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EXERGY ANALYSIS OF AN OPEN-MODE ADSORPTIVE HEAT STORAGE UNIT BASED ON COMPOSITE ADSORBENT 'SILICA GEL – CRYSTALLINE HYDRATE'

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Abstract. *Exergy analysis of an open-mode adsorptive heat storage unit has been performed when a composite 'silica gel – crystalline hydrate' used as an adsorbent. The crucial factors affecting the exergy efficiency factor are stated to be temperature and initial humidity of airflow supplied to the inlet of adsorbent layer, temperature of external air and methods of air flow humidification. Procedure of calculation of the operating characteristics of an open-mode adsorptive heat storage device was further developed. The suggested procedure involves determination of adsorption, specific adsorption heat and final airflow temperature, useful heat, heat inputs for operating heat storage device and its efficiency factor, then exergy recovered, exergy supplied and exergy efficiency are calculated. Exergy efficiency depends on characteristics of flow of humid air fanned into the adsorbent layer such as temperature and initial absolute humidity which strongly affect the adsorption and final airflow temperatures. Increase of initial temperature of the humid air leads to decreasing of the exergy efficiency. Maximal values of exergy efficiency are determined at the absolute humidity and temperatures of initial airflow within the ranges of 0.03 – 0.04 kg/m^3 and 20 – 30ºC, respectively. These characteristics are corresponded to the maximal airflow temperatures after passing through the adsorbent layer which meet to the Sanitary Regulations. Dependence of exergy efficiency vs. external air temperature and initial airflow temperature is shown. The exergy efficiencies of the open-mode adsorptive heat storage unit with steam and ultrasonic humidification were compared. Ultrasonic humidification is shown to allow increasing the exergy efficiency by 7 % against steam humidification. The obtained results can be used when energy-efficient heat and ventilation systems for residential premises developed.*

Key words: adsorptive heat energy transformation, open-mode adsorptive heat storage unit, exergy efficiency, composite adsorbent, adsorption.

Introduction. In a period of increasing scarcity of primary fuel and rising energy prices, climate warming and air pollution, it becomes crucial to use all available energy resources. For example, application low-potential heat energy sources still remain promising but highly difficult for commercialization option [1 – 3]. In these conditions adsorptive heat energy conversion becomes a promising process [3]. Operation cycle of such devices involves two modes: discharge (adsorption) and charge (regeneration of an adsorbent or desorption) [4].

Despite the fact that adsorptive heat conversion is promising technology, there is still gap between laboratory prototypes and semi-commercial devices. It results from not only because of poor adsorptive properties of convenient adsorbents or complicated technology of obtaining composites 'salt inside porous matrix' but also from absence of procedure for calculation of operating parameters of adsorptive heat storage unit. For example, the mathematical model developed by Nagel et al. [5], which was modified by Lehmann et al. [6] is based on the provisions of the Dubinin-Polyany theory. They provide for the determination of the adsorption potential and the specific adsorbed volume as its function, which allows determining the adsorption, i.e. water uptake.

Mathematical models focused on predicting the adsorption kinetics of silica gels, zeolites and/or salts that form crystal hydrates should allow to establish the optimal operating parameters of the adsorption unit should. All such models describe the kinetics of adsorption, based on the model of linear driving force (LDF). Michel et al. [7] developed a general two-dimensional model (2D) of the adsorber, which considers heat and mass transfer in the adsorbent layer and the flow of moist air. Due to additional assumptions, this model is modified to represent the same porous layer that interacts with pure steam. The model include heat and mass balances, as well as the kinetic equation. To study the thermal dynamics of a 13X zeolite-based adsorption heat storage device, a non-isothermal and non-adiabatic adsorption model including a mass and energy transfer equation was developed by Gaieni et al. [8]. First, the heat and mass balances used in the model are established. Then the kinetic model of LDF and the value of its coefficient are explained.

