Gas-dynamic resistance in the swirling zone of the vortex apparatus gas flow

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Abstract. At the end of the twentieth and beginning of the twenty-first century, almost all national policies in the world are oriented towards environmental problems. Therefore, environmental policy is aimed at reducing the consumption of various resources and reducing harmful emissions into the environment. This is especially true for dusts, which can be formed at almost all enterprises. One of the ways to improve environmental safety from gaseous, solid and liquid emissions from the production of various types and types of products in chemistry, petrochemistry and refining is modernization. Such modernization can be implemented in production management systems and resource consumption policies, as well as in modernization of technical processes and improvement of equipment design. In many chemical processes, dust-like particulate matter from gaseous emissions is captured by dust collection equipment, particularly cyclones and centrifuges. Such devices are usually installed in the "tail end" of the process circuit. However, despite the high effectiveness of these devices, their effectiveness decreases significantly as the size of solid particles in dust decreases, for instance, below 85-90% for cyclones of CN-15 type at particle size less than 10-15 microns. At the department "Machines and apparatuses of chemical productions" of Kazan National Research Technological University (KNRTU) a vortex apparatus has been developed, which retains high effectiveness at the size of solid particles in dust about 2.0-5.0 microns. In this paper, the gas dynamic resistance in the swirling region of the gas flow of the vortex device was investigated by changing the mode and velocity of the gas flow. Experimental research results of the resistance of the swirled flow of the vortex device for different modes and gas flow velocities are presented. The dependence and influence of the twist coefficient of the gas-air mixture (gas) flow on the resistance coefficient of the vortex device is revealed. Recommendations on application of research results for engineering calculations of similar apparatuses are given.

1 Introduction

Environmental protection from harmful emissions from the chemical, petrochemical and refining industries is an objective of paramount importance. Modern technologies and equipment play a key role in solving this problem. Increasing the effectiveness of

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technological processes and improving the design characteristics of apparatuses make it possible to significantly reduce the amount of gaseous, solid and liquid waste entering the environment. Effectiveness in dust and ash collecting equipment is a key parameter that determines both environmental safety and economic feasibility of production.

The effective reduction of fine dust emissions in industrial processes such as, for instance, detergent production, is an important objective in terms of environmental protection and human health. The fine dust generated in this production process contains various chemical components, including detergent active ingredients, allergens, and potentially toxic substances depending on the formulation. Breathing this dust can cause serious respiratory illnesses, and its release into the environment leads to soil and water contamination.

Retrofitting aspiration systems is one of the key ways to address environmental concerns. Traditional aspiration systems are often not efficient enough to capture fine dust, and miss a significant portion of it, resulting in atmospheric pollution. Modern approaches to renovation include the installation of more efficient filters, such as bag filters or electrostatic precipitators, which provide a higher degree of purification. The choice of filter type depends on the specific characteristics of the dust, particularly its particle size, density, and chemical composition. Bag filters work well for average to high dispersity dusts, while electrostatic precipitators are effective for very fine dusts that are difficult to capture by other methods. Currently, there are various designs that utilize centrifugal forces.

Devices that use centrifugal forces include cyclones, which are one of the most common and economical dust collectors. Their principle of operation is based on the swirling of the gas flow, which leads to the deposition of solid particles on the walls of the cyclone under the influence of centrifugal force. The effectiveness of cyclones depends on many factors including cyclone diameter, flow velocity, dust particle size and density. There are different types of cyclones that differ in design and characteristics. For instance, the cyclone models of the CH type, which differ in design characteristics, for instance, the angle of dust and gas flow entry into the apparatus. Such models are typical representatives of numerous productions in various industries, but their effectiveness of collecting fine dust (less than 5-10 microns) is limited. There are more efficient cyclones, for instance, models of SK-CN series, characterized by an elongated part of the conical part of the cyclone or Ogawa and Humboldt cyclones, which are designs of the same name scientists. Such cyclones use advanced design solutions such as multistage, optimized geometry, and the use of special inserts to increase effectiveness.

