

# Experimental study of the silica gel drying in a fluidized bed apparatus

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**Abstract.** In this paper, the design and principle of operation of the dryer with a centrifugal fluidized bed is considered. It is a batch apparatus with a vertical drying agent supply and is intended for drying dispersed materials with a particle diameter from 1 to 5 mm, having a high initial moisture content and a strong moisture and solid dry frame bond. Silica gel with a particle diameter from 2.2 to 2.5 mm, used for drying air and industrial gases, was used as a drying object. The scheme of the test bench is given and described. The results of an experimental study of the process of low-temperature drying of silica gel (the temperature of the drying agent ranged from 35 to 65 °C) are presented. The obtained experimental data is presented as a dependence of the thermophysical parameters of the material and the drying agent on the drying time. The comparison of drying efficiency at different modes is given. On the basis of the obtained data, a positive conclusion about the possibility of using this apparatus for low-temperature drying of capillary-porous bodies is made.

## 1. Introduction

Among all heat and mass transfer units used in industry for dispersed materials drying, a special place is occupied by a fluidized bed apparatus. This is primarily due to the high interphase heat and mass transfer intensity in such devices and their low hydraulic resistance [1-3]. Also their advantages include a relatively simple design, small dimensions, the ability to ensure continuous processes. This led to the presence of a wide range of dryers that implement this technological principle in modern industry [3-5]. Nevertheless, the development and research of new more energy-efficient structures is an urgent task of practical importance.

The results of theoretical and experimental studies of regenerative heat exchanger and absorber with centrifugal fluidized bed were summarized in [6-8]. Such a layer is formed in the annular channel of the apparatus having a cylindrical cross section when air is supplied to the layer at a predetermined angle to the horizontal plane. According to the results of these studies, the use of a centrifugal layer can significantly intensify the heat and mass transfer process and simplify the apparatus design by eliminating a special tool for the dispersed material moving. This paper presents new results for the application of such a layer for capillary-porous dispersed material (silica gel, which is widespread in industry and convenient for experimental research) drying.

## 2. Materials and Methods

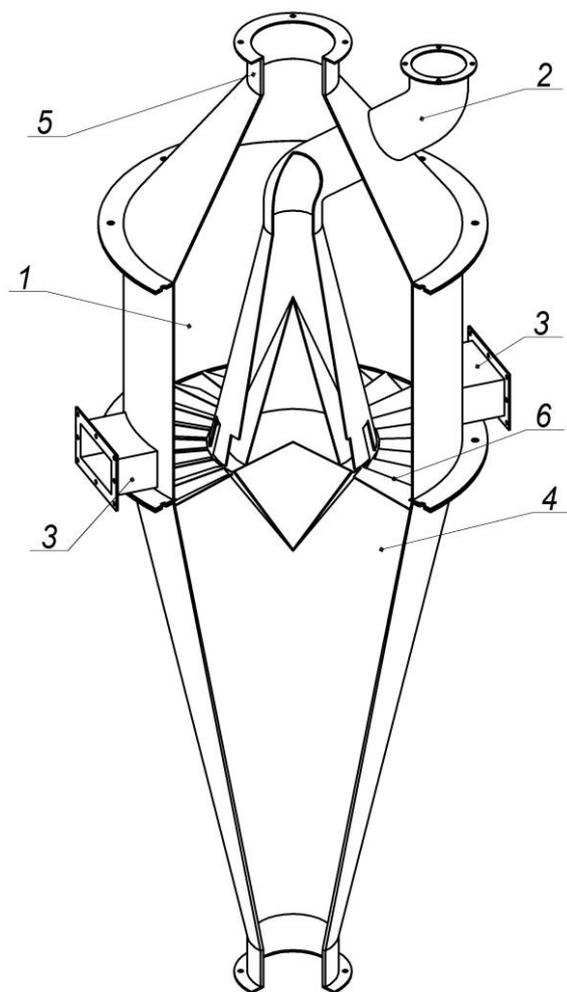
A centrifugal fluidized bed dryer is a batch apparatus with a vertical drying agent supply. Figure 1 shows its layout (a) and appearance (b). It is intended for drying dispersed materials with a particle



diameter from 1 to 5 mm, having a high initial moisture content and a strong moisture and solid dry frame bond.

The main dryer element is the working chamber 1 with a diameter of 0.4 m and a height of 0.4. The annular channel through which the material moves is formed by a cylindrical case of the apparatus and an inner conical shell with a base diameter of 0.2 m. The transparent cylindrical case of the pilot apparatus, shown in figure 1 (b), allows visual control of the fluidization process during operation. There are eight filling holes in the inner shell which are designed to supply fresh dispersed material to the working chamber from the branch pipe 2. The conical shape of the inner shell reduces the speed of the drying agent in the upper part of the working chamber 1. Unloading of the dried material is carried out through two discharge branch pipes 3 equipped with partitions. The drying agent enters the working chamber through the diffuser 4, and the waste one is discharged into the atmosphere through the chamber 5.

