ADVANTAGES OF USING SUPERHEATED STEAM AT ATMOSPHERIC PRESSURE IN DRYING PROCESSES

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This paper shows the variation of the driving forces of external and internal mass transfer in relation to the temperature of the heat-transfer media (superheated steam and air). It is indicated that the use of superheated steam at atmospheric pressure accelerates transport processes and leads to more efficient and more economic drying.

An examination of the kinetics of external and internal heat and mass transfer in drying in superheated steam at atmospheric pressure can be based on the concept of chemical potential [1, 2].

The kinetics of mass transfer in homogeneous open systems depends on the difference in chemical potentials at different points in the system.

Assuming that the conditions of molecular mass transfer are isothermal,

$$q_m = -D\mu \operatorname{grad} \mu, \tag{1}$$

then, according to [2, 3],

$$\operatorname{grad} \mu = -s \operatorname{grad} T + v \operatorname{grad} P + \left(\frac{\partial \mu}{\partial c}\right)_{T,p} \operatorname{grad} c. \tag{2}$$

In a first approximation, in which the mutual effect of energy and mass fluxes is ignored, Eq. (1) can be used in the case of nonisothermal conditions of molecular mass transfer.

We make a comparative estimate of the driving forces grad μ of external mass transfer in the case of evaporation from the surface of a capillary-porous body impregnated with water, when air and superheated steam at atmospheric pressure are used as the heat-transfer media.

The temperature range of the heat-transfer media is 100–500° C. We will confine ourselves to the constant-drying-rate period. Within the considered system we define two subsystems: 1) the main body of the flow of the heat-transfer medium; and 2) the boundary-layer space.

When superheated steam is used, the temperature of the evaporation surface is assumed to be 100° C (saturation temperature at atmospheric pressure); when moist air is used, it is assumed to be 60° C (approximate wet-bulb temperature for moisture contents of 0–100 g per kg of dry air).

Molecular transfer of heat and mass takes place between these subsystems. The change in entropy in one of the subsystems is given by the Gibbs equation [1, 3]

$$TdS = dU + pdV - \sum_{i=1}^{n} \mu_i \, dM_i, \tag{3}$$

which describes nonequilibrium processes in the case in which the changes in temperature, macroscopic velocity, and composition over the mean free path of the molecule are small in comparison with the actual temperature, the average velocity of the molecules, and their concentration [2, 3].

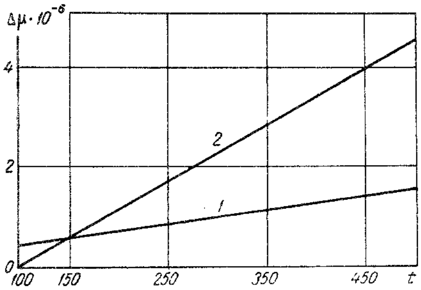

Fig. 1. Calculated differences in chemical potentials ($\Delta\mu$ in J/kg) in relation to temperatures in the main body of the flow (t in °C): 1) air; 2) superheated steam.

Under isobaric and isothermal conditions, the chemical potential for unit mass is

$$\mu = i - Ts. \tag{4}$$

Figure 1 shows the changes in the calculated differences of chemical potentials in superheated steam ($\Delta\mu_s$) and air ($\Delta\mu_a$) in relation to the temperature of the heat-transfer medium.

As the figure shows, up to a flow temperature on the order of 160–180° C, the ratio of the difference in chemical potentials of the two subsystems $\Delta\mu_s = \mu_{bs} - \mu_{ms}$ for superheated steam to the same difference $\Delta\mu_a = \mu_{ba} - \mu_{ma}$ for steam in a steam-air mixture is less than unity, i. e., the driving force of external mass transfer is greater in the case of drying air. At higher temperatures of the heat-transfer medium, the ratio $\Delta\mu_s/\Delta\mu_a$ becomes greater than unity. The temperature of the heat-transfer medium at which $\Delta\mu_s = \Delta\mu_a$ depends on the average temperature of the material in drying by air.

We can arrive at a similar conclusion by considering transport in a steam-air mixture at the surface of a capillary-porous body. If the nonisothermal nature of the heat and mass transfer processes is taken into consideration, the total mass flow from the surface of the material into the main body of the flow is

$$q_m = -D \nabla c_1 - \frac{D}{T}\left[c_1 + k_t\left(c_1 + \frac{M_1}{M_2} c_2\right)\right] \nabla T + uc_1. \tag{5}$$

The first term on the right-hand side of the equation represents mass transfer due to the concentration gradient (concentration diffusion), the second term represents the mass flow due to the temperature gradient, and the third term represents molar mass flow.

