Adsorption, 1, 303–312 (1995)

Waste Heat Driven Solid Sorption Coolers Containing Heat Pipes for Thermo Control

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Received May 17, 1994; Revised June 8, 1995; Accepted June 19, 1995

Abstract. This paper provides a focus on the R&D of solid sorption coolers and heat pumps made in the Luikov Heat & Mass Transfer Institute (CIS Countries Association "Heat Pipes") under Thermacore, Inc. Agreement.

Commercial and space applications of sorbent systems offer an attractive alternative to compression systems and liquid sorption systems for cooling, heating and air conditioning.

MgA zeolites solid sorption systems are analyzed. Some new results are presented.

Solid sorption heat pump technology utilizing heat pipe heat recovery with a condensing/evaporating refrigerant holds considerable promise for bivariant (space and domestic) applications due to the variable temperature and variable load capabilities of such machines.

Keywords: heat pipe, heat pump, zeolite

Introduction

Solid/vapor adsorption refrigeration was first demonstrated by Faraday in 1848 (Professor Leslie, 1924). Although commercial use of an adsorption machine had been from the 1920's (Miller, 1929; Hulse, 1929), it is only recently that adsorptive systems have been proposed for heat management.

The Jet Propulsion Laboratory of the California Institute of Technology has long been involved in developing solid sorption refrigeration systems for the cooling of cryogenic infrared sensors for spacecraft applications with both NASA and SDIO (Jones and Golben, 1984; Jones, 1988, 1992).

Adsorption cooling system which utilizes water and zeolite is attractive since it minimizes environmental problems in automobile air conditioning (Suzuki, 1992).

A two-adsorber zeolite-water heat pump has been built and tested in a slaughter house to provide hot water and refrigeration (Zanife and Meunier, 1992). The unit was based on a simple heat exchanger technology: adsorbers were finned tubes with the zeolite distributed between the tubes. This simple technology leads to low coefficient of performance (COP = 0.45).

Our principal interests have been concentrated on zeolite-water pair.

The heat and mass transfer inside these sorbent beds and in the evaporator/condenser is decisive for the operational characteristics of such coolers and heat pumps. While pure powder sorbent beds have very low effective thermal conductances (0.05–1 W m^{-1} K^{-1}), the consolidated sorbent beds (zeolites with a silica-aluminate gel, or porcelain clay inside the Ni metallic foam) have higher thermal conductance properties.

The use of highly conductive blocks with good heat transfer coefficients at the wall poses the problem of the nature of the external exchangers, for example heat pipes. Heat pipes are highly reliable, efficient energy transport devices and have a lot of terrestrial and space applications.

Heat pipe heat exchangers used to heat and to cool sorbent beds are attractive due to their autonomous functioning, wide range of temperature applications, low heat capacity and high thermal conductance.

For a finned sorbent bed/heat exchanger a micro heat pipe open type phenomena could be realized on the contact surface metal fin-porous media (Vasiliev, 1993). The global heat exchange coefficient from 200 to 400 W m^{-2} K^{-1} for sorbent beds of 5–10 cm in diameter and of variable degree of consolidation could be achieved using this new type of heat and mass transfer.

Some interesting models of sorbent beds were published in literature by now.

Diffusion of gases in microporous particles of a macroporous sorbent layers was analyzed in (Lee and Ruthven, 1987; Sun et al., 1986).

Nonisothermal diffusion in these sorbent layers was discussed by Meunier (Ruthven and Lee, 1981).

Shelton and independently Tchernev proposed a thermal analysis of sorbent bed with heat recovery based on propagation of a thermal wave (Miles et al., 1989; Chinch and Tcherner, 1989), thus increasing COP of a system.

Pressure and thermal fronts propagation in sorbent beds was investigated by Meunier (Guilleminot et al., 1987; Guilleminot and Meunier, 1989).

Following hypotheses of low pressure step in high permeability absorbers (10^{-12} m^2) a thermodynamic and economic optimization of a finned adsorber was fulfilled for a solar refrigerators (Passos et al., 1989). A bidimentional model incorporating the thermal wave concept, which takes into account the convective heat transfer and heat diffusion in particles was described in (Amar et al., 1992).

A lumped-parameter model of adsorption/desorption process and a finite-difference solution of the complete heat conduction equation of a sorbent bed were used to analyze a heat transfer in adsorbers (Douss et al., 1988; Worsoe-Schmidt and Lin, 1992; Cho et al., 1992).

The purpose of this paper is to analyze, design and fabricate a new high thermal conductivity MgA/water solid sorption machine based on heat pipe heat recovery.

Mathematical Model of Adsorber Based on Heat Pipe

Let us consider an adsorber/heat pipe heat exchanger, which has a uniform temperature field (vapor temperature inside of heat pipe is $T_{\mathrm{HP}} = \mathrm{const}$). Heat pipe finned surface contacted with a sorbent bed.

The process of heat and mass transfer in a single cylindrical porous adsorbent bed with length L, inner radius r_0 and other radius $r_1, r/1 \ll 1$ is analyzed. A one or two-phase heat carrier (heat pipe, or convective heat exchanger) circulates in a tube with diameter equal to $2r_0$ at the inner side of porous cylinder.