The louver grille 6 is used as a gas distribution device in the drying apparatus. Its blades are inclined to the horizontal plane by 24 degrees and serve to create a directed flow of the drying agent at the entrance to the material layer. A metal gauze is installed above the grille. Its purpose is to prevent particles drop in the diffuser 4 and to ensure a more uniform dried material fluidization.



(a)

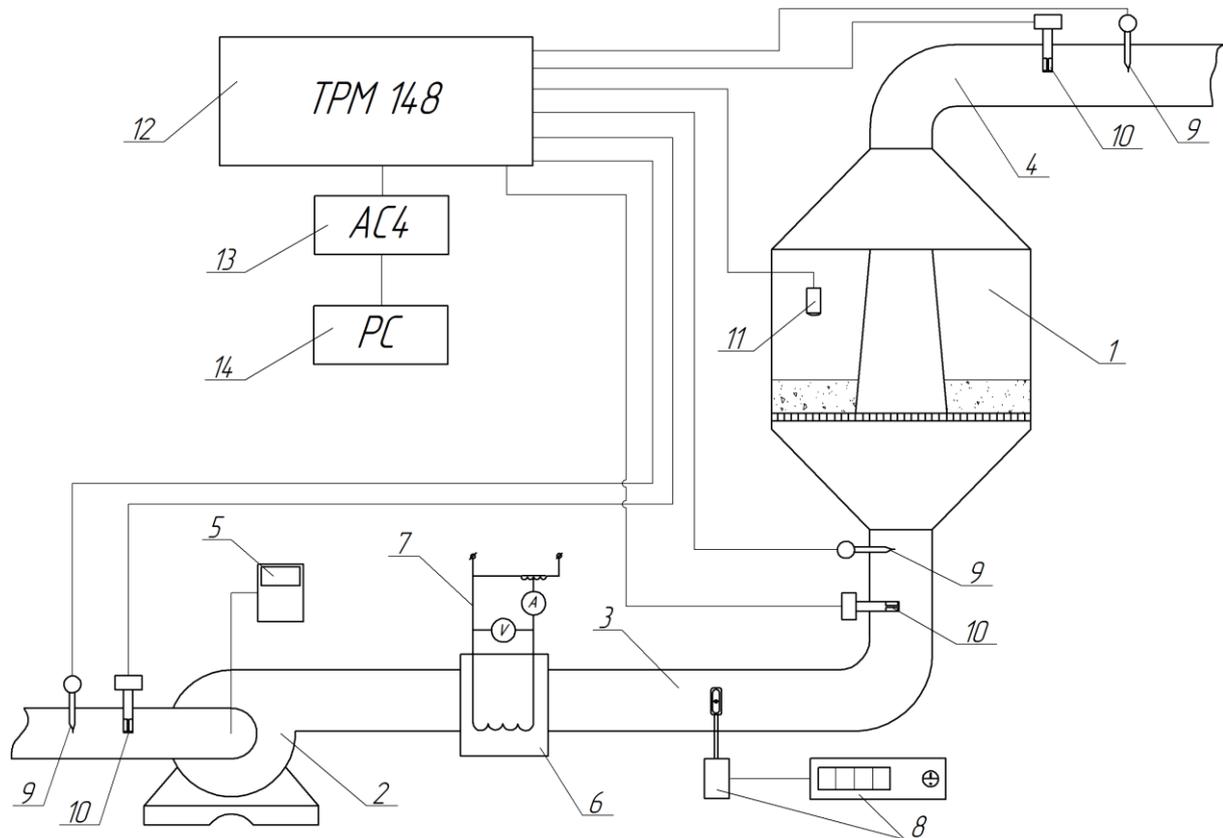


(b)

**Figure 1.** The layout (a) and the appearance (b) of the centrifugal bed dryer.

This dryer due to the annular channel has a very simple design, small dimensions and no stagnant areas. The hydraulic resistance of devices with a centrifugal fluidized bed is insignificant and has a value from 200 to 650 Pa [5, 7]. The heat and mass transfer intensification in such a layer occurs due to the action of centrifugal forces on the material particles [5, 6]. The height of the layer should not exceed 0.1-0.15 m [5-7].

A test bench was constructed to conduct an experimental study of the heat and mass transfer process during dispersed materials drying in this apparatus. Its layout is shown in figure 2.



**Figure 2.** The test bench layout: 1 – dryer; 2 – fan C10-28 No. 4; 3, 4 – air ducts; 5 – frequency converter Delta VFD150E43A; 6 – electric air heater CFOC-25/0,5-11; 7 – autotransformer PHO-250-5; 8 – thermo-anemometer TTM-2/4-06 and converter TTM-2-04; 9 – thermoelectric converters TP-2088; 10 – moisture sensors Galltec+Mela FRC 3/5; 11 – infrared temperature sensor MoreSunsDIY; 12 – PID controller OWEN TPM 148; 13 – interface converter AC4; 14 – PC.

