

## ANALYSIS OF THE SANITARY PURIFICATION OF GAS EMISSIONS FROM DUST IN THE LIME MANUFACTURE

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### Abstract

Experimental studies have been carried out to study the effect of the location of the blade vortex from the end of the flue (the flow outflow from the flue to the separation chamber) by the value  $V\varphi_{\max}$  and the determination of the optimum cross section where  $V\varphi_{\max}$  is reached, and also the study of the influence of structural changes on the purification efficiency. The dependence of this swirler on the value of the tangential velocity of the gas flow at its exit from the separator is established. The cross-sections of the flue duct in which, after the swirler, the maximum values  $V_\varphi$ ,  $V_r$  are reached, the features of the dust-gas flow in the studied sections are considered. Based on the studies of the hydrodynamic situation during the flow of a rotating flow in the flue after the swirler, the possibilities of agglomeration of dust particles in the investigated zones, as well as the destruction of  $\text{NO}_x$  gas impurities, are analyzed. During the operation of the reconstructed vortex dust collector, qualitative indices are attained, which confirm the expediency of the conducted studies and the expediency of reconstructing the vortex apparatus. It is proved that the installation of the blade vortex enhances the purification efficiency of the dust-gas flow in a vortex dust collector and will allow for a comprehensive purification of the exhaust gases.

**Keywords:** lime production, sanitary purification of gases, vortex swirler, dust agglomeration, separator.

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### 1. Introduction

Many branches of the processing industry in the technological cycle include redistribution of lime production by roasting carbonate raw materials in shaft furnaces using gaseous fuels. Earlier, the results of studies on the modernization of shaft furnaces and technological processes in them to improve furnace productivity, the degree of calcination of limestone and the reduction of heat consumption for the production of a unit of production were considered [1–4]. The obtained results of studies [1–4] indicate the advisability of introducing an improved furnace design in various industries.

So, at one of the alumina refineries in Ukraine, the basic layout solutions, compulsory heating scheme and technical proposals for the modernization of the existing shaft furnace were adopted in accordance with recommendations [1–4].

The diagram illustrates a complex gasifier system. At the bottom left, a vertical pipe labeled "Supply of natural gas" with a diameter of DN 200 enters the system. This pipe branches into two main paths. One path, labeled "Unloading", leads to a large cylindrical vessel with a diameter of  $D = 4.5\text{ m}$ . The other path, labeled "Air", leads to a fan and then to a vertical pipe with a diameter of DN 600. The "Unloading" path includes a vertical section with a height of  $0.14\text{ H}$  and a horizontal section with a diameter of DN 150. The "Air" path includes a fan and a vertical section with a height of  $0.60\text{ H}$ . The large cylindrical vessel has a total height of  $0.44\text{ H (CP)}$  and is equipped with several internal components, including a "Loading batch" at the top and a "Dust collector" on the side. The vessel is connected to a network of pipes with various diameters (DN 80, DN 100, DN 125, DN 300, DN 400) and valves. The system also includes a "Fan" at the top right, a "Dust collector" at the top left, and a "Supply of natural gas" at the bottom left. The diagram shows the flow of gas and air through the system, with various components labeled for identification.

**Table 1** shows the initial data for determining the performance of the dust collection apparatus.

**Table 1**

Physicochemical parameters of the gas flow at the inlet of the dust collector.

No.	The name of the indicator and its dimension	Basic operation mode	Reserve operation mode
1	Number of gases fed for purification, nm <sup>3</sup> /h, nm <sup>3</sup> /s	15600 4.33	24200 6.72
2	Gas temperature in front of the dust collector, °C, K	230–270 503–543	280–320 553–593
3	Required vacuum in the dust collector, mm. water, Pa	350–400 3431.4–3921.5	350–400 3431.4–3921.5
4	Composition of gases in front of the dust collector (%):		
	CO <sub>2</sub>	26–28	17–18
	H <sub>2</sub> O	15–16	12.0
	N <sub>2</sub>	56–58	63.8–65.0
	O <sub>2</sub>	1.1–1.3	6.0–7.0
	Other including (mg/nm <sup>3</sup> ):		
	CO	0.05	0.05
	NO <sub>x</sub>	50.0	50.0
	Dust content g/nm <sup>3</sup> , including:		
	– limestone dust (CaCO <sub>3</sub> )	6.08	5.86
	– Lime 100 % roasting (CaO)	5.21	5.04
	The size of dust particles	0.8	0.82
	CaCO <sub>3</sub>	10.0	10.0
	CaO	<5.0	<5.0
	The specific surface area according to BET, m <sup>2</sup> /g (mixture)	~3.0	~3.0
5	Dust content mg/nm <sup>3</sup> at the outlet of the dust collector	70.0	70.0
6	The temperature of the gases after the dust collector, °C, K	160–180 433–453	160–180 433–453
7	NO <sub>x</sub> content in the off-gas mg/nm <sup>3</sup>	~10.0	~10.0

