Utilization of dust and ammonia from exhaust gases: new solutions for dryers with different types of fluidized bed

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Abstract
Background The article is devoted to the development of new utilization methods of exhaust gases by cleaning them from fine particles, dust and harmful gas components. The basic design solutions, which allow to increase the degree of exhaust gases cleaning, were presented. The effectiveness of design solutions was supported by the results of experimental studies. Analysis of the research results allowed developing of new designs of equipment for dehydration in fluidized bed. The article also presents the calculation algorithm of eco-friendly dryers with fluidized bed.

Methods Physical modeling was based on methods of similarity theory. In studies in dryers experimental models the installation scale was changed (compared with industrial conditions). Geometric similarity was maintained by equity of constants and invariants of geometric similarity. Always similarity of respective particles movement and their trajectories in industrial design and in experimental models was also maintained. The creation of graphical dependences was carried out by differential methods of mathematical analysis and integral calculus. The reliability of obtained experiment results was caused by the application of time-tested in practice methods.

Results and discussion Control of product fractional composition allowed to make a selection of required fractions (including the fine granules) in a certain place of device. This allowed to increase the degree of purification of exhaust gas even before it output from the dryer working space. The process of separating the granules into fractions and the selection of fine fraction can be performed due to structural changes in dryer units and selection of optimal hydrodynamic conditions of fluidizing agent motion. Installation of special units in the dryers allowed to extract other contaminants from the exhaust gases.

Conclusions Proposed constructive solutions for fluidized bed dryers allowed to:
- provided of granules classification to the desired number of fractions with a simultaneous release and discharged of fine fraction from the working volume of dryer without the exhaust gases;
- increased the degree of monodispersity of commodity granules on 25–35%;
- reduced the amount of dust in the exhaust gases on 35–65%;
- reduced the ammonia content in the exhaust gas on 90–95%.

Keywords Dust · Ammonia · Exhaust gases · Utilization · Fluidized bed · Multi-stage shelf dryer · Vortex granulator-dryer

Background

One of convective drying ways was material contact with the heat transfer agent in stationary, weighted or semi-weighted states. Currently convection dryers, in which material is dried in suspended (fluidized) state, were used most frequently [1–5]. The main advantages of fluidized bed dryers are [6–9]:

- intense movement, close to the model of an ideal mixing of the particles;
- maximum surface evaporation;
- low hydraulic resistance of product layer;
- simplicity of design and convenience of operation.

It is noteworthy, that to provide the necessary material residence time in the convective dryer with classical fluid bed does not always possible due to the intensive mixing of
material and different moisture gradient in different parts of the device [10].

In addition, in such devices uniform contact of dispersed material and drying agent in wide range of loads on phases (flow ratio) is difficult. This complicates the dehydration process of heat-labile dispersed materials, e.g. such as grain crops. Significant costs for heating and whipping of drying agent is also considered as one of the drawbacks of devices.

Improvement of fluidized bed devices for mass transfer in system of “gas-solid” can be organized by organization of mutual flows traffic with multiple using of fluidizing agent, e.g. with the sectioning of dryer by setting in its height shelving contacts. Due to repeated contact of dispersed material with a drying agent, it is possible to significantly reduce material and energy costs for the process implementation [6].

The main advantages of multistage dryers with fluidized bed are [11, 12]:

– multi-function of device, i.e. the ability to simultaneously conduct the drying process, classification and particles separation;
– creation of counter-motion mode of interacting flows;
– organization of differential mode of dispersed material dehydration, i.e. creating the different material drying conditions in each stage, depending on its temperature and hydration characteristics;
– possibility to control the residence time of particles at each stage of the device and in the devise in general.

Another way to create a directional movement of dispersed material is the application of vortex fluidized bed in granulators-dryers [13–16].

Vortex granulators-dryers are characterized by following advantages, which are inherent to devices with vortex flows [17–22]:

– high specific volume and specific performance;
– availability of granule’s residence time and trajectory in the workspace of device management mechanism;
– universality, i.e. ability of granulation, classification, separation, drying and cooling processes in the volume of one device;
– possibility of quick changeover, changing design and technological parameters according to the task.

The results of computer simulation of hydrodynamics of flow motion [23–25] confirmed the indicated advantages.

