Experimental study of heat transfer, hydrodynamics and drying kinetics in a centrifugal fluidized bed apparatus

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Abstract. This paper presents the test results of a prototype installation for drying dispersed materials in a centrifugal fluidized bed. The prototype is a batch apparatus with a vertical supply of a drying agent. A diagram of a test bench designed to study the hydrodynamics of the apparatus and the heat and mass transfer process during drying in a centrifugal fluidized bed is given and described. Silica gel with a particle diameter of 3.8 mm was used as a dispersed material. Hydrodynamic experiments were carried out on a “cold” model. Based on their results, the relationship of the hydraulic resistance of the apparatus at various values of the air velocity and mass of material in the working chamber is constructed. Experimental data have been obtained on low-temperature drying of silica gel in a centrifugal fluidized bed for various modes. The data are presented as time relationships of the temperature and humidity of the material and the drying agent. Analysis of the data obtained showed that the heat and mass transfer process in a centrifugal fluidized bed has a high intensity. A positive conclusion is made about the possibility of using this apparatus for low-temperature drying of capillary-porous bodies.

1. Introduction
Among all the heat and mass transfer plants used in industry, an important place is occupied by fluidized-bed apparatus. This is due to the high intensity of interphase heat and mass transfer in such devices, their small hydraulic resistance, small dimensions and relatively simple design [1-3]. All of the above caused, in particular, the presence in industry of a wide range of dryers that implement this technological principle [3-4]. Therefore, the development and research of new, energy-efficient structures and processes occurring in them is an urgent task of theoretical and applied value.

2. Description of the drying apparatus and test bench
Let us first consider the schematic diagram and the appearance of the drying apparatus that implements such a heat technology principle (figure 1). Its feature is the use of one of the types of fluidized bed – centrifugal, which is formed in the annular channel of apparatuses having a cylindrical cross section. According to [5-7], the action of centrifugal forces on material particles leads to additional intensification of heat and mass transfer processes, due to the destruction of gas bubbles in the layer.
The working chamber (1) of the drying apparatus has a diameter and height of 0.4 m. The annular channel in which the formation of a centrifugal fluidized bed is carried out is formed by the housing of the working chamber and its internal conical wall (2) having a base diameter of 0.2 m. The dryer operates on the principle of periodic alternation of drying cycles. The process of full loading of the working chamber with wet dispersed material is carried out through the loading device (3). The process of complete unloading of the dried material is carried out through the discharge windows (4) equipped with partitions. Gas chambers (5) and (6) are used to supply and drain the drying agent, respectively.

The gas distribution device (7) of the drying apparatus is a louver grille made of sheet metal in the form of a solid disk 0.7 mm thick.

Since theoretical studies give only approximate results [5, 6, 8], we conducted experimental studies of the hydrodynamics of such an apparatus and the intensity of the heat and mass transfer in it. For this purpose, a test bench was created, the schematic diagram of which is shown in figure 2.

To supply the drying agent (air) to the dryer (1), a centrifugal fan Ц10-28 No. 4 (2) is used. In the duct connecting them (3), an electric air heater СФОЦ-25/0.5 (4) is installed, designed for heating cold air to operating temperature. Its power is automatically regulated using a solid-state relay (5) connected to the TPM-148 PID controller (6). For smooth control of fan performance, the Delta VFD150E43A frequency inverter (7) is used. To measure the speed of the drying agent, a TTM-2/4-06
hot-wire anemometer (8) is used. Its primary transformer TTM-2-04 is installed in the duct channel (3). The air speed in front of the gas distribution grid is determined through the equation of continuity of flow (constant flow).

To measure air temperature, thermoelectric converters TPI-2088 are used (9). They are installed in the suction pipe of the fan (10), in the duct (3) and in the duct (11), which is designed to discharge the spent moist air into the environment. Similarly installed humidity sensors Galltec + Mela FRC 3/5 (12), are designed to measure relative humidity. A MoreSunsDIY infrared temperature sensor (13) is installed in the working chamber of the apparatus above the gas distribution grill, designed to measure the surface temperature of the dispersed material during drying.

All temperature and humidity sensors are connected to the PID controller (6). Registration of experimental data is carried out using a personal computer (14) in the SCADA-system MasterSCADA. The interrogation frequency of all sensors is 1 second.

The DMC-01M micromanometer (15) is designed to measure the hydraulic resistance of the gas distribution grid and the dispersed material layer.

The limits of the total absolute error of temperature and humidity measurement (sensor + PID controller) are: for air temperature $\Delta t = \pm 2.8 \, ^{\circ}C$; for air humidity $\Delta \varphi = \pm 2.2 \, \%$; for material temperature $\Delta t = \pm 2.1 \, ^{\circ}C$. Differential Pressure Accuracy $\Delta \rho = \pm 2.0 \, \text{Pa}$. 

