Scientific Principles of Drying Technology

by

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Introduction

Drying is among the most commonly used, complex, important and energy-consuming processes. In all industrial branches and agriculture, tens of thousands of diverse products are dried, and the development of an efficient drier for each product (except the most large-tonnage productions) is unrealistic and uneconomical. Therefore the problem arises as to designing standard driers, which are fairly efficient within a large group of materials similar in their properties, and hence, the problem of classifying wet materials as drying objects. There is still no unique classification of materials as drying objects on which the selection of a rational type of the drier could be based. Fundamental works of A.V. Luikov concerning the drying theory markedly advanced the understanding of physics of complex interrelated processes in drying and prompted the development of novel methods of enhancing heat and mass transfer. Of great significance was the classification of wet materials, proposed by A.V. Luikov (the division of all materials into three groups: capillary-porous, colloidal, and colloidal capillary-porous). However, this classification did not provide direct indications as to the type of the drying device. The same applies to the well-known classification of P.A. Rebinder by the types and energies of moisture binding to materials, which is essential to a correct writing of the heat balances in drying with account for the energy of moisture binding to materials but does not make it possible to determine the type of the drying device based on analysis of the dried materials.

The classification of materials as drying objects should not be based solely on the evaluation of the material behavior in one or another (even standard, and all the more so nonstandard) drying device. The classification should reflect the results of comprehensive analysis of the material as a drying object and incorporate no more than three or four generalized indices, of which one (dominant) defines a class (a group) of the material according to this classification and the others define a subgroup and a category.

The dominant index should reflect the material nature and not depend on the drying conditions (for example, it is inexpedient to choose the diffusion coefficient as

the dominant index, since it depends on the drying temperature and other operating conditions).

In the classification, developed in studies [7, 12], that is based on the dominant index — the critical pore radius — all wet materials are divided into four groups in the order of decreasing critical pore diameter, to which corresponds a complication of the intraporous structure of the material and an increase in the diffusion resistance to the motion of moisture (as liquid or vapor) to the particle surface, and therefore, an increase in the drying duration and a complication of the forms of moisture binding to the material.

Each group is divided into subgroups with account for adhesion-cohesion properties of the material (the sticking to metal surfaces, the lump formation, etc.), which largely determine a rational structure of the drying device and the structure of charging facilities. To allow for these properties, a rank of the adhesion–cohesion coefficient is introduced that varies with these properties ($K_{a\text{-}c}$ varies from 1 to 5).

To the first group belong materials with the critical pore diameter larger than 100 nm (for the first subgroup, $K_{a\text{-}c} = 1$, and for the second subgroup, $K_{a\text{-}c}$ is up to 3). The drying duration for materials of the first group is not long (for example, 0.5-3.0 s in the suspension bed). The second group includes materials with the critical pore diameter ranging from 100 to 6 nm (for the first subgroup, $K_{a\text{-}c} = 1$, for the second subgroup, $K_{a\text{-}c} = 3$, and for the third subgroup, $K_{a\text{-}c}$ varies from 3 to 5). The drying duration for materials of the second group is appreciably longer than for the first group (up to 30 sec in the suspension bed). To the third group belong materials with the critical pore diameter ranging from 6 to 2 nm. Drying of such materials lasts minutes and tens of minutes. Materials of the fourth group, whose critical pore diameter is smaller than 2 nm, are characterized by a very low drying rate, and the drying duration comes to hours. The type of the drying device for materials of the fourth group should be selected taking into account also the particle size of the dried material.

The proposed classification can serve as a basis for conversion from drying statics to drying kinetics using the principle of respective states. Knowing drying kinetics for typical representatives of each group under nearly optimum conditions and the velocity of moisture removal from pores of various groups, proceeding from the referencing of the material to one or another group and from the characteristic of the pore space (like the pore-diameter distribution and the volume of pores of various diameters) it is possible to calculate and construct a curve of drying kinetics for this material under nearly optimum conditions and to select a rational type of the device and an active hydrodynamic regime.*

* In recent years, this term has been widely used in the literature, and in various senses. It seems reasonable to call "active" only such a regime, in which certain hydrodynamic conditions (the developed surface of the dried material, high relative velocities of its movement with the heat carrier, a definite flow structure, etc.) result in a marked drying intensification with high technical economic indices. Thus, the synonym to the attribute "active" is an "effective", rather than "intense", regime that comprises three components: intensity, economical efficiency, and quality of the dried product. This implies that for a certain technological problem, an active hydrodynamic regime can exist. However, it can also be nonexistent if efficiency of the technological process cannot be increased by hydrodynamic means (for example, for the internal mass transfer problem).

