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PERFORMANCE EVALUATION OF ADSORPTIVE REFRIGERATORS BASED ON COMPOSITE ADSORBENTS «SILICA GEL – SODIUM SULPHATE» AND «SILICA GEL – SODIUM ACETATE»

ОЦІНКА ЕКСПЛУАТАЦІЙНИХ ХАРАКТЕРИСТИК АДСОРБЦІЙНИХ ХОЛОДИЛЬНИХ УСТАНОВОК НА ОСНОВІ КОМПОЗИТНИХ АДСОРБЕНТІВ «СИЛІКАГЕЛЬ – НАТРІЙ СУЛЬФАТ» ТА «СИЛІКАГЕЛЬ – НАТРІЙ АЦЕТАТ»

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Abstract. *Performance of adsorptive refrigerators based on composite adsorbents ‘silica gel – sodium sulphate’ and ‘silica gel – sodium acetate’ was evaluated. The main characteristics of adsorbents which affect the structural parameters of the adsorptive chilling device are revealed. The method of determining operational characteristics of adsorptive refrigerator has been developed. The main factors affecting the mass of adsorbent are confirmed to be maximal adsorption and the amount of heat required to be taken from the cold box during the day. The advantages of ‘salt in the porous silica gel matrix’ composites are exhibited as compared with conventional silica gels and zeolites. Operational parameters of adsorptive refrigerators based on the composites ‘silica gel – sodium sulphate’ and 'silica gel – sodium acetate' are compared. The calculation procedure to determine the design and operational characteristics is suggested. Proposed procedure includes the calculation of the amount of heat required to be taken from the cold box during the day, water mass, mass of the adsorbent, heat required for regeneration of the adsorbent, computing the surface area of the solar collector, heat supplied by solar collector and net coefficient of performance. The efficiency of operating processes of adsorptive refrigerators based on composites 'silica gel - sodium sulphate' and 'silica gel-sodium acetate' was compared. The correlation between adsorbent composition and design and operational parameters was stated. The surface area of solar collector is stated to be of 9.46 – 9.93. The highest net coefficients of performance of 0.358 and 0.368 are revealed for devices based on composites containing, wt. %: silica gel – 20 and salt (sodium sulphate or sodium acetate) – 80. The influence of meteorological conditions on the net coefficient of performance of the adsorptive refrigerator has been confirmed. The higher efficiency of adsorptive chilling devices based on composites 'silica gel - sodium acetate' is explained by lower values of regeneration temperature, which leads to the decreasing the heat of regeneration. The results of the research can be used for the development of adsorptive chilling devices for domestic needs and warehouse premises.*

Анотація. *Оцінено експлуатаційні характеристики адсорбційних холодильників на основі композитних адсорбентів «силікагель – натрій сульфат» та «силікагель – натрій ацетат». Показано основні характеристики адсорбентів, що впливають на конструкційні характеристики адсорбційного холодильного пристрою. Розроблено метод визначення конструкційних та експлуатаційних характеристик адсорбційного холодильника. Підтверджено, що основними факторами, що впливають на масу адсорбе-*

нту, є максимальна адсорбція та кількість теплоти, яку необхідно відвести від холодильної камери протягом доби. Переваги композитів "солі в пористій матриці силікагелю" показано порівняно з традиційними силікагелями та цеолітами. Порівняно експлуатаційні параметри адсорбційних холодильних установок на основі композитів «силікагель – натрій сульфат» та «силікагель – натрій ацетат». Запропоновано методику розрахунку для визначення конструктивних та експлуатаційних характеристик. Запропонована методика включає розрахунок кількості теплоти, яку необхідно відвести від холодної камери протягом доби, маси води, маси адсорбенту, теплоти, яка необхідна для регенерації адсорбенту, обчислення площі поверхні сонячного колектора, теплоти, яку підведено за допомогою сонячного колектора і експлуатаційний холодильний коефіцієнт. Порівняно ефективність процесів експлуатації адсорбційних холодильників на основі композитів "силікагель – натрій сульфат " та "силікагель – натрій ацетат". Визначено співвідношення між складом адсорбенту, конструкцією та експлуатаційними параметрами. Встановлено, що поверхня сонячного колектора становить 9,46 - 9,93. Найбільші експлуатаційні холодильні коефіцієнти 0,358 та 0,368 виявлені для пристроїв на основі композитів, що містять, мас. %: силікагель - 20 та сіль (сульфат натрію або ацетат натрію) - 80. Встановлено вплив метеорологічних умов на експлуатаційний холодильний коефіцієнт адсорбційного холодильника. Більш високу ефективність адсорбційних холодильних пристроїв на основі композитів "силікагель – натрій ацетат " пояснено меншими значеннями температури регенерації, що призводять до зниження теплоти регенерації. Результати досліджень можуть бути використані для розробки адсорбційних холодильних пристроїв для побутових потреб та складських приміщень.