However, even the most efficient cyclones have their limitations. Very fine dust particles (less than 5 μm) require more advanced devices, for instance bag filters or electrostatic precipitators. Bag filters use a highly porous filter fabric that traps even the finest particles. Electrostatic precipitators are based on the principle of electrostatic precipitation of electrically charged particles.

The authors of this paper have designed a new generation of vortex dust separators, which is an improved design of a multi-section cyclone. The key difference is the use of three sequentially arranged zones with optimized geometry to increase the effectiveness in capturing particles as small as 3-5 microns. The multi-section design provides smoother deceleration of the gas flow and minimizes the removal of fine particles. Each sector has its own optimum gas flow velocity, ensuring efficient settling of different particle sizes. This makes it possible to achieve higher effectiveness of capture than traditional cyclones, surpassing both domestic analogs (SK-CN, CN series) and foreign models (Ogawa and Humboldt cyclones).

In addition to the geometry of KNITU vortex dust separator housings, additional elements can be integrated to improve effectiveness. For instance, the use of special inserts or coatings on the inner walls of the apparatus can reduce particle adhesion to the surface and improve particle removal. It is also possible to use various vibration cleaning methods to prevent clogging of the apparatus.

The research conducted at the department is aimed at optimizing the design parameters and selection of materials taking into account the specifics of captured particles and operating conditions.

In principle, the developed designs of vortex devices function according to the same principle as classical centrifugal dust collectors, based on the twisting of the flow, which leads to the effect on dust particles by centrifugal force. The multi-level design makes it possible for the three-zone centrifugal field to capture solid particles up to 2.5-4 microns in size with an effectiveness of about 90-99%.

The process of creating an engineering design methodology for a new type of vortex device involves consideration of various factors such as:

1. effectiveness of dust and ash collection in different gas-air systems;
2. Influence of design solutions, design parameters and operating modes on the result of capture;
3. of great importance is the gas-dynamic resistance formed in the apparatus and as a consequence is crucial to ensure environmental safety and efficient use of energy in the purification of gas-air mixtures.

The main objective of this research is to study the resistance that is formed in swirling flow of gas, dust. To analyze how different velocity modes and design features can help to minimize environmental emissions.

Various methods, including pilot plant experimental research and mathematical modeling, are used to evaluate the effectiveness of the developed vortex dust separators. Experimental research makes it possible to determine the effectiveness of capturing particles of different sizes depending on the flow parameters and design features of the apparatus. Mathematical modeling is used to optimize the design and predict the effectiveness of the apparatus under different conditions.

2 Modeling

Gas-dynamic resistance of the twisting zone (dust flow twisting zone) of the contaminated gas-air mixture in the vortex apparatus ΔP_{tw}, Pa was calculated according to the formula (1):

$$\Delta P_{tw} = \zeta_{tw} \cdot \frac{V_D^2}{2} \tag{1}$$

where ζ_{tw} – resistance coefficient of the contaminated gas twisting zone;

$V_D = \frac{G_V}{F_K}$ – is the velocity of the mixture in the cross section of the apparatus, m/s;

G_V – gas mixture volume flow rate, m^3/s;

$F_K = \frac{\pi}{4} \cdot (D^2 - d^2)$ – area of the cross / annular section of the apparatus, m; D - inner diameter of the apparatus, m;

d - outside diameter of the pipe for purified gas outlet, m.

The gas dynamic or drag resistance in the area of the swirler plays an important role in the process of gas flow control. It occurs when the contaminated gas-air mixture leaving the inlet connection changes its direction of travel and enters the channel designed for swirling the flow (see Figure 1). This process is particularly topical in nozzles where there is active interaction of gas with solid particles such as dust and ash. The change in flow direction is due to the differences in swirl angles that can be observed both in the inlet zone and in the nozzle itself, which in turn results in significant pressure losses.

