Development of apparatuses based on kinetic calculation data of the process of removing liquid from solid materials by reducing pressure of vapor-gas medium

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Abstract. The possibility of developing an apparatus based on the results of kinetic calculations of the processes occurring in it, is considered. The studies were carried out with the system solid-liquid-vapor-gas medium with a continuous increase in vacuum above the surface of a layer of the dispersed material. The presence of the liquid phase and the vapor-gas phase in equilibrium with it makes it possible to provide a change in concentration, structure, or cooling in the system due to artificial disturbance of the dynamic equilibrium of the system. To develop a mathematical model of the liquid removal process, a model of ideal mixing in the vapor-gas phase and a layer of the dispersed material was adopted. The calculation results are presented in the form of kinetic dependences of the main process parameters. Calculation of the apparatus is carried out at the highest load in the vapor-gas phase during the period of removal of the free moisture. In this case, the influence of rarefaction on the physical characteristics of the removed fluids and the design features of the apparatus being calculated was taken into account.

General information. The technological processes in the systems with a liquid phase can be classified into three groups: liquid-solid-vapor-gas medium; solid-liquid-vapor-gas medium; liquid-gas medium. The presence of the liquid phase and the vapor-gas phase, which is in equilibrium with it, makes it possible to provide a change in concentration, structure, or cooling in the systems due to artificial disturbance of the dynamic equilibrium of the system. Any deviation from the equilibrium state leads to a nonuniform distribution of the potential of transfer as well as an occurrence of the flows of transfer. Restoration of the equilibrium will be ensured by evaporation of a part of the moisture under the adiabatic conditions by reducing the accumulated thermal energy of the system [1-10].

Depending on a set of the apparatuses that introduce disturbances into the external environment, reduction of the pressure in the working volume can be carried out using the system of a vacuum pump-condenser. The specificity of the processes implies airtight conditions for their implementation, ensuring the reduction of combined-gas emissions into the environment. The principle of sealing the working volume is the basis for creation of the waste-free technologies, in which the apparatuses for carrying out the process and the vapour and gas purification equipment are technologically connected.

The steam and gas flows along the components from the surface of the wet material or solution are determined from solving a system of the equations that make up the internal task of the processes. The evaporation surface and the volume of the gas-vapor space determine the design parameters of the apparatus.

Theoretical part. To develop a mathematical model of the liquid removal process, we adopt a model of the ideal mixing in the vapor-gas phase and a layer of the dispersed material.
A mathematical description of the non-stationary modes of the objects with the lumped parameters in the phases is based on ordinary differential equations, often presented in the form of finite-difference relations between input and output values of the flows of the substances.

**Heat and mass transfer in the vapor-gas phase.** For non-stationary conditions of the processes, a difference between the inflow and discharge will be accumulation of the mass and energy in the free volume of the apparatus $V_{1,4,8}$.

When removing the multicomponent liquids in a system solid-liquid-vapor, those which have an interfacial area, the inflow of the mass of $i$-th component into the free volume of the apparatus and the temperature change of the vapor-gas mixture for the ideal mixing model are determined by the expressions:

\[
\text{Vin} = \dot{m}_{in} - \dot{m}_1, \\
\text{Vout} = -\dot{m}_r, \\
\rho c_p \frac{dT}{dt} = \left[ \alpha(T_f - T) + T_f \sum_{i=1}^{n} j_i c_i \right] \frac{\mu_{cm}}{R_{np}} - c_p \rho c_m T \frac{I_{cm}}{V},
\]

where $\dot{m}_{in} = \dot{m}_r$, $\dot{m}_1 = \dot{m}_{cm} P_r$.

The equations given above include the geometrical parameters of the apparatus and the volumetric capacities of the vapor and inert gas removal systems. After their transformations, the differential equations for changing the parameters of the gas-vapor mixture $p_i, p_r, T$ are written in the form

\[
\frac{dp_i}{dt} = \frac{F R^* T}{VM} j_i - P_i \left( \frac{I_{cm}}{V} - \frac{1}{T} \frac{dT}{dt} \right),
\]

\[
\frac{dp_r}{dt} = P_r \left( \frac{1}{T} \frac{dT}{dt} - \frac{I_{cm}}{V} \right),
\]

\[
\frac{dT}{dt} = \left[ \frac{\alpha(T_f - T) + T_f \sum_{i=1}^{n} j_i c_i}{FR} \right] \frac{I_{cm}}{V} - \frac{c_p \rho c_m T}{V}.
\]

The steam and gas flows along the components from the surface of the wet material $j_i$, included in the equations, are determined from solving a system of equations that make up the internal task of specific processes.

