Проведеними дослідженнями по оцінці впливу введення в малоефективний циклон додаткової «обвідний» труби, що з'єднує вхідний патрубок циклону і вихлопну трубу, встановлені механізми причин підвищення енергоефективності процесу очищення повітря від пилу. Доведено, що зростання ступеня очищення пояснюється зниженням радіальної швидкості потоку під вихлопною трубою циклону. Зниження гідравлічного опору пояснюється зниженням швидкості потоку у вхідному патрубку при роздільному введенні повітря в корпус-через вхідний патрубок і «обвідну» трубу. Експериментальними дослідженнями підтверджено, що при введенні в конструкцію циклона «обвідний» труби в найбільш небезпечної для виносу пилу області циклону (під вихлопною трубою), знижується негативно впливаючи на очистку радіальна швидкість газового потоку. Це призводить до підвищення загального ступеня очищення від пилу.

Результати аналітичних розрахунків і комп'ютерного моделювання програмою «SolidWorks-2009» експериментально підтверджені при дослідженні ефективності уловлювання пилу сухого знежиреного молока в промисловому циклоні (діаметром 630 мм) з «обвідний» трубою. Такий циклон встановлений в системі пневмотранспорту розпилювальної сушарки «ЦТ-500» Ічнянського заводу сухого молока і масла (Україна).

Зокрема встановлено, що при цьому винесення пилу знижується практично в два рази, гідравлічний опір– на 15 %, а енергоефективність циклону з «обвідною» трубою підвищується, практично, в 2,43 рази.

Таким чином, є підстави стверджувати про можливість значного підвищення енергоефективності циклону з «обвідною» трубою.

Завдяки цьому з'являється можливість оцінки підвищення енергоефективності циклону ще на ранніх стадіях проектування

Ключові слова: циклонний пиловловлювач, «обвідна» труба, CFD-моделювання, ступінь очищення, гідравлічний опір, енергоефективність

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IMPROVING THE ENERGY EFFICIENCY OF CYCLONE DUST COLLECTORS

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1. Introduction

The issue of air pollution with finely disperse dust (mostly of industrial origin) has become increasingly urgent over recent decades. At the same time, the aggravation of the ecological state of the air environment is clearly observed in the urban zone, that is, in places of a congestion of a huge number of people.

The emissions of suspended substances amount to hundreds of thousands of tons, and not all of them are cleaned up at industrial plants. In the scientific literature, fine dust now mostly implies the particles less than 10 μm in diameter, which, according to the latest data from the World Health Organization, causes maximum harm to human health and the biosphere in general [1].

Given the imperfection of technological and auxiliary cleaning equipment, the imperfection of the processes of recycling raw materials into targeted products, significant volumes of dust gases are formed in various sectors of industry. In this case, the poor efficiency of cleaning such emissions leads to the loss of the product, deterioration of the quality of the products received and a sharp deterioration in the environmental situation.

Various methods and devices are used to clean the gases from dust, including apparatuses for dry cleaning of gas dispersed systems. The most common and promising modern industrial method of protecting the atmosphere is cleaning the dusty gases in dry cyclones.

These devices are used to capture dust gases with various physical and chemical properties; they operate in a wide range of temperatures and concentrations of pollutants. At the same time, due to the imperfection of known cyclone structures and the lack of development of theoretical foundations of processes, gas treatment structures are unable to capture small fractions of dust from gas streams. For example, one of the most common cyclones, CH-11, at a hydraulic resistance of 1,000–1,200 Pa, captures dust measuring less than 10 μm with an efficiency of up to 40 %, and the overall efficiency of capturing polydisperse dust particles does not exceed 80 %.

Therefore, it is a relevant task to improve cyclone designs in order to improve their cleaning efficiency and reduce energy costs for the cleaning process.

2. Literature review and problem statement

Despite the nearly 140-year history of cyclones, the world is continuously improving the design of cyclone dust collectors, capable of effectively, and with minimal cost, to capture fine dust. Therefore, improving the energy efficiency of cyclones is one of the most pressing environmental challenges [1].

To date, many studies have been conducted around the world to improve the energy efficiency of cyclones and new improved cyclone designs have been proposed.

Work [1] describes a cyclone with an additional chamber to collect tangential dust in the conical part of the structure. According to the authors, this would increase the efficiency of capturing fine dust particles (<6 µm). The results of numerical modeling showed that when the hydraulic resistance of the cyclone increased by 8 %, particles with a diameter of 3 µm are 50 % are more efficiently captured.

The drawback of the cited work is the increased cyclone resistance and the lack of tests under industrial conditions.

It is shown in [2, 3] that the suction of gas from the vortex duster bunker with oncoming swirling streams can reduce dust removal by more than 3 times and increase dust cleaning efficiency. The disadvantages of such modernization include the need for additional equipment, a lower diameter duster and an additional fan to suck gases from the bunker.

Study [4] reports the results of the tests of a typical helix cyclone "CN-15u-300" and a patented cyclone with the reverse cone "COK-200-300" that makes it possible to regulate the depth of the exhaust pipe dive. It is shown that the resistance of "COK-200-300" is 2–2.2 times less than that of the conventional cyclone "CN-15u-300", and the efficiency of dust capture up to 5 µm increases by about 5–20 %. The disadvantages include the fact that the cited work uses the design of a cyclone, which is not able to highly effectively separate the two-phase flow from particles with a diameter of less than 5 µm.

The main method of reducing wind-dynamic resistance of cyclones is to install different kinds of stream straighteners in the exhaust pipe. Thus, the authors of work [5] examined the indicators of cleaning of the vortex cyclone apparatus with a diameter of 0.4 m, installed in the exhaust pipe, and, after it, various stream straighteners, and, most importantly, under the same industrial conditions. Dolomite dust was used with an average median particle diameter of $d50$=18 µm and a density of 2,100 kg/m^3. It is shown that the stream straighteners (a conical blade, screw-blade, ring diffuser, in the form of a drop on the end), installed both in the exhaust pipe and after it, lead to a deterioration in the efficiency of cleaning the vortex duster. And only for the stream straightener of the helix type the removal of dust decreased, on average, by 1.5 times with the hydraulic resistance decreased by 11 %. The drawback of the cited work is that the results were obtained only for the tested design of the vortex cyclone apparatus.

