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Original Research Article

ADSORPTIVE SOLAR REFRIGERATORS BASED ON COMPOSITE ADSORBENTS 'SILICA GEL – SODIUM SULPHATE'

Elena A. BELYANOVSKAYA[1*], Grigoriy N. PUSTOVOY[1], Kostyntyn M. SUKHYY[2], Yana O. SERGIYENKO[2], Oleksandr O. YEROMIN[3], Elena M. PROKOPENKO[3], Mikhailo V. GUBINSKYI[4], Ján KIZEK[5], Ladislav LUKÁČ[5]

[1]Department of Power Engineering, State Higher Education Institution 'Ukrainian State University of Chemical Engineering', Gagarine av. 8, Dnipro, Ukraine
[2]Department of Polymer and Nanocomposites, State Higher Education Institution 'Ukrainian State University of Chemical Engineering', Gagarine av. 8, Dnipro, Ukraine
[3]Department of Ecology, Heat Transfer and Labour Protection, National Metallurgical Academy of Ukraine, Gagarine av. 4, Dnipro, Ukraine
[4]Department of industrial power system, National Metallurgical Academy of Ukraine, Gagarine av. 4, Dnipro, Ukraine
[5]Technical university of Košice, Faculty of Materials, Metallurgy and Recycling, Institute of Metallurgy, Letná 9, 042 00 Košice, Slovak Republic

Abstract

The operation processes of adsorptive solar refrigerators based on composite adsorbents 'silica gel - sodium sulphate' were studied. The correlation between the adsorbent composition and the coefficient of the energy performance of the device was stated. As a consequence of the decreasing of adsorbent mass, the coefficient of performance is increased when sodium sulphate content in the composite increased. Effect of the regeneration process parameters on the composite on the coefficient of performance of the adsorptive refrigenerator was stated. The growth of the coefficient of performance

* Corresponding author: Department of Power Engineering, State Higher Education Institution 'Ukrainian State University of Chemical Engineering', Gagarine av. 8, Dnipro, 49600, Ukraine, e-mail: belyanovskaya@voliacable.com

is shown to result from decreasing the difference between adsorbent temperature and regeneration temperature from 85 to 55°C. The maximum values of the coefficient of performance of studied solar adsorptive refrigenerator about of 1.14 are stated for composites containing about 20 wt. % silica gel and 80 wt. % sodium sulphate.

Keywords: adsorptive refrigerator, coefficient of performance, composite adsorbent, adsorptive capacity, regeneration temperature

1. INTRODUCTION

One of the key problems of storage of agricultural products is to comply with the temperature regime of storage, especially in the summer, when the operation of traditionally used steam compression refrigeration units requires a significant amount of electricity, and therefore fossil fuels and complicates the utilization of thermal energy.

An alternative to such systems is adsorption refrigeration solar devices, the so-called solar adsorption refrigerators, which allow to use of unconventional sources of low-potential thermal energy and environmentally friendly refrigerants.

Adsorption refrigeration solar systems include a solar collector [1, 2], an adsorber, a condenser and an evaporator located near the refrigerating chamber. Their operation is usually carried out in two stages. The first is the adsorption and evaporation of the refrigerant, due to which the temperature in the refrigerating chamber decreases. The second is the regeneration of the adsorbent, that is the desorption and condensation of the refrigerant. In this case, the adsorbent is heated to the regeneration temperature by external sources. Water [3], ammonia [4], methanol [4], ethanol [4] are used as refrigerants, of which not only is the most environmentally safe, but also water is available. Activated carbon [4] silica gel [3], zeolite [4], salts of $MnCl_2$, NH_4Cl, strontium chloride, sodium bromide [5] are used as adsorbents. Typical adsorbents, in particular, silica gels and zeolites, have a low adsorption capacity and a high regeneration temperature in excess of 100 °C, which not only involves the use of large quantities of adsorbent, but also severely limits the potential of the heat source.

A higher adsorption capacity is registered for massive salts. However, the exploitation of massive salts is complicated by their corrosivity. In addition, the hydration of massive salts in the stationary mode is accompanied by the formation of hydrated films that block the access of moisture to anhydrous salts, which significantly slows down the process of adsorption and cooling. Therefore, the cycling of massive salts is impossible without mechanical dispersion during operation.

