PROSPECTS FOR EMPLOYING HEAT PUMPS IN THE REPUBLIC OF BELARUS

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A brief analysis of the possibilities of employing sorption heat pumps in the Republic of Belarus is given. Primary consideration is given to the light-duty heat pumps used for air-conditioning systems with automatic switching from the heating to the cooling state (air/water). One important component of sorption heat pumps is the low-temperature power source, which strongly influences the design of the heat pump in terms of economy and environmental protection.

The Republic of Belarus is situated in a geographical zone where the average summer temperature exceeds 20°C and in winter it is close to 0°C. Therefore, the application of heat pumps is economically sound mainly for heating, although in a certain period of the summertime they can also be used for air/water cooling. It is known that 90% of the global population need heat pumps for the purposes of heating and cooling. In the present paper, primary consideration is given to the light-duty heat pumps used for air-conditioning systems with automatic switching from the heating to the cooling state (air/water). In international practice, to achieve the above purpose, electrically operated steam compression heat pumps [1], in which, instead of the ecologically dangerous coolant R22, coolants R410A and R407C, as well as propane, propylene, ammonia, and CO_2 are used, are widely used. However, in the last few years, publications devoted to the development and implementation of sorption (absorption and adsorption) gas-operated (flame, gas burners) heat pumps have appeared. Unfortunately, quantity production of sorption heat pumps has been set up so far only in Japan and in the USA, while two or three years ago China began their quantity production as a part of air-conditioning systems for industrial enterprises (absorption heat pumps: heat-transfer material — lithium bromide/water) [2]. At present, of the 9 million heat pumps installed throughout the world, Europe has only 450 thousand, and they are used mainly on the basis of the gas–gas cycle for the purposes of heating in winter and cooling in summer. Of these, 135 thousand heat pumps operate in Central Europe only for air and water heating. The demands for heat pumps are satisfied mainly due to their importation from the USA and Japan. Therefore, national programs of production of heat pumps are welcomed and stimulated in every way. In Switzerland, 40% of new one- and two-family houses are equipped with heat pumps. A similar situation occurs in Austria. For private homes, of great interest are light-duty adsorption heat pumps (zeolites/water, silica gels+salts/water; active carbons/alcohol, etc.) [3–6]. One important component of sorption heat pumps is the low-temperature energy source, which strongly influences their design in terms of economy and environmental protection. Consequently, the design of a heat source depends in many respects on the chosen low-temperature energy source: atmospheric air, outflowing air of rooms (ventilation release), waters of rivers and lakes and ground waters, and rocks.

One must note the promising and economically sound combination of sorption heat pumps with heat exchangers on heat pipes for utilizing the heat of the soil, ground waters, river and lake waters, and rocks [7]. Obviously, the efficiency of the heat-pump operation depends not only on the sorption capacity of sorbents, but also on the degree of perfection of heat exchangers (intensification of the heat and mass exchange in sorption systems, evaporators, and condensers).

Sorption heat pumps have been the topic of conferences in Paris (1992) [8], Montreal (1997) [9], Munich (1999) [10], and Shanghai (2002) [11].
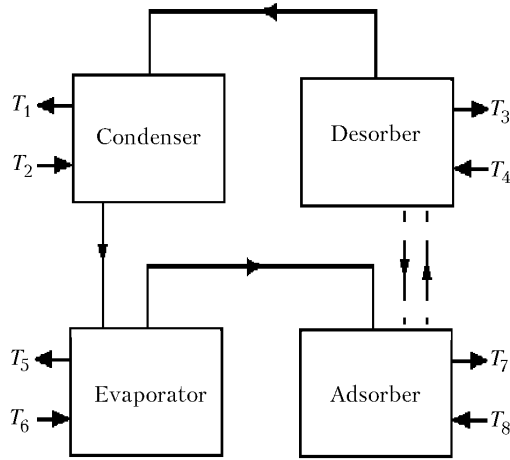

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Fig. 1. Schematical representation of the heat pump: T_1, T_2) heat-transfer material temperatures at the condenser output and input; T_3, T_4) temperatures of the heat-transfer material at the desorber output and input; T_5, T_6) temperatures of the cooling agent at the evaporator output and input; T_7, T_8) temperatures of the heat-transfer material at the adsorber output and input.

Thermodynamics and Heat and Mass Exchange in Sorption Heat Pumps. At present, there exist two types of electrically operated sorption heat pumps (flame, hot water, heated air, waste gases, waste steam, etc.) that are of practical interest:

1) absorption heat pumps using fluid sorbents (ammonia/water, lithium bromide/water);

2) absorption heat pumps using solid sorbents.

Both absorption and adsorption heat pumps have advantages and disadvantages. The common thing about the above pumps is the thermal drive (flame, hot gas, water, solar energy, etc.) — they do not require the application of electric compressors for generating heat and cold. Sorption heat pumps are characterized by the presence of an evaporator, a condenser, an adsorber (absorber), and a desorber (Fig. 1). The thermodynamic cycle of sorption pumps (Clapeyron–Clausius diagram) is schematically represented in Fig. 2. It is seen that there exist three possibilities of employing sorbents in heat engines:

1. Heat pump/refrigerator with an evaporator, a condenser L/G, and an adsorber S (Fig. 2a). The efficiency of such a heat pump/refrigerator is defined as $COA = 1 + \Delta H_{con}/\Delta H_{ads}$ for heating, $COP = \Delta H_e/\Delta H_{ads}$ for producing cold, and $COPA = (\Delta H_e + \Delta H_{con} + \Delta P_{ads})/\Delta H_{ads}$ for simultaneous heating and cooling.

