Design And Hydrodynamics Theory Of A Device With A Fructose Cone Contact Element

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ABSTRACT

The article theoretically presents the structure, operating principle and hydrodynamic resistance of an apparatus with a truncated conical contact element for wet cleaning of coke dust particles with an average size of 8.7 µm in 1 m^3 of dusty gas. The design of the apparatus is formulated in the MATLAB programming environment based on parametric evaluation of gas consumption, liquid consumption, contact element geometry, free cross-sectional area and the effect of a cyclonic droplet catcher. In the proposed solution, a liquid jet impinges on a truncated conical element located in the centre of the working chamber, forming a liquid screen, a layer of small droplets and a liquid film along the wall. As a result, the probability of dust particles coming into contact with water droplets and a liquid curtain increases.

Keywords: wet dust removal, coke dust, liquid screen, truncated cone contact element, gas-liquid flow, droplet catcher, hydraulic resistance, MATLAB

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Introduction

In the oil refining industry, during thermal cracking, coking, coke cooling, crushing, sorting, drying and pneumatic transportation of heavy oil residues, dusty gases containing finely dispersed coke particles are formed. Especially in coke ovens, coke unloading units, conveyors, crushers and drying technological lines, particles with a size of 5–20 µm are easily carried away by the gas flow and pose a risk of being released into the atmosphere. It is difficult to capture such small particles with high efficiency using only gravity chambers or simple inertial separators, since their mass is small and aerodynamic resistance is high.

Petroleum coke dust is a physicochemically high-carbon, black, hard and abrasive dispersed material. It mainly contains carbon, small amounts of hydrogen, sulfur, mineral ash and metal additives such as vanadium, nickel and iron. Since the surface of coke particles is relatively hydrophobic, simple wetting is not enough to separate them from the gas stream; it is necessary to bring the particles into forced contact with water droplets, a liquid film and a film formed on the wall of the working chamber.

$d = 8.7\ \mu m$ in 1 m^3 of dusty gas was taken as a basis. Particles of this size tend to move with the gas flow, and for their effective capture, it is necessary to increase the gas-liquid contact surface, evenly distribute water droplets along the working section, and increase the probability of particle-droplet collision. For this purpose, a wet dust collector design with a truncated conical contact element serving to mechanically break up the liquid jet inside the working chamber, spread it in the radial direction, and form a water film was recommended.

Parametric and visual evaluation methods were used in the MATLAB software environment to justify the design of the apparatus. In this case, the relationships between the inlet gas velocity, gas consumption, working pipe diameter, truncated cone large base diameter, water consumption, free cross-sectional area, actual gas velocity, gas-liquid ratio and hydraulic resistance were analysed. Using the visual evaluation criterion, the stable operating range of the apparatus in various combinations of parameters, the conditions for the formation of a liquid film and the factors affecting energy consumption were evaluated on the basis of graphs.

For the study, the inlet gas velocity υ gas = 5–25 m/s, the diameter of the large base of the truncated cone d k = 80, 90, 100 mm and the water flow rate Qs = 0.07–0.378 m^3/h were taken. The diameter of the dust inlet and main working pipe was set to D = 120 mm. These ranges allow a comprehensive assessment of the influence of the gas flow rate, liquid flow rate and contact element geometry on the efficiency of coke dust particle capture.

The purpose of the work is to substantiate the design of an apparatus for wet cleaning of fine dispersed coke dust particles generated in the oil refining industry using a water curtain and a truncated cone contact element, to describe its operating principle, and to select the range of research variable parameters based on visual evaluation criteria in the MATLAB environment. The general structural diagram of the apparatus is shown in Figure 1.

