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Energy efficiency analysis of air dehumidification methods that determine safe microclimatic working conditions

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Introduction. The article deals with the issues related to provision of air humidity parameters required for non-hazardous operation of various technical facilities.

Problem Statement. The paper considers analytical methods for energy efficiency assessment of adsorption and condensation methods of air dehumidification, which provide safe microclimatic working conditions, and the influence of the operating modes of dehumidifying plants on the parameters of the microclimate.

Theoretical Part. As indicators of the energy efficiency of each of the methods, it is proposed to use the energy costs that are minimally necessary for the implementation of ideal physical dehumidification processes and per unit mass of water units emitted from air. This ensures safe and comfortable microclimatic working conditions with minimal energy costs. The ratio of the specific energy costs of the condensation and adsorption methods shows their comparative efficiency. An electronic Id-diagram was used to determine the air parameters in the implemented dehumidification processes (cooling, condensation and adsorption of water vapor).

Conclusion. Analytical dependences are obtained for the analyzed energy efficiency indicators that provide safe and comfortable microclimatic working conditions with minimal energy costs. Numerical estimates were carried out according to the most probable modes of dehumidification processes and air parameters. The parametric restrictions on the implementation of the adsorption dehumidification method are justified, in which it becomes energetically more profitable. The conditions under which it is possible to implement a combined dehumidification method to ensure safe microclimatic working conditions are determined.

Keywords: safe microclimatic working conditions, air dehumidification, moisture content, enthalpy, energy efficiency.

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Introduction. One of the main tasks solved when ensuring the safety of operation of various technical facilities is the compliance with the temperature and humidity (microclimatic) parameters of the air environment outside and inside the facility set by the regulatory documentation [1]. First of all, this applies to the parameters of air humidity inside the object. High humidity refers to harmful production factors and, in certain cases, can cause condensation on various surfaces, the occurrence of metal corrosion [2], damage to electronic elements and other undesirable consequences. In this case, the increased humidity becomes a dangerous production factor. For example, fogging the windows of a vehicle increases the risk of a traffic accident. The appearance of condensate inside tanks and pressure vessels and subsequent corrosion can lead to their explosive destruction. Therefore, the humidity parameters that determine safe working conditions are subject to constant monitoring and control during the operation and storage of technical objects, which also provides integral indicators of their quality and reliability at a sufficient level [3]. Most often, there is an excess of the established humidity parameters inside the operated objects as a result of technological processes, condensation from the air, precipitation, loss of tightness of water supply systems, flooding and other natural and man-made impacts on the object. This makes it necessary to dehumidify the air to solve technological problems and ensure safe microclimatic working conditions in almost all sectors of the country's economy, especially in ventilation systems of various underground structures, "clean zones" of microelectronics enterprises, when storing agricultural products [4–7]. Currently, in order to bring the humidity parameters inside the objects to the normalized values, various dehumidifying installations are used.

Energy efficiency of air treatment processes in air conditioning systems is currently provided by a variety of methods and various measures [8–10], but in practice, the choice of energy-efficient solutions, especially for air dehumidification processes, is very difficult due to the influence of numerous factors. The issues of increasing the energy efficiency of dehumidification processes for various methods and schemes are considered in sufficient detail in [11–14]. However, there are no comparative efficiency estimates for different methods under the same conditions for the implementation of these processes. Therefore, the formulation of energy efficiency criteria and obtaining numerical values for various options for the implementation of air dehumidification processes that determine safe microclimatic working conditions is an urgent scientific task. At the same time, it is necessary to take into account that the most effective industrial dehumidifiers are built on adsorption and condensation methods of air dehumidification [15].

Problem Statement. Let us consider the energy efficiency of the adsorption and condensation methods by determining the minimum necessary energy costs for the implementation of ideal thermodynamic processes of dehumidification of a certain volume of air, the mass of the dry part of which is m = 1 kg. In this case, the same final values of the moisture content are set, determined by the safety requirements, and the initial conditions of the air before dehumidification are the same for both methods.