2. Heat transformer with an adsorber S and an evaporator/condenser L/G (Fig. 2b). The efficiency of such a transformer is defined as $COA_e = \Delta H_{ads}/(\Delta H_e + \Delta H_{ads})$ and by a value lower than unity; however, it makes it possible to considerably increase the potential (temperature) of the heat source.

3. Heat pump/transformer with two adsorbers S_1 and S_2 (Fig. 2c). The efficiency of such a heat pump is equal to $COA = 1 + \Delta H_{ads1}/\Delta H_{ads2}$. The efficiency of the heat transformer is equal to $COA_{ads} = \Delta H_{ads1}/(\Delta H_{ads1} + \Delta H_{ads2})$. Unlike the previous two variants of the heat pump, in the given heat pump the working substance is gas (superheated vapor). Among such heat engines are heat pumps with hydrogen or ammonia, or water, operating on superheated vapor.

Absorption heat pumps. The absorption heat pumps use the phenomenon of absorption of vapors of low-temperature liquids by the films of high-temperature liquids. In practice, the pair $LiBr/H_2O$ used in air-conditioning systems and the pair NH_3/H_2O used in refrigerating plants have found the widest application. In the literature, however, are publications in which new pairs of working fluids — organic heat-transfer materials — are described [12–14]. The chief advantage of the absorption heat pumps compared to the adsorption ones is the organization of the time-invariant processes of sorption/desorption, which upgrades the thermodynamic efficiency (COP) of the heat pump.

Disadvantages of absorption heat pumps are their sensitivity to the influence of the gravity force, the necessity of using electric pumps for liquid transfer, and the phenomenon of crystallization of the LiBr solution in water at higher temperatures.
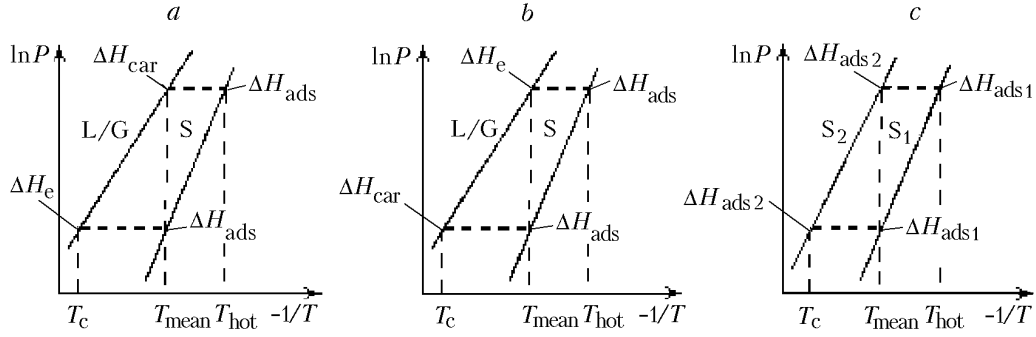
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Fig. 2. Clapeyron–Clausius diagram for the sorption heat pump: a) heat pump with an evaporator-condenser (L/G) and an adsorber S; b) heat transformer with an adsorber S and an evaporator-condenser (L/G); c) heat transformer with two adsorbers, S_1 and S_2.

In absorption heat pumps, primary attention is given to the heat exchange of the films of the solution of salts in a liquid $LiBr/H_2O$ (or a liquid in a liquid NH_3/H_2O) with a hot wall (desorption) and a cold wall (absorption). The NH_3/H_2O pair is characterized by ammonia desorption upon heating the solution. Ammonia vapors condense in the heat-pump condenser and the liquid gets into the evaporator and evaporates. Upon cooling of the stripped solution of ammonia in water, favorable conditions for absorption of ammonia vapors by the cooled liquid arise. Both processes are accompanied by thermal effects (heat absorption/heat release). Identification of the heat- and mass-exchange process in ammonia vapor absorption by water is possible with the use of special additives decreasing the surface tension of water [19]. Since the salt solution in water $LiBr/H_2O$ is the most widely used in the heat pumps produced in quantity, many publications are devoted to the investigation of the influence of surface-active substances on the intensification of adsorption of water vapors by the solution [20]. Of course, the viscosity and surface tension of the liquid have a considerable influence on the hydrodynamics of running-down films. The concentration and temperature gradients in the process of water vapor absorption by the enriched solution raise the rate of mixing of the liquid layers in the film and intensify the heat exchange. Accordingly, the presence of surface-active additives in the films on the hot surface of the heat exchange (desorption) retards the process of heat and mass exchange [21]. In liquid-sorbent heat pumps, the method of utilizing the generator (high-temperature heat exchanger) heat for preheating the absorber (low-temperature heat exchanger) is widely used. Such a method of heat utilization is called GAX (Generator–Absorber Heat Exchange) [20–22].

