

CERTAIN QUANTITATIVE RELATIONSHIPS IN THE DRYING  
OF GRANULATED SUPERPHOSPHATE

Yu. I. Andrianov and A. G. Bol'shakov

UDC 66.047.7

We present the results from an experimental investigation of the drying of a granulated superphosphate. We have derived an expression in criterial form to describe the process of drying the superphosphate.

To determine the manner in which the drying process takes place for granulated superphosphates and to choose the optimum drying regimes we must know the kinetics of the process. We can render a judgment as to the nature of the drying process, first of all, from the curves for the drying rate, as well as from the temperature curves.

The work that has been done on the drying of superphosphate dealt primarily with determining the effect of temperature on the retrogradation (the conversion of  $P_2O_5$  into the unassimilable form), the determination of the content of crystallized and hygroscopic water, etc. [1, 2]. Less attention has been devoted to studying the effect of the air temperature, the relative humidity of the air, and its velocity on the process of superphosphate drying.

It is precisely the partial filling of this gap that is the purpose of this paper; here we study the kinetics of the process involved in the drying of granulated superphosphate. The investigations were performed on a specially developed experimental installation whose diagram is shown in Fig. 1. Convection drying of granulated superphosphate was carried out in a range of air temperatures from 110 to 187°C, with a relative humidity of 18-36% for the air, and the velocity of the drying agent varying from 1.5 to 7.5 m/sec.

The air was heated to the required temperature in electric heaters 15 and 17. The magnitude of the current in the electric windings was regulated by means of laboratory autotransformers. The air temperature was kept constant by means of thermal regulator 27, hooked into the circuit of the main electric heater 15. The air-temperature sensor 9 in the drying chamber was a contact thermometer.

The humidification of the air to the required water-vapor content was achieved by heating water vapor from vapor generator 19 to mixer 16. The specified vapor flow rate was set by means of a rheometer. The vapor content in the air was determined from the change in the mass of two U-shaped tubes 11 filled with a mixture of phosphoric anhydride and pieces of pumice, after a specified volume of air had been drawn in by means of vacuum pump 28 [3].

The moist granulated superphosphate is loaded into a special container 10 which is first heated in a thermostat to prevent the water vapor in the heated air from condensing on the cold surface of the container; the moist granulated superphosphate was suspended in the chamber from a thread attached to the arm of the ADV-200M analytical balance 1.

The evaporation of the moisture in the air stream was accomplished through the latticed side wall of the container, 45 mm in length and 38 mm in diameter. During the experiment a stopwatch was used to determine the time for the reduction in the mass of the suspended superphosphate in the container, at intervals of 0.5 g. The superphosphate sample, on the average, amounted to 45 g. The change in the temperature of the superphosphate during the drying process and the change in the temperature of the heated air were measured by means of an R-307 potentiometer 8 and an M195/1 null galvanometer 3. The

---

Polytechnic Institute, Odessa. Translated from *Inzhenerno-Fizicheskii Zhurnal*, Vol. 16, No. 3, pp. 429-437, March, 1969. Original article submitted June 4, 1969.

