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DEVELOPMENT OF A HIGHLY EFFICIENT COMBINED APPARATUS (A COMBINATION OF VORTEX CHAMBERS WITH A BIN) FOR DRY DEDUSTING OF GASES

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Розглянуто застосування пиловловлювачів нового типу, які поєднують принцип дії відцентрових і жалюзійних-вихрових апаратів. Розглянуто застосування гетерогенного реактора для систем газ-тверде з двома потоками, що знаходяться в циклоні, прямотангенційного циклону з камерою попереднього зіткнення газопилових потоків, а також вдосконалені конструкції вихрових камер.

Комбінований пиловловлювач представляється у вигляді вихровий труби Ранка в поєднанні з бункером, в якому встановлені жалюзійні-вихрові пристрої. Комбінований досліджуваний пиловловлювач забезпечує організовану подачу газодисперсної системи з регульованим гідродинамічним режимом в очисну споруду (апарат), в якості якого використовуються жалюзійні-вихрові пристрої. При цьому передбачається, що в вихровий трубі будуть проходити процеси коагуляції частинок при відповідних гідродинамічних умовах, а також частково деструкція шкідливих газових домішок в суцільній фазі. Таким чином розглянуто: створення для заданих початкових умов обґрунтованої фізичної моделі (конструкцій) комбінованого пиловловлювача; на основі теоретичних і експериментальних положень обґрунтована працездатність конструкції.

Встановлено, що найбільш перспективним напрямком для підвищення ступеня очищення газодисперсного потоку є створення гідродинамічних умов в відцентрових апаратах і в трубопроводах. Ці умови повинні забезпечувати подачу газодисперсної системи в відцентровий апарат, що забезпечують агломерацію дрібних частинок.

Таким чином, конструкції пилоочисного апарата, в якому передбачається інтенсивне зіштовхування частинок пилу в спеціальній камері і їх агломерація, а потім сепарація в камері, яка представляє собою фактично циклон, є доцільним і ефективним рішенням. Воно забезпечує ступінь очищення газопилового потоку, незалежно від розміру частинок, на рівні 98–99 %

Ключові слова: вихрова труба, гідродинамічні умови, ефективність очищення, пиловловлювання, комбінований пристрій, пиловий потік

1. Introduction

Significant amounts of dusty gases are formed in various industries because of imperfection of manufacturing methods of processing raw materials into target products as well as imperfections of manufacturing and auxiliary cleaning equipment. Industrial emissions cause product losses and reduce product quality. In many cases, emissions cause significant heat losses because of lack of utilizing heat of the gases emitted into atmosphere that dramatically worsens ecological situation.

Various methods and apparatuses are used for gas dedusting including apparatuses for dry cleaning of gas-dispersed systems: cyclones, vortex chambers, vortex tubes. These devices are intended to extract dust possessing various physicochemical properties from gases. They operate in a wide range of temperatures and pollutant concentrations. At the same time, because of imperfection of known designs of such apparatuses and insufficient development of theoretical foundation of processes, gas cleaning devices are unable to separate fine dust fractions from gas flows. For example, the TsN-15 cyclone practically does not separate dust particles smaller than 20 μm. Overall efficiency of trapping polydisperse dust particles does not exceed 70 % while hydraulic resistance reaches 1,000–1,100 Pa. Therefore, improvement of designs of the dry dedusting apparatuses with the aim of increasing their efficiency and reducing energy consumption are the urgent tasks.

2. Literature review and problem statement

A concept which considers in aggregate the design and processes taking place in the main apparatus was proposed in [1]. Dedusting, hydrodynamics and processes occurring in the gas-dispersed system moving in pipelines before entering the main apparatus as well as in the dust-product and cleaned gas outlet fittings were considered. However, the issues related to physicochemical properties of gaseous systems and design of the apparatus which would not «allow» coalescence of dust particles were left unsolved there. Development of a gas cleaning apparatus that would solve this problem could be an option of overcoming such challenges. A similar apparatus is described in [2]. However, the concept of supply and discharge of the gas-air flow was not taken into account in [3]. Namely such approach and a concept were considered in [4]. All this suggests that according to the concept, an integrated «input – cleaning process – gas removal» system was considered in aggregate with mutual influence taken into account.

