Formation and motion of droplets in gas cleaning devices with porous rotating atomizers

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Abstract. This paper presents the study of characteristics of porous rotating nozzles recommended for use in gas cleaning devices. The influence of geometrical and technological parameters of atomizer on the size of droplets and the trajectory of their motion is investigated theoretically and experimentally.

To determine the droplet size when it is detached from the spherical granule of porous rotating atomizers (PRA), the simulation in the Flow3D program was used. A model for calculating the droplets trajectories when spraying a liquid with the help of porous rotating nozzles is compiled. The model is based on a joint solution of equations of droplet motion in a centrifugal field and evaporation of droplets.

The relationship between the volume of separating droplets and the size of granules of porous material and the geometry of atomizer is obtained. The regularities of droplet motion in cylindrical devices with porous rotating atomizers are established depending on the droplets sizes and parameters of the cross-flow. The relationship between parameters of droplets’ trajectory and their volume is recommended for calculating the geometry of the spray torch of PRA in gas cleaning devices.

Key words: porous rotating atomizers, gas cleaning device, formation and detaching of droplets, trajectories of droplets, cross-flow.

1 Introduction

“Wet” devices with intensive interaction of gas with droplets of sprayed liquid are widely used in gas cleaning systems of heat power industry. The efficiency of such devices substantially depends on the operation of atomizers. Atomizers capable to provide a high degree of spray monodispersity and its uniform distribution in the device volume are more advantageous. These properties are typical for porous rotating atomizers (PRA), which create a volumetric, uniform in cross-section and almost monodisperse torch of droplets [1, 2].

The PRA design and operation scheme are shown in figure 1. The atomizer is a hollow cylinder of porous material, which is formed from one-dimensional sintered granules. During rotation, water is supplied to the inner cavity of the atomizer, which, under the action of centrifugal force, is filtered through the porous wall of cylinder and is discharged from the granules on its outer surface by almost uniform droplets.

PRA has almost a monodisperse spraying mode. According to the data from [3], for peripheral rotation speeds exceeding \( v \geq 20 \text{ m/s} \), the ratio of diameters of the largest droplets to the smallest in the spray is \( k = d_{\text{max}}/d_{\text{min}} < 2 \), and for most droplets, \( k \) does not exceed 1.4. In [4], it was noted that PRA with a granule size of \( d_{g} \leq 50 \mu\text{m} \) is able to form droplets with diameters of 20-30\( \mu\text{m} \), which maximizes the intensification of “wet” processes in gas cleaning devices.
Figure 1. The PRA design and modes of droplets formation on its granules: a – droplet; b – jet.

Figure 2. The schemes of regulated and unregulated gas cleaning devices with PRA:
   a – ICEF scrubber based on PRA with hydraulic drive;
   b – Venturi scrubber with PRA mechanical drive;
   c – volume gas washer; g – modernized Feld absorber with PRA and cone pump.

Figure 3. The scheme of a PRA-based contact element for multi-stage devices.
The well-known PRA designs [5, 6] are of high strength, resistance to aggressive environments, and have commercially viable flow characteristics (up to 10 t/h of sprayed liquid). An important property of PRA is its manufacturability and a wide selection of structural and geometrical characteristics of the porous atomizer. PRA are easily integrated into the design of the existing spraying devices (scrubbers, absorbers, etc.). The atomizer rotation can be carried out by an electric motor, and using the energy of a gas stream or hydraulic drive (figure 2). Contact elements for tower devices with several stages of gas cleaning can be created based on PRA (figure 3).

The widespread use of PRA in industry is constrained by the absence of a method for calculating the dispersed characteristics of atomizer and droplet trajectories. It should be based on a physically and mathematically feasible model of the process of droplet formation on PRA granules and their further motion. It is necessary to determine the conditions for stable formation of one-dimensional droplets, since upon reaching some limiting values of rotation speed and fluid flow at PRA, a transition from the formation of individual droplets on granules to the formation of jets occurs (figure 1b). In this case, the degree of polydispersity of the spray torch sharply increases ($k \geq 10$).

The process of one-dimensional droplets formation has long been of interest to researchers working in the field of monodisperse technologies [7-9]. For example, in inkjet printing technologies, the tasks are to control the size and time of formation of ink droplets, as well as to prevent the appearance of satellite droplets that accompany detaching of the “main” droplet and cause the “ink mist” formation [10-12]. In chemistry and pharmaceuticals, it is necessary to achieve the accuracy of dropping dosage of components [13]. In welding, there are requirements for ensuring droplet metal deposition, which ensures the greatest process stability and high-quality weld formation [14].