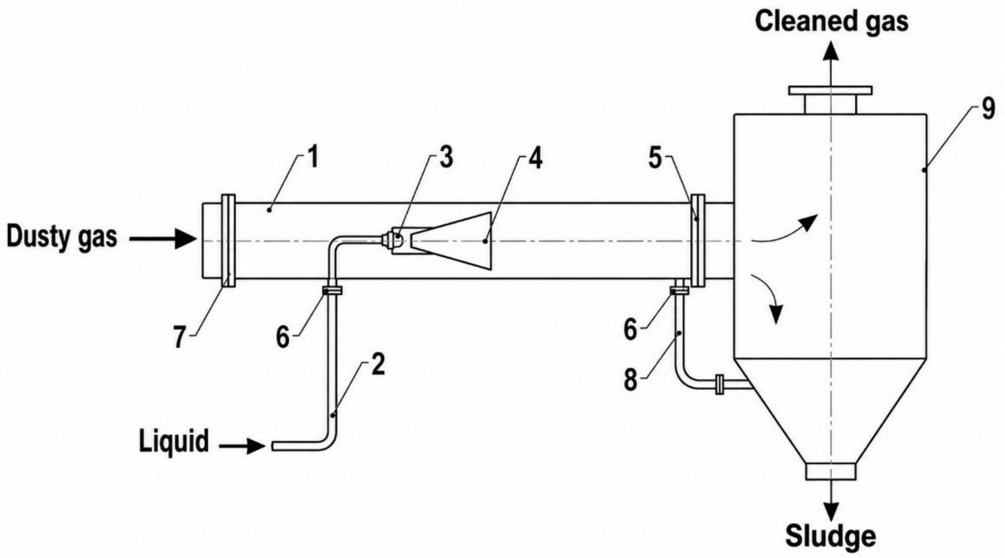

Figure 1. Preliminary structural diagram and main parts of the apparatus.

The device is based on introducing dusty gas into the working chamber, spraying water through a nozzle, impinging a liquid jet on a truncated cone contact element, directing the resulting gas-liquid flow to a cyclone-shaped drop catcher, and removing the slurry from the bottom. In this design, the working chamber is made in the form of a horizontal pipe, inside which the water sprayer and the contact element are placed in a coaxial position.

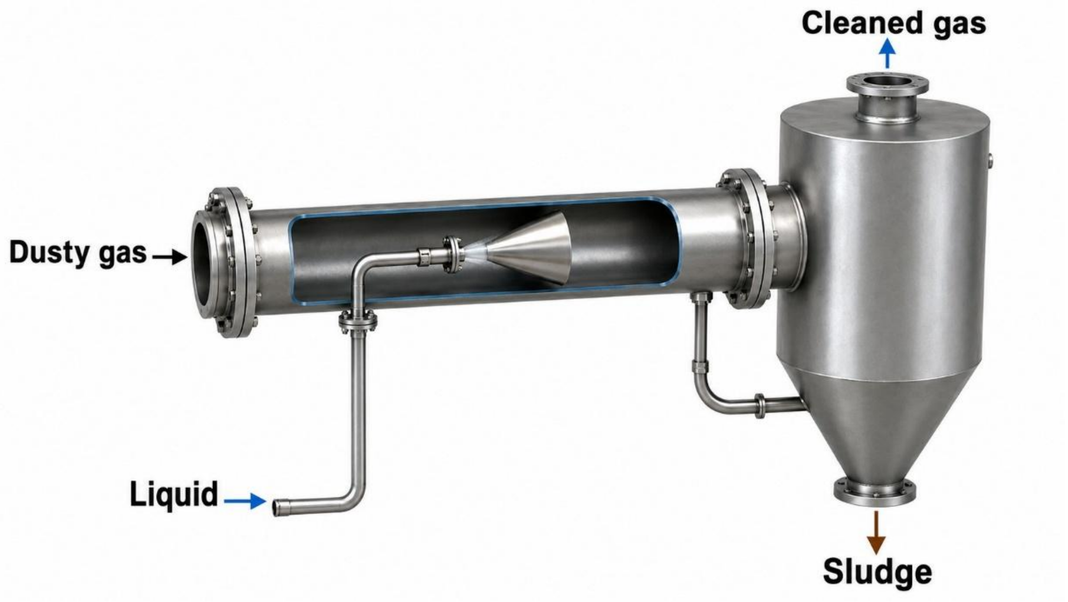

Figure 2. 3D CAD view of the apparatus.

Figure 2 shows a structural view of the apparatus that can be manufactured in industrial conditions. Since the working chamber pipe is shown in cross-section, the location of the liquid spray nozzle and the truncated cone contact element is clearly visible. On the right side of the apparatus is a cylindrical-conical cyclone drop catcher, which serves to separate liquid droplets and slurry particles that are carried away with the gas.