Based on theoretical foundations of hydrodynamics and experimental results, it was shown in [5] that frequency of particle collision sharply grows because of the accumulation effect. Mathematical description of a swirling flow model was used in [6]. The study results are based on processing gas-dispersed systems containing various concentrations of dust having various physicochemical properties of particles. These can be CaO, $Ca(OH)_2$, ZnO, BaO, SiO_2; $NaHCO_3$ with particle sizes from 6 to 7 μm in fittings (pipelines) before entering the main apparatus. A developed turbulent flow and a dominant influence of energy vortices of a larger scale on relative velocities were considered in [7]. This statement allows us to conclude that the study of movement of a dusty gas stream inside the apparatus is advisable to be carried out in more detail. Particle collision frequencies depending on the Re number and values of the inertial parameter of particles were considered in [8]. It was found that tangential velocities of the carrier medium have the same structure as the Rankine vortex. As a result, it was established in [9] that during such processing, agglomeration processes occur with a 5–6 times increase in particle size due to the high speeds and intensity of collision of dust particles. Besides, it was stated in [10] that a possibility of physicochemical transformation of gas-dispersed impurities was established in a carrier flow of NO_x, SO_2, CO, HCl or HF type in the presence of an excess H_2O vapor or sprayed H_2O_2 and NaOH solutions at a sufficiently high temperature of a carrier gas-dispersed flow. However, it was stated in [11] that an excess amount of these substances at such a content of impurities and vapors corresponds to the stoichiometric ratio between reactants but the issues connected with the increase in collision frequencies were not solved there. It was considered and proved in [12] that a significant increase in frequency of particle collision can be achieved by increasing contribution of small dispersed vortices. These dispersed vortices are more likely to occur during collision of intensely rotating flows in chambers from which the combined flows enter the gas cleaning apparatus. Collision of particles and occurrence of vortices was also considered in [13] which makes it possible to state feasibility of conducting studies in this direction.

It can be assumed that when designing an efficient apparatus for dry cleaning of a dust-dispersed system, it is advisable to unite flows in a chamber like one discussed in [14] where intensely rotating flows were colliding in an apparatus in which the well-known principle of dry cleaning (cyclone or vortex chamber) was implemented. The process of dry cleaning with formation of rotating flows was described in more detail in [15]. The field of flow velocity in a vortex chamber was experimentally studied by measuring movement of particles suspended in a liquid. It was shown that the swirling flow in the chamber is rotationally symmetric. Using measurements of the axial velocity component, a complete pattern of this flow lines in the axial section of the chamber was obtained. It was shown that when entering the chamber, the flow of liquid twists and spreads axially over the chamber wall in a form of thin annular flows to both sides of the inlet channel. The study of two-phase flows was continued, a new approach to the theory and practice of two-phase systems based on the global invariant, entropy, and other invariants was formulated and experimentally confirmed in [16].

The study [17] focused on dust characteristics. This work has more fully described and complemented the issue solution with the study of physicochemical characteristics of dusts like it was considered in [6]. Two different types of dust were studied in [17]: cyclone aluminum dust and aluminum dust. Dust characterization was performed using analysis of particle size distribution, chemical analysis, X-ray diffraction and differential thermal analysis. The results have shown that the base of the studied dusts was different and that both dusts should be treated as hazardous wastes. In the case of disposal, they should be disposed after removal of water-soluble phases at appropriate disposal tips prescribed by regulations. The result has confirmed feasibility of development of a highly efficient gas cleaning apparatus that will provide highly efficient cleaning of industrial gaseous emissions. It was once again proved in [18, 19] that it is necessary to conduct studies of dry and other technological processes occurring in a vortex tube.