Key words: *adsorptive refrigerator, composite adsorbent, coefficient of performance*
Ключові слова: *адсорбційний холодильник, композитний адсорбент, холодильний коефіцієнт*

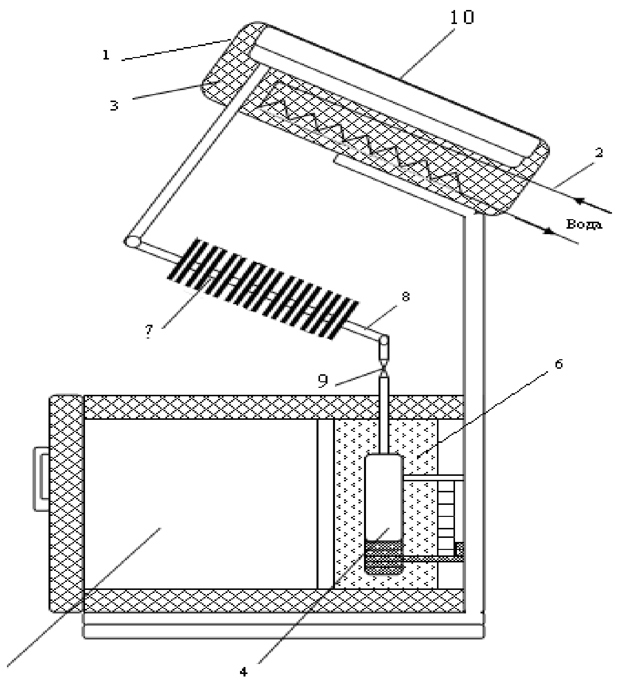
Introduction. Monotone growth of global energy demand is crucial factor affecting the economic development and environmental conditions in any country. Chilling agents in traditional vapor compressive cooling systems are chlorofluorocarbons and hydrochlorofluorocarbons [1]. These compounds occur to be of high ozone depletion potential and global warming potential and accelerate the depletion of the Earth's ozone layer. It requires the new alternative technical solutions to current refrigerating systems. Adsorptive refrigerators exhibit numerous advantages, such as using low grade heat source temperature, employing of natural cooling agents such as water, less moving mechanical parts, noiseless, low maintenance and environmental safety [2,3]. So, adsorptive cooling systems and devices are promising solution for changing or integration with conventional cooling systems. However, one of the crucial factors which determine the operating parameters of the adsorptive refrigerators are adsorbents properties, such as maximal adsorption, i.e. maximal water uptake, and regeneration temperature affecting the mass of adsorbent and driving temperature. It strongly inhibits the commercialization of adsorptive refrigerators based on convenient silica gels and zeolites as a consequence of their regeneration temperatures of 150 – 200°C [3]. As alternative material aluminophospate (AIPO) and silico-aluminophospate (SAPO) can be considered. AIPO and SAPO exhibit a moderately low regeneration temperature (60–100°C) which results in high performance [3, 4]. Nevertheless, their water uptake does not exceed 0.25 g/g that requires high mass of adsorbents. Composite adsorbents 'salt inside porous matrix' are shown to be promising materials for adsorptive heat energy storage [5 – 7] and regeneration [8 – 10] due to their high maximal adsorption and moderate regeneration temperature.

The aim of the present work is to estimate the performance of adsorptive refrigerators based 'silica gel – sodium sulphate' and 'silica gel – sodium acetate'. To accomplish this aim, the following tasks are set:

- to develop the procedure for calculation of operational characteristics of adsorptive refrigerator;
- to reveal correlation between adsorbent properties, design parameters, and performance of adsorptive chilling device;
- to state the basic characteristics of adsorbents corresponding with optimal performance of adsorptive refrigerator.