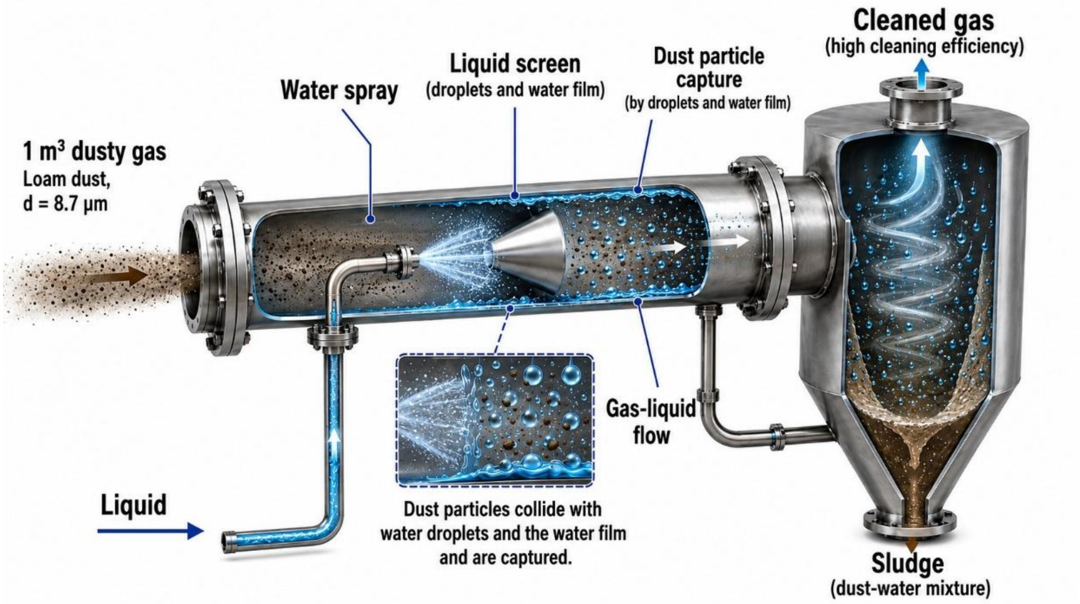

Figure 3. 3D visual model of the water purification process of dust particles with a diameter of d = 8.7 µm in 1 m^3 of gas.

Figure 3 shows the gradual capture of dust particles in the water spray, liquid screen, droplet layer and cyclonic separation zone. Dust particles are depicted as brown-gray dots, and water droplets are depicted as blue droplets. This figure shows that the cleaning in the apparatus is based on several sequential contact and separation mechanisms, not just one process.

Structure of the apparatus. The apparatus consists of the following main parts: a working chamber pipe (1) for directing the dusty gas, a liquid transfer pipe (2), a liquid spray nozzle (3), a truncated conical contact element (4) for returning the liquid and forming a screen, a flange connecting the working chamber with the drop catcher (5), connecting flanges (6), a flange connecting to the dust source (7), a slurry discharge pipe (8) and a cyclone-like device (9) for trapping liquid droplets in the purified gas.

Table 1
Working parts of the device and their functions

Sign	Part name	Task
1	Working chamber pipe	It receives a dusty gas flow and forms the main gas-liquid contact zone.
2	Fluid pipe	It delivers water to the nozzle inside the working chamber.
3	Stusser	It sprays water at high speed in the form of a jet or small droplets.
4	Truncated cone contact element	It breaks up the water jet, forming a liquid screen and wall film.
5	Connecting flange	The worker hermetically connects the chamber to the cyclone-shaped droplet catcher.
6	Flanges	Provides ease of assembly, disassembly and repair.
7	Inlet flange	Connects the device to the dust source.
8	Sludge pipe	It directs the dust mixture captured with water to the bottom.
9	Cyclonic drip catcher	It separates the droplets, pushes the slurry down, and expels the purified gas up.

The principle of operation of the device. The dusty gas is fed through the inlet flange into the working chamber pipe. The dust particles contained in the gas stream move along the working chamber. At the same time, water is supplied to the nozzle through the liquid pipe and is directed from the nozzle to the centre of the working chamber at high speed.

The water jet hits the small base of the truncated cone contact element. As a result of this impact, the jet breaks up, separates into small droplets and forms a liquid screen along the cross-sectional surface of the pipe. The dusty gas is forced to pass through this liquid screen. As a result, the particles collide with the water droplets, some of which adhere to the droplet surface, while the other part is caught by the liquid screen.