Proceeding from the analysis of methods for dry separation of two-component gas systems, the following can be stated. Processes of separation by mechanisms of inertial separation are insufficiently studied in the aspect of hydrodynamic flows in devices with a field of centrifugal inertial forces. The issues connected with physicochemical properties of gaseous systems and design of the apparatus itself which would not allow dust agglutination remain unsolved till now.

3. The study objective and tasks

The study objective was to substantiate and develop design of a dedusting apparatus which will be a combination of a reaction chamber enabling intensive collision of dust particles and their agglomeration and a separation chamber in a form of a direct-flow cyclone.

To achieve this objective, the following tasks were solved:

– to study hydrodynamic characteristics of the separation chamber of the gas-cleaning apparatus;

– to prove effectiveness of the process of cleaning the gas-air flow and operability of the proposed design;

– to conduct an experimental study of operation of the proposed design of the combined dedusting apparatus. Prove that dust separation efficiency reaches 94–98 % depending on physicochemical properties of the dust.

4. Studying the hydrodynamic characteristics of a gas cleaning apparatus

Let us consider one of the options of such an approach to development of an innovative design of a dust cleaning apparatus. Schematic diagram of a multipurpose single-stage heterogeneous reactor is shown in Fig. 1, 2. The reactor shown in Fig. 1 includes the following elements:

– reaction chamber for collision of counter rotating gas-dispersed flows;

– section A–A of the reaction chamber;

– curvilinear channels of a half-torus shape;

– centrifugal supercharger pump for the gas-dispersed system;

– input of the gas dispersed system;

– inlet fittings for water vapor or injected reagent solution;

– vane swirler of the outgoing flow;

– housing of the chamber for deposition of dust particles and release of the cleaned flow which consists of a takeoff tube for a clean gas flow with a coaxial insert;

– fittings for removal of the deposited dust.

Diameter of the tube 5 (D_1) is assumed to be the same as that of ordinary cyclones and is 0.6D (diameter of item 4), ratio of the tube (5) length to diameter D is 4÷6. In the zone of a limited height H_1, a stable swirling flow is formed around the coaxial insert (6) having an annular volume. This volume is saturated with dust particles and moves in the annular gap between (4) and (5) and the axial dedusted flow moves in the annular gap between the tube (5) and the coaxial insert (6).

A–A section view is shown in Fig. 2.

Height of the zone $H_1=f(\text{Re})$ after item (3) and at $\text{Re}\geq 10^4$ was approximately taken $H_1\approx(0.8\div1.2)D$. Diameter of the reaction chamber (1) was taken to be $D_2=0.8D$, the S gap between cylindrical surfaces (5) and (4) was taken $(D-D_1)/2$. Due to the vortex motion of the gas-dust flow in the cylindrical part of the reactor in the reactor volume determined by the height H_1, the dust layer does not occupy an elementary annular volume near the deposition surface but has a certain thickness. This thickness depends on certain factors: local secondary excitations, interaction of particles, change of the particle trajectory due to collisions with the wall (item 4), etc. The larger the S value, the more completely this value covers the dust layer. Organization of the purified gas (axial) flow entering tube 5 inside which the coaxial insert 6 is installed provides protection, that is, dramatically reduces intensity of penetration of vortices to the deposition surface (item 4). In the zone of separation of flows (the annular flow of the dust layer and the axial cleaned flow), occurrence of a vortex transition flow Q_2 is possible with its takeoff provided by the item 9. The Q_2 flow is directed to the bin for deposition. Schematic diagram of the reactor connection is shown in Fig 3.