Carrying out the drying process in these devices with active hydrodynamic mode, which ensures the increasing of relative velocity of interacting phases, helps to intensify the process without reducing of economic efficiency of device. The advantages of an active hydrodynamic mode also include [26]:

– hydrodynamic stability of the process;
– provision of advanced surface interaction of contacting phases;

Fig. 1. Diagram of porous ammonium nitrate production according to the method [24–28]: I – humidification of ordinary ammonium nitrate; II – heat treatment of ordinary ammonium nitrate after humidification; III – cleaning of spent heat transfer agent; 1 – multi-stage gravitational shelf dryer; 2 – vortex granulator-dryer.
reduction of energy intensity of process and metal consumption for devices.

Multi-stage gravitation shelving devices and devices for granulation and drying in the vortex fluidized bed have been proved as efficient equipment with high indicators of specific productivity. By changing of the cross-sectional area of drying units by the height of device (installation of shelves with varying degrees of perforation in multi-stage gravitation shelving devices and working space of conical shape in devices with vortex fluidized bed) there is the possibility of carrying out the granules classifying process into the size with the separation of fine and commodity fractions.

Despite the high efficiency of target process, drying units are source of harmful emissions from the exhaust gases. In this article we described how to obtain a porous ammonium nitrate by moisture and heat treatment [27–31] according to the scheme, which is shown in Figs 1, and 2. In this production waste are fine (sub-standard) grain, ammonium nitrate dust and ammonia.

The purpose of the article is the development of new recycling methods of waste gases in drying devices for porous ammonium nitrate production.

For the improving of environmental safety of dryers we offered such basic directions of ammonium nitrate production waste disposal and equipment:

1. Capturing of small fraction and dust with further shipment to prepare melt - separation stage [32].
2. Capture of ammonia to form ammonia water for production needs - vortex contact heat and mass transfer stage [33].
3. Capture of fine fraction with further dispatch to the growing is carried out directly in the vortex granulator-dryer [34].

The practical significance of research consists in the fact that we have proposed new designs, that allowed to reduce the amount of harmful emissions from the exhaust gases at the ammonium nitrate drying stage.

Methods

According to the tasks of experimental research of laboratory of Processes and Equipment of Chemical and Petroleum-Refineries Department of Sumy State University experimental unit was designed. Principled structure of this unit is shown in Fig. 3.

The process air is given by a gas blower $G_1$ into the heater $H$, where it is heated. Heated air is given into the lower part of the vortex granulator $VG$. Seeding agent as raw material in a certain amount, which is provided by the batcher $B_1$, is given in the upper part of the vortex granulator from the hopper $HP_1$. Granular ammonium nitrate with granule sizes of 2–3 mm is used as a seeding agent. Part of the fine ammonium nitrate granules is given from the hopper $HP_2$ to the batcher $B_2$ and then to the tank with a mixer $M$, where water is also given. Ammonium nitrate solution is obtained in the mixer. Then the solution passes through filters $F_{1,2}$, where it is purified from mechanical impurities. Then the solution is given to a vortex granulator using a pump $P_2$. The solution is sprayed with compressed air, which is given by compressor $C$. From the nozzle the solution is evenly distributed over the layer of moving granules (seeding agent). Porous ammonium nitrate is removed from the lower part of granulator. Product granules enter the gravitational shelf dryer $GHD$ for final drying and then into the fluidized bed cooler $FBC$. After cooling the granules are removed from the cooler and transferred to the packaging. Polluted air (spent heat transfer agent), which leaves the granulator,
passes a mass transfer and separation section in the vortex granulator. Here it is cleaned of ammonia and dust. Then the spent heat transfer agent enters the lower part of the absorber A, where it is further purified by spraying water. Purified air enters the atmosphere by the gas blower $G_6$. From the absorber polluted water enters to the tank $M$ with fine granules of ammonium nitrate for the solution obtaining. The water for spraying is given from the tank $T$ by the pump $P_I$.

**Main equipment** multi-stage shelf dryer, vortex granulator-dryer.

**Material** porous ammonium nitrate.

Humidification of porous ammonium nitrate was carried out by various types of humidifiers (water, ammonium nitrate solution, urea solution, ammonium nitrate and urea solution). Drying process was carried out until the moisture content was 0.2%. The temperature regime is 100–120 °C. The
productivity of unit (product granules) is 3000 kg per day. Water is used as the absorbent in the mass transfer and separation sections of the vortex granulator-dryer.

