AN INVESTIGATION OF THE EVAPORATION OF DROPS IN SUPERHEATED VAPOR

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A model of the evaporation of drops in the spray cone is proposed. A system of equations for calculation of the main characteristics of the spray cone is derived.

The well-known technological and energetic advantages of superheated vapor as a heat-carrier in driers [1] can be used in several cases for the production of efficient spray driers [2].

There are opportunities in this case for acceleration of evaporation, the realization of a practically closed entrainment-free system, and so on. The use of spray driers, which are designed for evaporation of droplets of a solution into its own superheated vapor is advantageous, for instance, in cases of drying of small amounts of particularly valuable or toxic materials. Design calculations for such driers require information about the quantitative relationships governing the evaporation, movement, and interaction of the drops (singly and in polydisperse aggregates).

This led us to carry out experimental and theoretical investigations to determine the basic prerequisites for the conduction of engineering calculations.

The experiments were carried out on two rigs. The first rig was designed for the investigation of drying of single drops attached to a thermocouple junction situated on the axis of a tube of diameter 60 mm. Superheated steam at atmospheric pressure flowed through the tube at a mean velocity of 1 to 12 m/sec. The temperature of the steam varied from 423 to 823° K. There was provision for spraying drops of water of different size into the steam flow.

In the experiments we measured the parameters of the steam flow, and the variable temperatures and sizes of the drops.

The second rig was a single-pass pilot-plant spray drier with a chamber 1.6 m high and 0.31 m in diameter.

The sprayer was a centrifugal nozzle providing a flow of solution at a rate of 1.4 to 2.8 g/sec. The steam flow rate varied from 8.3 to 33.4 g/sec, and its initial temperature from 423 to 823° K. All the parameters in the drier chamber were measured by means of a set of new measuring devices [2]. In all the series of experiments we investigated the evaporation of drops of an aqueous $NaNO_3$ solution (concentration 200 g/l) in the first drying period and twice-distilled water. To obtain comparative data we also used air as a heat-carrier. Figure 1 shows the experimental

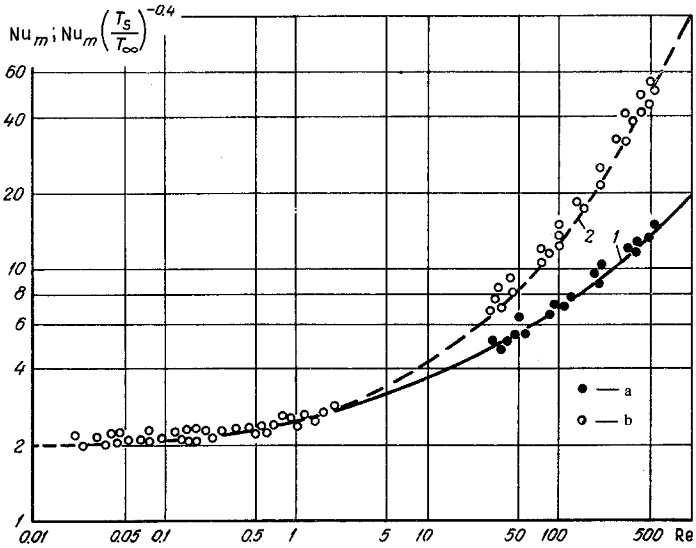

Fig. 1. Mass transfer in evaporation of drops: 1) from Fressing formula (air); 2) experimental data; a) air [$Nu_m = f(Re)$]; b) superheated steam ($Nu_m (T_S/T_\infty)^{-0.4} = f(Re)$).