The drying agent (atmospheric air) is supplied to the apparatus by a centrifugal fan 2 through the duct 3. The fan performance is regulated by a frequency converter 5, which also provides a convenient way to estimate the energy cost of creating a drying agent flow. The exhaust air is discharged into the atmosphere through the duct 4. The cold atmospheric air is heated in an electric air heater 6 having a rated power of 24 kW. Its power is regulated by an autotransformer 7. The drying agent speed is measured by a hot-wire anemometer 8, the primary transducer of which is placed in the duct. Knowing the geometric characteristics of the ducts, it is easy to determine the mass flow rate of the drying agent and its speed at the entrance to the working chamber.

The thermocouples 9 are used to measure the drying agent temperature; duct moisture sensors are used to measure relative moisture 10. Each pair of sensors is installed in front of the fan, in duct 3 in front of the dryer, and in duct 4 after the dryer. The dispersed material temperature is measured using

an industrial infrared temperature sensor 11 mounted above the layer in the working chamber of the dryer. The use of this sensor allows continuous recording of data without interfering with the process.

A PID controller 12 is used as a secondary device. An interface converter 13 (RS485-USB) is designed to provide communication between the secondary device and the personal computer 14. The experimental data logging is carried out in the Owen Process Manager SCADA system.

The moisture content of the dispersed material is determined using a moisture analyzer EVLAS-2M.

The limits of the total measuring temperature and moisture error using the appropriate sensors and a secondary device are: air temperature -  $\Delta t = \pm 2.7$  °C; air moisture -  $\Delta \varphi = \pm 2.3\%$ ; material temperature -  $\Delta t = \pm 2.0$  °C; material moisture content -  $\Delta w = \pm 0.05\%$ .

### 3. Experimental results

The main parameters that allow to review the intensity of the drying process are: the drying agent temperature and moisture at the apparatus inlet ( $t''_{air}$ , °C;  $\varphi''$ , %) and at the outlet ( $t'_{air}$ , °C;  $\varphi'$ , %), and the dispersed material temperature and moisture changing during the drying process ( $t_m$ , °C;  $w$ , %).

Silica gel with a particle diameter from 2.2 to 2.5 mm was used as a drying object. Its regeneration was carried out at a temperature of 180-200 °C [9]; however, it was noted in [10] that in devices with a high heat and mass transfer rate it is advisable to regenerate silica gel at a temperature of 40 °C. Thus, the minimum temperature of the drying agent at the apparatus inlet was 35 °C, the maximum temperature was 65 °C, and the accuracy of its maintenance was  $\pm 2$  °C. The maximum temperature value was limited by the operating conditions of the air moisture sensors.

The experiments duration in all modes ranged from 25 to 30 minutes. The readings of all sensors were recorded in Owen Process Manager with 5 seconds frequency. Small samples of the material were taken from the working chamber at specified intervals to determine the silica gel moisture content. Then the samples were placed in a moisture analyzer to determine the current moisture value. Since it is more convenient to express the liquid content in the material through the mass of its absolutely dry part, the moisture content  $w\%$  was being converted into hygroscopic water content  $u$  kg/kg db at the same time [2].

The parameters characterizing the various drying modes in the paper are:

- the drying agent temperature at the entrance to the working chamber  $t'_{air}$ , °C;
- the drying agent speed at the entrance to the fluidized bed  $v_{air0}$ , m/s;
- the weight of the material in the working chamber  $M_m$ , kg;
- the initial moisture content of silica gel  $u_0$ , kg/kg db.

