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Mathematical model of the drying process of Capillary-porous materials particles in the apparatus with a suspended-swirled flow of heat - carrying medium

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Abstract
Mathematical model of the drying process for particles of capillary-porous materials in the apparatus with a suspended-swirled flow of heat-carrying medium and its numerical solution with the help of Euler's method was presented in this article. The sequence of the problem solution was developed by the authors. The movement path of the particle of the capillary-porous material in the vortex chamber during the drying process, the change in the mass and temperature of the particle on time, the change in the relative air velocity and the heat transfer coefficient on time are represented graphically in the paper.

Keywords: model, process, drying, heat-carrying medium

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INTRODUCTION

Formulation of the Problem

The drying chamber consists of a vertical conical-cylindrical drying chamber 1, a branch pipe for supplying the drying agent main flow 2, a branch pipe for tangential supply of drying agent additional flow 3, the material feed pipe 4, windows for dried material unloading 5.

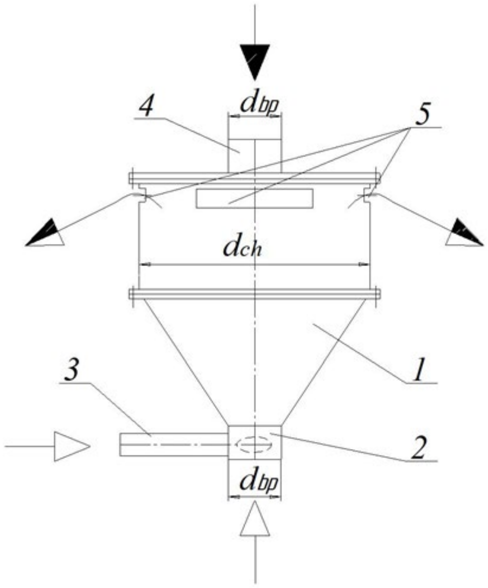

Fig. 1. Scheme of material flows movement in chamber. 1 - drying chamber; 2, 3, 4 - branch pipes for drying agent and material respectively; 5- unloading windows for the drying agent and material dried particles

The drying agent enters the chamber 1 (**Fig. 1**) through the lower branch pipe 2. A part of the flow is fed through the tangential inlet 3 to swirl the flow.

The wet material is continuously fed through the upper branch pipe 4 into the apparatus housing, where it is evenly distributed. The largest particles pass through the chamber and are withdrawn from it through the lower branch pipe 2. Lighter particles circulate in the chamber for a while, their mass decreases due to evaporation of moisture. After reducing the particles mass to a value at which the latter are carried upward the particles leave the apparatus through the windows 5 in the upper part of the housing. Let us consider the processes that occur when a particle moves in the vortex chamber.

Let us make a number of assumptions:

1. The air temperature and the partial pressure of the vapor are the same throughout the drying chamber space;
2. The temperature field in the particle is homogeneous;
3. Thermophysical parameters of air and particles are constant;
4. The vapor pressure at the particle surface corresponds to the equilibrium particle temperature.

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The Initial Equations

Gas velocities field in the apparatus

Determination of the velocities field in apparatus with complex geometry and turbulent flow is a complex hydrodynamic problem. On the basis of theoretical and experimental studies (Mushtaev and Ulyanov 1998), the following equations for calculating gas velocities field in the apparatus were proposed:

$$V_\phi = \left(\hat{r}e^{1-\hat{r}}\right)^k \cdot V_{\varphi m} \quad (1)$$

$$V_r = 2\alpha^2\left(\hat{r}e^{1-\hat{r}}\right)^k[(1+k-k\hat{r})^2 - kr] \cdot V_{\varphi m} \quad (2)$$

$$V_z = \left[-\frac{2\alpha^2}{\hat{r}}(\hat{r}e^{1-\hat{r}})^k((1+k-k\hat{r})^3 - 3k\hat{r}(1+k-k\hat{r}) - k\hat{r})\right] \cdot \xi \cdot V_{\varphi m} + c \quad (3)$$

where V_φ, V_r, V_z are tangential, radial and axial component of the velocity vector of the drying agent;