Active hydrodynamic regimes can be achieved, specifically, with a rational use of the suspension bed. Four groups of the suspension-bed regimes are discerned [4, 5, 10]: fluidization (including boiling, vibrated boiling, and passing boiling beds), spouting (including a spouted bed and free spouting), pneumatic transport (ascending, descending, horizontal, in "dunes", etc.) and swirl flows (single flows with and without guide channels, opposing and assisting coaxial vortex flows, a vortex layer, etc.).

It should be noted that the regime of passing bubbling bed is implemented in the devices with vertical walls, and the free spouting regime, in the devices with inclined walls, both regimes being possible in drying of only such materials, whose particle floating velocity noticeably decreases during drying [1, 8].

The measure of activity of the hydrodynamic regime should be an integrated index that takes account, on the one hand, of the technological effect produced by the given regime (the process intensification with a sufficient hydrodynamic stability of the bed in this regime, with a "satisfactory hydrodynamic model" providing the required degree of uniformity of the particle treatment and the process safety) and, on the other hand, of the economical efficiency of the technological process (a high degree of utilization of the drying agent).

From the foregoing follows that a high index of the hydrodynamic activity for materials having macropores with free and weakly bound moisture can be achieved only in the regimes with high velocities and temperatures of the heat carrier and a short residence of the material in the treatment zone. Comparison of the activity of hydrodynamic regimes is possible through comparing the exergy efficiency in the operation in these regimes.

Energy resources can also be saved by combining mechanical dehydration and drying, drying and grinding, drying and granulation (from solutions, suspensions, melts, and thermal granulation of powders), drying and encapsulation, drying and thermal treatment, drying and collecting, and also with a simultaneous conducting of a chemical reaction.

An example of a multifunctional device with controlled hydrodynamics is the device with opposing coaxial vortex flows designed for drying with a simultaneous dust collection, drying and thermal treatment, dehydration and granulation, and also for conducting some other processes of chemical technology (like adsorption, conditioning, and desorption) [2–4, 6, 9–11].

When the devices with opposing coaxial vortex flows are used as dust collectors, the gas phase capacity reaches 200 thous.m/h (for a single device 2 m in diameter), and when a bank of the devices is used, it is up to 500 thous.m/h with a degree of cleaning of up to 99.8% from dust with a particle size of up to 2–3 μm. Such indices are not the case with other known dust collectors, including standard cyclones. Moreover, the devices with opposing coaxial vortex flows are not sensitive to variations in the gas phase load and dust concentration.

By regulating the gas phase flow from the boundary-layer flow to the central flow it is possible to preclude a contact of the material, treated in the device with opposing coaxial vortex flows, with the device walls, which is of great practical importance for the treatment of materials with strong adhesion–cohesion properties.

The statement of scientific principles of designing highly efficient standard devices based on comprehensive analysis of materials as drying objects was first attempted in the book "Principles of Drying Technology" of Prof. B.S. Sazhin (Khimiya Press, Moscow, 1984). The book was favorably received in the USSR and abroad. This monograph presented scientific principles of drying technology that encompass all main aspects of the problem. In connection with an exceptional and ever increasing topicality of the questions as to saving and rational utilization of energy resources, they were given special attention, particularly since the energy consumption for drying reaches, according to various sources, up to 12–15% of the total energy consumption in the industrial production of developed countries. In view of this, some chapters are included concerning the exergy analysis of the operation of dryers and drying units. Special attention was also given to the questions of dust collection, since the problem of ecology, including the industrial ecology, comes to the foreground when the functioning of any industrial objects is considered.

The authors did not seek to analyze all research and calculational works on drying, performed by investigators in our country and abroad. Only those works were considered that are concerned with the main idea of the offered book — the statement of scientific principles of designing highly efficient standard dryers based on comprehensive analysis of materials as drying objects.

The monograph relies on the works of the authors and their students and associates. Some sections are based on materials of the book "Principles of Drying Technology" of B.S. Sazhin. Use was also made of materials of the monographs of B.S. Sazhin and his associates on the problems of exergy analysis, mathematical simulation, and dust collection.

