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OPERATING REGIME OF ADSORPTIVE HEAT-MOISTURE REGENERATORS BASED ON COMPOSITES «SILICA GEL – SODIUM SULPHATE» AND «SILICA GEL – SODIUM ACETATE»

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Abstract

Operational parameters of adsorptive regenerator of low-potential heat and moisture based on composite adsorbents «silica gel - sodium sulphate» and «silica gel – sodium acetate» synthesized by sol – gel method were studied. Correlation of the parameters such as airflow rate, switching period, and temperatures of internal and external air, temperature efficiency factor was stated. Purposeful changing the temperature efficiency factor in rather wide ranges is shown when the switching period and airflow rate variated. Maximal values of temperature efficiency factors are stated at the airflow rates and switching over time of at most 0.22 – 0.32 m/s and 5 – 10 min., when composite «silica gel – sodium sulphate» used. Regenerators based on composites «silica gel – sodium sulphate» are stated to surpass devices based on «silica gel – sodium acetate» by at least 9 – 10 % of temperature efficiency factors. Efficiency of adsorptive regenerators is revealed to be affected by the meteorological conditions. Maximal values of temperature efficiency factor of regenerators based on composites «silica gel – sodium sulphate» are corresponded with the external air temperature of –5 – 0 °C and internal air temperature of 15 – 16 °C.

Key words: adsorptive heat-moisture regenerator; temperature efficiency factor; maximal adsorption; composite adsorbent.

ЕКСПЛУАТАЦІЙНІ ХАРАКТЕРИСТИКИ АДСОРБЦІЙНИХ РЕГЕНЕРАТОРІВ ТЕПЛОТИ ТА ВОЛОГИ НА ОСНОВІ КОМПОЗИТІВ «СИЛІКАГЕЛЬ – НАТРІЙ СУЛЬФАТ» ТА «СИЛІКАГЕЛЬ – НАТРІЙ АЦЕТАТ»

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Анотація

Досліджено експлуатаційні параметри адсорбційного регенератора низькопотенційного тепла та вологи на основі композитних адсорбентів «силікагель – натрій сульфат» та «силікагель – натрій ацетат», які синтезовано золь-гель методом. Встановлено кореляцію таких параметрів, як швидкість повітряного потоку, період перемикання, температури внутрішнього та зовнішнього повітря, температурного коефіцієнта корисної дії. Показана цілеспрямована зміна коефіцієнта корисної дії в досить широких діапазонах при зміні часу зміни напрямку та швидкості повітряного потоку. Максимальні значення температурних коефіцієнтів корисної дії встановлено при швидкості повітряного потоку і часу перемикання протягом часу не більше 0.22 – 0.32 м/с та 5 – 10 хв. відповідно при використанні композиту «силікагель – натрій сульфат».

Ключові слова: адсорбційний регенератор теплоти та вологи; температурний коефіцієнт корисної дії; максимальна адсорбція; композитний адсорбент.

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ЭКСПЛУАТАЦИОННЫЕ ХАРАКТЕРИСТИКИ АДСОРБЦИОННЫХ РЕГЕНЕРАТОРОВ ТЕПЛОТЫ И ВЛАГИ НА ОСНОВЕ КОМПОЗИТОВ «СИЛИКАГЕЛЬ –СУЛЬФАТ НАТРИЯ» И «СИЛИКАГЕЛЬ – АЦЕТАТ НАТРИЯ»

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Аннотация

Исследованы эксплуатационные параметры адсорбционного регенератора низкопотенциального тепла и влаги на основе композитных адсорбентов «силикагель - натрий сульфат» и «силикагель - натрий ацетат», которые синтезированы золь-гель методом. Установлена корреляция таких параметров, как скорость воздушного потока, период переключения, температуры внутреннего и наружного воздуха, температурного коэффициента полезного действия. Показано целенаправленное изменение коэффициента полезного действия в достаточно широких диапазонах при изменении времени изменения направления и скорости воздушного потока. Максимальные значения температурных коэффициентов полезного действия установлено при скорости воздушного потока и времени переключения в течение времени не более 0.22 – 0.32 м / с и 5 – 10 мин. соответственно при использовании композита «силикагель - натрий сульфат».

Ключевые слова: адсорбционный регенератор теплоты и влаги; температурный коэффициент полезного действия, максимальная адсорбция; композитный адсорбент.

Introduction

One of the main and important tasks of ventilation and air conditioning in modern housing and utilities sector is providing optimal climatic conditions in residential premises. Air conditioning and desiccation is achieved in ventilation and air conditioning systems by cooling the air to a temperature below the dew point and then heating to the desired temperature. Generally, such devices work according to traditional steam-compressor cycle [1] that result in significant electric demand, and therefore enlarges consumption of traditional fossil fuels. Conventional steam compressor machines for air conditioning work on compressors with electric drive chillers [2]. Their operation is accompanied by high energy consumption during the peak load season in summer [3]. Air conditioning with the evaporation of a liquid moisture absorber are based on the periodical processes of sorption of moisture from the air and regeneration of the resulting diluted solution [4]. Similar systems based on a pair of ammonia-water usually consist of solar thermal collectors associated with a sorption chiller, a heat storage tank, a heat-cooled device, a cooling system in the room and an auxiliary (backup) subsystem [5–8]. Despite the fact that the cooling temperature is below 0ºC, these devices require controlled heat at temperatures up to 160 - 200 °C [9]. Expansion of their commercial use is heavily limited by the complexity of construction in existing systems for air conditioning and ventilation of residential premises.

