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OPERATING PROCESSES PARAMETERS OF OPEN-TYPE SORPTIVE HEAT STORAGE DEVICES IN HEAT SUPPLY SYSTEMS

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ПАРАМЕТРИ ПРОЦЕСІВ ЕКСПЛУАТАЦІЇ СОРБЦІЙНОГО АКУМУЛЯТОРА ТЕПЛОВОЇ ЕНЕРГІЇ ВІДКРИТОГО ТИПУ В СИСТЕМАХ ТЕПЛОПОСТАЧАННЯ

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Abstract. *Operating processes of open-type sorption heat accumulator in heating systems were studied. The algorithm for calculation of its performance is developed. It includes computation of mass transfer cofficient, sorption, useful heat sorption, heat input for heating the sorbent, device casing, water in the humidifier, evaporation of water, heating the sorbed water, desorption, and calculating efficiency coefficient. Operational performance of open-type heat storage device based on the sorbent composite 'silica - sodium sulfate' is estimated. Suggested composite sorbent is obtained from tetraethoxysilane, Na_2SO_4, ethanol (as a solvent), hydrochloric acid (as a catalyst) and polyionenes served as organic modifiers. The impact of vapor flow velocity on efficiency is taken into account by the coefficient equal sorption value. A monotonic increase of efficiency coefficient while increasing the vapor flow speed and its relative humidity is shown. The efficiency coefficient of heat storage device is shown to be with little to no dependence with regeneration temperature heightened from 90 ºC to 110ºC. The optimal operating conditions of the heat accumulating device which allow to operate with maximum magnitudes of efficiency coefficients 53 – 57 % are stated to be vapor-air mixture speed 0.6 - 0.8 m/s and relative humidity of 40 – 60 %. The results of simulative experiments and field trials are given. Field tests were carried out in two modes differed with start time. Heat storage device was switched on in the morning or in the evening for load-factoring of electric energy peaks, indoor temperature being kept within limits from 20 ºC to 22ºC during day or night hours. Correlation between efficiency coefficients deduced from experiments and calculated with suggested algorithm is confirmed. The possibility of reducing the power consumption by applying of the heat accumulators in 2,4 - 90 times versus decentralized heating systems on basis of solid fuel boiler, gas boiler and electric boiler is stated when open-type sorptive heat storage device used. Results of the study can be applied to develop sorptive storage devices in decentralized heat supply and ventilation systems and sorption units for utilization of low-temperature waste heat.*

Анотація. *Досліджено процеси експлуатації сорбційного акумулятора теплової енергії відкритого типу в системах теплопостачання. Запропоновано алгоритм розрахунку його експлуатаційних характеристик: обчислення коефіцієнта масопередачі, величини сорбції, корисної теплоти сорбції, визначення витрат теплоти на процес, які включають витрати теплоти для нагріву адсорбенту, корпусу установки, води в баку, випаровування води в баку, нагрівання сорбованої води і десорбцію, а також обчислення коефіцієнта корисної дії. Досліджені експлуатаційні характеристики теплоакумулюючого пристрою відкритого типу на основі композитного сорбенту «силікагель – натрій сульфат». Вплив швидкості пароповітряного потоку на коефіцієнт корисної дії враховано за допомогою коефіцієнта, рівного величині адсорбції. Показано монотонне зростання коефіцієнта корисної дії при збільшення швидкості пароповітряного потоку та його відносної вологості. Виявлена практична відсутність залежності коефіцієнта корисної дії від температури регенерації сорбента. Визначені оптимальні умови експлуатації теплоакумулюючого пристрою: швидкість пароповітряної суміші 0,6 – 0,8 м/с та її відносна вологість 40 – 60 %, які дозволяють експлуатувати теплоакумулюючий пристрій з максимальними значеннями коефіцієнта корисної дії 53 – 57 %. Наведені результати модельних та натурних випробувань. Підтверджена кореляція коефіцієнтів корисної дії, встановлених за результатами розрахунків згідно запропонованого алгоритму та дослідним шляхом. Встановлено можливість скорочення енергоспоживання теплоакумулюючого пристрою в 2,4 – 90 разів в порівнянні* *систем децентралізованого теплопостачання на основі твердопаливних, газових та електричних котлів. Результати дослідження можуть бути використані для розробки адсорбційних акумуляторів в системах децентралізованого теплопостачання та вентиляції, а також сорбційних модулів для утилізації низькопотенційних вторинних енергоресурсів .*

Key words: heat storage device, composite sorbent, sorption.