However, there is still no one opinion about criteria of estimation of efficiency of adsorptive heat conversion unit. Most of mathematical models are focused on a single stage of operation of adsorptive heat storage device. Basically, it is adsorption, estimation of efficiency of the device being based on only this stage [8]. However, operating cycle of adsorptive heat storage device involves the next stages: discharge of the device (adsorption of work fluid with heat storage media, i.e. adsorbent), heating the adsorbent up to regeneration temperature, charge, i.e. desorption, cooling the adsorbent down to the temperatures to begin an adsorption. Discharge is accompanied with evaporation of the work fluid.

Most of proposed mathematic models are concerned with estimation of the efficiency of adsorptive heat conversion unit by the first law of thermodynamic. And a very little number of works are focused on exergy efficiency of adsorptive heat energy conversion [9, 10]. They are mostly focused on methodology of calculation of exergy efficiency [9, 10] or exergy efficiency vs. operating parameters such as heat transfer fluid flow [11]. However, operating parameters of adsorption – desorption processes are crucial for estimation the efficiency of adsorptive heat conversion unit.

The aim of present work is to estimate the performance of open-mode heat energy storage unit by the exergy analysis. To achieve this aim, the next tasks are set:

- to state basic factors affecting the exergy efficiency factor;
- to reveal correlation exergy efficiency factor vs. operating mode of adsorptive heat storage device;
- to determine the basic requirements to performance of open-mode adsorptive heat storage units.

Experimental. The present work is focused on corellation exergy efficiency factor and performance of the open-mode adsorptive heat storage unit. Design of its laboratory prototype is given in [12], its length being 0.6 m. Operational mode of heat storage unit involves two alternating phases (Fig. 1). The first phase corresponds with discharge (Fig. 1a). i.e. adsorption, when external air pumped into humidifier and then directed to resistance element and the layer of adsorbent where water being adsorbed from flow humid air.

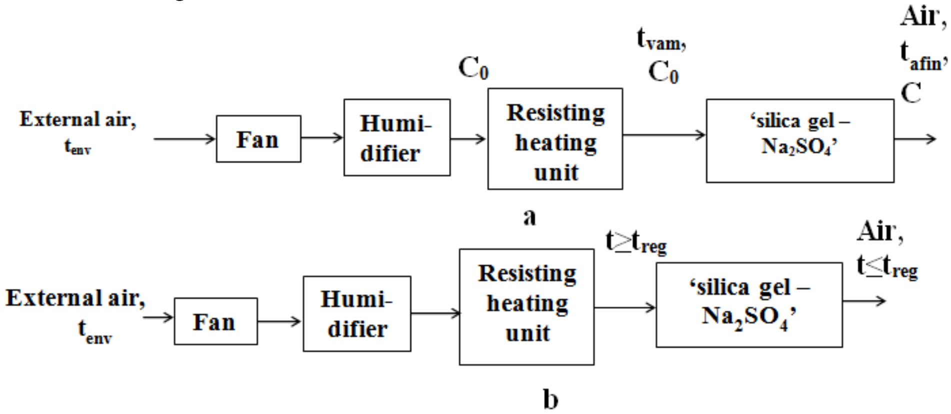


Fig. 1 – Prosesses of discharge (a) and charge (b) of open-mode adsorptive heat storage unit.

Temperatures of both adsorbent and air are increased. The second phase, i.e. charge (Fig. 1b) or regeneration of adsorbent, proceeds when layer adsorbent layer is heated by flow of hot air up to temperatures above t_{reg} which leads to desorption of water.

Operating cycle of adsorptive heat energy storage device is given in Fig. 2. Its stages are the next. Process 1 – 2 refers to the discharge of adsorptive heat energy storage device. Process 2 – 3 corresponds with heating the adsorbent up to regeneration temperature. Charge of the device is given by the line 3 – 4, and cooling the adsorbent up to temperatures of beginning the adsorption being presented by line 4 – 1.