Physical modeling was based on methods of similarity theory. In studies in dryers experimental models the installation scale was changed (compared with industrial conditions). Geometric similarity was maintained by equality of constants and invariants of geometric similarity. Always similarity of respective particles movement and their trajectories in industrial design and in experimental models were also maintained. The creation of graphical dependences was carried out by differential methods of mathematical analysis and integral calculus. The reliability of obtained experiment results is caused by the application of time-tested in practice methods.

The scheme for measuring of the dust and ammonia concentrations in the working space of the dryer and in the spent heat transfer agent (for example in vortex granulator-dryer) is presented in Fig. 4.

The methods of mathematical statistics for the optimal number of experiments determining and the highest degree of accuracy and reliability of the obtained results achieving, as well as the processing of these results were used [35].

Two types of measurement errors - random and systematic may occur during the experiment conducting [36].

A random error reduces the accuracy of experiment results. An analysis of this type of error is possible by using the root-mean-square deviation $\sigma$, calculated by following formula

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}},$$

where $\bar{x}$ – the arithmetic mean value; $x_i$ – the single parameter value; $n$ – the number of measurements.

The maximum possible error of a separate measurement was determined by three sigma rule

$$\Delta = 3\sigma,$$

The bilateral confidence interval of the arithmetic mean value $\varepsilon$ was determined by the dependence [32], providing that this parameter is located in the confidence interval with probability not less than 95%

$$\varepsilon = t \frac{\sigma}{\sqrt{n}},$$

where $t$ – Student’s t-test [37].

The root-mean-square error of indirect measurements

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n} \left( \frac{\partial y}{\partial x_i} \Delta x_i \right)^2}{n}};$$

where $y = f(x_1, x_2, \ldots, x_n)$.

The accuracy of the obtained regression equations is determined by the least-squares method [36].

The systematic measurement error had identical effect on all parameters that were controlled during the experiment conducting. All measurement devices were tared by calibration instrument by comparing their accuracy with declared in the technical documentation for excluding of above mentioned error. The connection between measurement devices and devices on the control panel was provided with a maximum error of processing signals within 1.5%.

Measurement devices:

- measurement of the hydrodynamic characteristics of the flow’s motion – thermoanemometer TES-1340;
- measurement of the temperature in air heater – register-selfrecording potentiometer;
- measurement of dryer’s workspace temperature – thermal imager Fluke Ti25;
- measurement of granule’s moisture – multimeter DT-838;
- measurement of dust concentration in exhaust gases – portable aspirator A-01;
– measurement of ammonia concentration in exhaust gases
– stationary gas analyzer AC32M / CNH3;
– measurement of fractional composition of granules (final product) after drying – sifting (sieve) machine AS 200 basic.

The hydrodynamic characteristics of the gravitational shelf dryer and the vortex granulator-dryer operation were varied due to the change of drying agent consumption. At the same time, due to the selection of optimal design of device the “hydrodynamic” residence time of the granules in the device should be equal to the “thermodynamic” drying time to the required moisture. The granules residence time in the working space of the shelf dryer and the vortex granulator-dryer was determined on the basis of a joint solution of the equations of hydrodynamics (the model is presented in [13, 14]) and kinetics (the model is presented in [28, 29]) of drying. The operating range of the devices was the velocity of the drying agent, which provided an interval between the first and second critical fluidization velocity.

Availability of data and material All data generated or analyzed during this study are included in this published article and its supplementary information files. While preparing the article it was used information about the original designs of vortex granulators (patents No. 29950 Ukraine, IPC (2006) B01J2/16; No. 82754 Ukraine, IPC (2006) B01J2/16; No. 90798 Ukraine IPC (2009) B01J2/16 B01J8/08 B01J8/18; patent No.99023 Ukraine IPC (2012.01) B01J2/16 etc.) and author’s software products (certificates of authorship No 62692, 65140, 67472).

Results and discussion

The results were summarized in the form of separate units:
1) multi-stage shelf dryers;
2) vortex granulators-dryers.

This section presented the main design solutions, which improve the environmental safety, as well as the results of experimental studies (fractional composition of product and concentration of harmful substances in exhaust gases as well as dust and ammonia in vortex granulators-dryers and dust in multi-stage shelf dryers).

It should be noted, that the control of product fractional composition allowed to make a selection of required fractions (including the fine granules) in a certain place of device. This allowed to increase the degree of purification of exhaust gas even before it output from the dryer working space. The process of separating the granules into fractions and the selection of fine fraction can be performed due to structural changes in dryer units and selection of optimal hydrodynamic conditions of fluidizing agent motion. Installation of special units in the dryers allowed to extract other contaminants from the exhaust gases.

