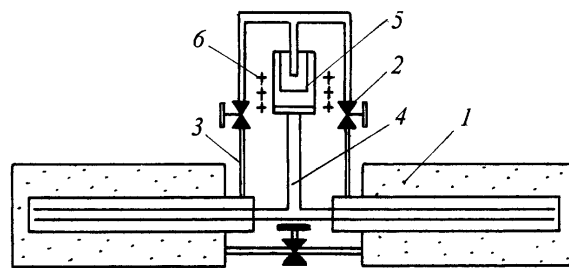


Fig. 2. Refrigeration cycle with two adsorbers: 1) sorbent; 2) valve; 3) channel for supply of a liquid; 4) channel for supply of a vapor; 5) evaporator; 6) energy source.

cooled to the ambient temperature, from a certain time, the pressure of the vapor in the vessel with a sorbent (adsorber) becomes lower than the pressure of the coolant in the evaporator/condenser and the process of adsorption accompanied by evaporation of the liquid in the evaporator and a decrease in its temperature (a_1-a_2) begins. The cooling cycle (a_1-a_2) is a final cycle because it occurs only when the sorbent absorbs the liquid vapor. This cycle is characteristic of a refrigerator with a single adsorber containing a sorbent.

Adsorption Refrigeration Cycle with Heat Recovery. If two adsorbers operating in antiphase (when at the same instant of time sorbent No. 1 is cold and sorbent No. 2 is hot) are used in the refrigerating cycle (Figs. 2 and 3), the energy stored by sorbent No. 2 can be used for preliminary heating of sorbent No. 1, i.e., it becomes possible to cool one hot adsorber using the other cold adsorber by transferring the energy of the hot adsorber to the cold one (diagram in Fig. 3). The cold adsorber is in the position a_2 , while the hot adsorber is in the position g_2 . If heat from the hot adsorber is transferred using the heat-exchange liquid to the cold adsorber, in the ideal case the hot adsorber will be cooled to the point c (Fig. 3), while the cold adsorber will be heated to the point c_1 (at the same temperature).

The hot adsorber gives up energy Q according to the scheme a_2-g_1-c (Fig. 3), which is the useful energy that is absorbed by the cold adsorber. In the ideal case, it amounts to 30% of the energy necessary for heating the cold adsorber to its hot state [8]. Thus, according to the scheme a_2-g_1-c (Fig. 3), an energy lower by Q is necessary to heat the cold adsorber.

Adsorption Refrigeration Cycle with Mass Recovery. A refrigeration cycle in which at least two adsorbers operating in antiphase are used can be optimized by means of organization of intense mass exchange between the adsorbers.

The heated adsorber has a high pressure of the vapor of the heat-transfer agent P_c at the end of the half-cycle of its operation, whereas the cooled adsorber has a low pressure of the vapor of the heat-transfer agent P_{c1} at the end of the half-cycle (Fig. 3, g_2-a_1). The heated adsorber requires cooling, and the cooled adsorber requires heating. Accordingly, the pressure in the heated adsorber must be decreased, and the pressure in the cooled adsorber must be increased. If, at a given moment, the two adsorbers are connected by a common channel for transfer of the vapor, the pressure in the heated adsorber will decrease (the temperature will also decrease), and, on the contrary, the pressure in the cold adsorber will increase (the temperature will also increase). This process of mass exchange between the adsorbers is called the process of recovery of energy through mass exchange.

A diagram of a refrigerator with mass recovery is shown in Fig. 2. A decrease in the pressure in the hot adsorber causes further, deeper desorption of the vapor of the heat-transfer agent from the sorbent to the volume filled with the gas, and an increase in the pressure in the cold adsorber causes further, deeper adsorption of the vapor of the heat-transfer agent in the sorbent. This process occurs until the equilibrium characterized by the pressure P_m is established in both adsorbers (Fig. 3).

After the complete equalization of the pressure in the adsorbers, the mass exchange between the two adsorbers is discontinued (the valve is shut off) and each of the adsorbers begins to cool (the hot adsorber) or heat (the cold adsorber) to the temperature g_2 (pressure P_c) and a_2 (pressure P_{c1}). The mass exchange between the adsorbers stimulates the process of regeneration of energy and accelerates the complete heating-cooling cycle.

