SOLAR SORPTION REFRIGERATOR

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Abstract

A new environmentally friendly solar refrigerator is developed, in which a physical adsorption and chemical reactions are used simultaneously for a heat and cold generation. A solar/gas-electrical refrigerator is made of a solar collector, adsorbed natural gas vessel (ANG), or electric heater, and compact refrigeration system, which consists of two small adsorbers with heat pipe heat recovery system. An active carbon fiber “Busofit” saturated with metal chlorides is used as a sorbent bed and ammonia is used as a working fluid. This refrigerator applies a solar energy and methane gas burner, or electrical heater as a back up. The goal of this work is the experimental determination of the main refrigerator parameters using solar/gas (electrical) high temperature source of energy and air/water as a low temperature source of energy to cool and heat air/ water.

KEYWORDS

Solar/gas (electrical) refrigerator, adsorption, chemical reactions, heat recovery, heat pipes

INTRODUCTION

The concept of solar-powered refrigeration cycles is known and several refrigerators operating on this principle are commercially available. Cohen and Cosar, [1] have analyzed solar powered refrigeration. Guilleminot at al. [2] demonstrated solar sorption refrigeration with cycle day/night to produce the ice using solar energy. Solar cooling processes using chemical reactions, realized the cycle day/night, Speidel and Kleinemeier [3]. Bougard and Veronikis [4] used ammonia/active carbon in solar refrigerator. Wang, 1999 [5] suggested a new hybrid system of solar powered water heater and adsorption icemaker.

However, there has been a little research into the integration of short time cycles sorption machines of solar power with natural gas (Nguyen at al. [6]), or solar power with electrical immersion heater as a back up, Vasiliev at al. [7]. Use of methane as an alternative heating system would be more economical and application of solar power simultaneously would reduce the cost and size of solar collectors. Actually two different solid sorption refrigeration cycles are mostly used – adsorption and chemical reaction, Miles et al. [8], Neveu et al. [9], Meunier [10], Wang [11].

The combined action of physical adsorption and chemical reactions for the cold production in the same space and at the same time is attractive initiative to enhance the COP of a system, Vasiliev et al. [12].

Vasiliev et al. [13] and Critoph [14], mentioned the use of heat pipes to improve the performance of carbon-ammonia adsorption refrigerator. It was shown that heat transfer within an active carbon sorbent bed could be improved dramatically by the use of finned heat pipe. Solar-guided sorption cycles can be also used in heat –driven refrigerators, or heat pumps in which the energy source is a burning fuel, or waste heat, Chua et al. [15]. The concept aim of such research program is to extract the most enthalpy from the low-grade heat before it is purged into the surrounding. It is easy to perform, if an autonomous low pressure ANG vessels are used together with gas burner (Vasiliev et al. [16]) and the energy of the waste gas is used to heat the low temperature sorbent bed. A solar-gas refrigerator based on a reversible solid sorption phenomena is competitive, if the process allow to store the energy of a high density, and if the heating, or cooling power is enough for consumers.

Spinner et al. [17], performed some theoretical research in this field. Castaing-Lasvignottes and Neveu [18] , demonstrated the application of the first and second law of thermodynamics in equivalent Carnot cycle concept applied to thermo chemical solid/gas resorption system.

Regarding the developing countries application there is a well-documented need for food refrigeration, air-conditioning in areas that do not have access to grid electricity. Spoilage of many products, particularly fish, can be as high as 50%.

Our intention is to design a refrigerator, which would operate without grid electricity, consuming a chip energy (solar energy concentrator and autonomous, low pressure adsorbed natural gas storage system), that can be built and maintained in the country of use, be light and portable and that is low enough in cost. This can be achieved if we use a solar energy as a main source, a gas flame as a second (alternative, or additional) source of energy and a set of sorbent beds which are switched on and off alternatively. These sorbent beds are used as single storage systems with physical sorption (active carbon fiber “Busofit”), complex compound single stage systems with physical sorption and chemical reactions (active carbon fiber “Busofit” + $CaCl_2$), or a complex compound two stage systems (“Busofit” + $BaCl_2$ and “Busofit” + $NiCl_2$) with the internal and external heat recovery. The application of a constant source of energy (~ 1kW) with special valves to heat and cool the sorbent beds alternatively increase a COP^R of the system, to compare with the application of periodically switched on and off sources of energy.

THE MAIN DESIGN OF THE SOLID SORPTION REFRIGERATOR

Two sorbent bed adsorption refrigerators can be used as a single stage system, when each of two canisters is switched on and off alternatively, or as a two-stage system with heat recovery between sorbent beds (Figs. 1- 3).

Solar concentrator (Figs. 1, 3) is made from the aluminum plate as a tray (TV parabolic antenna) with diameter 1.8 m; the inner surface is covered by the metallic polymer film with high degree of reflection 0.68 (mirror). Aluminum nitride coating increase the absorption coefficient of a solar receiver up to 92%.

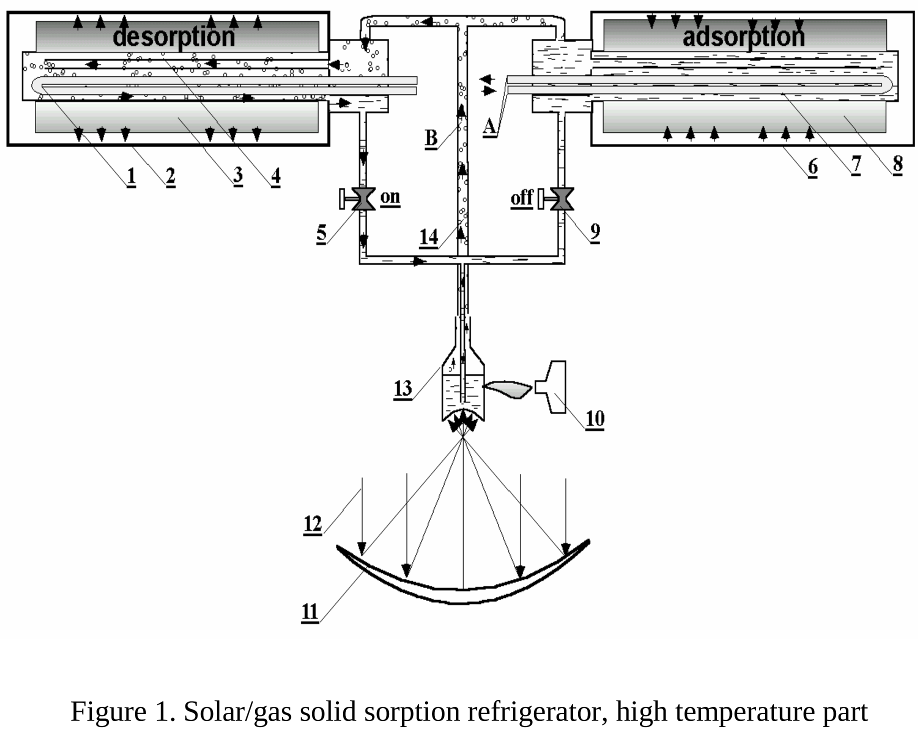

Figure 1. Solar/gas solid sorption refrigerator, high temperature part

This system needs to have a solar oriented mechanism to move solar concentrator. Solar/gas refrigerator has a solar receiver 11 (Fig. 1), gas flame system to heat the water boiler 10, two sorbent bed canisters 2 and 6, connected by the heat recovery loop A, two phase heat transfer system B (vapor-dynamic thermosyphon), one condenser 5 (Fig. 2) with low temperature two evaporators 10, 16 and two cold panels 11, 14 (loop heat pipes) heated by the air. When there is a forced convection heating by the air from surrounding two low temperature finned evaporators can be used without loop heat pipes.