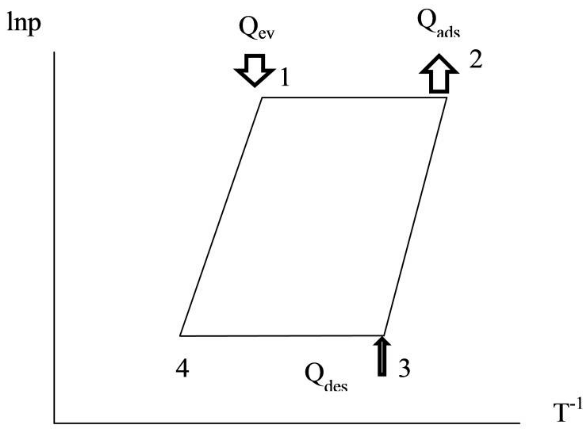


Fig. 2 – Operation cycle of adsorptive heat energy storage device

The general reaction can be presented as

$$\text{'silica gel} - Na_2SO_4\text{'} + nH_2O \leftrightarrow \text{'silica gel} - Na_2SO_4 \cdot 10H_2O\text{'} \cdot (n-10)H_2O + \Delta H_{ads} \quad (1)$$

The suggested model is based on the second law of thermodynamics. The next hypotheses are pre-supposed:

1. The system is operated at a stable state.
2. The heat losses are negligible.

Exergy recovered can be given as recommended in [10]

$$E_{rec} = Q_{ads} \cdot \left(1 - \frac{T_0}{T_2}\right) \quad (2)$$

where Q_{ads} is considered as heat of adsorption, kJ, T_2 refers to the final temperature of inflowing air, K; T0 is considered as temperature of external air, K.

Exergy supplied for heating, evaporation and desorption were calculated according to [11].

Exergy supplied can be calculated as the sum of exergy of desorption, evaporation and heating the airflow and adsorbent

$$E_{sup} = Q_{des} \cdot \left(1 - \frac{T_0}{T_3}\right) + Q_{ev} \cdot \left(1 - \frac{T_0}{T_1}\right) + Vair \cdot C' \cdot \left(T_3 - T_1 - T_0 \cdot ln\frac{T_3}{T_1}\right) + \quad (3)$$
$$+(M_{ads} \cdot C_{ads} + M_{ads} \cdot A \cdot C_w) \cdot \left(T_3 - T_{airfin} - T_0 \cdot ln\frac{T_3}{T_{airfin}}\right)$$

where Q_{des} and Q_{ev} refers to the heat of desorption and evaporation, respectively, kJ, V_{air} is the volume of air which passed through the layer of adsorbent, m^3, C' is special heat of air, $kJ/m^3 \cdot K$, C_{ads} and C_w is special heat of adsorbent and adsorbate, kJ/kg·K, A is adsorption, kg/kg; T_1 and T_3 are temperatures of airflow which supplied to the adsorbent layer and temperatures of regeneration of the adsorbent, K, T_{airfin} is a final temperature of inflowing air when discharged, K.

Heat of adsorption, desorption, adsorption or water uptake and final temperature of inflowing air are calculated by technique which was proposed earlier [13].

So exergy efficiency factor can be calculated as [10]

$$\eta_{ex} = \frac{E_{rec}}{E_{sup}} \cdot 100\ \% \quad (4)$$

Results and discussion

Correlation between performance and exergy efficiency of operating of open-mode heat storage unit is considered under conditions of convenient ventilation system of residual premise (a total area of 103 m^2, a height of 2.5 meters), the load for heating the inflowing air being about 327.9 MJ per a day. The mass of the composite '20 % silica gel – 80 % Na_2SO_4' corresponding to this thermal load is estimated to be 96 kg. Exergy efficiency was calculated when temperatures of composites achieved regeneration temperatures or adsorption reached up maximal value.