$\hat{r} = \frac{r}{r_{\varphi m}}$ is the dimensionless current radius;

$r_{\varphi m}$ is the radius corresponding to the maximum tangential speed of the drying agent (coincides with the radius of the branch pipe of the tangential inlet of the agent);

k is the indicator characterizing the structure of the swirled flow of drying agent;

α is the indicator characterizing the turbulent structure of the agent flow;

$V_{\varphi m}$ is the maximum radial velocity at the point of tangential inlet in the drying agent flow;

$\xi = \frac{L}{r_{\varphi m}}$ is the dimensionless chamber length;

L is the chamber length;

c is the parameter characterizing the average axial flow velocity of the drying agent.

$$k = \frac{\hat{r}^2_{fc} + 3\hat{r}^{5/3}_{fc} + 3}{\hat{r}^2_{fc} + 3\hat{r}^{5/3}_{fc} - 3} \quad (4)$$

where $\hat{r}_{fc} = \frac{\hat{r}_{fc}}{\hat{r}_{\varphi m}}$ is the dimensionless radius of the drying agent flow core.

Particle movement equations

Determination of the velocities field in apparatus with complex geometry and turbulent flow is a complex hydrodynamic problem. On the basis of theoretical and experimental studies (Mushtaev and Ulyanov 1998), the following equations for calculating gas velocities field in the apparatus were proposed:

Particle movement in the vortex chamber is recorded on the basis of Newton's 2nd law:

$$\frac{d(m\vec{v})}{d\tau} = F_1 + F_2 + F_3 + F_4 + F_5 \quad (5)$$

where $\vec{F}_1 = m\vec{g}$ is the particle gravity;

$\vec{F}_2 = \xi S_{ms}\rho_g\left|\vec{V} - \vec{U}\right|\frac{(\vec{V}-\vec{U})^2}{2}$ is the hydrodynamic resistance force of the particle;

$W = \vec{V} - \vec{U}$;

$\vec{F}_3 = m\vec{g}\frac{\rho_g}{\rho_p}$ is the lifting force of Archimedes;

$\vec{F}_4 = \rho\vec{u}\oint rot_n\vec{u}dS$ is Magnus force;

$\vec{F}_5 = f\vec{F}_n$ is the friction force;

ξ is the coefficient of particle hydraulic resistance;

S_{ms} is the area of particle midsection, m^2;

ρ_g is the gas density, kg/m^3;

$\vec{V}, \vec{U}$ are the velocities of gas and particle, m/s;

ρ_p is the particle density, kg/m^3;

f is the coefficient of particle friction against the wall;

$\vec{F}_n$ is the normal force upon particle impact against the wall, N.

Of the listed forces, the particle motion is most affected by the gravity force and the particle hydrodynamic resistance force. In the future, we will only consider the influence of these forces.

Equation (5), written in a cylindrical coordinate system, has the following form (Kalitkin 1978, Krisher 1974, Mushtaev and Ulyanov 1998):

$$U_z\frac{dm}{d\tau} + m\frac{dV_z}{d\tau} = -mg - \frac{1}{8}\xi\rho_g\pi d_p W \cdot W_z \quad (6)$$

$$U_r\frac{dm}{d\tau} + m\left(\frac{dV_r}{d\tau} - r\omega^2\right) = -\frac{1}{8}\xi\rho_g\pi d_p W \cdot W_r \quad (7)$$

$$\omega_r\frac{dm}{d\tau} + m\left(r\frac{d\omega}{d\tau} - 2\omega U_r\right) = -\frac{1}{8}\xi\rho_g\pi d_p W \cdot W_\varphi \quad (8)$$

where U_z, U_r are the projections of the particle velocity vector on the axis *z*, *r*;

ω is the angular velocity of the particle relative to the axis of the apparatus, rad;

m is the wet particle mass, kg;

z, *r*, φ are the cylindrical coordinates;

ξ is the coefficient of particle hydraulic resistance;