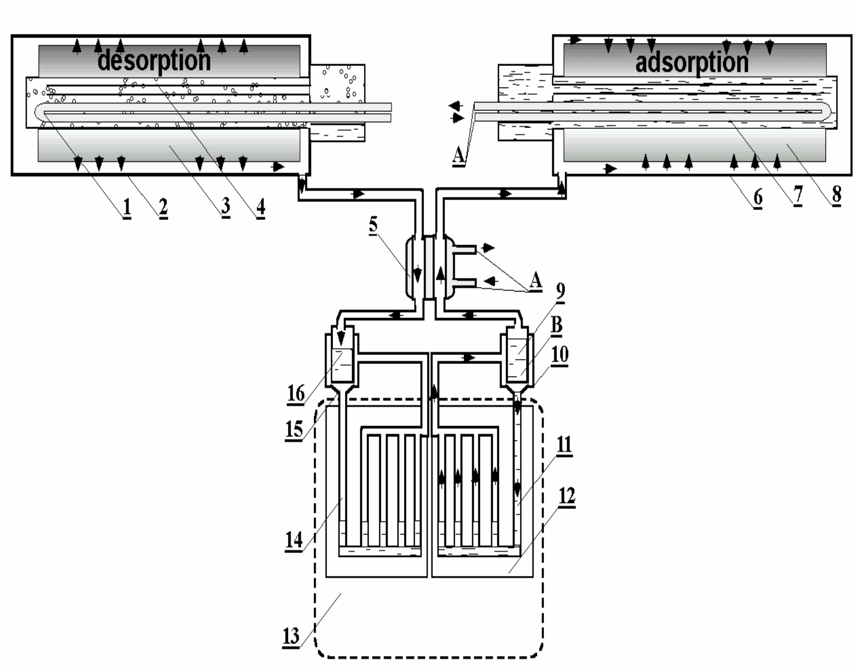

Figure 2. Solar solid sorption refrigerators, low temperature (ammonia) part

The two-phase heat transfer device B (Fig. 1) is designed to heat adsorbers and is made as a vapor-dynamic thermosyphon, which has a small boiler 13, two elongated cylindrical finned condensers 4 inside the sorbent bed canisters, vapor channel 14 and two flexible liquid pipes with special valves 5 and 9 to regulate the boilers water feeding.

The basic particularity of this thermosyphon is the periodical switch on and off (by valves) the condensers with constant rate of the boiler heat load.

The boiler 13 is disposed in the focus of a solar concentrator and simultaneously is heated by the gas flame of a gas burner 10, joint to the adsorbed natural gas vessel (ANG). The experimental data acquisition system includes the temperature sensors, vapor pressure gauge and computer. The gas flow rate is regulated as a function of the vapor temperature.

Figure 3. General view of the solar solid sorption refrigerator

Two solid sorbent canisters 2 and 6 (Fig. 1) are filled with an active carbon fiber “Busofit” 3,8, or are filled with “Busofit” saturated by chemicals and wrapped on the surface of condensers 4,7 between fins. The length of the canister is 1.2 m, the outer diameter of the canister is 50 mm. When the composition “Busofit”-salt was used the full heat output was at least two times more (for the “Busofit”-$CaCl_2$ combination a full adsorption capacity is more than 0.85 kg of ammonia for 1 kg of a sorbent bed), but the time of reactions is increased from 12 min, up to 20-25 min.

The full adsorption capacity of an active carbon fiber “Busofit” for different gases is presented on Table 1. The isotherms of ammonia adsorption/desorption on “busofit” and “Busofit” + $CaCl_2$ are shown on Fig. 3.

The temperature evolution of the surface of the boiler 13 and canister No.1 (2) and the canister No.2 (6) are shown on Fig. 4. The main level of the boiler surface temperature is near 110 ^{0}C, while the main temperature of the canisters during its maximum desorption after 5 cycles of the operation is 95 ^{0}C. The temperature difference is near 15 ^{0}C, it means that the thermal resistance between the source of the energy (boiler) and the sink of the energy (the surface of the canisters) is near R = 0.015 k/W.

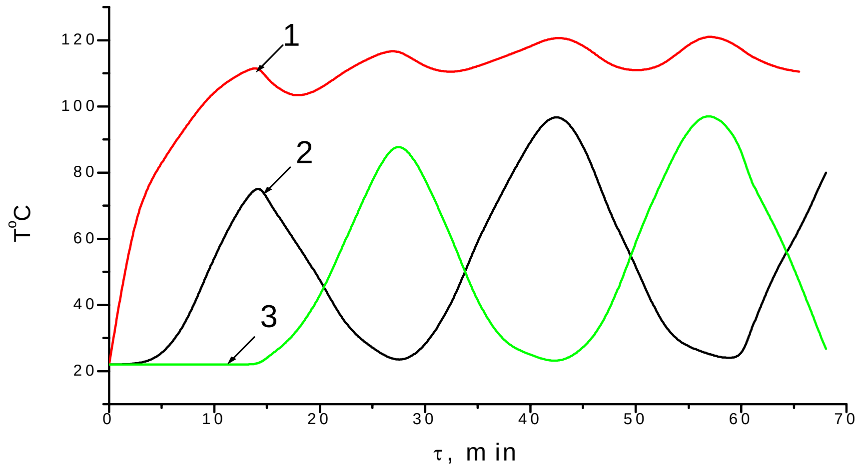

Figure 4. 1- temperature evolution of the evaporator surface; 2 - canister No.1 surface; 3 - canister No.2 surface

Table 1. Full adsorption capacity of a sorbent bed

Full sorption capacity, kg/kg of the sorbent	“Busofit”	“Busofit”+ $CaCl_2$
Acetone	0.61	
Ammonia	0.62	0.85
Ethanol	0.6	
Methanol	0.55	

The cooling power of the refrigeration

$$P = Q_e / t, \tag{1}$$

where “t” represents the duration of a single cycle of the cooling/heating. The cooling power may also be expressed per mass of the adsorbent, or the adsorber. The mass of the adsorber is equal to the sum of masses of the adsorbent, metal wall of canisters and heat pipe heat transfer system:

$$Q_e = \Delta WmL - C_{Pw}m\Delta W \tag{2}$$

$$COP^R = Q_e / (Q_{se} \tag{3}$$

The total heat of adsorption is equal:

$$Q_{ad} = \Delta H_{ad} \Delta W m_b \tag{4}$$

$$Q_{Se} = mC_p(T_3 - T_1) + m_b C_{Pb}(T_3 - T_1) + m_b W_i C_p(T_2 - T_1) = m_b W_{av} C_{pb}(T_3 - T_2) \tag{5}$$

where ΔH_{ad} – the heat of adsorption,
W_i – amount of ammonia vapor present in the "Busofit" during the isosteric phase of heating,
W_{av} – the average value of the amount of ammonia vapor in "Busofit» during the adsorption phase,
M_S – total mass of stainless steel tubes of canisters,
C_{ps} , C_{pb} – specific heat capacities of stainless steel and "Busofit".
T_1, T_3 – denote the minimum and maximum temperatures of the system, while
T_2 – represent the temperature at the beginning of the desorption time.

