UDK 677.044:66.012-52

PROBLEMS OF DRYING DISPERSE MATERIALS AND ACTIVIATION OF HYDRODYNAMIC REGIMES

B.S. SAZHIN

(The Moscow State Textile University named after A.N. Kosygin)

More than 85% of materials to be dried undergo drying in disperse and dispersgated conditions in all industry branches, including fuel and energy and agricultural as well as industrial complexes [1], [2]. Since drying is the most power-consuming process from all technological processes, special attention during a selection of a drying device is to be paid to energy factors of the machine [3]. The most efficient tool is exergy analysis which enables, in addition to all the rest, to expose the weakness of execution of the hardware and technological process and available reserves for saving energy costs, including pressure losses [4], [5]. Development of optimal technical solutions and technological drying modes should be related to maximum efficiency of the process which for a long period of time had been related only to intensity. At the present stage of development of science and engineering with consideration for economy and market demand, the following four major factors are to be included into the concept of efficiency: intensity, economical efficiency, quality of final products and safety (including environmental and industrial safety) [6].

Selection strategy of optimal execution of the hardware and technological process of drying of a specific material should comprise the following six major stages: 1) integral analysis of materials as drying object; 2) determination of a type of the dryer on the basis of integral analysis and available classification of drying apparatus; 3) determination of optimal drying conditions with consideration for technological requirements to quality of the dried final product; 4) design of the apparatus with consideration for the required performance; 5) environmental and industrial safety of technological process; 6) value engineering.

With integrated analysis of disperse materials as drying object, the following five groups of characteristics are distinguished: thermal (heat conductivity, temperature conductivity, heat capacity, etc.), hygrothermal and kinetic (types of bond of moisture with materials, thermographs and energographs, drying graphs, etc.); sorption-structural (isothermal curves of sorbtion-desorbtion, amorphism and crystallinity, curves of pore distribution by sizes, etc.); technological (desired residual moisture, permissible temperatures, fire and explosion safety properties and others) [6], [7] as well as hydromechanical (size, form of particles, fluidizing and terminal velocity, angle of natural slip, adhesive-autoadhesive properties and others).

At present, express methods and efficient devices for determination of all characteristics of wet materials (for instance, determination of thermal characteristics by means of two temperature-time points method, determination of isotherms of sorbtion-desorbtion using vacuum Mach-Ben's scales and others) have been developed [2], [8].

One of the most important problems during drying of disperse materials is classification of materials as drying objects. When there are many thousands of materials to be dried, it is impossible for each material to develop an individual dryer. Therefore there is a need for standard dryers suitable for processing of materials which are similar in properties and belong to one class of the appropriate classification. Classification by sorption characteristics with consideration for adhesion-autoadhesion properties of dryable materials can be recommended [2], [7]. This classification by the critical size of pores, which determines the measure of diffusion resistance (and therefore time of the drying process) during drying of this material, as well as by value of adhesive-autoadhesive coefficient, which determines degree of clotting and adhesion of wet particles on the walls of the apparatus, enables to determine place of this material in the classification table and the efficient standard apparatus in accordance with this place (Table 1).

