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-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, $K_{a-c} = 1$, and for the second subgroup, K_{a-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, $K_{a-c} = 1$, for the second subgroup, $K_{a-c} = 3$, and for the third subgroup, K_{a-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.

The authors are very grateful to the scientific editor of translation Dr. D. Luzhansky and Dr. M. Sazhin and Mr. D. Berezin for their assistance in preparing the English-language edition of the book.