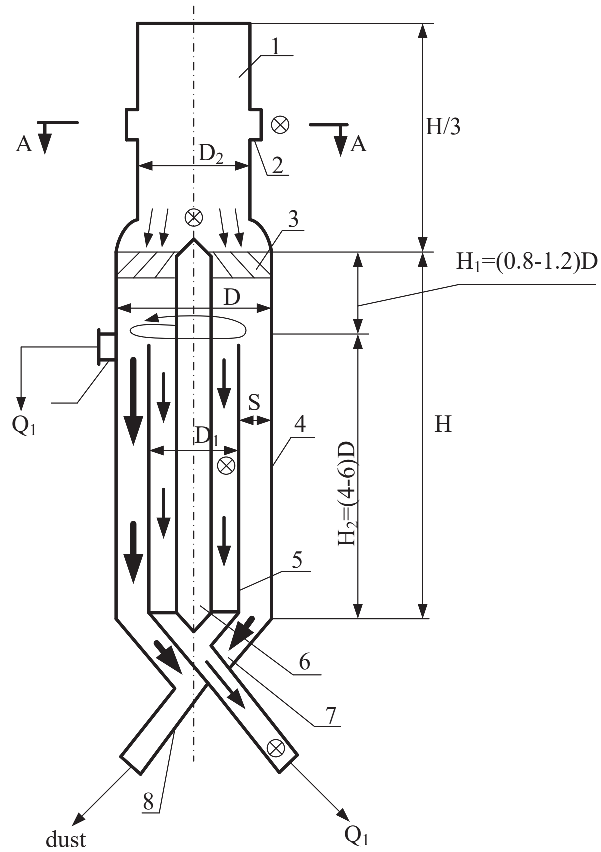

Fig. 1. Multipurpose single-stage heterogeneous reactor: reaction chamber for collision of gas-dispersed counter flows (1); gas supply fittings (2); vane swirler (45° blades) (3); housing of the deposition chamber (4); tube (5); coaxial insert (6); cone (7); fitting (8); takeoff (partial) of the flow disturbed during separation of the dust layer and the axial flow (9); ⊗ are sensors for measuring parameters of the vortex gas flow and gas sampling

Studies have been carried out with this pilot unit to determine aerodynamic characteristics, hydraulic resistance and dedusting efficiency of the reactor. Distribution of pressures and velocities directly in the reaction chamber (1) (Fig. 1) was not studied since the well-known experimental and theoretical studies of the processes in the reaction chamber (1) are fairly fully and reasonably given in [1–6]. When conducting studies in the separation section of the reactor, magnitude of pressure gradient and parameters of the vortex gas flow were measured using a cylindrical sensor which is the simplest in calibration and operation. Inductive (cylindrical) pressure and speed sensor has an electromechanical design based on movement detection with an anchor connected to the piston or membrane. The force resulting from the pressure of a liquid or gas balanced by a spring actuates the anchor to take a certain position. Information is transformed into the form of an electronic signal transmitted to the instrumentation or control system. The pressure sensor (pressure gradient transducer) is used to measure gas flow rate using narrowing devices, i. e. the pressure sensor here acts as a flow meter. When operated, the sensor transmits information as a digital signal. The sensor measurement log was formed automatically. Sapfir sensors produced by Manometr LLC, Russia, were used for measurements.

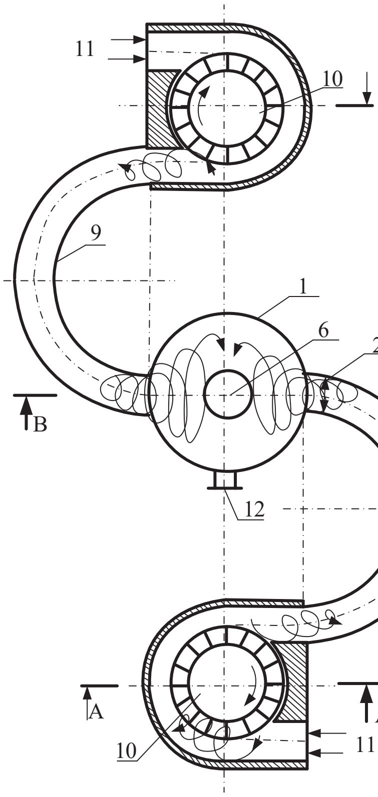

Fig. 2. A–A section view:
1 – corresponds to item 1 in Fig. 1; 2 – corresponds to item 2 in Fig. 1; 6 – corresponds to item 6 in Fig. 1; 9 – curvilinear channels of a half-torus shape; 10 – centrifugal dust injecting pump; 11 – gas-dispersed system inlet