However, these works mainly consider the droplet detaching in a gravitational field, which does not fit the description of process in a centrifugal field. The data on regularities of droplet formation on a wettable sphere [15-18] or a cone [19, 20] can only be considered as an illustration for a similar process on a PRA granule. A study of dynamics of droplet formation on the PRA surface was practically not carried out. In well-known works on designing centrifugal granulators and liquid atomizers, the main attention is focused on the decay of jets and liquid films from the edges of rotating disks and bowls [21-23].

A simplified approach to construction a mathematical model of droplet formation on a PRA granule in a centrifugal field was taken in [24], however, the simulation results are presented only for the case of a radially arranged cylindrical granule, and the surface porosity of PRA models a circular channel around it. This model is far from the real granule geometry and their packing in the PRA material (figure 1).

In this work, the mode of monodisperse formation of individual droplets on a spherical granule of PRA material is simulated. The detaching sizes of droplets are determined, and their motion in the volume of the cleaning device is investigated. The results provide the necessary information for PRA design and their application in gas cleaning systems.

2 Materials and methods

2.1 Modeling the droplet dynamics during detaching from a spherical PRA granule

To determine the droplet size during detaching from a spherical PRA granule, the simulation was performed using the Flow3D software. It numerically solves the Navier-Stokes equation for the selected two-dimensional flow region at the interface between the droplet-forming surface of granules and air (figure 4). The direction of the centrifugal force acceleration vector is taken down the $z$ axis.

An idealized arrangement of granules on the PRA surface was adopted, according to which:
- All granules are axisymmetric bodies (spheres) of the same radius $r_1$, so that the ratio of voids areas (feed pores) $\Sigma_0$ and the cross-sectional areas of granules is equal to the porosity coefficient of the PRA material:

$$\frac{\Sigma_0}{\pi r_1^2} = \varepsilon$$

(1)
- Granules are evenly packed and fixed in the volume of a cylindrical body with a given packing density (porosity, tortuosity of pore channels, etc.);
- The liquid is filtered through a PRA wall of thickness $\delta$ under the action of centrifugal force (figure 1) arising from rotation of porous PRA body around the longitudinal axis, and then flows onto the surface of granules at the periphery;
- The rate of fluid flow in pores is determined by the laws of filtration theory.

In numerical experiments we considered the development of an axisymmetric hanging droplet, which forms in the lower part of wettable sphere in the symmetric half of the computational domain. The density of the surrounding air was taken at a pressure of 101300 Pa. The condition of complete wetting was ensured by setting the zero contact angle at the interface “liquid-droplet-forming element”. For numerical calculations, the rheological parameters of water as a wetting liquid were set ($\sigma$=0.73 N/m; $\rho$=1000 kg/m$^3$; $\mu$=0.001 Pa·s).

A uniform mesh was taken with a total number of cells equal to 8000, with at least 20 cells along the sphere radius $R$. Doubling the mesh density had an insignificant influence on the size of separating droplets. The height of the computational domain was chosen sufficient to trace all changes in the droplet profile after the detaching moment. The process of droplets detaching usually lasts thousandths of a second. To obtain the calculated droplet profiles at the moment of constriction formation and detaching of the main droplet, the program was restarted with a shorter time interval and a reduced iteration step.

2.2 Experimental determination of PRA spray dispersion
To determine the PRA spray dispersion and compare it with the results of numerical simulations, tests on experimental plants were performed (figures 5, 6).

The scheme of installation for determining the PRA dispersed characteristics from an abrasive coarse material is shown in Fig. 5. The experimental bench included a direct current electric motor 2 for PRA drive 1. Power was supplied from the AC mains through a rectifier 4, which provided the possibility of a smooth change in the shaft rotation speed in the range of 0–250 r/s. An ammeter and a voltmeter are included into the rectifier circuit to determine power consumed by the engine.

Figure 4. The scheme of the flow area and computational mesh.
Figure 5. The scheme of experimental setup to study the PRA spray from abrasive material.

