Heat pipe thermal control for sorption machines

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Abstract

. The review of heat pipe thermal control systems for simple and multicascaded sorption machines (sorption technologies) developed in Belarus is presented. Different heat pipe heat transfer devices (conventional heat pipes, sorption heat pipes, heat pipe panels, loop heat pipes, vapor-dynamic thermosyphons, ets.) and new sorbent beds are oriented on efficient sorption chillers, refrigerators, heat pumps, thermal, cold and gas storage systems application in industry and space.

Key words: Heat pipes; sorbent bed; sorption technologies; thermal control; heat pumps; refrigerators; gas, thermal and cold storage systems.

1. INTRODUCTION

Sorption machines are used for more than 50 years, but recently its parameters became competitive with the vapor compression cycles. One of possibilities to improve the sorption machines parameters is heat pipe application as thermal control systems. Actually East Asian countries have a huge percentage of air-conditioning based on sorption technologies, due to limitation on the electricity network development. In Europe the big advantage of sorption technologies is related with the environmental problems. Sorption machines, or sorption technologies is a collective indication of refrigeration machines and heat pumps in which the mechanically driven compressors are replaced by a thermally driven (for example by heat pipes) thermo-chemical, or thermo-physical sorption loops (sorption heat pipes). Sorption technologies mostly are working with natural refrigerants (NH_3, H_2O). They can be built from a few tens of watts (refrigerator in mini-bar of hotel room) to the megawatts scale developed for industry. Sorption refrigeration is an environmental friendly technology, which can be moved by solar energy, gas flame, or waste heat. The sorption reversible heat pumps have important advantages in comparison with other heating technologies, a viable combination of recycling waste heat and heat recovery make the sorption heat pumps more competitive. Heat pipes as heat exchangers for sorption machines have some advantages such as short time of the cycle, improved compactness of cascading machines (less intermediate elements), increased COP (coefficient of performance) due to inter-cascaded heat recovery. Adsorption machines with heat pipe thermal control can be used combined with solar energy, process heat recovering (waste heat), or a burning fuel as their driving energy source. In some cases there is a possibility to combine different new and modern thermodynamic cycles (solar/gas, solar/electricity) in the same prototype due to heat pipes application. Recently developed sorption technologies are efficient with an emphasis on implementation and integration of sorption machines in industry, as well as domestic, commercial, administrative buildings and transport both for heating, cooling, air-conditioning, heat recovery and use of waste heat. In our case heat pipe thermal control system is the key element of the heat pump, refrigerator, heat transformer, gas and energy (heat and cold) storage machines. The ability to produce useful cooling from unused heat can considerably improve the economic case. Multi cascade machines based on heat pipe heat recovery have low maintenance cost, are reliable and can require low driving temperatures. Since 1968 the Luikov institute was engaged in heat pipe R & D. The main heat pipe applications were related to heat pipes with a wick made from metal sintered powder, axial grooves, carbon fiber, mesh. The first SU Patent on the electronic chip cooling (chip is introduced inside the porous structure of the heat pipe evaporator) was obtained in 1971. Recently heat pipes were used as efficient thermal control devices for different sorption machines [1-6]. Sorption technologies last time are popular for the adsorption refrigeration and ice making systems [7-8].

2.CONVENTIONAL HEAT PIPES

Some types of conventional heat pipes were developed and tested in the Luikov Institute, Belarus for a heat pumps application [9] (Fig.1-2), including miniature heat pipes. Conventional heat pipes are convenient as heat transfer devices for sorption machines like heat pumps, coolers and heat transformers cooling/heating, when evaporators and condensers are to be used in any heat pipe position. Essential is a possibility to change the direction of a heat flow along the heat pipe in time and to use heat pipes for cooling and heating alternatively. Such heat pipes are made as a copper envelope with copper sintered powder as a wick. The software was proposed, developed and used for prediction of heat pipe parameters. Heat pipe family qualified geometry: round tube diameter 4-25 mm, length 0.1 m – 0.8 m, wall thickness 0.2 -1.0 mm. Pipe material –copper 99.95% purity, wick - copper sintered powder with thickness of the wick - 0.2-0.8 mm. Transport capacity 10 -500 W. Water, methanol and propane are used as working fluids. The heat pipe mathematical model developed, Fig.3 and Fig.9 is including heat pipe parameters:

Input: heat pipe geometry, capillary structure parameters, working fluid properties, material properties, heat flow.

Output: maximum heat flow Q_{max} along the heat pipe vs. working fluid temperature, capillary and boiling limits, heat pipe axial temperature profile, temperature drop between the evaporator and condenser,

Analysis of the experimental data for a new optimised heat pipe with sintered copper powder wick was realized, which proves the possibility to use such heat pipes in the space independently of its orientation with the maximum heat transport capability near 500 W.