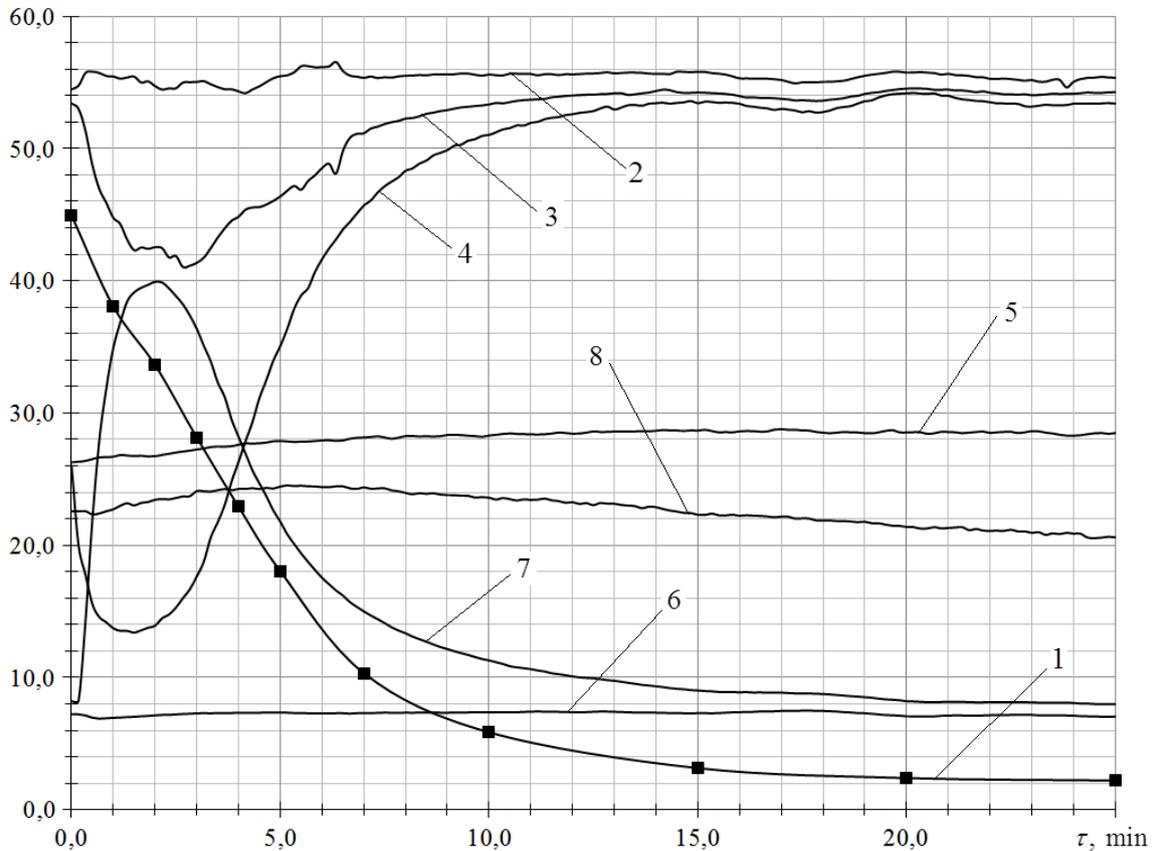
In the experimental study of the low-temperature silica gel drying process, these parameters had the following values:  $t'_{air} = 35; 45; 55$  °C;  $v_{air0} = 2.0; 2.3$  m/s;  $M_m = 1.0; 1.5$  kg;  $u_0 = 0.32; 0.53; 0.82$  kg/kg db. The experimental data processing was carried out according to the recommendations presented in [11].

Figure 3 shows the readings of all installed sensors at  $t'_{air} = 55$  °C;  $M_m = 1$  kg;  $u_0 = 0.82$  kg/kg db ( $w_0 = 44.92\%$ );  $v_{air0} = 2.0$  m/s. It also shows temperature and air moisture in the laboratory ( $t_{air0}$ , °C;  $\varphi_0$ , %).

It is known that the drying process can be divided into three periods – the material heating, the period of constant drying rate (first) and the period of falling drying rate (second). The type of drying curve 1 depends on the material class [2, 12].

The temperature curve 4 shows that the material temperature gradually decreases to the wet thermometer temperature. This time is the period of the material heating, its duration for this mode is 30-40 seconds from the beginning of drying. Then, up to 2-2.5 minutes from the beginning of drying, the material temperature is approximately constant. It is the period of constant drying rate. Its ending co-

incides with the local maximum humidity of the exhaust drying agent. After this, the material is heated to the drying agent temperature. It is the period of falling drying rate.



**Figure 3.** Silica gel drying process: 1 –  $w$ , %; 2 –  $t'_{air}$ , °C; 3 –  $t''_{air}$ , °C; 4 –  $t_m$ , °C; 5 –  $t_{air0}$ , °C; 6 –  $\phi'$ , %; 7 –  $\phi''$ , %; 8 –  $\phi_0$ , %.

Two moisture values can be distinguished on the drying curve, firstly, the critical one  $u_{cr}$  (transition from the first period to the second one in the 2nd-2.5 minutes of the process) and, secondly, the equilibrium one  $u_{eq}$  (balance with the drying agent moisture). Thus, the moisture removal process for this mode had been completed by the 16th minute.

It should be noted that the drying curve 1 and the material temperature curve 4 are typical of capillary-porous solids to which silica gel belongs. Curve 4 also shows that the material temperature is significantly lower than the ambient temperature. This is due to the high initial moisture and the intensive moisture removal from it, i.e. evaporative cooling of silica gel occurs.

Three to five experiments were carried out to check the data reproducibility for each temperature mode. Figures 4 - 6 show a comparison of drying and temperature curves obtained from three experiments for one drying silica gel mode ( $t'_{air} = 55$  °C;  $M_m = 1$  kg;  $u_0 = 0.82$  kg/kg db ( $w_0 = 44.92$  %);  $v_{air0} = 2.0$  m/s).