It should be noted that a significant influence on the efficiency of the process of reducing humidity in the room to ensure safe microclimatic working conditions is not the temperature of the air supplied inside, but its moisture content, i.e. the amount of water vapor per a kilogram of dry air, which follows from the thermodynamic analysis of the processes [14–15]. In addition, the real energy costs in dehumidifiers implementing the methods under consideration may be significantly higher due to losses that inevitably occur in actual processes, in contrast to the ideal thermodynamic processes considered in this study.

The main ideal thermodynamic processes in the adsorption method of dehumidification are the processes of water vapor condensation on the cooling surface of the air cooler when its temperature becomes lower than the dew point temperature of the dehumidified air. The dew point temperature t_p at a known barometric pressure (or compressed air pressure) p is uniquely related to the moisture content of the air in the saturation state $d_н$. This follows from the fact that the moisture content $d_н$, in turn, uniquely depends on the partial pressure of saturated water vapor $p_н$ [14]:

$$d_н = 622 \cdot p_н/(p - p_н). \qquad (1)$$

The dependence of the partial pressure of saturated water vapor $p_н$ on the temperature $p_н = f(t)$ is established according to the tables of the thermodynamic state of moist air. Consequently, when the air is cooled, its temperature reaches the value determined from equation (1), water vapor begins to condense in the air and this temperature is called the dew point temperature. Uncontrolled condensation of water vapor, as already noted, is a dangerous production factor, and the dew point temperature must be reduced. Since the pressure of saturated water vapor $p_н$ decreases with a decrease in temperature, therefore, the lower the dew point temperature of the air, the lower its moisture content. Therefore, to obtain drier air with low moisture content, it is necessary to lower the temperature of the cooling surface.

The energy costs for the implementation of the air cooling process are the main ones for the condensation method of dehumidification, but not the only ones. If the temperature of the cooling surface is less than 0°C, the condensate falling out on it freezes. This requires an additional amount of energy. In addition, with a long duration of the dehumidification process, it is necessary to take into account the energy costs of the air cooler thawing process.

Main physical processes in the adsorption method of dehumidification are the processes of adsorption of water vapor from the air when passing it through special substances — adsorbents. The most common adsorbent in modern dehumidifiers is granular silica gel, which is a material with a high specific surface area (up to 800 m^2/g) and a large amount of sorption holes. This leads to a sufficiently high adsorption capacity of silica gel, which reaches up to 30 % by weight [15]. The process of water vapor adsorption when air is passed through the adsorbent is theoretically carried out without heat supply or removal. In this case, the enthalpy of the air remains constant, which does not require energy costs. However, to restore the absorption capacity of silica gel during the operation of air dryers, it is necessary to periodically regenerate its properties by heating to a temperature of 200–250°C or calcinate at a temperature of 700-800°C [14]. These processes require significant energy costs.

Thus, the main physical processes associated with energy costs in the condensation method of air dehumidification are the processes of air cooling with water vapor condensation, as well as the processes of ice freezing and thawing of icy surfaces of air coolers, if it is necessary to dehumidify the air to negative dew point temperatures. In the adsorption method of air dehumidification, such processes are the processes of desorption of water vapor from adsorbents, carried out by heating or calcining the latter.

To analyze the energy costs in the processes under consideration, we will use the Id diagram of moist air [15].

Theoretical Part. The ideal processes of adsorption dehumidification and cooling of air with the formation of condensate, accompanied by a decrease in moisture content, in the Id diagram have the form shown in Fig. 1 (ВК, AB and BC processes).

Each of the points denoting the initial and final states of the air in the processes under consideration corresponds to certain values of the parameters [14]: temperature t,°C, relative humidity φ,%, moisture content d, g/kg d. a. (grams of water vapor per kilogram of dry air), dew point temperature t, °C, enthalpy (heat content) I, kJ/kg d. a. The initial state of the air (point A in Fig. 1) is set, as a rule, by the temperature t_A and relative humidity φ_A. The remaining parameters are determined using a graphical or electronic Id diagram. The final state of the air after cooling at a constant moisture content before condensation begins (the dew point for the air of state A is point B in Fig. 1), is determined as the intersection point of the line φ = 100 % and the line $d_A = const$.

