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INCREASE OF AGRICULTURAL PRODUCTS STORAGE EFFICIENCY BY OPTIMIZATION OF VENTILATION SYSTEMS OPERATION MODES

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ABSTRACT
A thermodynamic approach to the calculation of ventilation systems operating time in storage facilities of juicy vegetable raw materials basing on the humidity potential theory is suggested. Results of theoretical and experimental studies of the dynamics of heat and mass transfer processes in a layer of stored products are shown. Improving of agricultural products preservation is achieved by optimization of ventilation systems operation modes.

Keywords: ventilating system, humidity potential, microclimate, juicy vegetable raw materials.

INTRODUCTION
Juicy vegetable raw materials, as an object of storage, is characterized as biological heat and moisture generating substances. Changes in temperature and relative humidity within a layer causes significant deviation from the recommended microclimate norms, causing product wilting or sweating. Therefore, design and operation of microclimate control systems in the agricultural products storage facilities should take into account the dynamics of the processes of heat and mass transfer in a product layer [1- 5]. Investigation of the heat-and-moisture exchange laws should be based on the most general thermodynamic approach allowing to abandon wasting time on analyzing of particular patterns [6- 9].

Plant raw material is the capillary-porous colloidal material. Liquid moisture and vapor movement in materials is caused by action of diffusion-osmotic and capillary forces.

Presence of free moisture in the plant material determines its physiological activity (life-sustaining activity). Out of all the biochemical processes, occurring in grass and grain, respiration is of particular important - oxidation of organic substances. The reaction undergo in accordance with the known equation [10]:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Theoretical amount of heat generated in an oxidation process is approximately 2870 kJ on 1 gMole. The actual amount of the generated heat, that is intensity of respiration, depends on the humidity and temperature of the raw material.

MATERIALS AND METHODS
The most complete calculation of the intensity of the interrelated heat and mass transfer is based on the theory of moisture content (humidity) potential, allowing taking into account the effect of various force factors on moisture, both in liquid and in vapor state [11-13].

The specific moisture flow i, kg/(m^2·h), in the material is proportional to the gradient of moisture content potential

$$i = \chi \nabla \theta, \qquad (1)$$

where
χ = moisture conductivity, kg/(m·h·°B);
$\nabla\theta$ = humidity potential gradient, °B/m.

By analogy with other physical phenomena, the flow of moisture from the surface of the wet material is proportional to the humidity potential gradient [12]:

$$j_\theta = \alpha_\theta (\theta_{surf} - \theta_a), \qquad (2)$$

where
θ_{surf} = humidity potential of the material surface, °B;
θ_a = humidity potential of the purge air, °B;
α_θ =coefficient of the moisture transfer, kg/(kg·h·°B)

Value of air humidity potential can be determined analytically from the proposed dependences [14, 15]:

$$p_v = a_{t1} \cdot \left(1 - e^{-b_{t1} \cdot \theta}\right), \text{ at } 0 \le t \le 5\,^0\text{C and } 65\% < \varphi \le 100\% \qquad (3)$$

$$p_v = a_{t2} + b_{t2} \cdot r_t^{\,\theta}, \text{ at } t > 5\,^0\text{C and } 65\% < \varphi \le 100\% \qquad (4)$$

$$p_v = 0{,}023 + 0{,}017 \cdot \theta^{1{,}34}; \text{ at } p_v \le 0{,}4\,\text{kPa and } \varphi < 65\% \qquad (5)$$

$$p_v = 4{,}15 \cdot \ln(0{,}46 \cdot \ln(\theta)); \text{ at } p_v > 0{,}4\,\text{kPa and } \varphi < 65\% \qquad (6)$$

where a_{t1}, b_{t1}, a_{t2}, b_{t2}, r_t – temperature coefficients;

p_v = vapor pressure, Pa;
φ = air relative humidity.

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RESULTS AND DISCUSSIONS

To obtain a mathematical expression describing the coefficient values a_{t1}, b_{t1}, a_{t2}, b_{t2}, r_t, graphs of them where drawn up and are presented on Figures 1-5.