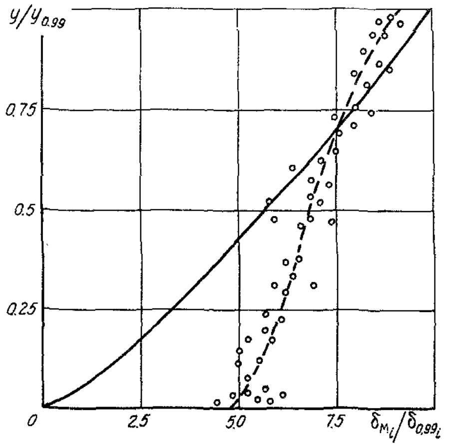

Fig. 2. Distribution of drop sizes in cross section of evaporating cone: the solid line is the theoretical distribution $y/y_{0.99} = (\delta_{M_i}/\delta_{0.99i})^{1.2}$; the dashed line represents the experimental data.

data for the evaporation of drops (Re = 0.01–500). At Re = 0.01–2 we used the results of measurements of the distributions of the phase velocities, irrigation densities, temperatures, and dispersity of the drops directly in the spray cone. The other results were obtained from the investigation of the kinetics of evaporation of single attached drops.

These experimental data could be approximated by the following relationships:

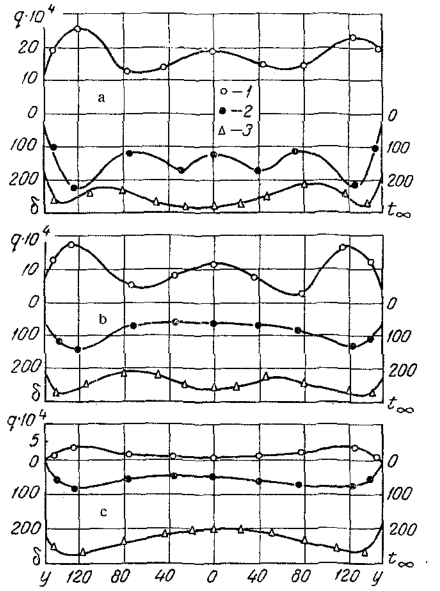

Fig. 3. Results of measurements inside evaporating cone in superheated steam (x and y in mm). a) x = 203; Z_Σ = 0.73 W_{av} = 32%; b) x = 345; Z_Σ = 0.85 W_{av} = 19%; c) x = 725; Z_Σ = 0.99 W_{av} = 3%; 1) irrigation density (q in g/cm^2 · sec); 2) volume-surface diameter of drops (δ in μ); 3) temperature of dispersed medium (t_∞ in °C).

1) for evaporation into superheated steam

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_m} = 0.7\pi_\rho K \quad \text{for} \quad T_\infty < 573\,^\circ\mathrm{K}, \tag{1}$$

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_m} = 0.95\pi_\rho K \quad \text{for} \quad 573\,^\circ\mathrm{K} < T_\infty < 773\,^\circ\mathrm{K}, \tag{2}$$

where $\pi_\rho = (\rho'' - \rho_\infty)/\rho(T_{av})$;

2) for evaporation into air

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_m} = \pi_\rho K \quad \text{for} \quad 423\,^\circ\mathrm{K} < T_\infty < 823\,^\circ\mathrm{K}, \tag{3}$$

where $\pi_\rho = (c_{v0} - c_{v\infty})/\rho m(T_{av})$;

The theoretical relationship for the determination of Nu_m is given below (relationship 10).

An evaluation of the confidence limits of the calculated heat and mass transfer coefficients by Student's method [4] showed that the error in the evaluation of these quantities was about 15%. The results of measurement of the velocities of the drops along the axis of the spray cone can be represented by the following approximate relationship:

$$C_x = 80\,\mathrm{Re}^{-0.2}. \tag{4}$$

The scatter of the experimental points was ±25%; Nu_m = 2–9, Re = 0.01–50.

Using the obtained relationships for the determination of Nu_m and C_x we analyzed the transfer processes in the spray cone.

