Drying Machines with Combined Hydrodynamic Regimes

N Artyukhova¹, J Krmela², V Krmelová³ and A Artyukhov¹
¹Marketing Department, Sumy State University, 2 Rymskogo-Korsakova st., 40007 Sumy, Ukraine
²Department of Numerical Methods and Computational Modeling, Faculty of Industrial Technologies in Púchov, Alexander Dubček University of Trenčín, 491/30, I. Krasku, 02001, Púchov, Slovak Republic
³Department of Materials Technologies and Environment, Faculty of Industrial Technologies in Púchov, Alexander Dubček University of Trenčín, 491/30, I. Krasku, 02001, Púchov, Slovak Republic

Corresponding author Email address: jan.krmela@tnuni.sk

Abstract. The article is devoted to the study of multistage dryers with vertical sectioning of the working space. The factors of influence of the design of the shelf contact and the consumption of the drying agent on the mode of movement of monodisperse and polydisperse material are analyzed. The achievement of the required hydrodynamic regime (at a constant consumption of the drying agent) was ensured by changing the length of the shelf contact, the angle of its inclination to the horizon, and the degree of perforation (free area of cross-section). The features of changing the mode of granular material movement at various stages of the gravitational shelf dryer are shown. A technique for the optimization calculation of a gravitational shelf dryer is proposed. As an objective function, the minimum residence time of the dispersed material in the dryer is taken, at which the required amount of moisture is removed. Variants of the designs of the stages of a gravitational shelf dryer are shown and the features of the movement of dispersed material on the steps are described. The results obtained can be used as the basis for the engineering design of gravitational shelf dryers.

1. Introduction
A comprehensive assessment of the quality of the drying process is determined not only by the amount of removed moisture and the provision of the material's necessary physical and chemical properties. It is also necessary to consider the energy costs of the drying process, the simplicity or complexity of the design of the dryer, the possibility of ensuring optimal technological parameters of the process, the possibility of utilizing and recovering heat and moisture, etc. Thus, the drying method's choice and the dryer design is a multifactorial theoretical and experimental study with elements of optimization for a given objective function.

The convective drying process is one of the most common in the technology of dehydration of dispersed materials. Despite the indisputable advantages noted in [1–4], the convective drying process as technology and dryers as "executors" of this technology require improvement. In particular, in the process of convective drying, it is necessary to solve the following problems:
- ensuring the minimum contact time of the drying agent with dispersed material;
- ensuring the maximum driving force of the drying process in the working space of the apparatus;
It should also be noted that it is not always possible to ensure the required residence time of the material in a convective dryer with a classical fluidized bed due to intensive mixing of the material and different moisture gradients in different parts of the apparatus. In addition, in such devices, it is difficult to uniform contact of the dispersed material and the drying agent in a wide range of phase loads (flow ratio). This complicates the process of dewatering thermolabile dispersed materials, such as cereals. Significant costs for heating and pumping the drying agent are also disadvantages of the considered devices.

Carrying out this process using an active hydrodynamic regime, which provides an increase in the relative velocity of the interacting phases, contributes to the process's intensification without reducing the apparatus's economic efficiency. The advantages of the active hydrodynamic regime also include:

- hydrodynamic stability of the process;
- providing a developed surface of the interaction of contacting phases;
- reducing the energy consumption of the process and the metal consumption of the apparatus.

One of the methods of convective drying is the contact of a material with a heat carrier in a stationary, suspended, or semi-suspended state. Currently, convective dryers are most often used, in which the material is dried in a suspended (fluidized) state.

The main advantages of multi-stage fluidized bed dryers are:

- multifunctionality of the apparatus - the ability to simultaneously carry out the process of drying, classification and separation of particles;
- creation of a countercurrent mode of movement of interacting flows;
- the organization of a differentiated mode of dehydration of dispersed material - the creation of different conditions for drying the material at each stage, depending on its temperature and humidity characteristics;
- the ability to control the residence time of particles at each stage of the apparatus and in the apparatus as a whole.