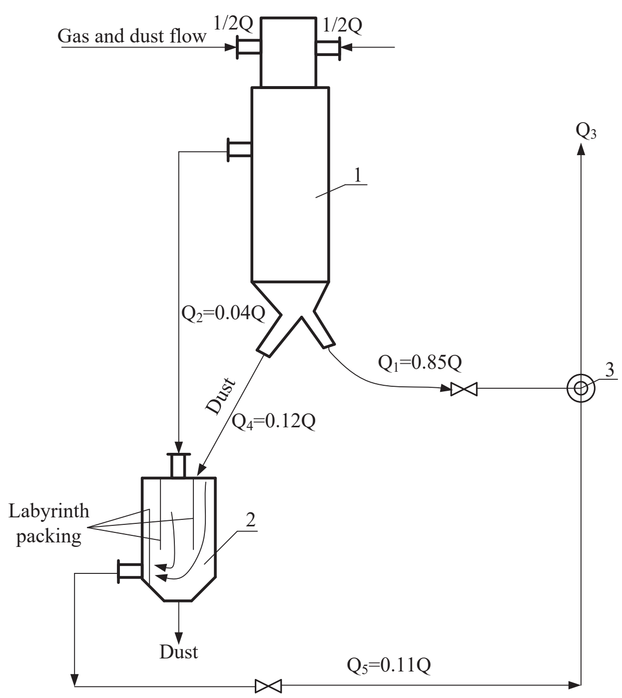

Fig. 3. Schematic diagram of connection of the reactor: heterogeneous reactor (1); dust collecting bin (2); Q_5 inflow ejector (3); Q is the total flow rate into the reaction chamber; Q_1 is the cleaned axial flow; Q_2 is the transitional vortex flow; Q_3 is the generalized purified gas flow into atmosphere or for further consumption; Q_4 is the dust flow into the bin

Dust concentration must be controlled in technological processes, therefore ProSens dust level sensors, Russia, were used in the studies.

Principle of operation of the dust sensor is as follows: a sensitive element in a form of a metal rod is placed in the pipeline. Dust particles in the air flow contacting with the rod generate a small electric charge which, in turn, results in appearance of an output current signal of 4–20 mA. Then, the current signal is electronically converted to a digital signal used for tracking dust concentration. Raise of the signal means that the filter is faulty. It was proved during the tests that this method of measuring the dust level is the most effective, produces accurate results with a minimal error and does not require large investments of time, effort and money for maintenance. The obtained data are sent to the data processing module which operates via RS-485 protocol and can be installed remotely. The data are obtained in a digital form.

Diameter of the working part of the sensor cylinder was $3{\cdot}10^{-3}$ m. Dust content in flows was measured using a sampling tube with internal filtration. Measurement of dust particles and determination of their structure at unloading from the conical part of the reactor were carried out using UEMV-100 electron microscope, Sumy, Ukraine. The dust structure is shown in Fig. 4, where it can be seen that dust does not stick together.

In order to qualitatively confirm formation of an annular volume of dust particles near the deposition surface (4), photo and video equipment was used in time-lapse filming and enlargement of images of movement of the swirling flows taken downstream the swirler (3) at height H_1 in section $H_1/2$.