REFRIGERATOR OPERATION

The rate of the adsorption/desorption of ammonia on the surface of "Busofit" can be evaluated by the isotherms analysis at different temperatures of the sorbent bed, Fig. 5.

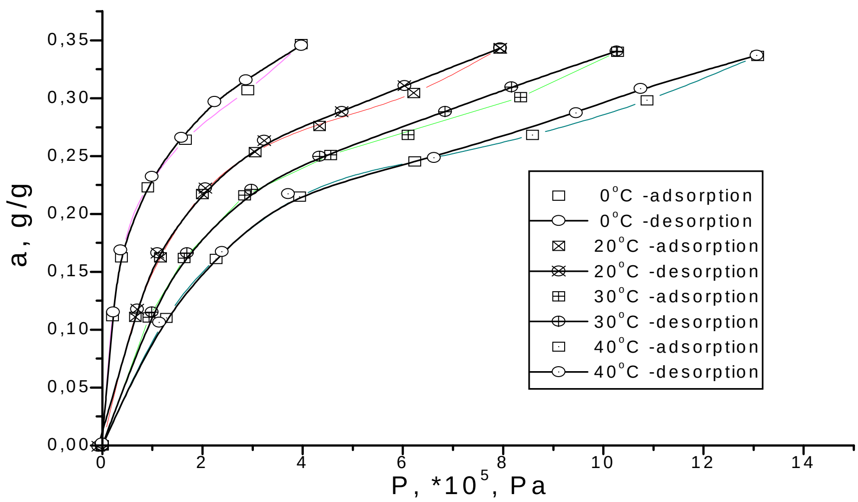

Figure 5. Adsorption/desorption isotherms of ammonia on the "Busofit"

In order to study the sorption capacity of the adsorbent it is necessary to know the quantity of gas adsorbed on each point of the cycle. There is a general need to have a good fit of experimental isotherms and temperature and to extrapolate some isotherms beside the experimental field (Figs. 5-6). For the carbon fiber "Busofit" the approach of Dubinin is well adapted and allows linking quite simply the physical properties of "Busofit" to the capacity of adsorption of the carbon fiber. The theory of micro porous volume filling, worked out by Dubinin, is widely used for quantitative characteristic of adsorptive properties and basic varieties of porous structure. The basic equation of this theory is Dubinin-Astakhov's equation, which describes the equilibrium gas adsorbtion on the adsorbents with micro porous homogeneous structure that has the following form:

$$a = \left({W_o}/{\nu} \right) \exp \left(-\left[{A}/{E_o \beta} \right]^n \right) \tag{6}$$

Dubinin-Radushkevich's equation is a special case of Dubinin-Astakhov's equation, (n=2):

$$a = \left({W_o}/{\nu} \right) \exp \left(-BT^2 \left[\lg \left({P_s}/{P} \right) \right]^2 \right) \tag{7}$$

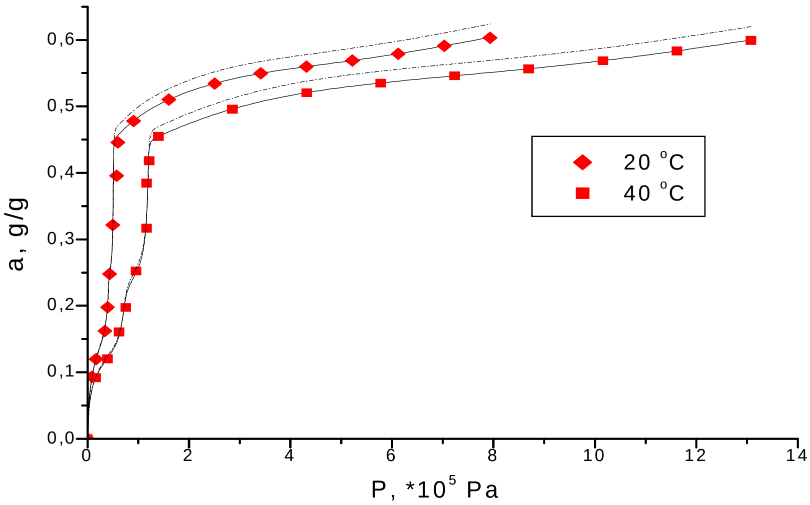

Figure 6. Experimental and calculated ammonia isotherms of "Busofit+ $CaCl_2$".
Dashed lines – calculated data.

The empirical coefficients in the equation (7) for the ammonia adsorption ACF "Busofit AYTM-055" case are: W_o= 0,491 and B = 8,56·10^{-6}.

The affined coefficient β is an independent argument and is defined as a ratio of two gas substances adsorptive potentials at invariable adsorbent in the equation (7). The ammonia calculated affined coefficients to benzene (this substance is usually taken as a standard one) differ from each other in different references. The β ammonia coefficient to benzene for ACF like "Busofit", β *Busofit* =0,309 was received on the experimental material.

Another important sorbent characteristic is a peculiar porous size. It can be defined according to the empiric expression for slit-like porous model, proposed by Dubinin: x=k/E_o, where x - half-width of the micro pore, nm; E_o - the characteristic energy of benzene, 20.5 kJ/mole; k - constant of proportionality, equal 12,0. The porous peculiar size of the ACF «Busofit AYTM -055» is 11,7 A. In these relationships: *a* – sorption capacity, g/g, mmole/g; $A = RT \ln \left({P_s}/{P} \right)$ – characteristic sorption energy, kJ/mole; *B* – structural constant, which characterizes the size and distribution of micro pores, K^{-2} ; E_o – characteristic energy of standard gas (usually – benzene) kJ/mole; *P* – pressure, Pa, kPa, MPa; *T* – temperature, °C, K; *R* – universal gas constant, kJ/(mole K); *V* – volume, m^3; W_o – micro porous volume limit cm^3/g; *z* – compressibility factor; β – affined coefficient, ν – adsorptive substance molar volume cm^3/mmole.

It is very important to estimate the COP of the process. Three levels of temperature- Tevap, Tamb, Tad and the two levels of pressure Pevap, Pcond, define the thermodynamic cycle, Fig. 7.