W_z, W_r, W_φ are the axial, radial and tangential components of the relative velocity, m/s.

$$U_z = \frac{dz}{d\tau} \quad (9)$$

$$U_r = \frac{dr}{d\tau} \quad (10)$$

$$\omega = \frac{d\varphi}{d\tau} \quad (11)$$

$$W_z = U_z - V_z \quad (12)$$

$$W_r = U_r - V_r \quad (13)$$

$$W_\varphi = \omega r - V_\varphi \quad (14)$$

$W = \sqrt{W_z^2 + W_r^2 + W_\varphi^2}$ is the particle relative velocity (modulo),m/s.

The hydraulic coefficient of particle friction is determined by the equation (Godunov and Ryabenky 1973):

$$\xi = 0.47 + \frac{24}{Re} \quad (15)$$

where $Re = \frac{Wd_ч}{\nu}$ is Reynolds number for the particle;

$d_ч$ is the particle equivalent diameter, m;

ν is the kinematic coefficient of air viscosity, m^2/s

It should be noted that the equation (15) is valid for 1<Re<1000, corresponding to the turbulent regime of gas flow.

The initial conditions for the system (6-8) have the following form:

$$z(0) = H; \varphi(0) = 0; r(0) = r_0$$

The boundary conditions (data) for the particle on the apparatus wall are given by the condition of elastic impact:

at $r = d_{ch}/2; U'_r = -U_r$

where U'_r are the corrected radial velocity values, m/s.

The wet particle mass is defined as the sum of the solid part and water:

$$m = m_s + m_w \quad (16)$$

$$m_s = \rho_s(1-\varepsilon)V_p \quad (17)$$

$$m_w = \rho_w \varepsilon V_p \quad (18)$$

where ρ_s, ρ_w is the density of solid phase and water, kg/m^3;

ε is the fraction of pores in the particle, filled with water;

$V_p = \frac{1}{6}\pi d_p^3$ is the volume of the equivalent diameter particle, m^3.

Equations of heat and mass transfer during particle drying

The wet particle with initial temperature T_{p0} entering the chamber interacts with the air flow. Due to convective heat transfer, the heat from hot air is supplied to the particle. It is used for water evaporation and heating of the particle itself at the initial stage of the process. After a certain relaxation time, the particle temperature becomes equal to the wet thermometer temperature.

The heat transfer equation for the particle has the following form:

$$cm\frac{dT_p}{d\tau} = \alpha(T - T_p)\cdot \pi d_p^2 + H\frac{dm}{d\tau} \quad (19)$$

where c is the wet particle heat capacity, J/(kg·K);

T, T_p are the air and the particle temperatures, K;

α is the heat transfer coefficient, W/(m^2·K);

H is the heat of water evaporation, J/kg.

The wet particle heat capacity is determined in accordance with the law of additivity:

$$c = \frac{c_s \cdot m_s + c_w m_w}{m} \quad (20)$$

where c_s, c_w are the the dry particle and water heat capacities, J/(kg·K).

The derivative $\frac{dm}{d\tau}$ characterizes the change in the particle mass due to water evaporation.

The heat transfer coefficient α is determined from the criterial equation [1]:

$$Nu = 2 + 0.51Re^{0.52}Pr^{0.33} \quad (21)$$

where $Nu = \alpha d_p/\lambda$ is the Nusselt number;

$Re = \frac{Wd_p}{\nu}$ is the Reynolds number;

$Pr = \frac{ab}{\nu}$ *is the Prandtl number;*

λ is the air thermal conductivity, W/(m·K).

The mass transfer equation for the particle is the following:

$$\frac{dm}{d\tau} = -\frac{\beta}{R_S T}(P_S - P_V)\pi d_p^2 \quad (22)$$

where β is the mass-transfer coefficient, m/s;

R_V=461.9 J/kg·K is the gas constant of water vapor;

R_S is the saturated vapor pressure on the particle surface, Pa.