Figure 2 shows the theoretical and experimental curves of $y = f(\delta)$. We attributed the noncoincidence of the curves to mixing of particles of different monodisperse groups as they moved together within the spray cone. This is largely due to the fairly powerful ejection streams which arise around the cone. The possibility of regarding the spray cone as a stage of ideal mixing is confirmed also by the experimental data in Fig. 3. For the three cross sections of the cone in which we measured the radial temperature distribution of the heat-carrier (steam) we obtained a practically constant (to within ±5%) value. In considering the question of evaporation of drops in the cone we used the arguments expounded in [3] and made the following assumptions:

a) The evaporating cone can arbitrarily be divided lengthwise into two zones (Fig. 4): the stagnation zone, $x_i < x_1$; the residence zone, $x_i > x_1$.

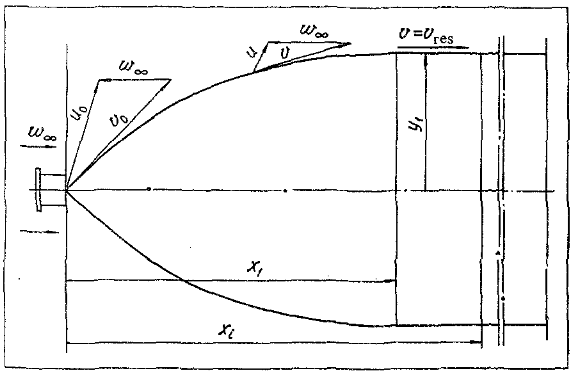

Fig. 4. Diagram of motion of drops in cone.

b) In view of the relatively small value of x_1 (in our experiments 150–250 mm) and the intense mixing of phases we can assume for the stagnation zone

$$T_\infty = T_{\infty i} = \text{const}, \tag{5}$$

$$w_\infty = w_{\infty i} = \text{const}. \tag{6}$$

In addition, on the basis of our experimental data, obtained on the rig for investigation of the evaporation of an attached drop in a stream of suspension of drops in gas, we assumed that there is no coalescence of drops in the stagnation zone ($K_{d0} = 0$).

c) For the residence zone we assumed:

$$T_\infty = T_{x_1} = \text{const}, \tag{7}$$

$$u = v_{res}, \tag{8}$$

$$0 < K_{d0} < 1. \tag{9}$$

The temperature T_{x_1} of the heat-carrier, corresponding to the cross section x_1 of the cone, is determined from the balance equation with allowance for evaporation of drops in the stagnation zone. Taking into account what was said above we derived a system of equations:

$$\mathrm{Nu}_m = 2 + 0.35\,\mathrm{Re}^{0.8}\left(\frac{T_s}{T_\infty}\right)^{0.4}, \tag{10}$$

$$m\frac{d\bar{v}}{d\tau} = -C_x f \rho_\infty \frac{u}{2}\bar{u}, \tag{11}$$

$$C_x = 80\,\mathrm{Re}^{-0.2},$$

$$\frac{\sum\limits_{0}^{\delta_i} G_i}{G_0} = 1 - \exp\left[-0.693\left(\frac{\delta}{\delta_M}\right)^n\right]. \tag{12}$$

The last equation describes the integral distribution of drops in a nonevaporating ("cold") cone.

The joint solution of Eqs. (10)–(12) leads to the following relationships. For the time of flight (in the stagnation zone)

$$\tau_{(x,y)} = \frac{A'}{(0.8 - 0.4\,\mathrm{K})u_0^{0.8}}\left[\left(\frac{u}{u_0}\right)^{0.4\mathrm{K}-0.8} - 1\right], \tag{13}$$

where

$$A' = \frac{1}{60}\frac{\rho_L}{\rho_\infty}\frac{\delta_0^{1.2}}{\nu_{(T_{av})}^{0.2}}.$$

For the range of a drop with initial diameter δ_0

$$x = \frac{A' w_\infty}{(0.8 - 0.4\,\mathrm{K})u_0^{0.8}}\left[\left(\frac{u}{u_0}\right)^{0.4\mathrm{K}-0.8} - 1\right] + \frac{A' u_0^{0.2}}{0.4\,\mathrm{K} + 0.2}\left[1 - \left(\frac{u}{u_0}\right)^{0.4\mathrm{K}+0.2}\right]\cos\beta. \tag{14}$$

