Theoretical preconditions for the development of mathematical models of the technology of desert plant drying

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Abstract. The formulation of stationary and non-stationary problems for drying dispersed materials is substantiated in the article. A mathematical model and its analytical solutions are developed to determine the patterns of the interdependence of temperature and moisture content. A mathematical model of the process of drying a dispersed material is based on the energy conservation law under heat and mass transfer in a multiphase medium.

1 Introduction

The basis of the drying theory is the dependence of the transfer of heat and water in wet materials when they interact with heated gases (a drying agent) and with hot surfaces, and in the process of irradiation with thermal and electromagnetic waves in the presence of phase transformations. The patterns of energy and mass transfer in wet materials during their dehydration are quite complex and insufficiently studied.

In developing a mathematical model of the drying process, the following assumptions are assumed: the wet material to be dried is a multi-phase (dry matter + water + air) and a multi-component (dry air + water vapor) medium.

The system of drying by penetrating with a drying agent is a process accompanied by heat and mass transfer between various phases and components of the system. Due to the multi-phase nature of the medium, the equations for its description must contain phase contact areas since the kinematic, dynamic, and thermodynamic interaction between the phases is conducted through them.

In general, the physical model of the process can be represented as:

1. Drying of the wet material takes place in a layer characterized by thickness h and surface area S.

The layer consists of unit elements, characterized by volume V_1, surface area S_1, density and moisture content ω_1 (hereinafter, the following indices are taken: 1 - refers to dry matter (a skeleton); 2 - to moisture content; and 3 - to air).

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2. The space between unit objects inside the layer is filled with air with temperature t_3^*, water vapor density ρ_n^*, and flow rate U_3^* (the air parameters outside the layer are denoted without the «*» sign).
3. Water evaporated from the material initially enters the air space inside the layer, and then, under the effect of convection (circulation), passes outside the layer and then moves to the surrounding medium.

2 Methods

Wet material is a colloidal capillary-porous body; the water in it is bound by various forms of bonds [1]. Water in the micro-pores and capillaries of the body has the least strong bond. When it is removed, the evaporation process can be considered as evaporation from the free surface, and the evaporation surface coincides with the surface of the body. As dehydration begins, the process of the deepening of the evaporation zone begins.

In mathematical modeling, the following concepts are used. We single out elementary volume ΔV inside the layer of wet material and denote by ΔV_I the volume of the i-th phase contained in volume ΔV. Then,

$$\sum_{i=1}^{i=n} \Delta V_i = \Delta V, \tag{1}$$

where n is the number of phases.

Let us introduce the concept of the relative volume of the i-th phase:

$$\alpha_i = \frac{\Delta V_i}{\Delta V} \tag{2}$$

Considering expression (1), we obtain:

$$\sum_{i=1}^{i=n} \alpha_i = 1. \tag{3}$$

The phases interact with each other through contact interfaces, which is the main characteristic of a multiphase medium.

The area of the surface of the mutual contact of the i-th phase with the j-th phase in the selected volume ΔV is denoted by ΔS_{ij}. The ratio of ΔS_{ij} to ΔV is the specific surface of mutual contact, denoted by:

$$\beta_{ij} = \frac{\Delta S_{ij}}{\Delta V}, \tag{4}$$

here, $\beta_{ij} = \beta_{ji}$.

The total specific surface of the i-th phase β_I is:

$$\beta_i = \sum_j \beta_{ij}. \tag{5}$$

An important characteristic of a multi-phase system is the characteristic linear size of phases δ_i, proposed by Prof. G.G. Umarov [2]; it is an analog of its thickness or hydraulic radius. This size is expressed in terms of the relative volume of phase α_i and its total specific surface area:

$$\delta_i = K_\Phi \frac{\alpha_i}{\beta_i} \quad , \tag{6}$$

where K_ϕ is the dimensionless parameter depending on the geometric shape of the phase.