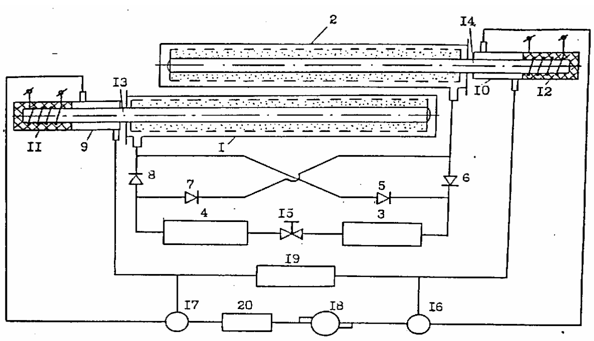

Fig.1. – Two-adsorber solid sorption heat pump [9]: 1,2 – adsorbers; 3 –condenser; 4 – evaporator; 5-8 – valves; 9-10 – liquid heat exchangers on the outer surface of the heat pipe condensers; 11-12 – heat pipe evaporators with the electric heaters on its outer surface; 13-14 – copper-water heat pipes; 15 – expansion valve; 16-17 – reversing valves; 18 – liquid pump; 19 - liquid flow meter; 20 – thermostat.

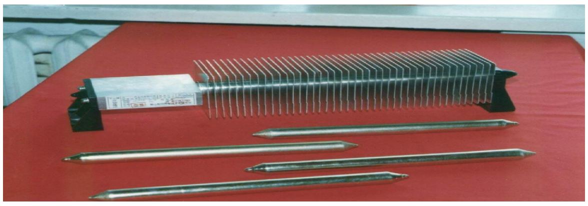

Fig. 2. Conventional copper sintered powder/water heat pipes

3.SORPTION HEAT PIPE

This device is a novelty and combines the enhanced heat and mass transfer in conventional heat pipes with sorption phenomena of sorbent bed inside it. It means, that this device could be used as a sorption heat transfer element and be cooled and heated as a heat pipe. Sorption heat pipe has a sorbent bed (adsorber/desorber and evaporator) at one end and a condenser + evaporator at the other end (Fig.4-7, Fig.18). The sorption heat pipe system include some basic phenomena interacting with each other: in the sorbent bed an adsorption phenomena (BET adsorption) is available , a vapour flow (two phase flow) with kinetic reaction rate and vapour pressure, geometry, conductive and convective heat transport with radial heat transfer. In the condenser and evaporator there is a vapour flow, liquid flow, interface position, radial heat transfer with kinetic reaction pressure, liquid pressure, vapour pressure, condensation and evaporation, shear stress, geometry, adhesion pressure, convective heat transport, radial heat transfer under the influence of the gravity field.

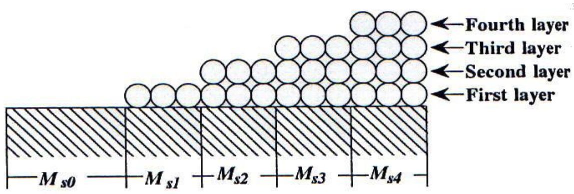

Fig. 3. Schematic model of BET theory of adsorption for the porous wick with sorbent media disposed on its surface. M_{s0} – M_{s4} the part of wick with adsorbed molecules of working fluid as a function of the time.

The original design of such a sorption heat pipe was patented in the USSR (patent 174411 “Heat pipe”, B. I. 24, 30.06.1992).

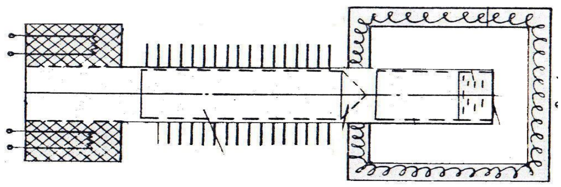

Fig. 4. Sorption heat pipe schematic, longitudinal cross, 1992, [12].

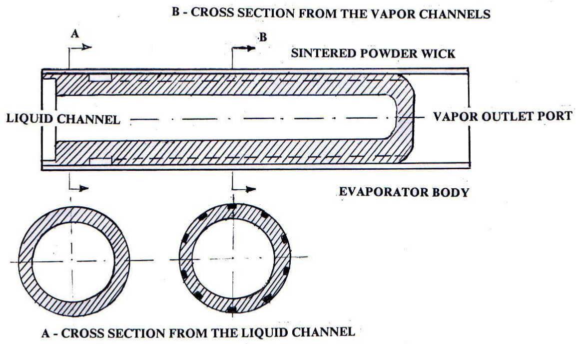

Fig.5. The condenser/evaporator designed for sorption heat pipe

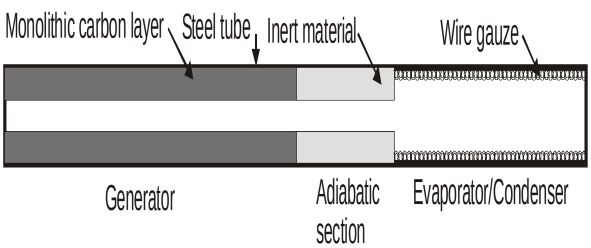

Fig. 6. Heat pipe sorption module [8], 2000

A single module [8] of the adsorption heat pipe is shown schematically in Figure 6. It is a tube having a sorption generator at one end and a combined evaporator and condenser at the other. The sorption structure is separated from the heat pipe evaporator-condenser by the porous inert wick. The porous inert material is used to transfer the fluid from the condenser to the sorption structure of the heat pipe. Sorption heat pipe application in the refrigerator/dryer is shown on Fig.10.

