ІННОВАЦІЙНЕ ОБЛАДНАННЯ ХІМІЧНИХ ВИРОБНИЦТВ

УДК 662.995 : 662.997

OPERATING CHARACTERISTICS OF ADSORPTIVE REGENERATOR OF LOW-POTENTIAL HEAT AND MOISTURE BASED ON COMPOSITE SORBENTS 'SILICA GEL – SODIUM SULPHATE' AND 'SILICA GEL – SODIUM ACETATE' SYNTHESIZED BY SOL – GEL METHOD

ЕКСПЛУАТАЦІЙНІ ХАРАКТЕРИСТИКИ АДСОРБЦІЙНОГО РЕГЕНЕРАТОРА НИЗЬКО-ПОТЕНЦІЙНОГО ТЕПЛА ТА ВОЛОГИ НА ОСНОВІ КОМПОЗИТНИХ СОРБЕНТІВ «СИЛІКАГЕЛЬ – НАТРІЙ СУЛЬФАТ» ТА «СИЛІКАГЕЛЬ – НАТРІЙ АЦЕТАТ» СИНТЕЗОВАНИХ ЗОЛЬ – ГЕЛЬ МЕТОДОМ

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The operating characteristics adsorptive regenerator of low-potential heat and moisture based on composite sorbents 'silica gel – sodium sulphate' and 'silica gel – sodium acetate' synthesized by sol – gel method are studied. Sorption heat regenerator operating and environmental test results are shown. Flows switch-over time is observed to depend on airflow rate and temperature differential between warm and cold ends of regenerator in steady-state conditions. Time dependences of absolute and relative humidity on the warm and cold regenerator ends are shown to be of periodic nature when both of sorbent used. Time dependences of temperature are observed to be periodic nature on warm and cold ends of regenerator and between holders with sorbent. Amplitude of time dependences of absolute and relative humidity and temperature for 'silica gel – sodium acetate' are stated to be less than observed when composite 'silica gel – sodium sulphate' used. Correspondence of temperature and humidity time dependences and sorbent sorption capacity is shown. Correlation between heat-regeneration-coefficient-dimensionless temperature differential and moisture-regeneration coefficients-dimensionless humidity differential dependences is approximated with fair accuracy for engineering calculation by linear polynomials of degree 2. Similarity of polynomials described both of dependences is shown to result from close interrelation between heat and mass transfer processes. These coefficients are shown to be capable of task-oriented variation in sufficient wide ranges by changing of half-cycle time, sorbent granules sizes and its amount. The investigation results can be used for development energy-efficient ventilation systems for residential and storage premises.

Досліджені експлуатаційні характеристики адсорбційного регенератора низько-потенційного тепла та вологи на основі композитних сорбентів «силікагель – натрій сульфат» та «силікагель – натрій ацетат», синтезованих золь – гель методом. Показані результати експлуатаційних та натурних тестів. Зареєстровна залежність часу перемикання потоків, витрати повітря та температурного перепаду між гарячим та холодним кінцем регенератора в стаціонарних умовах. Показано періодичний характер часових залежностей абсолютної та відносної вологості при використанні обох сорбентів. Зареєстровані періодичні часові залежності температури на гарячому та холодному кінцях регенератора та між касетами з сорбентом. Встановлені менші значення амплітуд часових залежностей абсолютної та відносної вологості та температури при використанні композиту «силікагель – натрій ацетат» в порівнянні з композитом «силікагель – натрій сульфат». З *достатньою для інженерних розрахунків точністю описано залежність коефіцієнту регенерації тепла від безрозмірного перепаду температур та залежність коефіцієнту регенерації вологи від безрозмірного перепаду абсолютної вологості повітря лінійними багаточленами другого ступеню. Показано, що подібність багаточленів є результатом тісного взаємозв'язку процесів тепло- та масопереносу. Показано можливість цілеспрямовано змінювати вище згадані коефіцієнти в досить широких діапазонах змінюючи час напівциклу, розмір гранул сорбенту та його кількість. Результати дослідження можуть бути використані при розробці енергозберігаючих вентиляційних систем для житлових та складських приміщень.*

Key words: adsorptive heat and moisture regenerator, heat regeneration coefficient.

Ключові слова: адсорбційний регенератор тепла та вологи, коефіцієнт регенерації тепла.