Adsorption heat pumps. The principle of their operation is based on the ability of solids (sorbents) to adsorb liquid vapors. An adsorption heat pump consisting of two adsorbers with a temperature control system and utilization of heat (heat pipes) is schematically represented in Fig. 3 [3, 5]. Activated carbons, zeolites, and silica gels have found the widest application as sorbents for air-conditioning and ventilation systems [15]. In the last few years, the possibilities of using silica gels jointly with metal salts have been explored [16]. Of great interest in creating heat pumps are activated carbon and ammonia [17], as well as activated carbon fibers and ammonia [18], and zeolite and water. To calculate the sorbate/sorbent pairs in a heat pump, one should know the following parameters:

1) sorption capacity (in accordance with the Dubinin–Radushkevich equation) at $P_{sat}(T, w)$;

2) properties of the liquid: ρ_{liq}, c_{liq}, c_v, $P_{sat}(T)$, ideal gas;

3) sorption heat $q_{ads}(T, w) = -r\left[\dfrac{\partial \ln (P_{ads})}{\partial(1/T)}\right]_{P,w}$;

4) heat capacity $\left[\dfrac{\partial c_{P,w}}{\partial w}\right]_{P,T} = -\left[\dfrac{\partial r_{P,T}}{\partial T}\right]_{P,w} = c_{P,v} - c_{P_{liq}}^{ads}$;

5) enthalpy h_{ads};

6) entropy $S_{ads}(T, w)$.

The elementary heat pump contains one adsorber, an evaporator, a condenser, and valves. The efficiency of its operation (COP) depends on the design features and the chosen sorbate (liquid)/sorbent (solid) pair:
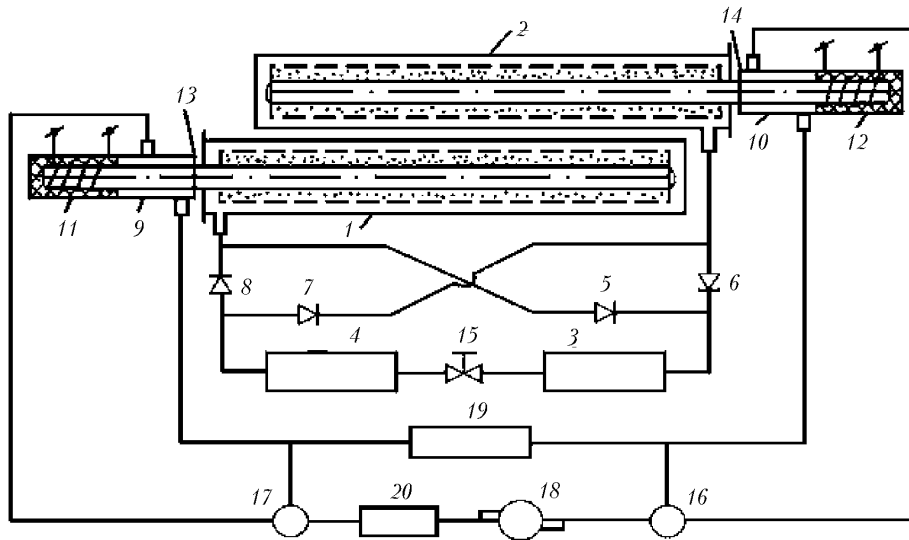
Fig. 3. Adsorption heat pump using heat pipes and a heat regeneration circuit: 1, 2) adsorbers; 3) condenser; 4) evaporator; 5–8) valves; 9, 10) liquid heat exchangers; 11, 12) evaporators of heat pipes with electric heaters; 13, 14) heat pipes; 15) constrictor; 16, 17) valves; 18) pump; 19) rotameter; 20) thermostat.

$$\mathrm{COP} = \frac{r\delta m}{\delta m \Delta H + \Sigma m c_P \Delta T} < \frac{r}{\Delta H},$$

where $r/\Delta H$ is the Carnot cycle efficiency for the given sorbate/sorbent pair. The constructional arrangement of the pump (heat capacity of the metal components) strongly influences its efficiency. The smaller the heat capacity of the metal components and the temperature difference between the evaporator and the condenser, the higher the COP.

Advantages of the adsorption heat pumps over the absorption ones are the possibility of using them in a wide temperature range and their insensitivity to the gravitational field (which is particularly important in installing heat pumps on transport).

A disadvantage of the adsorption heat pumps is their periodic operation (heating/cooling of the sorbent), leading to additional expenditures of energy for heating/cooling not only the sorbent but also the adsorber case. The low heat conductivity of a porous material retards the process of nonstationary heating/cooling, increases the cycle time, and decreases the COP of the heat pump. The application of the method of convective heating/cooling of the sorbent accelerates the cycle in the heat pump and solves this problem.