In the swirling nozzle, where the gas encounters changes in geometry and velocities, so-called secondary flows occur, which are caused by additional friction from the nozzle surface. These secondary flows lead to non-uniformities in the distribution of velocity and pressure fields, making the process of determining the pressure gradient in the apparatus from specific components quite complex. As a result, for more accurate analysis and calculation it is necessary to take into account everything that can affect the character of the working medium movement during the dust and ash collection process.

To solve this objective at the department "Machines and apparatuses of chemical productions" of KNITU the mathematical model of determination of gas-dynamic resistance of the nozzle taking into account the vortex channel (1) was developed. This model takes into account almost all types of losses that can occur in various zones of the vortex apparatus in the process of dust and ash collection. The model describes the resistance coefficient, denoted as ζz, for each of these zones, which makes it possible to more accurately assess the effectiveness of the apparatus.

Additionally, it is worth noting that research into gas dynamic drag is important not only for optimizing the performance of dust and ash collectors, but also for improving the overall effectiveness of chemical plants. Understanding of the processes occurring in vortex channels can help in the development of new technologies and improvement of existing ones, which, in turn, will lead to reduction of energy consumption and improvement of the quality of purified gases.

Thus, studying gas dynamic drag in swirling devices is a multifaceted objective that requires a comprehensive approach and the use of modern mathematical models to accurately analyze and predict gas behavior under various conditions.

In formula (1), the coefficient ζz is a factor that depends on various characteristics. The main such characteristics are: the design of the apparatus and the technological mode of operation. These characteristics were determined by experimental method and presented in the form of dependence (2):

$$\zeta_{tw} = f_1\left(\bar{d}, \bar{S_1}, \overline{\Delta_1}, \overline{h_{tw}}, Re_{tw}\right) \quad (2)$$

where $\bar{d} = \frac{d}{D}$ – relative diameter of the pipe from which the purified gas exits;

$\bar{S}_1 = \frac{S_1}{D}$ – relative pitch of the flow twist in the nozzle;

$\Delta_1 = \frac{\Delta_1}{D}$ – relative radial clearance between equally spaced "wings" of the swirler and the inner diameter of the apparatus D;

$\bar{h}_a = \frac{h_a}{D}$ – relative height of gas flow twist;

$Re_a = \frac{V_D \cdot d_3 \cdot \rho}{\mu}$ – Reynolds criterion, similarity coefficient - characterizing the flow of the working medium;

μ - dynamic viscosity of the gas mixture, Pa·s;

ρ_a - density of air (gas mixture), kg/m^3;

$d_e = D - d$ – equivalent diameter, m.

Formula (2) was transformed into the following form:

$$\zeta_{tw} = f_2\left(\theta_{ax\,tw}, \overline{\Delta_1}, \overline{h_{tw}}, Re_{tw}\right) \quad (3)$$

where $\theta_{ax\,tw} = \frac{\tan\varphi_{av} \cdot (1+\overline{d^2})}{(1+\bar{d})}$ – twist parameter from the twisting device [1], $\tan\varphi_{av} = \frac{\pi \cdot d_{av}}{S}$;

$d_{av} = \frac{D-d}{2}$ - average diameter of the swirl channel of the nozzle;

φ_{av}- average twist angle, deg.

The effectiveness of the device depends on its operating modes of the apparatus, and the effect of resistance in the swirling flow zone was evaluated using physical experiments. Ambient air, namely room air, was used as the working medium. At the same time, the design of dust and ash collecting devices remained unchanged: the diameter of the apparatus is $D_{ап}$ = 120 mm, outside diameter of air (gas) outlet pipe) d_{ax} = 47 mm, parameters of the air (gas) inlet nozzle - width and height: a = 24 mm, b = 60 mm. The methods of physical experiments are given in the literature [1-3].