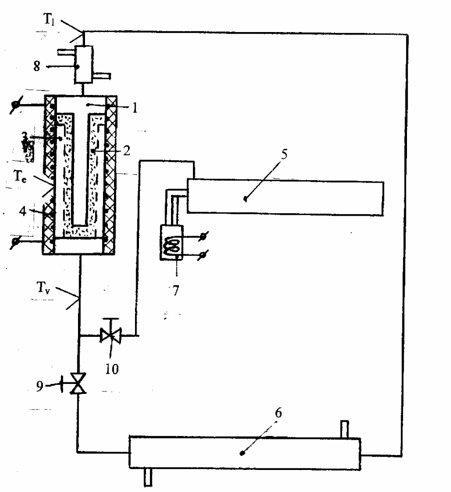

Fig. 7. Sorption heat pipe with the sorption canister, evaporator and condenser [18]: 1 - liquid accumulator, 2 - wick structure, 3 - vapor channels, 4 - electric heater, 5-solid sorption canister, 6 - condenser, 7 - heater, 8 - subcooler of the liquid

4.FLAT ALUMINUM HEAT PIPE PANEL

Another alternative to conventional heat pipes is a flat aluminum (multi-channel) heat pipe panel (Fig.8, Fig. 11-12) with propane as a working fluid to cool the low temperature sorbers. The main parameters of flat heat pipe panels are: HP width-70 mm, HP height- 7 mm, HP length –700 mm, evaporator length - 98 mm, condenser length – 50mm, heat pipe mass – 0.43 kg. HP thermal resistance R = 0.05 K/W, evaporator heat transfer coefficient α = 8500 W/m^2K, condenser heat transfer coefficient α = 2500 W/m^2K.

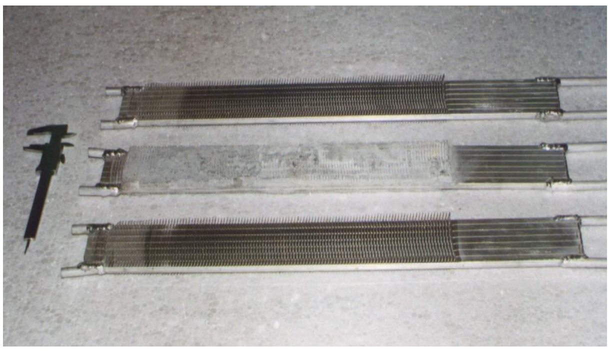

Fig. 8. Flat aluminium multi-channels pulsating heat pipe with propane as a working fluid and silica-gel monolitic sorption bed on its outer finned surface.