The provision of acceptable thermal and humidity conditions is one of the key tasks of ventilation and conditioning. In the conventional ventilation and air conditioning systems dehumidification achieved through cooling air to temperatures below dew point and then heating it up to comfortable temperatures. Such devices represent a significant energy consumption triggered by substantial demand on fossil fuels and reveal a challenge of energy utilization [1]. The traditional vapor compression machines used for air-conditioning operate on electrically-driven compressor chillers. Their operation causes high energy consumption during the peak load period in the summer. Liquid desiccant evaporation cooling air conditioning systems are based on consequential processes of moisture sorption from air and regeneration of obtained dilute solution [2]. Similar systems based on ammonia – water pair [3] usually consist of solar thermal collectors linked to a sorption chiller, a heat storage tank, the heat driven cooling device, the indoor air cooling system and an auxiliary (backup) subsystem. Despite the fact of providing refrigeration temperature below 0ºC these devices need the driven heat at temperatures up to 160 – 200 ºC [4]. Widening of their commercial application is strongly inhibited by complexity of building in existent residential air-conditioning and ventilation systems.

The easiest solution of this problem is usage of warm air to heat cold incoming air. Regenerative and recuperative heat exchangers are used for this purpose [5, 6]. These devices designed not only for the fossil fuel central heating systems [5] but for solar heating ones that can be exploiting as the support to conventional burning fuel system [6]. However, heat exchangers exploiting does not solve the problems concerned with considerable amounts of moisture in the air-out resulted in ice formation on the cold end of heat exchanger and blocking out its work. As a consequence, moisture balance upset occurs, *i.e.* removed moisture flow exceeds incoming one. These processes result in air humidity decreasing in premise that affects unfavorably on human health.

For air dehumidification silica gel is suggested [7]. However, despite of mathematic modeling results temperature in silica gel bed channel is not exceeded 20ºC that is lower then regeneration temperature of this material. One of promising trends of composite sorbents using is heat and moisture regeneration [8]. Devices based on composite sorbents are promising for sustaining of appropriate air-humidity in ventilated premises [9], that being apt to decrease energy consumption for heating of incoming air.

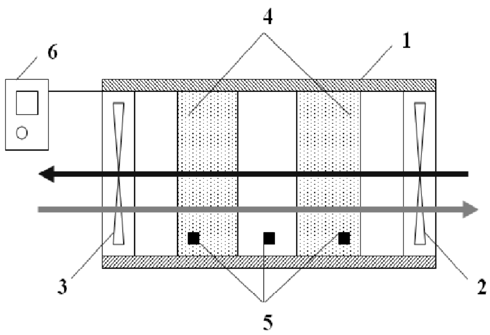


Fig. 1 − Heat regenerator construction: 1 – pipe (case); 2 – external ventilator; 3 – inner ventilator; 4 – heat storage checkerworks; 5 – temperature detector; 6 – operating console

The present paper is devoted to investigation of operating characteristic of sorption heat regenerator for ventilation systems and revealing of dependences of heat and moisture regeneration coefficients vs. temperature and air absolute humidity drops.

Experimental. The device for conditioning of premises (temperature 20 ºC and relative degree of humidity 50 – 60 % according to State Standard of Ukraine B EN 15251:2011) is developed to heat cold affluent air, to decrease its humidity when oxygen concentration kept to be constant. This sorption regenerator is suggested to be stated in ventilation channel. Its construction is shown on Fig. 1.

The basic elementary units of suggested sorption heat regenerator are cylindrical case (pipe) (1), checkerworks (4) fabricated from sorption heat storage material, external (2) and inner (3) ventilators. Length of laboratory prototype of heat regenerator is 0.6 m.

The device exploitative regimes are ‘inflow’ and ‘outflow’ which alternate one to another. When exploited ‘outflow’ regime, air is intaked by ventilator 3 and released into ambient medium. During this process heat storage checkerworks 4 are heated by ‘outflow’ air up to necessary temperature of inner premise. During ‘inflow’ regime ventilator 3 is switched off and ventilator 2 is switched on, ambient air is intaken and got through checkerworks into premise. During passing through the checkerworks air is heated, water excess being sorbed with checkerworks. So, premise airing is realized, temperature and humidity being kept constant.

