AN INTEGRATED METHOD OF ANALYZING THE PROCESSES OF SPRAY DRYING

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We discuss the essence of an integrated method of analyzing the processes of spray drying, and this procedure calls for the combined utilization of new measurement methods in drying chambers, the results of these measurements, as well as an analytical model of the transport processes in flows of gas suspensions.

To refine the physical essence of spray-drying processes, to improve the methods of engineering calculation, and to solve the problems of approximate modeling of drying installations, effective use has been made in a number of cases of the integrated application of new measuring devices [1] developed in recent years at the Moscow Power Engineering Institute, in addition to an analytical model of the transport applicable to flows of gas suspensions.

Characteristic features in the latter include the following:

1) the flow of the gas suspension is treated as quasihomogeneous and as consisting of two phases: particles (solids and liquid drops) and a heat carrier;

2) the equations of continuity, motion, and heat and mass transfer are written separately for each phase and include averaged measured quantities;

3) the processes of heat and mass transfer are covered by sources and sinks established theoretically or experimentally, under laboratory conditions, and referred to elementary volumes within which it is possible to measure all of the remaining quantities (temperatures, moisture contents, velocities, etc.). The system of equations written in dimensionless form for the general case of transport in the flow of a gas suspension in the presence of heat and mass transfer has the following form:

the equation of continuity for the quasihomogeneous phase of the particles

$$\frac{D\mathrm{R_p}}{d\mathrm{Ho}} + \mathrm{R_p}\,\mathrm{div}\,\mathbf{W}_\mathrm{p} = -K_{q_{mv}\mathrm{p}} Q_{mv}, \tag{1}$$

the equation of continuity for the heat carrier

$$\mathrm{S}_w \frac{D\mathrm{R_g}}{d\mathrm{Ho}} + \mathrm{R_g}\,\mathrm{div}\,\mathbf{W}_\mathrm{g} = K_{q_{mv}\mathrm{g}} Q_{mv}, \tag{2}$$

the equation of particle motion

$$\frac{D\,\mathrm{R_p}W_\mathrm{p}}{d\mathrm{Ho}} = \frac{\mathrm{R_p}}{\mathrm{Fr_p}} + \mathrm{Eu}\,\mathrm{grad}\,\mathrm{P_p} + K_{\Omega_\mathrm{p}} \mathrm{S}_{\rho_1} \xi\, \Omega_\mathrm{p} \frac{\mathrm{R_g}\mathrm{W_p^2}}{2} \tag{3}$$

the equation of motion for the heat carrier

$$\frac{1}{\mathrm{S}_w} \frac{D\mathrm{R_g}\mathbf{W}_\mathrm{g}}{d\mathrm{Ho}} = \frac{\mathrm{R_g}}{\mathrm{Fr_g}} + \mathrm{Eu}\,\mathrm{grad}\,\mathrm{P_g} + \frac{1}{\mathrm{Re_g}} \mu_\mathrm{g} \nabla^2 \mathrm{W_g} - K_{\Omega\mathrm{p}} \xi \frac{\Omega_\mathrm{p}\mathrm{R_g}\mathbf{W}_\mathrm{p}^2}{2}, \tag{4}$$

the equation of heat transfer in the particle phase

$$\frac{\mathrm{R_p}}{\mathrm{T_p}} \frac{DT_\mathrm{p}}{d\mathrm{Ho}} + \frac{\mathrm{R_p}}{\bar{\mathrm{C}}_\mathrm{p}} \frac{D\bar{\mathrm{C}}_\mathrm{p}}{d\mathrm{Ho}} + \mathbf{W}_\mathrm{p}\,\mathrm{grad}\,\mathrm{R_p} = K_{q_{mv}\mathrm{p}} Q_{mv} + K_{q_v\mathrm{p}} \frac{Q_v}{\bar{\mathrm{C}}_\mathrm{p}\mathrm{T_p}}, \tag{5}$$