Thus, the design parameters are as follows:

$$\bar{R}_{ax} = \frac{2R_{ax}}{D} = 0.8;\ \bar{R}_{ax} = \frac{a \cdot b}{F_K} = 0.15\ .$$

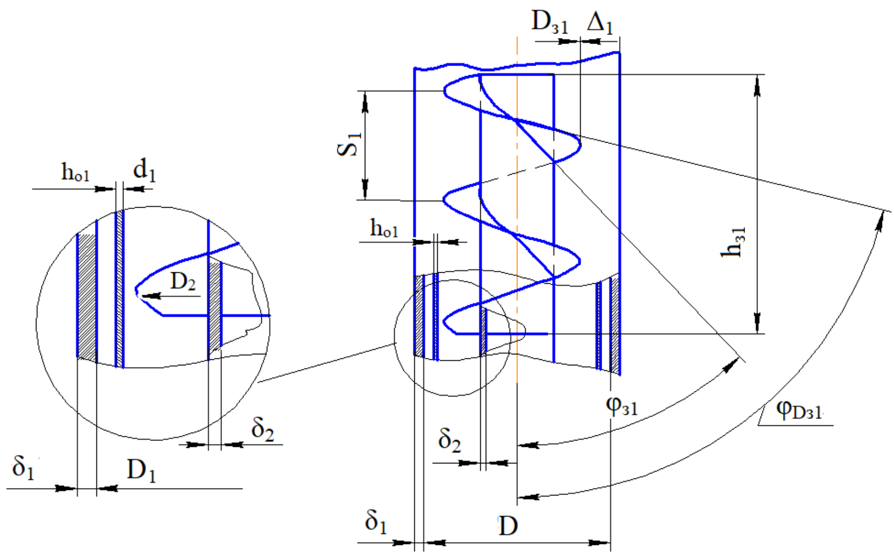
The air (gas) flow rate was set in the range from 50 to 250 m^3/h, and the air temperature was 20±1°C.

During the physical experiments, the gas dynamic resistance created by the nozzle was calculated as the difference in resistance between the air (gas) inlet and outlet, i.e., ΔP1 and ΔP12, Pa, respectively:

$$\Delta P_{tw} = \Delta P_{12} - \Delta P_{1}. \tag{4}$$

The peculiarity of the twisting device consisted in the presence of the main and additional twisting zones (Figure 1):

- main swirling zone (no h_{o1}), has structural dimensions: pitch of the swirling wing S_1 = 48 mm, number of turns n_1=4, distance between the device body and the nozzle Δ_1 = 6 mm;
- additional swirling zone (presence ho1) has a cylindrical liner (additional wall) to create high velocities and correspondingly higher centrifugal force than in the main zone. Distance between the apparatus body and cylindrical liner (additional wall) h_{o1} = 6 mm.



Fig, 1. Screwdriving device with main and additional screwdriving zones.

3 Results

Figure 2 shows the dependence of the gas dynamic resistance of the swirling zone of the apparatus on the velocity of air (gas mixture). Analyzing this graph, it is noticed that there is a significant resistance gradient. Namely, the resistance of the swirling zone of the apparatus significantly increases exponentially at gas velocities $V_D=4\div7$ m/s.

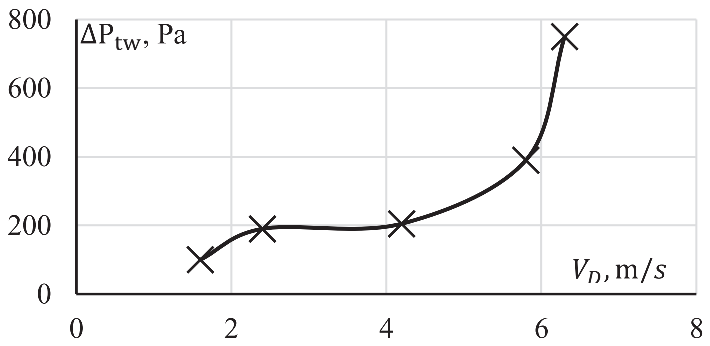


Fig. 2. Dependence of gas-dynamic resistance of the swirling zone of the apparatus ΔP_{tw} from the velocity of air (gas mixture) V_D.