The mass-transfer coefficient β was calculated on the basis of an analogy between the processes of heat and mass transfer [1]:

$$Nu_D = 2 + 0.51Re^{0.52}Pr_D^{0.33} \quad (22')$$

where $Nu_D = \beta \cdot d_p/D$ is Nusselt diffusion number of;

D is the diffusion coefficient, m^2/s;

$Pr_D = \nu/D$ is Prandtl diffusion number.

The dependence of the saturation pressure $P_H$on the particle temperature $T_ч$ can be obtained by integrating of the Clapeyron-Clausius equation:

$$\frac{dP_S}{dT} = \frac{\Delta H}{T(v''-v')} \quad (23)$$

where v', v'' are the specific volumes of water and saturated steam, m^3;

ΔH is the heat of water evaporation, J/kg.

Supposing that the water vapor is subject to the equation of the ideal gas state

$$P_S v'' = R_V T \quad (24)$$

and taking into account that $v'' >> v'$ we represent equation (23) in the form:

$$\frac{dP_S}{dT} = \frac{P_S \Delta H}{R_V T^2} \quad (25)$$

By integrating this equation, we obtain:

$$P_S = P_0 exp\left[\frac{\Delta H}{R_V}\left(\frac{1}{T_0} - \frac{1}{T_S}\right)\right] \quad (26)$$

where T_0, P_0 is any pair of parameters lying on the saturation line, K, Pa.

At *P*0*=4000 Pa*, the saturation temperature of the vapor is *T*0*=402.0 K*. The evaporation heat is ΔH *≈2400 kJ / kg*. Inserting these parameters into the expression, we obtain:

$$P_S = 4000exp\left(17.44 - \frac{5267}{T}\right) \quad (27)$$

The diffusion coefficient *D* is determined by the formula:

$$D = D_0\frac{P_0}{P}\left(\frac{T}{T_0}\right)^{1,5} \quad (28)$$

where T_0=273 K, $P_0=1.01\cdot 10^5$ Pa are normal conditions parameters;

$D_0=2.19\cdot 10^{-5}$ m^2/c is the diffusion coefficient of water vapor under normal conditions;

P, T are current air pressure and temperature, Pa, K.

Numerical Solution of the Problem of the Dispersed Material Particle Motion during the Drying Process

Since the previously recorded differential equations are nonlinear, the problem presented cannot be solved analytically. Therefore, we solve it numerically with a PC using Euler's method (Antipov et al. 2005, Antipov and Pribytkov 2001).

Let us write the discrete analog of the differential equation (6):

$$m_i\frac{U_{z,i+1}-U_{z,i}}{\Delta\tau}=-U_{z,i}\left(\frac{dm}{d\tau}\right)_i-m_ig-\frac{1}{8}\xi_i\rho_g\pi d_p^2W_iW_{zi} \quad (29)$$

Here i refers to the present, and i+1 to the next time step; Δτ is the time step, s.

To calculate the derivative $\left(\frac{\mathrm{dm}}{\mathrm{d\tau}}\right)_{\mathrm{i}}$ the equation (22) was used.

From equation (29) we write the formula for calculating the projection of the velocity vector $\mathrm{U}_{\mathrm{z,i+1}}$:

$$U_{z,i+1}=U_{z,i}+\Delta\tau\cdot\left[-\frac{U_{zi}}{m_i}\cdot\left(\frac{dm}{d\tau}\right)_i-g-\frac{1}{8m_i}\xi_i\rho_g\pi d_p^2W_iW_{zi}\right] \quad (30)$$