We used atomizers based on commercially available abrasive cylinders of electrocorundum with main granule fractions of 250 and 400 microns, which corresponded to the 25P and 40P granule grade, respectively. Water was supplied to the atomizer directly from water supply network or from supply tank 6. The necessary pressure in tank 6 was created by compressed air using compressor 7. The sprayed liquid through the receiving hopper went into tank 11, where it was possible to prepare working fluids with various physical properties. The working fluid was pumped into tank 6 by pump 12. The flow rate was controlled by valves 8 before and after rotameters 9. The PRA rotation speed was determined from rotational speed of motor shaft by measuring the latter with a tachometer with a clock mechanism 5. The fluid flow was determined by rotameters 9, which were previously calibrated by volumetric method. The pressure in front of the atomizer was measured using manometer 10.

The spray pattern was obtained using macro photography at a scale of 1:6 with a depth of field up to 50 mm. The camera 13 was mounted on the coordinate device 14 so that the optical axis of the lens was perpendicular to the plane of the torch. The duration of exposure during shooting was set by the lamp flashing time by flash 16, controlled through the discharge device 18. In a single discharge, the flash duration was \(1 \times 10^{-6}\) seconds. The ISSh-100-5 flash lamp, enclosed in a permeable housing of projector 17, was used as a light source. The location of flash lamp relative to the subject was selected according to the known relationship between illumination and distance. The photodevice was operated through sleeves and slots 15 made in a translucent camera 3.

The dispersion composition of spray was determined by analyzing the images of torch section with a radius up to 0.1 m and apex angle of 10°. The measured droplets were divided into the following fractions: less than 0.1 mm; 0.1–0.2 mm, 0.2–0.3 mm, etc. Fractional composition was used to determine the average volumetric-surface diameter of droplets \(d_{32}\) in the torch spray (Sauter mean diameter). It showed such a droplet size, for which the ratio of volume to its surface was equal to the ratio of the total volume of all droplets in spray to their surfaces:

\[
d_{32} = \frac{\sum_{i=1}^{n} d_i^3 n_i}{\sum_{i=1}^{n} d_i^2 n_i}
\]

where \(n_i\) is the amount of droplets of the diameter \(d_i\).

Abrasive samples with outer radius of \(R = 41\) mm were used in experiments. The fluid pressure in the power network ranged from 10 to 135 kPa. This corresponded to flow rates from \(2 \times 10^{-6}\) to \(105 \times 10^{-6}\) m\(^3\)/s. The angular velocity varied from 4 to 152 rpm, which corresponded to peripheral rotational speed from 0.8 to 25 m/s. The experiments were performed in winter and the temperature of tap water
was +5 ... +7 °C. Water had the following characteristics: density of 1010 kg/m³, viscosity of 1.43·10⁻³ Pa·s and surface tension of $\sigma=70\cdot10^{-3}$ N/m.

The experimental setup for working with PRA from finely dispersed materials is shown in figure 6. It includes an electric drive 1 with five fixed shaft speeds $n$=15000; 20,000; 25,000; 30,000 and 35,000 rpm. Atomizer 2 was rigidly mounted on the shaft of engine 1 using a collet. Water was supplied to atomizer from the supply tank 3. Droplets of spray were captured in the cell 4 with immersion medium. Hollow cylinders made of porous filtering ceramics (PFC) were used as PRA. The outer diameter of cylinders was $R_{1}=17$ mm, its height was $h=16$ mm. The experimental samples had porosity $\varepsilon=0.31\div0.34$, the size of the main fraction of granules was $d_m=50$ μm.

![Figure 6. The experimental setup for studying the disperse characteristics of PRA from PFC. PRA samples in experiments and photos of droplets captured in an immersion medium.](image)

A sample of the required droplet set for recording their disperse composition was taken through window 5 of the selective device; the exposure time of the flow of droplets through the selective window was set using the iris diaphragm. The captured droplets were photographed in transmitted light using camera 6 mounted on the microscope eyepiece with magnification range of 56. The image from the camera in real time was transmitted directly through the USB input of computer, and then to the monitor screen.

2.3 Numerical calculation of droplets trajectories in the device

PRA form flows of “main” droplets, which are close to monodisperse composition, and satellite droplets. So, unlike devices with other types of atomizers, which create polydisperse droplet systems, the aerodynamic and other types of PRA device calculations are significantly simplified, and the real processes in them are close to theoretical. At low volumetric concentrations of droplets in gas phase, the interphase interaction and motion of the dispersed flow as a whole are fairly well described by behavior of a single droplet.