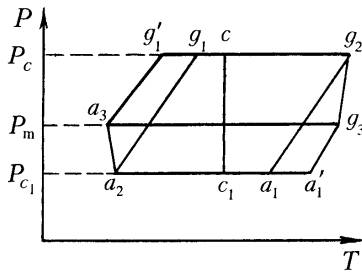


Fig. 3. Diagram of a refrigeration cycle with heat and mass recovery.

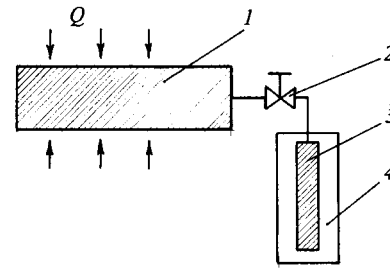


Fig. 4. Cooler based on a solid sorbent: 1) adsorber filled with an activated carbon fiber; 2) adjustable valve; 3) evaporator/condenser; 4) vessel with a liquid.

Adsorption Refrigeration Cycle with Heat and Mass Recovery. It is expedient to carry out the process of recovery of heat after the process of recovery of mass since, because of the high heat capacity of the bodies of the adsorbers and sorbents, the temperature of the hot adsorber is still high as compared to the temperature of the body and the sorbent of the cold adsorber. In Fig. 3, this process begins from the points a_3 (P_m) and g_3 (P_m) and is completed at the points $c-c_1$ when the temperature of both adsorbers is equal. The entire process is considered as an adiabatic process and can be divided into two parts: a_3-a_2 and g_3-g_2 . It is described with certain assumptions by the following model [8].

The entire vapor released in the process of desorption of the sorbent in the high-temperature adsorber is completely adsorbed by the sorbent in the low-temperature adsorber:

$$\Delta X_{a_3-a_2} = \Delta X_{g_3-g_2}. \quad (1)$$

The process is realized under adiabatic conditions. The temperature changes as a result of adsorption and desorption:

$$(C_{ps} + X_{a_3-a_2} C_{pa}) (T_{a_3} - T_{a_2}) = \Delta H_a \Delta X_{a_3-a_2}, \quad (2)$$

$$(C_{ps} + X_{g_3-g_2} C_{pa}) (T_{g_3} - T_{g_2}) = \Delta H_a \Delta X_{g_3-g_2}. \quad (3)$$

At the end of the cycle, the pressure in the two adsorbers becomes equal:

$$P_{g_3} = P_{a_3}. \quad (4)$$

Assuming that the pressure in the adsorbers has a finite value and using the iteration method (changing the temperature and concentration in the adsorbers), one can obtain the desired final result using Eqs. (1)–(4).

In a number of cases it is necessary to use a consumable refrigerator for production of refrigeration. It is precisely such a cooler that has been described in this work.

Description of the Experimental Setup. The experimental setup is shown in Fig. 4. The cooler consists of an adsorber 1 and a condenser/evaporator 3. Between them, there can be a valve 2 that is opened (closed) in accordance with the time of the sorption-desorption cycle.

The evaporator/condenser is placed in a vessel 4 with a cooled liquid (water). The body of the adsorber is made of stainless steel and has a diameter of 40 mm and a length of 250 mm.

The sectional view of the adsorber is shown in Fig. 5. The body of the evaporator is made of stainless steel and has a diameter of 25 mm and a length of 120 mm. The adsorber is filled with an activated carbon fiber (sample No. 1) or with a complex compound (activated carbon fiber impregnated with calcium chloride CaCl_2) (sample No. 2). The complex compound in the initial state at room temperature is impregnated with an ammonia vapor (adsorption + chemical reaction). When the adsorber walls are heated, heat is transferred to the sorbent, which is accompanied by