In the solid-sorbent heat pumps, the process of intensification of the heat and mass exchange is more critical compared to the absorption pump, since the sorbent-layer thickness is larger than the thickness of the liquid film. The effective heat conduction of the porous sorbent layer is small, and it is necessary to increase it by adding high-heat-conductivity materials (for example, foam metal) [23–25]. In the heat pumps based on solid sorbents, the process of heat and mass exchange inside the sorbent and the heat exchange between the sorbent and the heat-exchanger wall is of great importance. Intensification of the heat exchange, along with the increase in the sorption capacity of the sorbent and the kinetics and dynamics of the mass exchange, is a necessary requirement for increasing the efficiency of the heat-pump operation. In the last few years, several variants of utilizing the heat of high-temperature adsorbers for preheating low-temperature ones have been proposed. Heat utilization is realized by means of heat exchangers (heat pipes) or through the mass exchange between adsorbers [26–28]. Among the solid-sorbent heat pumps are also hydrogen heat pumps, in which, as sorbents, hydrides of metals are used. Hydrogen heat pumps are characterized by a change in enthalpy during a cycle within the range of ΔH = –30 to +40 kJ/mole with the use of hydrides of such metals of LaNi, LaNiAl, LaNiSn, and LaNiMn. Hydrogen heat pumps are characterized by a small change in entropy in the process of a cycle and, therefore, there is a weak temperature dependence of pressure (plateau). The hydrogen
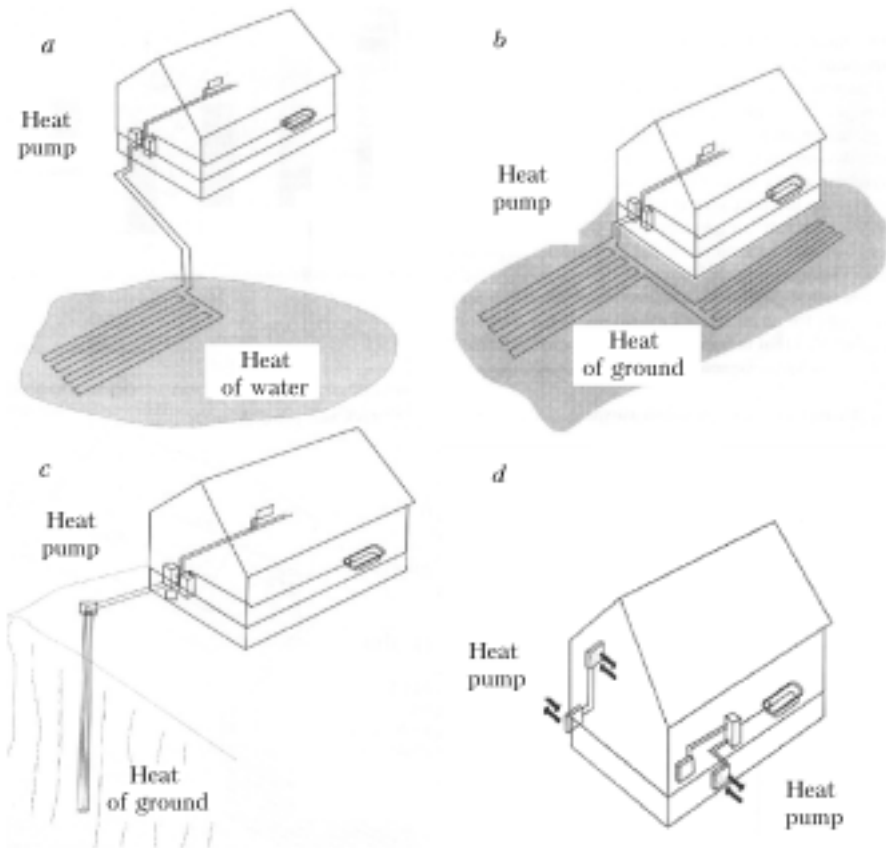
Fig. 4. Heat pump for utilizing the heat of a water pool (a), ground (horizontal heat exchanger) (b), ground and rocks (vertical heat exchanger) (c), and ambient air (d).

heat pumps feature a high thermodynamic efficiency, and they provide a wide range of temperature change; however, they require a high level of operating reliability and are relatively expensive.

Practical Application of Solid-Sorbent Heat Pumps. To heat single-family houses in the Republic of Belarus, heat pumps providing no less than 1.5 GW·h of energy per year are needed. Consequently, the annual requirement of a small district is about 100 GW·h. While in small heat pumps designed for individual heating one can use the heat of ambient or outflowing air or soil and ground waters, industrial heat pumps need a powerful low-temperature energy source (water pools, rivers, lakes, geothermal waters, etc.).

Let us consider the possibilities of using heat pumps for heating private houses. For such heat pumps we have the following low-potential energy sources: atmospheric (or outflowing) air, a river, soil, ground waters, and rocks. There exist two kinds ($Q = 3–7$ kW) of heat pumps for individual use: for heating water (hot water heating radiators in the house, analog of central heating); for heating the air in a room (American variant of heating). The heat pump designed for heating the air (Fig. 4) has a lower power and is often used as a reversible pump (it permits generating heat in winter and cold in summer). The approximate cost of such a pump is 3000–5000 U.S. dollars with its power of 3–5 kW. Of particular interest are pumps that use, as a low-temperature energy source, the ground/ground water energy. The low-potential heat (of ambient air, ground, etc.) is supplied to the evaporator with the aid of an intermediate heat exchanger (a long heat pipe), causing evaporation of the cooling agent at a low pressure. Useful heat is abstracted from the condenser and heats the air. The cooling-agent vapors formed in the evaporator are absorbed by the solid sorbent. In the next period of the cycle, the sorbent saturated with the heat-transfer material is heated by the external heat source — a gas burner — desorption of the heat-transfer material occurs, and the pressure in the adsorber increases.