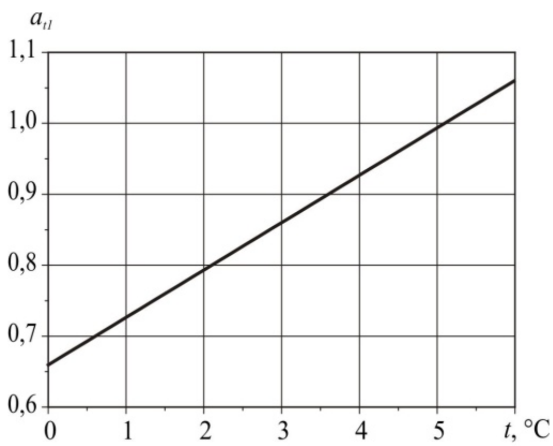

Figure-1. Dependence of coefficient a_{t1} on air temperature.

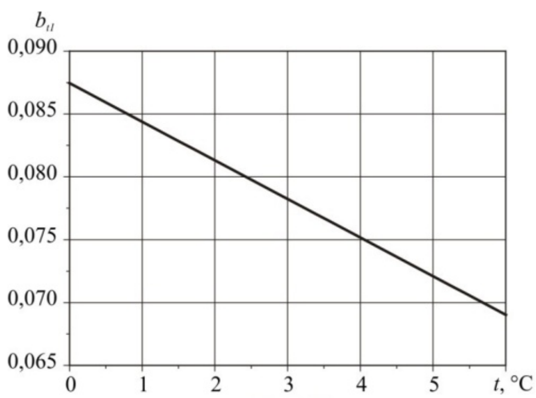

Figure-2. Dependence of coefficient b_{t1} on air temperature.

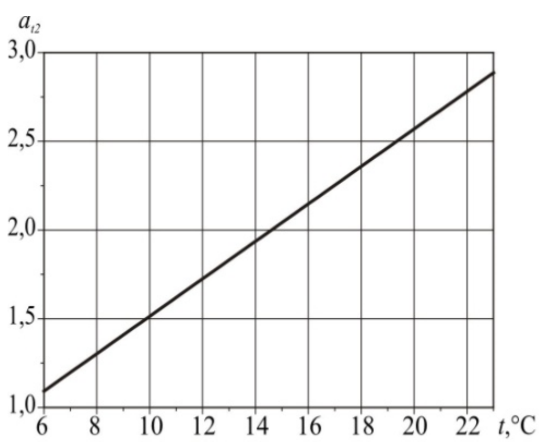

Figure-3. Dependence of coefficient a_{t2} on air on air temperature.

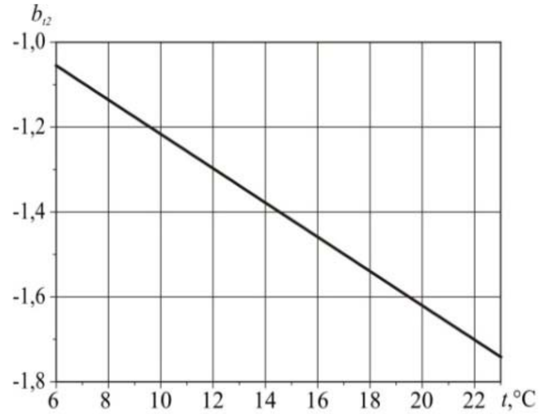

Figure-4. Dependence of coefficient b_{t2} on air b_{t1} on air temperature.

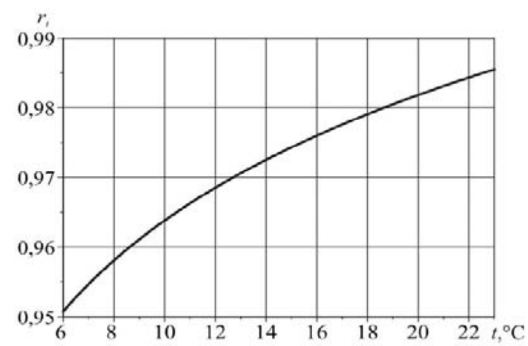

Figure-5. Dependence of coefficient r_t on air temperature.

Approximation of the curves results:

$$a_{t1} = 0{,}66 + 0{,}067 \cdot t; \tag{7}$$

$$b_{t1} = 0{,}088 - 0{,}0033 \cdot t; \tag{8}$$

$$a_{t2} = 0{,}46 + 0{,}11 \cdot t; \tag{9}$$

$$b_{t2} = -0{,}81 - 0{,}04 \cdot t; \tag{10}$$

$$r_t = 0{,}91 \cdot t^{0{,}027}. \tag{11}$$

Basing of the received dependences, lines of constant potentials where drawn-up θ = const and plotted on the *I*–*d*-diagram (Figure-6).

