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# CONDENSATION ENLARGEMENT OF AEROSOL PARTICLES WHEN A GAS MIXES WITH A VAPOR

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From the equations of material and heat balances of the process, functions are obtained for determining the amount of condensate and the diameter of the aerosol particles following the mixing of a gas with a vapor.

The condensation enlargement of aerosol particles in the mixing of a gas with a vapor is used to increase the efficiency of separation of mechanical impurities in the scrubbing of industrial exhaust gases and ventilating air [1-6]. The use of this method enables one not only to separate finer particles from the gas than under ordinary conditions, but it also considerably reduces the energy expended on scrubbing.

To start the condensation process in a two-phase system it is necessary to create supersaturation greater than the critical value determined by the Kelvin equation [7]:

$$S_{cr} = \frac{p_d}{p_s} = \exp\left(\frac{4\sigma M_v}{RT_m \rho_c d_i}\right). \qquad (1)$$

We note that Eq. (1) is valid in vapor condensation both onto liquid drops and onto solid particles, since the mechanism of the process is the same in both cases [7].

To determine the diameter of the aerosol particles after mixing we analyze the equations of material and heat balances of the process. Here we make the following assumptions: The volume of the aerosol particles and of the condensate formed is small compared with the volume of the vapor–gas mixture, the temperature of the particles and condensate after mixing equals the temperature of the mixture, the mixing takes place without heat exchange with the surrounding medium, and the gas and vapor obey the laws of an ideal gas.

The equation of heat balance, analogous to that presented in [8] but with allowance for the initial moisture content of the gas, can be written in the form

$$G_g c_g (T_m - T_g) + x_i G_g c_v (T_m - T_g) = G_v c_v (T_v - T_m) + G_c r. \qquad (2)$$

Dividing Eq. (2) by $G_g$ and introducing the notation $k = G_c/G_g$ and $\Delta x = G_v/G_g$, after transformations we obtain

$$(c_g + x_i c_v)(T_m - T_g) = \Delta x c_v (T_v - T_m) + kr. \qquad (3)$$

We represent the equation of material balance in the form

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$$G_g + x_i G_g + G_v = G_g + x_f G_g + G_c \tag{4}$$

or

$$x_i + \Delta x = x_f + k. \tag{5}$$

The vapor content in the vapor–gas mixture after condensation is determined by the relation [9]

$$x_f = \frac{M_v}{M_g} \frac{p_v}{P - p_v}. \tag{6}$$

After the formation of the condensate the partial vapor pressure in the mixture equals the pressure of saturated vapor at its temperature. If the surface area of the aerosol particles is greater than the surface area of the vessel in which the mixing occurs, then one can take it that all the condensate forms on the particles. Moreover, there is no possibility in principle for spontaneous (homogeneous) condensation to occur when aerosol particles are present in the gas, since the size of the newly formed condensation nuclei — liquid drops — is incomparably smaller than the usual size of aerosol particles [7], and for condensation on their surfaces, in accordance with Eq. (1), it is necessary to create far greater supersaturation in the mixture. Consequently, the partial vapor pressure in the system after mixing will equal the pressure of saturated vapor above a drop:

$$p_v = p_d = S_{cr} p_s. \tag{7}$$

The temperature dependence of the pressure of saturated vapor above a plane surface can be expressed by an equation, convenient for calculations, obtained from the Clausius–Clapeyron equation [10]:

$$p_s = \exp\left(A - \frac{rM_v}{RT_m}\right). \tag{8}$$

Substituting the expressions (7) and (8) into Eq. (6), after transformations using the laws of an ideal gas we obtain the expression for determining the vapor content in the vapor–gas mixture after condensation:

$$x_f = \frac{M_v}{M_g} \frac{T_g}{T_m} \frac{S_{cr}}{p_g} \exp\left(A - \frac{rM_v}{RT_m}\right). \tag{9}$$