The heat exchanger-evaporator (or the intermediate heat exchanger) of such a heat pump is placed in the ground at a depth of 0.6–1.6 m, its length is 50–500 m, and the heat-exchange area is about 600 m^2. In the second variant of installing the heat exchanger-evaporator, the heat exchanger is placed vertically at a depth of 50 m or more.
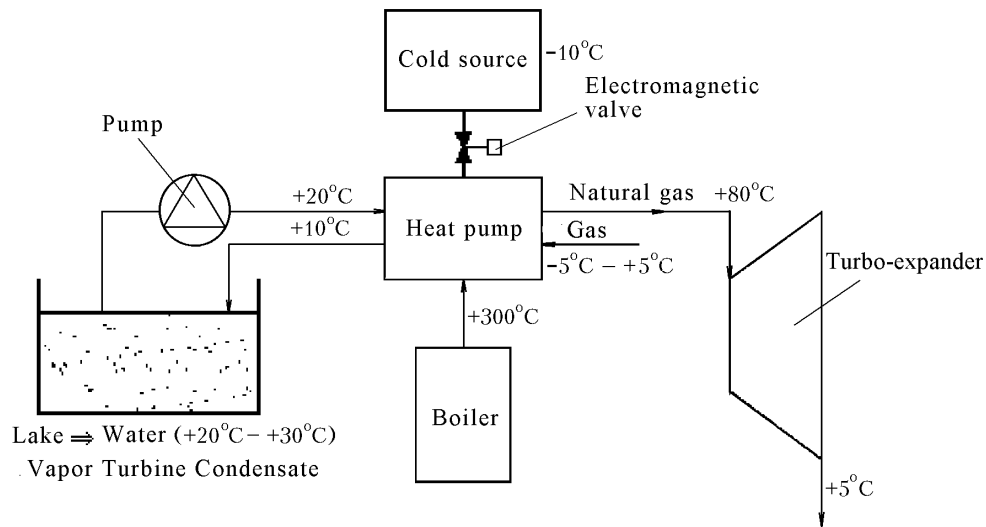
Fig. 5. Scheme of the waste heat (pool) utilization for heating natural gas at the entrance to the turbo-expander by means of a sorption heat pump with possible generation of cold at the exit from the heat pump.

It is possible to use several vertical holes spaced 50–70 m apart. For such a variant of the heat pump, the application of long thermosyphons (heat pipes) as intermediate heat exchangers is topical [29–31]. The cost of such heat pumps is 10,000–12,000 U.S. dollars with a pump power of 7–8 kW. Vertically installed thermosyphons have a long evaporator (dozens of meters) and a short condenser contacting the heat-pump evaporator.

Figure 4 shows variants of applying sorption heat pumps in combination with various low-temperature energy sources (air, water, ground) [2, 29]. For industrial application of the sorption heat pump, one can consider the variant of installing it at a natural gas-burning thermal power station with a gas turbo-expander (Fig. 5). The basic parts of the system under consideration are the expander, the gas turbine, and the electric generator. The expander is a heat engine in which natural gas expands with decreasing pressure and temperature. The energy of the adiabatic expansion of the gas transforms into mechanical energy of turbine rotation. The gas temperature at the inlet to the gas-distribution station varies, depending on the season of the year, from −10 to +20°C, and the pressure varies from 4 to 8 MPa. The gas pressure before the boiler burners is 0.12–0.3 MPa. If the gas before the expander is not heated, then after its expansion in the expander its temperature can decrease down to −100°C, which considerably complicates the operation of the expander, the turbine, and the regulating devices. Usually methane is heated on the gas-turbine plant due to the burning of organic fuel. The above disadvantage can be got ten rid of by installing the heat pump for heating the gas ahead of the expander [32] and generating cold in a refrigerator (vegetable store, etc.).

The high-temperature part of the heat pump is used for heating the gas before and after the turbo-expander (increase in the turbine efficiency). A high-pressure gas (methane) gets into the heat-exchanger (vapor–gas) in which the medium for methane heating is the vapor of the working agent of the heat pump. The heat pump raises the temperature level of methane before it gets into the expander. Upon its expansion in the expander, the gas heated by means of the heat pump is directed to the gas burner, and the mechanical work obtained in the expander transforms into electric energy in the electric generator.

The application of expander-generator plants in combination with heat pumps makes it possible to obtain additional electrical energy and use the heat pump and expander cold to organize food storage or cool natural gas with the aim of its further liquefaction and storage in the liquid form.