The simplest solution to this problem is to use warm air to heat the cold inlet air. For this purpose, regenerative and recuperative heat exchangers are applied [10–14]. These devices are not only suitable for central heating systems based on fossil fuel [15], but also for solar warming systems that can be used as a support for a traditional fuel combustion system [16]. However, the application of heat exchangers does not solve the problems associated with a significant amount of moisture in air ducts, which leads to the formation of ice at the cold end of the heat exchanger and blocks its operation. As a result, there is the moisture balance upset, that is, the outflow of moisture exceeds the input. These processes lead to lower humidity in the room, which unfavorably affects human health.

Silica gel is offered for air dewatering [17]. However, according to the results of mathematical modeling, the temperature in the channel of the silica gel layer does not exceed 20 ° C, which is lower than the temperature of the regeneration of this material. Disadvantages of silica gel are the next: a small sorption capacity, which requires large volumes of heat-accumulating material to provide the demand load. An alternative to traditional materials is the supply and exhaust ventilation with heat recuperation. One of the promising directions for using composite sorbents is regeneration of heat and moisture [18; 19]. Devices based on composite sorbents are promising to maintain

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the appropriate humidity of air in ventilated spaces [20; 21], which reduces the energy consumption of heating the incoming air.

Such materials are shown to be promising for adsorptive heat energy storage [22–24] which is one of the most common technical solutions in the conditions of exploitation of low-potential and renewable energy sources. The most promising materials for adsorptive heat energy conversion are composite materials «salt inside porous matrix» [25 - 28] due to their adsorptive capacity and heat of adsorption. Obviously, properties of adsorbent are the crucial factors determining operating regimes of adsorptive device for heat conversion.

The aim of present work is to compare the performance characteristics of the adsorptive heat energy converter based on the composite «silica gel – sodium sulphate» and «silica gel – sodium acetate» and to identify the most effective. To achieve this purpose, the following tasks are set:

- to develop a method for calculation the performance characteristics of an adsorptive regenerator based on the composite «silica gel - sodium sulphate» and «silica gel - sodium acetate»;
- to find out the correlation of the parameters of the operation processes and the efficiency factor of adsorptive devices based on the composite «silica gel – sodium sulphate» and «silica gel – sodium acetate»;
-to compare the effectiveness of devices based on the composites «silica gel - sodium sulfate» and «silica gel - sodium acetate».

Experimental

Design of the adsorptive heat-moisture regenerator is presented in Fig. 1 [21]. The length of laboratory prototype is 0.6 m, the diameter being 0.2 m. As heat storage materials composite adsorbents «silica gel – sodium sulphate» and «silica gel sodium acetate» were used. Both composites were synthesized by sol – gel technique [22; 23]. The device operational regimes are «inflow» and «outflow» which alternate one to another [21].

The outer end of investigated device is considered as cold, the end placed in ventilated premise being warm.

As efficiency criterion of adsorptive heat-moisture regenerator temperature efficiency factor or heat regeneration coefficient η_{tem} was used. Control-flow chart of suggested algorithm is presented on the Fig. 2. Algorithm involves calculation of the temperature efficiency factor or heat regeneration coefficient:

$$\eta_{tem} = \frac{t_{inf} - t_{ext}}{t_{out} - t_{ext}}, \qquad (1)$$

where t_{inf} is temperature of inflowing air, °C; t_{ext} is temperature of external air; t_{out} is temperature of outgoing air.

Temperature of inflowing air is computed as a temperature after mixing the cold air from the

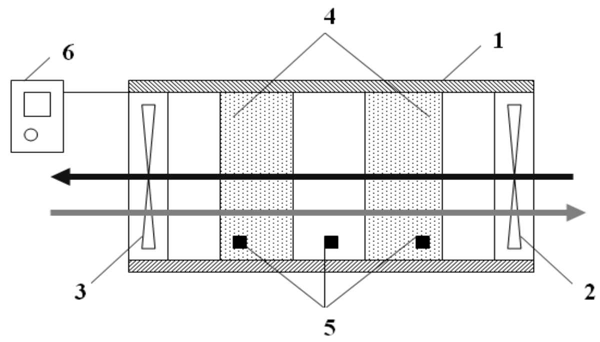

Fig.1. Heat regenerator construction
1 – pipe (case); 2 – external ventilator; 3 – inner ventilator; 4 – heat storage checkerworks; 5 – temperature detector; 6 – operating console [4].

street and the warm air in the room during inflow:

$$t_{fin.r.aft.mix.} = \frac{V_r \cdot t_{0r} + V_{inf} \cdot t_{fin.r}}{V_r + V_{inf}} \qquad (2)$$

where V_r is volume of premise, m^3; $t_{0.r}$ is initial air temperature at the room outlet (warm end), °C; $t_{fin.r}$ is final temperature of the inflowing cold air, °C.