In [6], gas purification, with temperatures of up to 130 °C and at a high initial concentration of dust, is proposed in a single complex gas treatment device – in a cycle filter combining a cyclone and a sleeve filter. This combination of cleaning methods in a cyclone at sharply different airspeeds (at an average speed in a cyclone up to 5 m/s, and in the sleeve filter – at a speed about an order of magnitude less) seems insufficiently reasonable.

The centrifugal filter, termed a cyclone with feedback, is significantly superior in its purification efficiency to all known cyclones [6]. Obviously, this is due to the implementation in the design of the device of gas speeds exceeding by several times the average speed of gas in conventional cyclones, as well as the absence of dust removal, characteristic of cyclones, from the exhaust pipe of anti-current cyclones. This is confirmed by the widespread introduction of cyclones with feedback in various industries [6].

The disadvantages of such dust collectors, obviously, include the complexity of the manufacture of centrifugal filters and the need to replace inefficient cyclones.

It is proposed in [6] to increase the efficiency of dust capture through a low-cost modernization of any type of a cyclone by using a two-body structure. It is assumed that, due to centrifugal forces, heavy dust fractions are concentrated at the wall of the inner body with slits on the first third of the cyclone's circumference.

According to the authors, this modernization of any cyclone apparatus makes it possible to reduce the emissions of dust particles by 2 or more times without increasing the cost of energy for purification. The disadvantage is obviously the lack of data on the variability of captured dust, the possibility of its implementation only in the manufacture of cyclones and the need to replace low-efficiency cyclones with new equipment.

In [7–10], the studies were carried out of the experimental-industrial centrifugal inertial dust collector-classifier with a spinning device with a capacity of up to 4,000 m^3/h, allowing for the redistribution between centrifugal and inertial forces. It was shown that the efficiency of cleaning from fine dust (an iron oxide pigment with a median diameter of 8.5 µm) is approximately equal to 60 %. However, if one compares it with the efficiency of cyclones for dust <10–20 µm, it is noted that cyclones either do not catch such dust (<10 µm) or catch dust with a diameter of 10–20 µm with an efficiency of 20–40 % [7, 8]. Similar efficiency of cleaning from fine dust was noted in foreign analogs [9, 10]. The disadvantages of the centrifugal-inertial dust collector-classifier include the complexity of manufacturing, increased additional costs for the manufacture and installation of a new cleaning system.

The authors of work [11] used numerical modeling methods to investigate the effectiveness of battery-powered cyclones. In the cited study, a single cyclone separator was divided into three sections. Each section consists of different diameters, decreasing from the top of the cyclone to the bottom. It is shown that the first cyclone separates particles with a diameter of 4.5...11.0 µm, the second stage captures dust particles measuring 3.4...7.9 µm, and the third collects particles ranging in size from 1.8 to 4.3 µm.

The drawback of such modernization is that the use of battery cyclones increases hydraulic resistance compared to a single cyclone, as well as the need to manufacture new cyclones.

In [12], numerical methods were employed to investigate the dependences of the length of the conical part of the cyclone on the efficiency of the separation of dust-gas flows. The calculations showed that in order to increase the efficiency of the separation of dust particles measuring 3 µm by 9.5 % and to reduce hydraulic resistance by 34 %, it is necessary to increase the length of the conical part of the cyclone by 5.5 times. The disadvantages include the lack of industrial verification of the method of modernization, the increased metal consumption, and the need to produce new cyclones.

A multi-channel cyclone reported in [13] is of interest, the distinctive feature of which is the possibility to change the ratio of air dust mixture as the separator passes within the peripheral (return-incremental) and transit (moving to a new channel) streams. The highest value of purification efficiency in a three-tier six-channel cyclone at a flow rate of 16 m/s for dust particles less than 20 μm (wood ash) was 92.8 % and 95.1 % for dust particles up to 50 μm (granite dust). The disadvantage is the need to make new cyclones.

A multi-channel cyclone made of unalloyed material with an airflow consumption of 40,000 m^3/h was examined in [14] when capturing lignin with a dispersity of 3 μm, the humidity of at least 95 % at elevated temperatures (50–75 °C). Despite the high degree of dust purification of lignin, the internal "stuffing" of the cyclone was destroyed by temperature and humidity. The disadvantage is the need to fabricate cyclones from expensive materials.

Work [15] shows that the new swirling element in the separator design, compared to the traditional element of the vortex dust collector, contributes to an increase in overall efficiency. Thus, the purification increased by 2...3 % and the hydraulic resistance decreased by 30 %. The drawback is the lack of data on dust dispersal and the need to manufacture new equipment when replacing low-efficiency cyclones.

The increase in centrifugal forces in vortex dust collectors, according to the authors of work [16], contributes to the additional swirling of the dust flow near the walls of the apparatus. This increases the separation factor of a two-phase flow, and the cleaning of the contaminated mixture is more efficient. The drawback is the lack of data on dust dispersal and industrial research into the proposed method of modernization.

The effect of different types of twisters on the efficiency of separating a two-phase vortex separator flow at the smallest hydraulic resistance was studied in [16].

The study showed that when using a cap that swirls the flow to the right side, as well-angled shoulder blades, the degree of cleaning increases. Thus, at a minimum drop in pressure, the degree of cleaning from dust exceeding 10 μm was 99 %.

The shortcomings of the cited study include the lack of data on purification from dust less than 10 μm and data on industrial tests of the proposed method of modernization.

The possibility of returning thin fractions of dust back to the cyclone was investigated in [17]. This gives the dust particles caught in the secondary stream an additional chance to re-pass through the centrifugal force field inside the cyclone and improve their cleaning efficiency.

The efficiency of dust capture with a diameter of up to 5 μm, owing to the special design of the dust collector outlet branch pipe, increases by about 5 and 20 % at the dust flow speed, respectively, 12.25 and 10.5 m/s.

The drawback is the lack of data on industrial tests of the proposed modernization method and the fact that a low-efficiency cyclone was used, unable to highly effectively separate the two-phase flow from particles less than 5 μm in diameter.