The angular surface of the truncated conical contact element directs the gas-liquid flow to the walls of the working chamber. A liquid film is formed on the wall. This film acts as the second cleaning layer of the apparatus, since small particles remaining in the gas composition come into contact with the liquid layer on the wall and turn into slurry.

The gas-liquid mixture leaving the working chamber enters a cyclone-shaped droplet catcher. In this zone, the flow begins to rotate. Under the influence of centrifugal force, water droplets and sludge particles hit the walls and fall into the lower conical section. The purified gas is discharged through the upper outlet pipe.

In conventional scrubbers, water is usually sprayed into the gas stream using a nozzle. In such a scheme, the probability of dust particles colliding with water is strongly dependent on the droplet diameter, gas velocity, and chamber length. If the droplets are large, small particles can bypass the droplets with flow lines; if the droplets are too small, they can be carried away by the scrubbed gas.

In the proposed apparatus, the liquid is not just sprayed, but also impinges on the truncated conical contact element, further fragmenting and forming a liquid screen across the chamber cross-section. Due to this, the gas flow directly intersects with the water layer. This is important for capturing finely dispersed, i.e., 8-10 µm, water vapour particles.

Another advantage of the device is that it combines the mechanisms of droplet collision, liquid screen passage, wall film capture, and cyclonic droplet separation. Such a multi-stage contact mechanism increases the purification efficiency and reduces the amount of water droplets that are carried away with the purified gas.

The design does not contain complex rotating parts. This simplifies the manufacture, assembly and maintenance of the device. The main energy consumption is associated with the ventilator pressure and the water transfer pump, and the correct assessment of the hydrodynamic resistance is crucial in determining the energy efficiency of the device.

To develop the device design in the MATLAB programming environment, the relationships between gas and liquid flow rates, working chamber diameter, contact element dimensions, and free cross-sectional area were initially calculated. These calculations allowed us to assess how the device geometry affects the hydrodynamic resistance.

$$Q_g = v_g F_k \tag{1}$$

$$F_k = \frac{\pi D_k^2}{4} \tag{2}$$

$$Q_s = v_{\mathrm{s}} F_s \tag{3}$$

$$L_g = \frac{Q_s}{Q_g} \tag{4}$$

$$S_k = \left(R_1 + R_2\right) l_k \tag{5}$$

$$l_k = \sqrt{\left(\left(R_1 - R_2\right)^2 + h_{к}^2\right)} \tag{6}$$

$$F_{er} = F_k - F_{kon} - F_q \tag{7}$$

$$v_{haq} = \frac{Q_g}{F_{er}} \tag{8}$$

where $Q g$ - gas consumption, m^3/s; $v g$ - gas velocity in the working chamber, m/s; $F k$ - chamber cross-section, m^2; $D k$ - working chamber diameter, m; $Q s$ - water consumption, m^3/s; $v s$ - water outlet velocity from the nozzle, m/s; $d s$ - nozzle diameter, m; $L g$ - water consumption relative to gas volume; $S k$ - contact surface of the truncated conical element; $F er$ - free cross-sectional area; $v haq$ - actual gas velocity in the contact zone.

When coke dust is cleaned with water, the main process is the contact of particles with water droplets, a liquid screen, and a wall film. For particles of 8.7 µm in size, inertial collision and capture mechanisms are the main ones. Diffusion convergence appears as an additional mechanism for even smaller fractions.

$$Stk = \frac{\rho_p \, d_p^2 v_g}{18 \, \mu_g \, d_t} \tag{9}$$

where Stk is the Stokes criterion; ρp is the density of the dust particle, kg/m^3; $d p$ is the diameter of the dust particle, m; $v g$ is the gas velocity, m/s; μg is the dynamic viscosity of the gas, Pa s; $d t$ is the diameter of the water drop, m. As the Stokes criterion increases, the probability of a particle hitting a water drop increases.

$$\eta = \frac{C_{kir} - C_{chiq}}{C_{kir}} 100\% \tag{10}$$

where *η* is the cleaning efficiency, %; *C in* - the dust concentration in the gas entering the apparatus, g/m^3; *C out* - the dust concentration in the gas leaving the apparatus, g/m^3.

The cleaning efficiency is determined by the liquid consumption, gas velocity, droplet diameter, contact surface, and the separation process in the cyclonic droplet catcher.

$$P_u = f\left(v_g,\, Q_s,\, S_k,\, d_p,\, d_t\right) \tag{11}$$

The probability of capture *P u is* the gas velocity *v g* , water consumption *Q s* , contact surface *S k* , dust particle diameter *d,* and the water droplet diameter *d, which can be considered as a function of t* . It is desirable to determine this relationship in the form of a regression model based on experimental results.