As heat storage materials composite sorbents ‘silica gel – sodium sulphate’ and ‘silica gel – sodium acetate’ are used. They are synthesized by sol – gel method from tetraethoxysilane, Na_2SO_4 or CH_3COONa, ethanol (as a solvent) and hydrochloric acid (as a catalyst) according to technique described in [10]. Sorption capacities of the used composites are stated to be 0.85 g/g for 'silica gel – sodium sulphate' and 0.42 g/g for 'silica gel – sodium acetate'.

Temperatures of air and sorbents are registered by group thermoelements Pt1000. Meteorological parameters (air speed, air flow direction, temperature, relative degree of humidity, atmospheric pressure) are measured by ultrasonic meteorological station Coastal Environmental Systems C–5 S1019RB.

For investigation laboratory prototype of heat sorption regenerator (Fig. 1) is installed into ventilation channel. The outer end of investigated device is considered to de cold. The end placed in ventilated premise is warm.

To registrate temperature-time curves and to determine equilibrium temperature time on 'inflow' or 'outflow' the air temperature is measured after each of the checkerworks holders when ventilators for air-in 2 or air-out 3 switched on. Temperatures of outer and inner air are 0 ºC and 20 ºC, respectively.

Results and discussion. In order to select an effective operating regime the investigation focused on determination of a time of equalization of temperatures on cold and warm ends of regenerator for 'inflow' and 'outflow' regimes. Temperature dependences of regenerator warm end, air between holders filled with sorbent and regenerator cold end are extreme. The first part of curve (cooling) corresponding to 'inflow' regime proceeds during 30 min. In this interval of time temperature is decreased from 20 ºC to 0 – 2 ºC. The last values are observed to be constant at about 5 min. Then, i.e. in 35 min. after regenerator start, regime is changed from 'inflow' to 'outflow'. It results in temperature rising during 1 – 5 min. upto 18 – 20 ºC. Then temperature is registered to be almost constant during the next 25 – 30 min. So, switching period (Δτ) set to 35 min. is sufficient to both device complete cooling to 0 ºC and heating upto 20 ºC. However, complete cooling and heating are insufficient to air comfort, because prolonged cold air inflow results in decreasing of temperature in the room.

Therefore, in order to air comfort switching period should be changed according to differential temperatures of regenerator warm and cold ends. It will allow to select a convenient regime for each of consumers.

Over the 10 January to 25 February 2015 period test in situ were carry out. Their averaged results are given in Fig. 2. As a comparison design chart is shown (Fig. 2, curve 1), it being calculated according to a formula:

$$\Delta\tau = \frac{cm}{c'_B V} \qquad (1)$$

where c is specific heat per unit mass of sorptive material, J/kg·K; c'_B corresponds to specific heat per unit volume of air, J/m^3·K ; *m* is mass of checkerworks, kg; V is air volume flow rate, m^3/h.

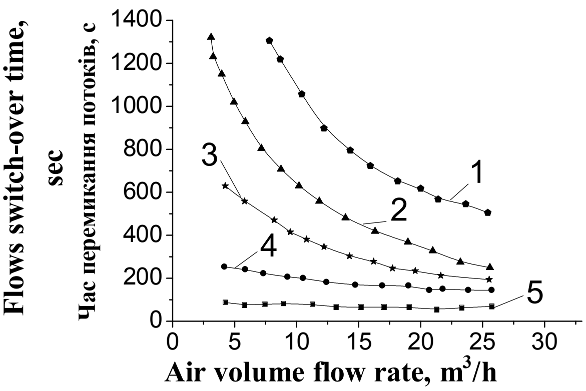


Fig. 2 − Flows switch-over time (Δτ) versus airflow rate graphs: 1 – results calculated by Eq. (1); 2 – ΔT = 10 ºC; 3 – ΔT = 7,5 ºC; 4 – ΔT = 5 ºC; 5 – ΔT = 2,5 ºC

Flows switch-over time is stated to vary with airflow rate and temperature differential ΔT between warm and cold ends of regenerator in steady-state conditions. When temperature differentials ΔT = 5 – 10 ºC and airflow rate increased, flows switch-over time is observed to be decreased (Fig. 2, curves 2 – 4). For ΔT = 2,5 ºC Δτ is slightly related to airflow rate, suggesting that heat front is low-sloped. When temperature differentials increased, flows switch-over time is observed to be increased.