In [18], a method for increasing the energy efficiency of a baking cyclone heat recovery unit (6.25 m in diameter) of a rotary kiln in cement production, in which the exhaust pipe is eccentrically displaced relative to the cyclone axis, was considered. The parameters of the cleaned gases and dust were as follows: gas temperature 800 °C, dust density 2,500 kg/m^3, gas speed in the inlet branch pipe 17 m/s. It is shown that when the magnitude of the exhaust pipe axis shifts relative to the axis of the cyclone by 100–200 mm (1.5–3 % of the diameter of the cyclone), the removal of dust from the cyclone decreased by 2 times. The hydraulic resistance of the cyclone decreased by 5.4 %, and the energy efficiency of the cyclone increased by about 2.1 times. The drawback of this modernization is the lack of information about the dispersibility of the captured dust, as well as the possibility of its implementation only in the manufacture of a cyclone.

A method for increasing the efficiency of cyclones by reducing the removal of dust (a diameter of 4.5 μm) from the cyclone by 5 or more times, depending on the dispersibility of dust, is proposed in [19]. This result is achieved by improving the degree of dust particulate treatment in cyclones by using various turbulence generators at the jet section. The advantage of this modernization technology is the ability to implement it in cyclones operating in various industries without replacing them with new, more efficient, but also more expensive dust-trapping equipment. The drawback of such modernization is a certain increase in energy costs to overcome the hydraulic resistance of cyclones.

Thus, based on our analysis of existing methods of modernization of cyclone dust collectors, it is very useful to further develop new technologies to improve the energy efficiency of inefficient cyclones – without replacing them with new ones.

That is why, since the beginning of the 21st century, there has been a dramatic increase in the number of scientific studies around the world aimed to improve the energy efficiency of cyclone dust collectors [1].

However, the scientific literature contains almost no studies by different authors on the possibility of applying, to improve the efficiency of cleaning and reduce hydraulic resistance, the effect of impacting streams of purified air. That is, there are no works on implementing, in the cyclone, the principle of "coherence" in the collision of two mutually divergent streams of dusty air or gases. Our paper is aimed at filling such a gap in the theory and practice of cyclone dust treatment. A series of studies have been carried out to justify the prospect of using the principle of "coherence" in cyclones when two mutually divergent streams of dusted air or gases collide. Thus, the principle of creating a phenomenon of "coherence" in a cyclone was devised when two mutually divergent streams collide [20] and the optimal values of the main parameters that affect cleaning and hydraulic resistance were determined. These parameters included the size of a "bypass pipe" and its location in the cyclone body, the efficiency of cleaning and hydraulic resistance of the cyclone with a "bypass" pipe. Therefore, the task has been set to develop and experimentally test a new method of cyclone modernization in order to improve dust cleaning efficiency and reduce hydraulic resistance, that is, improving the energy efficiency of cyclones. That would not require replacing low-efficiency cyclones with new, more efficient, but more expensive, dust collectors.

3. The aim and objectives of the study

The aim of this study is to improve the energy efficiency of the cyclone with an additional "bypass" pipe connecting the inlet branch pipe with the exhaust pipe of the cyclone, providing an intense collision of dust particles in front of the exhaust pipe, reducing radial velocity, hydraulic resistance and increased degree of purification [20].

To accomplish the aim, the following tasks have been set:

– to assess the impact of the introduction of an additional "bypass" pipe into the design of the cyclone on an increase in the degree of air purification from the dust of skimmed milk powder;

– to establish the optimal size of a bypass pipe and its location in the cyclone body;

– to establish the optimal ratio between the airflow rate through the inlet of the cyclone and the "bypass" pipe.

4. Materials and methods to study the impact of a "bypass" pipe on improving the energy efficiency of the cyclone dust collector

We assessed the impact of the introduction of a "bypass" pipe in the design of a cyclone on improving the energy efficiency of the cyclone of air transport based on the results of analytical calculations, computer simulations, and industrial tests. At the same time, the energy efficiency indicators of the conventional cyclone model and the modernized one with a "bypass" pipe were compared. The tests were conducted in accordance with the requirements in [21] and with the participation of the research team of Donaldson (USA).

We measured air pressures and velocities using two Pitot pneumometric tubes [22] and two Testo-521 differential gauge meters (Germany) with a built-in pressure sensor to measure flow speeds ranging from 5 to 100 m/s [23].

When measuring speeds from 1.5 to 40 m/s, the margin of error is no more than 3 %; the average dynamic (speed) conversion factor over the entire velocity range for the Pitot pressure differential tube is 0.95–1.05 [25].

The dispersibility and concentration of dust were determined by the eleven-stage impactor NIIOgaz directly in the airflow. The substrates used at the steps of the impactor were the "AFA-B" filters, which were weighed on the analytical scale "ADV-200" before and after dusting [21].

Simulation of the conventional and modernized cyclones for the pneumatic transport system of powdered milk in the spray dryer "CT-500" was carried out together with the computing center at the National Technical University of Ukraine " Igor Sikorsky Kyiv Polytechnic Institute" (KPI) employing the "SolidWorks Flow Simulation 2010" licensed package [24].

The main indicators for assessing the energy efficiency of the cyclone, which were determined in the experiment, were the following: airspeed (V), median dust diameter (d_{50}), hydraulic resistance of the cyclone (ΔP_c), air temperature (t_a), degree of cleaning (η_{gen}), energy efficiency (EE).

5. Results of analytical and computer calculations to improve the energy efficiency of the industrial cyclone "Niro-Atomizer"

A new method of improving the energy efficiency of cyclones is proposed in [20], the main idea of which is to reduce the radial flow rate in the conical part of the cyclone in the interaction of two oncoming streams under the exhaust pipe and a separate feed air in a cyclone. At the same time, by using a "convergence" effect of two oncoming streams under the exhaust pipe of the cyclone, the radial component of the gas flow in the conical part of the cyclone is reduced while the efficiency of cleaning is increased. Hydraulic resistance is reduced due to the distributed introduction of airflow into the cyclone body.

We tested the possibility of improving the energy efficiency of cyclones using, as an example, the analysis of the operation of the industrial cyclone "Niro-Atomizer" (Denmark) with a diameter of 0.63 m. The cyclone was used in the system of air transport of the spray dryer "CT-500" (Germany) when catching dust from skimmed milk powder.

Let us analytically calculate a cyclone of the pneumatic transport "Niro-Atomizer" as part of the "CT-500" dust dryer at Ichnya Milk Powder and Butter Plant (Ukraine).

