KINETICS OF DRYING OF MOIST MATERIALS IN SUPERHEATED STEAM

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A method is proposed for the approximate calculation of the drying time for different materials when drying in a medium of superheated steam with constant parameters at atmospheric pressure.

One method of intensification of the drying process is the use of superheated steam as the drying agent. Its use is most promising for those materials on which certain quality requirements are imposed after the drying. For example, the efficiency and economy of the process of drying in superheated steam has been demonstrated [6] for valuable types of wood. The variety of materials obtained in the chemical industry require searches for new means and methods of drying. The use of superheated steam in these cases can prove to be the most efficient and sometimes the only possible method. However, the use of superheated steam as the drying agent in industry is held back by the complexity of the experimental studies, the imperfection of the existing installations [4], and the absence of general methods of calculation. There are data in the literature on methods of calculating the drying in superheated steam only for certain materials [4, 5].

In certain cases the size of the experiment can be reduced if, for example, in studying the kinetics of drying one uses the method of generalization of the drying curves [1, 2]. From the results of individual tests of the drying of a specific material one can obtain data through such a generalization for the calculation of its drying time under any conditions.

The results of the generalization of experimental data for different drying methods are presented in [2, 3]. The possibility of applying the method of generalization of drying curves to results obtained during drying in superheated steam are examined in more detail in the present report, since in this case the drying mechanism has its own specific properties.

To study the kinetics of drying we have developed an installation which permits one to conduct an experiment over a wide range of temperatures and velocities of the superheated steam with continuous recording of the temperature and mass loss of the specimen. A diagram of the installation is presented in Fig. 1. It consists of a working chamber 1, which is a vertical rectangular metal channel of dimensions $210 \times 210 \times 1200$ mm, an airtight housing 2, which is 400 mm in diameter, a central ventilator 3, an electric air heater 4, and a steam generator 5. The central ventilator, which is located in the upper part of the working chamber, provides circulation of the drying agent through the circuit: the annular channel between the chamber and the jacket and between the air heater and the working chamber. The constant temperature of the drying agent in the chamber is maintained (with deviations of no more than ±3°C) by an automatic system consisting of a thermocouple 6, a potentiometer 7, and a regulator 8, which varies the voltage in the windings of the airheater in accordance with the assigned temperature. The heat of the air heater is expended on the drying and on compensation for heat losses. The velocity of the drying agent is measured by a thermoanemometer 9 and is recorded by a potentiometer 10. The drying is performed by steam from the steam generator. The absence of air from the superheated steam is monitored continuously by a "wet" thermocouple 11 and is recorded by a potentiometer 12. The installation makes it possible to conduct studies over a range of velocities of the superheated steam of from 0.5 to 7 m/sec and at temperatures of up to 500°C.

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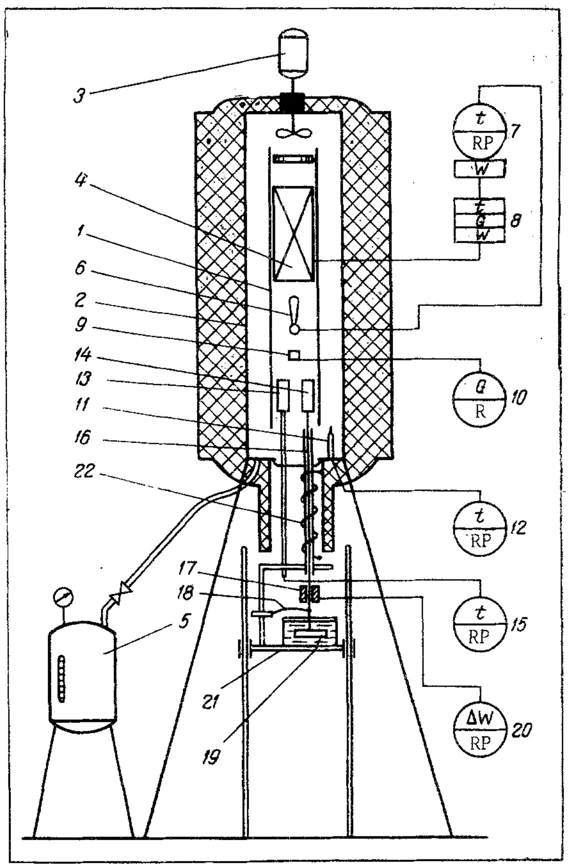

Fig. 1. Diagram of recirculation drier for the study of the process of drying with superheated steam at atmospheric pressure.