Analysis of the indices given in **Table 1** makes it possible to draw an unambiguous conclusion that the dust-collecting apparatus at the exit from which the above-mentioned indicators should be achieved should by classification be referred to as “dry” devices for purification of the gas-dust flow. At the same time, comparing the dust concentration in the flow at the inlet to the apparatus and at the outlet from it, the purification efficiency should be at the level of 98–99 %. Similar problems arise not only in the particular case under consideration, but also in other similar industries. In connection with this, the scientists [1–4] focused their attention on the introduction into the technological processes of dust and gas purification of apparatus in which complicated-swirled flows are organized at  $Re \geq 10^4$ .

However, for this period, the issues of the effect of the flow regimes of gas flow at the inlet to the purification apparatus and the effect of the swirling flow on the distribution of velocity components and the purification efficiency from the aerosol are not fully considered.

When studying the process of “dry” purification of dust and gas flows during the organization of a rotating centrifugal-inertial flow in the apparatus, the dissipation of the mechanical energy of the introduced flow into the apparatus is considered, and the angular velocity of the rotating flow at the entrance to the separation part of the apparatus is determined. As a rule, these are the main factors for calculating the fractional efficiency of dust collection [5–7].

The equation for determining the angular velocity of flow rotation in the separating part of the apparatus according to [5–7] is written as:

$$\omega_{o(z)} = \frac{2M_{in} \cdot r_*^2}{\rho \cdot (L_1 + L_2) \cdot r_o^2}, \quad (1)$$

where  $M_{in}$  – the incoming momentum of the flow, which is determined by:

$$M_{in} = 0,5\pi\rho V_z \cdot V_{\varphi} \cdot r_o. \quad (2)$$

Here:  $L_1, L_2$  – rate of primary and secondary flows, respectively,  $m^3/s$ ;  $V_z, V_{\varphi}$  – respectively axial and tangential flow velocities,  $m/s$ ;  $r_o, r_s$  – respectively the radius of the separation chamber and the radius of separation of the streams,  $m$ ;  $\rho$  – the density of the dust and gas flow.

A particular parameter in equation (2) is  $V_{\varphi}$  – which actually makes sense of the tangential flow velocity immediately after the swirler or the swirling flow. As is well known [8, 9], for any type of swirler (spout, annular, nozzle, scapular), the maximum value  $V_{\varphi}$  at the outlet of the flue into the separation chamber is not reached immediately after the swirler, but in some combination with the flue after the swirler, which along the length corresponds approximately to half the damping zone of the vortices. Therefore, it is necessary to pay attention to the study of complex processes that are observed in the flue gas duct (the branch pipe for the injection of dusty gas) in the areas of installation of the swirlers and immediately after them. According to [5–9], the most effective purification device after cyclones is the vortex dust collecting apparatus.

The aim of this article is investigation of the effect of the blade vortex location from the end of the flue (the flow outflow from the flue to the separation chamber) by the value  $V_{\varphi}$  and determine the optimal cross-section where  $V_{\varphi max}$  is reached, as well as to study the effect of these design changes on the purification efficiency. This will improve the efficiency of dust removal in lime production. It is necessary to study the velocity distributions in different sections along the channel length, as well as the mixing of the forward and backward gas flows.

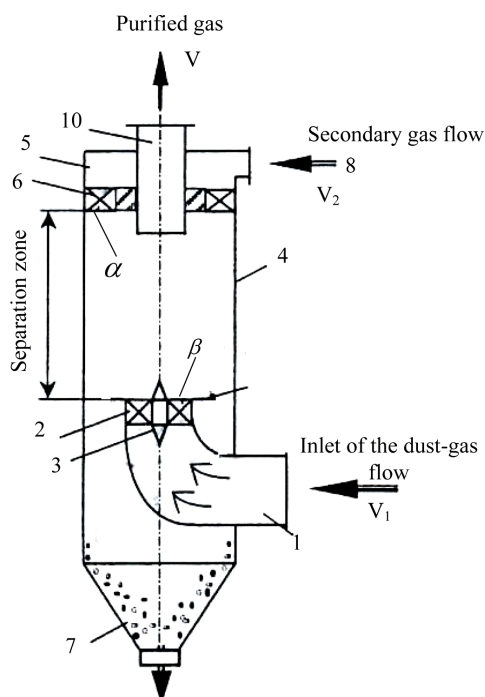
#### 4. Experimental investigation of the blade swirler