One dimensional nonequilibrium model of sorbent bed was developed following the publications (Guilleminot et al., 1987; Guilleminot and Meunier, 1989; Passos et al., 1989). The first main difference of this model is concerned with the boundary condition on the inner surface of adsorber due to heat pipe application (heat transfer α_{HP} is uniform of the whole length of adsorber and high up to 10^4–10^5 W/M^2 K). In our numerical simulation it was equal 500–1000 W/m^2 K. The second difference from (Guilleminot et al., 1987; Guilleminot and Meunier, 1989; Passos et al., 1989) is related with heat transfer phenomena on the outer surface of adsorber due to the limited heat transfer α_{env} with the surrounding media.

The mathematical model of the heat and mass transfer in a cylindrical bed of solid sorbent was suggested based on the following assumptions (Guilleminot et al., 1987; Guilleminot and Meunier, 1989; Passos et al., 1989).

1. In high porosity and permeability sorbent bed the pressure across the bed is uniform.
2. The axial adsorbent bed temperature is constant, heat is supplied and removed by heat pipe or two-phase heat carrier.
3. The sorbent bed porosity is high, mass diffusion process isn't limiting.
4. There is a local thermodynamic equilibrium inside the porous bed: the value of Q-heat source or sink (if negative), due to sorption or desorption processes is equal:

$$Q = q_{st}\rho_s\frac{\partial a}{\partial t}, \qquad (1)$$

where q_{st}—latent heat of adsorption [J/kg];

These estimation are realistic for zeolite/water combination with sorbent porosity up to 75% and permeability $K > 10^{-9}$ m^2.

The mathematical model is based on

— a one-dimensional transient heat conduction equation represented for a adsorbent bed in cylindrical coordinate system

$$\rho_s(C_{ps} + aC_{pa})\frac{\partial T_s}{\partial t} = \frac{1}{\partial r}\frac{\partial}{\partial r}\left(r\lambda_{\mathrm{eff}}\frac{\partial T_s}{\partial r}\right) + q_{st}\rho_s\frac{\partial a}{\partial t}, \qquad (2)$$

where ρ_g, C_{pg}—are gas density and heat capacity, ρ_s, C_{ps}—are dry solid adsorbent density and heat capacity, ρ_a, C_{pa}—adsorbat density and heat capacity, λ_{eff}—effective heat conductivity coefficient of porous structure;

— the equation describing the dynamic of sorption may be attached to the system and solved in a case of noticeable deviation from the mass equilibrium state. The ordinary form of dynamic equation is (Passos et al., 1989)

$$\frac{\partial a}{\partial t} = \beta e^{-\frac{E_0}{RT}}(a_{\mathrm{eq}} - a), \qquad (3)$$

where E_0 and β—phenomenological constants, R is universal gas constant.

— equation of mass balance. The mass balance is treated via Dubinin-Asthakov equilibrium state equation (Dubinin and Asthakov, 1971)

$$a_{\mathrm{eq}} = a_0 \exp\left[-\left(\frac{RT}{E_0}\ln\frac{P_s}{P}\right)^n - B(T)\right], \qquad (4)$$

where the empirical coefficients for a zeolite (MgA)/water pair

$$B(T) = \ln\frac{\rho_0(T - T_0)}{\rho_b(T_{cr} - T_b)},$$

$$T_0 = 293\ \mathrm{K}, \quad E_0 = 18.5 \cdot 10^3\ \mathrm{J/mol},$$

$$a = 0.263, \quad n = 2,$$

$$T_{cr} = 547.15\ \mathrm{K}, \quad T_b = 373.15\ \mathrm{K}.$$

were determined following (Maier-Laxhuber, 1983) results and our own experimental data;

— the saturating curve for the heat carrier

$$P_s = P_s(T), \qquad (5)$$

where functions $P_s(T)$ for different adsorbent-adsorbate pairs were taken with the interpolation between experimental points from literature. Tables of $P_s(T)$ and other tables for physical properties were set into computer program and can be easy find out from it;

In a case of two-phase heat carrier the thermal boundary conditions at inner surface of porous bed (2) may be written in a simple form

$$\left(\lambda_{\mathrm{eff}}\frac{\partial T}{\partial r}\right)_{/r=r_0} = \alpha_{\mathrm{HP}}(T_{\mathrm{HP}} - T_{/r=r_0}), \qquad (6)$$

where α_{HP}—the heat transfer coefficient between the bed boundary with temperature T and heat carrier with constant temperature T_{HP}.

At the other surfaces of the bed the condition of convective heat transfer with heat transfer coefficient α_{env} was adopted

$$-\left(\lambda_{\mathrm{eff}}\frac{\partial T}{\partial r}\right)_{/r=r_1} = \alpha_{\mathrm{env}}(T_{/r=r_1} - T_{\mathrm{env}}) \qquad (7)$$

The initial conditions for the concentration in sorbent and temperature fields were taken constant

$$T = T_0 \qquad (8)$$

$$a = a_{\mathrm{eq}}(T_0) \qquad (9)$$

The transient one-dimensional boundary value problem (2)–(9) was solved with the Gear's method (Shampine and Gear, 1986). Using a written computer code we were able to investigation and influence of such parameters as material properties, heat transfer coefficients and follow the dynamic of sorption and desorption reactions as applied to technical characteristics of coolers.