Experimental. The main structural elements of the adsorption refrigerator [11], according to Fig. 1, are the adsorber (1), the condenser (7) and the evaporator (4) located in the cold box (6). A transparent SAN polycarbonate plastic (8 mm thick) with an integral transmittance of 0.88 is installed on the front side of the adsorber, and the composite adsorbent 'silica gel-sodium sulphate' or 'silica gel - sodium acetate' which was synthesized according to [12], is located in the lower part. Water is used as a chilling agent. The 2.29 m^3 refrigerator compartment is made of steel grade 30X 0.5 mm thick. Polystyrene foam was used as thermal insulation.

Chilling proceeds due to evaporation of water and adsorption, and regeneration of the adsorbent, followed by desorption and condensation of water. The operation is carried out in two-phase mode. The first phase is getting cold. When the tap (9) opened, water vapor begins to diffuse through the condenser to the adsorber. Due to the adsorption of water by the adsorption material it evaporates in the evaporator (4), creates a cooling effect in



1 - adsorber; 2 – coil pipe; 3 - adsorbent; 4 - evaporator; 5 – cold box; 6 – cold storage unit; 7 - condenser; 8 - pipe; 9 - tap

Fig. 1. Adsorptive refrigerator

the cold box (5). Since a large volume of water is contained in the walls of the refrigerator, the cold in the chamber (5) is maintained at 5–10 °C for 10–20 hours until the next cycle. When water is sorbed by the adsorbent (3), the temperature in the adsorber (1) occurs to increase significantly due to the release of heat of adsorption. It can be used for heating the water in the coil pipe which can be used to warm the adsorbent during the second phase.

The second phase is the regeneration of the adsorbent. As the tap 9 closed, the adsorbent (3) is heated by solar energy. The water is collected in the condenser (7) and then drained into the evaporator (4) and the process of getting cold begins. The amount of heat that is required to be taken from the cold box during the day was calculated according to [13] as the sum of the heat going to cool the chamber itself and the introduced food substances and to cover the heat inleaks both of the chamber and when opening the chamber when adding products:

$$Q_1 = C \cdot m \cdot \Delta T + C_{pr.} \cdot m_{pr} \cdot \Delta T + \sum Q_2 \, , kJ \tag{1}$$

where C is the heat capacity of the structural elements, kJ/kg · °C; C_{pr} is the heat capacity of the food substances introduced into the refrigerating chamber, kJ / kg · °C; ΔT is the difference cbetween ambient temperature and average daily temperature in the refrigerating chamber, ° C; m, m_{pr} is mass of the cold box and introduced products, respectively, kg; ΣQ_z is the sum of heat leakage into the chamber as a result of heat transfer through its walls, floor and ceiling, from infiltration of outside air when the chamber is opened and loads from lighting, kJ.

Heat inleak into the cold box by heat transfer during the day was determined according to [13] as the product of heat load during heat transfer through the walls, floor and ceiling of the chamber and the period of operation:

$$Q_{\mathrm{ht}} = K \cdot F \cdot \Delta \mathrm{t} \cdot \tau, \mathrm{kJ} \tag{2}$$

where Q_{ht} is heat inleaks because of heat transfer, kJ;
K is the heat transfer coefficient of kW/m^2 ·°C;
F is the area of the outer surface of the chamber, m^2;
τ is the period of operation during the day, s;
Δt is the temperature difference between the air on both sides of the wall, °C.

Heat transfer coefficient was calculated according to [13]:

$$K = \frac{1}{\left(\frac{1}{\alpha_{\mathrm{v1}}} + \frac{\delta}{\lambda_m} + \frac{\delta_{\mathrm{iz}}}{\lambda_{\mathrm{iz}}} + \frac{1}{\alpha_{\mathrm{v2}}}\right)} \tag{3}$$

where α_{v1} and α_{v2} are heat transfer coefficients for air inside and outside the cold box, kW / m^2 · K, respectively;

δ and δ_{iz} are wall thickness of the refrigerating chamber and heat insulation, m;

λ_m and λ_{iz} are the thermal conductivities of the walls of the refrigerating chamber and thermal insulation, kW / m · K.