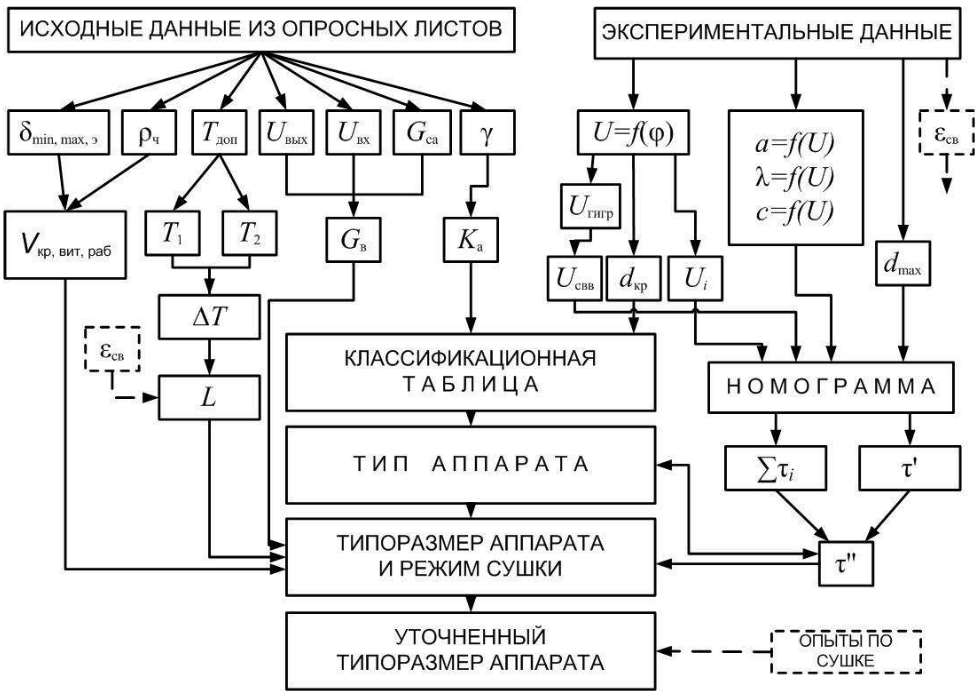


Fig. 1. Procedure of selecting drying apparatus on the basis of complex analysis of material as an object of drying

Nomenclature: $d_{ч_{экв}}, d_{ч_{max}}$ – equivalent and maximum diameters of particles; $\rho_ч$ – density of material particles; $\theta_{доп}$ – permissible temperature of material's heating; $\upsilon_{кр}, \upsilon_{вит}, \upsilon_р$ – gas velocities, correspondingly: critical, soaring working; $U_н, U_к, U_i, U_{мг}$ – content of liquid in material: initial, final, corresponding to filling of the i-group of pores, maximal hygroscopic; G, G_W – dry product and evaporated liquid-handling capacity; β – angle of natural slip; K_a – rank of adhesive-autoadhesive coefficient; L – consumption of drying agent; $d_{кр}$ – critical radius of pores; $Э_{св}$ – bond energy of water with material; $U = f(\varphi)$ – sorbtion and desorbtion isotherms; $a = f(U)$, $\lambda = f(U)$, $c = f(U)$ – dependences of temperature conductivity a, thermal conductivity λ, heat capacity c of material from content of fluid; $\tau, \tau', \sum \tau_i$ – total drying time, time of removal of free moisture and total removal of liquid from i group of pores.

Concept of active hydrodynamic regimes relates not only to drying of disperse materials: AHR – this is when by means of hydrodynamics significant intensification of drying process is reached (or another technological process) with good technical and economic indicators and quality of dried product.

We have developed a comparative assessment method of activity of hydrodynamic regimes using exergy analysis by the degree of exergy performance index. This method enables to select a hydrodynamic drying regime in a correct way. Useful effect obtained as a result of using active hydrodynamic regimes should be compared with the costs for their implementation.

As an index, characterizing thermodynamic efficiency of employed methods of activation of hydrodynamic conditions in the apparatus, it is advisable to use relation of exergy coefficient prior to and after employment of the above mentioned methods for alternative technical solutions. In this case hydrodynamic regime is to be considered as active (with regard to a specific material and utilization of instrumentation) for which the above mentioned index is bigger.