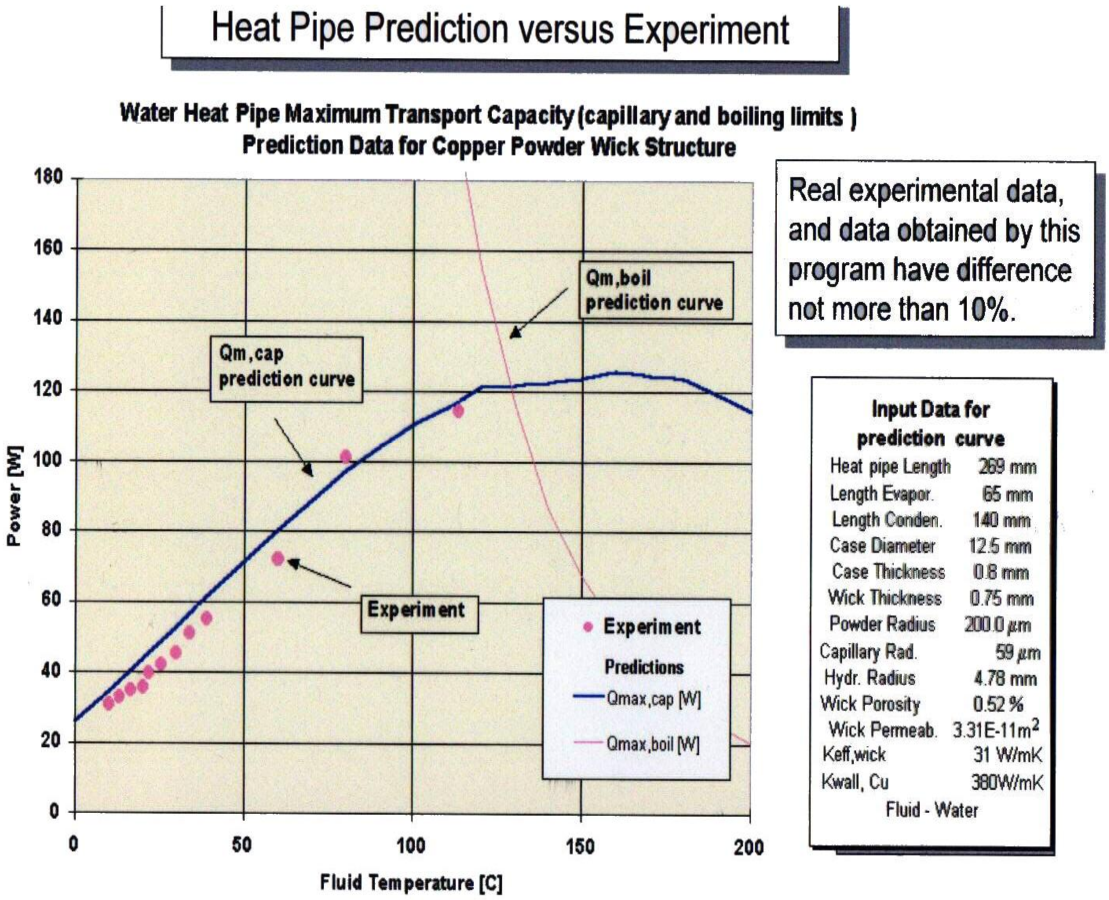

Fig. 9. Experimental verification of numerical modeling results for the conventional copper sintered powder/water heat pipe

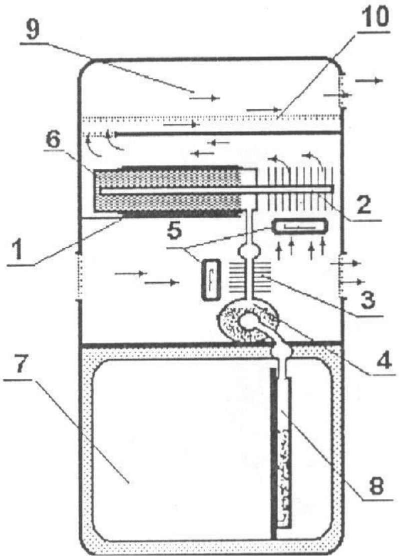

Fig.10. Schematic of the refrigerator/drying machine [10] based on the sorption heat pipe functioning. 1 –sorption heat pipe with an electric heater, 2- conventional heat pipe, 3- finned condenser, 4 – evaporator with the inverted meniscus of the liquid evaporation, 6 – sorbent bed, 7- refrigerator chamber 8-low temperature heat pipe panel, 9- drying chamber, 10–grid.

Flat heat pipe panels are convenient as modulus for its application in sorption refrigerators and heat pumps. Circulation of the working fluid (propane) is stable with liquid filling ratio near 0.6. The propane motion is continuous due to the interplay between the driving and restoring forces.

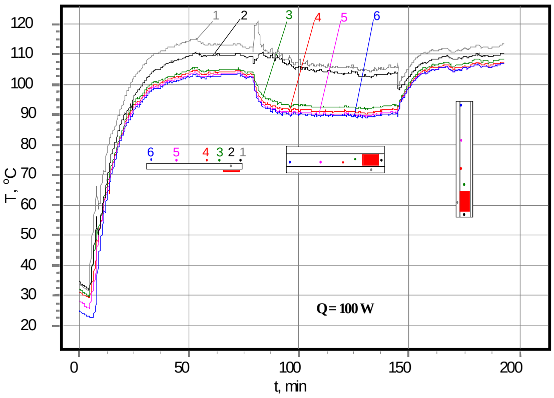

Fig.11.Temperature field evolution for different design of pulsating heat pipe panels orientation in space. T_1; T_2 – evaporator; T_3 –transport zone; T_4; T_5; T_6 –condenser. Heat pipe size 700x70x7 mm., R =0.05 K/W. The liquid circulation depends on the heat input and its velocity increases with the heat flow increasing.

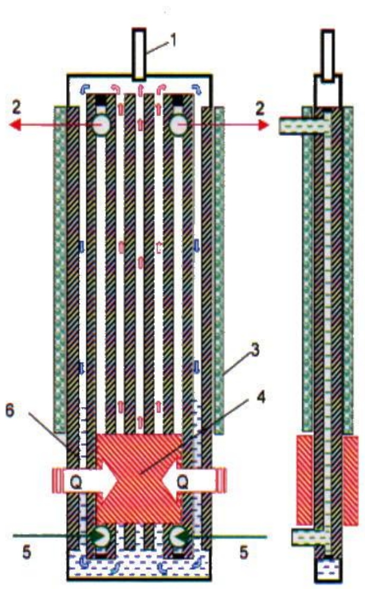

Fig.12. Multi-channel pulsating heat pipe with a sorption bed on its outer surface. 1- input for the working fluid initial charging; 2 – output for the cooling fluid; 3- sorbent bed integrated between fins; 4- heat load; 5 – input for the cooling fluid;
6 – working fluid

During the experiments circulation and oscillations of the propane working fluid was observed depending of the inclination angle and the liquid fill ratio. The thermal performance of this heat pipe panel depends on its parameters, Fig. 11.

5.VAPOR-DYNAMIC THERMOSYPHONS AND LOOP HEAT PIPES.