The refrigerator works on a four-phases cycle:

- isosteric heating,
- desorption/condensation,

- isosteric cooling,
- adsorption/evaporation.

  COP^R = cold output/high-grade heat input

The density of the adsorbed vapor is given by the Dubinin relation: with $\rho(T) = \rho_b - (\rho_b - \rho_0)$.

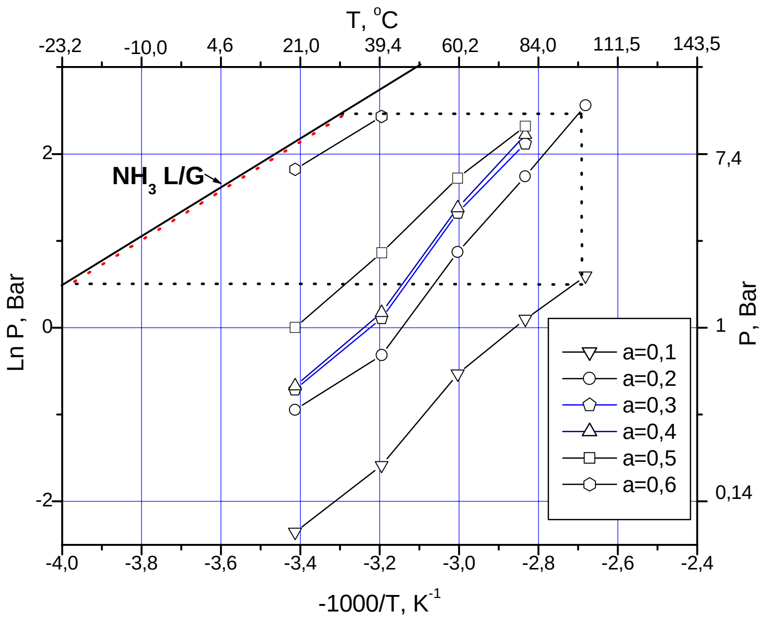

Figure 7. Clapeyron diagram for the complex compound“Busofit” + $CaCl_2$ and ammonia in the refrigeration cycle

The saturating vapor pressure is obtained from Clapeyron equation: $\ln (P_0) = -\Delta H/RT + \Delta S/R$ (for $T < T_c$) and by extrapolation of this equation for the temperature T greater than T_c. The energy required to start the refrigerator functioning comes mainly from the heat supplied to the solar collector and the gas flame burner. The air is considered as a second low temperature source of energy. During the cloudy days, or when solar energy is insufficient gas flame-heating system is switched on automatically in parallel with the solar heater to maintain the heating load 1 kW. However, a small amount of work is required by the valve system to switch on and off vapor-dynamic thermosyphon 15, (Fig. 1) to heat or to cool one sorbent bed after another (two step heat machine). This is in contrast to conventional vapor - compression systems, which require shaft work for the compression process. The main parameters of the refrigerator are included in the Table 2. Two special valves 5 and 9 (Fig. 1) give a possibility to switch on and off one, or another adsorber (2, 6). The temperature of the carbon fiber 3 and 8 inside the adsorber 2 and 6 is increasing up to 110-120 ^{0}C and there is a high-pressure ammonia generation in pores, the process being endothermic. When the pressure in the adsorber becomes lower than the ammonia pressure in the evaporator, the process of the liquid ammonia evaporation inside the porous structure is beginning with intense evaporator wall cooling down to -20 ^{0}C.

The evaporators 16, 9 (Fig. 2) are thermally connected with the surrounding through the loop heat pipes 11 and 14. Coaxial heat pipe condensers are disposed on the outer surface of the evaporators. Multi-bent heat pipe evaporating part is heating by the air. These two heat pipes are used as a second ammonia circuit thermally connected with the first ammonia circuit (evaporators 16, 9). When the temperature of the evaporator 16, 9 is decreasing and becomes lower than the air temperature, the ammonia evaporation in the heat pipe 11, 14 is starting with further its condensation on the outer surface of the evaporator 16, 9. Heat transfer between the air and cold heat pipe panels is realized by the natural convection, the temperature of heat pipe being lower – 3 ^{0}C.

Periodical switching on and off the loop heat pipe is realized automatically following the adsorption/desorption cycles of the sorbent bed.

The second alternative is to use finned evaporators and fan to heat these evaporators by the air. Such a device is more compact, but needs to use an electric energy for the fan action. The total reaction of the cycle (Fig. 4) is practically achieved in 12 minutes. The temperature evolution of the boiler is synchronized with the temperature evolutions of adsorbers. The boiler has his mean temperature near 110 ^{0}C during all the cycles. We don't need to switch on and off the heat supply system of the refrigerator, but we need only to cool and heat the sorbent bed periodically, changing the sorbent bed temperature with the help of the heat pipe condensers and a liquid cooling circuit A, Fig. 2.

SINGLE STAGE SYSTEM (COMPLEX COMPOUND "BUSOFIT" + $CACL_2$).

Let us consider the single stage refrigerator, in which the canister is filled with an active carbon fiber "Busofit" + $CaCl_2$. Ammonia is a working fluid. The chemical reaction of ammonia with the main sorbent material $CaCl_2$ is performed as:

$$CaCl_2 + nNH_3 \Leftrightarrow CaCl_2 (NH_3)_n + n\,\Delta H \qquad (8)$$

The canister during its first half cycle – cooling, is connecting to a heat exchanger (condenser + evaporator). The working fluid accumulated in the evaporator starts to boil, and we have the reaction $L_{(liq)} \rightarrow L_{(gas)}$, $\Delta H_{vap} > 0$. This reaction is endothermic with cold production in the evaporator. The canister during its first half cycle is operating as absorber, in which the chemical reaction of the gaseous ammonia with $CaCl_2$ takes place:

$$nCaCl_2 + nG_{(gas)} \rightarrow CaCl_2\,G_n \text{ , with } \Delta H < 0 \qquad (9)$$

The composition of "Busofit" with $CaCl_2$ as a complex compound sorption media is very convenient, because "Busofit" has uniform surface pore distribution (0.6-1.6 nm), small number of macropores (100-200 nm), with its specific surface 0.5-2 m^2/g, small number of mesopores with 50 m^2/g specific surface, the specific volume of micropores is 0.48 cm^3/g, with total packing porosity 0.43-0.48. The change of the volume and mass (expansion factor) for $CaCl_2$ microcristals disposed on the "Busofit" surface during absorption/regeneration occurs inside the volume of macropores and mesopores of "Busofit" and don't affect the "Busofit" structure. The coupled action of "Busofit" and $CaCl_2$ increase the thermal conductivity of a system, increase the gas permeability into the interfiber space, increase its sorption capacity to NH_3 , maintain a high porosity of a sorbent bed during the solid-gas reaction and finally increase the performances of a solid sorption refrigerator.