Heat and mass transfer when removing free moisture from capillary-porous materials. For a one-dimensional problem with the constant thermophysical properties of the material and the absence of a gradient of total pressure (due to a gradual decrease in pressure), the differential heat and mass transfer equation can be reduced to the form [4]:

\[
c dT_m = \sum_{i=1}^{n} \xi_i dx_i + dU \sum_{i=1}^{n} x_i,
\]

which is the heat balance equation for the case when the heat accumulated by the wet material goes only to the evaporation of a multicomponent liquid. By analogy with the simple distillation process, changes in the concentrations of the components in a liquid are determined by the ratio...
heat balance equation. The thermal load of the condenser when the aggregate state of the system changes is written in the form of the equation:

$$dQ = m_0 \int \sum_{i=1}^{n} (U_i - U) x_i c_i dT_i - U \sum_{i=1}^{n} \int r_i (c_i - c_{w, i}) \times (T_i - 273) dT_i - \sum_{i=1}^{n} \int r_i (c_i - c_{w, i}) (T_i - 273) dU .$$

Heat and mass transfer when removing bound moisture from capillary-porous materials with a mobile zone of phase transformations. The solution of a system of nonlinear differential equations with a moving zone of phase transformations and a variable criterion for vaporization by coordinate and time, taking into account the considerable complexity of the problem even in relation to an unlimited plate, it is often reduced to consider a more simplified mechanism in the form of a deepening of the evaporation surface. As the first approximation, a linear law of distribution of the moisture content and temperature in the evaporation zone is adopted:

$$U_{II} = \left( U_{IF} - U_{IC} \right) \frac{r - R}{\xi} + U_{IF} ,$$

$$T_{MI} = \left( T_{MF} - T_{MC} \right) \frac{r - R}{\xi} + T_{MF} .$$

and a parabolic law of distribution of the same parameters in the wet zone

$$U_{I2} = U_{III} - \left( \frac{r}{R_M - \xi} \right)^2 \left( U_{III} - U_{IC} \right) ,$$

$$T_{M2} = T_{MIII} - \left( \frac{r}{R_M - \xi} \right)^2 \left( T_{MIII} - T_{MC} \right) .$$

The boundary conditions for the equations have the form:

the evaporation zone

$$a_{m1} \rho_c \frac{U_{IF} - U_{IC}}{\xi} + a_{m1} \rho_c \delta_{rII} \frac{T_{MF} - T_{IC}}{\xi} + K \frac{P_i - P_{IC}}{\xi} - j_{IF} (\tau) = 0 ,$$

$$U_{IF} = b_i \left( \frac{P_i}{P_{hac}} \right)^{n_i} ,$$

where $b_i$, $n_i$ are constants.

the wet zone

$$\lambda_{m1} \frac{T_{MF} - T_{MC}}{\xi} = -\lambda_{w1} \left[ \frac{2}{R - \xi} \left( T_{MF} - T_{MC} \right) - \sum_{i} \int r_i (\tau) \right] ,$$

$$a_{m1} \left( \frac{U_{IF} - U_{IC}}{\xi} + \delta_{rII} \frac{T_{MF} - T_{MC}}{\xi} \right) + K \frac{P_i - P_{IC}}{\xi} = 2a_{m1} \left( \frac{U_{IC} - U_{III}}{R - \xi} + \delta_{rII} \frac{T_{MC} - T_{III}}{R - \xi} \right) .$$

The temperature of the liquid is related to the pressure in the capillary by the Thomson dependence, which, taking into account the Antoine equation, can be written this way:
The length of the section of the capillary, on which the transfer of the vaporous mixture occurs, is determined from the relation, transformed as applied to an unlimited plate

$$\frac{d\xi}{d\tau} = \frac{d}{\mu_{CM}} \frac{\rho_{CM}}{\rho C U_H} \frac{dP}{dx},$$

where $d$ is a permeability coefficient.

The amount of evaporating liquid under adiabatic conditions depends on changes in the heat content of the body. To maintain a high rate of moisture removal, the drying process is desirable to combine with the supply of heat in a closed coolant cycle, for example, with the convection.