© 1972 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

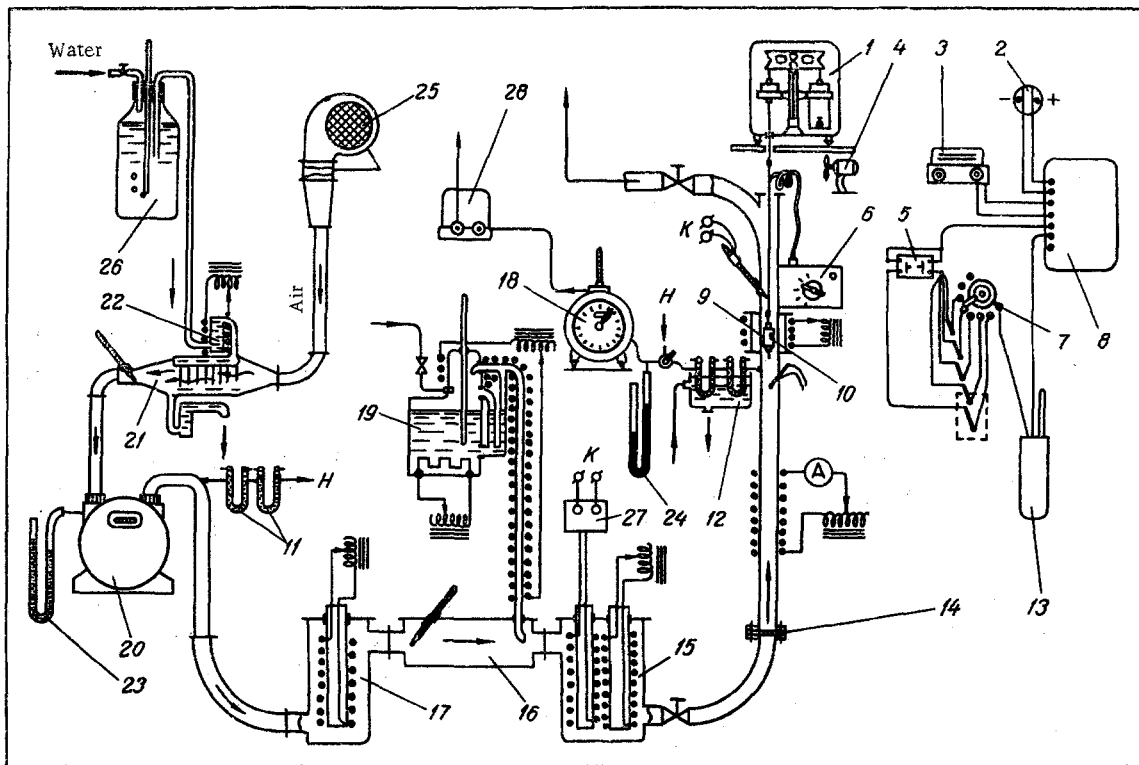


Fig. 1. Diagram of the experimental installation.

temperature sensors were copper-constantan thermocouples. The air flow rate was recorded by means of GKF-6 laboratory gas counters 20.

Figure 2 shows the characteristic curves for the drying of the superphosphate and the temperature curves, plotted from the experimental data.

Graphical differentiation was used to find the curves for the drying rate of the superphosphate for various regimes (Fig. 3). To determine the closest approximation of the drying process under laboratory conditions to the process which takes place in real dryers, we investigated an industrial granulated superphosphate which met the specifications of GOST 5963-53. The superphosphate was dried to a final moisture content of 3-4%, which corresponds to the lower limit of moisture content for commercial superphosphate, i. e., 4-8%. The moisture content  $W$  of the superphosphate was defined as the ratio of the amount of moisture in the specimen to the mass of absolutely dry superphosphate, i. e.,

$$W = \frac{M}{G_d} 100. \quad (1)$$

The initial moisture content of the superphosphate loaded into the container varied from 15-17.9%, which can be explained by the differing content of moisture in the samples, as a consequence of the mechanical inclusions contained in the industrial superphosphate. Moreover, the quantity of evaporated moisture was determined in conjunction with the gaseous compounds of the fluorine which settles out from the superphosphate as the latter is dried [4].

Analysis of the curves for the drying kinetics in conjunction with the temperature curves (Fig. 2) shows that the temperature at any point on the sample rises continuously. At the same time, the loss in moisture at the beginning of the drying process obeys a linear law. We find that the linear law for loss of moisture is disrupted when a specific value of the moisture content (the critical moisture content) is reached.

The drying rate thus exhibits two characteristic periods: a period of a constant rate and a period of a diminishing rate. The continuous rise in the surface temperature during the period of a constant drying rate indicates that the evaporation of the moisture is proceeding from within the sample, i. e., the