The final size of the aerosol particles is the determining size in the calculation of the amount of supersaturation after condensation. Assuming that the condensate formed is uniformly distributed over all the particles, we can obtain an expression for calculating the particle diameter after mixing:

$$d_f = \left(\frac{6k\rho_g}{n\pi\rho_c} + d_i^3\right)^{1/3}. \tag{10}$$

Then

$$x_f = \frac{M_v}{M_g} \frac{T_g}{T_m} \frac{1}{p_g} \exp\left[\frac{M_v}{RT_m}\left(\frac{4\sigma}{\rho_c \sqrt[3]{\dfrac{6k\rho_g}{n\pi\rho_c} + d_i^3}} - r\right) + A\right]. \tag{11}$$

The system of equations (3), (5), and (11) contains three unknown parameters: k, $x_f$, and $T_m$. After transformations it can be reduced to a transcendental equation with one unknown:

$$k = x_i + \Delta x - \frac{M_v}{M_g} \frac{T_g}{p_g} \frac{c_g + (x_i + \Delta x) c_v}{T_g(c_g + x_i c_v) + \Delta x c_v T_v + kr} \times$$
$$\times \exp\left[\frac{c_g + (x_i + \Delta x) c_v}{T_g(c_g + x_i c_v) + \Delta x c_v T_v + kr}\left(\frac{4\sigma}{\rho_c \sqrt[3]{\dfrac{6k\rho_g}{n\pi\rho_c} + d_i^3}} - r\right)\frac{M_v}{R} + A\right]. \tag{12}$$

Calculating from Eq. (12) the specific amount k of condensate obtained, from Eq. (10) one can determine the diameter of the aerosol particles after mixing, while the temperature of the mixture can be determined using Eq. (3).

Equation (12) was solved on a computer by Newton's method in the following intervals of variation of the main parameters: $T_g$ = 283-353°K, $d_i$ = 0.1-10 μm, n = $10^8$-$10^{12}$ m$^{-3}$, Δx =

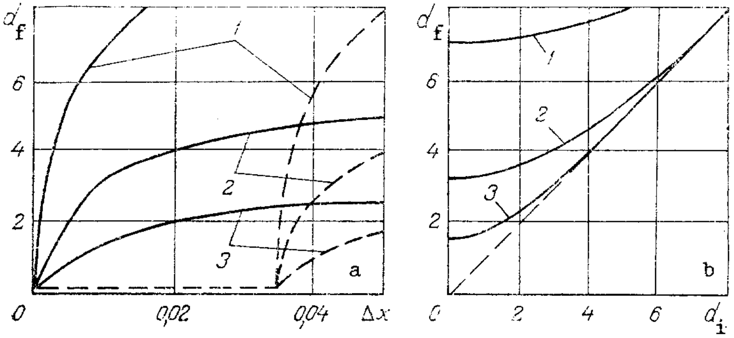

Fig. 1. Dependence of the diameter $d_f$ (μm) of particles after mixing on the specific vapor flow rate Δx (a) ($d_i$ = 0.1 μm, $T_g$ = 303°K, solid lines are φ = 100%, dashed lines are φ = 0) and their initial diameter $d_i$ (μm) (b) ($T_g$ = 303°K, Δx = 0.01, φ = 100%): 1) $n = 10^{10}$ $m^{-3}$; 2) $10^{11}$; 3) $10^{12}$.

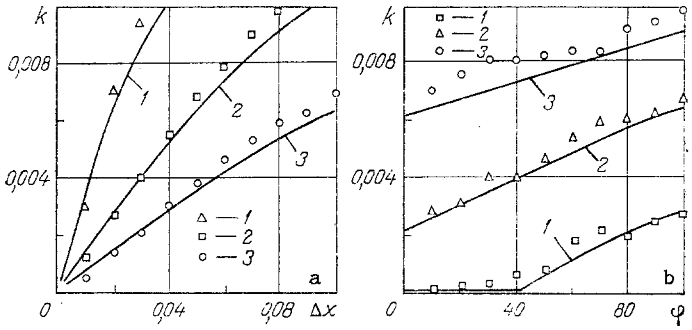

Fig. 2. Dependence of the condensate yield k on the specific vapor flow rate Δx (a) [φ = 100%: 1) $T_g$ = 283°K; 2) 303; 3) 323] and the initial humidity φ (%) of the gas (b) [$T_g$ = 303°K: 1) Δx = 0.02; 2) 0.05; 3) 0.08].