Two Sorbent Beds Cooler with Heat Recovery

The experimental device (Fig. 1) has two adsorbers (sorbent beds) 1 and 2, connected with a condenser 3 and evaporator 4 through four valves 5–8. The sorbent beds are heated and cooled by copper-water heat pipes 13 and 14, which have HP evaporators and condensers in series.

The HP evaporators are heated by electric cartridge heaters 11–12. The HP condensers 9–10 are cooled by the liquid circuits connected with a liquid pump 18. The liquid flow through the circuit is measured by the water flow meter.

The system of liquid circuits gives us the possibility to accomplish the regeneration through the use of heat transfer loop.

Copper-water HP devices were installed inside sorbent beds in horizontal position. HPs have a rectangular grooves as a wick, saturated with water. They have $d_{\mathrm{out}} = 0.016$ m, $d_{\mathrm{in}} = 0.013$ m and length $L_{\mathrm{HP}} = 0.65$ m. Sorbent bed envelope is made from stainless steel tube with $d_{\mathrm{in}} = 0.039$ m, $d_{\mathrm{out}} = 0.04$ m and length $L = 0.45$ m.

The outer HP surface is covered by ceramic cylinder made from zeolite 80% and white porcelain clay 20% mixture as a sorbent bed. The compound is compressed at some tens of mPa and dried (heated) in the mould for 3 h. The second combination of a test sorbent composition is a compound of zeolite powder immersed in a silica-aluminate gel. This suspension is pumped inside the metallic foam in form of nickel foils (thickness 8 mm, density: 0.25 g cm^{-3}, specific area: 900 m^2 m^{-3}). A metallic foam mesh is filled with the paste MgA and clay, or silica-aluminate gel (Fig. 1).

The final product is in the form of the cylinder with a diameter $d_{\mathrm{out}} = 0.038$ m, $d_{\mathrm{in}} = 0.016$ m and length $L_s = 0.4$ m. The apparent density of zeolite is 0.75, it is greater than for a non-consolidated fixed bed (0.52). The total mass of the sample studied is 0.2 kg. The mean diameter of the macropores is 7000 A

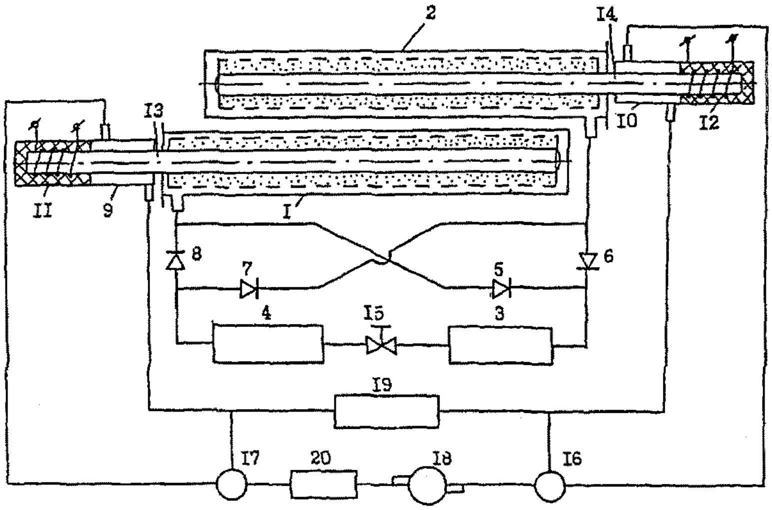

Fig. 1. Two sorbent beds solid sorption heat pump with heat pipe heat recovery system.

approximately. The total porous volume measured by mercury porosity is 0.28 $cm^3\ g^{-1}$.

To analyze the heat and mass transfer in condenser and evaporator it is necessary to realize the visualization and water flow control through condenser and evaporator. For such a reason they were performed as a glass cylinders.

At the time $\tau = 0$ s the porous beds in adsorbers No. 1 and No. 2 have the uniform temperature. At the time $\tau > 0$ s we start to heat the adsorber No. 2 by the electric heater through heat pipe 14 (HP2) till the temperature level in the porous bed reach the level TH.

At this time there is a situation when adsorber No. 1 is assumed to be cool and the adsorber No. 2 is assumed to be hot and is to be cooled.

The liquid pump 18 is switched on and the liquid is beginning to circulate through the heat exchanger 10 and 9 cooling adsorber No. 2 and heating adsorber No. 1 by heat pipes 14 and 13. When the temperature in the porous beds of the adsorbers No. 1 and No. 2 is reached $(T_H - T_L)/2$ the fluid reversing valve 17 is switched off and the liquid circulation only through the heat exchanger 9 is ensured.

The electric heater 11 begins to heat the porous bed in adsorber No. 1 up to the temperature level TH, while the porous bed in adsorber No. 2 is cooled till the temperature level TL near the ambient temperature with the help of the fluid cooler 19. At this time the first half of cycle is accomplished.

When the temperature TH of the porous bed (adsorber No. 1) is reached and the temperature TL in the porous bed of adsorber No. 2 is established, the second half of the thermodynamic cycle is beginning by liquid pump 18 and reversing valve 16 activation.

The temperature sensor on the HP wall through the electronic amplifier gives a command to switch on the electric heater 11 of the adsorber No. 1 and HP 13 begins to heat the sorbent bed till the temperature near TH is reached.

By proper bed heat exchanger design, a relatively small temperature gradients can be established in the sorbent beds with an efficient heat transfer.