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the equation of heat transfer for the heat carrier

$$S_c S_w \bar{C}_{mix} \frac{DT_g}{dHo} + S_w T_g \frac{D\bar{C}_g}{dHo} + K_{c_{vap}} S_w T_g \bar{d} \frac{D\bar{C}_{vap}}{dHo} + K_{J_{vap}} S_w \bar{J}_{vap} \frac{D\bar{d}}{dHo} + K_p S_w \bar{d} \frac{D\bar{r}}{dHo} - \frac{1}{Pe} \frac{\bar{\lambda}_g}{R_g} \nabla^2 T_g$$

$$- \frac{1}{Pe} \operatorname{grad} T_g \operatorname{grad} \bar{\lambda}_g = -K_{J_{mix}} K_{q_{mv} g} \frac{\bar{J}_{mix}}{R_g} Q_{mv} - K_{q_v g} \frac{Q_v}{R_g}, \tag{6}$$

the equation of mass transfer in the particle phase

$$u_{p0} \frac{DU_p}{dHo} = -K_{q_{mv} p} R_p^0 Q_{mv}, \tag{7}$$

the equation of mass transfer for the heat carrier

$$\frac{DR_{vap\,0}}{dHo} + \frac{R_{vap}}{S_w} \operatorname{div} \mathbf{W}_g = K_{q_{mv} p} S_{\rho_s} Q_{mv}. \tag{8}$$

The equations of system (1)-(8) should be broadened with characteristic relationships such as

$$\bar{\lambda}_g = \frac{\lambda_g}{\lambda_{g0}} = f(L,\ Ho,\ \mathbf{W}_{gb},\ T_{gb},\ R_{vap b}),$$

as well as with equations describing the boundary conditions.

In the general case, we should seek the determined quantities R_p, R_g, U_g, U_p, T_g, T_p, $\mathbf{W}_g$, and $\mathbf{W}_p$ as functions of L, Ho, $\mathbf{W}_{gb}$, T_{gb}, R_{vapb}, $K_{q_{mv}}$, Eu, $K_{\Omega p}$, Re, Fr, Pe, $\bar{K}_r$, $\bar{K}_J$, $\bar{K}_c$, $\bar{K}_{qv}$, S_w, and $S_{\rho i}$.

As the parameters we can use, for example, the values of the corresponding quantities for the non-evaporated ("cold") flow (the volume of the spray plume included).

The equations given above, as well as the generalized variables, serve as the basis for an analysis of the special problems of transport, the processing of the experimental data, and the examination of the problem relating to the approximate modeling of processes in the separate cells of spray drying chambers (in the spray plume, in the feed and drain zones for the heat carrier, and in the zone of steady motion). It is obvious that contemporary data on the kinetics of the drying of drops of various solutions, on the space – time development of the processes of spray drying, not to speak of the purely mathematical complexities of the problem, governs the impossibility of achieving applied results on the basis of a purely theoretical investigation.

Most important from the practical standpoint, and yet very inadequately studied, are the quantitative relationships of the kinetics of drying, on the structure – shape formation, and on the motion of an aggregate of polydisperse evaporating particles.

These quantities must be studied not only from the theoretical standpoint, but experimentally as well, on the basis of a special laboratory drying chamber [2], as well as through application of a method to measure particle velocities [1]. Proceeding from the fact that within spray-dryer chambers there exist characteristic spaces within which the motion and drying of drops determine the dimensions of the chambers and the technological perfection of the process, the investigations must be directed toward refining the situation within these regions. For example, an extremely important problem is the one of determining the approximation relationships and the theoretical analysis of the motion and drying within the volume of the spray plume along the direction of particle and drop motion, with maximum and minimum concentration in the flow. These directions are reliably determined on the basis of [3], as was done, for example, in [4].

In this case, the analytical model can be reduced to the one-dimensional case of analyzing the transport in the quasihomogeneous particle phase.