Improvement of devices with a fluidized bed for mass transfer in the "gas-solid" system is possible by organizing the mutual movement of flows with repeated use of the fluidizing agent, for example, when sectioning the dryer by installing shelf contacts along with its height [11]. In shelf units, the processes of pneumatic classification, dedusting, cooling, granulation, etc., are implemented. Such devices are not widely used in drying processes. Due to the multiple contact of the dispersed material with the drying agent, it becomes possible to reduce material and energy costs for the process significantly.

In the proposed apparatus for the implementation of intensive drying methods, it is assumed that the internal space is sectioned by establishing a cascade of perforated shelves at a certain angle, creating conditions for the gravitational movement of material along the shelves and its transfer from one shelf to another [12]. On each of the shelves in this design, effective mixing inherent in the suspended bed is created while maintaining the advantages of an organized countercurrent mode.

The presence of inclined perforated shelves in the working space of the shelf dryer reduces its free cross-sectional area. This design solution causes a local increase in the velocity and degree of turbulence of the flow of the drying agent, as well as changes in the nature of the velocity distribution around the shelf.

The indicators of heat and mass transfer processes in the suspended layer are essentially determined by the hydrodynamic indicators of the movement of continuous (gas) and dispersed (solid) flows. The efficiency of the apparatus of the suspended layer largely depends on the flow field of the gas flow, the distribution of which over the working space of the apparatus affects the profile of temperatures and concentrations of the granular material.

Justification of the possibility of using multistage devices with vertical sectioning of the working space and determines the relevance of the presented article.

The object of research is gravitational shelf dryers for the dehydration of dispersed materials.

The subject of research is the hydrodynamics of flow within the cascade of shelf contacts.
2. Experimental investigation

Scheme of multistage shelf dryer is shown in Figure 1. Its working principle is as follows [11]. To the bottom side-bar of case 1 drying agent is supplied. The drying agent is distributed evenly over the cross-section of the case and then rises up. As the drying agent moves up on the case, it consistently passes through the cross-sections of the lower side-bar, middle side-bar and top side-bar, tapered side-bar is withdrawn from the device.

Length of shelf provides a residence time of dispersed material, which promotes complete heating of the material, separating of small dispersed particles and unbound moisture remove from the top surface layer of dispersed material in the period of constant speed of drying.

Dispersed material during drying flow of drying agent gradually moves the top shelf is withdrawn from it on the middle shelf (further intensive removal of unbound water from the surface of the layer of dispersed material during the period of constant speed of drying) and then on the bottom shelf (remove bound water from the depth of the material in the period of falling speed of drying).

After passing all shelves dispersed material was withdrawn from the bottom part of the dryer.

![Figure 1. Multistage shelf dryer: 1 – case; 2 – shelf.](image-url)

For a theoretical description of the drying process in a shelf dryer, a mathematical model is proposed, consisting of three consecutive levels. The time for drying the dispersed material to the required final moisture content is determined at the first level. The second level of the model is devoted to describing the hydrodynamics of the process; the residence time of particles in the apparatus is determined, which is compared with the drying time from the first level. At the third level, a recurrent calculation of removing moisture from the material in the volume of the entire apparatus is carried out, the efficiency of each stage of the apparatus and the optimal design parameters of the dryer are determined.

By varying the design parameters of the shelf (angle of inclination, the gap between the end of the shelf and the wall of the apparatus, the free section area and the diameter of the perforation holes of...
the shelf), it becomes possible to determine their optimal values to achieve maximum drying efficiency at each stage of the apparatus.

Due to changes in the design parameters of the shelf contacts of the dryer, the necessary hydrodynamic conditions for the movement of material on each shelf of the cascade are provided. Note that when designing a gravity shelf dryer, it is necessary to ensure uniform contact of the drying agent with the dispersed material on each shelf of the dryer. Achieving this uniformity makes it possible to adjust the residence time of the particles on the shelves, taking into account their physical and chemical properties. Any uneven contact of the drying agent with the dispersed material can lead to underheating (with insufficient drying) or overheating with undesirable destruction of particles and reducing its consumer qualities.

The distribution of the gas flow in the working space of the gravitational shelf dryer at different initial velocities in the drying agent inlet is shown in Figure 2.