These experimental results in near complete heating (cooling) of the bed to a temperature TH (TL) while maintaining a low (high) temperature exiting the bed being heated (cooled).

As the heat flow moves through the heated (cooled) bed, the liquid outlet temperature starts to rise (fall).

This liquid temperature rise is the basis for the cycle reversal. This "reversal criterion" is an operating parameter that can be varied with a help of the temperature sensors on HPs to optimize performance. The heat rejected in the liquid cooler can be utilized for space heating along with the heat rejected from the condenser.

In such a simple 2 sorbent bed system following (Chinch and Tcherner, 1989) using oil as a heat pump working fluid a cooling coefficient of performance (COP) near 0.8 could be predicted when pumping heat from 4°C to 40°C.

The development of a thermodynamic performance model for the solid sorption gas-fired heat pump centers around the behavior of the adsorption beds is the subject of interest for the future research and applications.

Sorption Heat Pump Thermal Analysis

There is a quick increasing of a specific cold output (320 W kg^{-1}) and a heat flux in the evaporator (60 W) for the first 300 s and this time is optimal for the adsorption. After 400 s the rate of adsorption became low and stable ($Q_e = 18$ W), and the specific cold output falls from 300 W kg^{-1} to 70 W kg^{-1} (Fig. 2). This experiment was fulfilled with the evaporator inserted into the Dewar vessel filled with water, initially at the room temperature.

A set of experimental data have been registered on the transient temperature field inside of the sorbent bed during the period of adsorption and desorption (Fig. 3). Due to the low value of the thermal conductivity of the unconsolidated zeolite fixed bed ($\lambda_{\text{eff}} = 0.09$ Wm^{-1}K^{-1}) and consolidated by clay zeolite fixed bed ($\lambda_{\text{eff}} = 0.6$ Wm^{-1} K^{-1}) this transient period of time was mostly limited by thermal resistance of the bed.

The important radial temperature drops up to 30–40°C were measured between the surface of heat pipe and the outer surface of sorbent bed during desorption for the sorbent thickness 6 mm, while the temperature drop between the end of heat pipe evaporator and condenser was less than 3°C. This is the witness that this case could be considered as one dimensional.

The thermal gradient in radial direction of the bed sharply decreased at the time interval 800 s–1200 s.

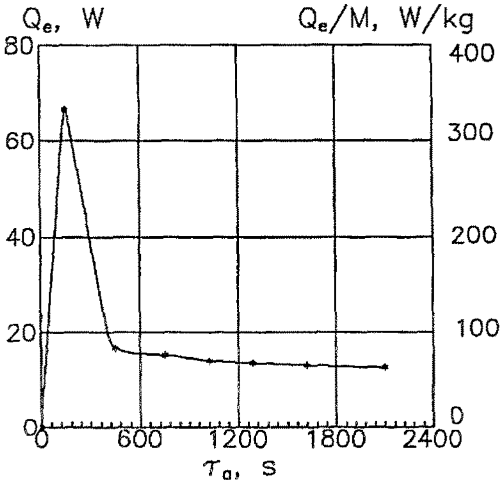

Fig. 2. Evaporator heat flow and heat output as a function of the cycle (adsorption) time.

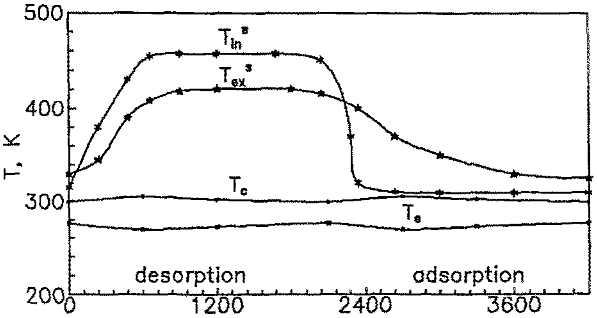

Fig. 3. Thermal gradients between the outer and inner surfaces of a sorbent bed as a function of the cycle time (desorption—adsorption).

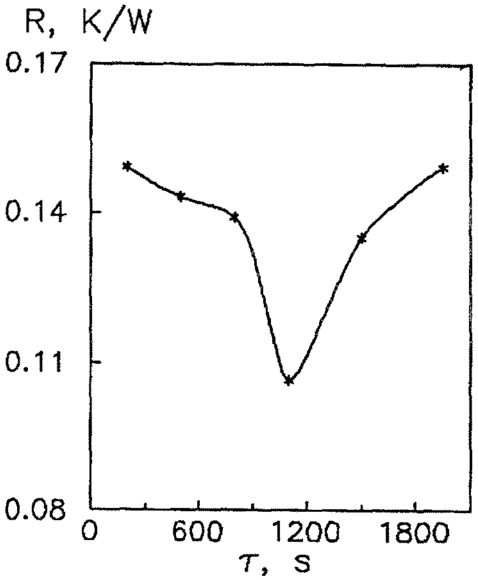

Fig. 4. Evolution of the effective thermal resistance (zeolite-water) as a function of desorption time.

The thermal resistance between the outer bed surface (T^s_{ex}) and the surface of heat pipe (T^s_{in}) was determined as:

$$R(\tau) = \frac{\left[T^s_{\text{in}}(\tau) - T^s_{\text{ex}}(\tau)\right]}{Q_d(\tau)}, \tag{10}$$

where $Q_d(\tau)$—heat flux from the electric heater.