In mixtures which do not contain hydrogen, we can neglect thermal diffusion, since $k_t \ll 1$, and then we obtain

$$q_m = -D\nabla c_1 - D\frac{c_1}{T}\nabla T + uc_1. \qquad (6)$$

The experiments of Nesterenko, Dokuchaev, and other have shown that the partial pressure of water vapor on the surface of an evaporating liquid is equal to the saturation pressure at a temperature equal to the surface temperature (a difference of not more than 1–5%). We assume that in air drying the surface temperature of the material does not exceed 60° C. The corresponding water vapor pressure is about 20 000 N/m^2. When superheated vapor is used as a heat-transfer medium, the temperature of the material is maintained at 100° C. The saturation pressure in this case is 98 066.5 N/m^2.

Making a numerical comparison of the difference in vapor concentrations at the surface of the material and in the main body of the flow for the case of evaporation into air and superheated steam, we see that up to a flow temperature of 180–200° C the concentration difference Δc_a in drying by air is greater than the Δc_s in steam. At higher temperatures $\Delta c_s > \Delta c_a$, and with increase in temperature Δc_s increases much more than Δc_a. For instance, when the temperature t of the heat-transfer medium is 150° C, $\Delta c_s/\Delta c_a = 0.53$; when $t = 250°$ C, $\Delta c_s/\Delta c_a = 1.3$; and when $t = 350°$ C, $\Delta c_s/\Delta c_a = 1.8$.

The coefficient of diffusion in air at 0° C is $D_a = 0.216$ cm^2/sec, and the coefficient of self-diffusion of steam at the same temperature is $D_s = 0.266$ cm^2/sec.

The relationship between these coefficients and the temperature is the same:

$$D_a = 0.216\left(\frac{T}{273}\right)^2, \quad D_s = 0.266\left(\frac{T}{273}\right)^2.$$

Thus, a comparison of the numerical values of the driving force of external mass transfer, expressed as the difference of chemical potentials or the difference of concentrations, shows a relative increase of mass transfer in superheated steam when the temperature in the main body of the flow is above 180° C.

A similar conclusion is reached from an estimation of the driving force of internal mass transfer, expressed as the difference in chemical potentials at different points in the body.

Considering the case of symmetry of temperature and moisture distributions in convective heat and mass transfer between a plate and the flow of a heat-transfer medium, we take the difference of chemical potentials at the center (μ_{cm}) and at the surface (μ_{sm}) of the plate as the driving force.

It is known [4] that the chemical potential of mass transfer inside a moist body depends on how the moisture is bound to the material. In the hygroscopic region, where $p/p_s = \varphi < 1$, the chemical potential of mass transfer is identical with this energy of binding of the moisture to the material.

In the region of the moist state of the material ($p - p_s \to 0$; $\varphi \to 1$), the chemical potential is a function of the temperature and moisture content. Proceeding from the fact that the binding of moisture in macrocapillaries is purely mechanical, Nikitina obtained an expression for the chemical potential of water in a capillary in the form [4]

$$\mu = i - Ts - \frac{2v_l\,\sigma}{r}. \qquad (7)$$

The variation of the chemical potential of mass transfer in material in relation to temperature of the material, calculated from formula (7), is shown in Fig. 2. The mean radius of the capillaries in the material was taken as $r = 1 \cdot 10^{-6}$ m.

As the figure shows, the difference in chemical potentials $\Delta\mu_1$ for a temperature difference of one degree increases with increase in the mean temperature $\bar{\vartheta}$ of the material. For instance, at a mean temperature of 30° C $\Delta\mu_1 = 0.37 \cdot 10^{-6}$ J/kg, at $\bar{\vartheta} = 60°$ C $\Delta\mu_1 = 0.9 \cdot 10^{-6}$ J/kg, and at $\bar{\vartheta} = 100°$ C $\Delta\mu_1 = 1.3 \cdot 10^{-6}$ J/kg.

Since the temperature of the material during drying in superheated steam is higher than in drying by air, the internal mass transfer, determined by the difference in chemical potentials, is more rapid when superheated steam is used as a heat-transfer medium than when air with the same parameters is used.

We can arrive at a similar conclusion when we consider that an increase in the mean temperature of the material improves the mechanism and coefficients of mass transfer. Phase change of the bound substance is first greatly intensified. The dominant process may be molar mass transfer due to the unrelaxed pressure gradient.

The intensification of molecular and molar mass transfer is also assisted by an increase in thermal conductivity, thermal diffusivity, and moisture diffusion.

Thus, the use of superheated steam as a heat-transfer medium has advantages over air as regards both external and internal heat and mass transfer in the drying of capillary-porous bodies during the constant drying rate period.

