ABSTRACT

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Development and calculation of cyclone-vortex apparatus for carrying out the combined processes of mass transfer and dedusting

The relevance of the dissertation research. Wet-type devices, which include hollow nozzle scrubbers, poppet and nozzle (with a stationary nozzle) devices, various types of rotoclons, Venturi scrubbers have found a fairly wide application for capturing weakly adhering dusts and absorbing easily soluble gases. They usually have a single-circuit irrigation system. However, for complex cleaning of gases containing adhesive dusts, their use is limited, because there are serious problems associated with the overgrowth of internal devices with deposits, which negatively affects the efficiency and operational reliability of the device.

Combined-type devices - inertial-turbulent with a movable (regular) nozzle (ITMN containing a zone of shock-inertial interaction of a gas flow with a liquid mirror and a packed zone with gas-droplet interaction refer to devices with internal circulation of liquid using a single-circuit irrigation system. gas of soluble dust, a single-circuit irrigation system leads to a decrease in the degree of absorption of both readily soluble and poorly soluble gases. This is due to the presence of an additional dissolved component in the irrigation solution (not interacting with the absorbed gas), which reduces the solubility of gases and leads to an increase in the equilibrium constant.

This problem is solved in the design of a combined device with autonomous irrigation circuits, separately for each of the zones - shock-inertia and nozzle, which prevent the formation of deposits and increase the driving force of the absorption process. However, studies have shown that the combined device with autonomous irrigation circuits (one of which uses a shock mechanism) has significant hydraulic resistance.

We use it for separate production of cyclone-vortex action with autonomous contact stages. In the lower stage of contact, the centrifugal mechanism of liquid capture in the upper stage of contact, dust capture and absorption process are used using the laws of vortex interaction of gas and liquid.

At the same time, the lack of relevant research and scientifically based calculation methods hinders the introduction of the cyclone-vortex device in the industry.

In this regard, research into the processes of dust collection and mass transfer, the development of a methodology for calculating and designing cyclone-vortex apparatus, recommendations for their operation are relevant.

The subject of research is the hydrodynamic laws, parameters of dust collection and mass transfer.

Purpose of the work: development of scientific foundations of dust collection and mass transfer processes in a cyclone-vortex action apparatus, creation of a scientifically grounded method of calculation and design, verification of the results obtained in experimental industrial conditions and implementation in industry.

Scientific novelty of the research:

- on the basis of the revealed regularities of the gas flow in a spiral, the vortex flow of gas and liquid flows in the volume of a regularly placed packing, equations were obtained for calculating the hydraulic resistance of the cyclone and vortex stages of contact, their total resistance, the amount of retained liquid and the gas content of the packed zone layer;
- using balance equations, the theory of local isotropic turbulence and using a dissipative approach, equations are obtained for determining the film thickness on the surface of plate packing elements, the diameter of jets and the average diameter of drops;
- on the basis of the centrifugal-inertial mechanism for trapping solid particles, a mathematical model of the centrifugal and inertial sedimentation of particles in the cyclone stage of the apparatus, based on equations for determining the design stages of the established and modified inertial parameter characterizing the state of the dust-gas mixture;
- taking into account the turbulent-diffusion mechanism of capturing solid particles on liquid droplets, a mathematical description of the turbulent and diffusion deposition of particles in the nozzle zone of the apparatus is given, based on the equation for determining the coefficient of turbulent diffusion of particles taking into account the degree of their entrainment by turbulent pulsations;
- using the dissipative approach, a calculated dependence for the mass transfer coefficients in the gas phase is obtained.

The theoretical significance of the study lies in the fact that, on the basis of theoretical and experimental studies of the regularities of the gas flow in a spiral, the vortex interaction of flows in the volume of a regularly placed packing, the methodology for calculating the cyclone-vortex action apparatus for carrying out the processes of dust collection and absorption has been scientifically substantiated.

Practical value. The design of the cyclone-vortex action apparatus, protected by the RK patent No. 33662, has been developed.

Methods of calculation, recommendations for the design and operation of cyclone-vortex action apparatus for carrying out dust collection and absorption processes have been developed.

Publications on the research topic. 10 articles have been published on the topic of the dissertation, including 6 articles in materials of international conferences, 1 article in a publication included in the international base of scientific journals SCOPUS (in the direction: Engineering: General Engineering. Percentile - 31), 3 articles in journals recommended by the Committee for Provision quality in the field of education and science of the Ministry of Education and Science of the Republic of Kazakhstan, 1 patent of the Republic of Kazakhstan was received. The content of the articles covers the main content of the dissertation.