Similarly, we transform formulas (7 – 11), (19), (22):

$$U_{ri}\left(\frac{dm}{d\tau}\right)_i+m_i\left(\frac{V_{r,i+1}-U_{r,i}}{\Delta\tau}-r\omega_i^2\right)=-\frac{1}{8}\xi\rho_g\pi d_pW_i\cdot W_r \quad (31)$$

$$U_{r,i+1}=U_{r,i}+\Delta\tau\cdot\left[r\omega_i^2-\frac{U_{r,i}}{m_i}\cdot\left(\frac{dm}{d\tau}\right)_i-\frac{1}{8m_i}\xi\rho_g\pi d_p^2WW_r\right] \quad (32)$$

$$\omega_{r,i}\left(\frac{dm}{d\tau}\right)_i+m_i\left(r\frac{\omega_{i+1}-\omega_i}{\Delta\tau}+2\omega_iU_{r,i}\right)=-\frac{1}{8}\xi\rho_g\pi d_pW\cdot W_\varphi \quad (33)$$

$$\omega_{i+1}=\omega_i+\Delta\tau\left[-\frac{2}{r}\omega_iU_{r,i}-\frac{\omega_i}{m_i}\left(\frac{dm}{d\tau}\right)_i-\frac{1}{8m_ir}\xi\rho_g\pi d_pW\cdot W_\varphi\right] \quad (34)$$

$$U_{z,i}=\frac{z_{i+1}-z_i}{\Delta\tau} \quad (35)$$

$$z_{i+1}=z_i+U_{z,i}\Delta\tau \quad (36)$$

$$U_{r,i}=\frac{r_{i+1}-r_i}{\Delta\tau} \quad (37)$$

$$r_{i+1}=r_i+U_{r,i}\Delta\tau \quad (38)$$

$$\omega_i=\frac{\varphi_{i+1}-\varphi_i}{\Delta\tau} \quad (39)$$

$$\varphi_{i+1}=\varphi_i+\omega_i\Delta\tau \quad (40)$$

$$\frac{m_{i+1}-m_i}{\Delta\tau}=-\frac{\beta_i}{R_\Pi T_i}\left(P_{S,i}-P_V\right)\pi d_p^2 \quad (41)$$

$$m_{i+1}=m_i-\frac{\beta_i\Delta\tau}{R_VT_i}\left(P_{S,i}-P_V\right)\pi d_p^2 \quad (42)$$

$$c_im_i\frac{T_{p,i+1}-T_{p,i}}{\Delta\tau}=\alpha_i\left(T-T_{p,i}\right)\cdot\pi d_p^2+\Delta H\left(\frac{dm}{d\tau}\right)_i \quad (43)$$

$$T_{p,i+1}=T_{p,i}+\frac{\Delta\tau}{c_im_i}\left[\alpha_i\left(T-T_{p,i}\right)\cdot\pi d_p^2+\Delta H\left(\frac{dm}{d\tau}\right)_i\right] \quad (44)$$

The task was solved using the Euler method in the following sequence:

1. The constant parameters of the task, the initial coordinates (cylindrical) and the projections of the initial velocity vector of the particle on the coordinate axis were set. From the coordinates, only the current radius r_0 was specified, since it was supposed that φ_0 =0 and z_0 =L.
2. The task initial data were introduced.
3. The projections of the air velocity vector were calculated from the formulas (1 – 3).
4. The projections of the particle relative velocity were calculated from formulas (12 – 14).
5. The heat transfer coefficient was calculated from formula (21).
6. The coefficients of diffusion and mass-transfer were calculated from formulas (28), (22′).
7. The pressure of saturated vapor at the particle surface was determined from formula (27)
8. The rate of change in the particle mass due to water evaporation was calculated from (42).
9. The coefficient of hydraulic resistance of the particle was calculated from (15).
10. The velocity of the particle in the next step in time was calculated from formulas (30), (32), (34).
11. The particle coordinates at the next step in time were calculated in accordance with formulas (36), (38), (40).
12. Upon the impact against the wall (that is, for r = $d_{ch}/2$) corrections were introduced for r and $\mathrm{U}_{\mathrm{z,i+1}}$ in accordance with formulas (15′).
13. The temperature at the next step in time was calculated from formula (44). The heat capacity c_i was calculated from formula (20).
14. The particle mass for the next step in time was calculated in accordance with (42).

Then the procedure described was repeatedly performed for subsequent instants of time.