This effect is most appreciable for low speeds. For example, as V =5 m^3/h Δτ is observed to be equal to 80 s for ΔT = 2.5 ºC, Δτ being most nearly eighteen times as much as it for ΔT = 10 ^{0}C. However, when airflow rate raised to 25 m^3/h, this differential is considerably lower, e.g. ΔT = 2,5 ºC corresponds to Δτ = 90 c, and when ΔT increased to 10 ºC, Δτ is 380 c.

When temperature differential increased and much of the sorbent entered a process of heat exchange, flows switch-over time versus airflow rate graph verges to hyperbolic curve calculated by equation (1).

During regenerator testing in addition to flows switch-over time temperature variation, air absolute and relative humidity are measured at the warm and cold ends of the device and between checkerworks holders. Averaged data of testing are given in Figs. 3 – 5. The regenerator is operated in steady-state conditions with constant airflow rate of 30 m^3/hour and temperature differential of ΔT = 10ºC. Each several of given dependences is observed to be of periodic nature, which corresponds to changing of flow direction. Increasing of absolute and relative humidity and air temperature on the regenerator warm end corresponds to airflow directed from room outwards. Decreasing of these values is observed when airflow directed from ambient media into premise. Absolute and relative humidity and air temperature on the regenerator cold end are changed in this manner, but their variation interval is much lesser. The highest amplitude is observed to be on a plot of temperature between holders with checkerworks, it being explained by checkerworks heat and mass exchange complication with sorption and desorption processes.

Dependences corresponded both sorbents occur to be of the same periodic nature. However, when composite 'silica gel – sodium acetate' used (Fig. 3 – 5, b), the amplitude of time dependences of absolute and relative humidities and temperature occur to be less than observed with 'silica gel – sodium sulphate' (Fig. 3 – 5, a). This distinction can be explained by low value of sorption capacity of composite 'silica gel – sodium acetate' as compared to 'silica gel – sodium sulphate'.

Obviously, the most important characteristics are regeneration factors of humidity and heat corresponded to actual quantities of water and heat ratio for their maximal values, respectively.

By analogy with [4], humidity regeneration factor K_W is calculated as ratio surface areas ratio S_{MOPK}/S_{MHPK} (Fig. 3), and heat regeneration factor K_H is evaluated as S_{ACDE}/S_{ABDE} (Fig. 5).

As differentials of inner and ambient air temperatures changed during experiments, heat regeneration coefficient is conveniently expressed in terms of dimensionless temperature differential ΔT_D:

$$\Delta T_Б = \frac{\Delta.T}{\Delta T_{max}} \tag{2}$$

where ΔT is temperature differential, $\Delta T_{\max}$ is maximal temperature differential.

Humidity regeneration coefficient can be expressed in terms of dimensionless absolute humidity differential:

$$\Delta d_Б = \frac{\Delta.d}{\Delta d_{max}} \tag{3}$$

where Δd corresponds to air absolute humidity differential, $\Delta d_{\max}$ is maximum air absolute humidity differential.

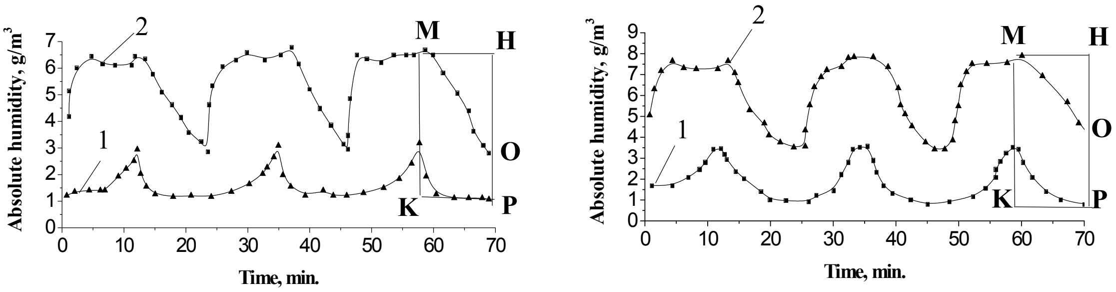
Having analyzed heat and humidity regeneration coefficients as a function of dimensionless differential of heat and absolute humidity, it was stated that all experimental data on heat and humidity regeneration coefficients can be approximated sufficiently for engineering evaluations by a linear polynomials of degree 2. The polynomial for heat regeneration coefficient K_H over the range of dimentionless temperature differential $0 \le \Delta T_D \le 0,35$ is stated to be