Expression for exergy performance coefficient can be obtained based upon the balanced heat to mass relations (1), (2). Using additivity law (relation 3), we can get from (1)…(3) equation (4), and inserting dimensionless groups (5) related to kinetic coefficient α and β, from relation (4) we will get (6) and then the expression (7) for exergetic coefficient of performance.

$$G_м \Delta h_м + Wz_n = \alpha F \Delta t_{cp}, \quad (1)$$

$$G_м \Delta U_м = \beta F \Delta x_{cp}, \quad (2)$$

$$\Delta h_c = c\Delta t_c + h_м \Delta x_c, \quad (3)$$

$$\Delta h_c = G_м \Delta h_м \frac{c}{\delta\alpha F} + \frac{c\beta}{\delta\alpha}\Delta x_{cp} h_n + \Delta x_{cp} h_n, \quad (4)$$

$$L_e = \frac{c\beta}{\alpha}, \quad g = \frac{G_c}{G_м}, \quad n = \frac{\beta F}{G_c}, \quad (5)$$

$$\Delta h_c = \frac{L_e}{gn}\Delta h_м + (1 + \frac{L_e}{\delta})\Delta x_{cp} h_n, \quad (6)$$

where Δx_{cp} – mean driving force of the process; $\delta = \frac{\Delta t_{cp}}{\Delta t_c}$:

$$\eta_e = \frac{\Delta e_n}{\Delta e_c} = \frac{\frac{1 - L_e \Delta e_м}{gn\Delta e_c}}{\frac{1 + L_e}{\delta}\Delta x_{cp.}}. \quad (7)$$

Useful effect obtained as a result of using active hydrodynamic regimes should be compared with the costs for their implementation.

Exergy coefficient of performance can also serve as a complex indicator for evaluation of the hydrodynamic regime and degree of pollution of environment by thermal pollutants, which characterize ecological cleanness of industrial equipment. For instance, in the drying machine with active hydrodynamic regime, thermal component of exergy of interacting flows is subjected to the maximum change, therefore thermal exergy function could be used for transfer from thermal characteristics of these flows to exergetic ones.

For a more complete characteristics of the drying machine, a component is to be inserted in the exergetic coefficient of performance η_e, which takes into account hydraulic resistance of the machine and energy costs, caused by extraction of dried product from the vaporized state or costs for dust cleaning, regardless whether this process proceeds direct in the dryer or outside (8)…(10):

$$\eta_э = \frac{k_1\eta_e + k_2\eta_{сеп}}{2}, \quad (8)$$

$$\eta_{сеп} = \frac{\eta_г + \eta_{ул}}{2}, \quad (9)$$

$$\eta_г = \frac{\ln(P^{вх} - \Delta P) - \ln P_o}{\ln P^{вх} - \ln P_o}, \quad (10)$$

where k_1, k_2 – relative level of damage from thermal and dust pollutants; $P^{вх}, P_o, \Delta P$ – pressure correspondingly: at intake into apparatus, environment and hydraulic resistance of equipment.

Results of exergy analysis demonstrate that active hydrodynamic regimes are resource-saving not only with regard to metal and production areas (due to small dimensions of equipment), but also with regard to specific energy consumption.

For disperse materials, which are processed in active hydrodynamic regimes, problem of calculating drying time without carrying out drying has been solved on the basis of simulation materials. Real materials have a complex structure and contain pores of different sizes, therefore drying time will depend on the quantitative relation of pores of different diameters. Emptying time of i-group of pores:

$$\tau_i = \frac{1}{\overline{N_i}} \frac{\rho_æ}{\rho_ì} \int_{d_i}^{d_{i+1}} f_V(d) d(d) = K_i \Delta U_i, \quad (11)$$

where $\rho_æ$, $\rho_ì$ – density of absolutely dry material and liquid being removed during drying; f_V – function of distributing volumes of pores by diameter; K_i – coefficient, which is inversely related to mean speed $\overline{N_i}$ of removing fluid from i-group of pores; ΔU_i – content of liquid in the material, which corresponds to filling of pores with diameter ranging from d_i to d_{i+1}.