Final temperature of cold air-in is computed by equation of thermal balance:

$$t_{fin.r} = (C' \cdot t_{0str} \cdot V_{inf} + 4.19 \cdot t_{0str} \cdot V_{inf} \cdot C_{0.str} + \Delta H_{ads.inf} \cdot M_{ads}) / (C' \cdot V_{inf} + 4.19 \cdot V_{inf} \cdot C_{fin.r}) \qquad (3)$$

where C' is volumetric specific heat of air, kJ/m·K; t_{0str}– temperature of outdoor air (near the cold end of regenerator), °C; V_{inf} – volume of the inflow air passed through a layer of heat storage material, m^3; $C_{0.str}$ is initial absolute humidity at the cold end of the regenerator, kg/m^3; $\Delta H_{ads.inf}$ is the heat of adsorption during inflow, kJ/kg; M_{ads} – mass of adsorbent, kg; $C_{fin.r}$ – final absolute humidity at the inflow, kg/m^3.

The volume of air passed through the layer of heat storage material at the inflow or outflow, V_{inf} or V_{outf}, m^3 is calculated as:

$$V = F_s \cdot w \cdot \tau \qquad (4)$$

where w is speed of humid air, m/s; τ is time of inflow or outflow, s; F_s is area of the cross-section of the regenerator, m^2.

The temperature of the exhaust air is determined as the temperature after mixing the

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cold air from the street and the warm air from the room at the outflow:

$$t_{fin.str.aft.mix.} = \frac{V_{str} \cdot t_{0.str} + V_{outf} \cdot t_{fin.str}}{V_{str} + V_{outf}} \quad (5)$$

where V_{str} is volume of air at the outside end of the regenerator, m^3; $t_{0.str}$ is the initial temperature of the outside air when ejected from the room, °C; $t_{fin.str}$ is final temperature of warm air during outflow, °C.

Final warm air temperature during outflow is alculated by thermal balance equation:

$$t_{fin.str.} = (C' \cdot t_{0r} \cdot V_{outf} + 4.19 \cdot t_{0r} \cdot V_{outf} \times \times C_{0r} + \Delta H_{ads.outf} \cdot M_{ads}) / C' \cdot V_{outf} + 4.19 \times V_{outf} \cdot C_{fin.str} \quad (6)$$

where C' is volumetric specific heat of air, kJ/m^3·K; t_{0r} is temperature of indoor air (near the warm end of regenerator), °C; V_{outf} is the volume of air passed through the layer of heat-storage material during outflow, m^3; $C_{0.r.}$ is initial absolute humidity at the warm end of the regenerator, kg/m^3; $\Delta H_{ads.outf}$ is heat of adsorption at the outflow, kJ/kg; M_{ads} is adsorbent mass, kg; $C_{fin.str}$ is final absolute humidity at the outflow, kg/m^3.