Let us introduce the phase density ρ_i into consideration, then the density of the "wet material + water + air" system is:

$$\rho = \sum_{i=1}^{i=n} \rho_i \alpha_i \, . \tag{7}$$

The volume of the dried material ΔV_1 consists of the volume of dry matter (a skeleton) ΔV_{11}, the volume of water ΔV_{12}, and the volume of moist air ΔV_{13}, i.e.

$$\Delta V_1 = \Delta V_{11} + \Delta V_{12} + \Delta V_{13} \, . \tag{8}$$

Similar to the multiphase layer *h,* we introduce the concept of the relative volume of the *j*-th medium in the volume of the product:

$$\psi_{1j} = \frac{\Delta V_{1j}}{\Delta V_1} \tag{9}$$

or

$$\sum \psi_{1j} = 1 . \tag{10}$$

If in equation (8) the numerator and denominator are divided by ΔV and denoted by

$$\eta_{1j} = \frac{\Delta V_{1j}}{\Delta V} \, , \tag{11}$$

then

$$\psi_{1j} = \frac{\eta_{1j}}{\alpha_1} \, , \tag{12}$$

or

$$\eta_{1j} = \frac{\psi_1}{\alpha_1} . \tag{13}$$

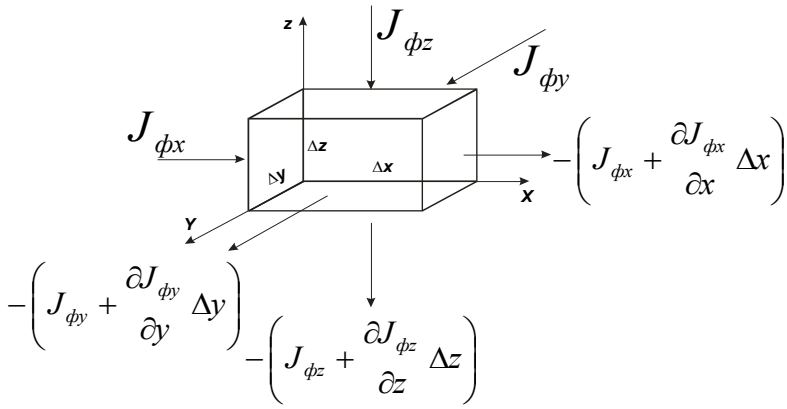

Fig. 1. Calculation scheme of flows in an elementary volume

The equation describing the law of conservation of a scalar variable is the basis, using it, we derive equations for the balance of other physical characteristics necessary to describe a multiphase and multicomponent medium. To obtain this equation, we consider an elementary volume with sides *Δx, Δy, Δz* (Fig. 1). Flow $\vec{J}_{\Phi}$ of some scalar value *Φ* passes through this elementary volume. The flux flowing through one face *ΔzΔy*, is denoted by $J_{\phi x}$. The flux inflowing through the opposite face is $J_{\phi x}+(\delta J_{\phi x}/\delta x)\Delta x$.

The balance of conservation of the scalar variable *Φ* along the *x*-axis has the following form:

$$J_{\Phi x}\Delta z\Delta y-\left(J_{\Phi x}+\frac{\partial J_{\Phi x}}{\partial x}\Delta x\Delta y\Delta z\right)=-\frac{\partial J_{\Phi x}}{\partial x}\Delta x\,, \tag{14}$$

where $\Delta V=\Delta x\Delta y\Delta z$ is the elementary volume.

Similar expressions for the balance of the scalar quantity *Φ* take place along the *y* and *z*-axes, i.e.:

$$J_{\Phi y}\Delta x\Delta z-\left(J_{\Phi y}+\frac{\partial J_{\Phi y}}{\partial y}\Delta x\Delta y\Delta z\right)=-\frac{\partial J_{\Phi y}}{\partial y}\Delta y\,, \tag{15}$$

$$J_{\Phi z}\Delta x\Delta y-\left(J_{\Phi z}+\frac{\partial J_{\Phi z}}{\partial z}\Delta x\Delta y\Delta z\right)=-\frac{\partial J_{\Phi z}}{\partial z}\Delta z\,. \tag{16}$$

The total balance of value *Φ* in volume *ΔV* due to its flow through the elementary volume is:

$$-\left(\frac{\partial J_{\Phi x}}{\partial x}+\frac{\partial J_{\Phi y}}{\partial y}+\frac{\partial J_{\Phi z}}{\partial z}\right)\Delta V=-div\vec{J}_{\Phi}\Delta V\,. \tag{17}$$

Vector $\vec{J}_{\Phi}$ is determined by two terms:

convective flow

$$\Phi\vec{U}\,, \tag{18}$$

and diffusion flow

$$-D_{\Phi} grad\Phi, \tag{19}$$

where D_{Φ} is the scalar diffusion coefficient.

Then,

$$\vec{J} = \Phi\vec{U} - D_{\Phi} grad\Phi . \tag{20}$$

If in an elementary volume, there is a flow off or a source of substance Φ, then its balance, related to a unit of volume, has the following form:

$$\frac{\partial\Phi}{\partial\tau} + div\vec{J}_{\Phi} = S_{\Phi}, \tag{21}$$

where S_{Φ} is the source (flow off) of scalar Φ.