As expected, exergy efficiency is affected by absolute humidity of airflow supplied into the adsorbent layer (Fig. 3) which resulted from increasing the water uptake, heat of adsorption and exergy recovered. However, speed-dependence is rather complicated, i.e. increase of the airflow speed leads to rise of adsorption and temperature of adsorbent layer.

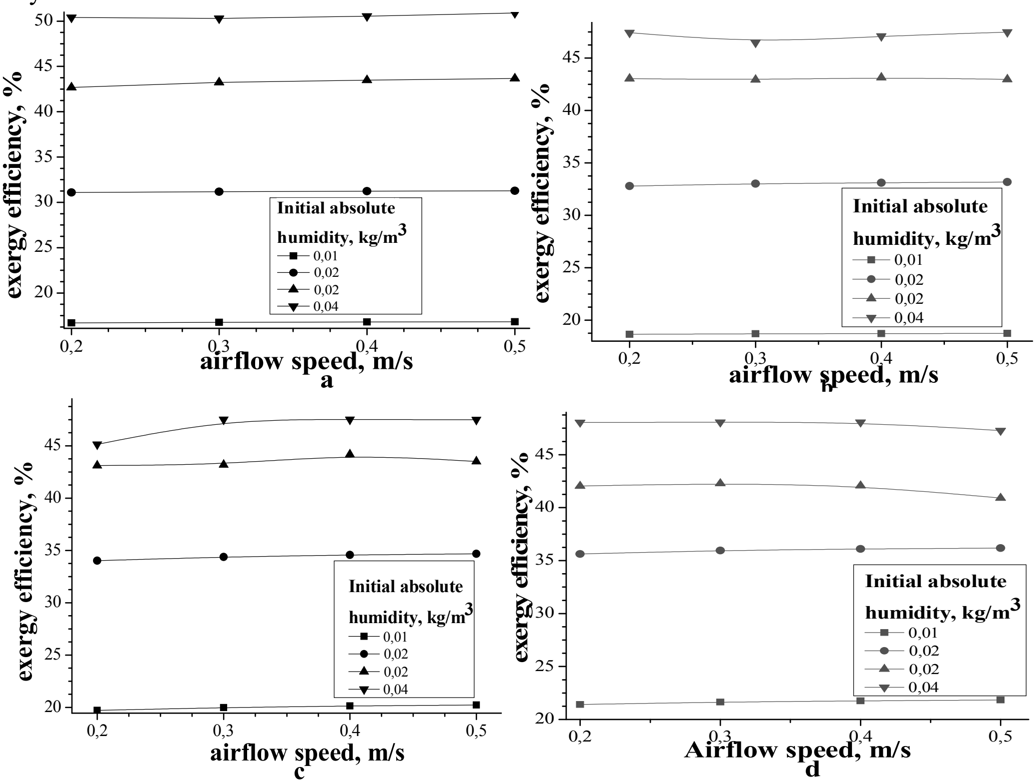


Fig. 3 – Exergy efficiency of open-mode heat storage unit vs. airflow speed. Temperature of flow of humid air, °C: 20(a), 30 (b), 40 (c), 50 (d)

As a result, time of achieving of regeneration temperatures, water uptake during discharge and as a consequence exergy recovered decrease. This is the most visually striking at temperatures of humid airflow of 40 – 50°C when aiflow heated upto 80°C in 1 – 3 hours. The adsorption doesn't surpass 20 % of its limit value under these conditions. Alongside with increasing exergy supplied, it also leads to decreasing the exergy efficiency.

Exergy efficiency strongly depends on temperatures of external air and inflowing humid air (Fig. 4). Maximal values are stated at temperatures of external air of -5 - 0°C and humid air pumped to the adsorbent layer of 20 – 30°C which results from minimal values of exergy supplied.