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Part I

SCIENTIFIC PRINCIPLES OF DEVELOPMENT OF EFFICIENT DRYING DEVICES AND RATIONAL DRYING METHOD

Chapter 1

Drying Statics and Kinetics

1.1. Main Factors Determining the Drying Process

As known, drying is a very complex technological process dependent on a great many factors, whose knowledge is essential to analysis and calculation of the process. In all cases, a highly volatile component (water, an organic compound, a mixture) is removed (as vapor or liquid) in drying.

The moisture content (dry basis or d.b.) of the body U is a ratio of the moisture mass W, contained in the body, to the mass of the dry body G

$$U = W/G\,. \tag{1.1}$$

Practical problems of drying are usually presented using the concept of the body humidity (wet basis or w.b.) ω

$$\omega = \frac{W}{W+G}\,. \tag{1.2}$$

From relations (1.1) and (1.2) follows

$$\omega = \frac{U}{1+U} . \tag{1.3}$$

At small values of the moisture content (d.b.) ($U << 1$), the magnitude of ($1 + U$) in expression (1.3) is about unity, and the humidity of the body (w.b.) is almost the same as its moisture content (d.b.).

In drying, the wet body tends to equilibrium with the surroundings, therefore the moisture content (d.b.) of the body U and its temperature T are functions of the time τ and coordinates of the body point x_1, x_2, x_3

$$U = U(x_1, x_2, x_3, \tau) ; \tag{1.4}$$

$$T = T(x_1, x_2, x_3, \tau) . \tag{1.5}$$

The time dependence of temperature can be disregarded if the temperature of the body reaches equilibrium much sooner than does its moisture content. Dependences (1.4) and (1.5) describe dynamics of the body drying and heating. The time variation of the body-volume-average moisture contents (d.b.) $\overline{U}$ and temperatures $\overline{T}$ characterizes the drying and heating kinetics

$$\overline{U} = \overline{U}(\tau) ; \tag{1.6}$$

$$\overline{T} = \overline{T}(\tau) ; \tag{1.7}$$

$$\overline{U} = \iiint_V U(x_1, x_2, x_3, \tau)\, dx_1 dx_2 dx_3 ; \tag{1.8}$$

$$\overline{T} = \iiint_V T(x_1, x_2, x_3, \tau)\, dx_1 dx_2 dx_3 . \tag{1.9}$$

The drying intensity is defined by the drying rate $d\overline{U}/d\tau$ that, as equilibrium is approached, decreases and generally tends to zero. The drying intensity depends on a number of factors indicating complexity of a real drying process, especially in production conditions, and difficulty in obtaining its adequate mathematical description. The most influential on drying are the factors, determining the drying material as a drying object. They characterize the resistance of the material to moisture transfer inside it and from its surface to the surroundings, the strength of moisture binding to the material and the ability of the material to take up the supplied heat. Among such factors are the internal structure of the material, its thermophysical properties and dimensions, the shape and state of the outside surface, the interval of a variation in the moisture content of the material in drying, etc. The internal structure of the material has the greatest

effect on drying. For example, for dispersed materials with the particles with a diameter larger than 2 mm and the critical pore radius* smaller than 2 nm, the duration of convective drying is over 1 h, while for dispersed materials with the critical pore radius larger than 100 nm (other conditions being equal) it is within 0.5–3 sec.

Drying of materials having very small particles or a surface with many sharp protrusions with a small radius of curvature involves the emergence of an additional moisture flow from the material to the drying agent. This is linked with an increase in the saturated vapor pressure above a convex surface. According to the Tomson–Kelvin formula [2, 6, 21], such an increase is noticeable for very small radii of curvature of the surface ($r < 10^{-7}$ m) and is

$$p_{\text{conv}} - p_0 = p_0 \left[\exp\left(\frac{M\sigma K}{\rho_{\text{liq}} RT} \right) - 1 \right], \tag{1.10}$$

where p_{conv} and p_0 are the saturated vapor pressures above a convex and a flat surface, respectively, K is the average surface curvature, $K = 1/R_1 + 1/R_2$, R_1 and R_2 are the principal radii of curvature of the interface, M is the molar mass of the substance, σ is the surface tension, ρ_{liq} is the liquid density, R is the universal gas constant, and T is the absolute temperature.

Drying is markedly affected by parameters of the drying agent (the heat carrier): the temperature t, the relative humidity (the relative pressure) φ, the velocity of movement with respect to the material v, and the pressure p. Experimental dependences of the drying kinetics on parameters of the drying agent are reported in the literature [4, 8, 12].

