Ecologically Sound Adsorption Chiller Based on Composite $CaCl_2$ in Silica Gel: Laboratory Prototype

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Abstract

The results of tests of the laboratory prototype of adsorption chiller based on ecologically sound working pair «water – SWS-1L adsorbent» are presented. The adsorbent relates to the family of selective water sorbents and is a mesoporous silica gel KSK modified with calcium chloride. The device produces cold water at a temperature of 5–10 °C, which can be used in air conditioning systems, to store food, *etc*. High coefficient of performance reaching 0.6 for low temperature of water desorption (90–95 °C) was obtained during the test of the device. This allows the investigated adsorbent to become a real alternative for traditional materials (silica gel, zeolites) for use in ecologically pure adsorption systems involving low-potential heat ($T \le 100$ °C).

INTRODUCTION

One of the possible reasons of climatic changes occurring on the Earth during the recent century is human activities resulting in the emission of substantial amount of gases enhancing the greenhouse effect and destruction of the ozone layer. In this connection, the International community accepted decisions concerning restriction of such an emission in the nearest future, first of all due to rigid control of the emission of CO_2 and fluorinated hydrocarbons (Montreal and Kyoto protocols). One of the efficient methods of this restriction is the application of adsorption heat pumps, which can become an essential alternative to the traditional compression systems [1, 2]. Indeed, adsorption systems make lower contribution into environmental pollution and allow using low-potential heat as the source of energy, thus allowing one to broaden the range of energy sources in use (for example, heat emission from the industry and household facilities, solar energy, heat of engine exhaust, *etc*.). Because of this, search for new promising adsorbents deserves much attention.

Recently, a new family of water adsorbents – selective water sorbents (SWS) – was developed and investigated [3–5]. Typical SWS is a two-component material composed of a porous host matrix and a hygroscopic substance placed into the pores of the matrix. Among several tens SWS synthesized and investigated by present, SWS-1L (mesoporous KSK silica gel modified with calcium chloride) has high sorption ability (up to 0.7 g of water per 1 g of the dry sorbent) and high energy accumulating ability (up to 2.0 kJ per 1 kg of the dry sorbent) [3–5]. Judging from sorption isobars, the major part of water sorbed by this material can be removed at a temperature of 90–