Ключові слова: теплоакумулюючий пристрій, композитний сорбент, сорбція.

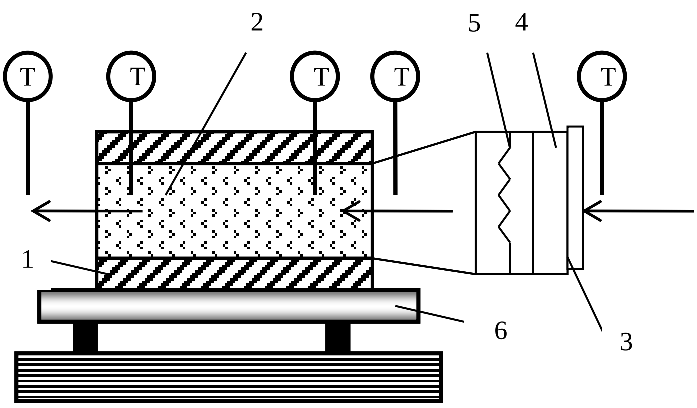
Monotonic growth of fuel costs resulted in unbridled increasing of energy rates demands of equalization of electrical load for electric power system. There are three zones on typical electrical load curve: minimal load (night-time valley) or off-peak demand, intermediate load and maximal or peak load [1]. Imbalance daily load of energy consumption resulted in decreasing of efficiency of generation, transmission and consumption of energy power because of necessity of rather expensive equipment with pessimistic performance working at its nominal load during limited amount of time. Equalization of energy load curves for energy system promotes decreasing requirements to generating capacities and also recurrent expenses for equipment installation due to its effective operation. Methods of electric load regulation are preferentially concerned with load control of plant [2], which includes production process shift to time intervals with low rates by means of batteries and capacitors with high capacity [3] taking into account limitations, these devices being rather expensive and operation complex. An effective method for filling of night-time valley can be using of electric power extra for decentralized heat supply of residential building. Consumers used electrical devices for water or air heating can become driven consumers-regulators storing up energy in out-of-peak periods of power consumption and consuming it in peak periods, electric load curve for energy system being equalized.

Sorptive heat accumulators are one of technical solution for it [4, 5]. These devices heat water for heat supply or air for ventilation in peak periods and consume electric power for sorbent regeneration in night period. Moreover, electric energy consumption can be substantially decreased utilizing solar energy transformed into heat energy in solar collector. Nevertheless, the main factors determining exploiting parameters of such devices are operating characteristics of heat storage materials. Despite the ample quantity of works concerned with synthesis of sorptive materials [6 – 8] operating processes of sorptive heat storage devices are close to be still unstudied.

The base principles of modeling and optimization of cyclic sorptive processes are developed by Lukin [9]. Nevertheless, estimation of operating parameters of heat storage device and selecting of its optimal parameter require of multifactorial studies of heat-and-mass transfer in these media, it being concerned with high material inputs. Consequently, developing of algorithm for calculation of optimal construction and working parameters of heat storage device takes central stage.

The present work is focused on operating processes of open-type heat energy storage device in autonomous heat supply system. According to the aim of present work, the tasks of investigation concerned with:

- developing of algorithm for calculation of efficiency coefficient of open-type heat storage device;
- identification of the key factor effecting weighing with efficiency coefficient of heat storage device;
- determination of operating parameters when maximal efficiency coefficients of heat accumulator obtained.