Let us consider the effects of parameters of the drying agent on the drying rate taking as an example a simplified mathematical model. Suppose that the entire heat, supplied to a spherical particle of the material, is spent in evaporation of moisture, contained in it. The material particle is small, and therefore the temperature and moisture content gradients can be neglected. The heat balance for such a particle is of the form

$$\alpha \pi d^2 f (t - \theta) = N \frac{\pi d^3}{6} \rho_{\text{m}} r_{\text{v}}, \tag{1.11}$$

from which

$$N = \frac{6\alpha f (t - \theta)}{\rho_{\text{m}} d r_{\text{v}}}, \tag{1.12}$$

where α is the coefficient of heat transfer from the heat carrier to the material particle, f is the shape factor, d is the material particle diameter, ρ_{m} is the material density, r_{v} is the heat of evaporation, and θ is the material temperature.

*The critical pore radius is a radius of the finest pores from which moisture is removed. The concept of the critical pore radius is conventional (in the case of a complex geometry of pores or nonporous materials). However, this concept defines the material resistance to moisture removal.

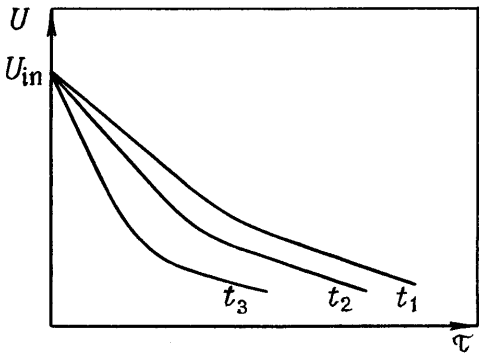

Fig. 1.1. Character of the dependence of the kinetic drying curve $U(\tau)$ on the heat carrier temperature $t_3 > t_2 > t_1$.

From Eq. (1.12) follows that the drying rate increases with a decrease in the particle size of the dried material and with an increase in the temperature of the heat carrier and the rate of heat supply to the material that is characterized by the heat transfer coefficient α. It should be noted that α, in turn, also depends on d and more weakly on t. For some correlations, for example, for the Frässling correlation [1], the heat transfer coefficient α is proportional to $d^{-0.5}$ and $v^{0.5}$. Then, the drying rate is $N \sim tv^{0.5}/d^{1.5}$. Clearly, the particle size has the greatest effect on the drying intensity.

Figures 1.1–1.4 illustrate the effect of the heat carrier parameters and body dimensions on the kinetic drying curve (a variation of the volume-average moisture content of the material with the time τ).

In conductive drying, the rate of heat supply is determined by the source power, the state and size of the heating surface, the thermal conductivity of the material, etc., which also has an effect on the drying intensity. When energy fields are used, the drying rate is a function of their parameters (such as the frequency and the amplitude).

Among factors influential on drying are the concentration and composition of admixtures, contained in liquid that is removed from the material. Admixtures change

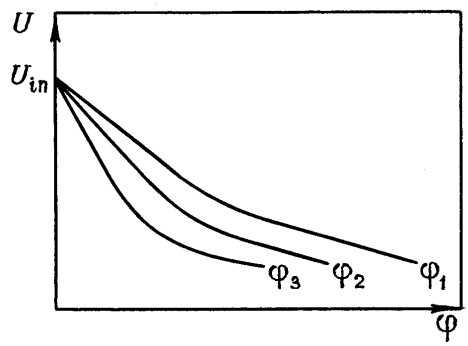

Fig. 1.2. Character of the dependence of the kinetic drying curve $U(\tau)$ on the relative humidity of the heat carrier $\varphi_1 > \varphi_2 > \varphi_3$.

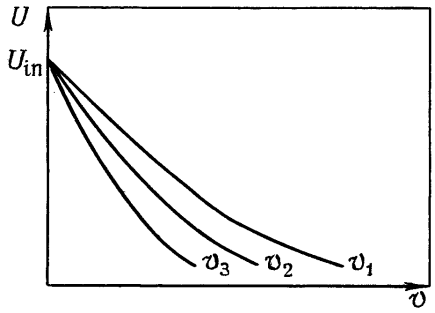

Fig. 1.3. Character of the dependence of the kinetic drying curve $U(\tau)$ on the heat carrier velocity with respect to the wet body $v_3 > v_2 > v_1$.

thermophysical properties of liquid (the viscosity, the thermal conductivity, etc.), alter the liquid interaction with the surface of a solid skeleton and thus influence the velocity of liquid migration from internal layers of the body to the periphery. In the presence of admixtures, the saturated vapor pressure above liquid or the body, wetted by it, decreases according to the Rauoult law, which leads to the reduction in the moisture flow from the material surface to the drying agent.

