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ANALYTICAL-CRITICAL REVIEW OF WIDELY USED INDUSTRIAL DEVICES FOR DRYING MINERAL FERTILIZERS

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Abstract: *The article is devoted to the review of the modern state of research in the mineral fertilizers drying field, critical analysis and comparison of widely used drying apparatuses. There are procedures of preliminary equipment selection for soluble fertilizers industrial drying on the basis of such criteria as productivity, efficiency, energy saving, environmental impact degree, indicating the possible advantages and disadvantages of different application variants.*
Keywords: *mineral fertilizers, moisture content, drying apparatuses, optimal apparatus selection, contact drying, convective drying, drum dryer, disk dryer, conveyor belt and mesh belt dryers, rotary dryer, fluidized bed dryer, vibrating fluid bed dryer, spray dryer, flash dryer.*

Annotatsiya: *Ushbu ish mineral o'g'itlarni quritish sohasidagi tadqiqotlarning zamonaviy holati, keng qo'llaniladigan quritish qurilmalarining tanqidiy tahlili va taqqoslanishiga bag'ishlangan bo'lib, unumdorlik, samaradorlik, energiya tejamkorlik va atrof-muhitga ta'sir darajasi kabi mezonlar asosida muayyan qo'llash variantlarining afzalliklari va kamchiliklari ko'rsatilgan holda eruvchan o'g'itlarni sanoatda quritish uchun quritish uskunalarini dastlabki tanlash tartibi keltirilgan.*
Tayanch so'zlar: *mineral o'g'itlar, namlik miqdori, quritish qurilmalari, optimal qurilmani tanlash, kontaktli quritish, konvektiv quritish, rolikli quritkich, barabanli quritkich, diskli quritkich, konveyerli quritkich, mavhum qaynash qatlamli quritkich, purkagichli quritkich, pnevmatik quritkich.*

Аннотация: *Работа посвящена обзору современного состояния исследований в области сушки минеральных удобрений, критическому анализу и сравнению широко распространённых сушильных аппаратов, приведены процедуры предварительного отбора сушильного оборудования для промышленной сушки растворимых удобрений на основе таких критериев, как производительность, эффективность, энергосбережение, степень воздействия на окружающую среду, с указанием возможных преимуществ и недостатков тех или иных вариантов применения.*
Ключевые слова: *минеральные удобрения, влагосодержание, сушильные аппараты, выбор оптимального аппарата, контактная сушка, конвективная сушка, вальцовая сушилка, дисковая сушилка, конвейерная сушилка, барабанная сушилка, сушилка с псевдоожиженным слоем, распылительная сушилка, пневматическая сушилка.*

Introduction

Nowadays manufacturers of drying equipment offer a wide range of produced apparatuses, the quality and competitiveness of fertilizers on the world market depends on the right choice of which.

All types of chemical fertilizers, as well as compound fertilizers, compost fertilizers, organic fertilizers, etc., are subject to drying. The mineral fertilizers quality is determined by the moisture content, which directly affects not only the caking and crumbliness of fertilizer mixes, but also the strength of granules. Usually, the moisture content of mineral fertilizers with good consumer properties does not exceed 2% [1-3].

In general, the properties of inorganic substances vary during the production process [3]:

- by initial moisture content – from salts after filtration and centrifugation with moisture content of about 5-12% to solutions, suspensions and crystalline hydrates with moisture content of 70-90%;

- by particle size — from materials containing classes of 50-70 microns to grains and granules with sizes ~ 4-6 mm;
- by decomposition temperatures from 30-50 °C and melting temperatures up to about 1000 °C, etc.

When selecting the optimal technological equipment for carrying out the drying process, the following main steps are guided [4-9]:

1) full-fledged analysis of the material to be dried;
2) selection of the type of drying apparatus based on the researches in the field of drying;
3) selection of a suitable material treatment mode based on the quality requirements of the desired product;
4) calculation of dryer parameters;
5) ensuring the safety of the environment and production;
6) performing an economic calculation.

In order to effectively carry out the drying process of fertilizers, it is necessary to know their physical and mechanical properties taking into account the aggregate state. Based on these parameters, all fertilizers are divided into three classes before drying [10-13]:

- solutions and suspensions;
- pasty and clumping fertilizers;
- semi-friable, loose and easily loosened fertilizers.

In order to organize a highly efficient drying process [14-15], to eliminate the problems associated with energy overconsumption, as well as in connection with the expansion of the manufactured product range, the proper design selection problem of drying apparatuses has arisen.

Drying plants are classified as follows [5-6, 16-18]:

1. Convective/direct (direct contact of the drying agent with the material), contact/indirect (transfer of heat flux through the heat transfer surface), radiation (heat flux generation of infrared radiation), electric (drying in a high frequency current field) and freeze drying (drying in deep vacuum and low temperature).
2. By hydrodynamic regime: with fixed bed, with stirred bed (including suspended bed).
3. According to the principle of operation: continuous and periodic.
4. Depending on the operating pressure inside the apparatus: under atmospheric pressure and under vacuum.

For the drying of mineral fertilizers, drying apparatuses based on convective, contact and combined heat transfer methods are mainly used [19-22].

At present, scientific research is actively conducted to improve drying units in order to reduce their energy consumption and increase the efficiency of the technological process [23, 29-53].

Contact dryers are more suitable for drying high-moisture or thin-layer materials. Heat for evaporation is supplied through heated surfaces, which also serve to transport or retain solids. The heat transfer medium for contact drying is usually saturated water vapor. The evaporated moisture is removed with a gas stream, which in most cases is the moisture carrier, or by means of a vacuum. Vacuum drying is recommended for drying temperature-sensitive solids.