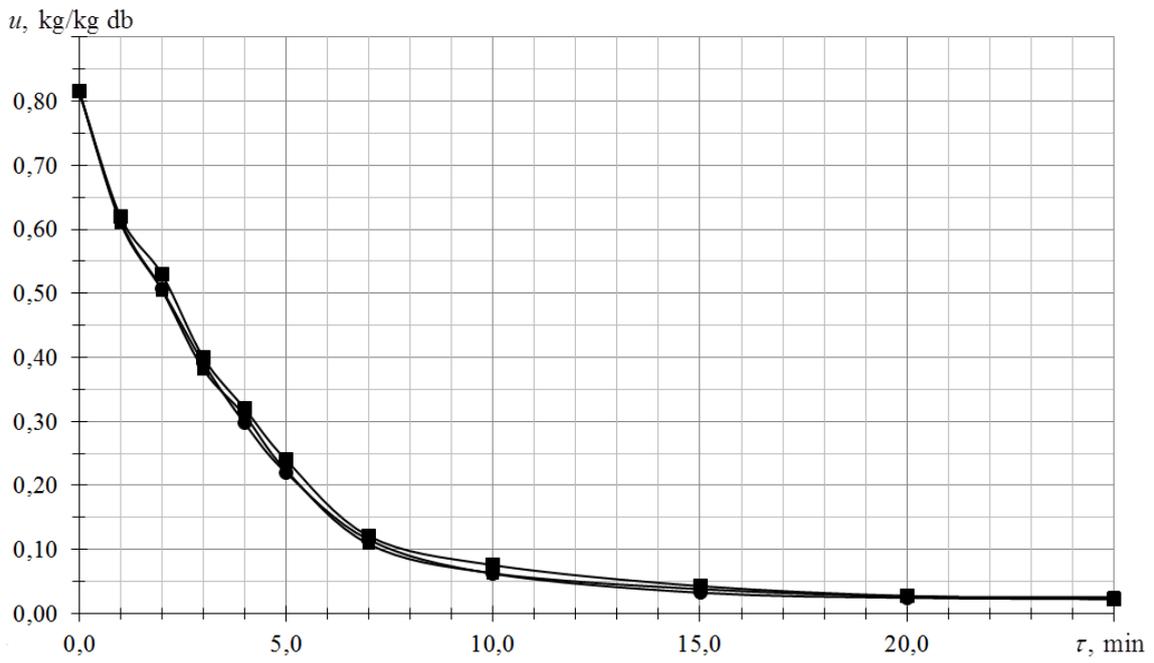


Figure 4. Silica gel drying curves.