0-0.1, and an initial humidity of the gas (air) of from 0 to 100%. Some results of the calculations are presented in Figs. 1 and 2.

An experimental test of the proposed model was made in a cylindrical mixing chamber, equipped with thermal insulation, on a dusty air—water vapor system. As the disperse phase we used powders of various origin (M-1 quartz powder, zinc oxide, phosphorite, carbon black, etc.) with a bulk density of from 1000 to 2000 kg/m³ and particle sizes of from 0.1 to 10 μm. The main parameters were varied in the intervals indicated above. The concentration and disperse composition of the aerosol particles in air and in the vapor—air mixture were determined with an AZ-5M counter.

The experimental investigations showed that the proposed mathematical model describes the process under consideration qualitatively correctly. However, the large error in determining the disperse composition and concentration of aerosol particles using an AZ-5M counter (up to 20% for particles more than 1 μm in diameter), as with other presently existing instruments [11], prevents us from making a quantitative comparison of the calculated and experimental data. Therefore, the experimental test of the proposed model was made with respect to the amount of condensate formed in the vapor—air mixture after mixing. The condensate obtained was separated from the mixture using a centrifugal separator with a screw swirler and an FPP-15-1.7 Petryanov filter [12]. The experimental values of the amount of condensate obtained are plotted in Fig. 2a and b. The discrepancy between the experimental and calculated [from Eq. (12)] data did not exceed 15% in the indicated intervals of variation of the main parameters.

The calculations and experimental investigations show that carrying out the process of condensation enlargement of aerosol particles during mixing of a gas with a vapor enables one to considerably increase their size and thereby facilitate their subsequent separation. It is most practical to carry out the process at relatively low number concentrations of the disperse phase (up to $10^{12}$ $m^{-3}$), a low initial temperature, and a high gas humidity. For higher number concentrations of particles and temperatures and a lower initial humidity the condensation enlargment requires large vapor flow rates for mixing and hence high expenditures of energy. In the enlargement of particles with an initial diameter of less than 1 μm their final size is determined mainly by the amount of condensate formed on their surfaces and depends little on the initial size (Fig. 1b), since in this case the volume of liquid on the particle is considerably greater than its initial volume. In this case the particles obtained after mixing are practically monodisperse.

## NOTATION

A, coefficient in Eq. (8), dependent on the properties of the condensing material [10]; $c_g$, $c_v$, specific heats of the gas and vapor, J/(kg·°K); $d_i$, $d_f$, diameters of aerosol particles before and after mixing, m; $G_g$, $G_v$, mass flow rates of dry gas and vapor, kg/sec; $G_c$, yield of condensate, kg/sec; $k = G_c/G_g$, specific yield of condensate; $M_g$, $M_v$, molecular masses of gas and vapor, kg/kmole; n, number concentration of aerosol particles in the gas, $m^{-3}$; P, pressure of vapor—gas mixture, Pa; $p_g$, $p_v$, partial pressures of gas and vapor in the mixture, Pa; $p_s$, $p_d$, pressures of saturated vapor above a plane surface and above a drop, Pa; $R = 8.31 \cdot 10^3$ J/(kmole·°K), universal gas constant; r, specific heat of the phase transition, J/kg; $S_{cr} = p_d/p_s$, critical supersaturation; $T_g$, $T_v$, $T_m$, temperatures of gas, vapor, and vapor—gas mixture, °K; $x_i$, $x_f$, initial and final moisture content; $\Delta x = G_v/G_g$, specific vapor flow rate; $\rho_g$, $\rho_c$, densities of gas and condensate, kg/m³; σ, surface tension of condensing liquid, N/m; φ, humidity of gas, %.

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