Calculation Results of the Process of the Particle with a Changing Mass Motion

The motion trajectory of the solid particle in the apparatus with the following parameters is shown in **Fig. 2**:

r_0=0.01 *m;* z_0=0.18 *m;* φ_0=0*;* U_{r0}=0*;* U_{z0}=-0.1 *m/s;* ω=0*;* ε=0.6*;* T=363 *K;* T_{p0}=293 *K;* P_V =1530 *Pa;* d_p =0.0014 *m;* ν=2.11^{-5} m^2/s*;* Pr=0.692*;* λ=0.0305 *W/(m·K);* R_V=461.9 *J/(kg·K);* ρ_s=1250 kg/m^3*;* ρ_w=996 kg/m^3*;* ρ_g=1.0 kg/m^3*;* c_s=2600 *J/(kg·K);* c_w=4180 *J/(kg·K);* ΔH=2.420·10^6 *J/kg;* r_{ch}=0.1 *m;* $V_{\varphi m}$=2 *m/s;* k=1,2*;* α=0.05*;* ξ=6*;* c=6 *m/s.*

A particle entering the apparatus through the upper branch pipe is picked up and accelerated by the air flow. Its angular velocity increases, resulting into its dropping to the apparatus wall. Repeatedly bouncing and jumping off the wall, the particle moves to the apparatus bottom.

The particle with reduced mass starts moving upwards and in 4 seconds after its entering the apparatus it is removed from it.

As a result of the process calculation with other values r_0, U_{r0}, U_{z0}, $U_{\varphi 0}$, it was established that the particle is in the apparatus for about 4 seconds. During this time, it also strikes and jumps off the apparatus wall many times, moves first down, then up.

The change in the particle temperature and mass in time is shown in **Figs. 3** and **4**.

The particle mass (**Fig. 3**) changes slowly in the initial period, which is explained by the relatively low temperature and vapor pressure at the surface of the particle. As a result of heat and mass exchange, the temperature of the particle, (**Fig. 4**) reaches the temperature of the wet thermometer approximately in 2 seconds and does not change any more later.

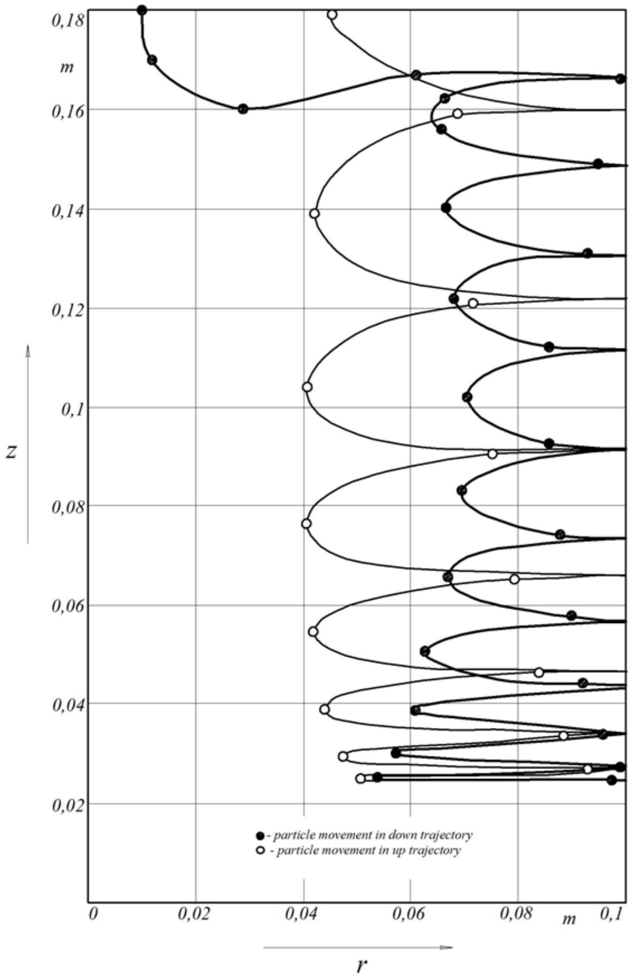

Fig. 2. The capillary- and porous material particle movement trajectory in a vortex chamber during the drying process