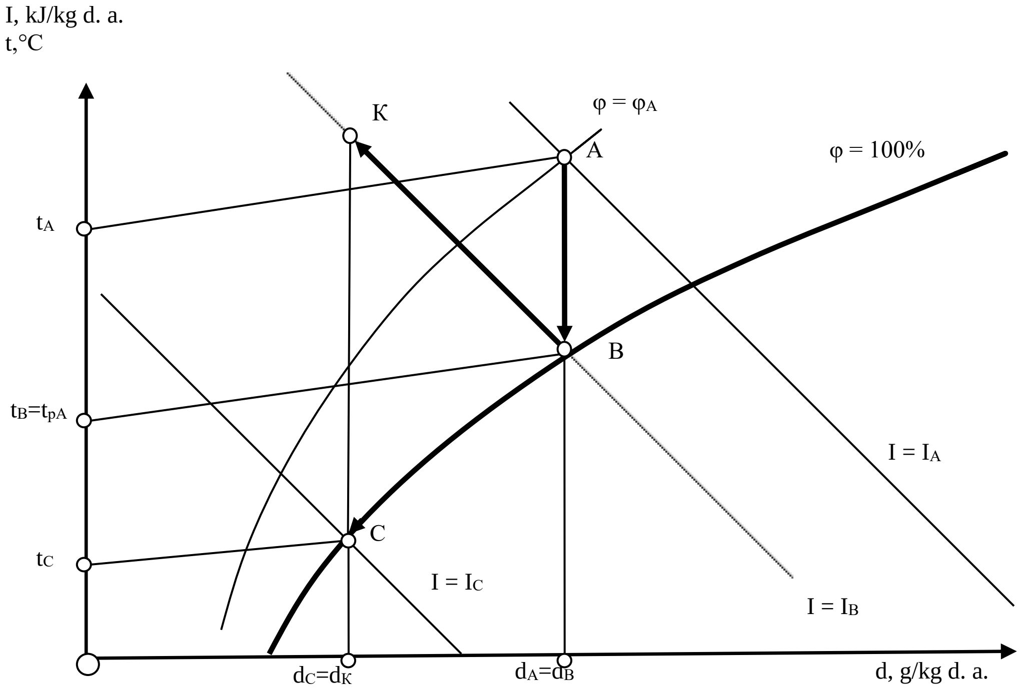

Fig. 1. Processes of condensation and adsorption of water vapor from the air:

AB — air cooling process without vapor condensation;

BC — air cooling process with condensation of water vapor;

ВК — water vapor adsorption process at a constant enthalpy

The process of condensation of water vapor during air cooling begins at point B, passes along the line φ = 100 % and ends at point C, the position of which is determined by the specified final drying temperature t_C (dew point temperature). This dew point temperature corresponds to the line of constant moisture content of the air $d_K = d_C = const$ also at the end point K of the adsorption drying process. The dew point temperature in this case is determined from the need to ensure safe microclimatic working conditions by preventing the occurrence of such a dangerous production factor as condensation. Therefore, the dew point temperature of the air after dehumidification should be lower than the possible temperatures of surfaces where condensation is dangerous.

The position of point K is determined by the intersection of the line of constant enthalpy $I_B = const$ and the line $d_C = const$. For example, Table 1 shows the values of air parameters at the considered points, determined using an electronic Id diagram.

Table 1

Air parameters at characteristic points of processes

Parameter		**Dimension**	**A**	**B**	**C**	**K**
Temperature	t	°C	35	26	–15	77
Rel. humidity	φ	%	60	100	100	≈0
Moisture content	d	g/kg d. a.	21.4	21.4	1.0	1.0
Dew point temperature	t_p	°C	26	26	–15	–15
Enthalpy	I	kJ/kg d. a.	90.4	80.8	–12.6	80.8

The amount of heat Q_x, kJ, removed by the refrigeration unit from the air, for the implementation of the processes of cooling and condensation of water vapor with its subsequent crystallization on the cooling surface, is determined by the formula

$$Q_x = m(I_A - I_C) + \lambda m(d_A - d_C)/1000. \tag{2}$$

where m — the mass of the dry part of the cooled air, kg d. a.; λ — the heat of crystallization condensation, kJ/kg, for water λ = 335 kJ/kg.