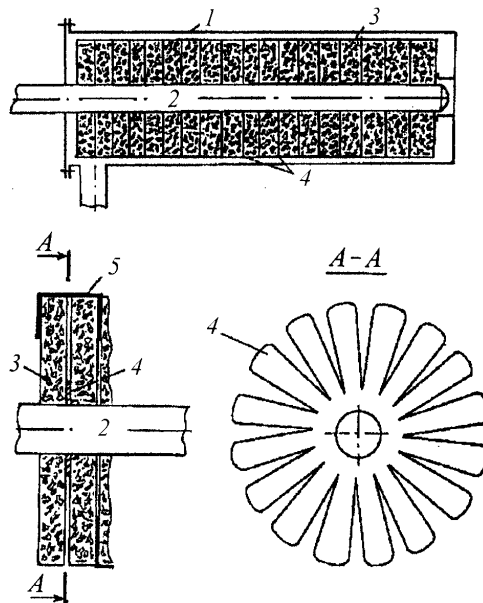


Fig. 5. Diagram of an adsorber: 1) steel body of the evaporator; 2) vapor channel; 3) carbon fiber; 4) aluminum fin; 5) metallic partition for fixation of the aluminum fins.

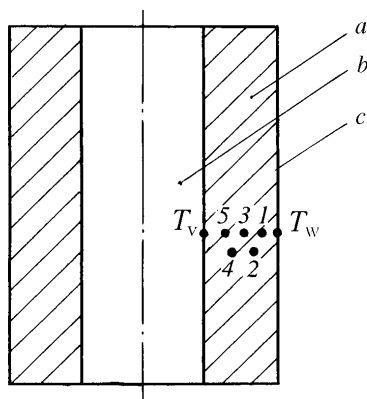


Fig. 6. Longitudinal section of an adsorber filled with a solid sorbent: a) sorbent; b) ammonia vapor; c) heated wall; 1-5; T_v and T_w are the thermocouples.

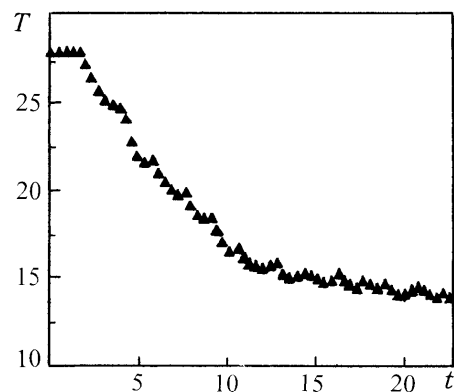


Fig. 7. Time dependence of the change in the temperature of the liquid in a heat-insulated vessel with an evaporator/condenser placed in it for sample No. 1. T , $^{\circ}\text{C}$; t , min.

the endothermic reaction of desorption of the carbon fiber and decomposition of CaCl_2 . The released superheated ammonia enters the condenser/evaporator where it is cooled and condenses with liberation of the heat of condensation.

In the adsorber structure, there are aluminum fins, between which an activated carbon fiber is placed. The fins are designed to intensify heat exchange between the sorbent and the channel in the process of its heating or cooling.

Figure 6 shows a diagram of an adsorber with thermocouples positioned on the inner T_v and outer T_w walls of a cylindrical sample filled with a sorbent as well as inside the porous body 1-5.

On this experimental setup, we measured the total and dynamic sorption capacity of the activated carbon fiber and of the complex compound, determined the refrigeration output of 1 kg of the sorbent, measured sorption-kinetics curves, and determined the adsorption heat [6]. For ammonia, the maximum sorption capacity of the activated carbon fiber was 0.43 kg/kg and the dynamic sorption capacity was 0.3 kg/kg.

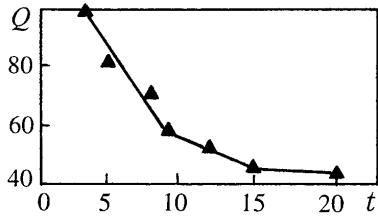


Fig. 8. Rate of time change of the heat flux given up by the water in a heat-insulated vessel with an evaporator/condenser which is placed in it for sample No. 1. Q , W; t , min.