On the photos (Fig. 8 a, b) the uniform disposition of the micro crystals on the "Busofit" carbon fiber surface is demonstrated. The experimental isotherms of the complex compound "Busofit"- $CaCl_2$ are shown on Fig. 6. A strong influence of $CaCl_2$ on the slope of the isotherms is evident. The experimental set-up to determine "Busofit" + ammonia isotherms was filled with 128 g of $CaCl_2$ and 248 g of "Busofit". The ammonia sorption capacity of this complex compound at the temperature T = 20^{0}C and P = 800 kPa was 0.604 g/g, the total mass of the and 248 g of "Busofit". The ammonia sorption capacity of this complex compound at the temperature T = 20^{0}C and P = 800 kPa was 0.604 g/g , the total mass of the ammonia was 227.1 g. "Busofit" had ammonia adsorption capacity 85 g, $CaCl_2$ had ammonia adsorption capacity 142.1 g. Small part of $CaCl_2$ (12.5 g) didn't react with ammonia.

The isotherms of the complex compound "Busofit" + $CaCl_2$ are multiplied on the mass ratio coefficients - χ_1 = 0.32 for "Busofit», and χ_2 = 0.68 for $CaCl_2$. The sum of these two isotherms for "Busofit" and $CaCl_2$, Fig. 6 for the temperature T = 20 ^{0}C and T = 40 ^{0}C can be considered as an integral isotherm, typical for this complex compound. These experimental data testify the independent action of "Busofit" and $CaCl_2$ during the ammonia sorption, when aphysical adsorption and a chemical reaction with ammonia take place.

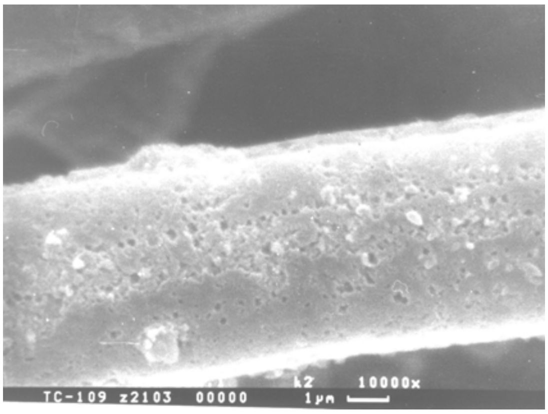

Figure 8a.”Busofit+$CaCl_2$”, multiplied by 10000 times

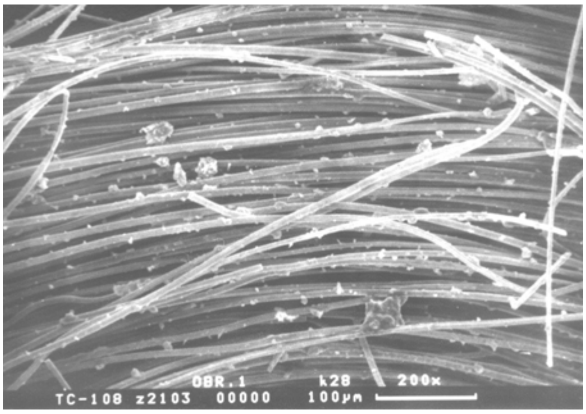

Figure 8b. “Busofit+$CaCl_2$ ”, multiplied by 200 times

Table 2. Solar-gas refrigerator main parameters

Solar-gas reactor	L = 1.2 m: D = 0.05 m
“Busofit” mass in the reactor	0.75 kg
$CaCl_2$ in one reactor	0.32 kg
Ammonia mass in one reactor	0.92 kg
Water mass in one reactor	1 kg
Ammonia mass in the pulsating heat pipe	0.05 kg
Total mass of the refrigerator	22 kg
Temperature of the hot reactor surface	120 ^{0}C
Condenser temperature	50 ^{0}C
Cabinet evaporator temperature (without heat pipes)	-18 ^{0}C
Heating capacity (W/kg sorbent)	850

A calculation based on a 70 minutes of working of the solid sorption refrigerator leads to a power of about 350 W/kg of the reactive mass. The considered reactive mass is the sum of all reactants masses: metal chloride + ammonia + active carbon fiber. Note that the utilization of high thermal conductivity carbon fibers can lead to highest power, the use of pitch-based carbon fibers (λ = 100 to 500 W/m.K.) permits to obtain a total reaction in less than 12 minutes and can give more than 1100 W/kg of the total mass of reactants.

This combination “Busofit” + $CaCl_2$ in one reactor with the condenser/evaporator is very useful for the designing of the portable and light autonomous cooler for space and hazardous conditions (a self-regulating cooling system to remove metabolic heat from the coolant loop in a life support system used in space activity, or hazardous conditions, like fire, et.). There is a possibility to perform the temperature and humidity control of the space suit very efficiently**,** Table 2.

SOLAR-ELECTRICAL REFRIGERATOR

A combined solar refrigeration and power system offers several advantages over a pure refrigeration system alone. Excess cooling capacity may be reduced and power generation increased, thereby allowing the system to run continuously at maximum efficiency. Combined refrigeration and heating system would allow operation as refrigeration and a salt-water desalination, refrigeration and drying, refrigeration and cooking, refrigeration and heating systems, and finally there is a possibility to combine refrigeration, heating and electricity production.

Photovoltaic electricity generation can be also joint together with refrigeration production and be used to power other building services, such as lightning or ventilation, or it may be used to power-up energy storage. It is interesting to consider a combined refrigeration and power-generation system with short cycles, which would allow operation systems require power for valve operation and a combined system would allow, unencumbered operation.

High temperature part of the refrigerator

Thermosyphons and heat pipes are one of the most convenient heat transfer devices for the solid and liquid sorption machines due to its flexibility, high thermal efficiency, cost- effectiveness, and reliability. Vapour-dynamic thermosyphons with water as a working fluid are capable to transport heat flow up to 10 kW and more for the distance 50-100 m, which is difficult to realize by conventional thermosyphons, horizontally disposed.

The vapour-dynamic thermosyphons in order to avoid the flooding limit and increase the maximum performance have a tube separator inside used as a vapour conduit and two-phase coaxial annular channel around this separator where the vapour condensation is produced with high efficiency. For the vapour-dynamic thermosyphons it is important to know the heat transfer coefficient within the compact evaporator when transient liquid boiling is in the pool or the liquid boiling on the porous tubes used as a heating elements inside the pool. An important heat transfer part is also a budgeting coaxial condenser with the vapour channel inside and two-phase coaxial channel around the vapour channel. Two-phase thermal devices which could be applied as a heater and cooler alternatively for one or another supplier being heated in the evaporation zone by a constant energy source (solar, electric) and cyclically cooled in the condenser zone is convenient for cyclic systems like the solid sorption refrigerators. They are new and need to be analyzed.

Solar concentrator of this Solar/electrical refrigerator is made the same as for the Solar/gas refrigerator, Fig.1, or this concentrator can be performed as a battery of the vacuum –glass solar tubes. The system of the concentrator orientation in space is available. In the focus of this solar concentrator a small boiler 23 is disposed. This boiler has an electric heater inside.