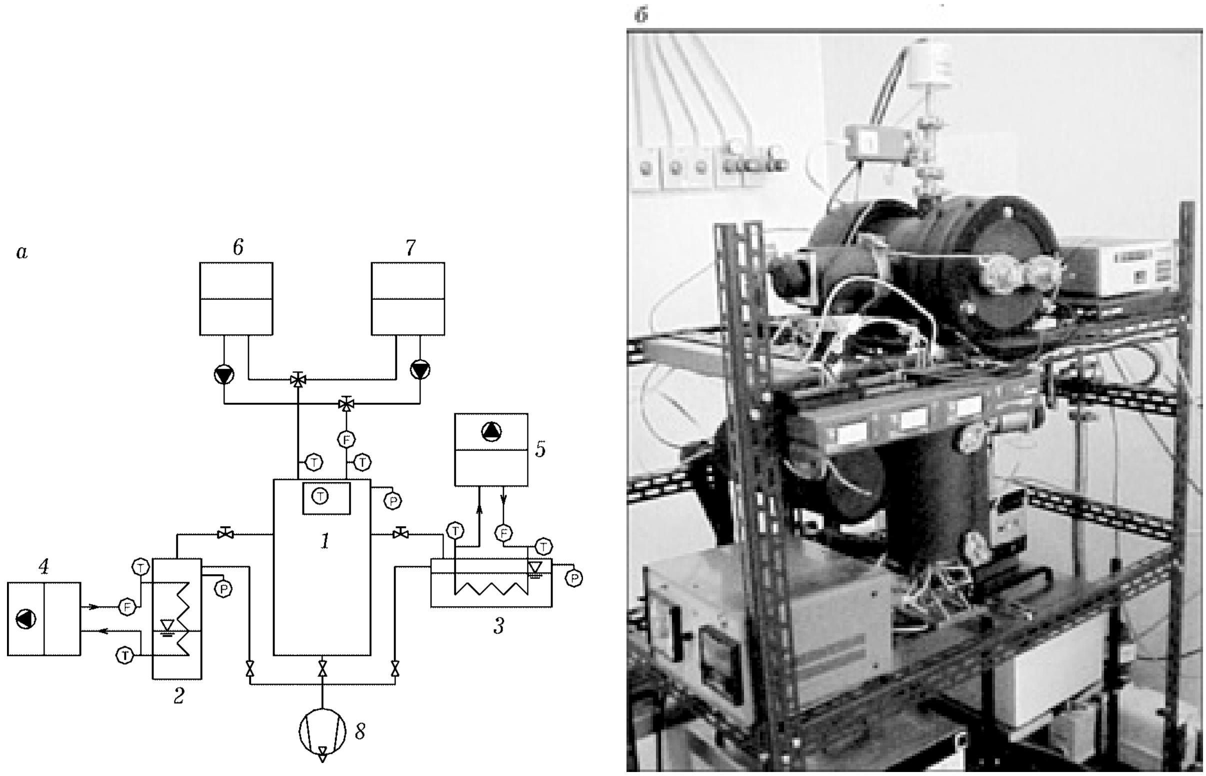

Fig. 1. Functional diagram (*a*) and the appearance (*b*) of the laboratory prototype of adsorption chiller: *1* – adsorber, *2* – condenser, *3* – evaporator, *4, 5* – thermo cryostats, *6, 7* – thermostats, *8* – vacuum pump, F – flow meters, T – thermocouples, P – vacuum lamps.

100 °C, that is, under rather mild conditions [6, 7]. Because of this, for the SWS-1L sorbent, theoretical analysis of its applicability in adsorption heat devices for cooling and heating was carried out [8, 9]. The results of this analysis showed that the use of the working pair water – SWS-1L allows in principle to reach η = 0.7–0.8 for cooling with maximal desorption temperature 90–100 °C. This efficiency is much higher than the reported values for other working pairs operating within the same temperature range [8–12].

The goal of the present work is to carry out experimental investigation of the possibility of using the working pair water – SWS-1L in adsorption cooling device and to compare the results obtained with the reported data for other pairs.

EXPERIMENTAL

In order to solve the formulated problem, a laboratory prototype of adsorption chiller was developed and built. It consists of adsorber connected with evaporator and condenser (Fig. 1, *a, b*). The adsorber was filled with 1.1 kg of the dry sorbent SWS-1L as granules 0.8–1.6 mm in size. The sorbent was prepared according to the standard procedure by impregnation of the mesoporous silica gel KSK with the aqueous solution of $CaCl_2$ [6, 7]. The salt concentration in the sorbent was 33.0 %.

A tubular heat exchanger made of stainless steel was placed inside the working chamber and surrounded by the granules of the adsorbent. The appearance of heat exchanger is shown in Fig. 2 and its characteristics are listed below:

Number of tubes	8
Tube length, mm	200
Distance between ribs, mm	7
Rib thickness, mm	0.4
Heat exchange surface, m^2	0.4
Metal to adsorbent mass ratio	3

A cylindrical working chamber is connected with the vacuum pump, evaporator and condenser through a system of pipes and valves. The external contour of heating/cooling is com-

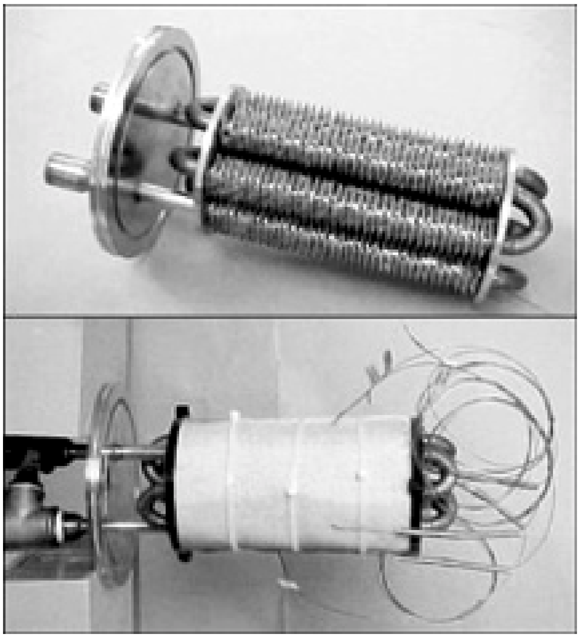

Fig. 2. Appearance of heat exchanger.