![Figure 2](image_url)

**Figure 2.** The distribution of the gas flow in the working space of the gravitational shelf dryer:

- a – $V = 3$ m/s;
- b – $V = 8$ m/s;
- c – $V = 15$ m/s.

The nature of the distribution of the gas flow rate at the stage of the shelf dryer under other conditions of experimental studies (design of the shelf and the flow of gas flow) does not change qualitatively. Peculiarities of the gas flow velocity field distribution depending on the initial conditions of the experiment are given below.

Analysis of the results of the experiment on the distribution of the speed of the gas flow at different stages of the dryer depending on the height of their installation with the same design of each stage showed that:

- the distribution of the velocity of the gas flow becomes more uniform with increasing value of the discharge gap;

Diagram of the gas flow velocity for shelf contact of one structure quantitatively changes its profile. This is due to the redistribution of gas flow in the cross-section of the dryer in height, and with height, it becomes more uniform.
When installing in the volume of the dryer shelf contact with different values of the free cross-section (increase in the free cross-section), the following picture is observed:

- the level of speed of movement of a gas stream on a shelf contact is partially leveled;
- there is a decrease in the peak velocity of the gas flow in the discharge gap;
- plot of the velocity of the gas flow in the transition from the shelf contact to the discharge gap has a smoother character.

Reducing the angle of the shelf contact at a constant value of the gap makes its features in the diagram of the distribution of the velocity of the gas flow:

- there is a decrease in the peak velocity of the gas flow on the shelf, the plot is aligned;
- the peak speed of the gas flow in the discharge gap decreases;
- the zone of the maximum speed of the gas flow in the discharge gap expands with the alignment of the plot.

The diagram of the distribution of the velocity of the gas flow with increasing consumption has the same qualitative law but is characterized by the following distinctive features:

- smoothing of the peak in the middle of the shelf contact;
- equalization of speed along the length of the shelf contact;
- the peak velocity of the gas flow in the discharge gap has a more pronounced character.

Diagrams of the distribution of the gas flow velocity make it possible to determine the zones of gravitational motion of the dispersed material, its soarking in the apparatus, separation, and possible removal. To fully describe the hydrodynamics of the movement of the dispersed material, determine the trajectory of its movement and residence time in the volume of the dryer and the impact on these parameters of the shelf contact design and gas flow rate, it is necessary to investigate the basic modes of movement of the dispersed material.

It should be taken into account that the design of the shelf and the peculiarities of its location in the working space of the dryer affect the gas flow rate in the overhead space.

This speed is decisive when choosing the mode of movement of dispersed material. The range of existence of the fluidized bed (as it shown in [13–16]) is determined by the first critical velocity \( V_{\text{c1}} \) (the gas flow rate that corresponds to the beginning of fluidization) and the second critical velocity \( V_{\text{c2}} \) (the gas flow rate that corresponds to the beginning of material removal from the dryer).

As a result of the experiment, as well as on the basis of earlier studies by the authors [17, 18], a general pattern of changes in the nature of the movement of dispersed material on the shelf was obtained (Figure 3).

Each of the modes is characterized by the peculiarities of the movement of dispersed material, as well as the residence time of the material on the shelf, depending on the degree of the constraint of the flow (the relative content of the dispersed phase in the volume of the apparatus) (Figure 4).

Optimization of the shelves' design, their placement features, and the number of stages in the dryer is carried out according to the criterion of the minimum required "hydrodynamic" residence time of the dispersed material. This time should not exceed by more than 10% the calculated drying time. This approach makes it possible to achieve minimum energy costs and ensure the preservation of the strength (and, in some cases, specific properties, such as, for example, seed germination) properties of the dispersed material.

Based on the obtained results, taking into account studies [19, 20] on the kinetics of moisture removal from dispersed material in devices with an active hydrodynamic regime, an algorithm for engineering calculation of a gravitational shelf dryer is proposed (Figure 5).

It should be noted that the engineering calculation algorithm can be implemented in two ways:

- determination of the design of the dryer, taking into account the provision of the required residence time of dispersed material;
- determination of the design of each stage to ensure the heating time of the dispersed material, the drying time in the constant speed mode and the drying time in the decreasing speed mode.