**Discussion of the results of mathematical modeling.** The system of equations describing heat and mass transfer when removing a multicomponent liquid from a layer of dispersed capillary-porous material was solved by the numerical Runge-Kutta method. The calculation results are presented in the form of kinetic dependences of the main process parameters.

The fig. 1-3 show the results of the calculation of the kinetics of the removal of a three-component liquid mixture of diethyl ether-ethyl alcohol-water from active recovery coal. An analysis of the obtained data makes it possible to evaluate the influence of regime parameters and the state of the material on the processes of moisture removal and condensation of its vapor. It was established that a decrease in pressure in the drying chamber leads to evaporation of moisture, which is carried out by reducing the thermal energy of the wet material, and is accompanied by a decrease in its temperature (Fig. 1).

![Graph](attachment:image.png)

**Fig. 1. Pressure dependence of wet material temperature**

In the calculation, the temperature of the wet material was set within 293 K, and the initial moisture content was set 0.35 kg/kg.

A joint analysis of the curves of the total moisture content and the moisture content of the components of the liquid mixture allows us to conclude that, when a multicomponent solvent is removed, the latent heat of vaporization of the removed liquid has a significant effect on the evaporation process. As can be seen from the curves (Fig. 2), the moisture content of the low-boiling component - diethyl ether, the evaporation rate of
which is greatest, with a decrease in pressure, it changed from 0.166 kg / kg to an equilibrium value. In this case, the change in moisture content in ethyl alcohol and water amounted to 7% and 3.5%, respectively. The analysis of the curves shows that the higher the initial temperature of the material, the greater the moisture removal from a unit mass of the product during the drying process. A decrease in the pressure of the medium above the surface of the material in the first drying period causes a decrease in the temperature of the evaporating liquid, and, therefore, requires a decrease in the temperature of the heat and mass transfer surface to condense the vapors.

Fig. 2. Dependence on the residual pressure of the total moisture content of activated carbon (1) and moisture content by components: 2 - diethyl ether; 3 - ethyl alcohol; 4 - water (the initial ratio of the components, respectively is 0.5, 0.45: 0.05):

The dependences of temperature and total moisture content on residual pressure with a high degree of certainty ($R^2 = 0.99$) were approximated by power and polynomial functions, respectively:

$$T = 235.39P^{0.119}.$$  
$$U = -0.0004P^3 - 0.0015P^2 + 0.0582P + 0.0467.$$  

Figure 3 shows the calculated curve of the change in the specific cold flow rate for vapor condensation. The analysis showed that at a sufficiently low residual pressure in the apparatus, the specific consumption of cold for vapor condensation increases significantly. This requires the use of large-capacity refrigeration units, which is not economically feasible.

**Design part.** The nature of the functional relationships of the equipment used to implement the process of removing moisture from dispersed materials by lowering pressure, largely depends on the type of apparatuses and the features of their work.
Fig. 3. Dependence of the specific flow rate of cold for vapor condensation on the residual pressure in the apparatus

Volumetric capacity of the gas removal system - \( I_{\text{v.g.s}} = I_{n.h} \) depends on the design of the vacuum pump and is determined by its operating characteristic. So for a rotary vacuum pump

\[
I_{n.h} = Q_0 \left(1 - k \frac{P_{\text{atm}}}{P}\right).
\]

The volumetric capacity of a condenser \( I_{c,h} = I_{c.n} \) can be determined from the heat balance equation

\[
I_{c,n} = \frac{k_c \Delta T_{\text{cp}} F_k}{\sum_i \rho_i [c_{\text{temp}}(T - T_{\text{inac}}) + c_i T_{\text{inac}} + \epsilon_i]}
\]

In the formula, the heat transfer coefficient - \( k_c \) for the condensation process of a multicomponent vapor-gas mixture is calculated according to the parameters of the cooling agent using the Kolborn-Hougen method or the Ward model.

The main indicator characterizing the process conditions in the local volume of the main apparatus for the system in question is a variation in the moisture content of the product. The magnitude of the variation is a regulated one, and it determines the difference in the pressure across a layer of the material.

The permissible difference in the moisture content of dispersed particles depends on the technological requirements for the product and can be determined on the basis of the equation of the Freundlich isotherm [7]

\[
\Delta U_{\Delta} = 1 - (1 + \Delta / P)^n.
\]

The implementation of the ideal mixing model in a layer of dispersed material is provided by introduction of the perforated distribution elements of the vacuum-pumping system into the layer. The volume of the material is divided into a number of layers of small thickness, which ensure homogeneity of the product in the final moisture content.