In formula (2) and in other formulas where the moisture content d is used, we use the conversion factor "1000", with which the dimension of g/kg d. a. is reduced to the dimension kg/kg d. a.

The minimum energy required for the operation of the compressor of the refrigeration unit $L_к$, kJ, is proportional to the number of air from exhaust heat Q_x and depends on the size of the refrigeration ε_x coefficient defined by the thermodynamic cycle refrigeration system:

$$L_к = Q_x/\varepsilon_x. \tag{3}$$

To ensure the continuity of the dehumidification process, it is necessary to thaw the air coolers. Therefore, to the operation of the compressor, determined by formula (3), it is necessary to add the cost of melting the ice formed in the air coolers $Q_{пл}$, kJ:

$$Q_{пл} = \lambda m(d_A - d_C)/1000. \tag{4}$$

The energy consumption for the BK adsorption process (Fig. 1) at a constant enthalpy is zero. However, the implementation of continuity of the necessary regeneration of the adsorbent, the energy cost of which are determined by the heat $Q_д$, kJ, is required for evaporation of water molecules absorbed by the adsorbent:

$$Q_{д} = rm(d_A - d_C)/1000, \tag{5}$$

where r — the specific heat of evaporation, kJ/kg.

According to the reference data at 200°C specific heat of evaporation r =1940 kJ/kg, at a temperature of 300°C — r =1400 kJ/kg.

To carry out the process of desorption of water from an adsorbent with a dry mass m_a, it is necessary to heat it (for silica gel, usually to a temperature of t_a = 300°C). The energy costs for this process $Q_н$ will be:

$$Q_н = [c_a m_a + c_в m(d_A - d_C)/1000]t_a, \tag{6}$$

where c_a — the heat capacity of the adsorbent, kJ/(kg·K); $c_в$ — the heat capacity of water, kJ/(kg·K).

For silica gel, according to reference data, c_a = 0.92 kJ/(kg·K), for water we accept $c_в$ = 4.2 kJ/(kg·K).

The minimum possible mass of the adsorbent m_a, which must be heated for the desorption process, can be estimated by its adsorption capacity. For silica gel, the adsorption capacity significantly depends on several factors: air flow velocity, pressure, granule structure and size, regeneration temperature, etc. The adsorption capacity shows how much vapor can be absorbed by an adsorbent of a single mass or volume. Higher values correspond to low air flow rates, fine fractions and high regeneration temperatures. We assume a sufficiently high value of the adsorption capacity of silica gel γ = 0.05 (or 5 %) by weight [15]. Then the mass of the adsorbent required for the adsorption of water vapor and their subsequent desorption will be determined by the formula

$$m_a = m(d_A - d_C)/(1000 \cdot \gamma). \tag{7}$$

There are no other costs for this drying method. Then the energy efficiency Э of these two methods can be estimated by dividing the total energy costs of the condensation method by the costs required for the adsorption method:

$$Э = (L_к + Q_{пл})/(Q_д + Q_н). \tag{8}$$

Substituting expressions from formulas (2-7) into this formula, after the transformations we get:

$$Э = \frac{1}{r + (c_в + c_a/\gamma)t_a}\left[\frac{1000(I_A - I_C)}{(d_A - d_C)\varepsilon_x} + \lambda(1 + \frac{1}{\varepsilon_x})\right]. \tag{9}$$

If the Э indicator is greater than one, then the condensation method is worse than the adsorption method in terms of energy costs. If the indicator is less than one, then the condensation method is better. A direct analysis of formula (9) does not allow us to draw an unambiguous conclusion about the energy efficiency of a particular method of air drying, since the value of the proposed indicator Э is determined by a number of parameters, the value of which vary in fairly wide ranges. These include the regeneration temperature of silica gel t_a, its adsorption capacity γ, the cooling coefficient ε_x, the parameters of the air after dehumidification at point C, which are determined from the need to ensure safe microclimatic working conditions. Therefore, we will conduct an analysis of energy efficiency based on the results of calculations, using the approaches of a multifactorial study.