We take into account that gravity, aerodynamic resistance, Coriolis and centrifugal forces have a significant influence on droplet motion in PRA devices. So, the system of equations for a single droplet with a diameter of $d_d$ and mass $m_d = \rho_d \pi d_d^3 / 6$ in a cylindrical coordinate system associated with PRA (the atomizer axis coincides with z axis of the coordinate systems), has the form [25]:

$$
\begin{align*}
\frac{dV_r}{d\tau} &= \frac{V_r^2}{r} + \frac{\rho_l}{\rho_d} \left( \frac{3}{4} V_r \alpha \left( U_r - V_r \right) \right) ; \\
\frac{dV_\theta}{d\tau} &= -\frac{V_r V_\theta}{r} + \frac{\rho_l}{\rho_d} \left( \frac{3}{4} V_r \alpha \left( U_\theta - V_\theta \right) \right) ; \\
\frac{dV_z}{d\tau} &= g + \frac{\rho_l}{\rho_d} \left( \frac{3}{4} V_r \alpha \left( U_z - V_z \right) \right) ; \\
\frac{dr}{d\tau} &= V_r ; \\
\frac{d\theta}{d\tau} &= \frac{V_\theta}{r} ; \\
\frac{dz}{d\tau} &= V_z .
\end{align*}
$$

(3)
where \( V_r, V_\phi, V_z \) are the components of the droplet velocity; \( g \) is the gravity acceleration; \( \rho_1 \) is the density of gas being cleaned; \( \rho_2 \) is the liquid density; \( \tau \) is the current time; \( r, \phi, z \) are the cylindrical coordinates; \( V_{rel} \) is the droplet velocity relatively to gas:

\[
V_{rel} = \sqrt{\left(U_r - V_r\right)^2 + \left(U_\phi - V_\phi\right)^2 + \left(U_z - V_z\right)^2}
\] (4)

\( U_r, U_\phi, U_z \) are the components of gas velocity.

Eqs. (3) are the first-order differential equations in which the droplet velocity is unknown, and time is argument. The aerodynamic resistance has the major influence on the droplet motion after its detaching from PRA if compared with other forces included in Eqs. (3). This force is directed opposite to the droplet relative velocity vector \( V_{rel} \). To calculate this force, one should know the aerodynamic resistance coefficient \( \xi \) in a wide range of speeds (from 1 to 60 m/s) and Reynolds numbers \( \text{Re} \) (from 0.1 to \( 10^4 \)) that are typical for various designs of atomizers in which PRA can be used. In this regard, the formula obtained in [26] is most suitable.

\[
\xi = \left( \frac{24}{\text{Re}} \right)^{0.52} + 0.32^{0.52} \times \left( \frac{1}{\text{Re}} \right)^{0.52}.
\] (5)

When droplet is moving in a device its mass decreases during evaporation. Therefore, the inertial part of droplet motion equations (3) must be corrected in time. To calculate the rate of droplet diameter \( d \) decrease during evaporation into air, one can use the Williamson formula [27], which gives the results closest to the experimental ones:

\[
\frac{dd}{d\tau} = -\frac{4m_2D}{d_2\rho_2RT_2} \Delta P \left( 1 + 0.276 \text{Re}^{0.12} \text{Sc}^{0.13} \right),
\] (6)

where \( m_2 \) is the molecular weight of water; \( T_2 \) is the average absolute temperature in the boundary level of the droplet surface; \( \Delta P = P_2 - P_1 \) is the difference between vapor pressure near the droplet and the ambient air; \( R \) is the air gas constant; \( D \) is the diffusion coefficient of vapor molecules into the saturated layer of air near the droplet;

\( \text{Sc} = v_1 / D \) is the Schmidt diffusion number for vapor.

To determine the pressure of water vapor over the curved surface of a small droplet, the Thomson (Kelvin) formula is used

\[
P_p = P_p \exp \left( \frac{\sigma \cdot m_2}{4 \cdot d_2 \rho_2 kT_2} \right),
\] (7)

where \( P_p \) is the pressure of saturated vapor over the flat water surface; \( k \) is the Boltzmann constant.