In the resulting equation, the first term on the left-hand side characterizes the change in Φ over time and in units of volume.

Substituting the value from (20) into (21), we obtain an expression that describes in differential form the generalized law of conservation of variable Φ in the following form:

$$\frac{\partial\Phi}{\partial\tau} + div\left(\Phi\vec{U} - D_{\Phi} grad\Phi\right) = S_{\Phi} . \tag{22}$$

In this equation, the convective velocity of the substance Φ

Let us take the value of Φ out of parentheses (22):

$$\Phi\left(\vec{U} - \frac{D_{\Phi}}{\Phi} grad\Phi\right) \tag{23}$$

The value of

$$\vec{U}_g^* = -\frac{D_{\Phi}}{\Phi} grad\Phi \tag{24}$$

is the diffusion velocity.

The total velocity is

$$\vec{U}^* = \vec{U} + \vec{U}_g^* . \tag{25}$$

In view of the above, equation (22) can be written in the following form:

$$\frac{\partial\Phi}{\partial\tau} + div\vec{U}^* = S_{\Phi} . \tag{22}$$

In the presence of a velocity field, the mass conservation equation for a multiphase medium has the following form:

$$\frac{\partial\alpha_i\rho_i}{\partial\tau} + div\alpha_i\rho_i\vec{U}_i = \sum_j \varepsilon_{ij} , \tag{27}$$

where ρ_i is the density of the *i*-th phase; $\vec{U}_i$ is the total velocity of the *i*-th phase; $\sum_j \varepsilon_{ij}$ is the volume velocity of transition of the *j*-th phase to the *i*-th phase.

In the case of water evaporation into the vapor-air medium, the expression takes the following form:

$$\frac{\partial \alpha_i \rho_i}{\partial \tau} + div\left[\alpha_3\left(\rho_n \vec{U}_3 - D_n^* grad\rho_n\right)\right] = \varepsilon_{n3}, \tag{28}$$

where ρ_n is the vapor density; $\vec{U}_3$ is the convective velocity of the air flow; ε_{n3} is the volume velocity of vapor-to-air transition.

For a Newtonian fluid (the fluid has no initial shear stress), the differential equation expressing the conservation of momentum in a given direction can be written likewise. However, one should take into account Stokes' viscous friction law and its difference from Fick's and Fourier's laws, which are used in describing the heat balance.

Let *x* be the velocity component of the *i*-th phase equal to U_{xi}, then the corresponding momentum equation (with the combined action of forced and natural convection) takes the following form:

$$\frac{\partial \alpha_i \rho_i U_{xi}}{\partial \tau} + div\,\alpha_i\left[\rho_i U_{xi}\vec{U} - \upsilon_i grad\left(\rho_i U_{xi}\right)\right] =$$
$$= \alpha_i \rho_i \vec{g} - \alpha_i \frac{\partial P_i}{\partial x} + \sum \frac{\chi_T \mu_i^* \mu_j^*}{\mu_i^* \delta_j + \mu_j^* \delta_i} \beta_{ij}\left(U_{xj} - U_{xi}\right), \tag{29}$$

where v_i is the coefficient of kinematic viscosity of the *i*-th phase; $\mu_i^* \mu_j^*$ are the effective coefficients of dynamic viscosity of the *i*-th and *j*-th phases; P_i is the partial pressure of the *i*-th phase; χ_i is the dimensionless coefficient of proportionality, according to the recommendations given in [3]; it can be taken equal to χ_i=0.9.

The value of $\sum \frac{\chi_T \mu_i^* \mu_j^*}{\mu_i^* \delta_j + \mu_j^* \delta_i} \beta_{ij}\left(U_{xj} - U_{xi}\right)$ characterizes the interaction between the phases [4].

The right-hand side of equation (29) is the source term S_Φ, due to the influence of gravitational forces and the presence of distributed resistances to fluid flow, which appear due to the presence of the flow-off momentum in the streamlined elements of the porous structure. These resistances tend to vary in magnitude and direction.

The concept of the distribution of resistances not only simplifies the problem, it allows one to use correlations for volume coefficients of resistance and heat and mass transfer of porous structures in calculations of local characteristics of transfer. These correlations are often obtained from relatively simple experiments [5], and their use allows for the calculation of complex fields of velocity, temperature, and concentration in the working space of the process equipment under consideration.