The main heat transfer system is performed as a two-phase heat transfer device (vapor-dynamic thermosyphon), Fig. 9. This thermosyphon consists of a small boiler-evaporator 23, two elongated condensers 14, 22 inside of the reactors 1, 2, vapour chamber 19 and two liquid pipes 24, 25 and one vapour pipe 19. There are 2 valves on the liquid pipes to regulate the water feeding of the boiler 23. The temperature of this boiler is near constant with small deviations, Fig. 4, while there is a change of the liquid movement from one condenser to another due to the valves switch on and off.

Low temperature part of the refrigerator

Ammonia condenser 5 (Fig. 9) is performed as a stainless steel tube with internal capillary grooves and vapor channels, Fig. 10 cooled by water. This condenser is enabling to condense the ammonia vapor down to the temperature of the ambiance with the high heat transfer intensity, Figs. 10,11.

A capillary pumped evaporator 6, 7 (Fig. 9) is more flexible with the point of view of its orientation is space and is compact. A cylindrical evaporator was made from Ni sintered powder wick with a central tube for a liquid flow and some vapor channels on the inner surface of the stainless steel tube.

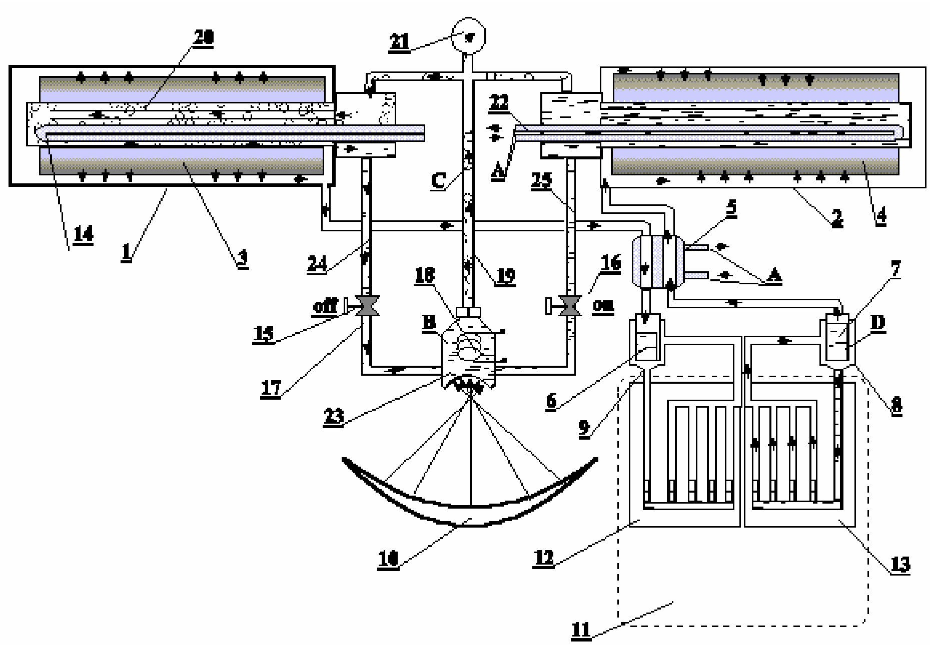

Figure 9. Solar/electrical refrigerator with heat pipe thermal control
1, 2 –reactors; 3, 4 – sorption bed; 5 – condenser; 6, 7 – evaporators; 8, 9 – heat pipe based condensers; 10 – solar concentrator; 11 – cooling chamber; 12, 13 – pulsating heat pipes; 14, 22 – thermosyphon condensers; 15, 16 – valves; 17, 24 25 – liquid pipes; 18 – electric heater; 19 – vapor pipe; 20 – vapor channel; 21 – pressure gauge; 23 – thermosyphon mini-boiler; A – water cooling loop; B – water; C – vapor; D – ammonia.

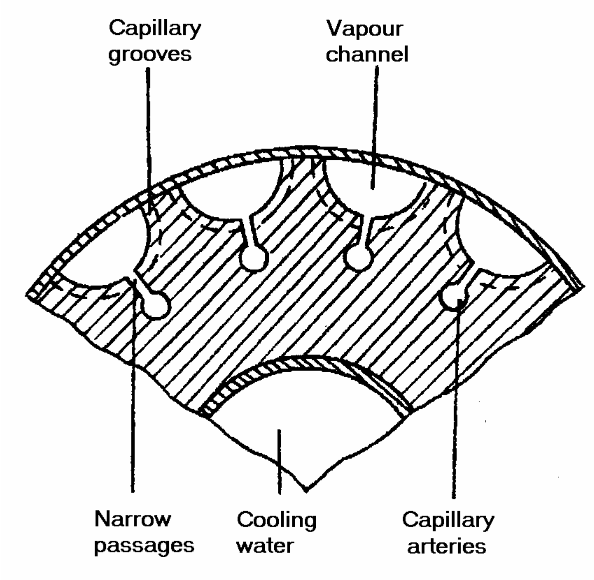

Figure 10. Schematic of the element of a condenser with narrow passages and arteries

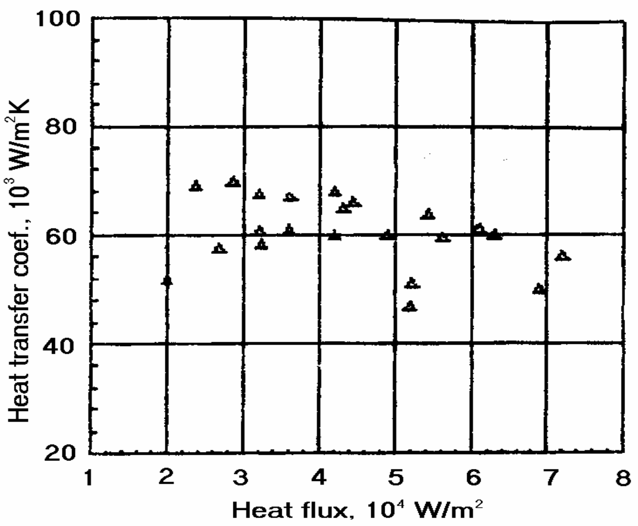

Figure 11. The heat flux effect on heat transfer in the condenser

The vapor output and the liquid input are separated by sintered powder capillary pump. The length of the evaporator is 280 mm, outer diameter – 38 mm, the wick porosity – 45 %, maximum pore diameter – 10 μ, medium pore diameter – 5 μ capillary pressure head – 0.4 Bar, wick thickness – 4 mm. Such design of the evaporator ensures a minimum pressure loss in the wick and guarantees favorable conditions for vapor generation inside a porous structure.

The maximum heat flux for this evaporator with ammonia is 1000 W. The overall thermal resistance of such a cooler is R=0.06 K/W.

The heat transfer efficiency of this evaporator is shown on Fig. 12.