Below are the main contact dryers types that are used for drying fertilizers:

1. Roller dryers (Fig. 1) are used for continuous drying of pasty materials sensitive to high temperatures [6, 12, 17-18, 24]. The main element of these apparatuses is rollers heated from the inside by a heat-transfer fluid, which slowly rotate in the casing towards each other. The material to be dried is continuously fed onto the top of the drums. The material covers the surface of the drums with a thin layer, which promotes active removal of moisture. The dry product is then removed by fixed knives.

The advantages include even drying and ease of operation.

The disadvantages include low capacity, high energy consumption and inapplicability to coarse-particle materials, as well as short drying times, after which it is often necessary to redry the material.

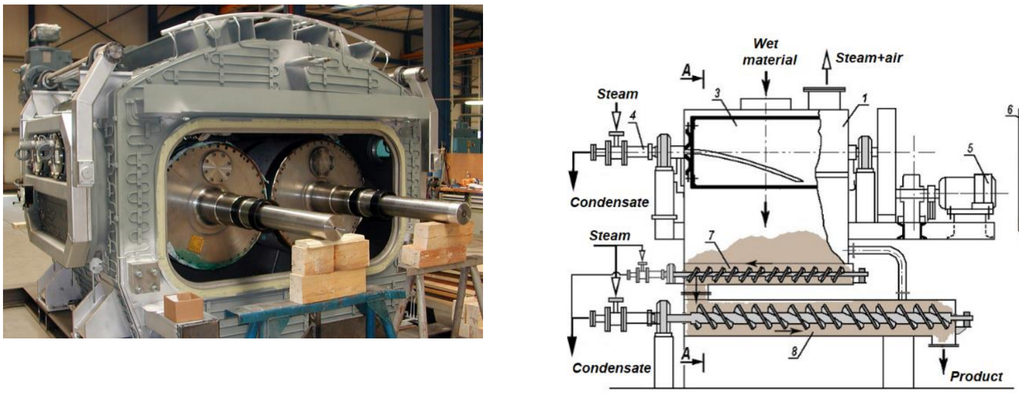

Figure 1. ***Drum dryer.***

2. **In disk dryers** (Fig. 2), the heat exchange takes place on the side surface of the disk [25]. Compared to roller dryers, disk dryers have a larger heat exchanger surface due to the possibility of installing up to 16 disks on one shaft with the same overall dimensions.

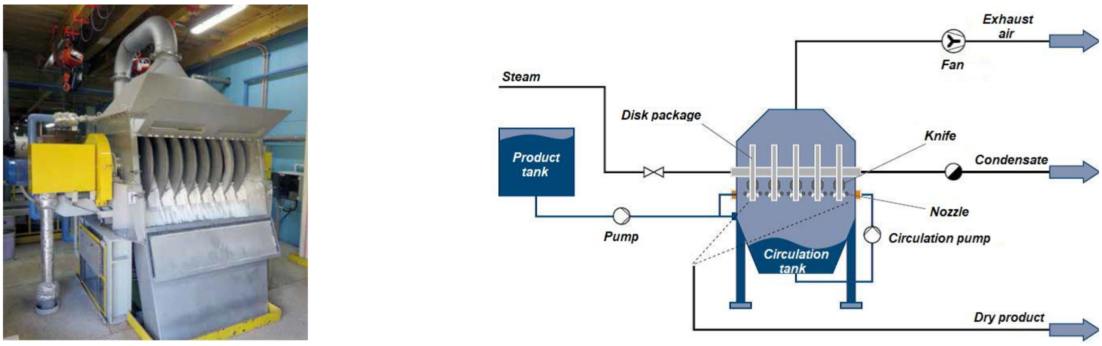

Figure 2. ***Disk dryer.***

The advantages include high productivity compared to roller dryers, versatility for drying different materials (grains, lumps and powders).

The disadvantages are: high energy consumption, limitations on the size of the processed material, increased wear of disk elements and complexity of construction.

3. Drum dryers belong to the widespread contact-convective type of drying equipment (Fig. 3), by means of which bulk, granular and lumpy materials in the form of salts, minerals, phosphorites, etc. are treated. [6-7, 24-25]. The main element of the design is a rotating cylindrical drum, which is usually mounted at a slight angle to the horizon. The material to be dried passes through a drum equipped with internal nozzles, which ensures its uniform distribution, mixing and good contact with the heating gas. Combustion products of natural gas, fuel oil and kerosene as well as air heated in an electric calorifier are used as a heat carrier. The gas and the material are fed into the apparatus in a direct flow at a velocity of 2 m/s, which prevents overheating of the material and excessive dust entetrainment from the apparatus.

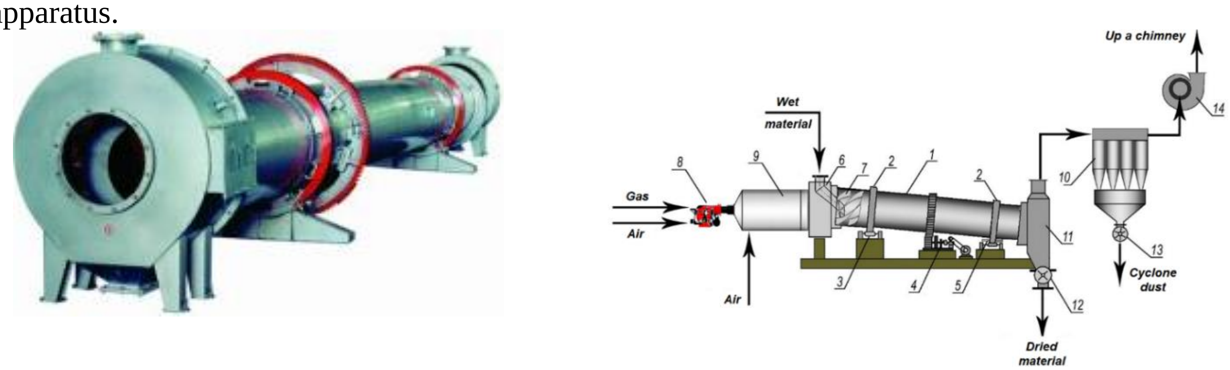

Figure 3. ***Direct-contact rotary dryer.***

Rotary dryers of the contact type (Fig. 4) are used to prevent contamination of the dried material by flue gases. In this version, only a small amount of air is supplied to the drum to remove water vapors, while the main heat transfer takes place through the drum wall, which is flush with flue gases from the outside.