The second option is more efficient because it allows dividing the dryer into separate zones and a differentiated contact of dispersed material with a drying agent with different temperature and humidity potential is provided.
Figure 3. Operating modes of a multistage gravitational shelf dryer: 1 – the gravitational falling layer mode of the dispersed material; 2 – the first transitional mode; 3 – the dryer’s operation in the weighted layer mode of the dispersed material; 4 – the second transitional mode; 5 – the dryer’s operation in the dispersed material ablation model.

Figure 4. The residence time of the material on the shelf.

3. Practical implementation
The research results allowed us to propose new designs of shelves, which allow providing the required residence time of the material in the dryer (Figure 6).
Figure 5. Algorithm for engineering calculation of a gravitational shelf dryer (large-block model).

Figure 6. Constructions of shelves of multilevel gravitational shelf dryer [21–23]: a – shelf with different gap on height of dryer; b – sectioned shelf with variable perforation of sections; c – partitioned sections shelf with constant perforation and variable angle of inclination; d – diameter of hole of perforation; L – length of the shelf; H – width of device; $\gamma_i$ – angle of inclination of shelf section to horizon.
The use of inclined perforated contact shelves of the above structures allows to creation at each stage of the dryer, such a hydrodynamic situation in which there is an alignment of the plot of the speed of the drying agent along the shelf, its action remains constant in all areas of the shelf. This causes the process of compensation of the action on the dispersed material of inertial forces and rolling on an inclined surface, braking of the dispersed material on an inclined perforated contact shelf, its uniform movement in the suspended layer and long-term contact with the drying agent.

It is possible to implement the proposed constructive solutions (in addition to the design of the dryer, which is shown in Figure 1) in various designs of dryers-classifiers (Figure 7).

![Figure 7. Constructions of dryers-classifiers](image)

The proposed designs of multistage shelf dryers (in accordance with the model material used in the experiments) can be implemented in industrial drying installations (Figure 8).

4. Conclusions and recommendations
One of the most important principles of designing new designs of convective dryers is compliance with energy efficiency requirements because this type of equipment is characterized by sufficiently high values of energy consumption per unit mass of grain product, which is dehydrated. A promising direction to reduce energy costs for creating a flow of high-temperature drying agent in the apparatus is the development of advanced equipment designs with internal partitioning of the working space using shelf contacts.

The engineering calculation method of such devices is based on the results of theoretical and experimental studies of hydrodynamic parameters of flow motion and kinetics of dehydration of granular materials.

Based on the results of modeling the kinetics of the drying process of a single granular particle, the required time of its dehydration in the flow of the drying agent with the specified characteristics is determined. The theoretically and experimentally hydrodynamic characteristics of the flow of drying agent and dispersed material allow determining the time of its stay in the apparatus depending on the design of shelf contacts and technological parameters of the process. At the stage of analysis of the laws of the kinetics of the process of dehydration of the dispersed material on the cascade of shelves, the optimal organization of the flow is determined, which will provide the minimum energy costs at the required final humidity of the product.
Figure 8. Technological line of the unit for production of the stabilized and painted polypropylene and polyethylene: 1 – silo for powdered polypropylene; 2 – screw conveyors; 3 – bucket batchers; 4 – high-speed mixer; 5 – the tape batcher; 6 – bunker; 7 – extruder; 8 – the starting valve; 9 – granulator; 10 – damper; 11 – water separator; 12 – dryer; 13 – vibrating sieve; 14 – pneumatic transport; I – polypropylene; II – supplements; III – waste gases; IV – dried polypropylene.

As a result of optimization calculation of the gravity shelf dryer according to the initial data established by the customer of the industrial equipment, it becomes possible to define its following design characteristics:
- the number of shelf contacts in the dryer;
- the angle of inclination of the shelf contacts to the horizon;
- the size of the gap between the end of the shelf contact and the wall of the dryer (or the length of the shelf contact);
- the area of the free section of the shelf contact.

The design characteristics of shelf contacts at each stage of the dryer may differ due to the physicochemical characteristics and strength of the granular material, its stability under long-term exposure to high-temperature drying agent, as well as minimizing energy consumption for the dehydration process.

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