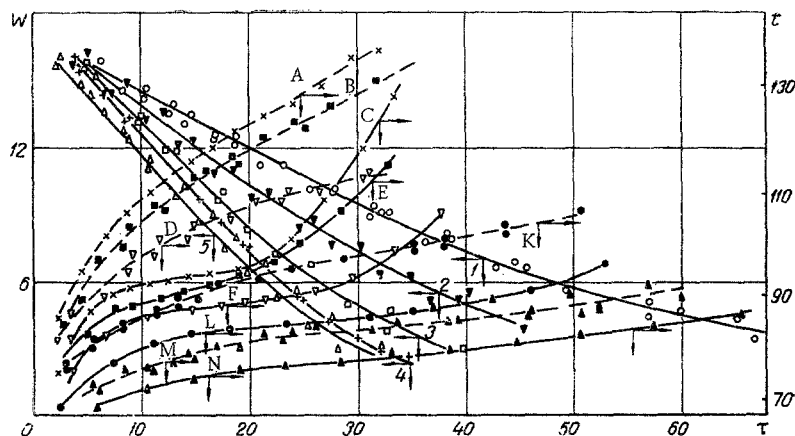


Fig. 2. Drying curves for granulated superphosphate and temperature curves for  $\omega_{av}^{\varphi} = 1.77$  m/sec,  $\varphi_{av} = 18.2\%$ : 1)  $W = f(\tau)$  for  $t_{av}^d = 110.8^\circ\text{C}$ ; 2) 125.4; 3) 147.5; 4) 185.7; 5) 165.7; M)  $t_{max}$  at the surface for  $t_{av}^d = 110.8^\circ\text{C}$ ; K) the same, 125.4; D) the same, 147.5; B) the same, 165.4; A) the same, 185.7; N)  $t_{mat}$  deep within for  $t_{av}^d = 110.8^\circ\text{C}$ ; L) the same, 125.4; F) the same, 147.5; E) the same, 165.4; C) the same, 185.7.

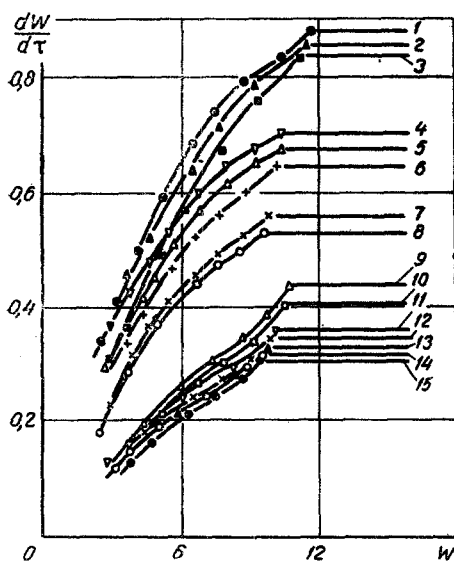


Fig. 3. Curves for the drying rate ( $dW/d\tau$  in %/min) for granulated superphosphate: 1-8) for  $t_{av}^d = 185.7^\circ\text{C}$ ; 9-15) for  $t_{av}^d = 125.4^\circ\text{C}$ ; 1) for  $\varphi_{av} = 18.2\%$ ; 2) 27.0; 3) 35.4 ( $\omega_{av}^t = 6.3$  m/sec); 4) 18.2; 5) 27.0; 6) 35.4 [4-6]  $\omega_{av}^t = 3.7$  m/sec; 7) 18.2; 8) 27.0 [7, 8]  $\omega_{av}^t = 1.95$  m/sec; 9) 27.0; 10) 35.4 [9-10]  $\omega_{av}^t = 6.30$  m/sec; 11) 18.2; 13) 27.0 [11, 13]  $\omega_{av}^t = 3.70$  m/sec; 12) 18.2; 14) 27.0; 15) 35.4 [12, 14, 15]  $\omega_{av}^t = 1.95$  m/sec].

evaporation zone shifts continuously into the depth of the material. It can be assumed that the transport of the vapor into the evaporation zone is accomplished not only by means of diffusion, but also as a consequence of effusion, which increases the coefficients of mass conductivity and results in a constant intensity of drying during the initial period.

As indicated earlier, the drying-rate curves in the range of variations in the moisture content of the superphosphate being studied here, exhibit only a single critical point which shifts toward the higher values of superphosphate moisture content with a rise in the temperature of the air and its velocity. An increase in the relative humidity of the air leads to a shift in the critical point toward the lower values of the superphosphate moisture content. The values of the critical superphosphate moisture content and the drying rate during the first period in the various drying regimes are shown in Table 1.