Multi-stage shelf dryers

To perform granules classification and fine fraction separation we proposed constructive solutions, which are shown in Fig. 5.

Perforation of inclined contact shelf with holes of different diameters (Fig. 5a) and its implementation in sectional form of separate parts with variable angle to the horizontal (Fig. 5b) can create on it such hydrodynamic situation in which the alignment of epures of drying agents speed on the length of shelf, its performance over the entire length remains

Fig. 5 Construction of contact shelves of multi-stage gravitational dryer: a – perforation of contact shelf with holes of different diameters; b – sectional contact shelf with different angles of inclination to the horizon of each of parts
constant. This phenomenon is confirmed by comparative
epures of drying agent velocity distribution on the length of
device at different design of the shelves (Fig. 6). Such hydro-
dynamic situation causes a process of compensation actions of
inertia forces on dispersed material and rolling down inclined
surface, slowdown of dispersed material on inclined contact
shelf, its uniform motion in weighted layer and long-term
contact with drying agent.

Given the consistency of drying agent expenses in each of
cross sections of the device, the presence in it a gap between
the end of inclined contact shelf and wall, as well as various
free cross-section of passage of drying agent in some parts of
device, installation of inclined contact shelves with mentioned
perforation will reduce the vertical speed of drying agent in
length of inclined contact shelf and in the gap between the end
of inclined contact shelf and wall. This improves the uniform-
ity of contact drying agent with dispersed material.

Installation in volume device inclined contact shelves of
specified structures improved drying efficiency during the re-
moval of moisture from the surface layer of dispersed material
and from the depth of material after heating.

These designs of inclined perforated contact shelves helped to
reduce the intensity of swirling process through the compensation
forces, that created vortex when rounding the end of contact in-
clined shelf, increasing the force of upward flow of drying agent.
Herein through the variable construction of contact shelf the gran-
ules with different diameters moved in the dryer during the dif-
ferent time. This made possible to separate the small granules and
output them separately from the stream of spent drying agent.

Comparative analysis of granules fraction composition at
different design of shelves is shown in Fig. 7.

Analysis of Fig. 7 showed that in improving contact
shelf structure we observed the increasing of number of
commodity fraction in the dried product. The fine fra-
tion is unloaded from the end of shelf in shorter time
and is discharged from the device through a separate
connecting pipe. In addition, due to dust separation pro-
cess in above shelf space and its directed removal of
dust concentration in exhaust gases was also reduced
(Fig. 8).
The sectioning of the drying space by the shelves of different construction allows to create different conditions for the material movement in each section. Depending on the initial and final fractional composition of the granules, each shelf can act as a classifier. Also, the variation of the shelf construction at each stage provides a predetermined residence time of each fraction in the dryer working space.

Thus, rational selection of shelf construction allows to stabilize the fluidized bed of granules by:

- reduction of granules removal from the upper shelf of the cascade (under conditions of separation of small non-commodity fraction);
- control the residence time of particles depending on the initial and necessary final characteristics;
- reduction of vortex intensity creation in the gap between the end of the shelf and wall of dryer.

We note, that the structural improvement of shelf contact does not give possibility to capture the ammonia, contained in the exhaust gas. We can organize this process by using the original mass-transfer-separation contact stages of vortex type [29, 30]. Application of such contact stages is discussed below on example of vortex granulators-dryers.

### Vortex granulators-dryers

Granulator with constant cross-sectional area do not provide the full granules classification and separation process of non-commodity fraction in volume granulator. This can be explained by the fact, that in vortex granulator workspace consistency of upward gas flow velocity remains, that corresponds to velocity of the granules (or granules factions within narrow range). To carry out granules classification processes in devices with a constant cross-sectional area is possible in case of gas input to the unit by several streams with place of injection location in different height marks. This classification method is quite energy intensive and is not widely used.

Application of devices with variable cross-sectional area of workspace is much more effective method of solid phase classification [34]. Through the creation in volume of device fields the velocity components of gas flow in the height of granulator the different hydrodynamic conditions for granules movement are created. In the height of device the distribution of granules with the different diameter (in case of simple material granules are classified) or the different mass (in case of creating granules with porous structure or multilayer granules). This allows not only to get the product with necessary quality, but also to carry out separation of small granules. Small granules later can be used as an internal seeding agent.