Vapor-dynamic thermosyphons, Fig.13 and loop heat pipes, Fig.14 provide the coupling between topping and bottoming sorption cycles (solid sorption refrigerators and heat pumps).

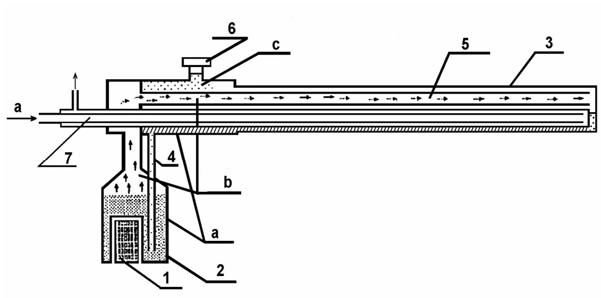

Fig.13. Water/SS "vapor - dynamic" thermo-syphon. 1-electric heater; 2-boiler; 3-condenser; 4-feeding liquid tube; 5-vapour passage ; 6- trap for NCG (on the top of additional condenser); 7- water heat exchanger; a - water; b -vapour; c – non-condensible gas (NCG)

The direct coupling between cycles of the different temperature range ensures the operating temperatures in both cycles more favorable from the thermodynamic point of view. The temperature drop is definitely smaller to compare with the conventional heat exchangers and the thermal storage system can be avoided. Heat pipes R&D was realized to perform the coupling between the heat pump topping and bottoming cycles, stimulate the heat and mass transfer in solid sorber designs, to heat sorbers and to cool condensers using heat pipe.

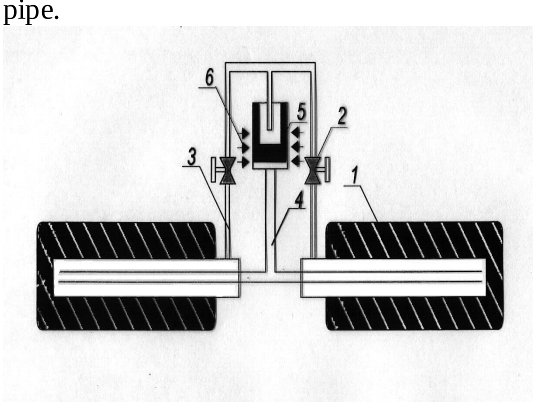

Fig. 14. - Loop heat pipe with one capillary pumped evaporator and two condensers switched on and off by the valves:1- adsorber; 2 – valve; 3 – liquid channel; 4 – vapor channel; 5 – capillary pumped evaporator, 6 – heating zone.

Loop heat pipe family qualified geometry has parameters: round tube 25 mm O. D., 0.8 m- 1.2 m - length, 0.5 mm - wall thickness. Pipe material – stainless steel. Evaporator wick –nickel sintered powder with a thickness of 0.8 mm. Condenser – tube-in-tube type. Heat pipe transport capacity is equal 100 -1500 W. Water is used as a working fluid. Heat pipes perform the advantage - heat recovery from the high temperature cycle to a low temperature cycle and are considered as new components for heat transfer. The example of thermosyphon and loop heat pipe application is shown on Fig.16-20. Solar/gas heat pump with heat pipe heat recovery was tested with COP (Coefficient of performance) near 1.44, [16], Fig.17.

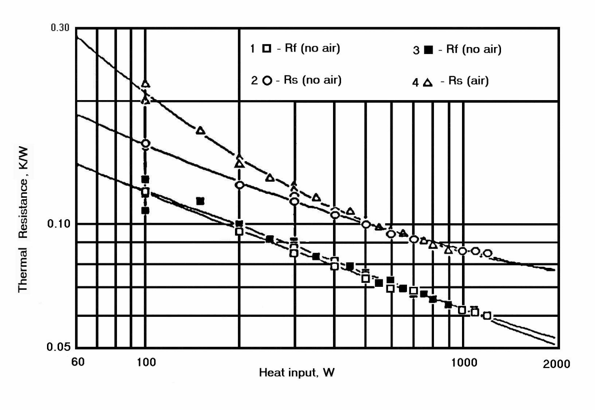

Fig.15. Thermal resistance R of "vapour-dynamic" thermosyphon as a function of heat input Q
1. - water; 2. - HCFC 22; 3. - water with air; 4. - HCFC 22 with air into the auxiliary condenser – gas trap

The technology of sorbers heating using heat pipes at up to 300^{0}C and condensers cooling by heat pipes at down to the ambient temperature seems to be promising for the future heat pump designes. It stimulates the possibilities to reduce the mass and volume of the air conditioning systems, refrigerators and heat pumps. High temperature sorbers may be heated by water steam. The complexity of the valve system for water steam channels at low temperatures made it difficult to prevent the ingress of air in the sub-atmospheric zones during the time of sorbers cooling. Hydrocarbons heat pipes (propane, butane, propylene) could avoid this difficulty. The control of the heat transfer in heat pipes may be achieved by low cost valves, Fig.14, Fig.16.