A rise in the air temperature noticeably increases the drying rate. The velocity of the drying agent also significantly affects the drying rate for the superphosphate. This effect is particularly pronounced in the high-temperature region. At the end of the second period, the velocity of the air has less effect on the drying rate for the superphosphate. With a rise in the relative humidity of the air the drying rate diminishes. At relatively low air temperatures ( $110$ - $120^\circ\text{C}$ ) and at low velocities for the drying

TABLE 1. Effect of Temperature, Velocity, and Relative Moisture Content of the Air on the Critical Moisture Content of the Granulated Superphosphate, on the Drying Rate, and on the Intensity Mass Transfer in the First Drying Period

$t_{av}^c, ^\circ C$	$\omega_{av}^f$	1,95			3,70			6,30			
		$\omega_{av}^p$	2,10	1,93	1,77	4,12	3,66	3,30	7,08	6,32	5,71
		$\varphi_{av}$	35,4	27,0	18,2	35,4	27,0	18,2	35,4	27,0	18,2
185,7	$N$	—	0,530	0,562	0,648	0,677	0,704	0,837	0,855	0,880	
	$W_{cr}$	—	9,6	9,85	10,1	10,3	10,4	11,0	11,3	11,5	
	$q_m$	—	2,46	2,49	2,97	2,99	3,02	3,83	4,05	4,13	
165,4	$N$	0,492	0,516	0,556	0,551	0,571	0,602	0,728	0,788	0,821	
	$W_{cr}$	9,3	9,55	9,75	9,90	10,2	10,3	10,65	11,1	11,25	
	$q_m$	2,12	2,18	2,32	2,25	2,36	2,50	3,19	3,32	3,57	
147,5	$N$	0,425	0,450	0,479	0,486	0,511	0,536	—	0,610	0,636	
	$W_{cr}$	9,25	9,50	9,70	9,85	10,15	10,2	—	10,8	10,9	
	$q_m$	1,94	1,98	2,05	2,21	2,21	2,29	—	2,70	2,92	
125,4	$N$	0,308	0,318	0,347	—	0,331	0,364	0,409	0,439	—	
	$W_{cr}$	9,2	9,4	9,65	—	9,80	10,10	10,35	10,6	—	
	$q_m$	1,38	1,42	1,49	—	1,47	1,60	1,83	1,86	—	
110,8	$N$	0,205	0,215	0,253	0,222	0,260	0,285	0,249	0,301	0,348	
	$W_{cr}$	8,9	9,3	9,5	9,6	9,75	10,0	10,25	10,5	10,6	
	$q_m$	0,89	0,98	1,13	1,01	1,19	1,31	1,17	1,32	1,53	

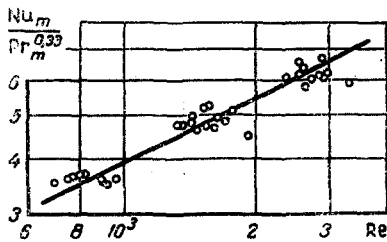


Fig. 4. Dependence of the ratio  $Nu_m/Pr_m^{0.33}$  on  $Re$ .

agent, within limits of variation from 18 to 36% for the relative humidity of the air, this effect is less significant, particularly during the second period, as can be seen from Fig. 3. It is obvious that the intensification of the process of drying granulated superphosphate becomes possible either by increasing the velocity of the drying agent or by raising its temperature. To reduce the expenditure of energy on the drying of the superphosphate, we can recommend the use of the air being discharged from the dryers (with the water vapors that it contains) as a part of the drying agent entering the dryer, i. e., to set up a process with partial recirculation of the drying agent.

Reduction of experimental data showed that the experimental points for the first drying period of the superphosphate line up (with an accuracy of  $\pm 8\%$ ) on the straight line plotted in logarithmic coordinates  $Nu_m/Pr_m^{0.33} - Re$  (Fig. 4). The Nusselt diffusion number in this case is calculated from the expression

$$Nu_m = \frac{\beta_{cr} \cdot \bar{S}}{\lambda_m}, \quad (2)$$

where  $\beta_{cr}$  is the moisture-exchange coefficient which is defined as the ratio of the intensity of mass transfer during the first drying period to the moving force in the drying process:

$$\beta_{cr} = \frac{q_m}{\Delta p}. \quad (3)$$

Analysis of the experimental data demonstrated that the intensity of mass transfer, referred to the area of the evaporation surface, can be expressed in turn (accurate to  $\pm 6.5\%$ ) by the empirical relationship

$$q_m = 4.4 N. \quad (4)$$

It should be noted that the value of the moving force  $\Delta p$  for the drying process in the case of a "hard" regime cannot be presented as the difference between the partial vapor pressures at the surface of the container with the superphosphate specimen and the ambient medium, since the evaporation surface is continuously penetrating into the depth of the layer of the material being dried. It was found [5, 6] that the point of flexure in the temperature curve indicates the instant at which the evaporation surface passes through the