Thermal resistance $R(\tau)$ have had a minimum value 0.11 K/W after the time interval $\tau = 1200$ s (Fig. 4).

The possible phenomena of a micro heat pipe open type operation inside of the sorbent bed was accomplished, accompanied by phase transitions in the macro and micropores and the liquid micro droplets ejection with a saturated vapor to the condenser region.

Following Michael Dubinin's theory (Dubinin and Asthakov, 1971) a volume filling of micropores of adsorbent beds during adsorption is possible.

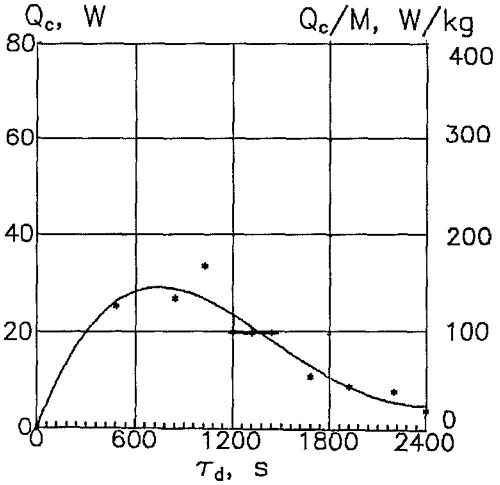

Fig. 5. Condenser heat flow and heat output as a function of the cycle (desorption) time.

Due to our hypothesis in a case of biporous adsorbents like zeolite/clay composition during the heating/cooling period macropores serves as a vapor channels and micropores as a open type heat pipe wicks to pump condensed liquid in the opposite to vapor flow directions.

This phenomena could be used to enhance heat transfer in sorbent beds and heater during desorption/adsorption cycles.

In our case this enhancement was checked as a transient decrease of sorbent bed thermal resistance during desorptions period (Fig. 4).

Mostly in this interval of time the highest value of the condensation rate (130 $\mathrm{Wkg^{-1}}$) was determined (Fig. 5).

The mean cold output (cooling capacity) 100 W $\mathrm{kg^{-1}}$ for a composite made of (MgA) zeolite (80%) and white porcelain clay (20%) was obtained during the first set of experiments with the maximum value of the cooling rate 320 W $\mathrm{kg^{-1}}$ at the first 300 s of the adsorption cycle. This maximum value of the cold output is typical for the beginning of the first adsorption cycle, when the evaporator has a room temperature and the sorbent bed is unsaturated. After the time interval $\Delta\tau = 300$ s of adsorption procedure the cold output is of 70 W $\mathrm{kg^{-1}}$ till the time interval $\Delta\tau = 2000$ s of the adsorption cycle.

It is interesting to note that the thermal gradients inside the sorbent bed during the adsorption period of time were drastically changed after 2000 s of a cycle, when HP heater was finally switched off and the cooling liquid was entered into the HP heat exchanger (Fig. 3).

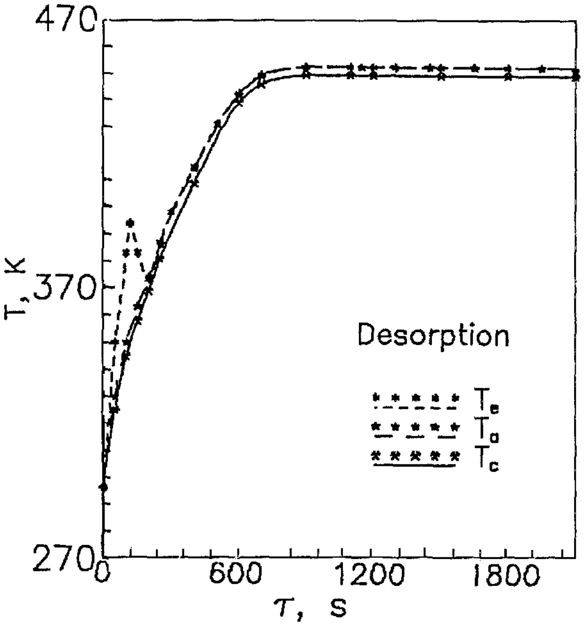

Fig. 6. Transient temperature field on the heat pipe evaporator, transport zone and condenser for heat input $W = 175$ W.

The temperature on the HP surface was quickly decreased from the value TH (470 K) up to the value TL (320 K), and was maintained on a constant level during the time of adsorption, cooling the porous media.

Transient response of effective power throughput with cooper/water heat pipe as a heating element for adsorber during desorption period is shown on Fig. 6. The temperature evolution of the heat pipe evaporator, transport zone and condenser were determined for two different heat flux. Slight overheating of the evaporator was checked for the heat flux.

The temperature on the sorbent bed surface at the time of heating-cooling changing mode ($\tau = 2000$ s) was near 420 K and at the time $\tau > 2000$ s there was a constant fall of the temperature accompanied by the adsorption phenomena, when the water vapor was sucked by the sorbent bed from the evaporator. The heat generation during adsorption of water vapor by the porous media of a sorbent bed was absorbed by the HP heat exchanger.