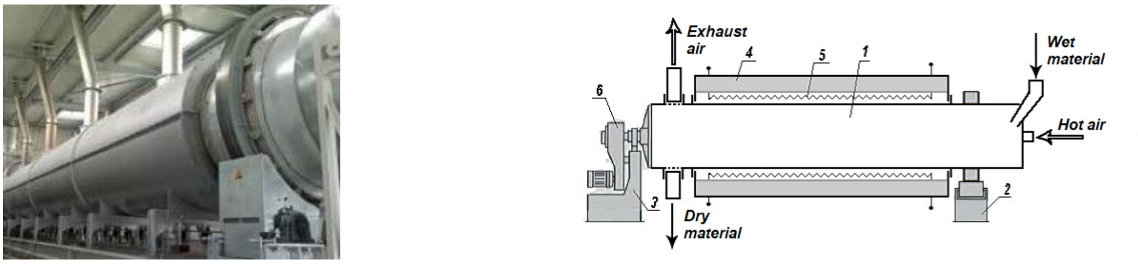

Figure 4. ***Indirect-contact rotary dryer.***

The advantages include even drying, ability to handle different types of material including chunks, granular and porous materials.

The disadvantages are high energy losses due to exhaust gas emissions into the atmosphere, impossibility to dry the material to the required moisture content in one pass.

The general advantages of contact apparatuses are:

1. Low emissions of particles and exhaust gases.
2. Gentle drying due to the use of relatively low temperatures.
3. Relative compactness of the equipment.
4. Versatility of contact drying application.

Common disadvantages of contact dryers are:

1. High energy consumption.
2. Limited productivity.
3. Requirements for the constancy of the material feed rate into the apparatus and the initial moisture content of the material.
4. Bulkiness requirements.
5. High capital costs.
6. High operating costs [11, 24].

Given the undeniable contact dryers advantages, they are inferior in energy efficiency terms to other drying methods in fertilizer production against the backdrop of a growing energy resources shortage. Drying with convective heat transfer methods can be an alternative.

Let's consider the main types of convection apparatuses for drying mineral fertilizers.

1. **Conveyor belt dryers** (Fig. 5) are continuous dryers [6, 25]. Moist material is dried on a moving belt stretched between the driving and driven gears. Hot air or flue gases are supplied against or across the belt movement with the material.

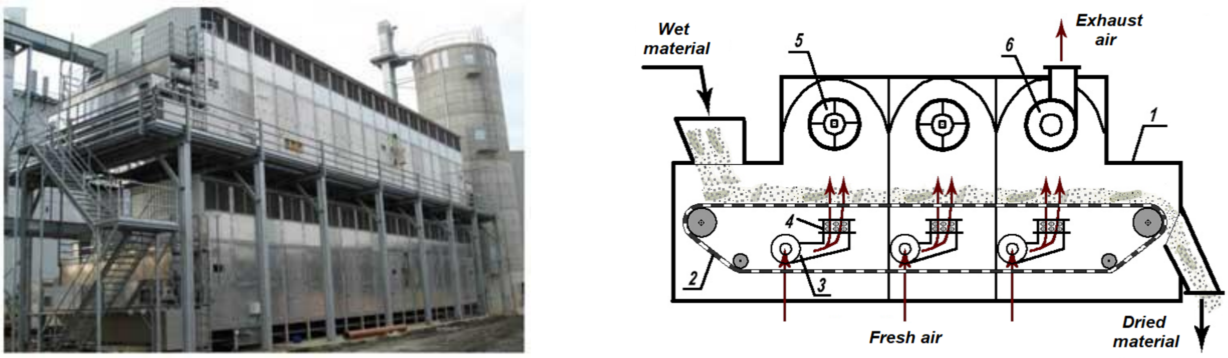

Figure 5. ***Conveyor belt dryer.***

The advantages include the handling of fragile, molded and granular products, the wide possibilities of adjusting parameters such as temperature, speed and gas direction for each drying section.

The disadvantages are:

- unwieldiness;
- uneven drying;
- difficulties in maintenance due to belt warping and stretching during operation;
- low specific productivity (per unit of belt surface) and high specific heat consumption (mass per unit of evaporated moisture);
- unsuitability for paste drying, due to which they are often used in combination with roller dryers.

2. Conveyor mesh belt dryers belong to continuous dryers, which are usually used for drying pastes [6, 24-25]. The material to be dried is fed onto a flexible mesh belt, which acts as a conveyor belt and passes through two hot rollers that press the paste into the cells on the belt. The mesh belt passes through the drying chamber and forms loops through the use of articulated links and cross bars supported by a looped conveyor. When leaving the chamber, the dried material is shaken off by an automatic impact mechanism, after which the material is discharged by an unloading auger.

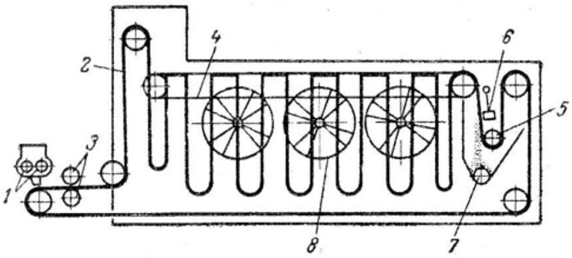

Figure 6. ***Conveyor mesh belt dryer.***

The heat transfer medium is directed across the belt by axial fans. The dryer operation mode with intermediate air heating is often used, which requires additional energy inputs and partial air recirculation in different zones of the apparatus. Drying of the material is carried out in a thin layer of material with bilateral air heating of the belt. Loop dryers have a complex construction and considerable operating costs.