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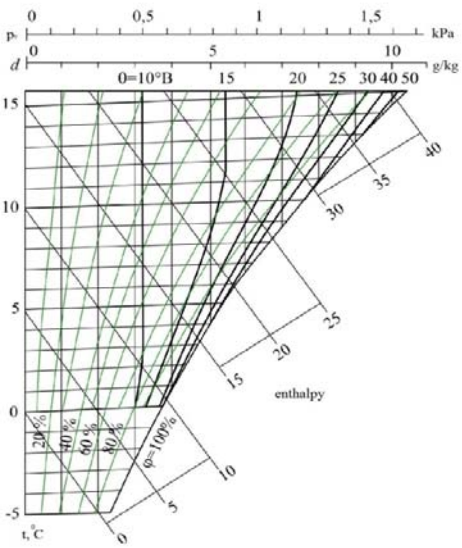

Figure-6. Refined *I–d–θ*- diagram at low positive temperatures.

Transfer of visible and latent heat between the blown air and products takes place in the same direction - that is the main feature of heat and mass transfer in a bulk of juicy plant raw material [16].

The change of heat and humidity characteristics of the blown air (presented on *I-d-θ* - diagram) is shown in Figure-7. The air blown to the bulk, passes through an adjustment layer in which it is humidified to equilibrium values and, at the same time, is heated to the temperature of the bottom part of the main layer (process *AB*), at that the evaporating moisture helps to reduce the temperature of the products. The moisture content potential θ_A at the entrance to the raw material layer is determined by the air parameters blown-in into the storage area. Section *BC* characterizes the process of the blown air parameters changing in the main layer, which is equidistant to the corresponding section of the full saturation φ = 100 %. Humidity potential on the stored plant matter surface depends on the moisture sweated due to breathing in the storage area. Air is removed from the bulk, with parameters corresponding to point *C* (t_C, φ_C, θ_C, d_C). When ventilation in the storage area is off, the temperature of the product in the upper layer may be lower than the temperature inside the main layer, causing air cooling and possible moisture condensation on the raw material surface (processes CD, CD_1).

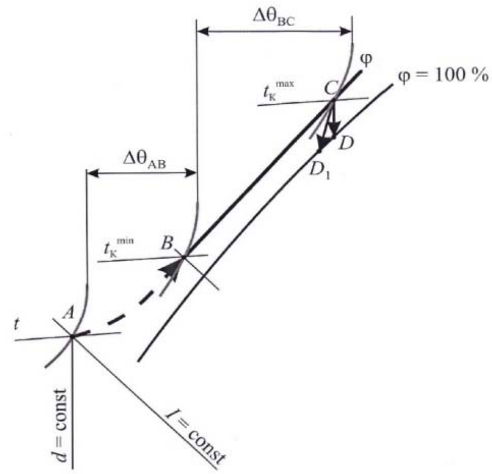

Figure-7. Changing of air parameters blown into the bulk of juicy vegetable raw materials. A,B,C - characteristic points, t-air temperature; t_k^{min} and t_k^{max} - minimum and maximum temperature in the layer.

According to the theory of moisture content potential, moisture-flow W, g/h, from the bulk of juicy plant raw material mass (G_{mat}, t), to the purge air (the process *AC* Figure-7) is equal to:

$$W = \alpha_\theta (\theta_C - \theta_A) G_{mat}, \quad (12)$$

where θ_A, θ_C - initial and final humidity potential in the layer of products during storage, °B; α_θ - moisture ratio, g/(t·h·°B).

For assessment of humidity potential dynamic changes in a layer of the stored products, full-scale research was conducted in potato-storage house. 24 containers with potatoes were selected in the middle of the storage house. Measurements of temperature and humidity were taken in distinctive zones of the selected containers and storage-house, at mid-height of the container. Measurements of temperature and humidity were taken in 36 points. Measurements were taken every fortnight, during the main months of storage (November - January). Based on the measurements results and the updated *I-d-θ*-diagram, the fields of humidity potentials were drawn-up for each day of the measurements (Figure-8).