The analytical calculations and *CFD* simulation employed the following initial data:

– the diameter of the cyclone made by "Niro-Atomizer" D_c=0.63 m;

– the diameter of the exhaust pipe (relative to D_c) D_e=0.63 m;

– the size of the inlet branch pipe a=0.2 m; v=0.4 m;

– air temperature t_a=35 °C;

– airspeed in the inlet branch pipe of the cyclone V_{in}=15.6 m/s;

– average airspeed in the horizontal cross-section of the cyclone V_{ave}=4 m/s;

– dust density of skimmed milk powder ρ_d=1,100 kg/m^3;

– the median diameter of the dust and the size of the standard dust deviation are equal to d_{50}=25 µm, σ_d=2, respectively;

– the factor of hydraulic resistance of the cyclone ζ=100;

– hydraulic resistance of the cyclone ΔP=915 Pa.

The analytical calculation of the main indicators of the operation of the "Niro-Atomizer" air transport cyclone as part of the CT-500 sprayer dryer at Ichnya Milk Powder and Butter Plant was performed according to the flow chart shown below in the following sequence [25, 26].

The flow chart of calculating the main indicators of the operation of the "Niro-Atomizer" air transport cyclone as part of the CT-500 sprayer dryer.

Table 1 gives the results of calculations based on the calculation flow chart shown in Fig. 1.

It is shown in [19] that the smaller the magnitude of the product of dust removal $\left(100-\eta_{gen}^{p}\right)$ by the hydraulic resistance factor ζ, the higher the energy efficiency of the cyclone.

Given the lack of a method of analytical calculation of the cyclone with a "bypass" pipe, we performed computer calculation of a "bypass" pipe in the pneumatic transport system of skimmed milk powder.

Improving the energy efficiency of the air transport cyclone of spray dryer No. 1, the type of "CT-500", at Ichnya Milk Powder and Butter Plant is based on the use of a "bypass" pipe in the cyclone. The "bypass" pipe connects the cyclone's inlet branch pipe with the exhaust pipe and, through the exhaust pipe cap, strictly along the cyclone's axis, is inserted to the conical part of the cyclone [20].

The CFD simulation of the conventional and upgraded cyclones was performed at the KPI computer center, employing the "SolidWorks Flow Simulation 2010" [24] licensed software, the most accurate in computer calculations of dust separation processes in the cyclones [18].

Table 1

Results of analytical calculation of the main indicators of the "Niro-Atomizer" air transport cyclone as part of the CT-500 sprayer dryer

Parameter	ρ_a, kg/m^3	ΔP, Pa	μ_a, kg/m.s	v_a, kg/m.s	d_{eq}, m	Re, 10^5	d_η=50, μm	$d_{\eta}^{zh}=50$, μm	t	η_{gen}, %	EE
Magnitude	1,143	915	$19{,}4\cdot10^{-6}$	15.10^{-6}	0,267	2,78	4,875	5,2	1,3	90,3	970

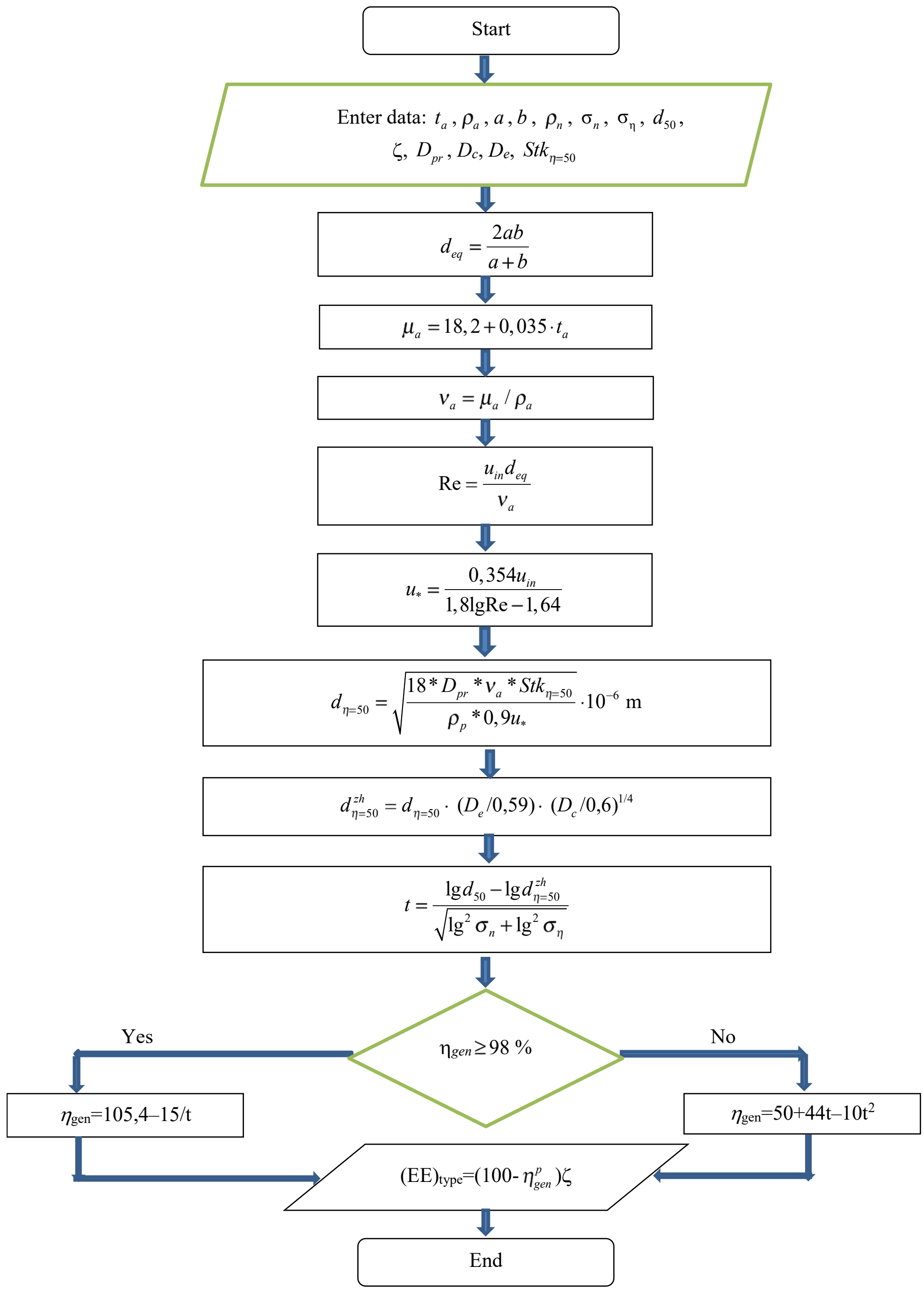

Fig. 1. Flowchart of calculation of cyclone energy efficiency

Fig. 2 shows the design and dimensions of the conventional "Niro-Atomizer" air transport cyclone for powdered skimmed milk. Fig. 3–5 show the results of computer simulation [24] of the conventional cyclone system of air transport and the cyclone with an additional "bypass" pipe with a diameter of 63 mm [20].