For practical purposes, of great interest is the application of resorption heat pumps in which the heat exchange in the low- and high-temperature parts of the pump occurs in the gas phase (Fig. 6). The name the "resorption heat pump" is associated with the process of superheated vapor (ammonia) transfer from the low-temperature adsorber under the action of the higher potential of the sorbent situated in the high-temperature adsorber. Such heat pumps have no evaporator and condenser. Their role is played by low- and high-temperature adsorbers. The amount of heat-transfer material in the pump is limited so that only one adsorber is saturated with the heat-transfer material. The heat-transfer
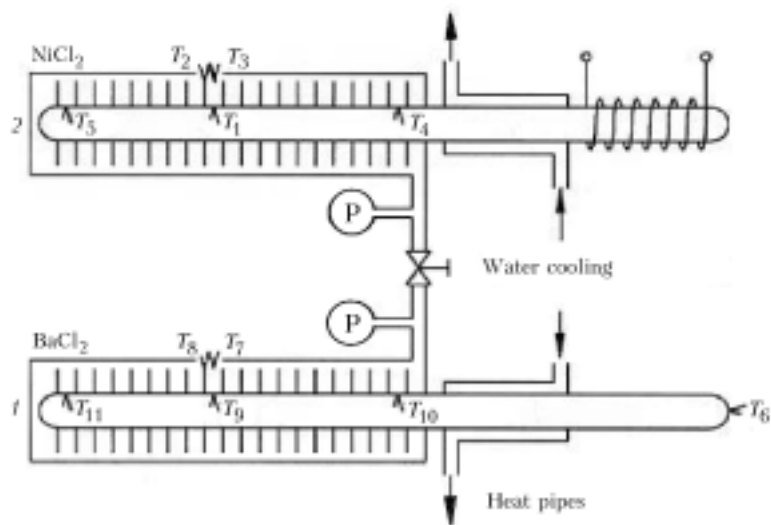
Fig. 6. Resorption (chemical) heat pump with heat exchangers on heat pipes: 1) low-temperature adsorber, analog of the condenser; 2) high-temperature adsorber, analog of the evaporator; T_1, T_4, T_5) temperatures of the wall of the heat pipe in its center, beginning, and end (adsorber 2); T_2) temperature of the rib in the adsorber; T_3) temperature of the adsorber wall; T_6) temperature of the heat pipe condenser; T_7) temperature of the rib in the adsorber; T_8) temperature of the adsorber wall; T_9, T_{10}, T_{11}) temperatures of the wall of the heat pipe in its center, beginning, and end (adsorber 1).
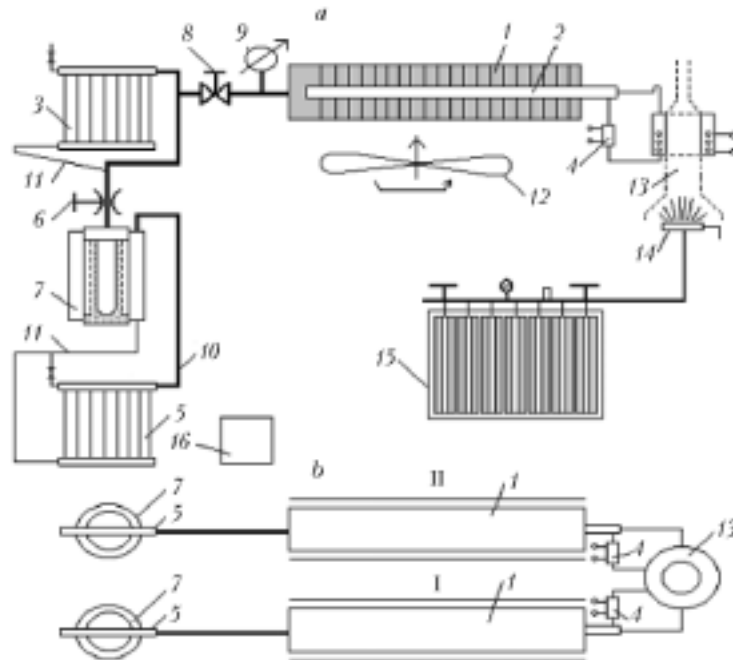

Fig. 7. Schematical representation of the sorption heat pump of power 3 kW for heating air and cooling water (adsorber heat source — a gas burner): a) side view: 1) adsorber; 2) heat pipe; 3) condenser; 4) controlled valve; 5) "spaghetti" heat panel; 6) restrictor; 7) evaporator; 8) regulated valve; 9) manometer, gas-channel; 10) vapor flow; 11) liquid channel; 12) fan; 13) gas duct; 14) gas burner; 15) vessel storing methane; 16) measuring stand; b) top view: I, II) adsorbers.

Fig. 8. General view of the sorption heat pump.

material (ammonia) is always superheated, i.e., its pressure is far from the saturation line. Ammonia vapors move from one adsorber to the other under the action of the pressure drop caused by the temperature drop (sorption potential). Figures 7 and 8 show the scheme and the general view of the resorption heat pump [5, 28]. The low-temperature adsorber 1 is filled with activated carbon fiber impregnated with $BaCl_2$ salt, and the high-temperature adsorber 2 is filled with activated carbon fiber impregnated with $NiCl_2$ salt — a stronger sorbent compared to $BaCl_2$. The amount of ammonia in the heat pump is such that the stronger adsorber 2 is saturated with it, whereas the weaker adsorber 1 at room temperature is in the unsaturated state and is ready to sorb ammonia vapors. Upon heating of adsorber 2 there occurs desorption of ammonia with heat absorption. The ammonia vapors get into adsorber 1, where they are sorbed by the sorbent with heat release into the environment (analog of the condenser). With further cooling of adsorber 2 the vapors of ammonia are taken by its stronger sorbent ($NiCl_2$), and in adsorber 1 desorption of vapors occurs with heat absorption from the environment (cooling effect similar to the action of the evaporator of the convectional heat pump). This principle of operation is also characteristic of hydrogen heat pumps in which metallic hydrides, e.g., $LaNi_4$, $Al_{0.52}$, $Mn_{0.37}$, $Ti_{0.99}$, $Zr_{0.01}$, $V_{0.43}$, $Fe_{0.09}$, $Cr_{0.05}$, $Mn_{1.5}$, and others, are used as a sorbent.