In drying of dispersed materials in the suspension-bed devices, the drying intensity is influenced by the interaction of the material particles among themselves and with the device wall. On impact of the particles on one another and the device walls, their surface layer is drawn away, which intensifies drying: the larger is the number of impacts, the more intense is the process.

From the aforesaid the conclusion can be drawn that the material drying should be intensified by increasing the temperature and velocity of the heat carrier (within technologically allowable limits), decreasing its initial moisture content, grinding the material (if allowed by the technology), applying the energy fields, etc. However, it should be remembered that intensification of the process increases economic expenditures for conducting it; therefore, a topical problem arises of the search for economically optimum conditions of conducting the process.

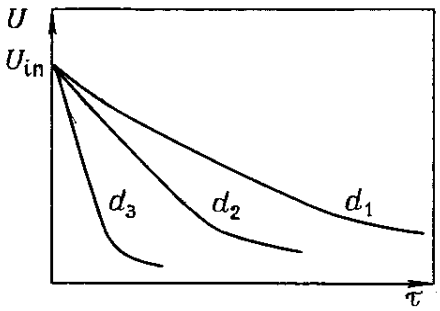

Fig. 1.4. Character of the dependence of the kinetic drying curve $U(\tau)$ on the dried body size $d_1 > d_2 > d_3$.

1.2. Conditions of Thermodynamic Equilibrium in Drying. Isotherms of Sorption–Desorption

The state of the wet body–gas system is equilibrium, if it does not change with time by the action of internal factors. It is implied here that external conditions do not change with time either. Otherwise, there is a displacement of the equilibrium position of the system. It should be emphasized that equilibrium is of dynamic character. If under certain external conditions the wet body is in equilibrium with gas (the mixture of vapors of the evaporated liquid and the heat carrier, which is most frequently air), this does not mean that reciprocal processes of evaporation and condensation do not occur — in equilibrium, these reciprocal processes proceed with the same intensity. The number of molecules that escaped from liquid in unit time is equal to the number of vapor molecules that got into liquid.

If the thermodynamic system is in stable equilibrium, any process in it, caused by the change in external conditions, is directed such that it tends to eliminate the system variations as a result of the change in external conditions.

Suppose that the wet body is in equilibrium with the surroundings and receives somehow an additional energy flux, for example, in the form of infrared radiation. Then, the internal energy of the wet body begins to increase. For counteracting this, the body moisture will begin to evaporate and pass to the surroundings to lower the new level of internal energy of the body. This will continue until a new, naturally, dynamic, equilibrium is established, i.e., until a new, larger number of liquid molecules, passing to the surroundings, is equal to the number of molecules, coming from the surroundings into liquid.

Let us consider in more detail the conditions of equilibrium of the wet body with gas (with the mixture of air and water vapor). For the processes of liquid or vapor transfer not to occur for mechanical reasons, mechanical equilibrium should be established. For this, the forces acting on the interface should be equal. If the interface is plane, the equality of the forces leads to the equality of the pressures on both sides of the interface. If the interface is curved, the equality of the pressures is upset by the action of surface tension forces, and on both sides of the interface there is a pressure difference [6, 11], defined by the Laplace equation

$$p_{\mathrm{v}} = - p_{\mathrm{liq}} = \sigma K , \tag{1.13}$$

where p_{liq} and p_{v} are the liquid and vapor pressures on both sides of the interface and K is the average curvature of the interface; K is taken with a minus sign if the meniscus is concave and with a plus sign if it is convex.

However, expression (1.13) corresponds to mechanical equilibrium for the case, where the interaction of a solid body and liquid is disregarded. When this interaction is taken into account, attention should be given to the forces, acting on the liquid–gas interface from the side of a solid skeleton of the body. At steady equilibrium, thermal equilibrium should also be fulfilled: the temperature of the body (a solid skeleton) T_{s} is equal to the liquid temperature T_{liq} and to the gas temperature T_{g}. Mechanical and thermal equilibrium does not yet mean that the wet body–gas system is in equilibrium: the

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