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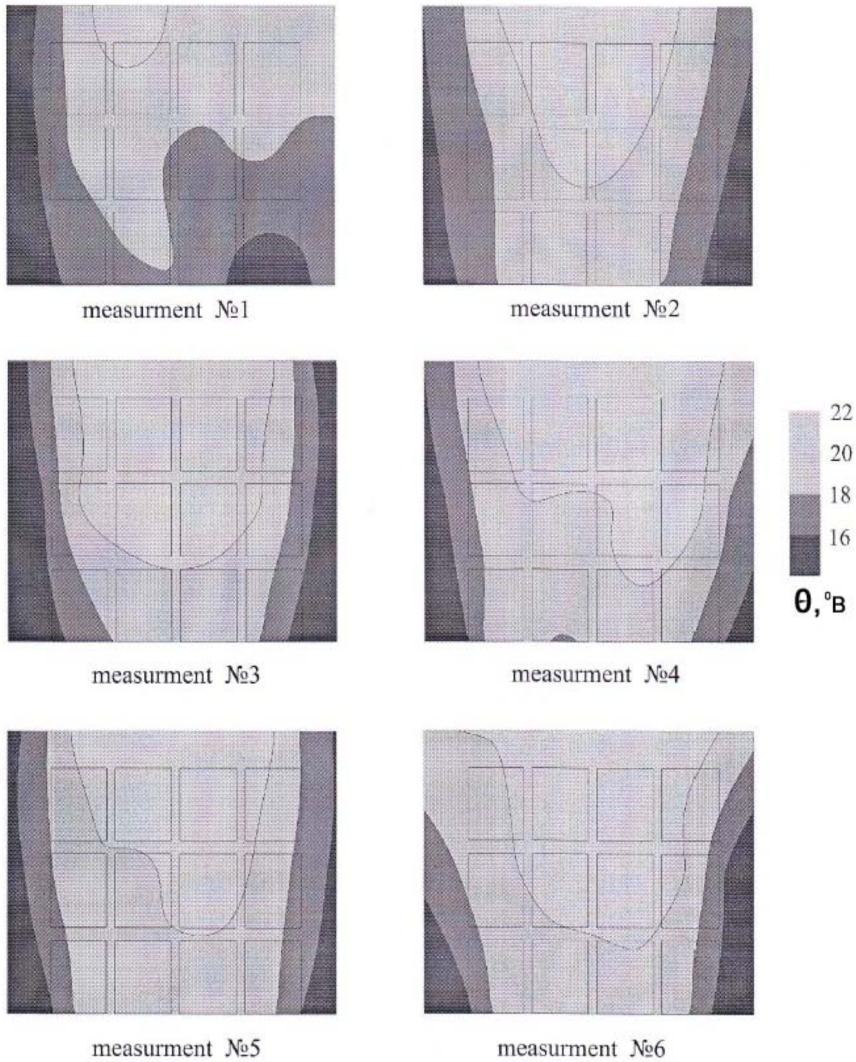

Figure-8. Humidity potential fields in the storage-house.

The uniform character of the fields of humidity potentials, justify the application of the humidity potential concept and *I*-*d*-θ-diagram for runtime of ventilation systems. The humidity potential values θ within the storage house vary from 14, 0 to 21, 9 °B, depending on the geometrical arrangement of the containers. Uniform gradient of the humidity potential was observed height-wise of the stack [17].

Observed dynamics of the humidity potential fields change allow to consider the stack of juicy plant raw material as a bulk with evenly distributed sources of heat and moisture over the volume.

Based on the obtained humidity potential fields, graph of humidity potential variation height-wise was plotted (Figure-9). As a result of approximation, dependence characterizing the humidity potential, ^{0}B, on the layer's height:

$$\theta = \frac{h + 9{,}37}{0{,}59}, \tag{13}$$

where *h* - product layer's height, m.