Overcoming this problem is possible by creating 'salt in porous matrix composites'. Examples of such materials are adsorbents $BaCl_2$/vermiculite [6], $CaCl_2$/expanded graphite [7], LiCl/silica gel [8], as well as nanodispersed composite adsorbents synthesized by the sol – gel method, namely, sodium sulphate/silica gel [9, 10]. The key factors affecting the performance of adsorption refrigerators are, above all, the properties of the adsorbents used, which determine the design and operational characteristics of the installation.
In this regard, it is advisable to study the correlation of the performance characteristics of adsorption refrigeration solar power plants and the properties of the composites 'silica gel-sodium sulphate' synthesized by the sol-gel method.

2. METHODOLOGY

2.1. Adsorption refrigerator

The main structural elements of the adsorption refrigerator [11], according to Fig.1, are the adsorber (1), the condenser (5) and the evaporator (4) located in the refrigerating chamber (6).

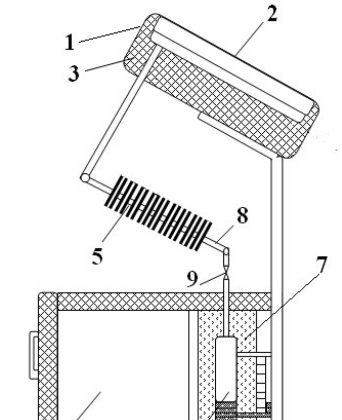

Fig. 1. Adsorption refrigerator: 1 - adsorber, 2 - transparent insulation, 3 – adsorbent, 4 - evaporator, 5 - capacitor, 6 - refrigerator, 7 - cold water battery, 8 – pipe, 9 - crane [11]

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', which was synthesized according to [9], is located in the lower part. Water is used as a refrigerating fluid [12]. The 2.29 m^3 refrigerator compartment is made of steel grade 30x0.5 mm thick. Polystyrene foam was used as thermal insulation.

2.2. Thermodynamic cycle adsorption refrigerator

The adsorption refrigerator operates according to the thermodynamic cycle shown in Fig. 2. Chilling resulted from evaporation of water and adsorption is represented by line 3 - 4 - 1, and regeneration of the adsorbent, followed by desorption and condensation of water – 1 - 2 - 3. The operation is carried out in two stages. The first stage is getting cold. When the tap (9) opened, water vapour 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 the refrigerating chamber (6). Since a large volume of water is contained in the walls of the refrigerator, the cold in the chamber (6) is maintained at 5–10 °C for 10–20 hours until the next cycle.

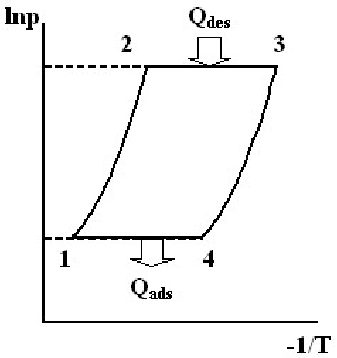

Fig. 2. Operation cycle of the adsorption refrigerator [13].

When water is sorbed by the adsorbent (3), the temperature in the adsorber (1) increases significantly due to the release of the heat of adsorption. The second stage 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 (5) and then drained into the evaporator (4) and the process of getting cold begins.

2.3. Data processing

The amount of heat that needs to be taken from the refrigerating chamber 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:

$$Q_1 = C \cdot m \cdot \Delta T + C_{pr} \cdot m_{pr} \cdot \Delta T + \Sigma Q_z \quad \text{(J)} \qquad (2.1)$$

C is the heat capacity of the structural elements, J/kg.K; C_{pr} is the heat capacity of the food substances introduced into the refrigerating chamber, J/kg.K; ΔT is the difference between ambient temperature and average daily temperature in the refrigerating chamber, K; m, m_{pr} is mass of the refrigerating chamber 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, J.