3. In devices with a fluidized (boiling or suspended) bed (Fig. 7), drying occurs under the conditions of a so-called "fluidized bed" of granular material, in which, due to the lifting flow of the drying agent, the particles pass into a "boiling" state [3, 6, 8-9, 17-18, 24-25]. In this drying mode, there is a *significant increase in the contact surface between the material to be dried and the drying agent*, which in turn accelerates the evaporation of moisture and reduces the processing time to a few minutes. Fluidized bed dryers are used not only for the treatment of free-flowing mineral and organic salts, but also for the drying of melts, solutions, pastes, suspensions and lump-forming materials.

The casing of this apparatus type is usually designed with a cross-section extending upwards. This shape ensures a more organized circulation of the dried material: the particles rise in the central part and fall (forming a less dense zone) at the chamber walls. Due to the decreasing velocity of the gases as they rise in the apparatus, the particles to be dried are evenly distributed in size, heated uniformly and dust drift is reduced.

These dryers achieve high moisture removal per unit volume of the drying chamber. This equipment class therefore replaces drum dryers and other less efficient types of dryers for the processing of a number of products. In industrial type dryers, the moisture evaporation rate can reach 1250 kg/(m^3·hour) [25].

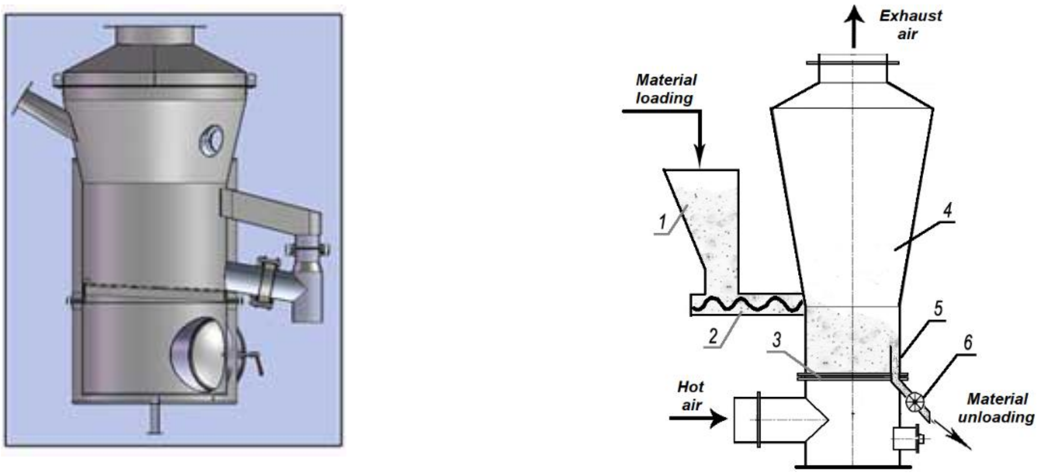

Figure 7. ***Fluidized bed dryer.***

The disadvantages are:

- complexity in process control;
- construction complexity;
- impossibility to ensure uniform particle residence time in the apparatus;
- necessity to install catching devices after the apparatus due to increased material abrasion and carry away of fine particle.

In addition to conventional fluidized bed drying, different equipment variations such as spouting, vortex and inert bed dryers are used.

7. **In dryers with vibratory fluidized bed**, the application of vibration to the suspended (fluidized) material bed improves its properties and increases the heat and mass transfer process intensification (Fig. 8) [24-25]. Vibrating fluidized bed is created by vibrations of the bottom, walls or additional partitions, as well as by special vibrating stimulators installed directly in the drying chamber.

The simultaneous vibration effect and gas supply through the porous bottom of the apparatus reduces the gas velocity to a value below the critical, which reduces the gas influence as the main mixing factor and leads to significant savings of drying gas.

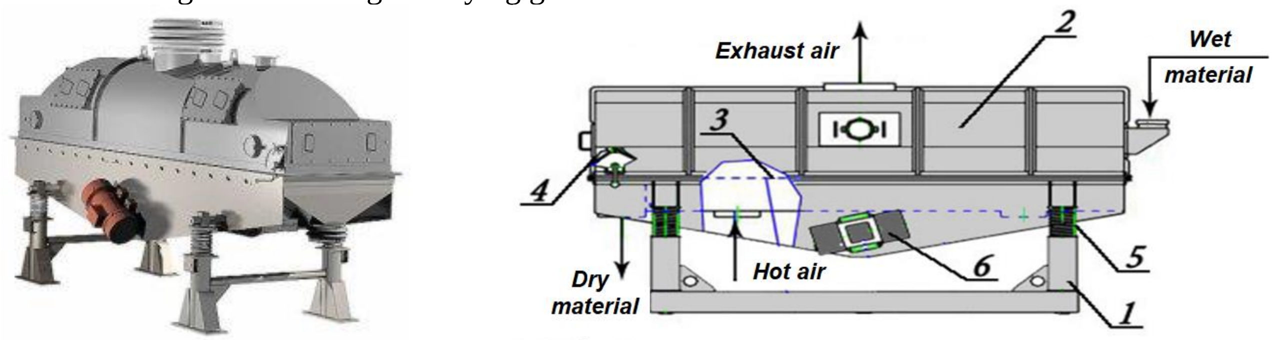

Figure 8. ***Vibrating fluid bed dryer.***

The advantages include gentle operation, economical operation, and easy parameter adjustment.

The disadvantages are: low productivity, complexity of vibration drive design and possible material sticking at low air temperature.

Vibratory dryers are used for drying a variety of bulk granular materials such as sand, minerals, salts, foodstuffs and pharmaceuticals. These dryers make it possible to combine the drying and cooling processes of the processed material.