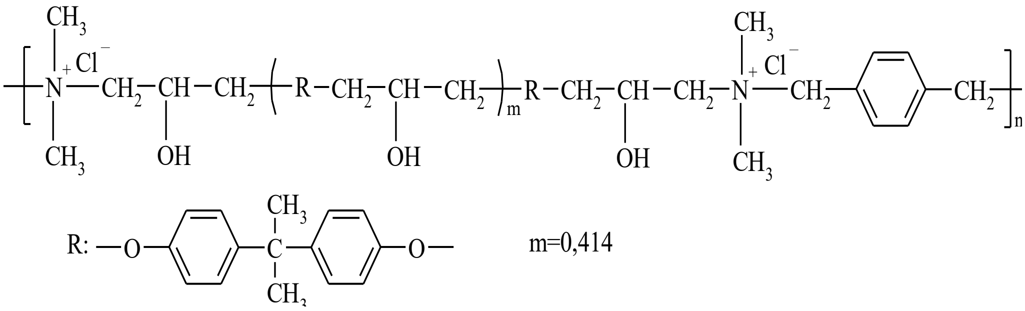
1 – thermal insulated casing; 2 – heat storage material; 3 – compressor; 4 – air humidifier; 6 – resistance element

Fig. 1. Test heat storage apparatus [10].

Experimental

Design of open-type heat storage device is given in Fig. 1 [10].

As heat storage materials composite sorbents ‘silica gel – sodium sulphate’ are used, they being synthesized from tetraethoxysilane, Na_2SO_4, ethanol (as a solvent), hydrochloric acid (as a catalyst) and polyionenes served as organic modifiers. The structural formulas of polyionenes are given below [4]:



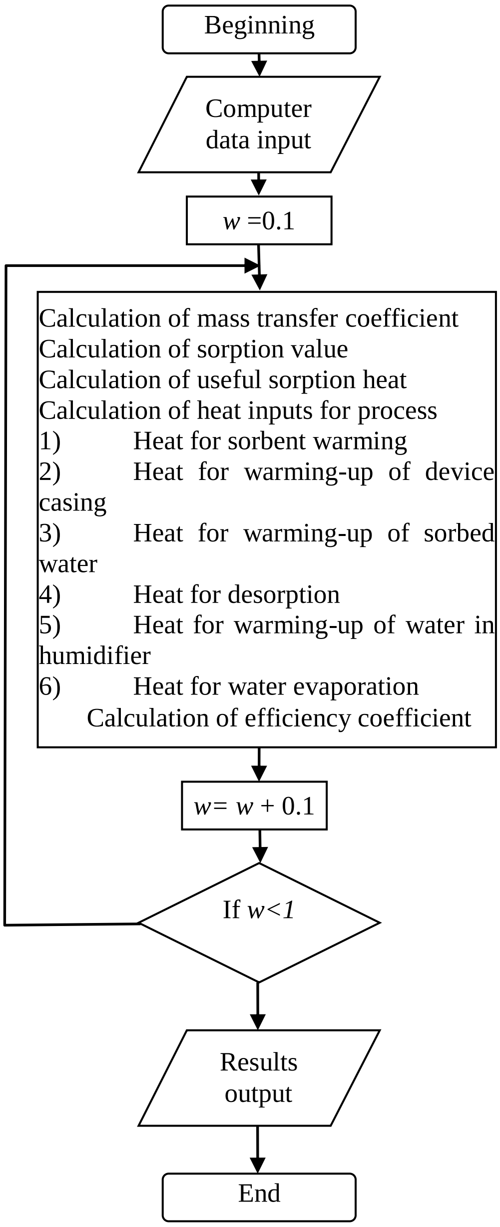


Fig. 2. Control-flow chart for calculation of efficiency factor of sorptive heat storage device.

Diameters of composite sorbents granules are 0.5 – 1.5 mm.