Heat inleak into the chamber by heat transfer during the day was determined according to [14] as the product of heat load during heat transfer through the walls, floor and ceiling of the chamber and the period of operation:

$$Q_{ht} = K \cdot F \cdot \Delta t \cdot \tau \quad \text{(J)} \qquad (2.2)$$

where Q_{ht} – heat inleaks because of heat transfer, J; K is the heat transfer coefficient of W/m^{2}K; 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 [14]:

$$K = \frac{1}{\left(\frac{1}{\alpha_{v1}} + \frac{\delta}{\lambda_m} + \frac{\delta_{iz}}{\lambda_{iz}} + \frac{1}{\alpha_{v2}}\right)} \qquad (2.3)$$

where α_{v1} and α_{v2} are heat transfer coefficients for air inside and outside the refrigerating chamber, W/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, W/m.K.

Heat inleak into the chamber due to the opening of the doors Q_{inf} [14], was calculated as the product of the heat load and the duration of the opening of the doors during the day:

$$Q_{\inf} = q \cdot D_\tau \cdot D_f \cdot (1 - E) \cdot \tau_{op} \quad \text{(J)} \qquad (2.4)$$

where q is the total daily heat load on the refrigerating chamber 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, W; 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 luminaires, luminaire power and the period of operation during the day [14].

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

$$Q_2 = \Delta H_{ev} \cdot m_w \qquad \text{(J)} \qquad (2.5)$$

where ΔH_{ev} is evaporation heat of water, J/kg; m_w is mass of water, kg.

From here you can calculate the mass of water to ensure the selection of the required amount of heat in the refrigerating chamber.

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 silica gel / Na_2SO_4 composite, according to the data of [10], 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) can be calculated by the formula:

$$Q_3 = m_k \cdot C_k \cdot \Delta T_1 + m_w \cdot C_w \cdot \Delta T_1 + m_B \cdot \Delta H_{des} \qquad \text{(J)} \qquad (2.6)$$

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

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

m_k and mw 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, J/kg.K.

The 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:

$$\varepsilon = \frac{Q_1}{Q_3} \qquad (2.7)$$

where ε is the coefficient of performance; Q_1 is the amount of heat that must be removed from the refrigerating chamber, J; Q_3 is the amount of heat that must be spent on the regeneration of the adsorbent, J.

3. RESULTS AND DISCUSSION

The results of the calculations are presented in table 1.

Table 1. Coefficient of performance of the adsorption solar refrigerator based on the composite 'silica gel – sodium sulphate'

The composition of the adsorbent, wt. %		Maximal adsorption [7], kg/kg	Adsorbent mass M_{ads}, kg.	Coefficient of performance at ΔT_1, K			
Na_2SO_4	Silica gel			55	65	75	85
80	20	1.349	24.68	1.14	1.11	1.09	1.07
60	40	1.060	31.41	1.13	1.10	1.08	1.06
40	60	0.771	43.18	1.12	1.09	1.07	1.05
20	80	0.482	69.07	1.09	1.06	1.04	1.02

Obviously, an increase in the content of sodium sulphate in the composite is stated to contribute to a decrease in the mass of the composite, and, consequently, the amount of heat that must be spent on the regeneration of the adsorbent.

The maximum values of the coefficient of performance correspond to composites containing, wt. %: silica gel – 20 and sodium sulphate – 80. The amount of heat required for regeneration of the Q_3 composite, and, consequently, the coefficient of cooling is significantly affected by the difference in the temperature of the adsorbent and the temperature of regeneration ΔT_1.

With its growth, a monotonous decrease in the coefficient of performance is observed. The maximum values of ε are established at ΔT_1 = 55 K.

4. CONCLUSION

The investigation of the processes of operation of the adsorption refrigeration solar system on the basis of composite adsorbents 'silica gel-sodium sulphate' was conducted. The main technological parameters affected the cooling coefficient of the cycle are determined.

A correlation between the composition of the adsorbent and the refrigeration coefficient of the installation is shown. An increase in the cooling coefficient is shown to result from an increase in the content of sodium sulphate in the composite. The correlation of the mode of the process of regeneration of the composite and the cooling coefficient of the installation was confirmed. An increase in the value of the cooling coefficient was established with a decrease in the temperature difference between the adsorbent and the regeneration temperature ΔT_1.

It is established that the maximum values of the refrigeration coefficient correspond to ΔT_l = 55 K for composites that contain about, wt. %: silica gel – 20 and sodium sulphate – 80.