posed of four thermocryostats, which imitate external sources or sinks of heat. Temperature was measured with T-type thermocouples; four of them were placed directly in the adsorbent, evaporator and condenser were equipped with one thermocouple each, input and output of the external contour of evaporator, condenser and heat exchanger heating/cooling contained two thermocouples each (see Fig. 1, *a*).

Pressure in the system was measured with three Edwards Barocell sensors; flow rates of heat carrier in the external contour were measured with flow meters. Total amount of water absorbed by the sorbent was measured on the basis of changes in the amount of water in the evaporator. The data collection system consisted of the AD converter and a personal computer to which all the sensors mentioned above were connected. On the basis of these measurements, all the thermal fluxes in the device were calculated.

Experiments were carried out under typical operation conditions of a low-temperature adsorption chiller: evaporator temperature T_{ev} = 5–10 °C, condenser temperature T_{cond} = 35–45 °C, temperature of the sorbent was varied between 35 and 110 °C.

Efficiency of cooling was calculated as a ratio of useful heat effect (that is, the heat absorbed in evaporator) to total quantity of heat input in the system from the external source within the working cycle:

$$\eta = \frac{\sum\limits_{4-1} [m_{heat} C_{p\ car} (T_{in} - T_{out})_{ev} \Delta t}{\sum\limits_{1-2-3} [m_{heat} C_{p\ car} (T_{in} - T_{out})_{sorb} \Delta t} \quad (1)$$

where m_{heat} is the flow of heat carrier; $C_{p\ car}$ is the heat capacity of the heat carrier; T_{in}, T_{out} is the input and output temperature of the heat carrier passing through the evaporator and adsorber; Δt is the time step.

It should be noted that η represents actual efficiency of the laboratory prototype taking into account all heat losses, heat capacities of inert metal parts of the device and the efficiency of heat exchangers in adsorber, evaporator and condenser.

Power density of cooling P_d was calculated as

$$P_d = \frac{\sum\limits_{4-1} [m_{heat} C_{p\ car} (T_{in} - T_{out})_{ev} \Delta t}{m_c \tau_{cycle}} \quad (2)$$

where τ_{cycle} is the total time of one cycle (depending on the efficiency of heat and mass transfer and is an indication of the dynamic efficiency of the device), and m_c is the mass of adsorbent.

RESULTS AND DISCUSSION

The major part of experiments was carried out under the following working conditions typical for adsorption chiller: $T_{dec} = T_4$ = 90 °C, $T_1 = T_{cond}$ = 35 or 40 °C, T_{ev} = 10 °C. The experimental and calculated working cycles are shown in the Clapeyron diagram (Fig. 3). It turned out that one succeeds in maintaining constant pressure in the system during stages 2–3 and 4–1. This means that the rate of heat exchange in the evaporator and condenser is sufficient for the system to follow the route along the theoretical cycle. At the stage of isosteric heating, the system also follows the route along the cycle; deviation is observed only at the stage of isosteric cooling, possibly due to thermal inertia of the system.