An analysis of the processes in dryers by the exergetic method can be used to determine the performance and sources of loss in various power plants [5]. The loss is defined as the difference between the maximum possible work and that actually performed:

$$\Delta e_{\text{loss}} = e - Ae. \qquad (8)$$

In real plants the loss is due mainly to the existence of finite temperature differences, hydraulic resistances, heat loss to the surroundings, and leakage of working fluids in plants working under excess pressure.

By compiling the mass and heat balance of a dryer when air or superheated steam is used as a heat-transfer medium, we can calculate the exergy of the working media at all characteristic points of the system. We can then compile the energy balance of the different parts and the system as a whole and determine the energy efficiency of the apparatus:

$$\eta_e = 1 - \frac{\Sigma\Delta e_{\text{loss}}}{e_{\text{exp}}} = \frac{e_{\text{use}}}{e_{\text{exp}}}. \qquad (9)$$

The determination and calculation of the quantities comprising the thermodynamic loss in the different parts of a specific type of dryer for nontextile adhesive materials, in the case of drying by steam and air with an initial temperature of 250° C, enabled us to establish that the energy efficiency η_e^s in the first case is higher than in drying by air η_e^a : $\eta_e^s = 26\%$ and $\eta_e^a = 18\%$. The smaller value can be explained as follows:

1. In the process of mass transfer occurring in a drying chamber with superheated steam as a heat-transfer agent, two substances of similar nature are mixed (water from the material and the superheated steam). The thermodynamic loss in the mixing of substances of different nature (water from the material and air) is much higher.

2. The loss due to the finite temperature differences is directly proportional to the temperature difference and inversely proportional to the product of the absolute temperatures of the bodies involved in the heat transfer. Since, as we have seen, the temperature difference between the drying agent and the surface of the material in the first drying period is higher when air is used as a heat-transfer medium than when superheated steam is used, the thermodynamic loss in the first case is higher than in the second.

Thus, from the thermodynamic aspect, drying by superheated steam is more efficient ($\eta_e^s > \eta_e^a$).

The use of superheated steam in dryers has several technical and economic advantages in comparison with air or furnace gases:

a) the specific heat consumption is reduced, since it is possible not only to minimize the heat loss with the discharged heat-transfer medium by the use of a closed-circuit system, but also to utilize a great proportion of the heat expended on the evaporation of moisture from the material;

b) the drying rate can be greatly increased usually without affecting the condition of the final material;

c) the absence of free oxygen in superheated steam rules out ignition of the material, which means that media with high initial temperatures can be used;

d) operating and, probably, capital costs are reduced in comparison with the use of dry air, since the volumetric specific heat of steam is 20–30% higher than that of air.

One of the serious drawbacks of dryers using superheated steam is the problem of sealing the system for continuous feed and withdrawal of material. The presence of admixtures of air in the steam cancels out the above advantages of superheated steam. The use of a heat-transfer medium with high initial temperatures, the possibility of operation at low (~2–5 mm water) excess pressure, and continuous progress in design will lead in the very near future to the extensive adoption of this method of drying.

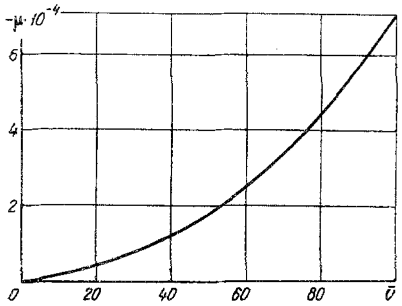

Fig. 2. Chemical potential (μ in J/kg) of material as a function of temperature ($\bar{\vartheta}$ in ° C).

NOTATION

q_m is the specific mass flux; D_μ is the molecular diffusion coefficient based on the gradient of the chemical potential; μ is the chemical potential per unit mass; s, T, v, p, and c are the entropy, absolute temperature, specific volume, pressure, and concentration respectively; U, V, μ_i, and M_i are respectively, the internal energy, volume, chemical potential, and mass of the i-th subsystem; i is the specific enthalpy; μ_b and μ_m are the chemical potentials calculated for parameters of the boundary layer and the main body of the flow, respectively; D is the molecular diffusion coefficient based on the concentration gradient; M_1, M_2, c_1, and c_2 are the molecular weights and concentrations of steam and air, respectively; k_t is the thermal diffusion coefficient; u is the velocity of the molar flow of mass in the direction of the normal to the evaporation surface; v_l is the specific volume of the liquid enclosed in the capillaries; σ is the surface tension; Δe_{loss} is the loss of exergy of the working media in individual parts of the plant; Δe_{exp} is the expended exergy of the working media; e_{use} is the usefully expended exergy.

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