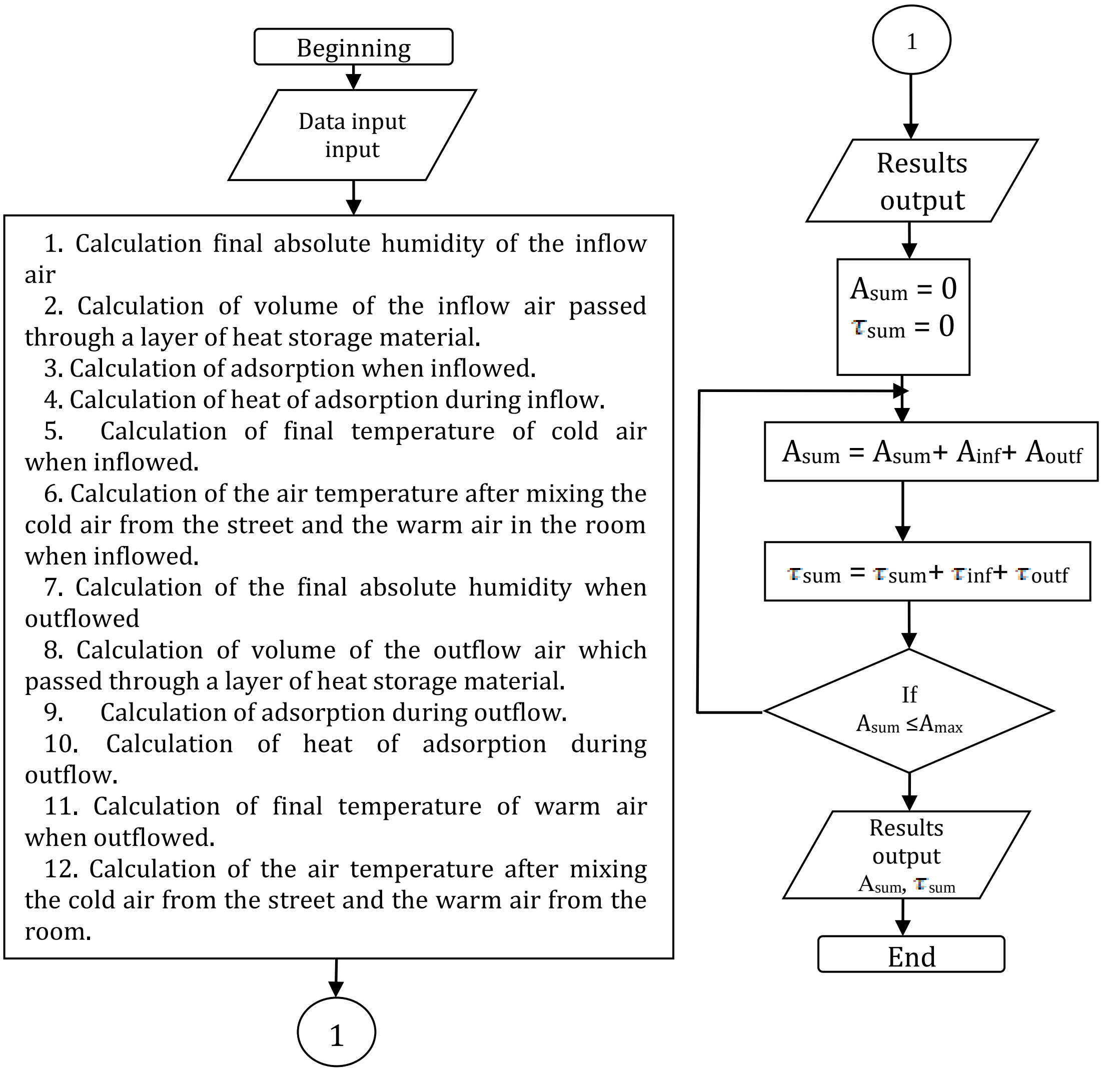

Fig. 2. Control-flow chart for calculation of efficiency factor of adsorptive regenerator

The adsorption heat during inflow or outflow is determined according to [28]:

$$\Delta H_{ads} = \Delta h \cdot A \cdot \frac{1000}{\mu_{H2O}} \quad (7)$$

where Δh is adsorption heat, kJ/mole; A is adsorption during inflow or outflow, kg/kg; μ_{H2O} is molar mass of water, g/mole.

Adsorption at the inflow or outflow is calculated corresponding to [28]:

$$A = \frac{C_0 - C_{fin}}{M_{ads}} \cdot V \quad (8)$$

where V is air volume passed through adsorbent layer, m^3; C_0 is initial absolute humidity at inflow or outflow, kg/m^3; $C_{fin.}$ is final absolute humidity at inflow or outflow, kg/m^3; M_{ads} is adsorbent mass, kg.

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Final absolute humidity at the outlet of the regenerator during inflow or outflow is determined according to [29]:

$$C_{fin} = \frac{C_0}{e^{\frac{\left[\beta \cdot \frac{(-\tau \cdot w \cdot C_0)}{A_{max}} + H\right]}{w}} + 1} \qquad (9)$$

where A_{max} is maximal adsorption, kg/kg; β is mass transfer coefficient, s^{-1}; w is speed of humid air, m/s; H is thickness of the heat storage material layer, m; τ is time of inflow or outflow, s.

The coefficient of mass transfer was calculated according to [28]:

$$\beta = \left(\frac{1}{\beta_y} + \frac{1}{\beta_{lc}} + \frac{1}{\beta_p}\right)^{-1} \qquad (10)$$

where β_y, β_{lc}, β_p – coefficients of mass transfer in the gas phase, in the longitudinal cross section and pores, s^{-1}.

Estimation of structural characteristics of adsorptive regenerator is based on calculation of load for inflow air-heating per a day Q_{inf} by traditional procedure according the Sanitary Regulations 2.04.05-91:

$$Q_{inf} = 0{,}28 \cdot L_{inf} \cdot \rho_{air} \cdot c \cdot (t_{in} - t_{ext}) \cdot \tau \qquad (11)$$

where L_{inf} is inflowing air consumption, m^3 per hour; ρ_{air} is density of inner air, kg/m^3; c is specific heat of air, kJ/(kg·°C); t_{in} is temperature of inner air, °C; t_{ext} is temperature of external air, °C; τ is operating period, hours per a day.

Then mass of adsorbent M_{ads}, kg is calculated as [28]:

$$M_{ads} = \frac{Q_{inf}}{\Delta H_{ads}}, \qquad (12)$$

where ΔH_{ads} is heat of adsorption, kJ/kg which estimated according to (7), the adsorption being maximal or limit.