Figure 2. Test bench layout: 1 – dryer; 2 – fan; 3 – air duct; 4 – electric heater; 5 – relay; 6 – PID-controller; 7 – a frequency converter; 8 – hot-wire anemometer; 9 – temperature sensors; 10 – suction pipe; 11 – air duct; 12 – humidity sensors; 13 – IR-temperature sensor; 14 – PC; 15 – micromanometer.
3. **The study of the hydrodynamics of the drying apparatus**

The purpose of this series of experiments was to study the hydraulic resistance of the drying apparatus. It mainly consists of pressure losses on the gas distribution device and pressure losses during the passage of air through a layer of dispersed material. In this case, the total pressure loss, \( \Delta P \), is not a simple sum of these two quantities [7, 9].

The experiments were carried out on a “cold” model (without heating the drying agent) for several dispersed materials. Most of the measurements were made using silica gel (equivalent particle diameter of dispersed material \( d_e = 3.8 \) mm; material density \( \rho_m = 780 \) kg/m\(^3\)). In total, 7 modes of operation of the apparatus were experimented on and processed, which differed in the mass of dispersed material in the working chamber of the apparatus \( M_m \), kg.

Figure 3 shows the results of an experimental study of the hydraulic resistance of the working chamber of the apparatus for silica gel at different values of the air velocity, referred to the full cross section of the chamber \( \nu_{air} \), m/s and mass of material \( M_m \).

![Figure 3](image-url)  
**Figure 3.** The hydraulic resistance of the working chamber for silica gel: 1 – 0.6 kg; 2 – 0.8 kg; 3 – 1.0 kg; 4 – 1.2 kg; 5 – 1.4 kg; 6 – 1.6 kg; 7 – 1.8 kg.

From this figure it is seen that an increase in these parameters leads to an increase in hydraulic resistance. The kink of all the curves corresponds to the onset of vibration of the particles of material. In this case, the movement of some particles from the depth of the layer to its surface was also observed. The air velocity at which the stable fluidization of the dispersed material begins is approximately 4.1 m/s for each mode studied.

As known [1-4], one of the characteristics of a layer of dispersed material is its height in a stationary state \( H_0 \), mm and fluidized \( H_b \), mm. From figure 4 we can conclude that up to air speed 2.5 m/s the layer is stationary. A gradual increase in air velocity leads to expansion of the layer and its
transition into a fluidized state. Layer height in the working chamber: at $M_m = 0.6$ kg $H_0 = 15$ mm, $H_{fb} = 19$ mm; at $M_m = 0.8$ kg $H_0 = 20$ mm, $H_{fb} = 24$ mm; at $M_m = 1.0$ kg $H_0 = 25$ mm, $H_{fb} = 30$ mm; at $M_m = 1.2$ kg $H_0 = 30$ mm, $H_{fb} = 35$ mm; at $M_m = 1.4$ kg $H_0 = 35$ mm, $H_{fb} = 41$ mm; at $M_m = 1.6$ kg $H_0 = 40$ mm, $H_{fb} = 46$ mm; at $M_m = 1.8$ kg $H_0 = 45$ mm, $H_{fb} = 52$ mm.

4. The study of heat and mass transfer when drying dispersed material

The purpose of this series of experiments was to obtain experimental data on the kinetics of drying (heat and mass transfer) in an apparatus with a centrifugal fluidized bed. The parameters that make it possible to judge the intensity of the drying process, as well as constituting the mathematical description of this process given in [8, 10], are:

- temperature and humidity of the drying agent at the entrance to the working chamber (respectively, $t'_{air}$, °C and $\varphi'$, %);
- temperature and humidity of the drying agent at the outlet of the working chamber (respectively, $t''_{air}$, °C; and $\varphi''$, %);
- temperature and moisture content of dispersed material ($t_m$, °C and $u$, kg/kg db).

Silica gel with a particle diameter of 3.8 mm was used as a dispersed material. In accordance with [11, 12], in apparatuses with a high heat and mass transfer rate, silica gels can be dried (reduced) in the low-temperature mode, i.e. with low energy costs for heating the drying agent. Therefore, the temperature of the drying agent at the inlet to the working chamber in this study did not exceed 60 °C.

The order of the experiment is as follows. At first, the dryer was brought into operation, characterized by a temperature $t'_{air}$ and the speed of the drying agent at the entrance to the material layer $v_{air}$. Then, wet dispersed material having an initial mass was loaded into the working chamber of the apparatus $M_{m0}$, kg and initial moisture content $u_0$, kg/kg db. During drying, small samples of material (5...10 grams) were taken from the working chamber at predetermined time intervals. The moisture content of each sample was measured using an ЭВЛАС-2M moisture analyzer. The remaining process parameters were recorded using a PC (figure 3). Drying time in all modes ranged from 25 to 30 minutes, after which the dried material was unloaded.