Our analysis of the *CFD* simulation results (Fig. 3–5) reveals that in the most dangerous zone for the removal of dust from cyclones (under the exhaust pipe), in case of the cyclone with a "bypass" pipe, the speed of the flow rising to the exhaust pipe decreases [20]. The result of the collision between the swirling airflow rising to the exhaust pipe and the unwhirled air flowing from the "bypass" pipe is the following effect [20].

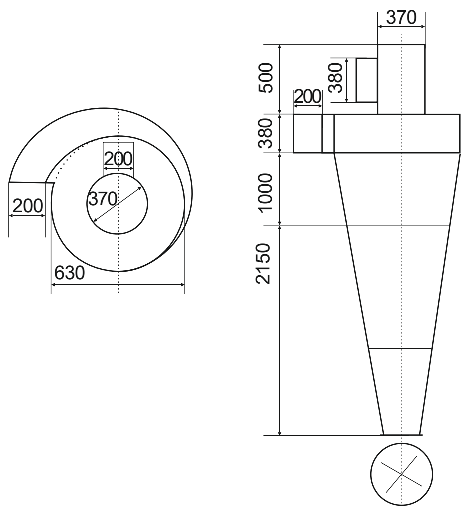

Fig. 2. Design and dimensions of the conventional cyclone "Niro-Atomizer"

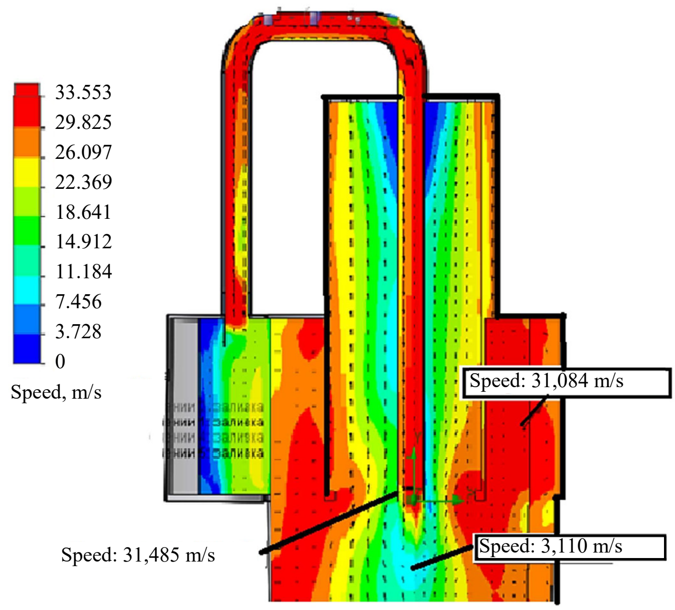

Fig. 4. Distribution of airflow speeds at the optimal location of a "bypass" pipe in the body of the conventional cyclone "Niro-Atomizer" – at the level of the lower plane of the cyclone's inlet branch pipe

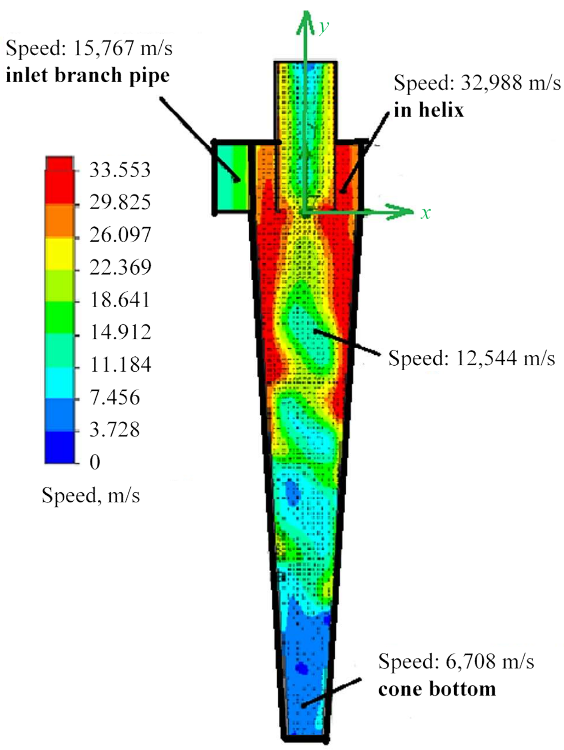

Fig. 3. Distribution of airflow speeds in a conventional cyclone made by "Niro-Atomizer"

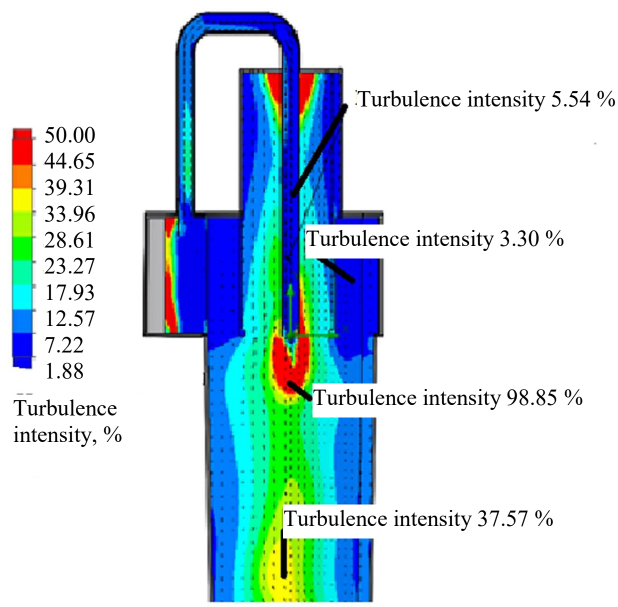

Fig. 5. Distribution of airflow turbulence intensity at the optimal location of a "bypass" pipe in the body of the conventional cyclone "Niro-Atomizer" – at the level of the lower plane of the cyclone's inlet branch pipe

A swirling airflow rising from the bunker to the exhaust pipe collides with the unwhirled flow, lowering the axial speed and thereby increasing in size. That reduces the negative impact on the efficiency of cleaning by the radial component of speed in the area of the lower exhaust pipe cut and explains the reason for the increase in dust cleaning efficiency in the cyclone with a "bypass" pipe.