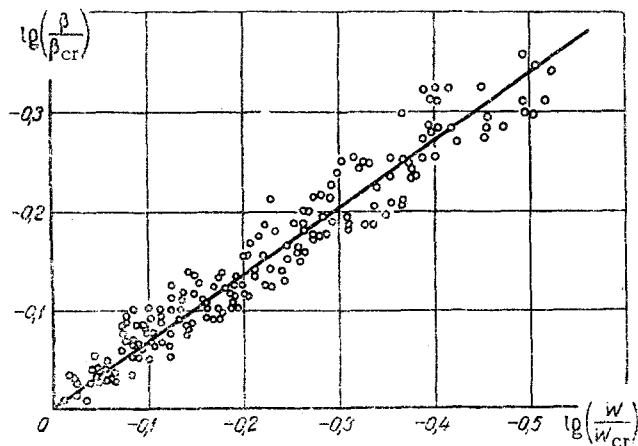


Fig. 5. Dependence of  $\log(\beta/\beta_{cr})$  on  $\log(W/W_{cr})$ .

point at which the thermocouple is located. The temperature at this point gives the temperature of the evaporation surface at a given instant.

Assuming that the temperature of the evaporation surface during the drying process varies only slightly with time and over the entire length from the surface of the container to the point of thermocouple insertion, we will assume the temperature of the evaporation surface to be constant and equal to the temperature at the point of flexure for the temperature curve, as derived by means of the thermocouple imbedded into the central portion of the container, at a distance of 6 mm from the container surface.

The moving force of the drying process can then be presented as the difference between the partial vapor pressure  $p_{ev}$  at the evaporation surface, calculated from the temperature of the evaporation surface, corresponding to the point of flexure on the temperature curve (Fig. 2), and the partial vapor pressure  $p_{med}$  in the ambient medium, as found from the temperature of the air entering the drying chamber:

$$\Delta p = p_{ev} - p_{med}. \quad (5)$$

The coefficient of mass conductivity  $\lambda_m$  for the water vapor is calculated without consideration of the effect of vapor effusion on the diffusion mechanism of transfer by means of the formula

$$\lambda_m = 0.307 \cdot 10^{-6} T \left( \frac{760}{B} \right). \quad (6)$$

The value of  $T$  in (6) is

$$T = 273 + \frac{t_{ev} + t_{med}}{2}. \quad (7)$$

We used  $(S)^{1/2}$  as the decisive dimension in (2). As a result, the process of drying granulated superphosphate in the first period is expressed by a criterial relationship such as

$$Nu_m = 0.147 Re^{0.48} Pr_m^{0.33}, \quad (8)$$

valid when  $650 < Re < 3500$ .

Expression (8) encompasses only the period of a constant drying rate. During the period of a diminishing drying rate the coefficient of moisture exchange is no longer constant and begins to diminish as the moisture content of the superphosphate declines. The specific features of mass transfer in the second drying period, according to [8], were taken into consideration by introduction into the criterial relationship (8) of the parametric factor  $(W/W_{cr})^\sigma$ .

On the basis of the derived experimental data we determined the relationship between the parametric factor and the ratio of the moisture-exchange coefficient during the second drying period (calculated for the corresponding values of the superphosphate moisture content) to the coefficient of moisture exchange during the period of a constant drying rate. We see from Fig. 5 that this relationship (accurate to  $\pm 10\%$ ) can be assumed to be equal to

$$\frac{\beta}{\beta_{cr}} = \left( \frac{W}{W_{cr}} \right)^{0.68}, \quad (9)$$

where the exponent  $\sigma = 0.68$  was found to be the tangent to the angle of inclination of the straight line

$$\lg \left( \frac{\beta}{\beta_{cr}} \right) = f \left( \lg \frac{W}{W_{cr}} \right). \quad (10)$$

In final form, with consideration of the parametric factor which turns into unity for the period of the constant drying rate when  $W = W_{cr}$ , the entire drying process for the superphosphate can thus be described by an equation of the form

$$Nu_m = 0.147 Re^{0.48} Pr_m^{0.33} \left( \frac{W}{W_{cr}} \right)^{0.68}. \quad (11)$$

The moisture-exchange coefficients for the second drying period, determined from (11), for superphosphate moisture-content values (in terms of dry mass) up to 4% agree satisfactorily (accurate to  $\pm 15\%$ ) with the moisture-exchange coefficients found from the drying curves applicable to the granulated superphosphate.