Volume of an adsorbent is calculated as [28]:

$$V_{ads} = \frac{M_{ads}}{\rho_{ads}}, \qquad (13)$$

where ρ_{ads} is adsorbent density, kg/m^3

Results and discussion

Proposed algorithm was confirmed by experimental data for regenerator based on composite «silica gel – sodium acetate» presented in [10]. The results of the calculations reveal the periodic dependence of the temperatures on the cold and warm ends of the adsorptive regenerator with (Fig. 3, curves 1 and 2), which qualitatively corresponds to the experimental data (Fig. 3, curves 1 'and 2').

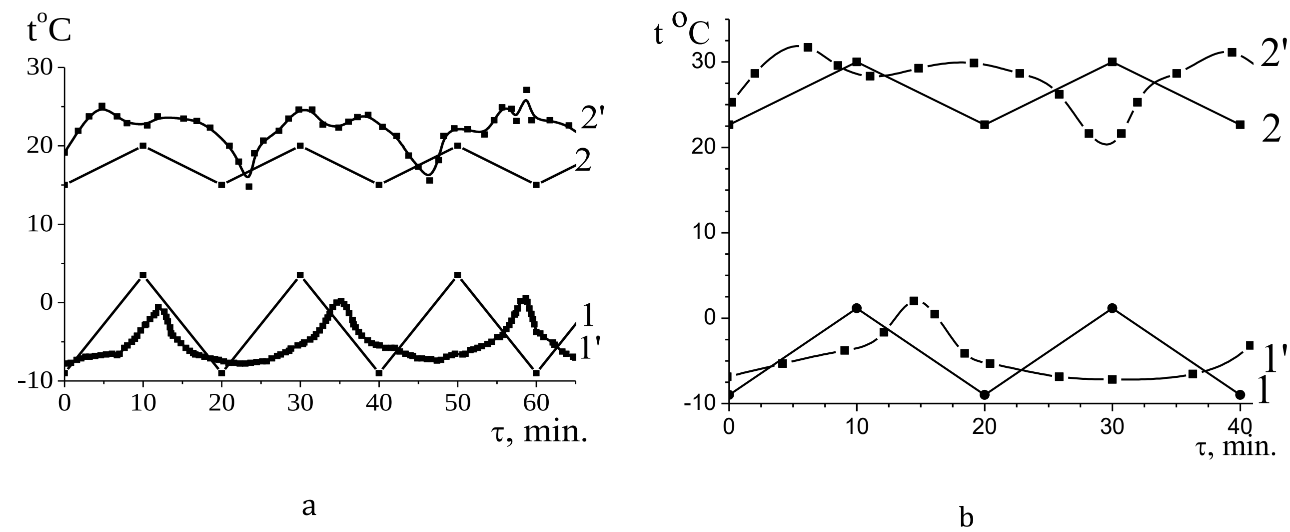

Fig. 3. Periodic temperature dependences for adsorptive heat regenerator based on composites «silica gel – sodium sulphate» (a) and «silica gel – sodium acetate» (b). 1, 2 – calculation results; 1», 2» – experimental data; 1, 1» – temperatures on cold end of regenerator; 2, 2» – temperatures on warm end of regenerator

When composite «silica gel – sodium sulphate» used, the difference between calculated and experimental temperatures does not exceed 2 – 3 ° C at the cold end of the regenerator, and 1 – 5 ° C on the warm. As adsorbent «silica gel – sodium sulphate» applied, the similar deviations are at most 2 – 2.5 ° C for both cold and warm ends of the regenerator. Calculated values of temperature efficiency factors of the regenerators based on «silica gel – sodium sulphate» and «silica gel – sodium acetate» are 91 % and 82 %, respectively. According to the experimental data, the temperature efficiency factors of the regenerators based on «silica gel – sodium sulphate» and «silica gel – sodium acetate» are approximately 95% and 85 %, respectively. So, this mathematical model is proved to be adequate for qualitative evaluation of the performance characteristics of adsorptive regenerators in ventilation systems.

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An adsorptive regenerator can be efficient when the inflow air warmed in the conditions of a residential apartment. According to the results of the calculation by the Sanitary Regulations 2.04.05-91, the thermal load for heating the inflowing air for three-room apartment with a total area of 103 m^2 and a height of 2.5 meters is about 327.9 MJ per a day. Then the mass and volume of the adsorbents corresponding to the thermal load were estimated according by Eq. (12) – (14).

Results of calculation of composites mass are given in Tables 1 and 2.