A large complex works on the development of sorption machines has been carried out since 1991 at the Porous Media Laboratory of the A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus. In particular, it was proposed to apply new sorbents based on the "Busofit" activated fibrous carbon material and use heat pipes and thermosyphons for heating and cooling the adsorbers (Fig. 9). This idea was realized. Heat pipes were chosen as heat-transfer devices capable of transporting large heat flows at small temperature drops and providing fast heating of the sorbent in the adsorber under unstable conditions due to the highly intensive heat exchange inside the heat pipe, having an effective heat conduction of 10^3–10^5 W/(m·K). Heat pipes are easy to mount inside the sorbent and have a small mass. To create a wide spectrum of heat pumps of various powers, it is economically reasonable to use unified modules of 0.5–5 kW containing two adsorbers.

At present, such a module has been developed at the Heat and Mass Transfer Institute of the NAS of Belarus. It is an ammonia sorption heat pump using, as a sorbent, a complex compound ("Busofit"/metal salts). Its power is 3 kW and it is able to heat air up to 90°C, and the possibility of cooling water down to a temperature of 3–5°C exists. Figure 10 schematically represents the heat pump.

Besides the heat pumps using the heating/cooling process, it is reasonable to use heat transformers designed to increase the temperature of the working medium. The heat transformers have a lower efficiency coefficient COP, but with their help one can increase the potential of the low-temperature heat source (e.g., water with a temperature of 20–30°C) to the liquid or gas temperature at the output from the heat transformer (80–90°C).

Figure 11 gives the scheme and the Clapeyron–Clausius diagram of a high-temperature chemical heat transformer, in which, as an intermediate heat-transfer material, carbon dioxide is used [33]. The heat transformer consists of a CaO reactor and a PbO reactor and contains two vessels — for storage and utilization of high-temperature energy.
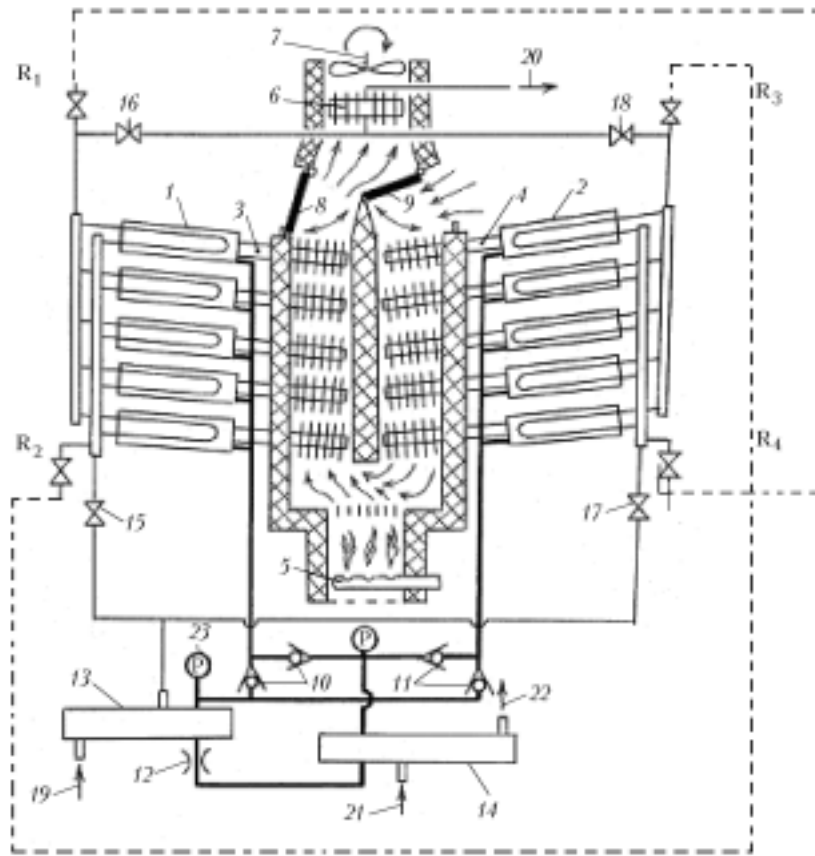
Fig. 9. Gas sorption heat pump with internal and external regeneration of heat: 1, 2) adsorbers; 3, 4) vapor-dynamic thermosyphons; 5) gas burner; 6) heat exchanger-utilizer; 7) fan; 8, 9) shutters; 10, 11) check valves; 12) restrictor; 13) condenser; 14) evaporator; 15–18) stop valves; 19, 20) inlet and outlet of water flowing through the evaporator; 21, 22) inlet and outlet of water flowing through the condenser, adsorbers, and heat-exchange-utilizer; 23) manometer; R_1–R_4) regeneration loop valves.
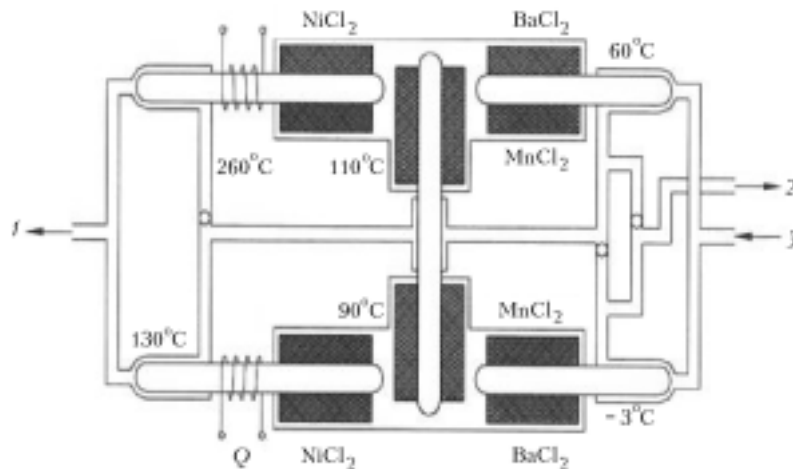