The hydrodynamic resistance in the apparatus differs from the frictional resistance in a simple pipe. Because the liquid is sprayed into the working chamber, the contact element partially blocks the flow, a gas-liquid mixture is formed, and then the flow enters the cyclone-shaped drop catcher and moves in a circular motion. Therefore, it is advisable to calculate the total resistance separately by zones. In this case, the total hydraulic resistance of the apparatus *ΔP um* can be written as follows, Pa;

$$\Delta P_{um} = \Delta P_{kir} + \Delta P_{ish} + \Delta P_{sht} + \Delta P_{kon} + \Delta P_{gs} + \Delta P_{fl} + \Delta P_{cyc} + \Delta P_{chiq} \tag{12}$$

where, Pa; *ΔP in* - pressure loss at the inlet, Pa; *ΔP out* - friction resistance in the working chamber pipe, Pa; *ΔP sht* - resistance due to the action of the nozzle and the liquid spray zone, Pa; ΔP con - local resistance in the truncated conical contact element, Pa; *ΔP gs* - additional resistance due to the gas-liquid mixture, Pa; *ΔP fl* - resistance in the flange and connecting parts, Pa; *ΔP cyc* - resistance in the cyclone drop catcher, Pa; *ΔP out* - resistance at the outlet.

The friction resistance in the working chamber is determined as follows, Pa;

$$\Delta P_{ish} = \lambda \left(\frac{L_k}{D_k} \right) \cdot \left(\frac{\rho_g\, v_g^2}{2} \right) \tag{13}$$

$$Re_g = \frac{\rho_g\, v_g\, D_k}{\mu_g} \tag{14}$$

$$\lambda = \frac{0.3164}{Re_g^{0.25}} \tag{1 5 }$$

The working chamber moves in a turbulent mode, and the friction coefficient is determined by *Re g* . However, due to the presence of internal elements and liquid splashes in the apparatus, the value of *λ found for a dry pipe* can be corrected in practice by an experimental coefficient.

Local resistance in a truncated cone contact element is defined as follows, Pa;

$$\Delta P_{kon} = \zeta_{kon} \frac{\rho_g\, v_{haq}^2}{2} \tag{16}$$

$$\zeta_{kon} = f\left(\alpha, \frac{D_{kon}}{D_k},\, \frac{Q_s}{Q_g},\, Re_g \right) \tag{1 7}$$

The truncated cone contact element partially shortens the flow path and increases local resistance. However, this element also increases the cleaning efficiency, since it forms a water screen and wall film. Therefore, when choosing the ratio *D con / D k,* it is necessary to find the optimal balance between hydraulic resistance and cleaning efficiency.

The additional resistance due to the gas-liquid mixture is determined as follows, Pa;

$$\varphi_s = \frac{Q_s}{Q_g + Q_s} \tag{18}$$

$$\rho_{ar} = \rho_g \left(1 - \varphi_s\right) + \rho_s \ \varphi_s \qquad (19)$$

$$v_{ar} = \frac{Q_g + Q_s}{F_{er}} \qquad (20)$$

$$\Delta P_{gs} = \zeta_{gs} \frac{\rho_{ar} \ v_{ar}^2}{2} \qquad (21)$$

(18), (19), and (20) are expressed by equation (21). The equation for determining the additional resistance due to the gas-liquid mixture takes the form: , Pa;

$$\Delta P_{gs} = \frac{\zeta_{gs}}{2F_{er}^2 er2}(\rho_g Q_g + \rho_s Q_s)(Q_g + Q_s) \quad (22)$$

As the fluid flow rate increases, the relative density of the gas-liquid mixture and the proportion of droplets in the flow increase. This can improve the cleaning efficiency, but at the same time, it also increases the hydraulic resistance and the risk of droplet entrainment. Therefore, the water flow rate should be selected not only from the point of view of maximum cleaning, but also from the point of view of total energy consumption and sludge formation.