The heat storage device is operated into two steps. On the first step external air is fanned by compressor 3 into humidifier 4 where its relative degree of humidity is increased to 60 – 80 %. Then humidified air is heated in resistance element 5 to 30 – 40 °C because of low rates of sorption at lower temperatures. Furthermore humidified air is directed into heat storage material. After short-term warm-up of heat storage material (15 min.) water sorption from air passed to heat storage material occurs. Exothermic sorption processes resultes in temperature increasing of both heat storage material and air. Therewith, outlet air temperature is 90 – 115 ºC. On the second step (regeneration) heat air pumped through sorbent layer to warm up sorbent to temperatures above 90ºC up to desorption.

According to these steps, algorithm for computation of efficiency coefficient open-type heat storage device is suggested, its control-flow chart being given on Fig. 2.

Having been considered operation steps of heat storage device, efficiency coefficient (η) is calculated as %:

$$\eta = \frac{Q_u}{Q_{in}} \cdot 100 \tag{1}$$

where Q_u is useful heat (sorption heat), kJ:

$$Q_u = M_{sor} \cdot \Delta H_{sor}, \tag{2}$$

where M_{sor} is sorbent mass, kg; ΔH_{sor} – sorption heat, kJ/kg;

Q_{in} is heat input, kJ:

$$Q_{in} = Q_{des} + Q^h_{sorb} + Q^h{}_{cas} + Q^h_w + Q^h_{s.w.} + Q^{ev}_w, \tag{3}$$

where $Q_{des}, Q^h_{sorb}, Q^h{}_{cas}, Q^h_w, Q^h_{s.w.}, Q^{ev}_w$ are heat inputs for desorption, heating of sorbent, device casing, water in the humidifier, sorbed water, water evaporation, kJ.

Heat quantity for warming of materials and device components is calculated by common formula:

$$Q=M \cdot C \cdot \Delta t \tag{4}$$

The influence of air-vapor flow rate on efficiency coefficient is taken into account by coefficient A showing sorption value, kg/kg. This coefficient is used for heat costs for desorption

$$Q_{des} = \Delta H_{des} \cdot M_{sorb} \cdot A, \tag{5}$$

and for heating of sorbed water:

$$Q^h_{s.w.} = M_{sorb} \cdot A \cdot C_w \cdot (t_{reg} - t_{env.}) \tag{6}$$

where ΔH_{des} = 2850 kJ/kg is heat of desorption, M_{sorb} is mass of sorbent, kg, C_w – specific heat of water, kJ/kg·K, t_{reg} and $t_{env.}$ are temperatures of regeneration and environment, ºC.

Sorption value is calculated by formula [11] :

$$A = \frac{C_0 - C}{M_{sor}} \cdot V_{air} \tag{7}$$

where V_{air} is air volume: $V_{air} = F_{hs} \cdot w \cdot \tau$, m^3; F_{hs} is cross-section area of heat storage device, m^2, w is air-vapor flow rate, m/s, τ is sorption time, s, C_0 and C are inlet and outlet concentration of air-vapor flow, kg/m^3 [11]:

$$C = \frac{C_0}{e^{\frac{[\beta(\frac{-\tau \cdot w \cdot C_0}{A_{max}}) + H]]}{w}} + 1}, \tag{8}$$

where H is heat storage device height, m, A_{max} is sorption capacity of sorbent, kg/kg; β –mass transfer coefficient, s^{-1}, calculated by [12]:

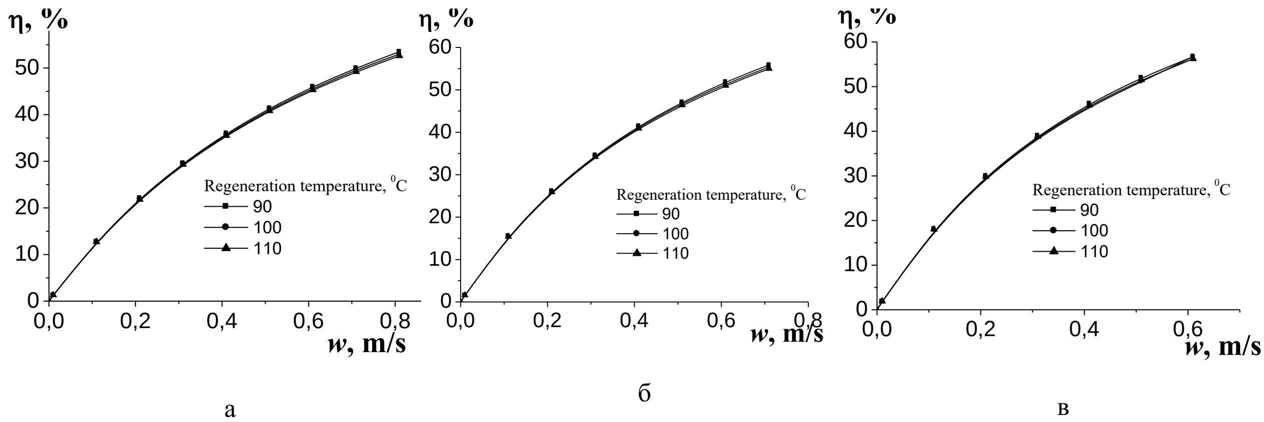
$$\frac{1}{\beta} = \frac{1}{\beta_y} + \frac{1}{\beta_p} + \frac{1}{\beta_{c.s.}}, \tag{9}$$

where β_y, β_p and $\beta_{c.s.}$ are mass transfer coefficients for gas phase, pores and coplanar stirring, s^{-1} [12].

According to results of calculations sorption rate is limited with rate of diffusion in pores, that being confirmed by kinetic study of water vapor sorption [10].

Results and discussion

Dependences for efficiency coefficient of open-type heat storage device based on composite silica gel – sodium sulphate vs. air-vapor flow rate calculated by (1) – (9) are given on Fig. 3. Increase in air-vapor flow rate and its relative degree of humidity are followed by rise of efficiency coefficient of heat storage device η. Value η is shown to be near permanent when regeneration temperature increased from 90 to 110ºC. Maximum efficiency coefficients of 55 – 57% are evaluated for vapor-air mixture speed 0.6 – 0.8 m/s and relative humidity of 40 – 60%.



a – 40 %, b – 50 %, c - 60 %.

Fig 3. Efficiency coefficient-vs-air flow rate. Relative humidity degree.

Heat storage device tests was carried out in premise with floor area during period from 1 of November 2014 to 28 of February 2015. Tested device was used for load-factoring in power systems instead of fan heater and oil heater, their energy consumption being 1.5 – 2.5 kW. The initial temperature in premise was 12ºC. Vapor-air flow rate was set at 0.25 m/s. Heat storage device was filled with 10 kg of sorbent ‘silica gel – sodium sulphate’. Mineral wool (thickness 100 mm, thermal conductivity coefficient 0.035 W · m/K) was used as warmth-keeping material.

Accumulating device was tested in two modes. In the first half-term it was switched on for load-factoring of electric energy in the morning, indoor temperature being kept within limits from 20 ºC to 22 ºC during day hours. During the second half-term heat storage device was switched on for load-factoring of evening peak of electric energy, indoor temperature being kept within limits from 20 ºC to 22 ºC during night hours up to next morning. Average temperature plots for both test modes are given on Fig. 4. Two peaks according to discharging and charging of heat energy device are observed on both curves, they being registered as the first and second after accumulator start. Peak sorbent temperature when discharged is almost 60 ºC, it being resulted from sorbent cooling with air-in flow. Hotter temperature when charged is corresponded with composite sorbent regeneration temperature. When composite regenerated during day hours, heat for its warming and regeneration carried by solar collector, in night hours

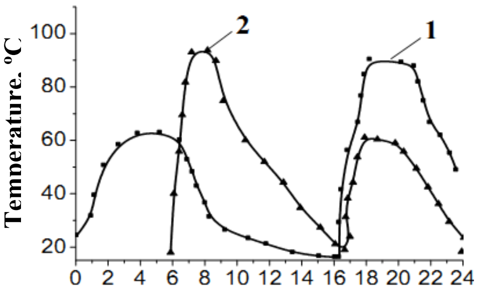


Fig. 4. Averaged temperature sorbent curves when heat storage device started in the morning (1) and in the evening (2).

this being carried by resistance element. Efficiency factors calculated with ratio of two peaks ratio are almost 32 % for both operating modes, it being correlated with calculated values 33 % for the same conditions.