Discussion. Let us perform as an example the calculation of the economic efficiency indicator according to formula (9) using the data given in Table 1.

$$Э = \frac{1}{1400 + (4{,}2 + 0{,}92/0{,}05) \cdot 300}\left[\frac{1000 \cdot (90{,}4 + 12{,}6)}{(21{,}4 - 1{,}0) \cdot 2} + 335 \cdot (1 + \frac{1}{2})\right] = 0{,}37 \cdot$$

The obtained result shows that the energy costs of the adsorption method in this case are 2.7 times higher than the costs of the condensation method. If the cooling coefficient ε_x in formula (9) decreases to 1, the costs of the condensation method will increase, which will lead to an increase in the indicator Э, which will be equal to 0.7. The costs of the adsorption method in this case are also greater than the costs of the condensation method, but only by 40 %. This is due to the large specific energy costs for the regeneration of silica gel (for heating the adsorbent and evaporation of one kilogram of water at normal atmospheric pressure) E_{ya}, kJ/kg. In formula (9), these costs are reflected by the denominator of the first multiplier of the right part. We will analyze the dependence of these specific energy costs on the regeneration temperature t_a and the adsorption capacity γ of silica gel.

$$E_{ya} = r + (c_в + c_a/\gamma)t_a. \qquad (10)$$

For the above data, the specific energy costs will be equal to

$$E_{ya} = 1400 + (4{,}2 + 0{,}92/0{,}05)300 = 8180 \text{ kJ/kg}.$$

A change in the regeneration temperature t_a leads to a nonlinear change in energy costs, since the evaporation heat r changes simultaneously. Graphs of changes in the specific energy costs for regeneration when the regeneration temperature changes from 100 to 400°C at different values of the adsorption capacity of silica gel are shown in Fig. 2.

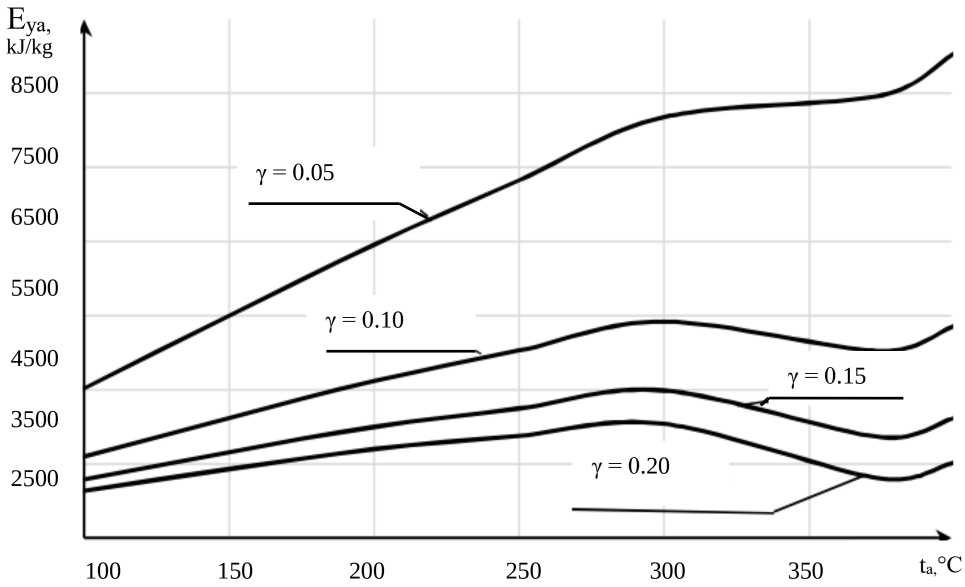

Fig. 2. Dependence of specific energy costs on temperature

As it can be seen from the above graphs, an increase in the silica gel regeneration temperature above 375°C is impractical from the point of view of energy costs. The local minimum of specific energy costs in this area is explained by the fact that at a temperature of 374.15°C, the heat of evaporation becomes equal to 0 due to the water reaching a critical state.

More significant for reducing energy costs is an increase in the adsorption capacity of silica gel γ. The calculations used the value $\gamma = 0.05$, which corresponds to the average value of the flow or dynamic adsorption capacity of silica gel [15]. If the calculations use the values of the static or equilibrium adsorption capacity of silica gel on water, which are determined by the value of the maximum possible amount of moisture absorbed by a unit of mass (or volume) of the adsorbent under static or equilibrium dynamic conditions, then the specific energy costs will be significantly lower. Thus, at $\gamma = 0.1$ and the regeneration temperature $t_a = 300$°C, the value $E_{ya} = 5420$ kJ/kg.