Total time τ'' of removal of liquid from pores of material, which has a structure of different pores, can be defined from the relation:

$$\tau'' = \sum_{i=1}^{i=n} \tau_i = \sum_{i=1}^{i=n} K_i \Delta U_i \,. \qquad (12)$$

Total drying time of porous material (with consideration for removal of free moisture):

$$\tau = \tau' + \tau'' = \tau' + \sum_{i=1}^{i=n} K_i \Delta U_i \,, \qquad (13)$$

where τ' – time of removal of free moisture, which usually ranges with active hydrodynamic regimes from fractions of a second to 2…3 seconds.

Average speed of removing moisture from each group of pores is determined by kinetics of drying of simulated materials with structure of different sizes in real apparatus with different temperatures of the drying medium. The obtained data in the aggregate with values τ', which we have defined with consideration for thermal characteristics according to a developed technique, enabled us to chart a nomogram for calculating kinetics of drying any material without conducting the tests on drying this material in real dryers. Comparison of kinetics of a computational experiment with a real one for 15 different materials has confirmed the efficiency of this method.

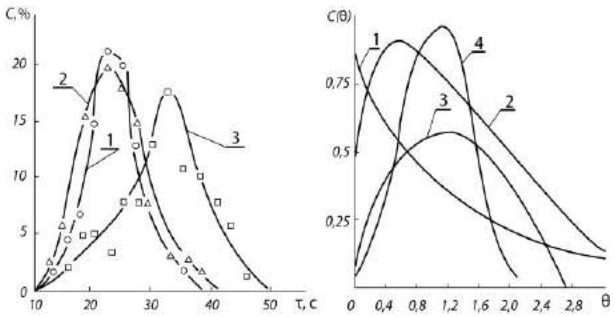
The procedure of selecting drying machines for disperse materials on the basis of a complex analysis of material as object of drying, using classification table of the calculating nomogram, is illustrated in Table. 1.

Table 1. Classification table for disperse materials

Index of technological task Bi'	Class of materials	Code (class, group, разряд)	$d_{кр}$, nm	Pores group	K_a	Index of dispersivety according to the dusty fraction		Characteristics of porous structure of material and type of moisture bonding	Drying time in active hydrodynamic mode
						Coarse	Fine		
Bi'<0.1 $\delta \le 3$ mm	First	1.1.1.	> 100	0	2	1		Nonporous materials with free moisture	0.5-2.0 s
		1.1.2.					2		
		1.2.1.			3	1			
		1.2.2.					2		
Bi' < 1 $\delta \le 3$ mm	Second	2.1.1.	100-8	1	2	1		Materials with wide pores and weakly bonded moisture (evaporation of liquid from liquid film)	3.0-5.0 s
		2.1.2.					2		
		2.2.1.			3	1			
		2.2.2.					2		
		2.3.1.			4	1			
		2.3.2.					2		
Bi'< 10 $\delta \le 3$ mm	Third	3.1.1.	8-6	2	2	1		Highly wet materials with transitional pores and bonded moisture (Knudsen diffusion)	10-40 s
		3.1.2.					2		
		3.2.1.			3	1			
		3.2.2.					2		
Bi' < 20 $\delta \le 3$ mm	Fourth	4.1.1.	6-4	3	2	1		Thin pores with free and bonded moisture (Knudsen and surface diffusion)	0.5-2.0 min
		4.1.2.					2		
		4.2.1.			3	1			
		4.2.2.					2		
Bi' > 20 $\delta \le 3$ mm	Fifth	5.1.1.	4-2	4	2	1		Micropores with bonded moisture (surface diffusion)	2-20 min
		5.1.2.					2		
20< Bi' <<30 $\delta \le 1$ mm	Sixth	6.1.1.	< 2	5	1			Ultramicropores comparable to size of molecules (solid state diffusion)	2-20 min

For each class of the developed classification table (mentioned above) of disperse materials as drying objects, standard machines are recommended which implement those hydrodynamic regimes being active during drying materials of this class.