In the working chamber are placed two identical specimens. One specimen 13 is intended for recording the temperature of the material using thermocouples (electrodes 0.1 mm in diameter) and the multipoint potentiometer 15. The other specimen 14 was fastened to the sensor of an electric balance. The system for recording the mass loss consists of a moving shaft 16, a transformer pickup 17, a flat spring 18, a float 19, and an electronic bridge 20 which continuously records the mass loss of the specimen. The lifting force of the float was selected with allowance for the mass of the shaft, the pickup loop, and the dry mass of the specimen, which increased the accuracy in the measurement of the mass loss. The specimens and the electric balance are mounted on a moveable carriage 21 permitting the rapid

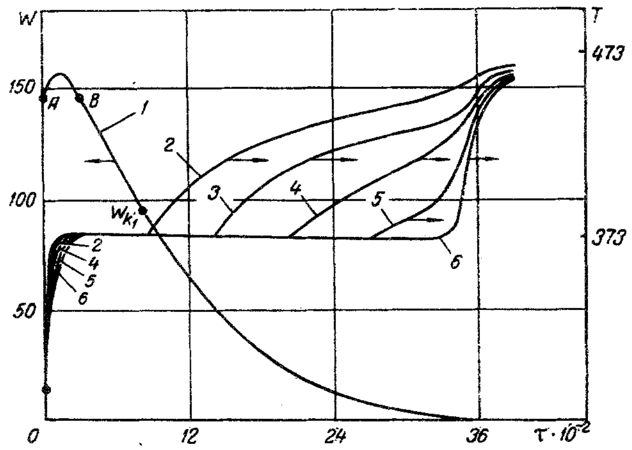

Fig. 2. Drying of filter paper specimens in superheated steam (W_i = 145%, T = 473°K, v = 1.8 m/sec): 1) curve of mass loss of specimen during drying process; 2-6) curves of temperature variation of specimen at different distances from the surface; 2) 0.15 mm from surface; 3) 1; 4) 2; 5) 3; 6) 4 mm.

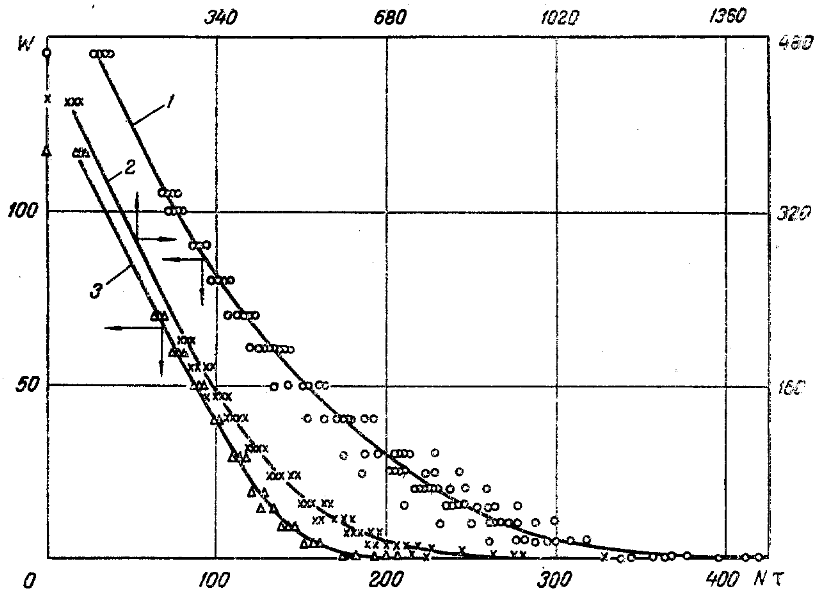

Fig. 3. Generalized drying curves. Dependence of W (%) on $N\tau$ (%): 1) filter paper; 2) paste consisting of a mixture of calcium and nickel phosphates; 3) paste of inorganic pigment.

insertion of the specimens into the chamber. The shaft is warmed by the electric heater 22 to prevent the condensation of water vapor on it. A slight excess pressure of the superheated steam was created in the dryer during a test to prevent the entry of air into the chamber. The housing of the heater was insulated with a layer of asbestos to reduce heat losses.

Colloidal capillary-porous solids having all types of bonding of the moisture with the material and having different thermophysical properties were used as the subjects of the study: filter paper, $W_i = 145\%$; a paste consisting of a mixture of calcium and nickel phosphates, $W_i = 420\%$; a paste of inorganic pigment, $W_i = 117\%$. The studies were conducted on specimens 80×100 mm in size and 8 mm thick. The specimens were placed vertically in the chamber in special frames and dried on both sides. A frame consists of two 110×130-mm plates each 4 mm thick. There is a cutout of 80×100 mm inside for the specimen. The plates are fastened to each other. A filament 0.15 mm in diameter was stretched along the outside of the plates at 3 mm intervals to hold the specimens in the frame. The filament was stretched along the short wide of the frame parallel to the steam flowing over the specimens.