We have performed computer calculation of the "Niro-Atomizer" air transport cyclone as part of the CT-500 sprayer dryer at Ichnya Milk Powder and Butter Plant.

Table 2 gives the results of computer *CFD* simulation to assess the impact of the introduction of a "bypass" pipe into the cyclone's design. At the same time, the impact exerted on the degree of cleaning by the location of a "bypass" pipe in the cyclone was assessed.

Table 2

Results of computer calculations using *CFD* simulation to assess the cyclone effectiveness [24]

No. 1	No. 2	No. 3	No. 4
1	19	23	25 (+6)
2	18	31	35(+17)
3	27	40	41(+14)
4	39	52	64(+25)
5	50	63	73(+23)
6	60	85	87(+27)
$\delta_{\eta=50}$, μm	5,0	3,8	3,3

Note: No. 1 – particle diameter, μm; No. 2 – effectiveness of a conventional cyclone (without a "bypass" pipe), %; No. 3 – effectiveness of a cyclone with a "bypass" pipe, placed 0.2 m below the exhaust pipe, %; No. 4 – effectiveness of a cyclone with a "bypass" pipe placed at the level of the lower plane of the exhaust pipe, %; (+) – magnitude of improvement in cleaning efficiency compared to a conventional cyclone, %; the average value of the magnitude of improving the efficiency of cleaning dust fractions 1...6 μm compared to a conventional cyclone amounted to 20 %

Table 2 shows that the magnitudes of the diameters of dust particles, captured with an efficiency of 50 % «$\delta_{\eta=50}$», amounted to (average of three calculations) «$\delta_{\eta=50}$»=5 μm – for a conventional cyclone, and «$\delta_{\eta=50}$»=3.3 μm – for the cyclone with a "bypass" pipe.

The result of calculations, based on the flow chart shown in Fig. 1, applying the derived values «$\delta_{\eta=50}$»=5 μm (for a conventional cyclone) and «$\delta_{\eta=50}$»=3.3 μm (for the cyclone with a "bypass" pipe), is the degree of purification, $\eta^p_{gen} = 90{,}8\,\%$, and $\eta^p_{gen} = 95{,}3\,\%$. respectively.

Thus, the "removal" of dust from powdered skimmed milk by the cyclone with a "bypass" pipe would decrease, in comparison with the cyclone without a "bypass" "pipe, by about 2 times.

The energy efficiency index (the product of dust removal by the factor of hydraulic resistance of the cyclone) of the modernized cyclone with a "bypass" pipe is

$$EE_{byp.pipe} = (100 - \eta^p_{gen})(\xi - 0.15\xi) = 400.$$

The energy efficiency index (EE) indicates that the less the removal of dust from the cyclone is and its hydraulic resistance, the higher the energy efficiency of the cyclone.

Thus, the modernized cyclone with a "bypass" pipe in terms of energy efficiency exceeds the conventional cyclone by

$$\frac{970}{400} = 2{,}43 \text{ times}.$$

Table 3 gives the results of analytical calculations to assess the cleaning effectiveness of the conventional cyclone and the cyclone with a "bypass" pipe.

Our analysis of data from Table 3, derived by calculation based on the above algorithm (flow chart), reveals that the estimated magnitude of the ratio of dust removal from the conventional cyclone and the cyclone with a "bypass" pipe, depending on the median diameter of the dust, can be described as a dependence in form

Table 3

Results of analytical calculations on the assessment of degrees of efficiency of cleaning of the conventional cyclone and the cyclone with a "bypass" pipe

d_{50}, μm	5	10	15	25	30
$(\eta^p)_{type}$, %	48,7	71	82,4	90,4	92,85
$(100-\eta^p)_{type}$, %	51,3	29	17,6	9,6	7,15
$\left(\eta^p_{gen}\right)_{byp.pipe}$, %	64	82	90,4	95,4	97,1
$\left(100-\eta^p_{gen}\right)_{byp.pipe}$, %	36	18	9,6	4,6	2,9
$\left(100-\eta^p\right)_{type} / \left(100-\eta^p_{gen}\right)_{byp.pipe}$	1,43	1,6	1,81	2,0	2,47

Note: For dust d_{50}=25 μm, data from the experiments are given; the rest of the results were calculated using experimental data on dust d_{50}=25 μm

$$\left(100-\eta^p\right)_{type} / \left(100-\eta^p_{gen}\right)_{byp.pipe} = 1{,}2 + 0{,}042 d_{50}. \quad (1)$$

Data from Table 3 indicate that in the range of changes in the median diameter of dust from 5 to 30 μm, the removal of dust from the cyclone with a "bypass" pipe is reduced by 1.5...2.5 times in comparison with the removal of dust from the cyclone without a "bypass" pipe.

Thus, we have performed an estimation regarding the effect exerted on the effectiveness of cleaning by the introduction of an additional "bypass" pipe to the air transport cyclone system and the location of the "bypass" pipe in the cyclone body (Fig. 3–5).

6. Industrial tests of the main indicators of the "Niro-Atomizer" air transport cyclone system

Table 4 gives the results of industrial aerodynamic tests of the conventional cyclone in the system of air transport.

While performing industrial tests, aimed to perform the tasks set in the work, we specified the required initial data in Tables 4–9.

Table 4 gives the results of industrial aerodynamic tests of the conventional cyclone system of air transport.

Table 4

Results of aerodynamic tests of the conventional cyclone "Niro-Atomizer" with a diameter of 630 mm of the air transport system

Parameter	t_a, °C	ρ_a, kg/m^3	$V_{in.b.p.}$, m/sec	V_{ave}, m/sec	ΔP, Pa	L_a, m^3/h
Value	35	1,143	15,6	4,0	915	4500

Note: $V_{in.b.p.}$– airspeed in the cyclone's inlet branch pipe; V_{cve}– average speed in the horizontal cross-section of the cyclone; ΔP – cyclone resistance; L_a – airflow

Table 5 gives the results of studying dust concentration in the air of the air transport system and the degree of purification in a conventional cyclone.