The resistance coefficient of the contaminated gas torsion zone ζ_{tw} was determined from equation (1) using the values of ΔP_{tw}, Pa known from physical experiments as a function depending on the velocity of air (gas mixture) movement) V_D, m/s:

$$\zeta_{tw} = \frac{2\cdot\Delta P_{tw}}{\rho_a\cdot V_D^2} \quad (5)$$

Figure 3 shows the dependence of the resistance coefficient of the contaminated gas twisting zone ζ_{tw} in the nozzle or swirl element of the considered apparatus from the Reynolds criterion Re_z.

Analyzing the presented data (Figure 3), we can conclude that there is a significant influence of the Reynolds number (Re_z) on the drag coefficient of the swirled zone of the vortex nozzle (ζ_{tw}). As Rez increases, there is a tendency to decrease ζ_{tw}. This effect is especially pronounced when the critical value of Re_z is reached ≈ (35÷40)·103. In this region, a transition to the auto model regime is observed, when the resistance ceases to depend on Rez and is determined solely by the roughness of the apparatus surfaces.

At smaller values of Re_z ($Re_z \leq (35\div40)\cdot10^3$) resistance coefficient is influenced by both operating parameters (flow rate, swirl) and design features of the apparatus. In particular, the geometry of the inlet nozzle significantly affects the gas dynamic resistance of the swirled zone.

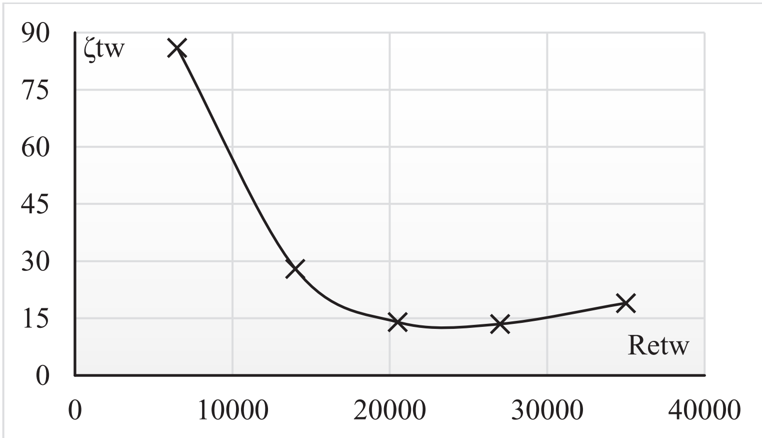


Fig. 3. Dependence of the gas dynamic resistance coefficient of the swirling zone ζ_{tw} on the Reynolds criterion Re_{tw}.

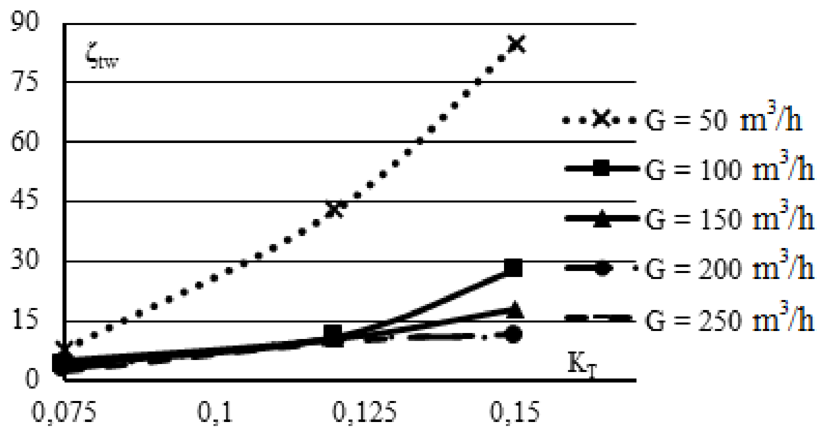


Fig. 4. Dependence of the resistance coefficient of the helical zone ζ_{tw} on the twist coefficient K_t,