The gas-dust flow (continuous air phase + dispersed phase) was cleaned at a flow rate from 0.4 to 1.1 m^3/s in the gas supply fitting (2), Fig. 1. The following materials were used as the dispersed phase: ZnO with particle size of 0.3–10 μm, specific surface of ~8 m^2/g, $\rho=5{,}700$ kg/m^3 and CaO with particle size of 5–30 μm, specific surface of ~1 m^2/g, $\rho=2{,}930$ kg/m^3. Concentration of the dispersed phase in the stream was 10 g/m^3. Air was used as the continuous phase with $\rho=1{,}205$ kg/m^3 at temperature of 303 K. ZnO and CaO dust was used in the study because processes of limestone burning, lime processing and production of various fillers are common in the Ukrainian industry. Main studies of air-dispersed systems were performed using ZnO, CaO, etc. aerosols.

5. The results obtained in experimental studies with the use of a combined apparatus

Qualitative pattern of the process of distribution of dust particles and carrier medium in the gas-dispersed flow was observed at the reactor diameter $D=1.5$ m in flows of a gas-dust system before entering the swirler (3). The process was observed using photo and video equipment in front of entrance to the separation section of the reactor (Fig. 4) at the process speed of 0.4÷1.1 m^3/s. According to the results of observations with the help of slow-motion photography, qualitative pattern of distribution of dust particles in a gas-dispersed flow was obtained.

The photograph in Fig. 4 demonstrates a pronounced annular volume of the concentrated dust layer and a darkened axial flow of the carrier medium almost devoid of dust particles. The coaxial insert is also seen. Obviously, trajectory of dust particles is displaced to the outer wall of the reactor under the action of inertial force and then removed along the cylindrical annular channel formed by the reactor wall (4) and the outer surface of the tube (5). The axial flow is removed along the cylindrical annular channel formed between the inner surface of the tube (5) and the coaxial insert (6). This pattern of movement of particles and the carrier medium both in the vortex tubes and in various shaped elements of gas reactors was theoretically substantiated and experimentally confirmed. Separation capacity in the separation section itself, that is, in the abovementioned channels and the bin is determined by hydrodynamic features of motion of corresponding flows in the channels [19].

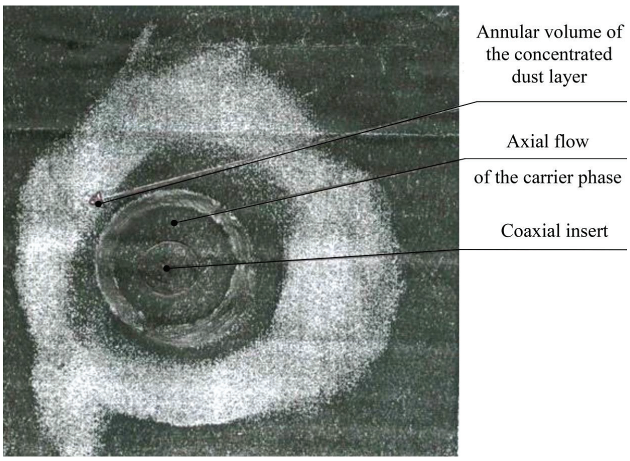

Fig. 4. Qualitative pattern of distribution of dust particles and the carrier medium in the gas-dispersed flow before entering the separator

Pattern of distribution of the flow velocity along the annular dust takeoff channel is shown in Fig. 5.

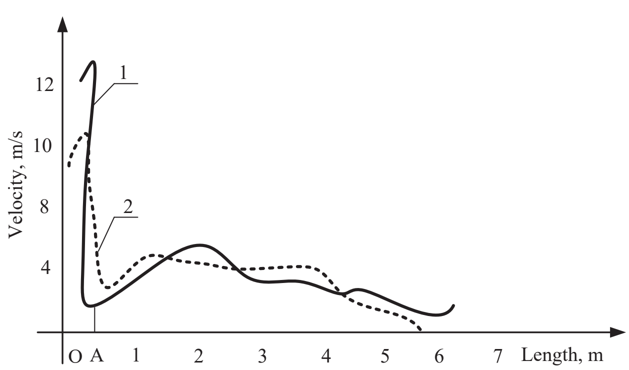

Fig. 5. Distribution of flow velocity along the annular dust takeoff channel: flow rate of 1 m^3/s (1); flow rate of 0.4 m^3/s (2); O—A zone: formation of a concentrated dust layer; O: the section immediately downstream the swirler

As follows from Fig. 5, flow velocity in the considered channel after formation of flows did not fall below 3.5÷4.0 m/s. The obtained data met requirements of [14] and exclude the channel blockage by depositing particles.