The introduction gives an assessment of the current state of the solved scientific problem, the Foundation and initial data for the development of the topic, justification of the need for scientific research, information on the planned scientific and technical level of development and the Metrology support of the thesis, the relevance and novelty of the topic, the relationship of this work with other research works, the aim, object and subject, objectives of the study, methodology, provisions for protection, practical value, and approbation of practical results.

The first section analyzes the operation of gas cleaning equipment using centrifugal and vortex flow analysis, as well as the methods for calculating them. Based on the analysis carried out, the research tasks were formulated.

The second section describes an experimental setup for studying hydrodynamic parameters, as well as methods for conducting experiments.

The range of changes in operating parameters in the studies being carried out: gas velocity $w_г$ - 1÷5 m/s in the vortex stage, which corresponds to the gas velocity at the inlet to the cyclone stage $W_{вх}$ =4,575÷22,875 m/s; irrigation density L - 25÷100 $m^3/m^2 \cdot h$

Constructive relations of cyclone and vortex contact stages are given.

The results of investigations of operating parameters on the hydrodynamic characteristics of the cyclone stage of the apparatus are presented. It is noted that an increase in hydraulic resistance with an increase in gas velocity is due to an increase in dynamic head and losses associated with a change in the direction of gas movement and friction losses.

To study the regularities of the interaction of the gas and liquid phases in the vortex zone of the cyclone-vortex action apparatus, studies of hydrodynamic parameters (hydraulic resistance and the amount of retained liquid), visual observations and photographing of the layer structure were carried out.

The studies were carried out with constant design parameters of the lamellar packing ($t_в/b=2$; $t_р/b=2$) in a given range of operating parameters.

When the gas flow velocity changes, the presence of three hydrodynamic modes is noted: film-drop, drop-drop, and spray-flow. As the gas velocity increases, the dynamic pressure increases, which increases the hydraulic resistance and keeps more liquid in the nozzle volume, while the calculated gas content decreases. Increasing the irrigation density increases the amount of liquid retained and reduces the calculated gas content.

To calculate the hydraulic resistance of the cyclone-vortex apparatus, the following equation is proposed:

$$\Delta P_{ап} = \Delta P_{ц} + \Delta P_{L} \quad (1)$$

The hydraulic resistance of the cyclone stage is determined by the equation:

$$\Delta P_{ц} = \Delta P_{вх} + \Delta P_{кольц} + \Delta P_{вых}, \quad (2)$$

To calculate the hydraulic resistance of the components of the cyclone stage of the contact $\Delta P_{вх}$ - inlet section; $\Delta P_{кольц}$ - ring zone; $\Delta P_{вых}$ - the outlet section proposed a classic calculated dependence in which the subscripts at ΔP, ξ and w correspond to the name of the calculated section. As a result of the research carried out, the experimental values of the resistance coefficients were obtained: $\xi_{вх} = 3{,}32$; $\xi_{кольц} = 4{,}1$; $\xi_{вых} = 5{,}7$.

The hydraulic resistance of the packed zone is determined according to the known equation for apparatus with a regular movable nozzle.
The resistance coefficient included in it is calculated by the formula:

$$\xi_L = 0{,}7 \cdot \theta_{в} \cdot \theta_{р} \cdot \frac{\mathrm{Re}_{ж}^{0{,}25}}{\mathrm{Re}_{г}^{0{,}1}}. \tag{3}$$

The amount of retained fluid (CFL) is determined by the equation:

$$h_0 = (h_{пл} + h_k) \cdot \frac{H}{t_{в}}, \tag{4}$$

in which the film component of the CLS:

$$h_{пл} = \frac{\delta_{пл} \cdot b^2}{t_p^2}. \tag{5}$$

Drip component (CLS):

$$h_k = 0{,}88 \cdot \xi_L \frac{\rho_{г} W_{г}^2}{2g\rho_{ж}} \cdot \frac{(2-\varepsilon_0)(1-\varepsilon_0^2)}{\varepsilon_0^2} \tag{6}$$

Gas content is calculated by the formula:

$$\varphi = \varepsilon - \frac{h_0}{H} \tag{7}$$

The expressions for the structural components of the liquid phase, $\delta_{пл}$, $U_{стр}$, $d_{стр}$ and d_k, obtained for the packed zone of the cyclone-vortex action apparatus, take into account the features of the regime and design parameters of the apparatus, as well as the physical properties of the interacting flows.