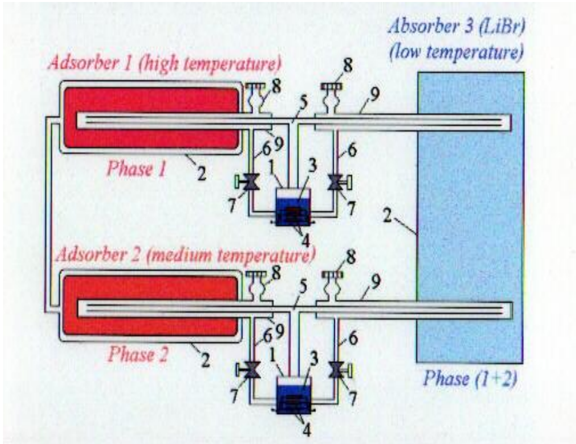

Fig.16. Three adsorbers heat pump with internal and external heat recovery, using vapor-dynamic thermosyphons.

New loop heat pipe heat transfer devices (water/stainless steel) are suggested and tested as a thermal link between topping and bottoming sorption cycles with heat recovery, Fig.16. Another example of vapor-dynamic thermosyphons and loop heat pipe application is demonstrated on Fig.17-20. Solar-gas sorption refrigerator [11] was suggested and successfully applied in India. The experimental set-up was tested with ammonia as a working fluid and is ready for tests with water as a working fluid.

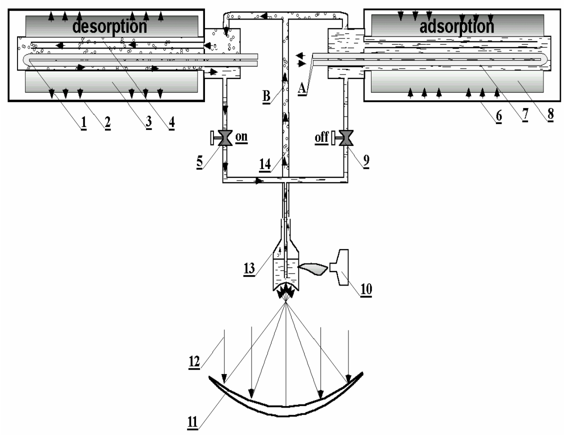

Fig.17. Solar/gas solid sorption refrigerator, high temperature part [11].

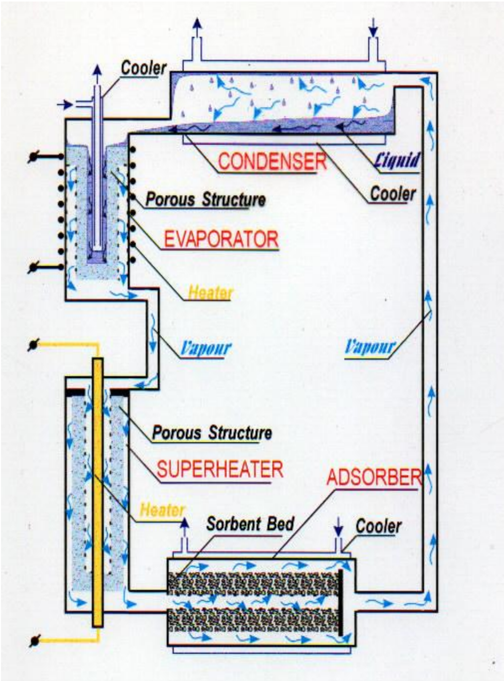

Fig.18. Sorption loop heat pipe with vapor superheater (convective mode of sorber heating)

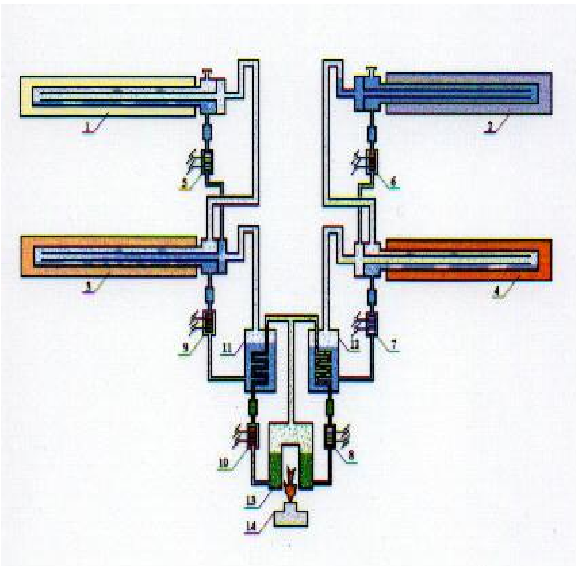

Fig.19. Four adsorbers heat pump with heat recovery, using heat pipe (thermosyphons) control. 1,2 –low temperature adsorbers filled with "Busofit"+$BaCl_2$; 3,4 – high temperature adsorbers filled with "Busofit"+$MnCl_2$; 5-10 – thermal regulated valves; 11-12 – heat exchangers; 13 – miniboiler; 14 – gas flame