For the radial coordinate of a drop with initial diameter δ_0

$$y = \frac{A' u_0^{0.2}}{0.4\mathrm{K} + 0.2}\left[1 - \left(\frac{u}{u_0}\right)^{0.4\mathrm{K}+0.2}\right]\sin\beta. \tag{15}$$

The trajectory of drops in the stagnation zone can be calculated more easily by assigning various intermediate values of $u = u_0 - v_{res}$. The total degree of evaporation of drops in the cross section x_i is

$$Z_\Sigma = \sum_{\delta_{min}}^{\delta_{max}} G_i\left[1 - \left(\frac{u}{u_0}\right)^k\right], \tag{16}$$

where

$$k = \frac{C_1}{10}\frac{D_{(T_{av})}}{\nu_{(T_{av})}}\frac{\rho'' - \rho_\infty}{\rho_\infty}\left(\frac{T_s}{T_\infty}\right)^{0.4}$$

The expression for calculating the size of the drop in the residence zone from cross section x_1 to x_i is

$$\delta_{x_i} = \left[\delta_{x_1}^3 - \frac{6\delta_{x_1}}{\rho_L} D_{(T_{av})}(\rho'' - \rho_\infty)\,\mathrm{Nu}_m\frac{x_i - x_1}{v_{res}}\right]^{1/3}. \tag{17}$$

Calculation from relationship (17) is carried out for each monodisperse group of drops which continue to move after the cross section x_1. The number of cells which must be taken within the space of the evaporating cone is determined in each specific case by the required accuracy of the calculation. Using the calculation procedure presented above we determined the dimensions of an industrial model of spray drier. Tests of this model confirmed the correctness of the postulated picture of the process and the reliability of the experimentally obtained relationships.

NOTATION

ρ_L, ρ'', and ρ_∞ are the densities of liquid, saturated steam, and dispersed medium; $\rho_m(T_{av})$, and $\rho(T_{av})$ are the densities of steam-air mixture and superheated steam at T_{av}; T_s and T_∞ are the temperatures of equilibrium evaporation and gas phase; $T_{av} = 0.5(T_s + T_\infty)$ is the average temperature in boundary layer; c_{v0} and $c_{v\infty}$ are the concentrations of steam in air on surface of drop and outside it; C_x is the dynamic drag factor of drop in steam; δ and $\delta_{0.99}$ are instantaneous diameter of drop and diameter corresponding to 99% of total weight of drops less than $\delta_{0.99}$ in diameter; W_{av} is the average moisture content of particles over cross section; x_1 is the range of drops with diameter $\delta_{0.99}$; $T_{\infty i}$ and $w_{\infty i}$ are the initial temperature and velocity of gas phase; v_{res} is the residence velocity; u and v are the relative and absolute velocities of drop; K_{d0} is the effectiveness of coalescence of drops on collision; w_∞ is the velocity of gas phase; m and f are the mass and cross section of drop; G_i and G_0 are the weight of monodisperse group of drops and output of nozzle; δ_m and n are the constants of size and uniformity of Rozin–Ramler distribution in "cold" cone; $\tau_{(x,y)}$ is the instantaneous time of flight of drop; U_0 and V_0 are the initial relative and absolute velocities of drop; δ_0 is the initial diameter of monodisperse group of drops; $\nu(T_{av})$ is the kinematic viscosity of gas at T_{av}; β is the angle of spray cone; x and y are the longitudinal and radial coordinates; Z_Σ is the total degree of evaporation of drops; $D(T_{av})$ is the diffusion coefficient of gas at T_{av}; Re, Nu, Nu_m, and K are the Reynolds, Nusselt, mass transfer Nusselt, and Kutateladze numbers; $C_1 = (\mathrm{Nu}_m/\mathrm{Re}^{0.8})(T_s/T_\infty)^{0.4}$.

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