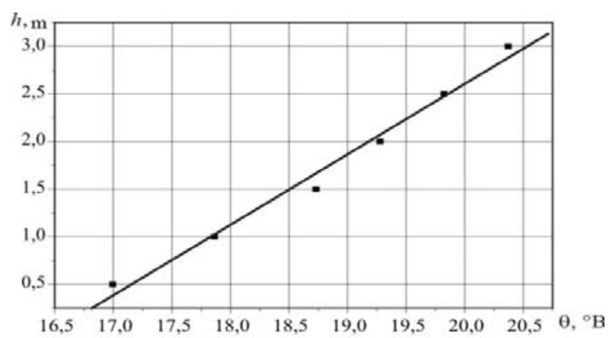

Figure-9. Humidity potential dynamic changes depending on a layer's height.

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Basing on the definition of the moisture flow from the standpoint of the theory of the humidity potential, mass transfer coefficientα_θ, g/(t·h··^{0}B), is calculated as:

$$\alpha_\theta = \frac{g_s(d_e - d_i)}{\theta_e - \theta_i}, \qquad (14)$$

Where

θ_i = initial humidity potential of the air blown into the storage, °B;

θ_e = humidity potential of the exhaust air, °B;

g_s = specific airflow, kg/(h·t);

d_i, d_e = the moisture content of the supply and exhaust air, g/kg.

Basing revised *I-d*-θ-diagram, graphically presented dependence of mass transfer coefficient α_θ via temperature and specific air flow rate was obtained (Figure-10).

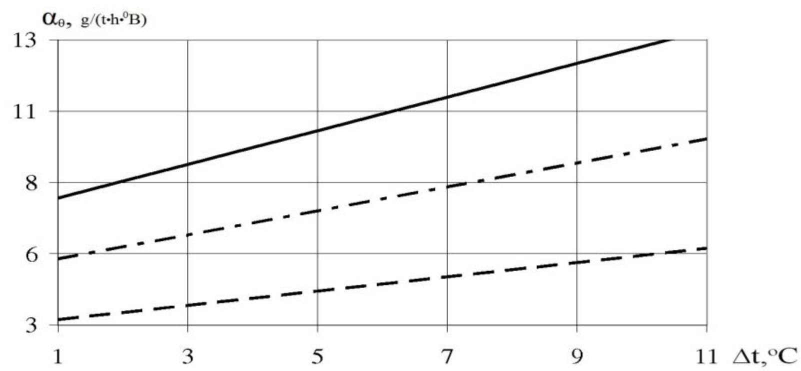

Figure-10. The values of the coefficient α_θ in a layer of juicy vegetable raw materials, depending on the specific consumption of purge air:
– – – – at 10 < g_s < 20; — — — – at 20 < g_s < 30; —— – at 30 < g_s < 40

For the analytical assessment of the mass transfer coefficientα_θ, with sufficient for engineering calculations accuracy, the following expression is proposed to use:

at 10 <g_s<20: $$\alpha_\theta = 0{,}25 \cdot \Delta t + 2{,}94; \qquad (15)$$

at 20<g_s<30: $$\alpha_\theta = 0{,}42 \cdot \Delta t + 4{,}9; \qquad (16)$$

at 30<g_s<40: $$\alpha_\theta = 0{,}59 \cdot \Delta t + 6{,}86, \qquad (17)$$

where Δt - temperature difference of the exhaust and supply air, °C.

At present, the existing engineering assessment of the microclimate of juicy vegetable raw materials storage in bulk is limited only to temperature regime assessment [3].

To achieve maximum product preservation, ensuring the required microclimate parameters the system should operate during a day:

$$K^{\theta}_{t.vent} = \frac{W}{\alpha_\theta(\theta_e - \theta_i)G_{mat}}, \qquad (18)$$

where $K^{\theta}_{\mathrm{t.vent}}$ – is the coefficient characterizing the time of ventilation system running during the day, depending on the humidity of a bulk; W - specific moisture generating by products, g/h.

CONCLUSIONS

a) Description of the heat and mass transfer processes from the standpoint of the theory of the humidity potential, allows evaluating the thermodynamic performance of the systems qualitatively and quantitatively, assuring the appropriate storage microclimate of biologically active products.
b) Engineering method developed for calculating the operating time of ventilation systems based on the use of the *I–d*–θ-diagram allows to improve the quality of the design and operation of the systems providing the required parameters of the microclimate during storing.
c) Optimization of a ventilation system operation mode in storage of agricultural products taking into account the dynamics of the heat and mass transfer processes in a product's layer allows reducing energy consumption and increasing the products preservation.

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