In connection with the problem of dust cleaning, multi-purpose non-entrainment apparatus with counter-vortex flows and controllable hydrodynamics [7…12] hase been developed in recent years, which can be recommended as a new generation of standard apparatus for materials with critical diameter of pores up to 6 nanometers. Capabilities of dryers with counter-vortex flows are restricted by a short dwelling time, nevertheless, the authors [2] managed due to the new hydrodynamic regime – annular circulating bed - to increase dwelling time of dryable material by 5…6 times, which has enabled to use devices with counter-vortex flows for drying products of the third and partially of the fourth class according to a variant of classification of materials as drying objects which we have suggested, i.e. to expand the range of materials by several thousands of types, which are dried in dryers with counter-vortex flows.



a) b)

Fig. 2. Curves of response to impulse disturbance of input signal with different consumptions (a) (1 – L= 0.08 m^3/c; 2 – L= 0.09 m^3/c; 3 – L= 0.10 m^3/c) and C-curves (b): for ideal mixing apparatus (1), KS (2), with counter-vortex flows (3), with counter-vortex flows in the annular bed regime (L – □ – 0. 12 m^3/c; Δ – 0.10 m^3/c.

Taking into consideration dependence of quality of the dried product both from average dwelling time, as well as from the range of dwelling time of particles forming the bed, one of the tasks of experimental study of regime of annular bed was to record the curves of response to disturbance of input signal, which allow to obtain a curve of distributing disperse particles by dwelling time in the annular bed (Fig. 2).

Analysis and processing of experimental response curves given in Fig. 2-a have been carried out by means of the statistical method. Moments of the first and second order were defined which characterize dwell time and dispersion according to the following formulas:

$$\bar{\tau} = \frac{\sum_{i=1}^{n} \tau C_i}{\sum_{i=1}^{n} C_i}, \qquad (14)$$

$$\delta^2 = \frac{\sum_{i=1}^{n} \tau^2 C_i}{\sum_{i=1}^{n} C_i} - (\bar{\tau})^2. \qquad (15)$$

Nondimensional dispersion was calculated by the following formula:

$$\delta_\theta^2 = \frac{\delta^2}{\bar{\tau}^2}. \qquad (16)$$

Number of cells of hydrodynamic model of the device was evaluated by the value δ_θ^2:

$$n_{ÿ} = \frac{1}{\delta_\theta^2}. \qquad (17)$$

The data presented in Fig. 2-a indicate that the dwell time reached is 5…6 times longer than with standard regimes.

Evaluation of range for dwell time can be obtained on the basis of C-curves response recorded during the experiments. In Fig. 2-b C-curve of response for device with counter-vortex flow in the regime of annular bed with different consumptions L in nondimensional coordinates in comparison with response curves of the device with counter-vortex flow operating in standard regime is presented (without forming an annular bed), fluidized bed apparatus and ideal mixing apparatus. The presented data indicate that the quantity of conditional cells, which characterize hydrodynamic conditions in the apparatus, equals for fluidized bed to 1.5…2, for the apparatus with counter-vortex flow in standard regime $n_{ÿ} = 3 \div 4$, and for the apparatus with counter-vortex flow in the annular bed regime $n_{ÿ} = 6 \div 8$. The obtained parameter evaluations $n_{ÿ}$ of the hydrodynamic structure of flows in the apparatus are an indication of a possibility to achieve more uniform drying of disperse materials in the annular circulating bed in contrast to standard regime of the apparatus with the counter-vortex flow, and even more so, in contrast to fluidized bed apparatus, since with the increased number of cells more uniform drying is reached.

To facilitate selection and design of standard fluidized bed devices, which correspond in the best way to the assigned task, generalized codes are developed: technological tasks and their implementation, which contain information regarding difficulties of the technological task on drying of this material (regarding diffusion resistance during this material, its adhesion-autohesion properties, availability and absence of dust fraction), as well as information regarding optimal solution to this problem (efficient type of dryer, type of feeder of the drying apparatus, availability and type of special dust separator as a component of the drying apparatus, availability or absence of closed cycle of heat medium).