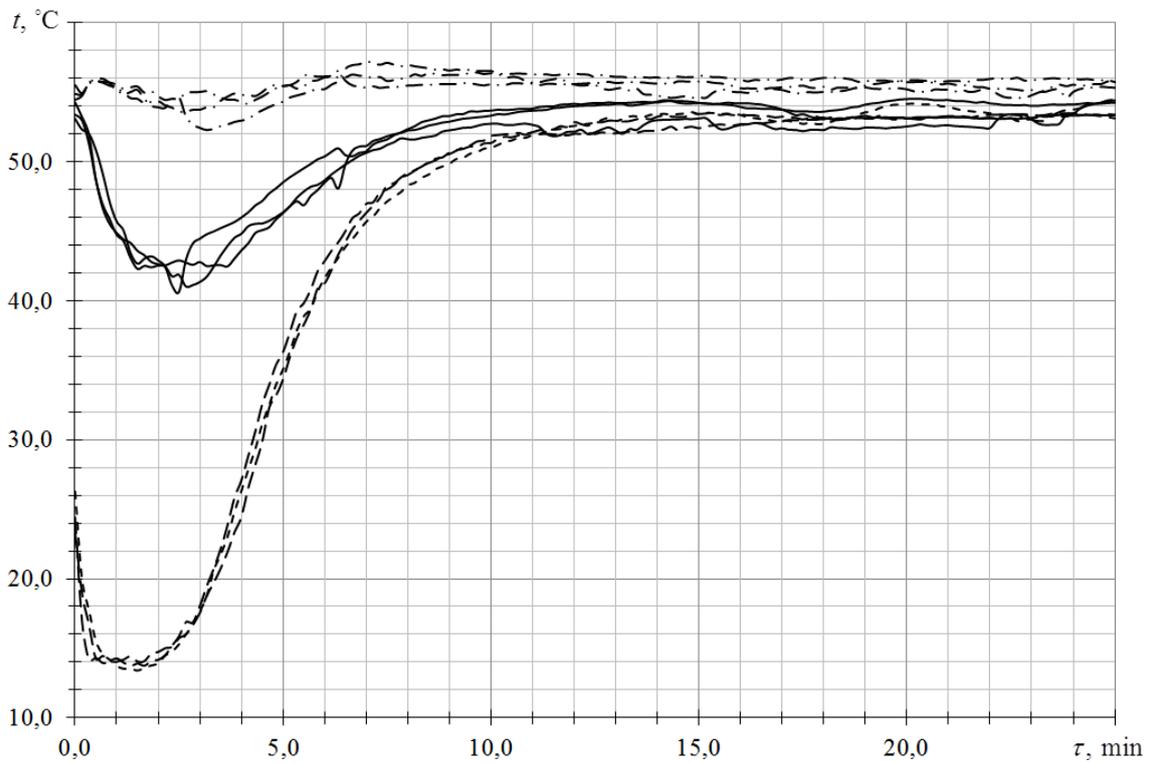
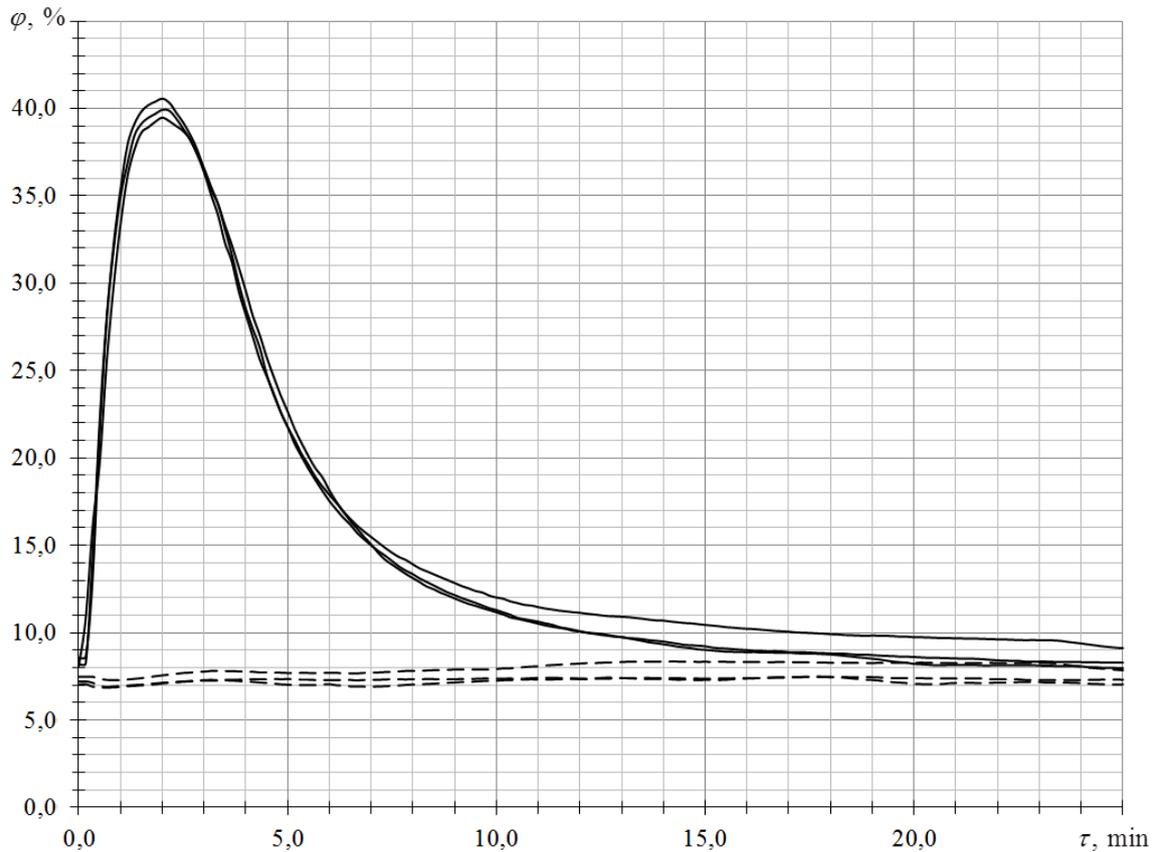


Figure 5. Temperature curves:  $-\cdot-\cdot-$   $t'_{air}$ ;  $—$   $t''_{air}$ ;  $- - -$   $t_m$ .



**Figure 6.** Air humidity curves: — — —  $\varphi'$ ; — — — —  $\varphi''$ .

The results of statistical experimental data processing [13] led to the conclusion that the adopted research methodology is adequate and allows to obtain sufficiently reliable data on the material and the drying agent parameters. During the repeated experiments it was observed that moisture and temperature in the laboratory influenced on the measurement results.

Figures 7 and 8 show a comparison of two drying modes that differ in the air temperature at the working chamber inlet  $t'_{air}$  – 45 °C and 55 °C. The other mode parameters are:  $M_m = 1$  kg;  $u_0 = 0.82$  kg/kg db;  $v_{air0} = 2.3$  m/s.

These relations prove that with increasing drying agent temperature, the rate of moisture removal from the material increases and the duration of the first period and the duration of the drying cycle decrease. At  $t'_{air} = 55$  °C the drying process ends by the 14th minute;  $u_{cr} = 0.48$  kg/kg db;  $u_{eq} = 0.044$  kg/kg db. At  $t'_c = 45$  °C  $u_{cr}$  the drying process ends by the 16th minute = 0.52 kg/kg db,  $u_{eq} = 0.041$  kg/kg db.

It should also be noted that each temperature mode of silica gel drying is characterized by a coincidence of the final air humidity curves  $\varphi''$  at the initial stage of the process (the first 1-1.5 minutes).