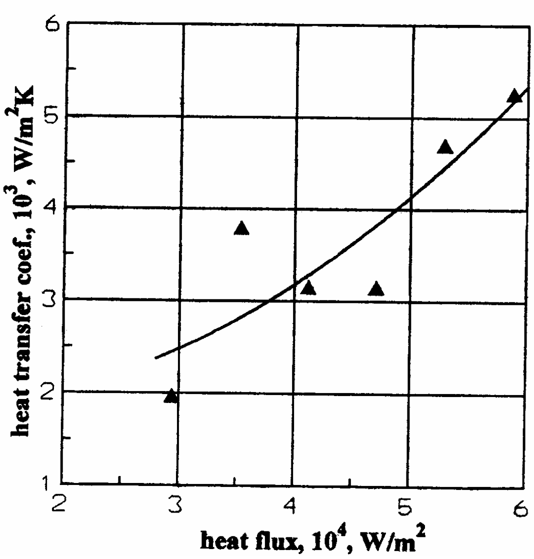

Figure 12. Heat transfer coefficient as a function of heat flux in the evaporator

The refrigerator cabinet has a volume 0,2 m^3 and is used to cool the goods in the temperature interval 0 ^{0}C– 10 ^{0}C. Two pulsating loop heat pipes 8, 9 made from stainless steel and have a cooling surface 1,2 m^2. They are disposed inside the cooling cabinet (V = 0.2 m^3) for the air cooling.

The compact ammonia evaporators (Fig. 13) cool these pulsating heat pipes, Fig. 14.

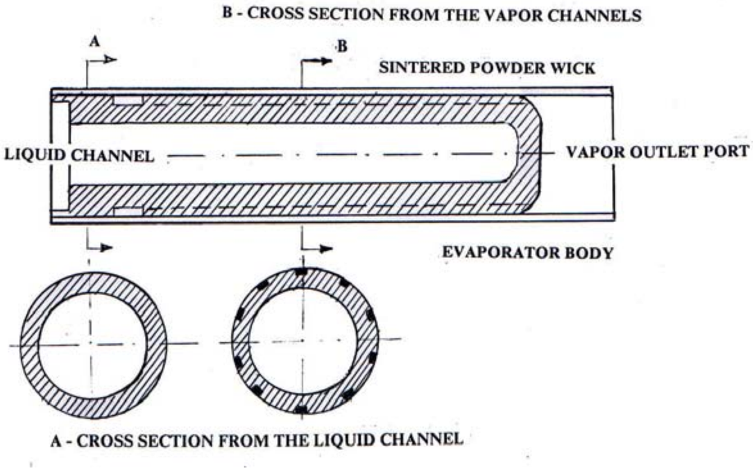

Figure 13. The evaporator/condenser of loop heat pipe

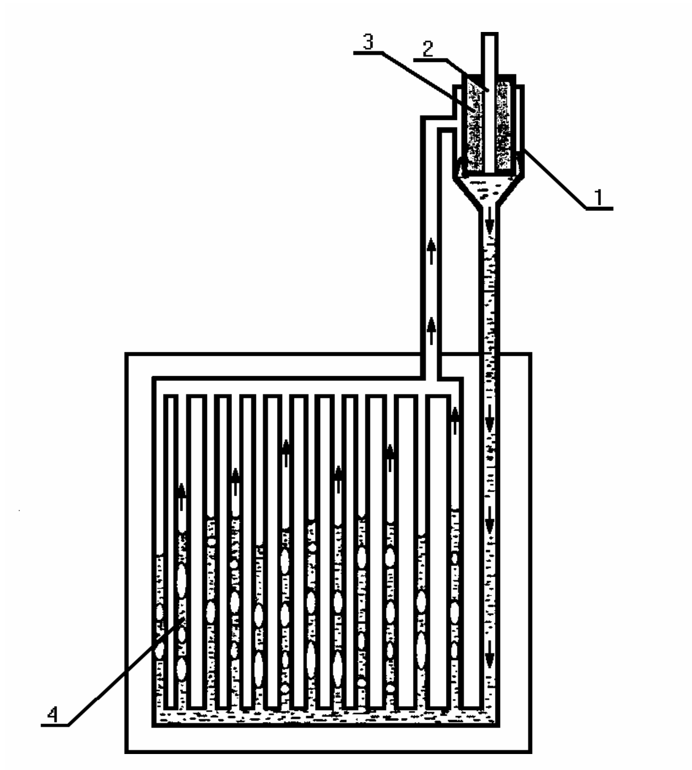

Figure 14. Schematic of the pulsating loop heat pipe panel. 1- condenser of the heat pipe, 2- evaporator of the adsorption refrigerator, 3- porous structure, 4- heat pipe evaporator zone

Loop heat pipe panels are used as uniform temperature sheets inside the cold chamber connected with a cold store unit (solar sorption refrigerator, cold accumulator), Fig. 15. The evaporator was disposed on the upper part of the cabinet. Heat pipe panels on its upper side (heat pipe condenser) have a good thermal contact with the cooling machine. Such type of heat pipes with diameter 3 mm and the length near 1 m have no capillary structure inside and are functioning under the oscillating motion of the two-phase ammonia due to a big difference between the liquid and vapor density under the heat load. The driving force of loop heat pipes is the pressure force generated by the liquid boiling at high temperature zones (lower part of the refrigerator cabinet), non-equilibrium state between vapor and liquid and vapor bubbles collapse in the upper cold part of the panel. Vapor plugs (bubbles) pushes the liquid plugs to the cold part of the unit where vapor bubbles collapsed with the increasing of pressure difference between vapor and liquid. Due to the inter-connections between the two-phase channels the motion of vapor bubbles and liquid plugs is influenced the motion of fluid in the next sections on loop heat pipe panel, Fig. 14. The ambient (room) temperature was 37 ^{0}C.

Table 3. Solar-electrical refrigerators

Adsorber dimensions	L = 1.2 m: ;D = 0.05 m
“Busofit” mass	0.75 kg
Ammonia mass	0.3 kg
Water mass in the thermpsyphon	0.6 kg
Refrigerator cabinet volume	0.2 m^3
Temperature in the cabinet	0 ^{0}C – 10 ^{0}C
Ammonia mass in heat pipe	0.05 kg
Cold output in the cabinet	150 -300 W
Heat output from the condenser	300-500 W
Heat pipe surface inside the cabinet	1.2 m^2
The time of the cycle	15 min

The cooling temperature dynamic inside the refrigeration chamber, when two pulsating loop heat pipes are functioning, is shown on Fig.15.