The overall value of the amount of adsorbed water on zeolite composite during cyclic steady state is shown on Fig. 7. Cyclic steady state was reached after a number of successive cycles where the amount of water adsorbed during the adsorption step Δa_{ads}, and the amount of water desorbed during the next regeneration step Δa_{des} become equal.

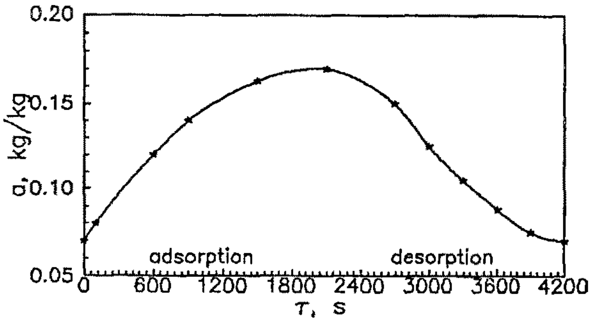

Fig. 7. The evolution of the amount adsorbed on zeolite-water compound during the cycle (adsorption—desorption).

From these results, the cooling capacity per unit mass of adsorbent $L^* \cdot \Delta a_{\text{ads}} \cdot \tau^{-1}$ is determined, where L^* is the latent heat of vaporization of water and τ_{ads} is the time of the adsorption step.

In our case to determine Δa during the cycle of adsorption-desorption it is necessary to measure the volume of liquid being adsorbed-desorbed. The value of "a" was calculated as:

$$a = \left(m_r^0 + \Delta V \rho_l\right)/m_s, \qquad (11)$$

where m_r^0—the mass of adsorbed liquid at the beginning of the experiment and ρ_l—the liquid density; V—volume and m_s—the mass of a completely desorbed sorbent bed. The adsorption rate of water in our experiments was rather high and equal 17% of the sorbent mass.

To verify the reliability of the mathematical model of the adsorber, the numerical data were compared with experimental. Fundamental initial data adequate to experimental ones were specified: during desorption process heat pipe temperature—463 K, environment temperature—323 K, initial temperature 323 K, pressure level—4230 Pa, heat transfer coefficient with environment—0 or 20 W/(m^2 K), heat transfer coefficient at the heat pipe boundary—1000 W/(m^2 K), zeolite density 1000 kg/m^3, effective heat conductivity value $\lambda_{\text{eff}} - 0.4$ W/(m K), energy of activation constant $E_0 - 18.5 \cdot 10^3$ J/mol, β constant—$8.55 \cdot 10^{-3}$ s^{-1}, inner radius of sorbent layer r_0 – 0.02 m, outer radius of sorbent layer r_1 – 0.026 m.

Calculation results for water-zeolite working pair are given in Figs. 8–10. Time τ and spatial coordinate r^* dependencies of the temperature T, the amount adsorbed "a", the difference between current local value of "a" and its equilibrium value "a_{eq}" at the same temperature were analyzed.

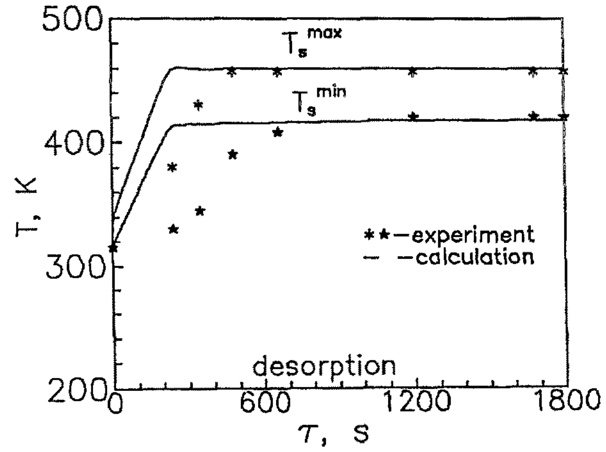

Fig. 8. Temperatures of the outer and inner surfaces of a sorbent bed (zeolite-water) as a function of the cycle time (calculation and experiment).

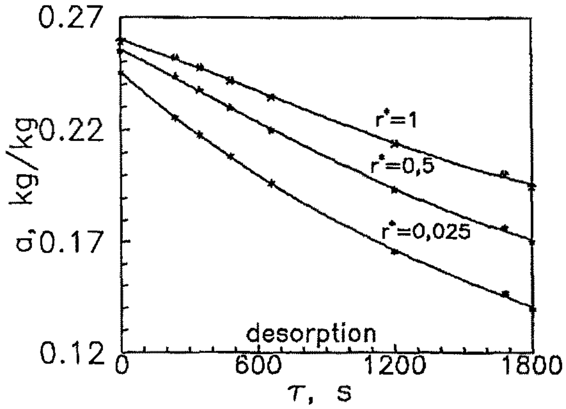

Fig. 9. Change of amount adsorbed vs cycle time for different dimensionless radius (zeolite-water).

Some calculations and experimental results corresponding to desorption process and convective heat transfer conditions at the outer boundary of sorbent layer are represented in Fig. 8. The comparison of experimental data and calculation results shows their satisfactory agreement. On the whole, one-dimensional non-equilibrium model of sorption describes properly the dynamic of the varying temperature field.