The relationship between pressure of saturated water vapor over a flat surface and the ambient temperature is well described by the empirical expression

\[
P_p = 610.7 \times 10^7 T^{2.57} \exp(0.001157 T).
\] (8)

The expression for partial vapor pressure by a dry thermometer was proposed by List in [28]:

\[
P_i = P_p - \gamma (T_r - T_w),
\] (9)

where \( \gamma \) depends on atmospheric pressure \( B \) and temperature of wet thermometer \( T_w \):

\[
\gamma = 0.000668B(1 + 0.001157 T_w).
\]

For numerical calculation of evaporation rate, it is also necessary to know the relationship between temperature of wet thermometer \( T_{ws} \), temperature \( T_r \) and relative air humidity \( \varphi \). For all \( \varphi \) at \( T_r = 10 \div 20 \) °C this dependence is well described by the equation

\[
T_w = T_r - \left( a_0 + a_1 T_r \right) \varphi + \left( b_0 + b_1 T_r \right) \varphi^2 + \left( c_0 + c_1 T_r \right) \varphi^3
\] (10)

with constants \( a_0 = 5.1055; a_1 = 0.4295; b_0 = 0.04703; b_1 = -0.005951; c_0 = -4.005; c_1 = 1.66 \times 10^{-5}. \)

Further we write the well-known equations that were used to estimate other parameters that affect the process of droplet evaporation:

- Water density

\[
\rho_2 = 1000.0 - 0.00653(T_2 - 3.98)^3;
\] (11)
Kinematic viscosity of water
\[ \nu_2 = \left( 7.1 + 0.067T_2 - 0.00047^2 \right) \times 10^{-6}; \quad (12) \]

Diffusion coefficient of water vapor in air
\[ D = 21.2 \times 10^{-6} \left( 1 + 0.0071T_2 \right) \quad (13) \]

The algorithm for calculation the system of Eqs. (3)-(13) was implemented as a program code. The program allows one to determine the trajectory of droplets at given geometrical and physical parameters of PRA material, physical properties of liquid and air, and rotation speed of atomizer.

The system of equations (3) of droplet motion together with the Eq. (6) for changing the diameter of a droplet upon evaporation is solved numerically using the fourth-order Runge-Kutta method under initial conditions: \( \tau = 0 \), \( r = R_1 \), \( \varphi = 0 \), \( z = 0 \), \( V_r = v_f \), \( V_\varphi = \frac{2mnR_1}{60} \), \( v_z = 0 \), where \( n \) is the number of revolutions of PRA.

3 Results and discussion

3.1 The influence of PRA parameters on the filtration speed

Analysis of the well-known PRA studies [3, 5, 6] shows that transition from one spraying mode to another primarily depends on the rate of fluid outflow from the pores of the wall material. Excess liquid supplied to granules results in formation of liquid jets on them. So, the primary task during the analysis of PRA operation is to determine the allowable values of fluid flow rate and the speed of atomizer rotation, for which a monodisperse droplet outflow can be obtained.

The limits of monodisperse formation mode of individual droplets in PRA are obviously determined by a certain critical fluid flow \( Q \) at a given angular rotation speed. Therefore the characteristics of porous structure and the geometry of (average diameters of granules \( d_g \) and pores \( d_p \), material porosity \( \varepsilon \), granule shape, outer \( R_1 \) and inner \( R_2 \) radii of PRA, wall thickness \( \delta \), etc.) atomizer were set. The limits of the region of droplet outflow also depend on the properties of the sprayed liquid (dynamic viscosity \( \mu \), density \( \rho \), surface tension coefficient \( \sigma \)) and the nature of its interaction with PRA material (wetting or non-wetting).

The rate of fluid outflow from pores (filtration flow rate on the outer surface of PRA) determines the dynamics of droplet formation on the granules of the PRA outer surface. The expression for velocity was obtained in [24] using the methods of linear theory of filtration:
\[ v_f = \frac{\chi}{\mu} \rho \omega^2 \cdot \frac{R_1^2 - R_2^2}{2} \cdot \frac{1}{\ln(R_1/R_2)} \cdot R_1, \quad (14) \]

where \( \chi \) is the PRA wall permeability, which is related with granularity \( d_g \) and porosity \( por \) by the Koseni formula
\[ \chi = \frac{\beta}{(1-\varepsilon)} d_g^3, \quad (15) \]

where \( \beta = 1.10 \) is an experimental coefficient.

It should be noted that the linear theory adequately describes the filtering process for Reynolds numbers \( Re = \nu/d_g \rho / \mu \leq 3.10 \). The same \( Re \) values are typical for water flow through PRA pores during monodisperse sputtering.