Heat inleak into the cold box due to the opening of the doors Q_{inf} [13], was calculated as the product of the heat load and the duration of the opening of the doors during the day:

$$Q_{\mathrm{inf}} = q \cdot D_{\tau} \cdot D_{f} \cdot (1 - E) \cdot \tau_{\mathrm{op}} \tag{4}$$

where q is the total daily heat load on the cold box for the air flow, fully established taking into account the difference in density, heat and moisture content of indoor and outdoor air, as well as the size of the door opening, kW;

D_{τ} is coefficient taking into account the time when the doors are open during the day;

D_f is coefficient taking into account the nature of the air flow in the doorway;

E is the degree of effectiveness of the doorway security device;

τ_{op} is the time when the doors are open during the day, s.

Thermal inflows as a result of the work of lighting devices were defined as the product of the number of luminaries, luminaire power and the period of operation during the day [13].

The heat is taken from the cold box due to the evaporation of water in the evaporator. The amount of heat taken from the cold box when water evaporated can be calculated as:

$$Q_2 = \Delta \mathrm{H}_{\mathrm{ev}} \cdot m_w \text{ , kJ} \tag{5}$$

where ΔH_{ev} is evaporation heat of water, kJ/kg;

m_w is mass of water, kg.

From here the mass of water can be calculated to ensure the selection of the required amount of heat in the cold box.

To compensate for daily fluctuations in weather conditions, the mass of working fluid is proposed to increase by 50 %. Thus, the mass of water in the evaporator will be 33,29 kg.

On the basis of the adsorption capacity of the composites ‘silica gel – Na_2SO_4‘ and ‘silica gel – sodium acetate’, according to the data of [13], it is possible to calculate the mass of the adsorbent, which must be placed in the adsorber. The amount of heat required for the adsorbent regeneration (Q_3, kJ) can be estimated by the formula:

$$Q_3 = m_k \cdot C_k \cdot \Delta \mathrm{T}_1 + m_w \cdot C_w \cdot \Delta \mathrm{T}_1 + m_B \cdot \Delta \mathrm{H}_{\mathrm{des}} \tag{6}$$

where ΔT_1 is the difference between the temperature of the adsorbent and the temperature of regeneration, ºC;

ΔH_{des} is the heat of desorption of water, kJ / kg;

m_k and m_w are respectively, the mass of the composite and the adsorbed water, kg;

C_k and C_w are the heat capacity of the composite and water, respectively, kJ / kg·°C.

The net coefficient of performance was defined as the ratio of the amount that is taken in the refrigerating chamber when water evaporates, and the heat consumption for the regeneration of the adsorbent, that is:

$$\mathrm{COP}_n = \frac{Q_1}{Q_s} \tag{7}$$

where COP_n is the net coefficient of performance;

Q_1 is the amount of heat that must be removed from the refrigerating chamber, kJ;

Q_s is the amount of solar energy which supply to system, kJ.

The value of Q_s is corresponded to product of surface of solar collector and solar radiant flux.

So, the surface area of solar collector can be calculated according to [6]

$$\mathrm{F_k} = \frac{\mathrm{Z_k \cdot Q_3}}{\mathrm{Q_k}} \tag{8}$$

where F_k is surface area of collector, m^2;

Q_3 is the amount of heat required for the adsorbent regeneration, MJ;

Q_k is the amount of heat which supplied by 1 m^2 of solar collector, MJ/m^2;

Z_k is the coverage factor which considered irregularity of solar radiation during a day or a season.

Results and discussion

The results of the calculations are presented in table 1. Mass of adsorbent is determined by its maximal adsorption. So, to provide the same refrigerating power mass of ‘silica gel – sodium sulphate’ is required in 1.5 – 2.0 as much as compared with ‘silica gel – sodium acetate’.

Obviously, an increase in the content of sodium sulphate or sodium acetate in the composite results in a decrease in the mass of the composite, and, consequently, the amount of heat that is required for the regeneration of the adsorbent. The minimal masses of adsorbent of 24.68 or 43.92 kg are determined for composites containing, wt. %: silica gel – 20 and salt – 80, that is sodium sulphate or sodium acetate, respectively.