Time dependencies of the amount adsorbed water in zeolite sorbent at three separate points of sorbent layer (close to inner surface $r^* = (r - r_0)/(r_1 - r_0) = 0.025$, at a half of thickness $r^* = 0.5$ and at the outer boundary $r^* = 1$) during desorption process are represented in Fig. 9. These temperatures have its minimum values at the start of the process while heat input haven't come into the bed and amounts adsorbed are maximum at all points. Then ($\tau > 0$ s) the sorbent in a thin layer close

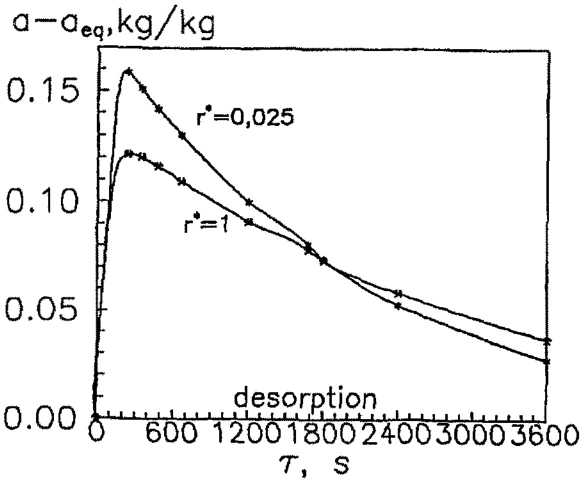

Fig. 10. Difference between solid sorption value and solid sorption equilibrium value ($a-a_{eq}$) as a function of the cycle time for different dimensionless radius (zeolite-water).

to heat pipe boundary begins to release adsorbat and amounts adsorbed decrease correspondingly.

A deviation of current amount adsorbed from the equilibrium state presents a driving force of the desorption process which decrease as time goes on and tends to zero. This process isn't however fast as it is shown in Fig. 10 where one-fifth part of the starting sorption potential ($a - a_{eq}$) remains unrealized even since one hour heating. As at the start of heating process the maximum deviation from the equilibrium state exists near the heating surface $r = r_0$ we should note that at the end of the process it is obtained at $r = r_1$. It can be explained due to a time delay while temperature wave reaches back side of the bed.

It is evident that a quicker cycle with the higher heat transfer coefficient naturally provides a higher capacity of a cooling, which results in smaller amount of adsorbents for the required cooling capacity (cold output).

In order to realize these quicker cycles the need for the molded (sintered) adsorbents which provides good adsorption characteristics and heat transfer ability will be the most probable way, when this system is to be commercialized. The consolidated adsorbent should have a good resistance to vibrations and shocks met when for example they are loaded in the automobile.

The second part of our experimental program was devoted to analyze as a promising sorbent bed the zeolite/clay composition pressed inside of the nickel foam elements (parallelepipeds) with porosity 98%, mean pore diameter 2.5 mm and total mass 400 g.

The testing samples have a thickness $\delta = 8$ mm, density 0.25 g cm^{-3}, specific area 900 m^2 m^{-3}.

Figure 11 illustrates a schematic view of the vertical sorbent bed element (two nickel foam plates) disposed inside a 10 m^3 vacuum chamber on the balance to check the water amount deviation during adsorption desorption. This big vacuum chamber gives the possibility to decrease the hydraulic resistance of the vapor flow and maintain near constant pressure inside due to the porous evaporator and condenser with chill water circulation inside.

The source of energy supply (electric heater, or flat heat pipe) is placed between these nickel foam samples. The outer surfaces of a sorbent beds are cooled by the needle water miniature heat exchangers, pressed to the nickel samples.

The water amount desorbed from the sorbent bed was checked by balance data and condensed by means of a water cooled helical tube coil. During the desorption time the source of energy release between the nickel samples was swathed on and unregistered by electronic register.

During desorption period the miniature tubular water cooler was in action to cool the sorbent bet from the outer surface. Experimental COPs are calculated as the ratios of cooling output to driving heat input.

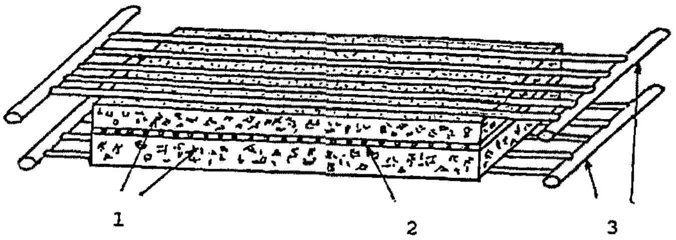

Fig. 11. Experimental set up: 1. two nickel foam parallelepiped samples saturated by zeolite 80% and clay 20%; 2. electric heater; 3. two needles water heat exchangers.

Main Characteristics of the Nickel Foam Adsorption Elements

Two different adsorption Ni/MgA/clay-water elements were tested, which have had a different permeability, but the same geometrical forms.

The first one was made as a homogeneous (nonperforated) plate, the second one have had a regular vapor channels $d = 1.1$ mm, drilled regularly through the whole nickel foam surface on the deepness to 6 mm with the step between drills 5 mm in row and 12 mm between rows.

The mass of the first one was 400 g, and the second one 390 g. A set of thermocouples were installed throughout the sorbent bed to check the temperature variation during the heating/cooling of a samples.

Figure 12 demonstrates the rate of heating/cooling mode of a sorbent beds. It is interesting to note, that due to the good thermal conductivity of a samples there were a small temperature gradients inside the sorbent beds but it was evident, that micro heat pipe effects were valid during the period of samples heating.