The research shown in (Figure 4) has shown that an increase in the swirl coefficient (SC) and air flow rate through the vortex device leads to an increase in the drag coefficient ζ_{tw}. This is due to the increase in the intensity of vortex motion and the increase in frictional energy loss. That is, the role of the swirl coefficient and air flow rate is quite a significant factor in dust or ash capture

The obtained results qualitatively agree with the data presented in the literature [4-7] for counterflow cyclones, vortex chambers and other similar devices. This indicates the general regularity of the influence of Reynolds number and design features on the resistance of swirling flows.

Additional factors affecting drag besides Reynolds number, swirl ratio, and airflow rate on the drag of the swirled zone:

1. Gas nozzle profile shape: Optimizing the shape of the nozzle profile makes it possible to reduce energy loss for flow separation and drag;
2. Material of manufacture: The surface roughness of the material affects the intensity of turbulence and, consequently, the friction losses;
3. Presence of additional elements: Various elements (reflectors, turbulizers) may be present inside the vortex apparatus which affect the flow structure and resistance.

For a deeper understanding of the processes occurring in the swirled zone of the apparatus considered in this research, it is necessary to conduct additional research aimed at:

1. Detailed studying of the flow structure: The use of modern methods of experimental diagnostics (laser Doppler anemometry, hot wire method) will make it possible to obtain detailed information on the distribution of velocities and pressures in the flow;
2. Numerical simulation: Development and application of numerical models will make it possible to study the influence of various parameters on the flow characteristics and optimize the design of the vortex apparatus;
3. Experimental research on the effect of different design features: Conducting a series of experiments with different designs of swirl elements will make it possible to identify the optimum geometric parameters.

Thus, the analysis of this research has shown that the resistance of the swirled zone of a vortex apparatus is a complex function of various factors. For effective design and optimization of such devices, it is necessary to take into account both general regularities and specific features of a particular design. Further research in this area will make it possible to develop more perfect and efficient vortex apparatuses for various technological processes.

4 Conclusions

1. Research on the gas dynamic resistance of the inlet section of the swirling device has been carried out and conclusions regarding the influence of the mode parameters inside the swirling device are presented;
2. The influence of the air (gas) flow twist coefficient on the resistance coefficient inside the vortex device is revealed;
3. In addition, the reconstruction may include optimization of air flow velocity, improvement of equipment sealing and introduction of additional aspiration points at the locations with the highest dust generation. To maximize effectiveness, the design of the aspiration system should take into account the specifics of the process, calculating the concentration of dust in the air and determining the optimal parameters of filter operation. It is important to regularly monitor the effectiveness of the system, including measuring the dust concentration in the emissions and assessing the wear of the filter elements. In case of a significant increase in dust concentration, maintenance and replacement of filters should be carried out promptly. For the most comprehensive solution, in addition to reconstruction of aspiration, the possibility of replacing process equipment with more modern, less dust-forming equipment, or introducing dry or wet dust suppression methods directly in the area of dust generation should be considered. Only an integrated approach will make it possible to ensure effective reduction of fine dust emissions and create safe working conditions at production facilities, for instance, in the production of detergents.

Development and introduction of new highly efficient dust collecting devices, such as vortex dust separators KNITU, is an important step towards improving environmental safety of chemical, petrochemical and refining industries. It contributes to the reduction of harmful impact on the environment and improvement of the quality of life of the population in the areas where the enterprises are located. Further research in this area aims to develop even more efficient and cost-effective devices adapted to different types of production and types of pollutants. This includes the development of new materials, optimization of designs and improvement of methods for controlling the dust collection process. In the future, the integration of such devices into automated control systems will make it possible to ensure continuous monitoring and optimization of dust collection systems, achieving maximum effectiveness at minimum cost.

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