Table 1 – Net coefficients of performance of solar adsorptive refrigerators based on composite 'silica gel – sodium sulphate' and 'silica gel – sodium acetate'

Composition, %		'Silica gel – sodium sulphate'					'Silica gel – sodium acetate'				
Silica gel	Salt	Maximal adsorption, A_{lim} [9], kg/kg	Adsorbent mass, M_{ads}, kg	Heat of regeneration, Q_{reg}, MJ	Surface area of collector, m^2	Net coefficient of performance, COP_n	Maxi-mal adsorption, A_{lim} [9], kg/kg	Adsorbent mass, M_{ads}, kg	Heat of regeneration, Q_{reg}, MJ	Sur-face area of collector, m^2	Net coefficient of performance, COP_n
20	80	1.35	24.68	102.97	9.73	0.358	0.756	43.92	100.07	9.46	0.368
40	60	1.06	31.41	103.29	9.76	0.357	0.596	55.72	100.41	9.49	0.367
60	40	0.77	43.18	103.82	9.81	0.355	0.462	71.88	100.85	9.53	0.365

The coefficient of performance is strongly affected by the amount of heat for regeneration of the composite Q_3, and, as a consequence by the difference in the temperature of the adsorbent and the temperature of regeneration ΔT_1 which is determined by the regeneration temperature.

As it decreased, a monotonous growth in the coefficient of performance of cycle is observed. The maximal values of COP are established at $\Delta T_1 = 50$ ° C or 20 – 30°C when composite 'silica gel – sodium sulphate' or 'silica gel – sodium acetate' used. Having been applied adsorbents with lower regeneration temperatures, e.g. 'silica gel – sodium acetate' (60°C), the decrease of regeneration heat can be achieved as compared with 'silica gel – sodium sulphate' (90°C).

Values of net COP for adsorptive refrigerators based on both of composites are nearly equal. Nevertheless, COP_n of adsorptive refrigerators based on composite 'silica gel – sodium acetate' surpasses the devices using 'silica gel – sodium sulphate' by nearly 1 %. Obviously, it is resulted from lower regeneration temperature of composite 'silica gel – sodium acetate' as compared with 'silica gel – Na_2SO_4'.

According to data M.S. Fernandes et al. [14] net coefficients of performance of chilling units based on pair 'silica gel – water' and 'zeolite – water' does not surpass 0.2 – 0.3. So, the efficiency of solar adsorptive refrigerator based on 'silica gel – sodium sulphate' and 'sodium acetate' conform to the system with the same working fluid.

Net coefficient of performance is determined solar radiation flux (Table 2).

Table 2 – Net coefficients of performance of solar adsorptive refrigerator based on composite 'silica gel – sodium sulphate' and 'silica gel – sodium acetate'

Month	Daily solar radiant flux, MJ/m2	'Silica gel – sodium sulphate'		'Silica gel – sodium acetate'	
		Heat supplied by solar collector, MJ	Net coefficient of performance	Heat supplied by solar collector, MJ	Net coefficient of performance
May	21.56	214.56	0.25	203.96	0.27
June	21.09	209.90	0.26	199.51	0.28
July	21.81	217.06	0.25	206.32	0.27
August	20.37	202.74	0.27	192.70	0.29
September	15.87	157.96	0.34	150.13	0.37

The maximal values of COP_n are observed in September which resulted from minimal solar radiant flux.

Conclusions. Performance of adsorptive refrigerators based on composite adsorbents 'silica gel – sodium sulphate' and 'silica gel – sodium acetate' was studied. The method of calculation of the main operational characteristics of the adsorptive chilling device was suggested. The correlation between mass of adsorbent, surface area of collector and maximal adsorption is shown.

Advantages of composites 'silica gel – sodium sulphate' and 'silica gel – sodium acetate' are shown as compared with conventional adsorbents. Composite adsorbents 'silica gel – Na_2SO_4' and 'silica gel – CH_3COONa' are exhibited as promising materials for adsorptive refrigerators due to lower value of necessary mass. Maximal adsorption and regeneration temperature are stated to be crucial factors affecting an adsorbent mass, surface area of solar collector and heat of regeneration.

Operational parameters of adsorptive refrigerators based on composite 'silica gel – Na_2SO_4' and 'silica gel – CH_3COONa' were compared.

The highest net coefficients of performance are revealed for devices based on composites containing, wt. %: silica gel – 20 and salt (sodium sulphate or sodium acetate) – 80.

The performance of adsorptive refrigerators based on ‘silica gel – Na_2SO_4’ and ‘silica gel – CH_3COONa’ were compared. Higher coefficient of performance of regenerators based on ‘silica gel – CH_3COONa’ is shown to result from lower value of regeneration temperature.

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