8. Spray dryers (Fig. 9) have such an important advantage as fast drying under mild temperature conditions with obtaining high quality powdery product, which is especially convenient for further transportation and storage [24-25]. These dryers are used to produce mineral fertilizers, ceramic powders, additives for dry construction mixtures, etc.

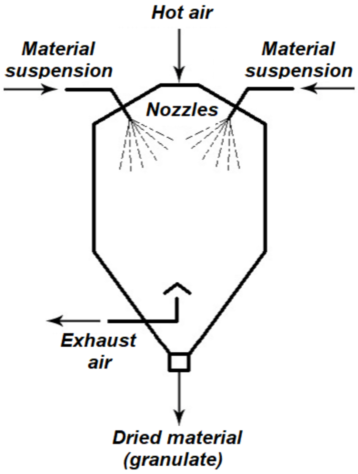

Figure 9. ***Spray dryer.***

The apparatuses have a high intensity degree due to the fine material atomization to be dried in the drying tower, along the height of which the drying agent is directed in the form of heated air or flue gases. Drying under such conditions usually takes place in 15-30 seconds. The material surface temperature remains relatively low, even when the drying agent temperature is high.

It is also possible to dry using a cold heat transfer medium, but the material to be atomized is preheated. Spraying is carried out by mechanical and pneumatic nozzles, or by centrifugal disks rotating at speeds from 4,000 to 20,000 revolutions per minute.

The disadvantages are large dimensions, as well as rather complicated and expensive in operation equipment (spraying and dust collecting devices), increased fire hazard and degradation of the material due to its deposits on the tower walls.

9. Flash dryers (Fig. 10) are used to remove surface moisture from bulk materials such as sand, powders and crushed minerals [24-25]. The apparatus is a vertical tube up to 20 meters long, in which the bulk material moves in the drying agent flow at speeds of 10-30 m/sec, which exceeds the particles velocity. The drying time takes only seconds, so only part of the free moisture is removed from the material.

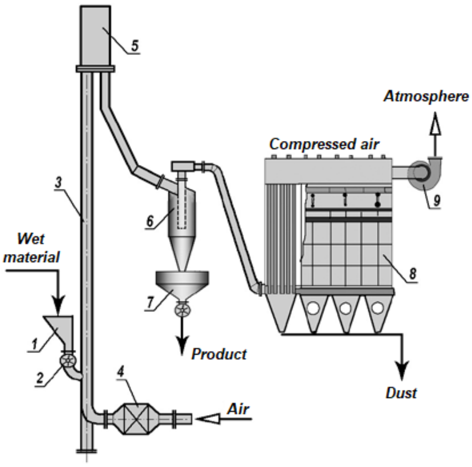

Figure 10. ***Flash dryer.***

The dryers consume a lot of energy, but as the particle size of the dried material decreases (8-10 mm), the energy consumption also decreases. Drying of large particles and removal of bound moisture is possible by combining pneumatic dryers with other types of dryers.

Flash dryers are popular due to their compactness and construction simplicity, they can be used for combining the drying process with pneumatic conveying, as well as for particle classification in multi-tube apparatuses.

To summarize, it should be noted that suspended bed dryers are the most advanced units for drying fine and coarse dispersed materials, lumpy substances, pastes, solutions and suspensions [26-27].

Suspended bed drying significantly increases the contact surface of the drying agent and the dried material, which leads to an increase in the moisture evaporation rate and reduces the processing time to a few minutes. At high process intensity, representatives of this equipment class are compact devices. Full automation of the fluidized bed drying process allows to reduce operating costs.

The advantages of fluidized bed dryers include [8-9, 28]:

1. High drying performance and efficiency due to large contact surfaces of the phases.
2. Relative equipment simplicity.
3. It is possible to combine the drying process with other important and energy-consuming processes in one module, such as mixing, dedusting, granulation, coating, agglomeration, cooling, chemical reactions, combustion, gasification, etc., resulting in significant resource savings.
4. Easy of material conveying.
5. A wide range of options for controlling temperature, humidity and airflow rates.
6. A decrease in particle size leads to a decrease in diffusion resistance within the particles.
7. Relative equipment compactness.
8. Versatility of application.
9. Equipment contamination doesn’t cause loss of drying efficiency as quickly as with a rotary dryer.

However, some disadvantages of fluidized bed dryers should be noted:

1. Limited drying options for materials requiring a more delicate drying approach or drying at low temperatures.
2. Inapplicability to materials that don’t lend themselves well to fluidization. For example, some forms of phosphate fertilizers, such as tricalcium phosphate ($Ca_3(PO_4)_2$), in their crude form generally have low solubility and are not easily fluidizable. This is due to their low reactivity with water.

Table 1 summarizes the typical capacity and energy consumption in existing industrial dryers [24].

Table 1.

Performance and energy consumption of different dryers.

Dryer type	Typical evaporation capacity (kg H_2O/h m^2 or kg H_2O/h m^3)	Typical energy consumption (kJ/kg of H_2O evaporated)
Belt conveyor dryer	—	4000 – 6000
Rotary dryer	30-80/m^3	4600 – 9200
Drum dryer (for pastes)	6-20/m^2	3200 – 6500
Fluidized bed dryer	no data	4000 – 6000
Flash dryer	5-100/m^3(depending on particle size)	4500 – 9000
Spray dryer	1-30/m^3	4500 – 11500

Note. Figures are approximate and are based on industry practice. Better results can be obtained by optimizing operating conditions and using advanced technology to modify earlier designs.

Table 2 summarizes the comparative characteristics of common types of dryers [24].

Table 2.

Comparison of common dryer types.