In the third section, a methodology for studying the overall and fractional efficiency of the dust collection process and the results of research in the cyclonic and vortex stages of contact are presented.
To calculate the efficiency of the cyclone (dry) stage, a centrifugal - inertial model is proposed, according to which:

$$\eta_C = 1 - \exp\left[-2(C_k \cdot \psi)^{1/(2n+2)}\right] \tag{8}$$

The coefficient $C_к$, depending on the design ratios of the dry stage, is calculated by the equation:

$$C_к = \frac{\pi \cdot D_ц^2}{a \cdot в_1} \cdot \left[1 - \left(\frac{d}{D_ц}\right)^2\right] \cdot \left(\frac{2 \cdot h_T}{D_ц} - \frac{h_в}{D_ц}\right) + \left[\left(\frac{d}{D_ц}\right)^2 - \left(\frac{d_1}{D_ц}\right)^2\right] \cdot \left(\frac{4 \cdot H_ц}{D_ц} + \frac{4 \cdot H_к}{D_ц}\right) \tag{9}$$

Modified inertial parameter characterizing the state of the dust-gas mixture:

$$\psi = \frac{d_ч^2 \cdot \rho_ч \cdot W_{вх}}{18\mu_г \cdot D_ц}(n+1), \tag{10}$$

The quantity $n = 1 - (1 - 0{,}0165 \cdot D_ц^{0{,}14}) \cdot \left(\frac{T_г}{283}\right)^{0{,}3}$.

To calculate the efficiency of the packed zone of the apparatus, a turbulent-diffusion model of the deposition of solid particles has been developed:

$$\eta_м = 2{,}97 \cdot \left(\frac{W_г \cdot d_k}{D_т}\right)^{-1/4}. \tag{11}$$

Turbulent diffusion coefficient:

$$D_T = B_T \cdot (\xi_L)^{1/3} \cdot (1 - \varepsilon_0)^{1/3} \cdot \left(\frac{H}{t_B}\right)^{1/3} \cdot \left(\frac{\rho_г}{\rho_ж}\right)^{1/3} \cdot \left(\frac{1}{h_0}\right)^{1/3} \cdot d_k^{4/3} \cdot u_г \cdot Stk, \tag{12}$$

where $B_T = 8{,}38 \cdot (1 - \varphi)$ is the correction factor; $Stk = \frac{\rho_ч \cdot d_ч^2 \cdot u_ч}{18\mu_г \cdot d_k}$ - Stokes criterion.

The overall efficiency of the cyclone-vortex apparatus, taking into account the efficiency of the dry and wet stages, can be calculated using the formula:

$$\eta_{общ} = 1 - (1 - \eta_c)(1 - \eta_м). \tag{13}$$

In the fourth section, methods and results of studies of mass transfer data of a cyclone-vortex action apparatus are presented, depending on the mode of parameters. At the same time, the analogy of changes in the obtained curves with the curves of hydrodynamic parameters was noted.

To calculate the mass transfer coefficients in the gas phase, based on the dissipative approach, the main provisions of the theory of local isotropic turbulence and the first Fick law, the equation is obtained:

$$\beta_{\text{гs}} = B_{\text{г}} \left[D_{\square}^{2} \cdot \frac{\xi_L (1-\varepsilon) \cdot U_{\square}^{3}}{\delta_{\square} \cdot \varphi_{\square} \cdot \nu_{\square}} \right]^{1/4}, \tag{14}$$

where $B_{\text{г}} = 6{,}44/(1\text{-}\varepsilon)^{1/4}$ - is the coefficient of proportionality, determined empirically.

The fifth section contains design recommendations, which contain information on the choice of operating and design parameters, as well as the results of testing and implementation of a cyclone-vortex apparatus.

Based on the results of the studies, the design of an industrial cyclone-vortex apparatus was developed, which was introduced at the Aktobe Plant of Chromium Compounds JSC in the process flow for cleaning gases leaving the KS dryer in the production of chromium sulfate. At the same time, the concentration of dust emissions was reduced to $C_{\text{цик.вихр}}$=0,088 g/s, which is 4.6 times lower than the standard indicators.

In the conclusion, brief conclusions are given on the results of dissertation research, an assessment of the completeness of solutions to the assigned tasks, recommendations and initial data on the specific use of the results are developed, an assessment of the technical and economic efficiency of implementation and the scientific level of the work performed in comparison with the best achievements in this area is given.