To ascertain advisability of sorptive heat storage device for space heating energy consumption of solid fuel combustion boiler, gas-fired combustion boiler and electric boiler were compared when heat demand equaled to 339.5 MJ per day for floor area 100 m^2.

Indexes min and max correspond to energy consumption at solar and cloudy weather respectively. Results are given in the Table.

When open-type sorptive heat accumulator applied, energy consumption in heat supply system was decreased in minimum of 3.5 times versus gas-fired combustion boiler. As compared to solid fuel combustion boiler and electric boiler, energy consumption was reduced no less than 2.9 and 2.4 times. When heat for sorbent regeneration carried by solar collector, energy consumption was lessened about 90, 76 and 61 times versus gas-fired combustion boiler, solid fuel combustion boiler and electric boiler, respectively.

Table 1 – Energy consumption when sorptive open-type heat energystorage device used for space warming (floor area is 100 м^2)

Heat source	Solid fuel combustion boiler PRO-TECHN TT	Gas-fired combustion boiler PROSKURIV AOGV-16 B	Electric boiler Dnipro-mini 12kW, 380V	Heat energy storage device$_{min}$	Heat energy storage device$_{max}$
Capital input, Thous. UAH	7	7	5	6	6
Energy consumption, kg of standard fuel per day	22	26	17,69	0,29	7,5

Conclusions. Operating processes of open-type sorptive heat storage device were studied. Algorithm for calculation efficiency coefficients of this device is developed. It involves computation of mass transfer cofficient, sorption, useful heat sorption, heat input for heating of sorbent, device casing, water in the humidifier, evaporation of water, heating the sorbed water, desorption, and efficiency coefficient.

Optimal technological parameters of exploiting processes of open-type heat storage device based on composite sorbent ‘silica gel – sodium sulphate’ are estimated by suggested algorithm. They are stated to be vapor-air mixture speed 0.6 – 0.8 m/s and relative humidity of 40 - 60%, efficiency coefficient being ranged from 53 to 57 %.

Power consumption decreasing in 2,4 - 90 times versus decentralized heating systems from solid fuel, gas and electric boilers is stated when open-type sorptive heat storage device used. Its operating economy is stated for decentralized heat supply systems. Application perspectiveness of open-type heat storage device is shown for heat supply systems.

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ЗАСТОСУВАННЯ СПОСОБУ ДИСКРЕТНО-ІМПУЛЬСНОГО ВВЕДЕННЯ ЕНЕРГІЇ ДЛЯ НЕЙТРАЛІЗАЦІЇ КОНДЕНСАТУ ПРОДУКТІВ ЗГОРЯННЯ ПРИРОДНОГО ГАЗУ

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USING OF THE ENERGY DISCRETE-PULSE INPUT METHOD FOR THE CONDENSATE NATURAL GAS COMBUSTION PRODUCTS NEUTRALIZING

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Анотація. *В даній роботі запропоновано новий спосіб нейтралізації конденсату продуктів згоряння природного газу без використання хімічних реагентів з метою його повторного використання для промислових потреб, а також як води для живлення водогрійних котлів промислових і комунальних котельних. Висунуто гіпотезу, що конденсат димових газів за своїм складом є знесоленою водою, що наближається до дистильованої води з присутніми в ньому діоксидом вуглецю в розчиненому стані і у вигляді стабільних нанорозмірних бульбашок (bubstones), вугільної кислоти і газової фази у вигляді мікробульбашок, що містять*