Assuming the limiting value \( Re_{lim} = 10 \), we obtain the following ratio of parameters, which imposes a restriction on filtration rate \( v_f \) to achieve a “droplet” monodisperse spraying mode using PRA:
\[ v_f^{lim} = \frac{Re_{lim} \mu}{d_g \rho} = \frac{10 \mu}{d_g \rho} = \frac{\beta}{(1-\varepsilon)} d_g^3 \cdot \frac{R_1^2 - R_2^2}{2} \cdot \frac{R_1}{R_2} \cdot \frac{\rho \omega^2}{2 \mu}, \quad (16) \]

Expression (13) can be presented as:
\[ \beta \cdot P_1 \cdot P_2 \cdot P_3 \cdot \omega^2 \leq 1, \quad (17) \]
where \( \beta \) is the parameter, which characterizes the texture of the porous body material and its interaction with liquid;

\[
P_1 = \frac{e^3}{(1-e)^2} d_s^{3/2}
\]

is the parameter, which characterizes porous structure of PRA; \( P_2 = \frac{R_1 - R_2}{\ln(R_1/R_2)} \frac{1}{R_1} \)

is the parameter, which characterizes the atomizer geometry;

\( P_3 = \frac{\rho^3}{20 \mu^3} \)

is the parameter, which characterizes properties of the liquid being sprayed.

The geometrical parameter \( P_2 \) must be less than the limiting value \( P_2^{lim} \) determined from the condition of laminarity of the fluid flow in pores of the atomizer material (\( Re_{por} \leq 10 \)).

\[
P_2^{lim} = \frac{20(1-e)^3 \cdot \mu^2}{\beta \cdot d_s^{3/2} \cdot e^{3/2} \cdot \rho^3 \cdot \omega^2}.
\]  

By solving the problems (14)-(18) with value \( \beta = 3 \) typical for water-wetted granule, one can obtain the limiting angular velocity \( \omega_{lim} \) for PRA of various geometry, porosity, and granularity (figure 7).

The dependencies shown in figure 6 make it possible to determine the PRA geometry and the range of angular velocities \( \omega \) (this is the technological parameter of PRA operation) for which the rates of filtration and leakage on the PRA surface granules correspond to the monodisperse droplet formation mode.

![Graph](image_url)

**Figure 7.** Determination of the limiting angular velocity \( \omega_{lim} \) for PRA operation in monodisperse spraying mode.

### 3.2 Numerical determination of droplet sizes

Numerical experiments to determine the detaching volumes of droplets were performed using models of granule in the form of a sphere. Figures 8-10 show some results of calculations of droplet profile formed on spheres of different radius \( R \). The filtration rate at the upper boundary of the computational domain was set corresponding to the monodisperse droplet formation mode according to Eq. (14).
The obtained data show that the detached volumes of droplets decrease with increased centrifugal acceleration $R\omega^2$. With increasing filtration rate $v_f$, the bridges behind droplet lengthens. The frequency of droplet formation increases, and in a certain range of values, the bridges between adjacent droplets cease to break and there is a transition from the formation of individual droplets to jet outflow – the liquid flows from the granules surface in a form of a continuous stream.

**Figure 8.** The change in the profile of droplets separating from spherical granules of $R=100 \, \mu m$ at various centrifugal accelerations $R\omega^2$:
- $a$ – 10000 m/s$^2$
- $b$ – 150000 m/s$^2$
- $c$ – 30000 m/s$^2$
- $d$ – 50000 m/s$^2$.

**Figure 9.** Calculated profiles of droplets, detached from spherical granules of $R=200 \, \mu m$ at various centrifugal accelerations $R\omega^2$:
- $a$ – 6000 m/s$^2$
- $b$ – 42000 m/s$^2$.

**Figure 10.** The change in bridge length when droplets are detached from spheres of $R=100 \, \mu m$ ($R\omega^2=30000 \, m/s^2$) for various filtration rates $v_f$:
- $a$ – 0.05 m/s
- $b$ – 0.1 m/s
- $c$ – 0.15 m/s
- $d$ – 0.25 m/s.
Figure 11 shows the calculated values of the detached volumes of droplets $V_d$ as a function of the granule radius $R$ and the PRA outer radius $R_1$. The data are reduced to dimensionless form by dividing all linear quantities by a parameter $c = \sqrt{2\sigma/\rho \omega^2}$, which has dimension of length.