Differentiating the first term of equation (29) and expanding the contents of sign *div*, we obtain:

$$U_{xi}\frac{\partial \alpha_i p_i}{\partial \tau}+\alpha_i\rho_i\frac{\partial U_{xi}}{\partial \tau}+\alpha_i\rho_i\vec{U}_i gradU_{xi}+U_{xi}div\alpha_i\rho_i\vec{U}_i-$$
$$-\nu_i divgrad\alpha_i\rho_i U_{xi}=\alpha_i\rho_i g_x-\alpha_i\frac{\partial P_i}{\partial x}+\sum\frac{x_T\mu_i^*\mu_j^*}{\mu_i^*\delta_j+\mu_j^*\delta_i}\beta_{ij}(U_{xj}-U_{xi}) \quad (30)$$

We separate variables

$$\alpha_i\rho_i\frac{\partial U_{xi}}{\partial \tau}+\alpha_i\rho_i\vec{U}_i gradU_{xi}+U_{xi}\left(\frac{\partial \alpha_i p_i}{\partial \tau}+div\alpha_i\rho_i\vec{U}_i\right)=$$
$$=\alpha_i\mu_i^0 divgradU_{xi}+\alpha_i\rho_i g_x-\alpha_i\frac{\partial P_i}{\partial x}+\sum\frac{x_T\mu_i^*\mu_j^*}{\mu_i^*\delta_j+\mu_j^*\delta_i}\beta_{ij}(U_{xj}-U_{xi}) \quad (31)$$

Based on the continuity equation

$$\frac{\partial \alpha_i\rho_i}{\partial \tau}+div\alpha_i\rho_i\vec{U}_i=0, \quad (32)$$

and conditions

$$g_x=0,$$

expression takes the following form:

$$\frac{\partial U_{xi}}{\partial \tau}+U_{xi}\frac{\partial U_{xi}}{\partial x}+U_{yi}\frac{\partial U_{xi}}{\partial y}+U_{zi}\frac{\partial U_{xi}}{\partial z}=-\frac{1}{\rho_i}\frac{\partial P_i}{\partial x}+$$
$$+\nu_i\nabla U_{xi}+\frac{1}{\rho_i\alpha_i}\sum\frac{\chi_y\mu_i^*\mu_j^*}{\mu_i^*\delta_j-\mu_j^*\delta_i}\beta_{ij}\left(U_{xj}-U_{xi}\right) \quad (33)$$

Thus, an expression is obtained that describes the momentum balance in a multiphase medium. For a homogeneous medium, we obtain:

$$\alpha_i=1;\quad U_{xj}=U_{xi},$$

then expression (33) is transformed into the Navier-Stokes equation:

$$\frac{\partial U_{xi}}{\partial \tau}+U_{xi}\frac{\partial U_{xi}}{\partial x}+U_{yi}\frac{\partial U_{xi}}{\partial y}+U_{zi}\frac{\partial U_{xi}}{\partial z}=-\frac{1}{\rho_i}\frac{\partial P_i}{\partial x}+\nu_i\nabla U_{xi}. \quad (34)$$

Similarly, momentum balances are derived in the *y* direction:

$$\frac{\partial U_{yi}}{\partial \tau}+U_{xi}\frac{\partial U_{yi}}{\partial x}+U_{yi}\frac{\partial U_{yi}}{\partial y}+U_{zi}\frac{\partial U_{yi}}{\partial z}=-\frac{1}{\rho_i}\frac{\partial P_i}{\partial x}+$$
$$+\nu_i\nabla U_{yi}+\frac{1}{\rho_i\alpha_i}\sum\frac{\chi_y\mu_i^*\mu_j^*}{\mu_i^*\delta_j-\mu_j^*\delta_i}\beta_{ij}\left(U_{yj}-U_{yi}\right) \quad (35)$$

and in the *z* direction:

$$\frac{\partial U_{zi}}{\partial \tau} + U_{xi}\frac{\partial U_{zi}}{\partial x} + U_{yi}\frac{\partial U_{zi}}{\partial y} + U_{zi}\frac{\partial U_{zi}}{\partial z} = -\frac{1}{\rho_i}\frac{\partial P_i}{\partial x} +$$
$$+ \nu_i \nabla U_{xi} + \frac{1}{\rho_i \alpha_i}\sum \frac{\chi_y \mu_i^* \mu_j^*}{\mu_i^* \delta_j - \mu_j^* \delta_i}\beta_{ij}\left(U_{zj} - U_{zi}\right) . \quad (36)$$

Thus, the validity of the recording of the momentum balance in the form of a generalized differential equation was proved.