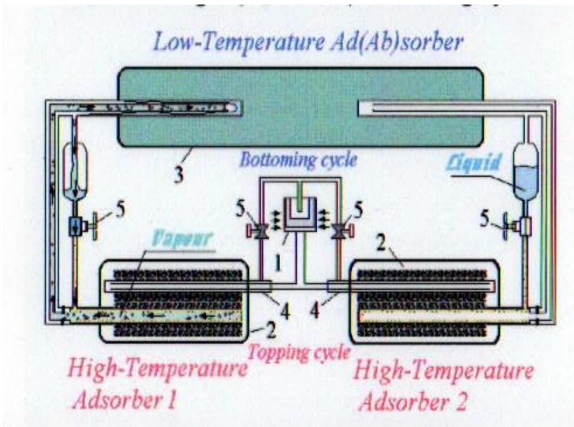

Fig.20. Two adsorbers zeolite-H_2O topping cycle and H_2O –silica-gel (H_2O/LiBr) bottoming cycle with heat pipe (thermosyphons) heat recovery. 1- capillary pumped HP evaporator; 2- high temperature adsorbers; 3 – low-temperature ab/adsorber; 4 – HP condenser; 5 –valve

Ten adsorbers sorption heat pump with heat pipe thermal control is shown on Fig. 21, designed and tested in the Luikov Institute in 1996.

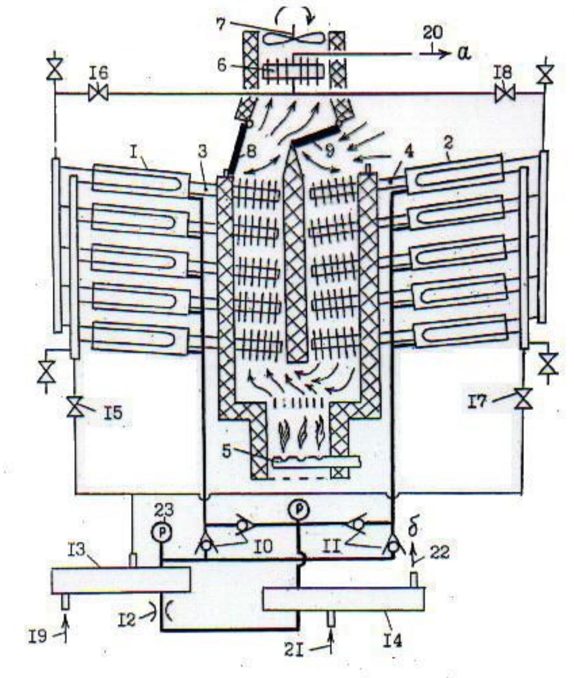

Fig.21. 5 kW sorption heat pump [15]. 1,2 – adsorber; 3,4 – heat pipes; 5 –gas flame; 7 – fan; 8,9 – gas distributors; 10-11 – reversing valves; 12 – expansion valve; 13 – condenser; 14 – evaporator; 15-18 – flow valves; 19-22 – water flow inlet and outlet.

Different heat pipe devices (cylindrical copper pipes with metal sintered powder as a wick, flat aluminum heat pipe panels, stainless steel loop heat pipes with capillary pumped evaporators, vapor-dynamic thermosyphons, gas-loaded heat pipes) were integrated in different designs and tested to verify its heat transfer efficiency, Fig. 22-23.

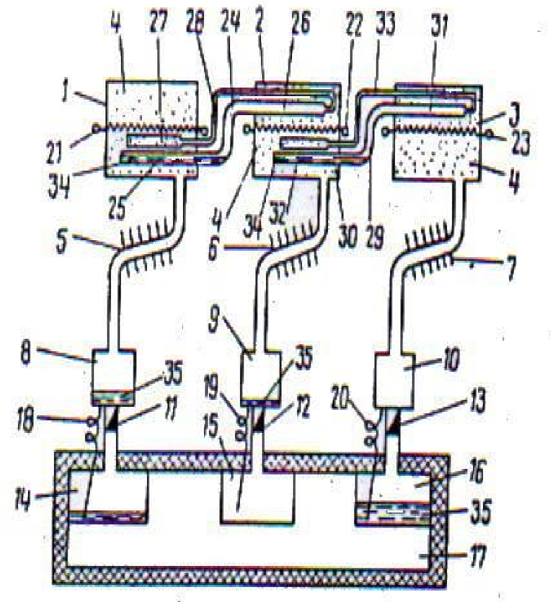

Fig.22. Three adsorbers refrigerator with gas-loaded heat pipe heat recovery and thermal control [13]. 1-3 – adsorbers; 5-7 gas loaded heat pipes; 14-16 – evaporators; 17 – cooling chamber.

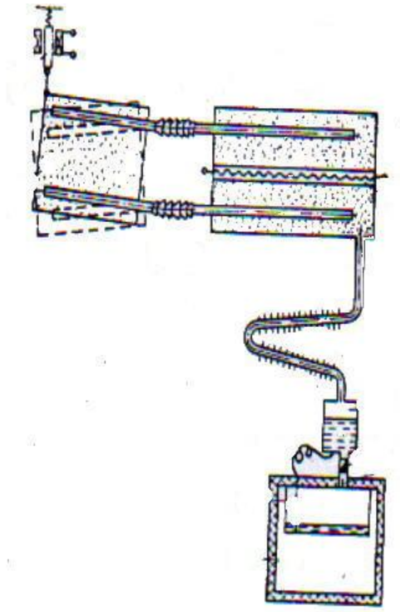

Fig. 23. Solid sorption refrigerator with flexible heat pipes and thermal storage chamber for the heat recovery [14].