The hydrodynamic process in a cyclonic droplet catcher is defined as follows, Pa;

$$\Delta P_{cyc} = \zeta_{cyc} \frac{\rho_g \ v_{cyc}^2}{2} \qquad (22)$$

$$F_m = \frac{m_p \ v_\theta^2}{r} \qquad (23)$$

In the cyclone-type droplet catcher, the gas-liquid flow is circular. Under the influence of centrifugal force, water droplets and sludge particles strike the wall and fall. This element is an important part of the apparatus, as it reduces the amount of water droplets that escape with the purified gas.

Based on the above analyses, it is recommended to determine the total hydraulic resistance of the apparatus using the following generalised equation, Pa;

$$\Delta P_{um} = \left[\zeta_{kir} + \lambda \left(\frac{L_k}{D_k} \right) + \zeta_{sht} + \zeta_{kon} + \zeta_{gs} + \zeta_{fl} + \zeta_{cyc} + \zeta_{chiq} \right] \frac{\rho_{ar} \ v_{haq}^2}{2} \quad (24)$$

This equation takes into account the pressure losses in each functional zone of the apparatus through a single common coefficient. The common resistance coefficient is written as follows. This equation is convenient for parametric calculations in the MATLAB environment. Here, the coefficients *ζ con* , *ζ gs* and *ζ cyc* should be determined based on the experimental results of the apparatus or CFD modelling data. In the initial engineering assessment, they can be selected based on literature data and coefficients adopted for similar structures.

Discussion.

In the proposed design, the main intensifier of the cleaning process is a truncated conical contact element. As a result of the impact of the liquid jet on this element, water droplets and a liquid screen are formed. When the gas flow passes through this screen, the dust particles of the gas come into contact with the water multiple times.

From a hydrodynamic point of view, an increase in resistance in the apparatus is natural, since the contact element reduces the free cross-section and complicates the movement of the gas-liquid mixture. However, this resistance can be justified by an increase in cleaning efficiency. The main task in the design is to find the optimal ratio between cleaning efficiency and hydraulic resistance.

If the cone diameter is chosen too large, *v hak* increases sharply and *ΔP um* becomes high. If the cone diameter is too small, the liquid screen is not fully formed, and the possibility of trapping dust particles is reduced. Therefore, *D*

kon / D $k$ratio, water consumption Q_s and gas velocity v_g are the main optimised parameters of the apparatus.

The cyclone-shaped droplet catcher is the second important part of the apparatus, which prevents the release of water droplets with the purified gas. Without this part, small droplets formed in the working chamber can escape into the atmosphere with the gas flow and increase humidity. Therefore, when assessing the cleaning efficiency, it is necessary to take into account not only the dust concentration, but also the amount of droplets in the exhaust gas.

Conclusion.

As a result of the conducted analyses, a structural scheme of a new wet dust cleaning apparatus with a truncated conical contact element, designed for water cleaning of dust particles with a size of d = 8.7 μm in 1 m^3 of dusty gas, was substantiated. It was shown that in the proposed apparatus, the process of dust particle capture is not limited to water spraying alone, but is carried out through the combined action of a liquid screen, a water film formed on the walls of the working chamber, and cyclonic droplet separation mechanisms. This increases the probability of contact of finely dispersed particles with water droplets and a liquid film.

In the study, a parametric calculation algorithm for gas consumption, water consumption, free cross-sectional area, actual gas velocity, and total hydraulic resistance in the MATLAB programming environment was proposed to evaluate the main operating parameters of the device. This approach allows calculating hydrodynamic processes in the device, comparing the effects of variable parameters, and selecting optimal operating modes. The main difference of the proposed device from existing wet scrubbers is that in it, a liquid jet is directed against a truncated conical contact element, creating an additional liquid screen and an expanded gas-liquid contact surface in the working chamber.

The hydrodynamics of the device were expressed as the sum of local resistances occurring in the inlet, working chamber, nozzle, truncated cone contact element, gas-liquid mixture movement zone, flanged joints, cyclonic droplet catcher and outlet. In the final engineering calculations, an equation was proposed to determine the total hydraulic resistance. This expression can be used as the main calculation equation in the computational model of the device in the MATLAB environment.

It was also proved that the developed constructive solution can be used for wet cleaning of fine dispersed dust gases generated in cement, lime, mineral fertilisers, building materials and drying technological lines. The combined operation of the water curtain and the truncated cone contact element in the apparatus serves to increase the cleaning efficiency, retain dust particles in the active contact zone and make technological gases environmentally safe.

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