A total of 9 modes of operation of the apparatus with the temperature of the drying agent were experimented on and processed, $t'_{air} = 35; 45; 55$ °C and its speed, $v_{air0} = 4.1; 4.3; 4.5$ m/s. The minimum drying agent rate corresponds to the fluidization start rate. Silica gel initial parameters for each mode: $M_{m0} = 1.0; 1.5$ kg; $u_0 = 0.32; 0.53; 0.82$ kg/kg db. Using sensors installed in the suction pipe of the fan, the temperature and humidity in the room were measured (respectively, $t_{air0}$, °C and $\varphi_0$, %). For all operating modes of the device, their values were: $t_{air0} = 25...28$ °C, $\varphi_0 = 30...35$ %.

To verify the reproducibility of the experimental data, each experiment was repeated at least three times. Data processing on the drying kinetics was carried out in accordance with the procedure given in [13].

Figures 4-6 illustrate the course of the drying process for two drying modes that differ in air temperature at the inlet to the working chamber $t'_{air} = 45$ °C and 55 °C. Other mode options: $M_m = 1$ kg; $u_0 = 0.82$ kg/kg; $v_{air0} = 4.3$ m/s.
Figure 4. Silica gel drying curves: — — — $t_{\text{air}}' = 45$ °C; — — — $t_{\text{air}}' = 55$ °C.

Figure 5. Temperature curves: — — — — $t_{\text{air}}' = 45$ °C; — — — $t_{\text{air}}' = 55$ °C; 1 — $t_{\text{air}}'$; 2 — $t_{\text{air}}''$; 3 — $t_{\text{in}}$. 
The drying curve (figure 4) shows that for the first mode \( t'_{\text{air}} = 55 \, ^\circ\text{C} \) the moisture removal process is completed by the 14th minute, for the second mode \( t'_{\text{air}} = 45 \, ^\circ\text{C} \) – to the 17th minute. In this case, the equilibrium moisture content \( u_{\text{eq}} \) practically unchanged and equal to 0.03 kg/kg db.

Three periods can be distinguished on the heating curves of the material (figure 5) \[14\]. The initial period corresponds to the heating of silica gel, its duration for both modes is 30…40 seconds. In this period, the material temperature decreases \( t_{\text{m}} \) to wet bulb temperature \( t_{\text{w}} = 14…15 \, ^\circ\text{C} \), due to the phenomenon of evaporative cooling. The occurrence of this phenomenon is associated with a high initial moisture content of silica gel and intensive removal of moisture from it.

A characteristic feature of the period of constant drying speed (the first period) is the constancy of the temperature of the material, its duration is 2…2.5 minutes. In this period, a decrease in the temperature of the drying agent \( t'_{\text{air}} \) (figure 5) and increase in its humidity \( \varphi'' \) (figure 6) is observed.

In the period of the decreasing drying rate (second period), the material is gradually heated to the temperature of the drying agent \( t''_{\text{air}} \). Its duration for the first mode is 12 ... 13 minutes, for the second – 14…15 minutes. During this period, an increase in temperature \( t''_{\text{air}} \) to \( t'_{\text{air}} \) (figure 5) and lower air humidity \( \varphi'' \) to \( \varphi' \) (figure 6).

The critical moisture content of the material, corresponding to the transition from the first period to the second, is important for the first mode \( u_{c1} = 0.47 \, \text{kg/kg db} \), for the second mode \( u_{c2} = 0.52 \, \text{kg/kg db} \). It should be noted that the type of the drying curve (figure 4) is characteristic of capillary-porous bodies, which include silica gel.

Thus, an increase in the temperature of the drying agent leads to an increase in the rate of moisture removal from the material, as well as a decrease in the duration of the first drying period and the entire cycle.

**Figure 6.** Humidity curves: \(-\quad t'_{\text{air}} = 45 \, ^\circ\text{C}; \quad t'_{\text{air}} = 55 \, ^\circ\text{C}; \quad 1 - \varphi'; \quad 2 - \varphi''\).
We also note that each temperature regime of drying is characterized by a coincidence of the curves of the final air humidity $\varphi^*$ at the initial stage of the process (figure 6).

5. Conclusions
Based on an experimental study of the hydrodynamics of the drying apparatus, we can conclude that its hydraulic resistance in operating condition is negligible. The data obtained confirm the results of studies of apparatus with a centrifugal fluidized bed of another technological purpose (absorbers, regenerative heat exchangers, etc.) [7, 15].

Experimental data on heat and mass transfer show that the drying rate of the dispersed material in a centrifugal fluidized bed is sufficiently high, which allows drying at a low temperature of the drying agent. This is specifically true when drying heat-sensitive dispersible materials.

The results of processing the entire array of experimental data showed that the research methodology used is adequate and allows one to obtain sufficiently reliable data on changes in the basic parameters of the dispersed material and the drying agent. Note that a significant contribution to the deviation of the results during repeated measurements is made by humidity and air temperature in the laboratory.

The data obtained made it possible to make a preliminary estimate of the average heat transfer coefficient by the method described in [16]. For all the experimented modes, its value lies in the range of 150 to 220 W/(m²·K).

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