ADDITIONAL INFORMATION

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REFERENCES

1. Rimar, M, Fedak, M, Hatala, M and Smeringai, P 2015. The synergistic effect of thermal collectors rotation in relation to their energy efficiency and stagnation compared with the static thermal system in the conditions of central Europe. *International Journal of Photoenergy* **2015**, 19.
2. Rimar, M, Kuna, Š and Fedak, M 2014. *Energy yield of solar panels in the system of their position control 2014*. Applied Mechanics and Materials: ICSEEE 2013: 2nd International Conference on Sustainable Energy and Environmental Engineering: Shenzhen, China, 28-29 December 2013. **521**, 37-40.
3. Lu, ZS, Wang, RZ, Xia, ZZ, Wu, QB, Sun, YM and Chen, ZY 2011. An analysis of the performance of a novel solar silica gel–water adsorption air conditioning. *Applied Thermal engineering* **31**(17 – 18), 3636 – 3642.
4. Santori, G and Di Santis, Ch 2017. Optimal fluids for adsorptive cooling and heating. *Sustainable Materials and Technologies* **12**, 52 – 61.
5. Bao, HS, Oliveira, RG, Wang, RZ, Wang, LW and Ma, ZW 2011. Working pairs for resorption refrigerator. *Applied Thermal Engineering* **31**(14 – 15), 3015 – 3021.
6. Zhong, Y, Critoph, RE, Thorpe, RN, Tamainot-Telto, Z and Aristov, YuI 2007. Isothermal sorption characteristics of the BaCl2–NH3 pair in a vermiculite host matrix. *Applied Thermal Engineering* **27(**14–15), 2455 – 2462.
7. Li, SL, Xia, ZZ, Wu, JY, Li, J, Wang, RZ and Wang, LW 2010. Experimental study of a novel CaCl2/expanded graphite-NH3 adsorption refrigerator. *International Journal of Refrigeration* **33**(1), 61 – 69.
8. Maggio, G, Gordeeva, LG, Freni, A, Aristov, YuI, Santori, G, Polonara, F and Restuccia, G 2009. Simulation of a solid sorption ice-maker based on the novel composite sorbent "lithium chloride in silica gel pores". *Applied Thermal Engineering* **29**(8 – 9), 1714 – 1720.

9. Sukhyy, K, Belyanovskaya, E, Kovalenko, V, Kotok, V, Sukhyy, M, Kolomiyets, E, Gubynskyi, M, Yeromin, O and Prokopenko, O 2018. The study of properties of composite adsorptive materials “silica gel – crystalline hydrate” for heat storage devices. *Eastern-European Journal of Enterprise Technologies* **91**(1), 52 – 58.
10. Sukhyy, KM, Belyanovskaya, EA, Kozlov, YaN, Kolomiyets, EV and Sukhyy, MP 2014. Structure and adsorption properties of the composites ‘silica gel – sodium sulphate’, obtained by sole gel method. *Applied Thermal Engineering* **64**, 408 – 412.
11. Pat. 86227 Ukraina, MPK F 25 B 17/00. Adsorptsiyniy kholodilnik / Sukhyy K.M., Sukhyy M.P., Kolomiyets O.V. [ta in.]; Dergavniy vischthiy navchalniy zaklad “Ukrainskiy dergavniy khimiko-tekhnologitcheskiy universitet”. – № u 2013 05136; zayavl. 22.04.2013 opubl. 25.12.2013, Bul. № 24 (in Ukraine).
12. Fedak, M, Kulikov, A and Abraham, M 2018. Using a Tracker Rotation System with Flat Collectors to Increase System Efficiency. *Advances in Thermal Processes and Energy Transformation* **1**(4), 78-82.
13. Kolomiyets, OV, Belyanovska, OA, Sukhyy, KM, Prokopenko, OM, Kozlov, YaM and Sukhyy, MP 2015. Osnovni robochi kharakteristiki sonyachnogo adsorbtsiynogo kholodilnika na osnovi kompositnogo sorbentu «silikagel/Na2SO4. *Odeska natsionalna akademiya kharchovyh tekhnologiy. Naukovi pratsi,* **2**(47), 176 – 181, (in Ukraine).
14. Ostrov, M 1999. Rukovodstvo po raschetu teplovogo balansa kholodilnykh kamer i vyboru osnovnykh proektnykh parametrov kholodylnykh ustanovok, (in Russian).

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