Table 1

Results of calculation of adsorption heat and mass of composite adsorbents «silica gel – sodium acetate» for inflow air warming (thermal load 327.9 MJ per a day)

Adsorbent composition, wt. %		Maximal adsorption, A_{max} kg/kg	Adsorption heat ΔH_{ads}, kJ/kg	Mass of adsorbent M, kg	Volume of adsorbent V, m^3
Silica gel	Sodium acetate %				
20	80	0.557	1856.10	177	0.25
40	60	0.455	1517.07	216	0.3
60	40	0.353	1178.05	278	0.39
80	20	0.252	1099.11	298	0.41

Table 2

Results of calculation of adsorption heat and mass of composite adsorbents «silica gel – sodium sulphate» for inflow air warming (thermal load 327.9 MJ per a day)

Adsorbent composition, wt. %		Maximal adsorption, A_{max} kg/kg	Adsorption heat ΔH_{ads}, kJ/kg	Mass of adsorbent M, kg	Volume of adsorbent V, m^3
Silica gel	Sodium sulphate %				
20	80	1.055	3506	94	0.130
40	60	0.842	2807	117	0.162
60	40	0.628	2093	157	0.218
80	20	0.414	1380	238	0.330

Calculation results confirm that composites «silica gel – sodium acetate» are inferior in adsorption heat to composites «silica gel – sodium acetate» by a factor of 1.25 – 2.0. So, to support with the same heat load the more mass of «silica gel – CH_3COONa» is necessary as compared with composite adsorbents «silica gel – Na_2SO_4» (Table 1 and 2). So, to fulfill the same heat load mass and volume of composite «silica gel – sodium sulphate» is estimated to be half as much as compared with «silica gel – sodium acetate» with the same content of salt.

So, the composites containing 20 wt. % silica gel and 80 wt. % salts are suggested to use as an adsorptive materials. The weight of the composite «silica gel – sodium acetate» corresponding to the calculated thermal load is estimated at 177 kg and the volume is 0.25 m^3 (Table 1). So, according to an optimal option of installation four adsorptive regenerators, mass of this adsorbent per one regenerator is 45 kg. At the same time, for the same heat load mass of composite «silica gel – Na_2SO_4» of 94 kg is required (Table 2). Accordingly, when the same scheme of installation used, mass of composite «silica gel – Na_2SO_4» per one regenerator is 24 kg.

Then operating of regenerators based on «silica gel – Na_2SO_4» and «silica gel – CH_3COONa» was simulated. Results of mathematical modelling confirm that the temperature efficiency factor η_{tem} of both heat-moisture regenerators strongly depends on airflow rate (Fig. 4). When the rate increased, the temperature efficiency factor is decreased. It is explained by increasing of volume of inflowed air. Similarly, when switching over period (that is changing direction of flows) increased, amplitudes of time-temperature dependences on both cold and warm ends of the device are stated to be magnified. This results in decreasing values of η_{tem} (Fig. 4). Maximal values of temperature efficiency factors are observed at the airflow rates 0.22 – 0.32 m/s and switching over time at most of 5 – 10 min. Time of achieving of maximal adsorption is negligibly affected by switching over time of flows (Fig. 5). However, it is observed to strongly depend on airflow rates. Maximal time of achieving of maximal adsorption is stated at airflow rate of 0.22 m/s, it being stated of 125 and 135 hours for composite «silica gel – sodium acetate» and «silica gel – sodium sulphate».

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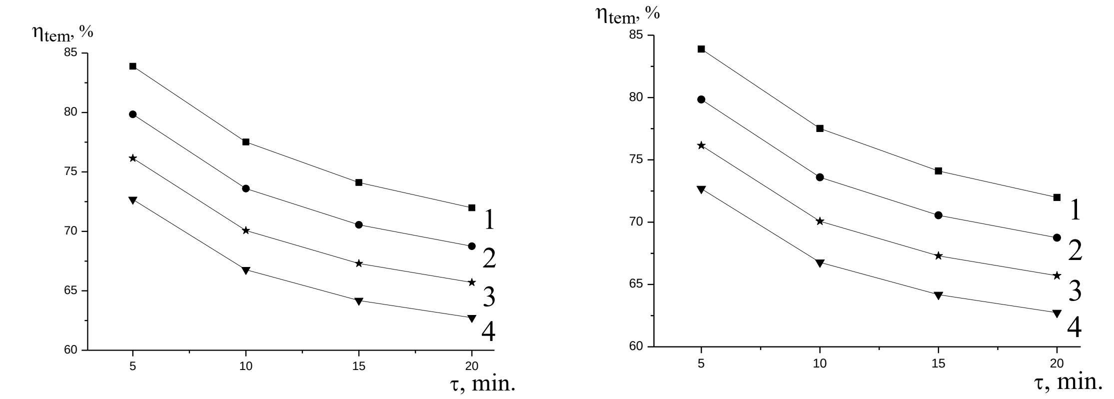
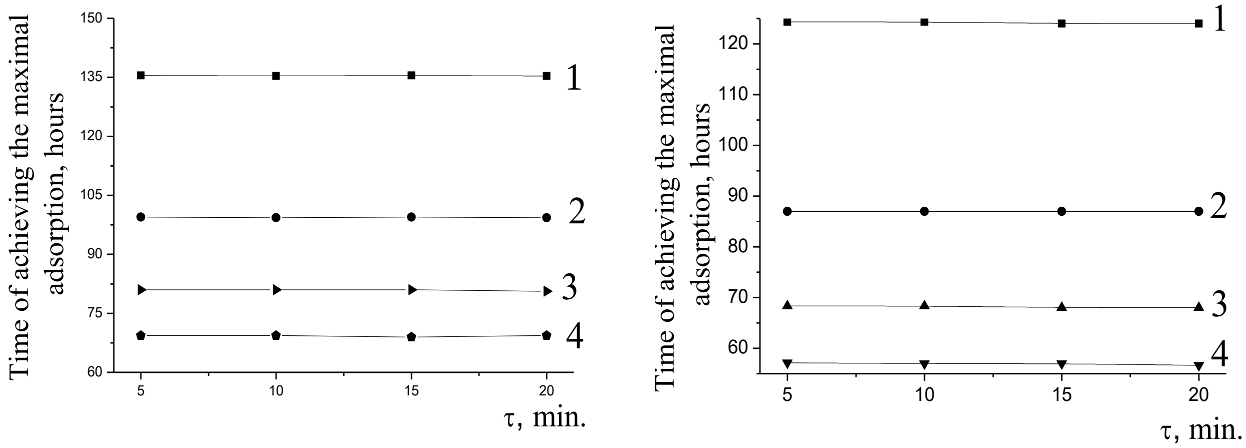
Also, meteorological conditions affect the efficiency of adsorptive heat-moisture regenerator. For example, the external air temperature and temperature efficiency factor are increased simultaneously (Fig. 6). Obviously, time of achieving of the maximal adsorption is negligibly affected by the external air temperature. Decreasing the internal temperature leads to increasing the temperature efficiency factor (Fig. 7)