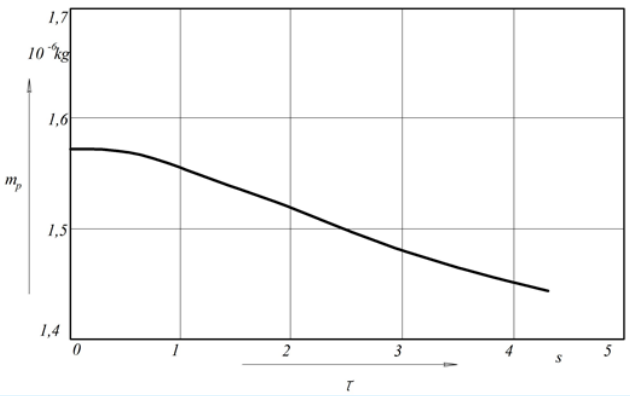

Fig. 3. Change in the particle mass with time

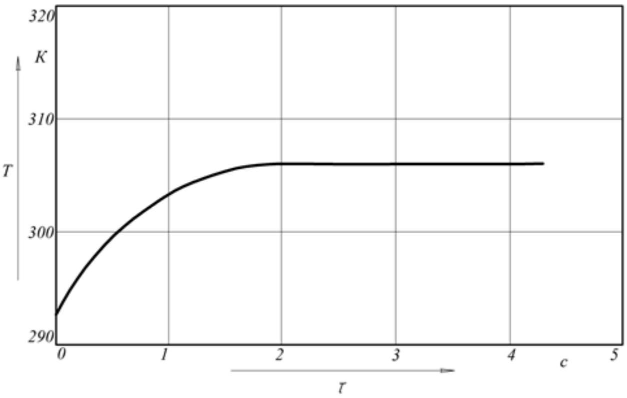

Fig. 4. Change in the particle temperature with time

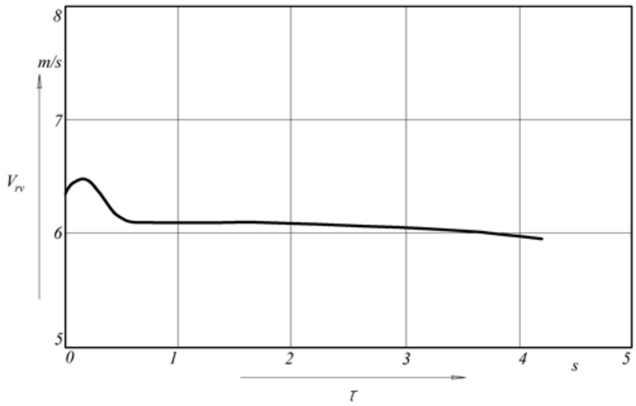

Fig. 5. Change in the relative air velocity with time

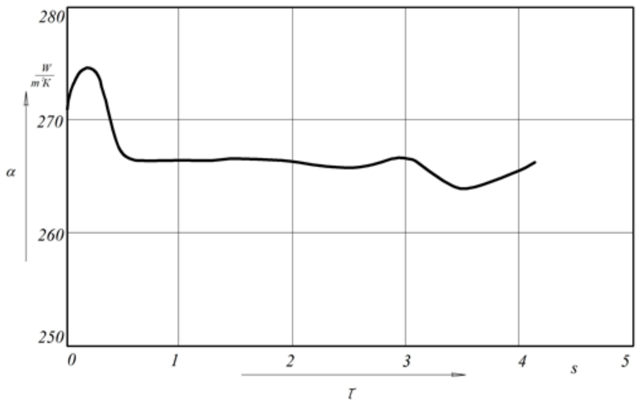

Fig. 6. Change in heat transfer coefficient with time

The air velocity decreases a bit with time relative to the particle velocity because of the change in the particle mass (**Fig. 5**).

This leads to a certain (by 3-5%) decrease in the coefficients of heat and mass transfer (**Fig. 6**).