$$K_H = 1 - 0,31 \cdot \Delta T_D - 0,13 \cdot \Delta T_D{}^2 \tag{4}$$

The similar polynomial is evaluated for humidity regeneration coefficient K_W on interval $0 \le \Delta d_D \le 0.8$ as

$$K_W = 1 - 0,31 \cdot \Delta d_D - 0,13 \cdot \Delta d_D{}^2 \tag{5}$$

Similarity of equations described dependences K_H vs. ΔT_D and K_W vs. Δd_D and equality their numerical coefficients can indicate close affinity between heat and mass transfer processes. Along with that values of these coefficients are probably related to regenerator construction and nature and quantity of adsorbent.



a b

Fig. 3 − Change of absolute humidity during exploitation of sorption regenerator in the warm end (1) and in the cold end (2) of the device when composite 'silica gel – sodium sulphate' (a) and 'silica gel – sodium acetate' (b) used

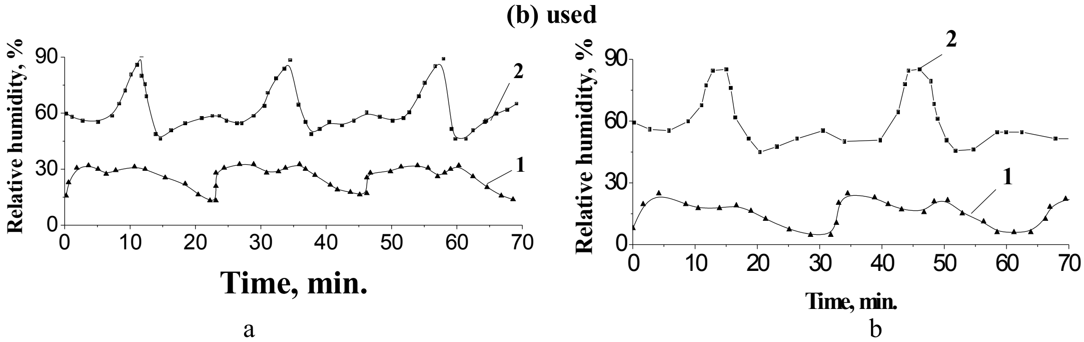


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Fig. 4 − Change of relative humidity during exploitation of sorption regenerator in the warm end (1) and in the cold end (2) of the device when composite 'silica gel – sodium sulphate' (a) and 'silica gel – sodium acetate' (b) used

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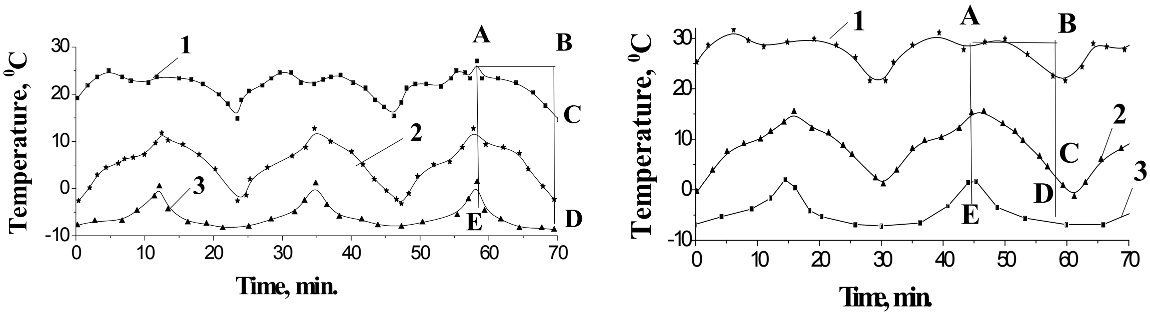

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Fig. 5 − Temperature dependences of the sorption regenerator in the warm end (1), between holders with checkerworks (2) and in the cold end (3) of the device when composite 'silica gel – sodium sulphate' (a) and 'silica gel – sodium acetate' (b) used

Experiments prove that increasing of dispersiveness allows to raise flows switch-over time. However, it results in appreciable growth of hydrodynamic resistance of checkerworks layer ΔP (Fig. 6) and, therefore, increasing of energy consumption for air pumping through checkerworks:

$$W = \frac{V \cdot \Delta P}{\eta} \quad (6)$$

where V corresponds to airflow rate, η is efficiency coefficient.