Parameter	Rotary dryer	Flash dryer	Conveyor dryer	Traditional fluidized bed dryers	Modified fluidized bed dryers
Particle size	wide range	fine particles	500 μm to 10 mm	100-2000 microns	10 μm to 10 mm
Particle size distribution	flexible	limited size distribution	free	limited size distribution	wide distribution
Approximate drying time	up to 60 min	10-30 c	up to 120 min	up to 60 min	up to 60 min
Floor area	large	large length	large	small	small
Turndown ratio	high	small	small	small	small
Attrition	high	high	low	high	high
Power consumption	high	low	low	medium	medium
Maintenance costs	high	medium	medium	medium	medium
Energy efficiency	average	medium	high	high	high
Ease of operation	low	medium	high	high	high
Capacity	high	medium	medium	a medium	high

Among the options presented in Table 1, the energy consumption of the fluidized bed dryer ranges from 4000 to 6000 kJ per kg of evaporated water, which is within the range of comparable values with other types. And if the capacity of the plants is taken into account (see Table 2), the fluidized bed dryer may be the best option.

Taking into account the presented parameters, the use of combined fluidized bed dryers may be a better option than the drum dryer because of its wide particle distribution, comparable drying time, small working surface area, high energy efficiency and ease of operation.

At present, many studies and patents have been devoted to fluidized bed drying technologies [29-54]. There are many directions of innovative drying methods, which can include:

- improving the energy process efficiency by changing the equipment design or process flow diagrams (including the use of recycle);
- improved safety and convenience in plant operation (e.g., introduction of complex automation systems, easier cleaning of the working chamber, etc.);
- increasing the versatility of the plant, the ability to process a wide range of input materials (e.g., application of special coatings to increase the wear resistance of the working part of the equipment, or to increase resistance when working in an aggressive environment, under extreme conditions, etc.);
- methods aimed at improving the initial product quality, which generally result from improved control and the drying process quality;
- development of effective plant control algorithms aimed at improving efficiency.

One or more of these goals can be achieved in several ways. The following is a short list of them:

- using of hybrid dryers;
- using of heat pumps to save energy;
- using of multistage dryers.

The most promising areas of research into fluidized bed drying technologies are to create or modify existing designs and control methods to achieve the benefits outlined above.

Let us consider some qualitative changes in drying technology in recent years. Based on the study of recent patents [29-53], it can be concluded that the work in the fluidized bed drying field is going in the following directions:

- application of multistage processes;
- changing the path of the drying agent and the material to be dried;
- application of various intensifiers;
- application of combined drying;

- establishment of control systems;
- technology changes (e.g., change of drying agent, change of process operating parameters, introduction of additional control loops, etc.).

Combinations of these areas of research are very often used.

The following are descriptions of patents directed to **modifying the path of the drying agent and the material to be dried.**

The authors of the invention RU2798165C1 (2022) [29] propose to improve the granulation quality in a fluidized bed of high-moisture and temperature-sensitive materials such as urea and ammonium nitrate by means of perforated inclined channels in the distribution grid. The channels reduce the capital cost of cleaning the plant and reduce the load on the dust cleaning system.

The main disadvantage of this device is the limitation on the material type to be dried.

It is an object of the invention JP2020-139715A [30] to stabilize the quality of the dried product at unstable moisture content of the material fed to fluidized bed drying by providing a space in the construction under the feed chute for additional material and air circulation.

The invention disadvantages include the risk of stagnant areas under the chute in the event of failure of the outlet opening under the chute, and difficulties in maintaining the device due to the retractable design of the chute extension and its limiter.

A fluidized bed drying apparatus (JP2018-54271A) [31] reduces the drying time of powders and granules by forcibly moving the material diagonally downwardly by air from the side of a drying chamber from an additional air supply unit.

The disadvantages of this device include:

— operation of the dryer in batch mode;
— risk of uneven distribution and movement of material within the drying chamber;
— design complexity;
— high energy consumption.

A fluidized bed dryer (JP2018-44732A) [32] improves the speed of a drying process and reduces heat loss by directing the initial wet material against a gas stream swirled in the form of a cone-shaped spiral.

The device disadvantages are:

— uneven drying, especially when processing large volumes of material;
— limited applicability to materials requiring low drying gas feed rates;
— at high gas velocities the dried material may be carried away;
— limited throughput of the device due to the geometry of the design.

The advantages of changing the material path include:

1. Improved heat transfers due to the increased contact surface between the drying agent and the material to be dried.
2. More even drying.
3. Improved product quality (uniform moisture and texture of dried material).
4. Flexible control of process parameters (drying agent flow rate, temperature, etc.).
5. The ability to take advantage of gravity or centrifugal forces to control the residence time of particles in the apparatus and reduce product transporting costs.

The disadvantages of changing the material path include:

1. Technical complexity of technology development and implementation.
2. Additional difficulties in setting up and operating the equipment.

The following are a number of patents dealing with the **using of various intensifiers.**

Fluidized bed dryer RU2313745C1 (2006) [33] increases the rate of moisture evaporation and accelerates the drying process due to the sound emitter installed under the support grid of the drying chamber. Sound vibrations contribute to the destruction and additional mixing of the wet material layer.

The invention disadvantages include:

— negative noise exposure of sound;

— unsubstantiated assertion of the facts of increased plant performance without providing specific figures.

A utility model RU204191U1 (2021) [34] allows increasing the drying process efficiency in a fluidized bed by introducing a pulsator in the design, which provides a pulsating supply of drying agent with resonant oscillations of high amplitude and contributes to more intensive mixing of the material in the bed, improving the contact between the surface of the material and heated air, as well as more uniform drying due to the regular and uniform flow of heat.

The invention disadvantages are:

— low device performance the due to the stiffness limitations of the springs on which the gas distribution grid is mounted;

— presence of wear elements in the design (corrugations, springs).

The fluidized bed dryer US10955189B2 (2017) [35] allows increasing the process intensification by applying mechanical vibrations generated by the movement of an eccentric shaft mounted under a longitudinal distribution grate. The grate height is adjustable, allowing a uniform distribution of the process air flow, control of the transportation speed and residence time.

The device disadvantages include:

— possibility of uneven distribution of the process air flow due to randomly varying material conveying speeds;

— increased wear on the eccentric shaft.