**Fig. 8** The average dust concentration of ammonium nitrate in the exhaust air from the multistage gravitational shelf dryer: 1 – dryer without shelves; 2 – shelf with constant perforation in length; 3 – sectioned shelf with variable sections perforation; 4 – sectioned shelf with constant sections perforation and variable angles of their inclination.

**Fig. 9** Dimensions of vortex granulator workspace at gas flow rate $Q = 1 \text{ m.cub/s}$: a – half of angle cone $\varphi = 10^\circ$; b – $\varphi = 13^\circ$; c – $\varphi = 16^\circ$.
The results of granules calculation process according to the model [34] are shown in Fig. 9 (Fig. 10 shows the qualitative experimental distribution of granules by fractions in vortex granulator-dryer). The analysis of these results allowed to make the selection of optimal design of vortex granulator-dryer and provided directional removal of fine particles before their removal with the exhaust gases. The results of theoretical calculations were confirmed by the results of computer simulation (Fig. 11), which showed clear granules separation into fractions in height of working unit of granulator-dryer.

For capturing dust and ammonia from exhaust gases we proposed to use inertial-filtering vortex separation section [32] and vortex tray with mass transfer and separation elements [33] (Fig. 12).

Due to vortex granular-dryer equipment with inertial-filtering vortex separation section (Fig. 13a) we obtained opportunity for inertial separation of granules of fine fracture and creating of vortex intensively water-air layer for hydro filtration of dust and gas flow absorption cleaning. Herewith energy of vortex gas flow from working volume was used, that allowed to utilize energy of waste (spent) heat transfer agent and to simultaneous use for efficient capture of fine dust particles in mechanisms of hydro filtration and cleaning the exhaust gas flow of waste heat transfer agent from additives of harmful gases through the absorption.

Integration of vortex mass transfer contact section with vortex tray with mass transfer & separation elements of into the vortex granulator-dryer (Fig. 13b) allowed to conduct the absorption cleaning of exhaust gases directly in volume of vortex granulator-dryer at passing of used coolant through the mass transfer & separation elements, in which ammonia vapors were captured by liquid.

The fractional composition of the product was significantly improved due to the process of classification and additional capturing of fine particles and dust in the mass transfer sections (Fig. 14).

Initial data for calculation of inertial-filtering vortex separation section and vortex tray with mass transfer and separation elements were:

- gas flow rate, its physical and chemical properties;
- fractional composition of dispersed phase in the exhaust gases;
- content of ammonia in the exhaust gases.

Calculation method of inertial-filtering vortex separation section was based on model [32].

The results of the calculation:
- consumption of absorbent;
- optimal diameter and height of inertial-filtering vortex separation section;
- required number of blades of swirler and its design concept.

Calculation method of vortex tray with mass transfer and separation elements is based on data of model [33].

The results of the calculation:
- consumption of absorbent;
- optimal diameter of vortex tray;
- required number of mass transfer and separation elements.

The results of experimental studies, which are presented in Figs 15 and 16, show the effectiveness of vortex granulator-dryer application in classification mode and vortex stages of exhaust gas cleaning from dust and ammonia.
The method of granulation in a vortex fluidized bed with the purification of spent heat transfer agent allowed:

- to distribute streams containing granules of fine fraction and dust in separate stages within one device for further treatment by different separation mechanisms;
- to separate the granules of the fine fraction from the flow of the spent heat transfer agent and turn them to the annular space between the cylindrical and conical shells of the working volume of device, and then to the granulation area for growing to the size of the product fraction;
- to use a zone of hydro filtration of spent heat transfer agent from dust with an intensively foamed water-gas layer with a high specific surface of phase contact.

Main advantages of the method:

- the energy of the vortex gas flow is used for the inertial separation of fine fraction granules and for the creation of vortex water-air layer;
- the utilization of spent heat transfer agent energy.

Conclusions

Proposed constructive solutions for fluidized bed dryers allowed to:

- provide of granules classification to the desired number of fractions with a simultaneous release and discharge of fine fraction from the working volume of dryer without the exhaust gases;
- increase the degree of monodispersity of commodity granules on 25–35%;
- reduce the amount of dust in the exhaust gases on 35–65%;
- reduce the ammonia content in the exhaust gas on 90–95%.

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Authors contributions NA created the background of research, carried out experimental study, summarized the results of the work, participated in drafting of manuscript and preparation of critical version. AA created the methods and methodology of experimental study and carried out the experimental research. All Authors have read the manuscript and have agreed to submit it in its current form for consideration for publication. All read and approved the final manuscript.

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Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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