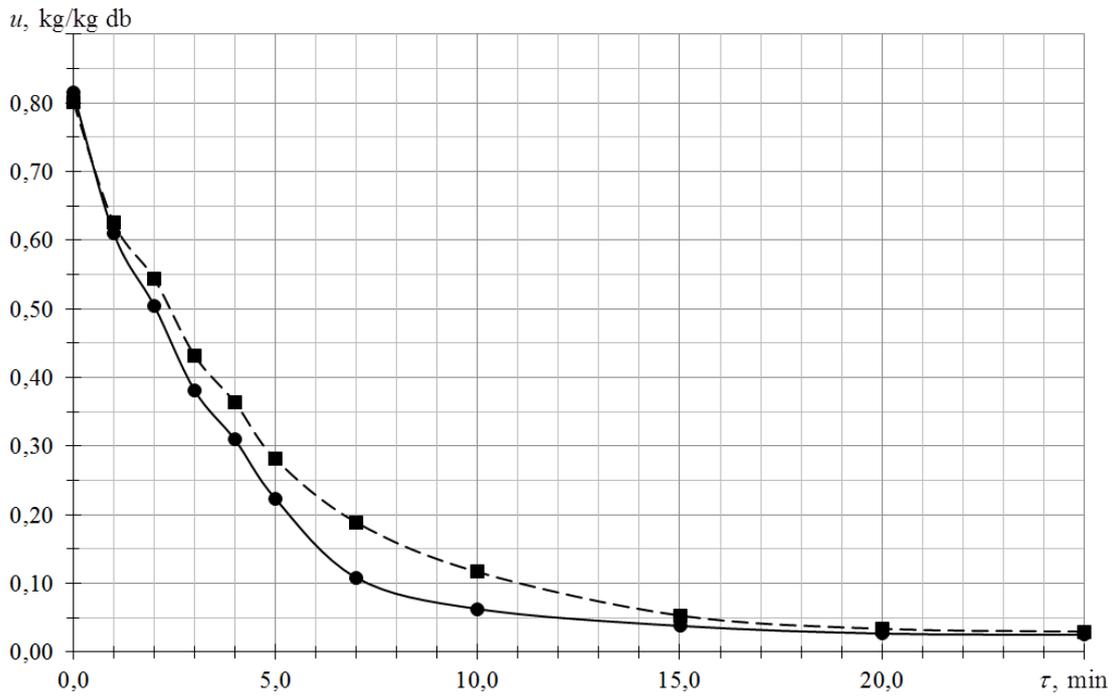


Figure 7. Silica gel drying curves: - - - -  $t'_{air} = 45\text{ °C}$ ; ——— -  $t'_{air} = 55\text{ °C}$ .

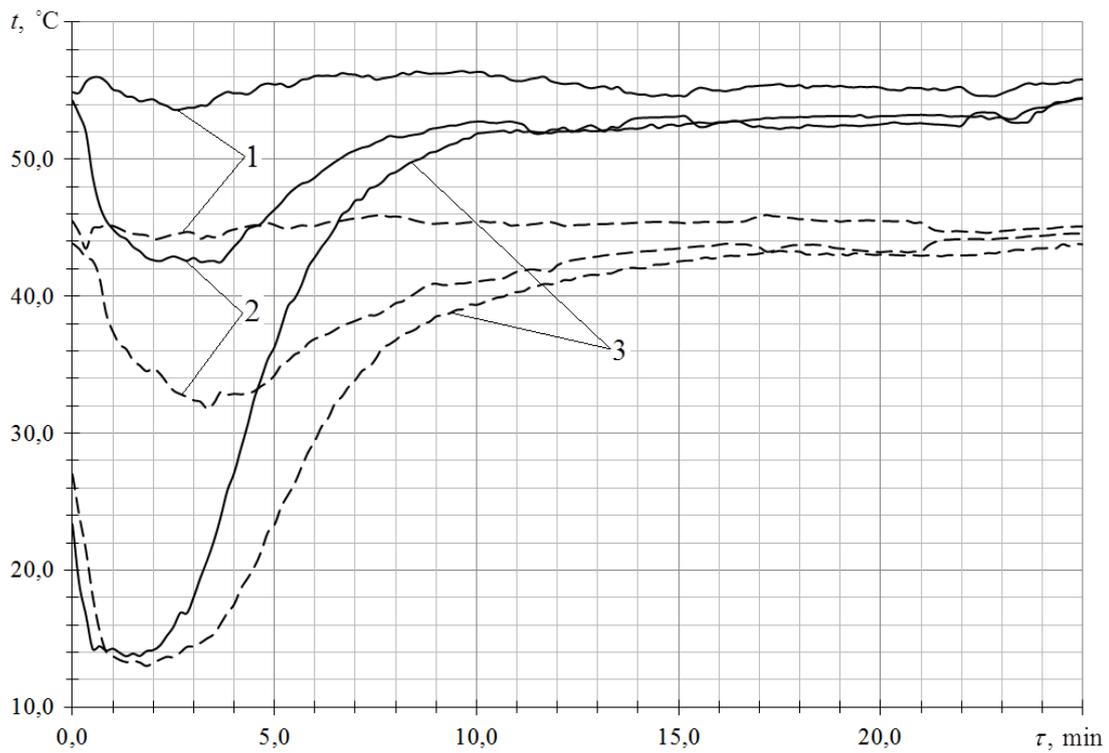


Figure 8. Temperature curves: - - - -  $t'_{air} = 45\text{ °C}$ ; ——— -  $t'_{air} = 55\text{ °C}$ ; 1 -  $t'_{air}$ ; 2 -  $t''_{air}$ ; 3 -  $t_m$ .