The invention CN215523931U (2022) [36] provides a fluidized bed drying system with improved quality by implementing an automated control system based on an exhaust fan that discharges exhaust air and ensures moisture removal from the system. The system is also equipped with a frequency converter to control the blower force of the draft fan.

The disadvantages of the dryer are as follows:

— increased energy consumption due to the exhaust fan;

— complexity of setting up and coordinated drying control;

— increased maintenance costs for the dryer;

— increased noise during dryer operation.

Patent RU2305240C1 (2006) [37] is directed to improving drying performance by installing a fan in the upper part of the drying chamber.

It should be noted that the fan treatment will not have a significant effect in increasing the productivity, as it will only lead to an increase in energy costs associated with the resulting additional hydraulic resistance of the fluidized bed.

The invention CN218269826U (2023) [38] is directed to solving the problem of non-uniform drying, due to the accumulation of the feed material at the dryer inlet and the failure of the hot air to fully pass through, by utilizing mechanical vibrations acting on an inclined metal conveyor belt with small openings.

The invention disadvantages include:

— complexity of assembly and maintenance of the structure;

— difficulty in adjusting the dryer;

— increased noise level.

The following are patents that utilize the **introduction of inert materials.**

Fluidized bed drying apparatus RU2650250250C1 (2017) [39] allows increasing the efficiency of the process by introducing an inert particles and vibrating plates installed in the dryer body with the ability to rotate.

The invention disadvantages are:

— reduced material dispersion due to inert particles insertion;

— increased maintenance and repair costs;

— increased energy expenditure;

— complexity of setting and controlling the dryer parameters.

Invention RU2719155C1 (2019) [40] allows intensifying the process of drying liquid dispersed products in a fluidized bed, preventing the formation of stagnant zones and improving the quality of the dried product due to the pulse feeding of the dried liquid to the blades of the stirring device and the fastest possible removal of the dry product from the inert particles.

The disadvantages of the device include:

— unintentional change of the motor speed may lead to mismatch of the approach torque of the stirrer blades with the torque of the impulse liquid supply;

— complicated process regulation process.

Among the advantages of using intensifiers are the following:

1. Improved drying efficiency due to the increased contact area between the drying agent and the material to be dried and their more intensive mixing.
2. More even distribution of the material inside the dryer.
3. Flexible and adaptable application for drying different materials.

The disadvantages of using intensifiers can be:

1. Technical complexity of implementation, need for additional engineering solutions development.
2. Increased power consumption.
3. Wear and tear of intensifiers require timely maintenance and replacement.
4. Application limitations.

In the following invention RU2756618C1 (2020) [41], an additional cooling agent injection is carried out in order to control the temperature in the drying chamber. The additional coolant input reduces energy costs and provides improved fluidized bed drying of thermosensitive thermoplastic materials.

The device disadvantages include the control complexity.

The following patents utilize **combinations of methods for altering the path of the drying agent and the material to be dried using various intensifiers.**

The technical objective of utility model RU204983U1 (2020) [42] is the effective utilization of air flow affecting the dried product. The drying chamber is made in the form of a vibrating flat and narrow chamber, mounted on springs at an angle to the horizontal plane, through which flue gas is fed into the counterflow.

The disadvantages of the drying plant are:

— material type restrictions;

— limited plant capacity;

— risk of material not passing through and uneven drying due to poor material mixing caused by only vibration.

The following patents are directed to **the use of multistage processes.**

The apparatus proposed in RU2202080C1 (2001) [43] is used for fluidized bed drying of high-moisture and heat-sensitive materials, has increased productivity due to the presence of successive zones in the chamber with autonomous drying mode and fluidized bed height control. Each zone is equipped with gas-distributing grids with perforated caps in the holes of the grids, which create the vortex gas flows. The disadvantages are:

— limited applicability;

— difficulties in determining the optimal parameters of the apparatus operation;

— increased power consumption of the device.

The US7908765B2 (2006) [44] continuous dryer and pelletizer has improved performance by transferring material from the pelletizer sections to the drying sections as quickly as possible by dividing the chamber by rotating baffles, and using a rotating granular material feed channel to selectively communicate the inlet and outlet of the sections.

The disadvantages of the unit are:

— the need for careful adjustment for coordinated operation of the granulation and drying chambers;
— increased power consumption;
— limited applicability of the device;
— limited applicability.

The invention RU2737213C2 (2019) [45] has improved drying efficiency by dividing the vertical body of the apparatus into a fall-free section (supports the material layer) and a gas-distributing section (for supplying the drying agent). The gas distribution grid is equipped with movable guide vanes, which allow the fluidized bed to be moved in the desired direction across the fall-free section. To regulate the residence time of the material, the chamber is equipped with a movable partition.

Disadvantages of the device include:
— difficulties in ensuring optimum drying speed;
— drying feed material with unstable moisture content will result in uneven drying or the need for constant readjustment of the moving parts of the dryer.

The advantages of using multistage processes are:
1. Increased drying efficiency due to better control and optimization of each drying step.
2. Improved quality of the final product.
3. Energy saving.
4. Versatility of application.

The disadvantages of using multistage processes are:
1. The need for proper and consistent customization of each step of the process.
2. Additional equipment and maintenance costs.
3. Bulky equipment.

The following patents deal with the use of **combined drying regimes.**

The invention RU2765844C1 (2021) [46] proposes to increase the efficiency of the process of drying dispersed materials in a fluidized bed by introducing into the design a vertically located screw made of mesh material, which performs the function of an electrically conductive heating element in the gas distribution chamber.

The disadvantages include:
— applicable only to high-moisture and conductive materials;
— design complexity;
— complexity of apparatus in control;
— application of electric current for direct heating;
— scale formation on the grid due to electrolysis;
— difficult to clean;
— high risk of electric shock;
— heating grid is not capable of carrying heavy weight loads.