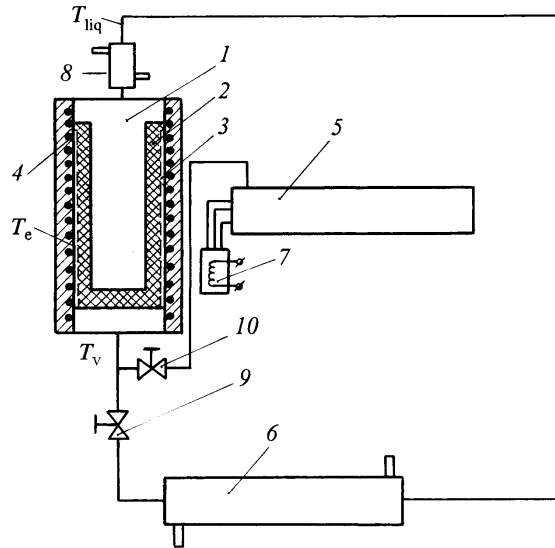


Fig. 9. Scheme of cooling of an electronic unit using a CHP and a CSS: 1) liquid CHP accumulator; 2) porous structure inside the CHP evaporator; 3) vapor channels on the surface of the porous CHP fuse; 4) electric heater; 5) CSS; 6) CHP condenser; 7) CSS heater; 8) CHP supercooler; 9, 10) adjustable valves.

Discussion of Experimental Results. The cooling of the liquid in the vessel was carried out using a cylindrical evaporator (cooler based on solid sorbents) introduced into the vessel in the regime of natural convection. The heat-insulated vessel with water of capacity 1 liter has the initial temperature equal to an ambient temperature of 27.5°C . When the valve 2 is open (Fig. 4), there occurs intense evaporation of ammonia in the porous material (foam metal), accompanied by droplet wetting of the inner surface of the evaporator; the heat from the vessel with water is absorbed (phase transition). The wall of the evaporator is cooled, which causes convective heat exchange between the water in the vessel and the cold wall of the evaporator (Fig. 4).

The rate of cooling of the water is determined by the thermal boundary layer on the outer surface of the evaporator. The time dependence of the change in the temperature of the liquid in the vessel is shown in Fig. 7. In 10 min, the temperature of the cooled water in the vessel decreased by 14°C ; the removal of heat from the surface of the evaporator decreased from 100 to 40 W (Fig. 8).

Figure 9 shows the scheme of two-phase cooling of electronic equipment with the use of a cooler based on solid sorbents (CSS). Under steady-state conditions, the electronic equipment is cooled by a circuit heat pipe (CHP). Under unsteady conditions, where the regime of intense cooling of the equipment is required, the cooler based on solid sorbents is switched on; the efficiency of cooling of the electronic equipment increases by a factor of 4–5 as compared to the cooling by the heat pipe.

Heating and cooling of the water in a heat-insulated vessel using a cooler based on solid sorbents depend on the conditions of convection of the liquid in the vessel. In the case of natural convection of the liquid, the rate of the process of heating/cooling is limited by the thermal resistance of the boundary layer. The rate of heating/cooling of the liquid increases in the case of forced convection of the liquid (mixer in the vessel).

CONCLUSIONS

1. A self-contained, portable cooler based on solid sorbents (mass 850 g), in which cooling is carried out with the use of the phenomenon of sorption and a chemical reaction caused by the interaction of the sorbate with the solid

sorbent has been designed and investigated in two variants (sample No. 1 is filled with an activated carbon fiber; sample No. 2 is filled with a complex compound).

2. The rate of cooling provided by the cooler proposed depends on the properties of both the sorbent and the porous fuse of the evaporator/condenser.

3. The maximum refrigeration output is 0.3 kW/kg for cooler No. 1 and 0.35 kW/kg for cooler No. 2 over a period of cooling of 10 min.

NOTATION

C_{ps} , heat capacity of the sorbent; C_{pa} , heat capacity of the sorbate; X , mass of the vapor; Q , heat flux; T , temperature; P , pressure; H_a , enthalpy of the sorbate; T_{liq} , temperature of the liquid; T_e , temperature of the wall of the CHP cooler; T_v , temperature of the vapor in the vapor path. Subscripts: e, evaporator; v, vapor; w, wall; m, mean; s, sorbent; a, sorbate, liq, liquid.

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