Distribution of static pressure in the cross section of the separation section of the reactor is shown in Fig. 6.

A conclusion can be drawn from the above graph on the prevailing energy costs in the central section of the channel system, that is, in the axial flow channel. Pressure loss exceeded 300 Pa in the curve segments 0÷0.375 and 1.25÷1.5. The segment 0.375÷1.1 corresponds to the central section, that is, the annular channel in which the cleaned axial flow moves. In this zone, the axial flow had the same structure as the Rankine vortex [1, 3, 4, 5] at assumed flow rates of the gas-dust flow. Therefore, pressure losses in this area were 1.5–2 times greater than in other zones and measured 500 Pa. Total aerodynamic resistance of the separation section of the reactor was 452 Pa at a flow rate of 0.4 m^3/s and 754 Pa at a flow rate of 1.0 m^3/s. Coefficient of hydraulic resistance, ξ, varied from 16 to 25, respectively, which is a characteristic value for conventional cyclones with pressure gradient $\Delta P = 600 \div 1{,}000$ Pa. Main technical parameters of reactor operation for the gas-dispersed flows under study are given in Table 1.

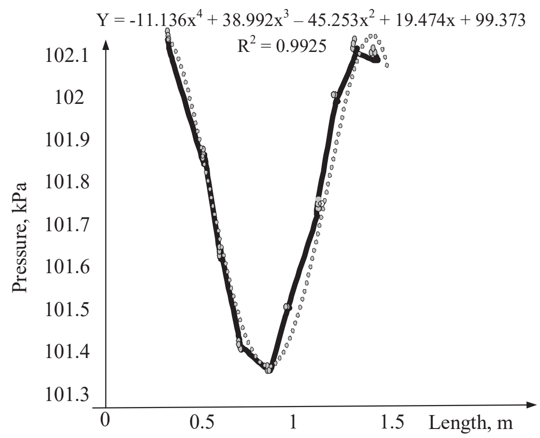

Fig. 6. Static pressure distribution in the cross-section of the separation section of the reactor

Table 1

Main technical parameters of reactor operation when using the gas-dispersed systems under study

Parameter	Presence of Q_2 flow	
	Yes	No
Temperature of the gas-dispersed flow at the inlet, °C	30	30
Gas flow rate at the inlet, m^3/s	0.4	0.4
Gas flow rate at the exit, m^3/s	0.41	0.41
Dust content in gas at the inlet, g/m^3	10.0	10.0
Dust content in gas at the exit, g/m^3	0.2–0.25	0.3–0.6
Aerodynamic resistance, Pa	500.0	470.0
Coefficient η of dust separation for various types of the dispersed phase. Growth of average particle size, Mα, on the exit from the reaction chamber:		
ZnO: from 0.3 to 10 μm; η, %	98.0	97.0
CaO: from 5 to 30 μm; η, %	97.5	94.0

The following materials were used as a dispersed phase: ZnO with particle size of 0.3–10 μm, specific surface of ~8 m^2/g, $\rho = 5700$ kg/m^3 and CaO with particle size of 5–30 μm, specific surface of ~1 m^2/g, $\rho = 2930$ kg/m^3. Concentration of the dispersed phase in the flow was 10 g/Nm^3. Continuous phase: air, $\rho = 1205$ kg/m^3 at temperature of 303 K.

As follows from the data given in Table 1, when organizing the Q_2 flow, the dust separation coefficient, η, increases which confirms expediency of taking a part of the vortex flow when it is distributed among channels.