For example, when η intaken as 0.7, airflow rate set 30 m^3/h, hydrodynamic resistance of checkerworks layer of composite 'silica gel – sodium sulphate' granules in diameter of 2,0 – 2,5 mm is 260 Па, energy consumption for air pumping through checkerworks equals to 3.1 W. When diameter of composite granules increased to 3 – 3,5 mm, hydrodynamic resistance occur to be 100 Pa, and energy consumption goes down to 1.2 W.

In situ testings of described sorption regenerator in situ over the 10 January to 25 February 2015 period revealed ability of supporting convenient temperatures (20 – 22ºC) and relative humidity (50 – 60 %) by this device.

Conclusions. The adsorptive heat regenerators based on composite sorbent 'silica gel – sodium sulphate' and 'silica gel – sodium acetate' synthesized by sol – gel method are studied. It was shown that heat and humidity regeneration coefficient can be changed purposefully in a wide range by variation of flows switch-over time, temperature differential, device construction, diameter and quantity of sorbent granules.

Experimental data on heat and humidity regeneration coefficients vs. dimensionless temperature and humidity differentials can be formulated sufficiently for engineering evaluations by linear polynomials of degree 2:

$$K_H = 1 - 0{,}31 \cdot \Delta T_D - 0{,}13 \cdot \Delta T_D{}^2$$

$$K_W = 1 - 0{,}31 \cdot \Delta d_D - 0{,}13 \cdot \Delta d_D{}^2$$

Close affinity between heat and mass transfer processes is assumed by similarity of both of polynomials.

Hydrodynamic resistance of checkerworks layer of composite 'silica gel – sodium sulphate' increases from 3 to 200 – 500 Pa depending on sorbent granules diameter when airflow rate raised in interval from 5 to 47 m^3/h.

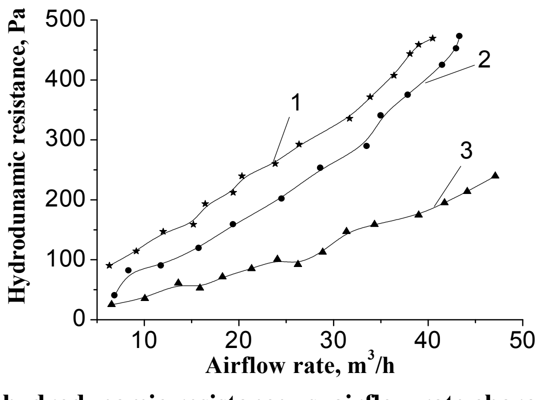

Fig. 6 − Checkerworks layer hydrodynamic resistance vs. airflow rate characteristic when as heat storage material used glass spheres in diameter of 2 mm, composite 'silica gel – sodium sulphate' granules in diameter of 2,0 – 2,5 mm (2) and 3 – 3,5 mm (3)

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УДК 658.28:665.63:338.44

ИСПОЛЬЗОВАНИЕ ЭНЕРГЕТИЧЕСКОГО ПОТЕНЦИАЛА ПРОЦЕССА РЕКТИФИКАЦИИ СМЕСИ ВОДА – УКСУСНАЯ КИСЛОТА
ENERGY POTENCIAL USAGE OF WATER-ACETIC ACID MIXTURE RECTIFICATION PROCESS

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В работе рассмотрен процесс разделение однородной системы (вода – уксусная кислота) с целью сокращения энергозатрат. Для получения максимального энергосберегающего эффекта была проведена как внешняя так и внутренняя интеграция технологического процесса.

Выполнена оценка расхода тепловой энергии ректификационной установки для разделения смеси вода – уксусная кислота производительностью 1,38 кг/с по исходной смеси концентрацией 35% (масс.). Суммарный расход тепловой энергии до модернизации для горячих утилит 3539 кВт, для холодных утилит 3302 кВт.