Table 5

Results of studying dust concentration in the air of the air transport system of the "Niro-Atomizer" cyclone

Parameter	s, g	τ, min	G_a, l/min	K_{init}, g/m^3	K_{fin}, g/m^3	$(\eta_{gen})^{exp}_{type}$, %
Value	0,05	1,0	2.0	25	2,43	90,3

Note: s – dust weight in the filtering device; τ – time of sampling; G_a– air consumption during sampling reduced to normal conditions, K – concentration of dust

The experimentally determined degree of cleaning in a conventional cyclone was $(\eta_{gen})^{ex}_{type}=90{,}3\,\%$, and the estimated degree of purification in a conventional cyclone was $\eta^{p}_{gen}=90{,}8\,\%$.

In this case, the magnitude of deviation in the removal of dust in the experimental and computational data was 5.2 %, which does not exceed the allowable deviation of 15 % [25, 26]. This is the verification of the results of the *CFD* simulation.

Table 6 gives the results of studying the disperse dust composition in the air of the air transport system of the "Niro-Atomizer" cyclone.

Table 6

Results of studying the disperse dust composition in the air of the "Niro-Atomizer" air transport system cyclone

Particle size, μm	0–10	10–15	15–20	20–30	>30	d_{50}, μm	$\sigma_п$
Weight composition of particles	11	9	21	25	34	25	2

Note: the magnitudes of diameter d_{50} and $\sigma_п$ were determined when the results from Table 6 were mapped onto a probability-logarithmic coordinate grid

Table 7 gives the results of studying dust concentration in the air of the air transport system of the "Niro-Atomizer" cyclone and the degree of purification.

Table 7

Results of experimental studies of the degree of cleaning of the cyclone with a "bypass" pipe

Parameter	s, g	τ, min	$G_в$, l/min	K_{init}, g/m^3	K_{fin}, g/m^3	$(\eta_{gen})_{byp.pipe}$, %
Value	0,01	2,0	5,0	25,0	1,05	95,8

Note: s – dust weight in the filter; τ – time of sampling reduced to normal conditions; K_{init}, K_{fin} – concentration of dust, respectively, initial – before the cyclone and final –behind the cyclone; $(\eta_{gen})_{byp.pipe}$ – degree of cleaning of the cyclone with a "bypass" pipe

For the cyclone with a "bypass" pipe and Table 7 conditions, the purification degree from computer calculation was $\eta^{p}_{gen}=95{,}8\,\%$. The magnitude of deviation on the removal of dust from experimental and computer data was 11.9 %, which does not exceed the allowable deviation amount of 15 % [25, 26]. This is the verification of the results from *CFD* simulation.

Given the impossibility to change under industrial conditions the diameter of a "bypass" pipe and its location, the diameter of the "bypass" pipe and its location were accepted based on the results of computer calculations (Table 2). That is, we have adopted the optimal diameter of a "bypass" pipe of 0.063 m (0,1D_c) of its location at the level of the lower plane of the cyclone exhaust pipe.

Table 8 shows the results of our study to determine the magnitude of an increase in the hydraulic resistance of the cyclone with a "bypass" pipe.

Table 8

Results of our study to determine the magnitude of a decrease in the hydraulic resistance of the cyclone with a "bypass" pipe

$G_{byp.pipe}$, %	0	2	4	5	7,5
$(\Delta P)^p$, Pa	915	880	846	830	792
$(\Delta P)^{exp}$, Pa	915	892	857	840	802

Note: the estimated resistance value of the cyclone – $(\Delta P)^p$; experimental cyclone resistance value – $(\Delta P)^{exp}$

It follows from Table 8 that deviations in the magnitudes of resistance of the calculated and experimental magnitudes do not exceed 5 %. Therefore, the estimated magnitude of the resistance decrease by 15 % was practically confirmed at optimal air consumption through a "bypass" pipe ($G_{byp.pipe}$=7,5 %).

When evaluating the optimal ratio between airflow rates through the inlet of the cyclone branch pipe and a "bypass" pipe, experimental studies were performed, the results of which are given in Table 9.

Table 9

Dependence of the optimal ratio between airflow rate through the inlet branch pipe of the cyclone and a "bypass" pipe

$G_{byp.pipe}$, %	2,0	4,0	5,0	7,5	12	15
$(q_{type}/q_{byp.pipe})_{exp.}$	1,0	1,6	1,8	2,1	1,6	0,8
$(q_{type}/q_{byp.pipe})_{est.}$	1,0	1,6	1,8	2,05	1,618	0,7

Note: $G_{об.тр.}$ – amount of air through a "bypass" pipe (as a percentage of the total volume through the cyclone); q_{type}, $q_{byp.pipe}$ – removal of dust from the cyclone, respectively, from a conventional cyclone and a "bypass" pipe

The result of solving the problem on finding the smallest squares for a linear matrix equation using the feature "l_alg. lstsq function" [27], the data from Table 6 can be represented by the dependence in the form

$$(q_{type}/q_{byp.pipe})=0{,}25+0{,}45G_{byp.pip}-0{,}028(G_{byp.pipe})^2. \quad (2)$$

Fig. 6 shows the estimated and experimental data on reducing the removal of dust from the cyclone with a "bypass" pipe depending on the airflow rate through a "bypass" pipe – $G_{byp.pipe}$.

Table 9 shows that the function has an extremum, which corresponds to the maximum reduction of dust removal from the cyclone with a "bypass" pipe.

Thus, it can be concluded that the maximum degree of purification is achieved at an airflow rate through a "bypass" pipe in the amount of 7.5 % of the total amount of air in a cyclone at the size of the diameter of the "bypass" pipe (0,1 D_c). At the same time, the removal of dust from the cyclone decreases by 2.1 times.

During industrial tests of the air transport cyclone system, it was noted that the frequency of cone clogging of the cyclone decreased as well as the number of stops to clean up the cone part of the cyclone. There were no difficulties in introducing a "bypass" pipe into the design of the cyclone, which indicates that the process of modernization of the proposed cyclone modernization technology is feasible and can be carried out by the enterprises themselves.