It was stated previously [4] that maximal values of efficiency factor of open-mode heat storage device of nearly 50 – 60 % can be observed at **the airflow speed of 0.3 – 0.5 m/s with an absolute humidity of 50 – 60%. Moreover,** initial temperatures and absolute humidity of initial airflow have to sustain at 20 – 30ºC and 0.03 – 0.04 kg/m^3 to achieve maximal temperatures of airflow of 65 – 80ºC corresponded with Sanitary Regulation [13]. These conditions are corresponded to the maximal values of exergy efficiency.

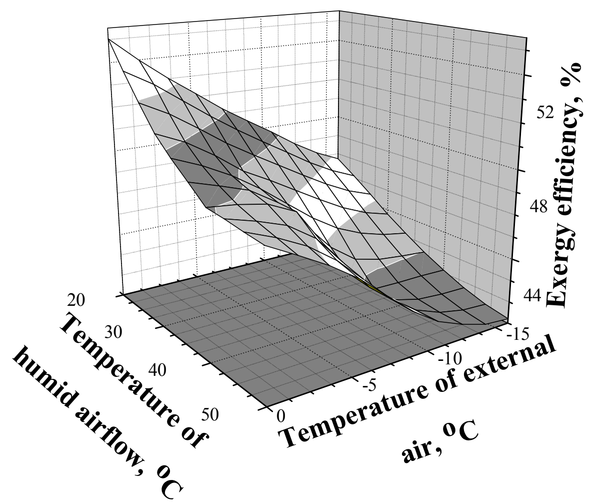
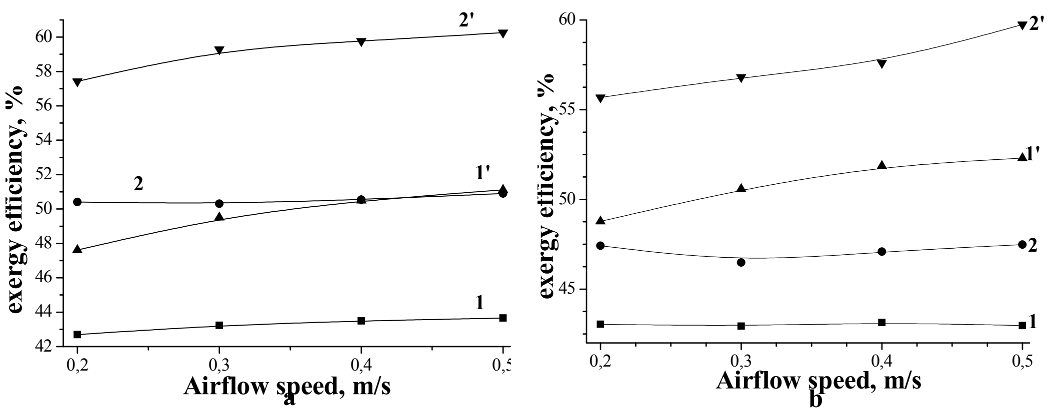


Fig. 4 – Exergy efficiency factor vs. temperatures of humid airflow and external air

Then, ways to improve efficiency of heat storage device were considered. It should be noted that the maximal heat inputs for operating the heat storage units results from desorption and evaporation.

Dependences of exergy efficiency vs. airflow speed for the open-mode adsorptive heat storage device when steam or ultrasound air humidification used are compared in Fig. 5.



a) **b)**

Fig. 5 – Exergy efficiency of open-mode heat storage unit vs. airflow speed. Air humidification: steam (a) and ultrasonic (b). Absolute humidity of air flow 0.03 (1, 1') and 0.04 (2. 2'). Temperature of flow of humid air, ºC: 20(a) and 30 (b)

It should be noted that using ultrasonic humidification results allow to increase exergy efficiency by 7 – 10 % against steam humidification (Fig. 5, curves 1' and 2'). Maximal values of exergy efficiency are stated at airflow speed 0.4 – 0.5 m/s which are corresponded to maximal values of adsorption.