6. Discussion of the results obtained in studying the process of cleaning the gas-air flow

Proceeding from analysis of the methods used for dry separation of two-component gas systems, the following was found. As concerned the mechanisms of inertial separation, separation processes are insufficiently studied in the aspect of hydrodynamic flows in devices with a field of centrifugal-inertial forces. The mechanism and conditions for separation of dust particles with sizes less than 10 μm in this field were not studied as well. This has led to the fact that the known designs of centrifugal dust collectors (cyclones, vortex chambers, rotoclones) provide cleaning below 80 % for polydisperse systems. It has been established that creation of such hydrodynamic conditions in centrifugal devices which ensure supply of a gas-dispersed system to the centrifugal apparatus is a promising way to improvement of the degree of cleaning a gas-dispersed flow ensuring agglomeration of small particles. Such conditions can be achieved if the dust collector design will include a pretreatment zone in addition to the design of conventional centrifugal devices to correspond to hydrodynamic and design parameters. Then, intense vortex flow and collision of dust particles will be observed in the vortex zone.

A mechanism for separation of fine particles from a gas-dispersed flow was proposed. It has been established that due to a change in magnitude and direction of the averaged velocity, micro-inertial forces arise perpendicular to the separator walls caused by small-scale vortices of high intensity. With a decrease in the scale of pulsations and their acceleration, sufficiently large micro-inertial forces appear. They ensure movement of the liquid fraction to the separator walls.

Proceeding from the results of observations, a qualitative pattern of distribution of dust particles in the gas-dispersed flow was obtained. A pronounced annular volume of a concentrated dust layer and a darkened axial flow of the carrier medium practically devoid of dust particles were obtained with the use of a coaxial insert. Under the action of inertial force, trajectory of dust particles is shifted to the outer wall of the reactor and then taken off along the dynamic annular channel.

According to the data obtained, it was established that the flow velocity in the channel under consideration does not fall below 3.5÷4.0 m/s after formation of flows. The data meet requirements to the gas-air flows necessary to exclude channel blocking by deposited particles.

Thus, the results of experimental studies have shown that purposeful pretreatment of the gas-dispersed flow before entering the gas cleaning apparatus (passing the gas-air flow through the reaction chamber where flows collide and particles coarsen) significantly improves efficiency of dust particle collection up to 97–98 % compared to the cleaning efficiency of conventional cyclones (80–85 %). Also, pretreatment of the gas-dispersed flow before entering the apparatus makes it possible to expand functionality of the apparatuses for dry cleaning of gas-dust flows. The experimental results obtained do not contradict the well-known theoretical approaches describing frequency of collision and agglomeration of inertial particles in a developed turbulent flow. The results have shown that the h value was in the range of 97–98 % and the dust unloaded from the reactor bin was an agglomerate of 25–35 μm particles. Also, the experimental results do not contradict the known experimental results of kinetics of interaction of gaseous impurities in a developed turbulent flow. With an increase in gas velocity in the absence of particles in the gas flow, turbulence increases and leads to formation of a vortex motion. Introduction of particles into a moving gas leads to a partial conversion of this energy into kinetic energy of particles instead of increasing turbulence. Therefore, pressure gradient in the presence of particles in the flow may be lower than in their absence at high velocities of the gas flow.

7. Conclusions

1. Hydrodynamic characteristics of the separation chamber of the gas cleaning apparatus were studied. Turbulence increases and leads to formation of a vortex motion when gas velocity increases in absence of particles in the gas flow. It has been established that the flow velocity in the channel in question did not fall below 3.5÷4.0 m/s upon formation of flows. It has been found that the dust separation coefficient reached 97–98 % depending on physicochemical properties of the dust.

2. Design of a dedusting apparatus which is a combination of a reaction chamber providing intense collision of dust particles and their agglomeration and a separation chamber in a form of a direct-flow cyclone was proposed.

3. The results have shown that the h value was in the range of 97–98 % and the dust unloaded from the reactor bin was an agglomerate of 25–35 μm particles. Application of the proposed design in separation systems is expedient and requires further studies in this direction.

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