The velocity, temperature, and moisture-content fields for the gas in this case are determined either in the assumption that the spray plume is a cell of ideal mixing [5], or on the basis of the data derived from models or under the real conditions of the drying installation. In the assumption that C_p is constant, we find that the system of transport equations for the case of one-dimensional steady-state particle motion (along the coordinate x) assumes the form

$$\mathbf{W}_p \frac{dR_p}{dX} + R_p \frac{d\mathbf{W}_p}{dX} = -K_{q_{mv} p} Q_{mv}, \tag{9}$$

$$\mathbf{W}_{\mathrm{p}} \frac{d\mathrm{R}_{\mathrm{p}}\mathbf{W}_{\mathrm{p}}}{dX} = \frac{\mathrm{R}_{\mathrm{p}}}{\mathrm{Fr}} + \mathrm{Eu}\,\frac{d\mathrm{P}_{\mathrm{g}}}{dX} - \mathrm{K}_{\Omega_r}\mathrm{S}_{\rho_1}\xi\overline{\Omega}_{\mathrm{p}}\,\frac{R_{\mathrm{g}}\mathbf{W}_{\mathrm{p}}^2}{2}, \tag{10}$$

$$\frac{R_{\mathrm{p}}}{\mathrm{T}_{\mathrm{p}}}\mathbf{W}_{\mathrm{p}}\frac{d\mathrm{T}_{\mathrm{p}}}{dX} + \mathbf{W}_{\mathrm{p}}\frac{dR_{\mathrm{p}}}{dX} = \mathrm{K}_{q_{mv}\mathrm{p}}Q_{mv} + \mathrm{K}_{q_v\mathrm{p}}\frac{Q_v}{T_{\mathrm{p}}\bar{C}_{\mathrm{p}}}, \tag{11}$$

$$u_{\mathrm{p}0}\mathbf{W}_{\mathrm{p}}\frac{d\mathrm{U}_{\mathrm{p}}}{dX} = -\mathrm{K}_{q_{mv}\mathrm{p}}\mathrm{R}_{\mathrm{p}}^0\,Q_{mv}. \tag{12}$$

It is evident that the additional simplifications for the system (R_p = const, $dP_g/dX = 0$, etc.), confirmed for a number of cases, substantially expand the possibilities of its practical application in obtaining analytical solutions, in simulation on analog computers, etc.

To use the above developments, in addition to the achievements of related branches [3, 6] – depending on the specific purposes – for an integrated analysis of spray-drying processes, realization of the following basic stages should prove effective:

1. Measuring temperatures, moisture content, velocities, dispersion, and other quantities within the chambers of spray dryers and laboratory test stands, to refine the physical essence of the processes, and to obtain the working approximation relationships on a uniform basis.

2. The study of problems related to the aerodynamic characteristics of dryers, as well as studying problems related to the mixing in chambers through use of geometric models and under natural conditions.

3. Experimentation under laboratory conditions to determine the effect of regime parameters on the structure–formation of the particles.

4. Analysis of the model of the process (used in the analysis) to determine the interrelationships between the quantities significant in the drying process, and the evaluation of their relative import. This involves both the determination of general quantitative solutions, and the application of computer techniques.

5. Determination of the working relationships, containing generalized variables needed to perform the calculations for spray-dryer chambers on the basis of their primary cells.

NOTATION

ρ	is the density;
τ	is the time;
l	is a determining dimension;
W	is the velocity vector;
q_{mv}	denotes the mass forces (sinks);
q_v	denotes the heat sources (sinks);
g	is the acceleration of the gravitational field;
P	is the pressure;
Ω_p	is the midsection area of the particles;
V	is the volume of the flow space;
ν	is the coefficient of kinematic viscosity;
t	is the temperature;
c	is the specific heat capacity;
r	is the heat of evaporation;
λ	is the coefficient of thermal conductivity;
u	is the moisture content;
ρ_{vap}	is the vapor density;
ξ	is the resistance factor;
m	is the porosity;
Fr, Eu, Re, and Pe	are, respectively, the Froude, Euler, Reynolds, and Peclet numbers.