The paste-like materials were cemented into the frame before the test started. The specimens of filter paper were prepared by the following method. Flat specimens of the required thickness were built up from moistened sheets 0.15-0.16 mm thick.

For uniform distribution of the moisture in the specimen it was kept under a small weight for 2 to 3 days at $\psi = 100\%$. The nonuniformity of the moisture distribution in the sheets of the specimen before the test did not exceed ±10%.

The study of the kinetics of the drying of the selected materials was conducted in the following ranges of velocity and temperature of the drying agent: filter paper v = 0.5-6.2 m/sec, T = 393-673°K; paste consisting of mixture of calcium and nickel phosphates v = 2.2-4 m/sec, T = 473-723°K; paste of inorganic pigment v = 1.2-2.5 m/sec, T = 393-523°K.

TABLE 1. Constants for Calculating Drying Times for Different Materials

Material	c	w_{cr1}	w_{cr2}	χ_1	χ_2
Filter paper	31	105	29	0,00444	0,0097
Paste of phosphate mixture	58	200	54	0,00223	0,00433
Paste of pigment	20	70	33	0,00706	0,0185

The results of one test for the filter paper specimens are presented in Fig. 1. The drying curve of specimen 1 has three periods. The warmup period (section AB, curve 1) occurs with an increase in the moisture of the specimen (this peculiarity of drying in a medium of superheated steam has been noted by a number of authors [4]). The temperature of the specimen reaches approximately 100°C (curves 2-6), which corresponds to the boiling temperature at atmospheric pressure and confirms the absence of air in the drying chamber. The temperature remains at about 100°C throughout the volume of the specimen during the first period of drying. The second period is characterized by a clearly expressed deepening of the evaporation zone (curves 2-6 in Fig. 2) and the gradual heating of the specimen to the drying temperature.

The experimental results obtained for the selected materials were analyzed by Krasnikov's method [2, 3]. The following assumptions were made in the analysis.

1. The time it takes to reach the initial moisture content W_i of the specimen from the start of the test (section AB on curve 1 of Fig. 2) was taken as the warmup period.

2. An analysis of the effect of the drying conditions on the critical moisture contents W_{cr1} and W_{cr2} for the materials studied established that W_{cr2} is almost independent of the drying conditions, while W_{cr1} varies with the drying temperature within certain limits. The greatest variation in W_{cr1} was observed for filter paper, which in the temperature range of T = 393-673°K is described by the equation

$$W_{cr1} = 64.5 + 0.075\,T. \quad (1)$$

Since W_{cr1} varies by no more than 25% in the temperature range studied, the constant value W_{cr1} = 105% was adopted to describe the drying kinetics. For the paste consisting of calcium and nickel phosphates the deviations from W_{cr1} = 200% did not exceed ±10%, while there was a constant value of W_{cr1} = 70% for the paste of inorganic pigment.

The results of the generalized drying curves, obtained with allowance for the assumptions made above, are presented in Fig. 3. The warmup time for the specimens was allowed for in the plotting but the warmup curves were not plotted, since only the value $N\tau_{wa}$ proved to be constant for a given material, while the moisture increase of the specimen during this period depended on the drying conditions. The maximum deviations of the experimental points of the drying curves from the mean values did not exceed ±20% in all cases, which indicates the possibility of using the method of generalization of drying curves for data obtained during the drying of moist materials in a medium of superheated steam.

Using a generalized curve one can calculate the drying time for any conditions from the equation

$$\tau = \frac{1}{N}\left(C + W_i - W_{cr1} + \frac{1}{\chi_1}\lg\frac{W_{cr1}}{W_{cr2}} + \frac{1}{\chi_2}\lg\frac{W_{cr2}}{W_f}\right). \quad (2)$$

The drying rate in the first period can be calculated by equations from [4]. The values of the quantities entering into Eq. (2), obtained from the generalized drying curves, are presented in Table 1.

Thus, the results of the experimental studies of the kinetics of drying in a medium of superheated steam at atmospheric pressure can be generalized, which allows one to calculate the drying time for any conditions rather simply from the results of individual tests with the condition that the warmup time for the specimen is allowed for in the calculating equation.

NOTATION

W	is the moisture content, %;
τ	is the drying time, sec;
N	is the drying rate in first period, %/sec;
T	is the temperature of drying agent, °K;
ψ	is the relative humidity of air, %;
v	is the linear velocity of drying agent, m/sec;
$C = N\tau_{wa}$	is the constant which allows for warmup period of specimen, %;
χ_1, χ_2	are the relative drying coefficients in first and second parts of second period.

Subscripts

i	initial;
f	final;

cr1 first critical;
cr2 second critical;
wa warmup.

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