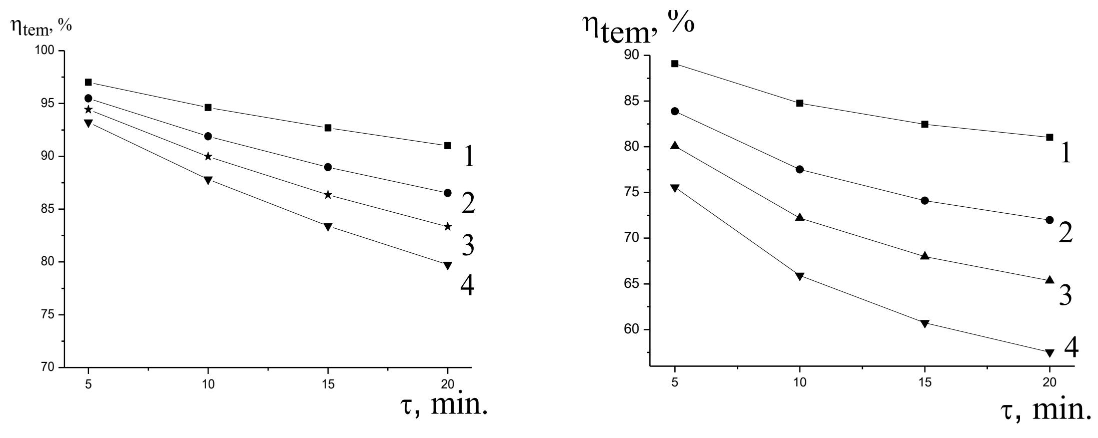
A B

Fig. 4. Temperature efficiency factor vs. switching over time for adsorptive regenerator of heat and moisture based composite «silica gel – sodium sulphate» (A) and «silica gel – sodium acetate» (B). Air flow rate, m/s: 1 – 0.22; 2 – 0.32; 3 – 0.42; 4 – 0.52.



A B

Fig. 5. Time of achieving the maximal adsorption vs. switching over time of adsorptive heat moisture regenerator based composite composite «silica gel – sodium sulphate» (A) and «silica gel – sodium acetate» (B). Air flow rate, m/s: 1 – 0.22; 2 – 0.32; 3 – 0.42; 4 – 0.52.



A B

Fig. 6. Temperature efficiency factor vs. switching over time of adsorptive heat moisture regenerator based composite composite «silica gel – sodium sulphate» (A) and «silica gel – sodium acetate» (B) at the temperatures of external air, °C: 1 – –3; 2 – –9; 3 – –15; 4 – –25.