Conclusions. Exergy analysis of the open-mode adsorptive heat storage unit based on composite 'silica gel – sodium sulphate' is performed. The procedure of calculation of exergy efficiency of adsorptive heat has been obtained a further development. The correlation of exergy efficiency and operating mode of adsorptive heat storage unit is shown. The basic factors affecting the exergy efficiency are stated to be initial humidity and temperature of airflow supplied into the adsorbent layer, temperature of external air and methods of air flow humidification. It was stated that exergy efficiency factor strongly depends on initial absolute humidity and temperature of air which supplied to the adsorbent layer. The initial temperatures and absolute humidity of this airflow of 20 – 30ºC and 0.03 – 0.04 kg/m^3 and airflow speed 0.3 – 0.5 m/s are confirmed to be an operational mode which allows to achieve not only maximal efficiency factors but also maximal exergy efficiency.

The exergy efficiencies of adsorptive heat storage unit were compared when steam and ultrasonic humidification were used. Ultrasonic humidification allows to increase exergy efficiency at least by 7 % as compared with steam humidification, maximal exergy efficiency being stated at the absolute humidity and initial temperatures of this airflow of 0.03 – 0.04 kg/m^3 and 20 – 30ºC and airflow speed 0.3 – 0.5 m/s.

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ЕКСЕРГЕТИЧНИЙ АНАЛІЗ АДСОРБЦІЙНОГО ТЕПЛОАКУМУЛЮЮЧОГО МОДУЛЯ ВІДКРИТОГО ТИПУ НА ОСНОВІ КОМПОЗИТНОГО АДСОРБЕНТУ «СИЛІКАГЕЛЬ – КРИСТАЛОГІДРАТ»

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Анотація. *Проведено ексергетичний аналіз адсорбційного теплоакумулюючого модуля відкритого типу, коли в якості адсорбенту використовується композит «силікагель – кристалогідрат». Вирішальними факторами, які впливають на ексергетичний коефіцієнт корисної дії, є температура та початкова вологість потоку повітря, що подається до шару адсорбенту, температура зовнішнього повітря та способи зволоження повітряного потоку. Отримала подальший розвиток процедура розрахунку експлуатаційних характеристик адсорбційного тепло акумулятора відкритого типу. Запропонована процедура включає визначення адсорбції, питомої теплоти адсорбції та кінцевої температури повітряного потоку, корисної* *теплоти, теплових витрат для роботи теплоакумулятора та його коефіцієнт корисної дії, потім розраховують використану ексергію, витрати ексергії та ексергетичний коефіцієнт корисної дії. Показано, що ексергетичний коефіцієнт корисної дії залежить від характеристик потоку вологого повітря, що подається до шару адсорбенту, таких як температура та початкова абсолютна вологість, які впливають на адсорбцію, теплоту адсорбції та кінцеву температуру потоку повітря. Підвищення початкової температури вологого повітря призводить до зниження ексергетичної ефективності. Максимальні значення ексергетичного коефіцієнта корисної дії визначаються при абсолютній вологості та температурах початкового повітряного потоку в межах 0,03 – 0,04 кг/м^3 та 20 – 30ºС відповідно. Ці характеристики відповідають максимальним температурам повітряного потоку після проходження шару адсорбенту, що відповідають санітарним нормам. Показана залежність ексергетичного коефіцієнту корисної дії від температури зовнішнього повітря та початкової температури повітряного потоку. Порівняно ексергетичні коефіцієнти корисної дії відкритого адсорбційного теплоакумулюючого модуля з паровим та ультразвуковим зволоженням. Показано, що ультразвукове зволоження сприяє підвищенню ексергетичного коефіцієнта корисної дії на 7 % проти парового зволоження. Отримані результати можуть бути використані при розробці енергоефективних систем опалення та вентиляції житлових приміщень.*

Ключові слова: адсорбційна трансформація теплової енергії, адсорбційний теплоакумулюючий модуль відкритого типу, ексергетичний коефіцієнт корисної дії, композитний адсорбент, адсорбція.

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