**Fig. 2** shows a schematic diagram of the vortex apparatus, which is used for carrying out experimental work. The internal diameter of the flue (1) is 350 mm, which corresponds to the outer diameter of the blade swirler  $D_s$  (2). The diameter of the sleeve  $D_s$  (3) is 150 mm, the diameter of the separation part (internal diameter of the apparatus)  $D=440$  mm. The diameter of the washer  $D_w$  (9) is 210 mm. The inclination angle of the blade swirler blades at the inlet of the flow to the separator is  $\beta=45^\circ$ , the inclination angle of the secondary flow nozzles  $\alpha$  (6) is also  $45^\circ$ . The above-mentioned slope angles of the blades and nozzles are chosen from the necessary conditions for the operation of the vortex apparatus [10], which should ensure the equality of the drift time of the aerosol from the axis of the apparatus to the wall and the residence time of the gas in the apparatus. Based on the same considerations, the separation zone (L) is selected from the ratio  $L/D=2.5-3.5$ . In our case,  $L/D=3$  that is 1320 mm.

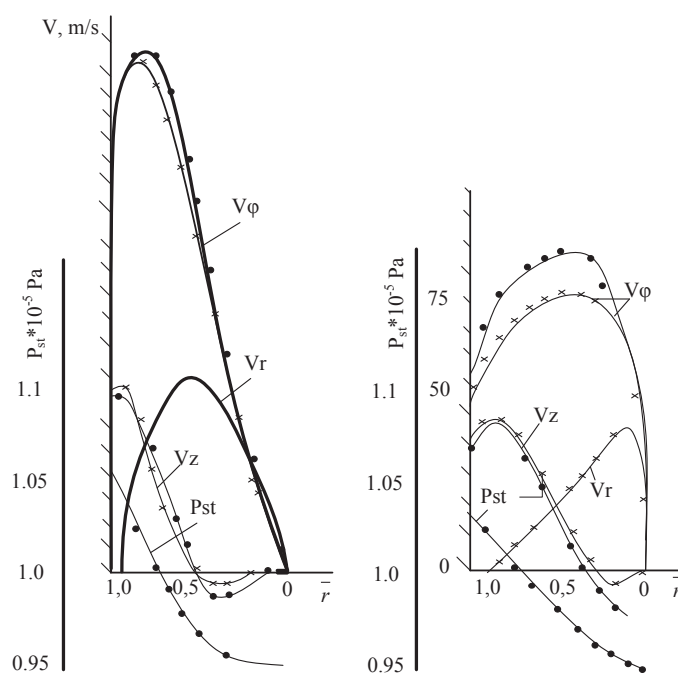
The object of research is the characterization of the flow of the dust-gas flow (the nature of the distribution of the velocity components) in the cylindrical-shaped flue after the swirler (2), which is installed below the gas flue end (below the washer (9)) at a distance  $D_s 1+4$ , that is, a distance of 1÷4 caliber from the plane of the swirler from which a swirling flow of gas leaves. With the parameters indicated in **Table 1**, the inlet gas flow velocity  $V_{in}$  is 150÷200 m/s and, accordingly,  $Re \geq 10^6$ . To measure the parameters of the vortex gas flow, a cylindrical sensor is used, the diameter of the working part of the cylinder is 3 mm. To measure the three-dimensional velocity field, a ball sensor with a ball diameter of 5 mm is used. The calibration is carried out according to [11].

During the tests in the dust collector, sampling and analysis of samples from a gas flow at the entrance to the flue gas, at the outlet of the dust collector, and also samples of precipitated dust from the bunker is carried out. The dust concentration in the gas flow is determined by a dust sampling device ППО-2 (Russia), the concentration of gaseous oxides in the gas stream is determined by a universal gas analyzer УГ-2 (Ukraine). Measurements of dust particles and determination of their structure are carried out on an electron microscope УЭМБ-100 (Russia) and on a transmission electron microscope “Elmiscop 1” (Siemens, Germany). The specific surface of dust samples is determined by the BET method (the method of mathematical description of physical adsorption).

**Fig. 3** shows the typical distribution curves  $\varphi_{(r)}, V_{r(r)}, V_{z(r)}, Pst_{(r)}$  in two cross sections after the swirler.