In designing drum dryers used to dry superphosphate under industrial conditions, we should refer to the value of the linear velocity of the air in the determination of  $Re$  to the effective cross section of the installation. As the determining dimension in the  $Nu_m$  number we should take the square root of the total area of the outside surfaces of the jet streaming away from the dryer's bladed lifting system.

It should be pointed out that in the production of superphosphates we use drum dryers of the simplest type, and these make no provision for the possibility of substantial intensification of the drying process. This might serve to explain the fact, noted in the literature [9], that there is a significant difference between the intensities of drum dryers in various superphosphate plants.

The drum dryers using lateral injection of air through the bed [7] represent an interesting and efficient attempt to achieve additional intensification of the drying process by dealing with a layer of the material in avalanche form.

#### NOTATION

- $\omega_{av}^t$  is the average value for the air velocity at constant temperature and variable relative humidity of the air, m/sec;
- $\omega_{av}^\varphi$  is the average value of the air velocity at a constant relative humidity of the air, m/sec;
- $\varphi_{av}$  is the average relative humidity of the air, %;
- $N$  is the drying rate in the first period, %/min;
- $W$  is the instantaneous value of the superphosphate moisture content, %;
- $W_{cr}$  is the critical moisture content of the superphosphate, %;
- $q_m$  is the intensity of the mass transfer during drying in the first period,  $kg/m^2 \cdot h$ ;
- $Nu_m$  is the Nusselt diffusion number;
- $Re$  is the Reynolds number;
- $Pr_m$  is the Prandtl diffusion number;
- $M$  is the quantity of moisture in the specimen, g;
- $G_d$  is the mass of the absolutely dry superphosphate, g;
- $\beta$  is the moisture-exchange coefficient referred to the difference between the partial vapor pressures,  $kg/m^2 \cdot h$ ;
- $\beta_{cr}$  is the moisture-exchange coefficient during the period of the constant drying rate, referred to the difference between the partial vapor pressures,  $kg/m^2 \cdot h$ ;
- $\Delta p$  is the moving force of the drying process,  $N/m^2$ ;
- $p_{ev}$  is the partial pressure of the water vapors at the evaporation surface,  $N/m^2$ ;
- $p_{med}$  is the partial pressure of the water vapors in the heated air,  $N/m^2$ ;
- $\lambda_m$  is the coefficient of mass conductivity, referred to the difference between the partial vapor pressures,  $kg/m \cdot h$ ;
- $S$  is the evaporation surface,  $m^2$ ;
- $B$  is the barometric pressure,  $N/m^2$ ;

$t_{ev}$  is the temperature of the evaporation surface, °C;  
 $t_{av}^d$  is the average temperature of the drying agent, °C;  
 $t_{mat}$  is the temperature of the superphosphate during the drying process, °C;  
 $t_d$  is the temperature of the drying agent, °C;  
 $\sigma$  is the exponent of the parametric factor;  
 $\tau$  is the drying time, min.

#### LITERATURE CITED

1. L. E. Berlin and S. T. Kalugina, *Khimi. Promysh.*, No. 5 (1933).
2. L. E. Berlin, O. I. Vognesenskaya, et al., *Khim. Promysh.*, No. 1 (1937).
3. F. N. Kel'man, E. B. Brutskus, and R. Kh. Osherovich, *Methods of Analysis in Production Control for Sulfuric Acid and Phosphoric Fertilizers* [in Russian], Khimiya, Moscow (1965).
4. M. L. Chepelevetskii and E. B. Brutskus, *Superphosphate* [in Russian], Goskhimizdat, Moscow (1958).
5. A. V. Luikov, *The Theory of Drying* [in Russian], Gosenergoizdat (1950).
6. A. V. Luikov, *Heat and Mass Transfer in Drying Processes* [in Russian], Gosenergoizdat (1956).
7. M. Yu. Lur'e, *The Science of Drying* [in Russian], Gosenergoizdat (1948).
8. P. D. Lebedev, *Drying with Infrared Radiation* [in Russian], Gosenergoizdat (1955).
9. K. Aver'yanov, *Ekonomich. Gaz.*, No. 24, 149 (1964).