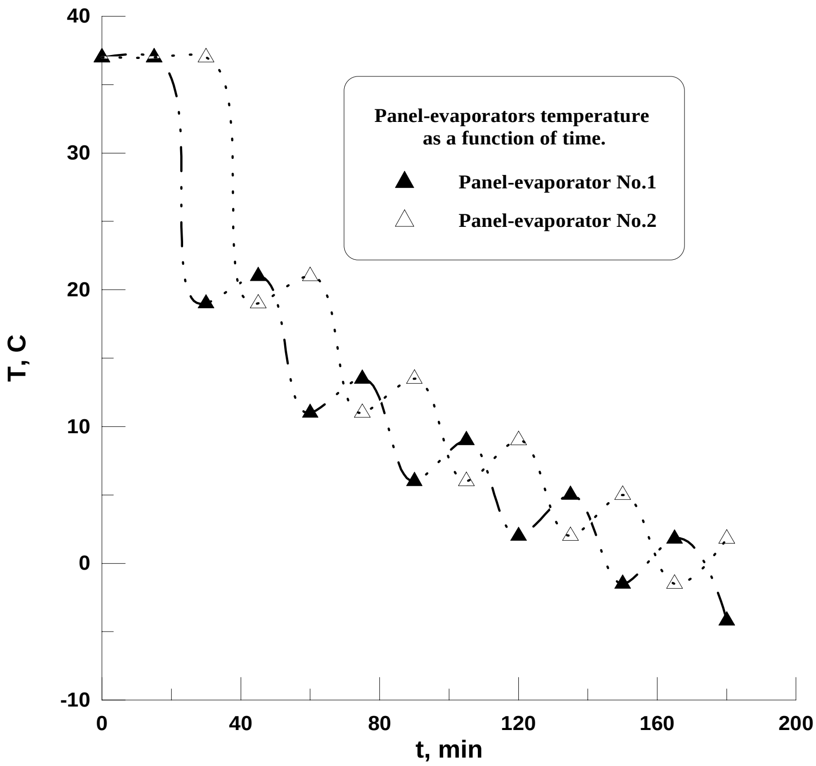

Figure 15. The temperature deviation of two loop heat pipe panels

“Busofit” as a dynamic sorbent bed was used in both refrigerators with solar/gas and solar/electrical heating sources of energy. Due to its micro and mesoporous structure , his mesopores were filled with $CaCl_2$, this allow to involve in the cycle more ammonia, Table 2, Fig. 7. A direct consequence is the increase in the specific cooling energy. “Busofit” microporous structure is also active in sorbing ammonia at the all spectre of working temperature, including high temperatures.

CONCLUSIONS

A solar gas/electrical solid sorption refrigerator with 1.8 m^2 collection surfaces was designed and studied. The ratio between solar energy and gas flame, or electrical energy supply is automatically maintained on the total level of 1 kW. The COP^R of the refrigerator is near 0.44. The combination an active carbon fiber "Busofit" + chemicals in one reactor with the porous condenser/evaporator is very useful for the designing of the portable and light autonomous cooler for space and hazardous conditions (a self-regulating cooling system to remove metabolic heat from the coolant loop in a life support system used in space activity, or hazardous conditions, like fire, et).

References

1. Cohen, B.M., Kosar, D., Solar water heating with natural gas back-up, Gas Research Institute, Chicago, Illinois, USA, 1991.
2. Guilleminot, J.J., Meunier, F., Mischler, B., Etudes de cycles intermittants a adsorption solide pour la refrigeration solaire, *Rev.Phys.Al*, 1998, Vol.15, pp.441-452.
3. Speidel, K., Kleinemeier, H.P., Solar cooling processes using chemical reactions, *Proc. of the Solid Sorption Refrigeration Symposium*, Paris, France, 18-20 November 1992, pp.288-293.
4. Bougard, J., Veronikis, G., Adsorbeur modulaire pour machine frigorique solaire charbon actif-ammoniac, *Symposium "Le froid a sorption solide"*, Paris, 18-20 November 1992, pp.282-287.
5. Wang, R.Z., Li, M., Xu, X., Wu, J.Y., Anew hybrid system of solar powered water heater and adsorption ice maker, *ISHPC'99, Proc. of the Int. Sorption Heat Pump Conf.*, Munich, Germany, March 24-26, 1999, pp.123-128.
6. Nguyen, J.M., Riffat, S.B., Whitman, D., Solar/gas absorption heat-pump systems, *Applied Thermal Engineering*, 1996, Vol.16, pp.347-356.
7. Vasiliev, L.L., Mishkinis, D.A., Antuh, A.A., Vasiliev, L.L. Jr., A solar and electrical solid sorption refrigerator, *Int. J. Therm. Sci.*, 1999, Vol. 38, pp.220-227.
8. Miles, D.G., Sanburn, D.M., Nowakowski, G.A., Shelton, S.V., Gas fired sorption heat pump development, *Proc. of "Solid Sorption Refrigeration" symposium*, Paris, November 18-20, 1992, pp.91-96.
9. Neveu, P., Castaing, J. and Ino, N., Solid-gas chemical heat pumps: field of applications and performance of the internal heat of reaction-recovery process, *Heat Recovery System and CHP*, 1993, Vol. 13, pp.233-251
10. Meunier, F., Solid sorption heat powered cycles for cooling and heat pumping applications , *Applied Thermal Engineering*, 1998, Vol. 18, pp.715-729.
11. Wang, R.Z., Adsorption refrigeration research *SJTU, IV Minsk International Seminar "Heat Pipes, Heat Pumps, Refrigerators*", Minsk, Belarus, September 4-7, 2000, pp.104-112.
12. Vasiliev, L.L., Kanonchik, L.E., Antoukh, A.A., Kulakov, A.G., Rosin, I., Waste heat driven solid sorption coolers, *SAE Technical Paper 941580, 24th International Conference on Environmental Systems and 5th European Symposium on Space Environmental Control Systems*, Friedrichshafen, Germany, June 20-23, 1994.
13. Vasiliev, L.L., Kanonchik, L.E., Antiukh, A.A., Kulakov, A.G., NaX Zeolite, Carbon Fibre and $CaCl_2$ Ammonia Reactors for heat pumps and refrigerators, *Adsorption 2*, 1996, pp. 311-316.
14. R.E. Critoph, The use of thermosyphon heat pipes to improve the performance of a carbon-ammonia adsorption refrigerator, *IV Minsk International Seminar "Heat Pipes, Heat Pumps, Refrigerators"*, Minsk, Belarus, September 4-7, 2000, pp. 35-41.
15. Chua, H.T., Ng, K.C., Malek, A., Kashiwagi, T., Akisawa, A., Saha, B.B., Multi-bed regenerative adsorptionchiller – improving the utilization of waste heat and reducing the chilled water outlet temperature fluctuation, *International Journal of Refrigeration*, (2001), Vol. 24, pp.124-136.
16. Vasiliev, L.L., Kanonchik, L.E., Mishkinis, D.A., Rabetsky, M.I., Adsorbed natural gas storage and transportation vessels, *Int. J. Therm. Sci.*, 2000, Vol. 39, pp.1047-1055.
17. Spinner, B., Sorin, M., Stitou, D., Internal energy flow analysis within a single effect sorption heat pump, *International Journal of Refrigeration*, 2001, Vol. 24, № 2, pp.185-191.
18. Castaing-Lavignottes, J., Neveu, P., Equivalent Carnot cycle concept applied to thermochemical solid/gas resorption system, *International Heat Powered Cycles Conference*, University of Nottingham, UK, 15-17 September, 1997, pp. 61-69.