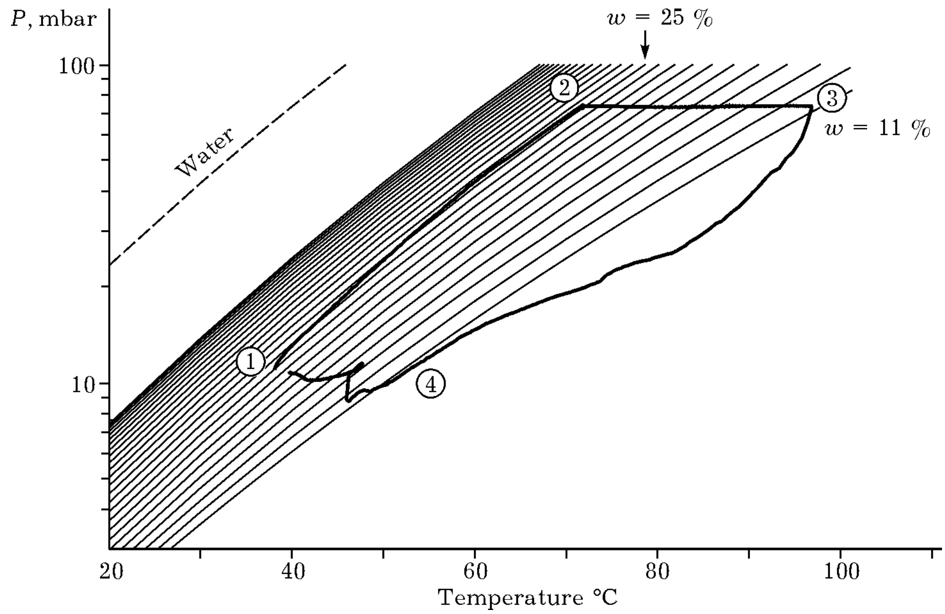

Fig. 3. Experimental working cycle of the adsorption chiller.

Evolution of temperature and pressure during the working cycle of the cooling device under investigation is shown in Fig. 4 (sorbent temperature was calculated as a mean over the volume). Total time of one cycle is 200 min; isosteric heating and cooling were rapid, while the slowest process was isobaric desorption (stage 2–3), which lasted for 110 min, possibly because of low efficiency of heat transfer in the granulated adsorbent layer. It is likely that for this reason the heat supply power during this stage is not high and does not exceed 80 W (Fig. 5). For the stage of isobaric adsorption, approximately the same heat sink power was obtained; it is close to the power input to the evaporator. For isobaric stages, power of heating and cooling decrease monotonously with time while the difference in temperatures of the sorbent and heat carrier decreases (see Fig. 5).

An interesting feature of isosteric stages is that the specific thermal power input to the sorbent (or output from it) is much higher than the power for isobaric stages and reaches 200–250 W. This may be due to the heat pipe effect arising in the sorbent layer, which is adjacent to the heat exchanger. This effect involves transfer of water vapour from the hot layers of the sorbent to cool ones followed by condensation there, which provides a substantial increase in the effective heat transfer in comparison with usual heat transfer mechanisms [14, 15].

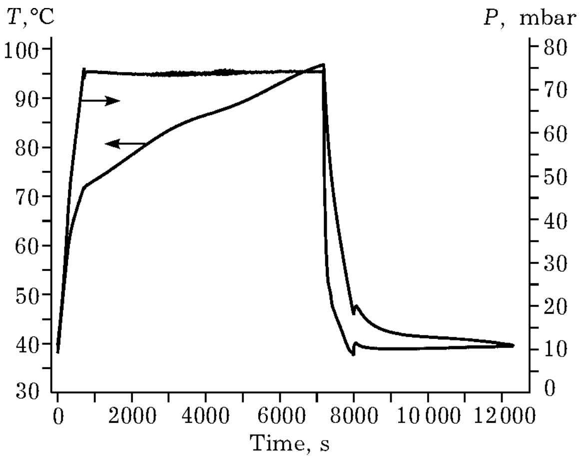

Fig. 4. Evolution of temperature and pressure during the working cycle.

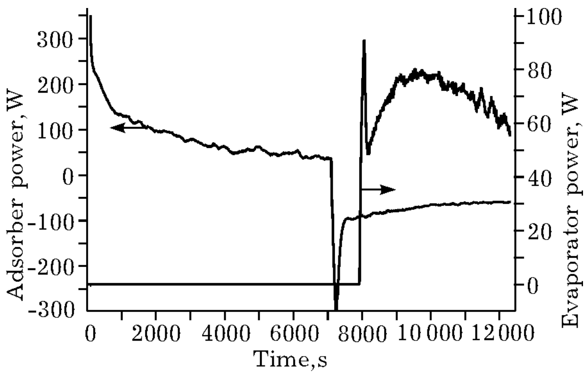

Fig. 5. Changes in heat sink power during the working cycle.