The time step was small enough to ensure the stability of the computational scheme. In the calculations performed it was supposed that *$\Delta\tau$=0,005 s.*

In **Fig. 7** the particle trajectory with the following parameters is presented:

r_0=0.01 *m;* z_0=0.18 *m;* φ_0=0*;* U_{r0}=0*;* U_{z0}=-0.5 *m/s;* ω=0*;* ε=0,6*;* *T*=393 *K;* T_{p0}=293 *K;* P_V =1530 *Pa;* d_p =0.0016 *m;* ν=2.11^{-5} *m²/s;* *Pr*=0.686*;* λ=0.0334 *W/(m·K);* R_V=461.9 *J/(kg·K);* ρ_s=*I kg/m³;* ρ_w=996 *kg/m³;* ρ_g=1.0 *kg/m³;* c_s=2600 *J/(kg·K);* c_w=4180 *J/(kg·K);* ΔH=2.420·10^6 *J/kg;* r_{ch}=0.1 *m;* $V_{\varphi m}$=2 *m/s;* *k*=1,2*;* α=0.05*;* ξ=6*;* *c*=6 *m/s.*

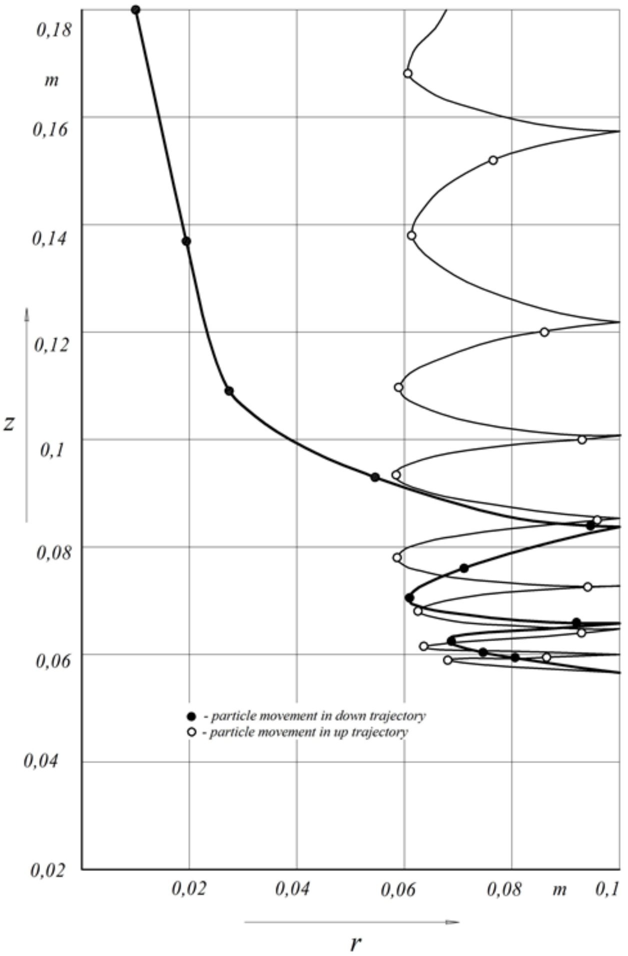

Fig. 7. The capillary- and porous material particle movement trajectory in a vortex chamber during the drying process

Here the particle behavior is similar to that previously indicated, but the time of the particle being in the chamber is lower, which is explained by the higher drying velocity due to the high temperature of the drying agent.

The numerical analysis of the solid particle drying process in the chamber allows us to draw the following conclusions:

1. The diameters interval of the particles retained in the drying chamber is determined by the air velocities in the upper and lower branch pipe.
2. Solid wet particles that are unable to exit down through the lower branch pipe will circulate in the apparatus until their mass due to the moisture evaporation reaches the mass at which the entrainment takes place.
3. The coefficients of heat and mass transfer decrease somewhat in time. However, this decrease does not exceed 10%.
4. The time of the particles being in the apparatus is approximately equal to the drying time of the particle to a mass characterizing its entrainment velocity from the apparatus. For particles of the same size and initial humidity, this time is practically independent of the initial coordinates and velocity.

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