Recording polydispersity of dryable materials is a serious problem. Calculation is usually made based on big fraction (thus ensuring drying of finer fractions) or by using fractional drying. Reducing polydispersity index of dryable material allows this process to become significantly more efficient. One of the methods to solve this problem is establishing identical conditions for formation of disperse particles in the course of obtaining them (for instance, in annular reactors with mixers) [2].

In a number of technological processes it is possible to influence the capillary-porous structure in the course of production of disperse materials, for instance, during polymerization processes, which makes it possible to obtain easy dryable wide-pored materials instead of microporous ones, removal of water from which is related to significant heat and time waste to reach the required residual moisture of the dryable material (for instance, during polymerization when producing polyolefines) [2]. The same seems to be true also with regard to controlling adhesive-autoadhesive properties in the course of production of disperse materials to be dried, which has impact on associated equipment of dryers (feeders, measuring hoppers, discharging machines).

When drying disperse materials (but not only disperse materials), important problem is providing environmental and industrial safety of drying equipment [11], [13]. One of the core issues is providing dust cleaning and development of non-entrainment dryers. Significant progress has been reached in recent years in this direction, especially with regard to employment of non-entrainment dryers with counter-vortex flows and highly efficient dust separators with counter-vortex flow [11], [12]. At present, more than ten thousand of apparatus with counter-vortex flow of different design and versions (including group and multi apparatus) have been introduced into production, which make it possible to carry out non-entrainment drying, as well as dust arresting, containing extra-fine nano-size particles (up to 50…100 nanometers).

In addition, considerable advances have been made in creating methods and designs which allow to sharply decrease noise level and harmful impact of vibrations from operating drying machines, thus ensuring the required industrial safety [14…16].

B I B L I O G R A P H Y

1. *Sazhin B.S.* Principles of drying equipment. – M.: Khimiya, 1984.
2. *Sazhin B.S., Sazhin V.B.* Scientific Principles of Drying Technology. – New York, 2007.
3. *Sazhin B.S., Tyurin M.P.* Energy efficient processes and devices for textile and chemical enterprises. – M., 2001.
4. *Sazhin B.S., Bulekov A.P.* Exergy method in chemical technology. – M.: Khimiya, 1992.

5. *Sazhin B.S., Bulekov A.P., Sazhin V.B.* Exergy analysis of operation of industrial plants. – M., 2000.

6. *Sazhin B.S., Sazhin V.B.* Scientific principles of drying equipment. – M.: Nauka, 1997.

7. *Sazhin V.B., Sazhina M.B.* Selection and design of fluidized bed devices. – M., 2001.

8. *Sazhin V.B., Sazhina M.B.* Drying in vortex flows. – M., 2001.

9. *Sazhin B.S., Dmitrieva L.B., Sazhina M.B.* // Proceedings of higher educational institutions. Technologiya textilnoy promyshlennosty, 2007. – #4 (299). – p. 89…91.

10. *Sazhin B.S., Bulekov A.P., Sazhin V.B.* // Theoretical principles of chemical technology, 1999. – 33, #5. – p. 93…102.

11. *Sazhin B.S., Gudim L.I.* Vortex dust separators. – M.: Khimiya, 1995.

12. *Sazhin B.S., Kochetov L.M., Belousov A.S.* // Theoretical principles of chemical technology, 2008. – 42, #2. – p. 135…145.

13. Sazhin B.S., Kochetov O.S., Gudim L.I., Kochetov L.M. Environmental safety of technological processes. – M., 2007.

14. Sazhin B.S., Kochetov O.S., Sinev A.V. Vibroprotection systems of technological equipment. – M., 2003.

15. *Kochetov O.S., Sazhin B.S.* Reducing noise and vibration in production: theory, design, technical solutions. – M., 2001.

16. *Sinev A.V., Kochetov O.S., Sazhin B.S.* Dynamic properties of vibroisolation systems. – M.: IMASH RAS, 2002.

Recommended by the department of processes and apparatus of chemical technology and industrial safety. Received 05.06.09.