The distance between the distribution elements, taking into account the permissible difference in moisture content and the resistance of the layer to mass transfer, is determined by the Ergan formula [8]

\[
L = \Delta P / 150 \left(\frac{1 - \epsilon_0}{\epsilon_0}\right)^3 \frac{w \mu}{d^2} + 1.75 \frac{1 - \epsilon_0}{\epsilon_0} \frac{w^2 \rho}{d^2}
\]

The calculations found that the distance between the distribution elements at \( \Delta U_{\Delta} = 0.001 \text{ kg/kg} \) is \( L = 0.15 \text{ m} \).
Calculation of the apparatuses is carried out at the highest load in the gas-vapour phase. This corresponds to the period of free moisture removal (period of constant drying speed). As the residual pressure decreases, the vapor density lowers. With a constant flow rate and a low density of the vapor phase, entering the condenser, a branch pipe diameter connecting the apparatus to the condenser increases significantly. To reduce the hydraulic resistance between the apparatus and the condenser, as well as to create the same process conditions at different points of the dispersed layer, a design of the vacuum apparatus was developed in which the condenser was combined with the working volume of the drying apparatus (Fig.4).

The apparatus comprises a vertical drying chamber 1 with a perforated shell 2 and a system of perforated distribution elements 3, a surface condenser 4. The apparatus and the condenser are placed in a common housing 5 and communicate with each other through a perforated wall and distribution elements. The apparatus is equipped with the loading units 6 and unloading ones 7.

Distribution elements 3 are installed at an angle of the natural slope ($\alpha$) to the perforated shell 2. For activated carbon, the angle of the natural slope, depending on humidity, varies within $\alpha = 34 - 40^0$.

The device operates as follows. A wet material is loaded into the apparatus 1 through the loading unit 6, after which the apparatus is sealed and connected to a vacuum system. With a decrease in the residual pressure, the moisture, evaporated from the material through the system of perforated elements 3, enters the condenser, where it contacts the cooled surface and condenses. The absence of the inert gas (air), which is removed from the apparatus by a vacuum pump, increases the efficiency of the phase transition.

To make the strength calculation of the apparatus, working at the external pressure, some various CAD/CAE systems can be used that provide a calculation and an analysis of the results of the static and dynamic [9], structures.

The strength calculation of the apparatus is based on determining the wall thickness at the largest amount of vacuum. In this case, the nominal wall thickness of the housing is taken as the calculated value [10]

$$s' = 1,15D\left(\frac{P_n}{E_t} - \frac{1}{D}\right)^{0,4},$$

with a check of the results on the admissible pressure

$$p_{ad} = \frac{2\sigma_{cd}(s - C_x)}{D_b \left[1 + 1,02 \left(\frac{1}{s - C_x} \frac{\sigma_{cd}^2}{E_t}\right)^{\frac{3}{2}}\right]} \geq P_n.$$

Fig. 4. Apparatus for removing liquid from dispersed materials by lowering the pressure
The calculations found that the nominal thickness of the outer wall of the apparatus with a diameter of $D = 1000 \text{ mm}$ is $s' = 5.4 \text{ mm}$.

**Legend keys.** $R^*$ - universal gas constant, $p_P$ - full and partial pressure, $j$ - flow of mass, $M$ - molecular mass, $\mu$ - coefficient of dynamic viscosity, $T$ - temperature, $K$; $c$ - mass heat capacity, $\rho$ - density, $w$ - speed, $\lambda$ - heat conduction coefficient, $\tau$ - time, $\alpha$ - heat-transfer coefficient, $F$ - surface, $V$ - volume, $\tau_0$ - latent heat of vaporization at the current temperature and $0 \degree C$, $A, B$ - empirical coefficients in the Antoine equation; $U$ - moisture content, $\varepsilon$ - free space in the layer, $\xi$ - evaporation zone thickness, $m$ - mass porosity, $a_m$ - mass conductivity coefficient, $\delta$ - relative coefficient of thermal diffusion, $K_p$ - molar transfer coefficient, $d, r$ - diameter and radius, $\tau_1$ - material yield strength, $\sigma_{ca}$ - permissible compressive stress of the material, $E'$ - modulus of elasticity of the material.

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