The results of calculations of the specific energy costs E_{ya} at different regeneration temperatures and the adsorption capacity of silica gel are shown in Table 2.

Table 2

Energy costs of the E_{ya} adsorption method, kJ/kg

Regeneration temperature	Vaporization heat	γ = 0.05	γ = 0.10	γ = 0.15	γ = 0.20
t_a, ^{0}C	r, kJ/kg				
100	2256	4520	3600	3290	3140
150	2112	5500	4120	3660	3432
200	1941	6460	4620	4000	3700
250	1675	7330	5030	4250	3880
300	1404	8180	5420	4490	4040
375	0	8475	5025	3860	3300
400	0	9040	5360	4120	3520

Similarly, we will analyze the specific energy costs for the condensation method of drying $E_{ук}$, kJ/kg, the value of which is determined by the expression in square brackets in formula (9):

$$E_{ук} = \frac{1000(I_A - I_C)}{(d_A - d_C)\varepsilon_x} + \lambda\left(1 + \frac{1}{\varepsilon_x}\right). \qquad (11)$$

For the air parameters given in Table 1, $E_{ук}$ value will be equal to:

$$E_{ук} = \frac{1000\cdot(90{,}4 + 12{,}6)}{(21{,}4 - 1{,}0)\cdot 2} + 335\cdot\left(1 + \frac{1}{2}\right) = 3030 \text{ kJ/kg.}$$

This value shows the minimum required energy costs for "removing" 1 kg of water vapor from the air. As it can be seen, the obtained value is less than all the values given in Table 2. Therefore, it can be concluded that the condensation method is more efficient in terms of energy costs than the adsorption drying method. However, to confirm this conclusion, it is necessary to analyze how the specific energy costs $E_{ук}$ change when the initial and final states of the air change during the dehumidification process. These states on the Id diagram correspond to points A and C (Fig. 1). The position of point A is set by two parameters (for example, temperature and relative humidity). The position of point C is determined by one parameter (usually the dew point temperature). The position of this point is determined based on the need to ensure safe microclimatic working conditions. Initially, we will analyze the influence of the first two parameters on the value $E_{ук}$, i.e. we will assume the temperature of point C to be equal to – 15°C.

The range of air temperature changes is from 10 to 50°C, relative humidity — from 30 to 90 %. An electronic Id diagram was used to determine the air parameters at point A (moisture content and enthalpy). The results obtained are summarized in Table 3. The desired values of the specific energy costs of the condensation method are also given there, determined by formula (11).

The analysis of the results obtained, given in Tables 2 and 3, shows that under certain conditions, air dehumidification by the adsorption method becomes energetically more profitable than the condensation method. It should be noted here that the data in Table 2 are determined by the modes of regeneration of the adsorbent and, therefore, can be selected or assigned based on the technological and design features of the implementation of this method. For example, increasing the energy efficiency of the adsorption method at low temperatures of adsorbent regeneration is in contradiction with the need to reduce the duration of this process.

Table 3

Energy costs of the condensation method $E_{ук}$, kJ/kg

Air temperature t_A, ^{0}C	Parameters	φ = 30 %	φ = 50 %	φ = 70 %	φ = 90 %
20	d_A, g/kg d. a.	4.3	7.3	10.2	13.2
	I_A, kJ/kg d. a.	31.2	38.6	46.1	53.7
	$E_{ук}$, kJ/kg	7140	4570	3690	3220
30	d_A, g/kg d. a.	7.9	13.3	18.8	24.4
	I_A, kJ/kg d. a.	50.6	64.3	78.4	92.6
	$E_{ук}$, kJ/kg	4580	3630	3060	2750
40	d_A, g/kg d. a.	13.9	23.5	33.4	43.6
	I_A, kJ/kg d. a.	76.2	101.0	126.5	152.8
	$E_{ук}$, kJ/kg	3940	3030	2650	2440
50	d_A, g/kg d. a.	23.6	40.3	58.0	76.6
	I_A, kJ/kg d. a.	111.7	155.1	200.9	249.1
	$E_{ук}$, kJ/kg	3250	2640	2370	2230

High values of the adsorption capacity are achieved only with prolonged contact of the adsorbent with the dehumidified air, which leads to low performance of dehumidifiers through the air. Therefore, taking into account these restrictions, the value E_{ya} = 4600 kJ/kg can be chosen as the maximum (minimum) value of the specific energy costs of the condensation method. In Table 2, this mode is indicated in green.