Subscripts

p and g	denote quantities relating, respectively, to the particle and heat-carrier phases;
0	denotes the parameters;
b	denotes the quantities pertaining to the boundary of the cell:

$$\mathrm{Ho} = \mathrm{w}_{p0} \cdot \tau / l_0;\ \mathrm{K}_{q_{mvp}} = q_{mv0} l_0 / \rho_{p0} \cdot \mathrm{w}_{p0};\ \mathrm{K}_{q_{mvg}} = \mathrm{K}_{q_{mvp}} S_{\rho_1} / S_w;$$

$$\mathrm{K}_{\Omega_p} = l_0 \Omega_{p0} / V;\quad \mathrm{K}_p = d_0 r_0 / t_{g0} c_{g0};\quad \mathrm{K}_{J_{vap}} = J_{vap\,0} d_0 / t_{g0} c_{g0};$$

$$\mathrm{K}_{J_{mix}} = J_{mix0} / t_{g0} c_{g0};\ \mathrm{K}_{q_{vg}} = q_{v0} l_0 / \rho_{g0} \cdot \mathrm{w}_{g0} \cdot t_{g0} c_{g0};$$

$$\mathrm{K}_{q_{vp}} = q_{v0} l_0 / \rho_{p0} \cdot \mathrm{w}_{p0} \cdot c_{p0} t_{p0};\ \mathrm{R}_p = \rho_p / \rho_{p0};\ \mathbf{W}_p = \mathbf{w}_p / \mathbf{w}_{p0};$$

$$\mathrm{R}_g = \rho_g / \rho_{g0};\ \mathbf{W}_g = \mathbf{w}_g / \mathbf{w}_{g0};\ T_p = t_p / t_{p0};\ T_g = t_g / t_{g0};$$

$$\mathrm{U}_p = \frac{u_p}{u_{p0}};\ \mathrm{R}_{vap} = \frac{\rho_{vap}}{\rho_{vap\,0}};\ \bar{\lambda} = \frac{\lambda_g}{\lambda_{g0}};\ \mathrm{P}_g = \frac{p_g}{p_{g0}};$$

$$\mathrm{S}_w = \frac{\mathbf{w}_{p0}}{\mathbf{w}_{g0}};\quad \mathrm{S}_{\rho_1} = \frac{\rho_{g0}}{\rho_{p0}};\quad \mathrm{S}_{\rho_2} = \frac{\rho_{p0}}{\rho_p^0};\quad \mathrm{S}_{\rho_3} = \frac{\rho_{p0}}{\rho_{vap0}};$$

$$Q_{mv} = \frac{q_{mv}}{q_{mv0}};\quad Q_v = \frac{q_v}{q_{v0}};\quad \mathrm{M} = \frac{m}{m_0};$$

$$\bar{\Omega}_p = \frac{\Omega_p}{\Omega_{p0}};\quad \bar{\nu} = \frac{\nu}{\nu_0};\quad \bar{\mathrm{C}}_p = \frac{c_p}{c_{p0}};\quad \bar{\mathrm{C}}_{vap} = \frac{c_{vap}}{c_{vap\,0}};$$

$$\bar{r} = \frac{r}{r_0};\quad L = \frac{l}{l_0};\quad \mathrm{R}_p^0 = \frac{\rho_p^0}{\rho_{p0}};\quad S_c = \frac{c_{mix0}}{c_{r0}};$$

$$\bar{\mathrm{C}}_{mix} = \frac{c_{mix}}{c_{mix0}};\quad \mathrm{J}_{mix} = \frac{J_{mix}}{J_{mix\,0}}.$$

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