Fig. 10. Resorption heat pump with six reactors ($NiCl_2$ + "Busofit"; $MnCl_2$ + "Busofit"; $BaCl_2$ + "Busofit"). 1) superheated vapor; 2) cold water (3–5°C); 3) water of room temperature (20°C). Two branches of the pump are in antiphase. Heat-transfer material — ammonia.
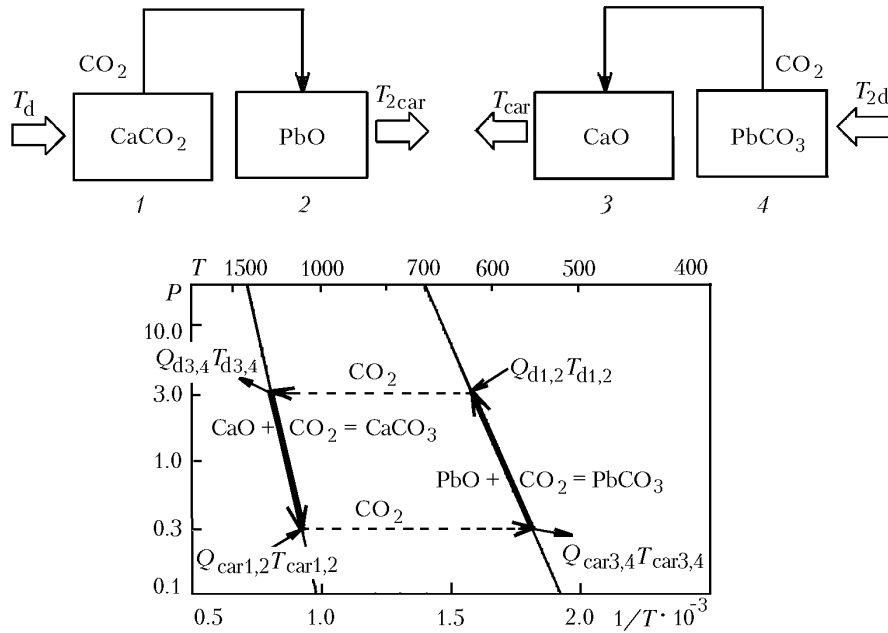
Fig. 11. Scheme and Clapeyron–Clausius diagram of the high-temperature chemical heat transformer: T_d, decarbonization temperature (reactors 1, 2); T_{2d}, decarbonization temperature (reactors 3, 4); T_{car}, carbonization temperature (reactors 3, 4); T_{2car}, carbonization temperature (reactors 1, 2).

The efficiency coefficient COP of such a heat transformer is close to unity. The gas temperature at its input is 700 K, while at the heat transformer output it is 1400 K at a working pressure inside the transformer of about 1 atm.

Of great interest for cooling electronic components are miniature sorption heat pumps. Such minipumps are primarily topical for cooling microprocessors and minicomputers, as well as the electronic drive on transport [34–38]. The currently existing technology of producing chips in electronic devices can be useful for making heat-exchangers with minichannels made in silicon plates by the etching method [39]. In such pumps, the sorption blocks should have a very high sorption capacity at minimal sizes. Miniature heat pumps are also indispensable for use in medicine.

CONCLUSIONS

1. In the 21st Century, the population of the leading countries of the world will purchase twice as many heating and cooling systems (heat pumps) as 10–15 years ago. The main purchasing factor will be the cost of using these machines.

2. In the future, mainly double-purpose gas sorption machines (generation of heat and cold) will be employed.

3. Natural gas is the purest and most ecologically safe organic fuel in the world for heat pumps.

4. Gas heat pumps generate twice as much heat as gas stoves with the same fuel consumption.

5. The heat-transfer materials used in heat pumps (ammonia, water, carbon dioxide) produce no harmful effect on the environment and do not influence the global warming of the world.

6. Sorption heat pumps have no moving parts.

7. Sorption heat pumps have a high thermodynamic efficiency; they are reliable and feature a long service life, ecological cleanness, and a low concentration of CO_2 in burning natural gas.

8. The heat pumps are characterized by a low level of noise and vibrations. Therefore, they can be used in transport, in systems for cooling electronic parts, and in medicine for stimulating the vital activity of man.

NOTATION

c, heat capacity, J/(kg·K); ΔH, sorption heat, J/kg; h, enthalpy, J; m, mass, kg; P, pressure, bar; Q, power, W; q, heat flow density, W/m^2; R, universal gas constant, J/(kg·K); r, latent heat of vaporization, J/kg; S, entropy, J/K; T,

temperature, K; w, sorbent concentration, g; ρ, density, kg/m^3. Subscripts: ads, adsorption; liq, liquid; sat, saturated; v, vapor; c, cold; mean, mean; hot, hot; e, evaporator; con, condenser; car, carbonization; d, decarbonization.

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