**Fig. 2.** Schematic diagram of a vortex dust cleaner with a blade-type flow swirler: 1 – gas flue for the supply of dusty gas; 2 – blade swirler; 3 – fairing; 4 – separator box; 5 – secondary flow collector; 6 – swirler, twisting the secondary flow in the same direction as the swirler 2; 7 – dust bunker; 8 – input of the secondary flow; 9 – dust extractor washer; 10 – outlet of purified gas



**Fig. 3.** Distribution of  $V\varphi(\bar{r})$ ,  $Vz(\bar{r})$ ,  $Vr(\bar{r})$ ,  $Pst(\bar{r})$  along the length of the channel

Analyzing the distribution curves, it is possible to say that up to section 2 the rotation of the gas-dust flow passes as quasi-solid, that is, the law  $V\varphi = cr$  is satisfied, and only a very thin boundary layer develops near the wall itself. There are laws of inverse flows, and in sections close to the swirler, they have an annular shape. Further downstream, the distribution of  $V\varphi_{(r)}$  becomes different. The zone of quasi-solid rotation contracts, the absolute value of  $V\varphi_{(r)}$  decreases due to

the friction of the gas flow against the flue wall and internal friction between the layers of gas, the boundary layer grows. The character of the distribution of the axial velocity  $V_{z(r)}$  also varies somewhat. The axial flow in the initial sections is pressed against the wall of the flue and the main mass flows by 1/3 of the radius, then the stream expands and takes about 2/3 of the radius. The transition  $P_{st}$  through the zero line is almost always carried out at the point where  $V_{\varphi(r)}$  has a maximum. Thus, right after the swirler in the plane of the flow out of it to the volume of the separator  $V_{\varphi(r)}$  less than  $V_{\varphi_{max}}$  is approximately 25–30 %. For the radial component  $V_{r(r)}$  it is characteristic to reach a maximum at a radius where the axial velocity passes through the zero mark. The results of measurements of the velocity distribution in different sections along the length of the channel make it possible to judge the damping of the vortices, which is caused by the friction of the gas flow against the flue wall, and also the mixing of the direct and reverse gas flows. In vortex flows, there is the concept of vortex intensity, the most accurate expression for it is:

$$m = \frac{B}{FR} = \frac{2\pi\rho \int_0^R V_{\varphi} V_z r^2 dr}{\left(2\pi\rho \int_0^R V_{\varphi}^2 r dr\right) R}, \quad (3)$$

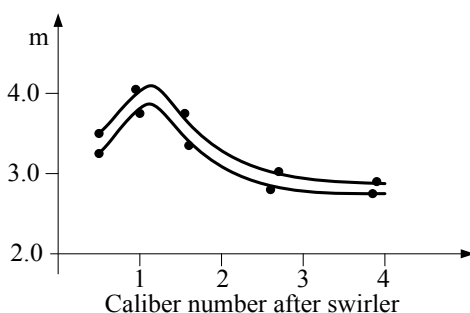
where  $B$  – flow of the angular momentum of the momentum,  $\text{kg}\times\text{m}^2/\text{s}$ ;  $F$  – axial momentum flow,  $\text{m}^2\cdot\text{kg}/\text{s}$ ;  $R$  – radius of the channel,  $\text{m}$ ;  $\rho$  – gas density,  $\text{kg}/\text{m}^3$ ;  $V_z$  – the axial velocity component,  $\text{rad}/\text{s}$ ;  $V_{\varphi}$  – the tangential velocity component,  $\text{rad}/\text{s}$ ;  $r$  – the current radial coordinate.

If we have a velocity distribution, then  $V_{\varphi} = ar$  and  $V_z = br$ ,

If  $a, b$  are constants, then the velocities are averaged, and then

$$m \approx \frac{V_{\varphi_{max}}}{V_{z_{max}}}. \quad (4)$$

The dependence of the damping of the vortex along the length of the flue after the swirler is shown in **Fig. 4**.