Now we consider the heat balance in a multiphase medium. The change in time of the heat content of the *i*-th phase, located in a unit volume of the medium is:

$$\frac{\partial \alpha_i c_i \rho_i t_i}{\partial \tau}$$

where c_i is the specific heat of the *i*-th phase; t_i is the temperature of the *i*-th phase.

The change in heat content depends on the inflow or outflow of heat in an elementary volume due to convection, heat conduction, and radiant heat exchange.

The general expression for the heat flux in a multiphase medium can be written as:

$$\vec{Q}_i = \alpha_i \lambda_i^* gradt_i + \alpha_i c_i \rho_i t_i \vec{U}_i + \vec{J}_{ki} + \vec{J}_{gi}, \quad (37)$$

where λ_i^* is the coefficient of effective thermal conductivity; $\vec{J}_{ki}$ is the flux of short-wave radiation; $\vec{J}_{gi}$ is the flux of long-wave radiation.

Heat transfer through the contacting surfaces of phases is [1]:

$$\sum \frac{\chi_y \lambda_i^* \lambda_j^*}{\lambda_i^* \delta_j - \lambda_j^* \delta_i}\beta_{ij}\left(t_j - t_i\right),$$

where χ_T is the dimensionless coefficient of proportionality *($\chi_T \approx 6$).*

The intensity of the internal source associated with phase transformations is:

$$\sum Q_{\varepsilon ij} .$$

Thus, the total heat balance of a multiphase medium in a unit volume is:

$$\frac{\partial \alpha_i c_i \rho_i t_i}{\partial \tau} + div\left[\alpha_i\left(c_i \rho_i t_i \vec{U}_i - \lambda_i^* gradt_i\right) + \vec{J}_{ki} + \vec{J}_{gi}\right] =$$
$$= \sum_j \frac{\chi_i \lambda_i^* \lambda_j^*}{\lambda_i^* \delta_j + \lambda_j^* \delta_i}\beta_{ij}\left(t_j - t_i\right) + \sum Q_{\varepsilon ij} . \quad (38)$$

We rewrite the resulting equation in the following form:

$$\frac{\partial \alpha_i c_i \rho_i t_i}{\partial \tau} + div\left[\alpha_i \left(c_i \rho_i t_i \vec{U}_i - \lambda_i^* gradt_i\right)_{gi}\right] =$$
$$= \sum_j \frac{\chi_i \lambda_i^* \lambda_j^*}{\lambda_i^* \delta_j + \lambda_j^{*0} \delta_i} \beta_{ij}\left(t_j - t_i\right) + \sum Q_{\varepsilon ij} - div\left(\vec{J}_{ki} + \vec{J}_{gi}\right) \quad . \tag{39}$$

This equation has taken the form of a generalized differential equation for the conservation of a scalar variable (22), and its right-hand side is the source term S_ϕ.

Assuming that $c_i = const$ and taking into account the mass balance, we write:

$$\frac{\partial \alpha_i \rho_i}{\partial \tau} + div \alpha_i \rho_i \vec{U}_i = \sum_j \varepsilon_{ij}$$

and transform it into the following form:

$$\alpha_i c_i \rho_i \left(\frac{\partial t_i}{\partial \tau} + \vec{U}_i gradt_i\right) = div(\alpha_i \lambda_i^* gradt_i + \vec{J}_{ki} + \vec{J}_{gi}) +$$
$$+ \sum \frac{\chi_i \lambda_i^* \lambda_j^*}{\lambda_i^* \delta_j + \lambda_j^* \delta_i} \beta_{ij}(t_j - t_i) - \sum (Q_{\varepsilon ij} - c_i t_i \varepsilon_{ij}) \quad . \tag{40}$$

For a homogeneous medium, we have:

$$\alpha_i = 1; \quad t_j = t_i; \quad \varepsilon_{ij} = o,$$

then, expression takes the following form:

$$c\rho\left(\frac{\partial t}{\partial \tau} + \vec{U} gradt\right) = div(\lambda^* gradt + \vec{J}_k + \vec{J}_g) . \tag{41}$$

3 Conclusions

Based on the above, the problem of heat and mass transfer in a multiphase medium for the process of drying is formulated in a general form. All balance equations are reduced to a generalized equation of scalar variable conservation. To solve this system of equations, it should be supplemented with the corresponding equations describing the heat fluxes absorbed by the drying agent and the intensity of moisture evaporation. It is also necessary to know the main thermo-physical characteristics of a particular product to be dried and the features of the structural elements of the drying plant set by the boundary conditions.

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