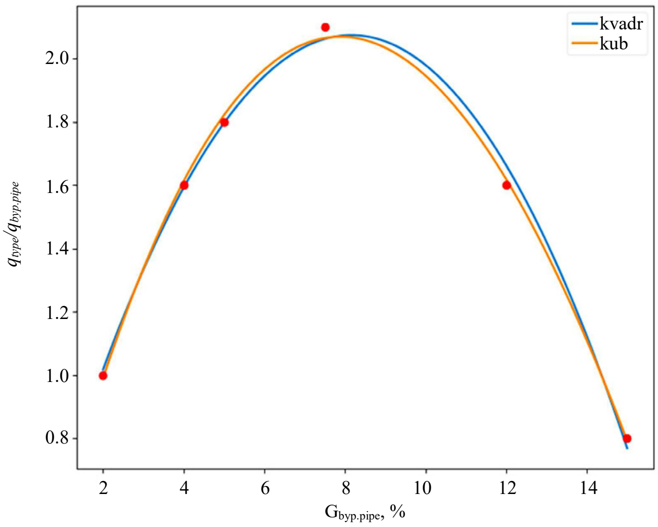

Fig. 6. Dependence of a dust removal decrease from the cyclone with a "bypass" pipe on airflow rate

7. Discussion of results of studying the impact of the introduction of a "bypass" pipe in the design of the cyclone on energy efficiency

The obtained results of the improved energy efficiency of the cyclone with a "bypass" pipe are explained by the decrease in the level of airspeed radial component negatively affecting the cleaning in the conical part of the cyclone – in front of the exhaust pipe. This is achieved by the fact that a promising method of distributed supply of air flows into the cyclone is applied (through the inlet branch pipe and a "bypass" pipe), as well as the implemented principle of "coherence". That is, the effective interaction of two colliding oncoming air flows (dusty stream falling from the "bypass" pipe and the purified air rising from the dust of the output hole to the exhaust pipe) is ensured.

When these two mutually divergent air streams collide, due to the difference in pressures in them, dust particles from the stream with higher pressure of the falling dusty flow jump into the flow of clean air with less pressure, thereby impairing the efficiency of cleaning. In the cyclone with a "bypass" pipe, as seen from Fig. 3, 4, the result of the interaction between the two counter-directed air streams is an increase in the flow of clean air. At the same time, the speed of the purified flow under the exhaust pipe is reduced, as well as its radial speed and, as a result, the pressure increases because the product of pressure by speed is a constant magnitude. This reduces the difference of pressures in mutually divergent air flows with fewer dust particles slipping into the flow of purified air, that is, the efficiency of cleaning is increased. Thus, at the efficiency of cleaning a conventional cyclone of the air transport system of 90.3 % (Table 5) the efficiency of the cyclone system of air transport with an additional "bypass" pipe was 95.8 % (Table 8). This means that the removal of dust has almost halved.

In an experimental study of the magnitude of the reduction of hydraulic resistance of the cyclone with a "bypass" pipe, it was found that in the cyclone with a "bypass" pipe the hydraulic resistance is reduced by 15.56 % (Table 8). At the same time, the deviation of the estimated and experimental values of hydraulic resistance magnitudes does not exceed 5 %.

In the experimental determining of the optimal ratio between airflow rate through the inlet branch pipe of the cyclone and a "bypass" pipe it was established (Table 6, formula (2), Fig. 9) that the maximum efficiency of cleaning in the cyclone with a "bypass" pipe is achieved at airflow rate of 7.5 % of the total air consumption in a cyclone.

Thus, it was established that the new method of cyclone modernization, with the introduction of an additional "bypass" pipe into the design, makes it possible to increase the efficiency of cleaning by 1.5...2.5 times (depending on dust dispersity) and reduce the magnitude of hydraulic resistance by up to 15 %.

The special features of the proposed method and the results obtained, in comparison with studies [1–5], are related to that the implementation can be carried out on working equipment by the enterprises themselves. In this case, the removal of dust into the atmosphere would be reduced in half and, when the cyclone stops for cleaning, there would be no losses of captured valuable products, which in different industries could include milk powder, sugar, starch, glucose, etc. In addition, there will be no significant cost for manufacturing and installing new, more expensive, dust-capturing equipment.

The limitations of this study include a possible probability of dust sticking to a "bypass" pipe when catching some types of dust with high clumps.

The disadvantage of the current work is that the tests of method effectiveness were performed only at one type of dust.

The prospects for implementing a new method to improve the energy efficiency of cyclones could be its application in almost all low-efficiency cyclones in various industries.

Such modernization, for example, is being prepared in order to clean the used drying air from the dust of skimmed milk powder at two cyclones of the "Niro-Atomizer" type (diameter 1.4 m). The cyclones are installed in the dust-cleaning system after the sprayer dryer "CT-500" No. 2 at Ichnya Milk Powder and Butter Plant.

The current study may be advanced by extending the obtained results to a wider range of different cyclone dust collectors and types of captured aerosols. This may require further development and investigation.

8. Conclusions

1. As a result of assessing the impact of introducing an additional "bypass" pipe into the design of the pneumatic transport system in order to increase the degree of air purification from dust of skimmed milk powder, it was found that while a typical pneumatic transport system cyclone cleaning efficiency is 90.3 %, the efficiency of the pneumatic transport system cyclone with an additional "bypass" pipe is 95.8 %. This means that dust entrainment has almost halved.

2. As a result of evaluating the optimal size of a "bypass" pipe and its location in the cyclone body by computer *CFD* simulation, it was found that the maximum cleaning efficiency is achieved with a diameter of the "bypass" pipe of 0.1 D_c (63 mm). Moreover, the best place for its placement in the cyclone body is the level of the lower plane of the cyclone exhaust pipe.

3. As a result of determining the magnitude of the decrease in hydraulic resistance of a cyclone with a "bypass"

pipe, it was established that in the cyclone with a "bypass" pipe the hydraulic resistance is reduced by 15.56 %.

4. As a result of determining the optimal ratio between the airflow through the inlet branch pipe of the cyclone and the "bypass" pipe, it was found that the maximum cleaning efficiency in the cyclone with the "bypass" pipe is achieved with an airflow through the "bypass" in the amount of 7.5 % of the total airflow in the cyclone.

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