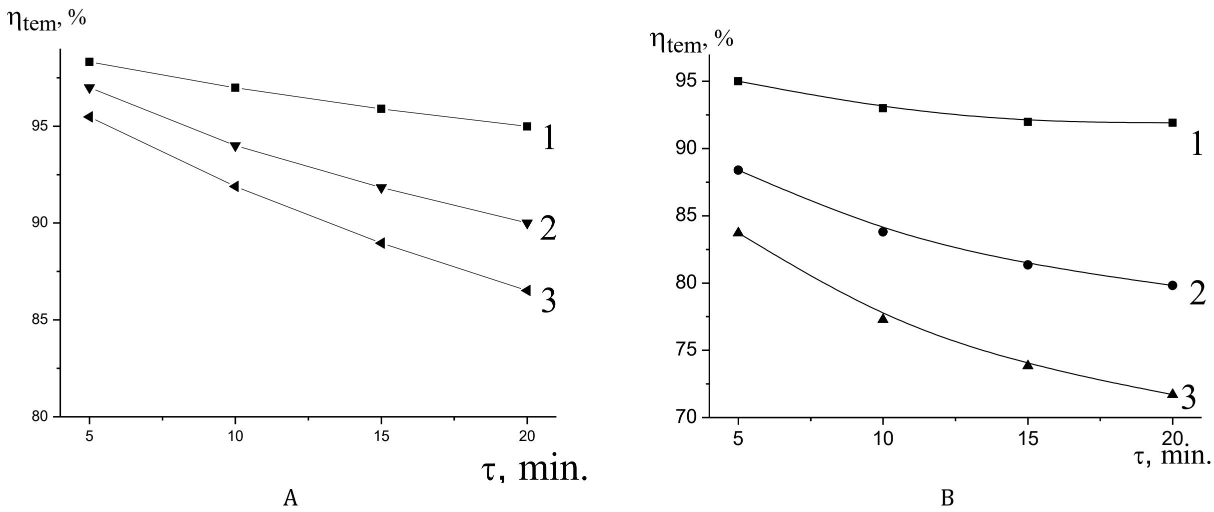


Fig. 7. Temperature efficiency factor vs. switching over time of adsorptive heat moisture regenerator based composite composite «silica gel – sodium sulphate» (A) and «silica gel – sodium acetate» (B) at the temperatures of internal air, °C: 1 – 15; 2 – 20; 3 – 25.

It should be noted that temperature efficiency factors of regenerators based on composites «silica gel – sodium sulphate» are stated to exceed η_{tem} for devices based on «silica gel – sodium acetate» by at least 9 – 10 %. This difference becomes more significant at higher airflow rates, switching over times or internal temperature (Fig. 4, 6, 7). It appears to increase when external temperature decreased (Fig. 7)

Therefore, the correlation of the temperature efficiency factor and meteorological conditions were considered for regenerator based on composite «silica gel – sodium sulphate» (Fig. 8). Maximal values of temperature efficiency factor are observed at the external air temperature of –5 – 0°C and internal air temperature of 15 – 16°C.

Conclusions

Regime of adsorptive heat-moisture regenerators based on composites «silica gel – sodium sulphate» and «silica gel – sodium acetate» were compared in the conditions of ventilation systems of residential premises. An algorithm for calculation of temperature efficiency factor of adsorptive heat was suggested and confirmed by results of testing of the laboratory prototype.

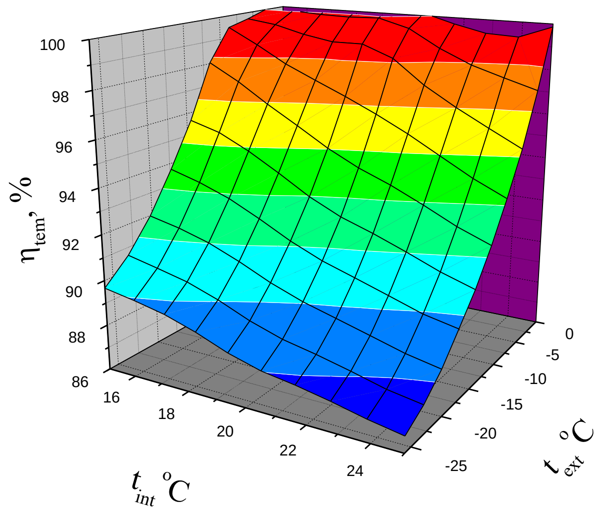


Fig. 8. 3D plot of temperature efficiency factor vs. internal and external temperatures for adsorptive heat-moisture regenerator based composite «silica gel – sodium sulphate»

Performance of heat-moisture regenerators based on composites «silica gel – Na_2SO_4» and «silica gel – CH_3COONa» is simulated in the conditions of typical residential premise. An optimal composition of adsorbents is stated to be 20 % of silica gel and 80 % of salt, that is, sodium sulphate or sodium acetate. Due to the higher value of maximal adsorption composite «silica gel – Na_2SO_4» is shown to be required in half as much as compared with «silica gel – CH_3COONa».

Correlation of the operating processes parameters and efficiency factor of the temperature efficiency factor is shown. For both composites maximal values of temperature efficiency factors are stated at the airflow rates and switching over time of at most 0.22 – 0.32 m/s and 5 – 10 min. Nevertheless, regenerators based on composites «silica gel – sodium sulphate» are in excess of at least 9 – 10 % of temperature efficiency factors as compared with devices based on «silica gel – sodium acetate».

Correspondence of efficiency of regenerators and meteorological conditions is revealed. Maximal values of temperature efficiency factor of regenerators based on composites «silica gel – sodium sulphate» are stated at the external air temperature of –5 – 0 °C and internal air temperature of 15 – 16 °C.

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