The data in Table 3 are determined by the initial parameters of the air before the drying process, which, in the case of using outdoor air, are determined by climatic and weather conditions. In the case of using indoor air they are determined by the parameters of the indoor air. As you can see, only one value of specific energy costs, highlighted in yellow, exceeds the value selected for comparison from Table 2. This value corresponds to low relative humidity and temperature. This fact is explained by the fact that in this case a significant part of the energy is spent on cooling the air without condensation of water vapor. In Fig. 1, this process is depicted by the segment AB.

Next, we will consider the influence of the dew point temperature at the beginning and end of the drying process on the energy efficiency of the condensation method. To exclude the influence of energy losses on the implementation of the air cooling process without condensation, we will assume that the air has a relative humidity of φ = 100% before drying. Table 4 shows the calculation results. The analysis of the obtained data shows that an increase in the degree of air drying, characterized by the dew point temperature at the outlet of the dryer, leads to an increase in specific energy costs. Consequently, to ensure more stringent requirements for the safety of microclimatic working conditions, large energy costs are necessary. When dehumidifying air that already has a low dew point temperature (less than 5°C), the use of the condensation drying method becomes energetically less profitable than the adsorption method, if the specific energy costs for the regeneration of silica gel equal to 4600 kJ/kg are used for comparison (Table 2). In Table 4, specific energy costs not exceeding 4600 kJ/kg are highlighted in green.

Table 4

Energy costs E_y, kJ/kg, at different degrees of drying

	Parameters		t_{pA} = 0°C	t_{pA} = 5°C	t_{pA} = 10°C	t_{pA} = 15°C
t_{pC},°C	d_A, g/kg d. a.		3.8	5.4	7.6	10.6
	I_A, kJ/kg d. a.		9.4	18.6	29.3	42.1
–10	d_C, g/kg d. a.	1.6	4030	3750	3450	3180
	I_C, kJ/kg d. a.	–6.1				
–15	d_C, g/kg d. a.	1.0	4430	4050	3680	3350
	I_C, kJ/kg d. a.	–12.6				
–20	d_C, g/kg d. a.	0.6	4880	4380	3920	3540
	I_C, kJ/kg d. a.	–18.6				
–25	d_C, g/kg d. a.	0.4	5460	4790	4220	3760
	I_C, kJ/kg d. a.	–24.3				

Conclusion. The considered results of the study show that the condensation method exceeds the adsorption method of air dehumidification in most calculated cases (sometimes several times) in terms of energy costs, while ensuring safe microclimatic working conditions. However, if deep dehumidification is necessary, there is already enough dry air with a dew point temperature at the entrance to the dehumidifier less than 5°C. In this case, adsorption dehumidifiers become more energetically advantageous. This allows us to conclude that when constructing combined dehumidification methods, it is initially advisable to use a condensation dehumidification method to a dew point temperature of 5°C, and then an adsorption method — to the required dew point temperature, which determines safe microclimatic working conditions indoors.

If it is necessary to obtain not only dry, but also air cooled to low temperatures, which prevents the appearance of dangerous production factors associated with an unacceptable temperature increase (for example, in refrigerating units of freezers, refrigerated trucks, cooling systems of special structures, etc.), the condensation method is energetically the most profitable.

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V. V. Deryushev — statement of the problem, development of the concept of the article. E. E. Kosenko — description of the results and formulation of the conclusions of the research; V. V. Kosenko — critical analysis of the literature; M. A. Krivchuk — tabular representation of the results; I. V. Deryushev — collection of statistical data; A. S. Timofeev — graphical representation of the results.