**Fig. 4.** Dependence of the damping of the vortex intensity  $m = f(L/D_s)$

As follows from **Fig. 4** and small values of  $L/D_s$ , the drop in  $m$  is significant, since the magnitude of the coefficient of friction is proportional to  $V^2$ . In the future, after reaching the maximum value of  $m$  is close to a constant value. If we compare equation (2) with the value of  $B$  in equation (3), then they are identical in structure and in meaning. This indicates that the intensity of the vortex after the swirler will determine the possibility of achieving the maximum angular velocity of flow in the separation part of the dust collector for this apparatus. As noted above, the axial flow in the initial sections after the swirler is pressed against the wall and due to the formation of a significant radial gradient of the static pressure, the dust particles are also pressed against the wall and move in the form of an annular flow by a dense layer. In these conditions, based on the theory of physico-chemical aggregation of bodies of variable mass [12, 13], it is possible to expect

the coarsening of particles. In this case, according to [12, 13], the aggregate consists of particles of different sizes and the main mechanisms of the process are collision of particles, the formation of a defect zone at the point of contact of particles during a collision, and the formation of crystalline “bridges” between particles in aggregates. In high-speed flows, when the probability of collision of particles is large, the growth rate of agglomerates increases with increasing number of collisions [14]. If the velocity of approach of the particles when they collide with one another is sufficiently large and the particle surface is sufficiently developed, then under the influence of collisions a relief appears on the surface of the particles, which sharply accelerates the growth of agglomerates [15]. Similar considerations can also be developed regarding the possibility of  $\text{NO}_x$  destruction processes in a given hydrodynamic environment, especially since the gas stream contains water vapor in sufficient excess relative to  $\text{NO}_x$  [16].

However, these phenomena require special studies of the mechanism and kinetics of the processes. Nevertheless, the physical and chemical characteristics of the gas flow and the properties of the deposited dust at the outlet from the dust collector may indicate the reliability of the noted phenomena.

Thus, the presented experimental studies provide a justification for improving the design of the vortex dust collector (**Fig. 2**) by installing a blade swirler below the end gas outlet from the flue to 1.5–2 calibers that is  $(1.5 \div 2) D_s$ . Below, **Table 2** shows the averaged quality indicators for the operation of the reconstructed dust collector.

**Table 2**

The average performance of the reconstructed vortex dust collector (the gas flow at the outlet from the dust collector, the period of the experimental operation of 72 hours, the parameters at the inlet, see **Table 1**)

The name of the indicator and its dimension	Basic operation mode	Reserve operation mode
Dust content, $\text{mg}/\text{nm}^3$ , Purification degree, %	$48.0 \pm 10$ 99,2	$118.0 \pm 10$ 98.0
$\text{NO}_x$ content, $\text{mg}/\text{nm}^3$ , Purification degree, %	$7.5 \pm 5$ 85.0	$10.0 \pm 2$ 80.0
The size of dust particles in the exhaust gas, $\mu\text{m}$	$< 5.0$	$< 5.0$
The temperature of the gases after the dust collector, $^{\circ}\text{C}$	285.0	205.0
The particle size of the dust deposited in the separator, from the bunker (7 <b>Fig. 1</b> ), $\mu\text{m}$	$35.0 \pm 2$	$30.0 \pm 5$

As can be seen from the data given in **Table 2**, qualitative indicators of the operation of the vortex dust collector, which was reconstructed, confirm the expected results of the experiment. Apparently, when the dust collector is operated in the main mode of operation of the shaft furnace, an increase in the purification efficiency the dust-gas flow is achieved.

## 5. Conclusions

1. Studies are carried out for the first time on the influence of the location of the blade swirler. The dependence of this swirler (installed at the end of the flue gas duct of the vortex dust collector) on the value of the tangential flow rate of the gas as it leaves the separator is established. The cross-sections of the flue duct in which, after the swirler, the maximum values  $V_{\varphi}$ ,  $V_r$ , are reached, the features of the dust-gas flow in the studied sections are considered. The relationship between the attainment of  $V_{\varphi\text{max}}$  and the intensity of vortex formation is established.

2. Based on the studies of the hydrodynamic situation during the flow of a rotating flow in the flue after the swirler and using known literature data, the possibilities of agglomeration of dust particles in the investigated zones, as well as the destruction of  $\text{NO}_x$ -type gas impurities are analyzed.

3. It is recommended to improve the design of the vortex dust collector by installing a blade vortex in the flue, which provide the effect of achieving  $V_{\phi_{\max}}$ .

4. During the operation of the reconstructed vortex dust collector, qualitative indices are attained which confirm the expediency of the conducted studies and the expediency of reconstructing the vortex apparatus.

Thus, the main conclusion should be assumed the results of measurements of the distribution of velocities in different sections along the length of the channel, which allow one to judge the damping of vortices, which is caused by the friction of the gas flow against the flue wall, and also the mixing of the direct and reverse gas flows. It is proved that the installation of the blade vortex enhances the purification efficiency of the dust-gas flow in a vortex dust collector and will allow for a comprehensive purification of the exhaust gases.

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