The authors of patent RU2716354C1 (2019) [47] propose to increase the intensity and productivity of industrial fluidized bed drying of mineral fertilizers by introducing a pre-drying stage operating on the jet principle.

The disadvantages include:
— additional heat input for the first stage of drying;
— limiting the average grain size of the feed material to 0.25mm;
— limiting the moisture content of the feed material in the range of 7-8%;
— absence of an automatic monitoring and control system.

The next two inventions are a combination of fluidized bed drying and spray drying.

The RU2669894C1 (2018) [48] describes an apparatus for solutions drying which improves operational reliability and process quality by atomizing the solution in a fluidized bed using nozzles with swirler inserts.

Disadvantages of the invention include:

- rotary vane agitator with rotating blades, which are subjected to increased wear when interacting with granules and liquid;
- the chamber is not designed to allow the dried material to escape spontaneously;
- difficulty in setting the parameters of agitator rotation speed and atomization mode.

The invention RU2645829C1 (2017) [49] is aimed at improving the efficiency, reliability and quality of drying by installing spray nozzles along the involute of the circumference for uniform distribution of the suspension in the fluidized bed, as well as the use of a special fluid flow dissector consisting of coaxially arranged perforated conical shells separated by a fine mesh, and a spring-like swirler.

The device disadvantages are:

- complex configuration of the fluid flow splitter;
- the fine mesh screen will soon clog;
- slurry viscosity limitations.

Circulating fluidized bed device US10612843B2 (2014) [50] performs operations such as drying, grinding, sieving, mixing and ultraviolet sterilization of powdered materials to obtain a desired product quality.

The device disadvantages include:

- periodic operation of the dryer;
- combining multiple processes in one machine makes it difficult to accurately control and optimize each parameter;
- restrictions on the type of materials: soft and non-heavy powders;
- presence of elements requiring frequent maintenance (fans, pipe ducts).

The advantages of using combined drying modes are:

1. More complete moisture removal from the material through the use of various technologies.
2. Versatility in application.
3. Energy efficiency.

The disadvantages of using combined drying modes are:

1. Difficulty in setting and coordinated operation of different drying modes.
2. Bulky equipment.

The following are the works that we believe are the most advanced in the field of fluidized bed drying.

Vibrating fluidized bed dryer US011466931B2 (2022) [51] provides a perforated vibrating deck on which a fluidized bed of material is formed to uniformly distribute the material, thereby preventing an accumulation or hardening of the material. A distinctive feature of the dryer is the presence of at least two zones on the deck, each of which has a different degree of air permeability and contributes to optimal drying of the material.

Disadvantages of the apparatus include limitations associated with the use of vibrations.

The fluidized bed apparatus US20070013092A1 (2007) [52] is designed for rapid preparation of solid granular urea with moisture content of 0.3 wt.% or less of urea solution (94-98.5 wt.%). The device effectively utilizes the heat of crystallization released during the formation of urea agglomerates due to the use of lower temperatures in the fluidized bed, which becomes possible with a separate supply of fluidizing, atomizing and spouting air flows. Lower temperatures allow to reduce air pressure for atomization of urea solution, in contrast to known methods, where air pressure is usually 1-2 bar, which requires the significant energy costs.

The disadvantages include the need for frequent cleaning of the fluidizing air supply openings, as well as energy costs for creating additional air flows.

The invention US11000817B2 (2021) [53] relates to a fluidized bed granulator for fusion/urea solution that allows for separate control of process flows, efficient use of space within the granulator, and ease of assembly and maintenance.

The granulator has three separate chambers arranged from top to bottom in the following order:

1. The fluidized bed working chamber, which is divided into compartments by means of separating partitions, allows to precisely regulate the residence time of the particles in the granulator, the temperature conditions, as well as the step-by-step enrichment of granules with necessary additives.
2. Low temperature fluidizing gas supply chamber (below 70°C).
3. High-temperature auxiliary gas supply chamber (above 100°C) required for the pelletizing process.

Temperature separation of the gas streams prevents granulation fluid (e.g., urea melt) from solidifying in the auxiliary gas supply chamber, allowing for easy system cleaning.

A plurality of risers, made in the form of concentric tubes in which the outer tube surrounds the inner tube, is fed to the working chamber. The inner pipe carries the granulation liquid and the outer pipe carries the high-temperature auxiliary gas. With this configuration of the device, the granulation liquid is in indirect heat exchange contact with the hot auxiliary gas in the manifold, which greatly reduces heat loss during the granulation. From above, the riser is bounded by a nozzle through which the auxiliary gas and granulation liquid are atomized. Levers are provided to ensure that the lifting height of each individual nozzle can be adjusted.

The fluidization plate is usually horizontal or can be slightly inclined (usually no more than 2-10°) along the length direction, with the highest part of the plate closer to the exhaust gas outlet. This solution helps to organize the flow of gas and particles, which facilitates further cleaning of the granulator from undissolved biuret, as it can be flushed to the underside of the plate.

To clean the unit, first remove coarse particles from the working chamber. Afterwards, the working chamber clean with water (or other solvent) to dissolve the remaining solids. After cleaning, the contaminated water and remaining solids enter the fluidization gas supply chamber through openings in the fluidization plate. The fluidizing gas supply chamber is easily accessible for cleaning due to the rational arrangement of the risers.

The invention disadvantages include:

1. Relative complexity of equipment and assembly.
2. Limited applicability: this granulator configuration is optimazed for urea applications only.
3. There is no recycling, allowing the energy of the heat carriers to be reused.
4. The need for periodic cleaning of the device.

The given analysis of different types dryers functioning shows that the most perspective directions in the mineral fertilizers drying field are researches connected with the apparatuses working in a fluidized bed, as against the background of other dryers they possess higher efficiency, are energy-saving and are amenable to wider and more accurate control of technological parameters. The solution of the optimal control problem of these devices with the help of modern methods in deficit conditions of energy resources will lead to significant savings with high quality of the final product.

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