#### 4. Conclusion

Based on the data obtained, we can confirm the conclusion that the heat and mass transfer intensity in a centrifugal fluidized bed apparatus is quite high. This allows to implement the low-temperature drying process, which is especially important for drying of thermolabile materials.

It should be noted that the heat transfer coefficient during moisture evaporation from the material at the beginning of the drying process can be 1.5-2 times higher than at the end of drying [14]. A certain average value of this parameter is used in mathematical models describing the drying process, which impairs the calculations accuracy. The obtained experimental data will also allow to obtain an empirical relation for the heat transfer coefficient, taking into account the material moisture content.

Also a semi-empirical mathematical model that describes the heat and mass transfer process in an apparatus with a moving fluidized bed was proposed in our works [15, 16]. As a result of the analytical model solution we obtained the time relations of the temperature and the material moisture content to the drying agent, containing an empirical coefficient - the drying intensity. The experimental study results will determine this parameter for each drying mode.

#### References

- [1] Gibilaro L G 2001 *Fluidization Dynamics* (Oxford: Butterworth-Heinemann)
- [2] Mujumdar A S 2006 *Handbook of Industrial Drying* (Boca Raton: CRC Press)
- [3] Yang W-C 2003 *Handbook of Fluidization and Fluid-Particle Systems* (New York: Marcel Dekker, Inc.)
- [4] Srivastava S and Mishra G 2010 Fluid Bed Technology: Overview and Parameters for Process Selection *Int. J. Pharm. Sci. Drug. Res.* **2(4)** 236-46
- [5] Ambrosio-Ugri M C B and Taranto O P 2007 Drying in the rotating-pulsed fluidized bed *Braz. J. Chem. Eng.* **24(1)** 95-100
- [6] Agapov Yu N, Barakov A V, Zhuchkov A V and Sannikov A V 1986 Ocenka gidravlicheskogo soprotivleniya i mezhfaznogo teploobmena v centrobeznom psevdoozhizhennom sloe [Assessment of hydraulic resistance and interfacial heat transfer in a centrifugal fluidized bed] *Himicheskaya Promyshlennost'* **63(4)** 61-3 [In Russian]
- [7] Faleev V V and Barakov A V 2003 Issledovanie mezhfaznogo teploobmena v regenerativnom teploobmennike s dispersnoj nasadkoj [Study of interphase heat transfer in a regenerative heat exchanger with a dispersed material checker] *Prom. Energetika* **6** 35-7 [In Russian]
- [8] Barakov A V, Dubanin V Yu and Prutskikh D A 2009 Issledovanie gidrodinamiki regeneratora s dispersnoj nasadkoj [The study of the hydrodynamics of a regenerator with a dispersed material checker] *Energoberezhenie i Vodopodgotovka* **1** 47-8 [In Russian]
- [9] Weintraub S 2002 Demystifying Silica Gel *Proceedings of the Objects Specialty Group Session (Miami, 10 June 2002)* vol 9 ed V Greene, P Griffin (Washington, DC: American Institute for Conservation) pp 169-94
- [10] Pramuang S and Exell R H B 2007 The regeneration of silica gel desiccant by air from a solar heater with a compound parabolic concentrator *Renew. Energ.* **32(1)** 173-82
- [11] Kemp I C, Fyhr B C, Laurent S, Roques M A, Groenewold C E, Tsotsas E, Sereno A A, Bonazzi C B, Bimbenet J-J and Kind M 2001 Methods for processing experimental drying kinetics data *Dry. Tech.* **19(1)** 15-34
- [12] Williams-Gardner A 1971 *Industrial Drying* (London: George Godwin)
- [13] Mandel J 1984 *The Statistical Analysis of Experimental Data* (New York: Dover Publications)
- [14] Watano S, Yeh N and Miyanami K 1999 Heat Transfer and the Mechanism of Drying in Agitation Fluidized Bed *Chem. Pharm. Bull.* **47(6)** 843-6
- [15] Barakov A V, Byrdin A P, Dubanin V Y and Nadeev A A 2017 The asymptotic solution of model equations for heat capacities of fluidized bed phases *J. Phys. Conf. Ser.* **891** 012325
- [16] Barakov A V, Byrdin A P and Nadeev A A 2016 Study of heat and mass transfer in the dryer with a pseudo liquefied layer of a disperse material *Sci. Herald Vor. Stat. Univ. Architec. Civ. Engineer. Constr. Architec.* **31(3)** 18-26