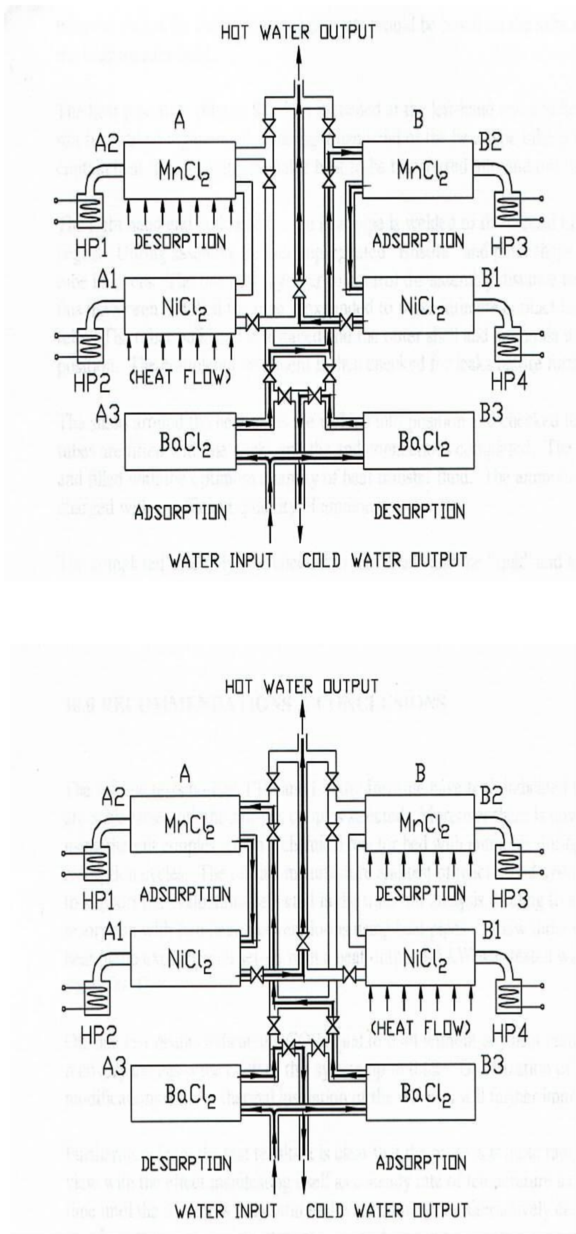

Fig. 24. Six- adsorber heat pump (“Busofit” + salts)with internal heat recovery [19].

A new three salts-active carbon fiber (“Busofit”) heat pump (Fig.24) experimental set-up with heat output 1.5 kW was suggested, performed and tested with the temperature lift near 100^{0}C. Heat pipes (vapor-dynamic thermosyphons) were used in this set-up to ensure the heat recovery between the topping and bottoming cycles. COP of the system is equal to 1.48.

The experimental set-up was tested with ammonia as a working fluid.

Fig. 25. Solid sorption refrigerator (lower part) and drying chamber (upper part) [10] with heat pipe thermal control. Refrigerator cooling capacity is 200 W.

Solid sorption refrigerator and dryer, Fig. 25 was designed and used in hot climate countries. This experimental set-up has possibilities to use the same energy consumption (electricity) to ensure the drying procedure and cold generating inside the cold chamber.

Fig. 26. Two sorbers resorption (gas-gas) heat pump with internal and external heat recovery made by heat pipes.

Two adsorbers heat pump is shown on Fig. 26. This heat pump is working in the gaseous phase and is insensitive to the gravity field.

6. CONCLUSIONS

Different heat pipe heat transfer devices were developed and tested, oriented on the application in highly efficient sorption machines and electronic components cooling. These machines are feasible based on the coupling of different sorption cycles. Software for prediction heat pipe parameters was developed and applied during the heat pipe design and fabrication. The accuracy of the predicting parameters and comparison with the experimental data is in the limit of 10%. Different heat pipe devices (cylindrical copper pipes with metal sintered powder as a wick, flat aluminum heat pipe panels, stainless steel loop heat pipes with capillary pumped evaporators, vapor-dynamic thermosyphons, gas-loaded heat pipes) were integrated in different designs and tested to verify its heat transfer efficiency. Some new solid sorption devices were suggested and tested, supplied with a heat pipe thermal control. For example, three salts-active carbon fiber heat pump (1,5 kW experimental set-up) with heat pipe heat transfer system for its cooling/heating to increase the COP of the device was designed, developed and tested, which has a cool water (3-5 ^{0}C) as the low temperature output and superheated water vapor as a high temperature output, with COP near 1.48.

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