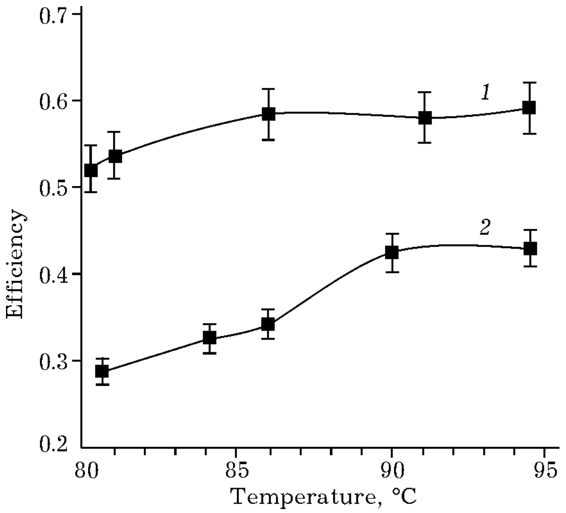

Fig. 6. Dependence of the efficiency of adsorption chiller on desorption temperature. T_{cond}, °C: 35 (*1*), 40 (*2*).

We calculated the efficiency of the cooling device from the experimental data for two temperatures of condenser using Eq. (1) (Fig. 6). It turned out that the efficiency increases with an increase in desorption temperature to T_{dec} = 85–90 °C, and after that it reaches the limiting value of 0.59 ± 0.05 (for T_{cond} = 35 °C) and 0.42 ± 0.05 (for T_{cond} = 40 °C) . The obtained efficiency values substantially exceed the data for other water adsorbents operating at the same temperatures [8–12, 16].

Such a high efficiency opens outlooks for further application of this adsorbent in sorption chillers, especially because the described laboratory prototype consisted of one adsorber and no heat recovery was performed in it; second, the obtained efficiency is an actual efficiency of the tested device and takes into account all the heat losses, thermal capacity of the inert metal parts of the device and the efficiency of all the heat exchangers; their further optimization will allow one to improve the output characteristics.

In our opinion, the high efficiency observed in experiment is explained by good sorption properties of the SWS-1L material and first of all by the fact that a large amount of water is exchanged between the evaporator and condenser within a working cycle (for example, $\Delta w \approx 14$ % mass. for T_{cond} = 35 °C). Correspondingly, evaporation of this amount of water gives high value for the energy absorbed in the evaporator during the cycle: Q_{ev} = 280 kJ/kg. For higher condenser temperature, Δw decreases, which causes a decrease in efficiency.

Specific useful power during isobaric stages is 35–60 W/kg, which is typical for adsorption chillers with granular adsorbent layer [10–12, 16]. This power can be increased substantially by using the adsorbent as a layer directly deposited on the surface of heat exchanger [17], which is assumed for the forthcoming stage of investigation.

Another important experimental result is invariability of the properties of SWS-1L composite during 60 complete working cycles, which is the evidence of high hydrothermal stability of this material. Analysis of the material after 60 cycles indicated that destruction of the granules and the corresponding formation of dust do not occur. We also did not detect any traces of $CaCl_2$ in condensing water or on the inner surfaces of the set-up. This fact is the evidence of high hydrothermal stability of the composite and confirms the possibility of its application in sorption technologies of air conditioning.

CONCLUSION

The results of experimental test of the laboratory prototype of adsorption chiller on the basis of composite sorbent SWS-1L (mesoporous silica gel KSK modified with calcium chloride) are presented in the work. It is shown that the use of this composite allows achieving high efficiency of the device, which reaches 0.6 for low desorption temperature T = 85–95 °C. The resulting efficiency takes into account all the heat losses, thermal capacity of the inert metal parts of the device, and the efficiency of all heat exchangers, which will be further optimized, which allows expecting an increase in this output characteristic. One more reserve is arrangement of internal heat recovery in the version of a chiller with two adsorbers. High efficiency is connected with good adsorption properties of the new material in comparison with the traditional ones (zeolites, silica gel) in the region of relatively low temperatures.

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