Mean temperature transient response for the nonperforated and perforated samples was different, the cycle of heating/cooling for the perforated nickel plate was shorter and the $T_{\max}$ lower, then for the nonperforated sample.

Change of the water amount adsorbed on zeolite/clay nonperforated and perforated samples during one cycle desorption/adsorption is shown on Fig. 13 for different heat generations and vapor pressures in the vacuum chamber.

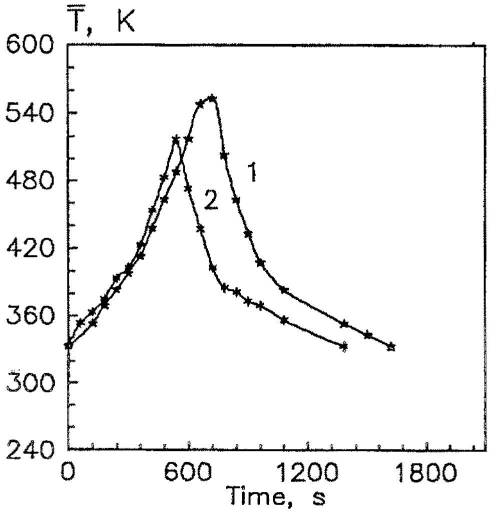

Fig. 12. The rate of heating/cooling of Ni-MgA-clay/water adsorber; 1. nonperforated adsorbent bed; 2. perforated adsorbent bed.

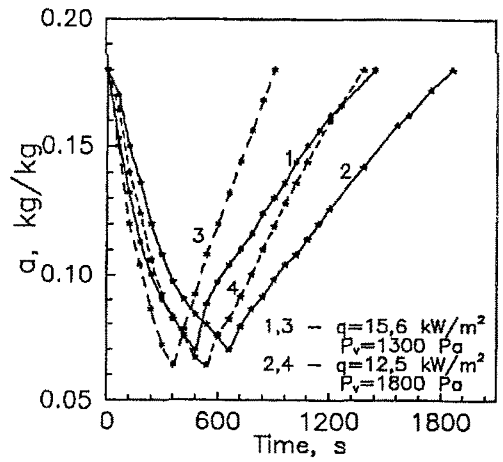

Fig. 13. Change of amount adsorbed on Ni-MgA-clay/water adsorber; 1. nonperforated adsorbent bed; 2. perforated adsorbent bed.

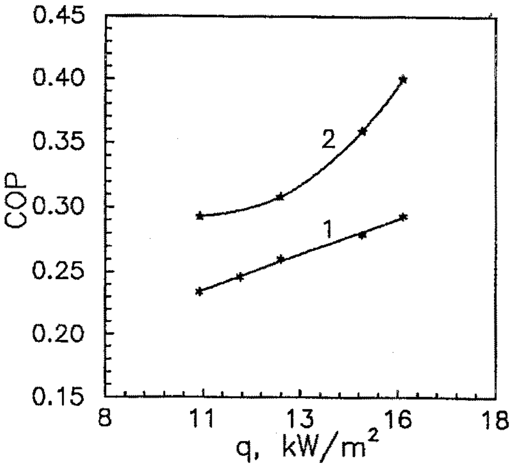

Fig. 14. The effect of heat input on the COP for Ni-MgA-clay/water adsorber; 1. nonperforated adsorbent bed; 2. perforated adsorbent bed.

Experimental COP via the heat flow generated by the electric heater or flat heat pipe is demonstrated on Fig. 14.

The cold output for the nonperforated sample was 185 W/kg with COP = 0.3, for the perforated sample the cold output was 320 W/kg with COP = 0.4 for one canister set up.

Summary and Conclusions

— The proposed heat pipe heat exchangers to cool and to heat the sorbent beds show a good thermal response and could be used to heat and desorb the porous media up to 300°C and to cool down this system to the ambient temperature due to beneficial effects of thermal contact between finned heat pipe and sorbent system.

- The anomalous decreasing of $R(\tau)$ for the compound (MgA) zeolite/porcelain clay with water was registered during the desorption cycle. This decreasing of $R(\tau)$ could be explained as a "micro heat pipe" open type action inside the sorbent bed with transient time of heating/desorbing.
- Consolidated (MgA) zeolite sorbent beds allow faster kinetic then powder, or pellets, which indicates that a good compromise between heat and mass transfer is achieved.
- A (MgA) zeolite/clay-water experimental set up using ceramic cylinders with heat pipe heat exchangers has been designed and tested;
- Nickel foam with MgA/clay-water system was used to enhance thermal conductivity;
- Perforation of nickel foam plates increase COP up to 0.4 for one canister cooler with heat flows densities 16 kW/m^2, decrease the mein sorbent bed temperature during desorption from 55 K to 490 K and decrease the time of a desorption/adsorption cycle from 1400 s to 800 s.
- The cold output for the nonperforated sample was received equal to 185 W/kg with COP = 0.3, for the perforated sample and the cold output was 320 W/kg with COP = 0.4 for one canister set up.
- Two sorbent beds cooler with heat pipe heat recovery gives a possibility to increase COP of a system Ni/MgA/clay-water up to 0.8.

Acknowledgment

This work was supported, in part, by a Soros Foundation Grant awarded by the American Physical Society and by Thermacore, Inc.

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