The calculated curves in Fig. 11 are approximated by the relationship:

$$ V_d = \frac{R}{(0.32RR_1^{0.685} + 0.33R + 0.5)}. \quad (19) $$

This relationship can be used for calculation the size of droplets generated by PRA spraying.

3.3 Results of experimental determination of dispersity of PRA spraying

To verify the results of numerical simulation, the dispersion characteristics of sprays of PRA prototypes from abrasive material of 25P grade (water flow rate $Q=33.8 \times 10^{-6}$ m$^3$/s) and 40P grade ($Q=21.2 \times 10^{-6}$ m$^3$/s) were determined. The experimental results are presented in Table 1. The data shows that PRA allows one to get fine dispersion of water into droplets of 150–300 μm diameters.

Figure 12 shows the results of determining the spray dispersion of PRA of fine porous filtering ceramics (PFC). It can be seen that when rotational speed increases from 15000 to 35000 rpm, the polydispersity of the spray torch gradually decreases. According to this it can be judged that the "jet" mode on granules transforms into the "droplet" mode. So, for peripheral speed $v<26$ m/s (25000 rpm), there is a large amount of droplets having a large size $d_d \geq 50$ μm (more than 50%). For peripheral speed $v> 30$ m/s ($n=30000–35000$ rpm), large fractions disappear, and the range of droplet sizes narrows. For $v=36.6$ m/s (35000 rpm), more than 50% of droplets in the spray have a diameter $d_d =20+30$ μm. We can assume that for this speed PRA from PFC reaches the limit of the monodisperse “droplet” spraying mode.
The experiments showed that PRA based on PFC from granules with a size $d_p=50 \mu m$ are able to form droplets with an average diameter of less than 30 $\mu m$. The discrepancy with the calculation according to formula (16) was $+30\%$, which can be explained by the difference in manufacturing technology of PRA products from abrasive, which were obtained not by casting, but by granules sintering using a binder.

### Table 1: Dispersity of spraying for PRA-250 and PRA-400

| Rotation speed, m/s | Centrifugal acceleration, m/s² | Range of droplets diameters, µm/number of droplets, n, in hundreds of pcs | Average droplets diameter, µm |
|---------------------|--------------------------------|--------------------------------------------------------------------------|-----------------------------|
|                     |                                | <100 | 101-200 | 201-300 | 301-400 | 401-500 | 501-600 | 601-700 |
| PRA-250             |                                |      |         |         |         |         |         |         |
| 6.3                 | 980                            | 1.78 | 3.29    | 0.89    | 0.18    | -       | -       | -       | 200     |
| 8.4                 | 1740                           | 5.70 | 9.26    | 0.89    | 0.09    | 0.18    | -       | -       | 200     |
| 10.6                | 2770                           | 43.16| 19.31   | 1.60    | -       | -       | -       | -       | 140     |
| 15.1                | 5630                           | 69.00| 18.24   | 1.25    | -       | -       | -       | -       | 130     |
| PRA-250             |                                |      |         |         |         |         |         |         |
| 4.3                 | 450                            | 1.62 | 2.70    | 7.38    | 3.96    | 0.72    | -       | -       | 310     |
| 8.6                 | 1810                           | 8.46 | 8.46    | 2.34    | 0.90    | 0.18    | 0.18    | -       | 250     |
| 12.9                | 4060                           | 7.85 | 1.62    | 1.80    | 0.36    | -       | -       | -       | 210     |
| 17.2                | 7220                           | 0.18 | 12.42   | 0.36    | -       | -       | -       | -       | 160     |
| 21.4                | 11180                          | 12.46| 28.98   | 0.54    | -       | -       | -       | -       | 150     |

Figure 12. The spray dispersity for PRA from PFC at various rotation frequencies.

3.4 Calculation of droplets trajectories in devices with PRA

**Droplets trajectories in a cylindrical device in an axial cross-flow**

The system of equations (1)-(10), which determines the motion of a single spherical drop, taking into account the change in its diameter upon evaporation in the presence of a blowing air stream, was solved numerically by the fourth-order Runge-Kutta method. The calculations were carried out for the axial motion of air in a cylindrical device with a radius of $R_0=0.2 \div 2.0$ m. The device is equipped with PRA with outer radius of $R_1=0.04 \div 0.12$ m and an inner radius $R_2=0.02 \div 0.08$ m, the material of which is characterized by granularity $d_p=10 \div 400$ $\mu m$ and porosity $\varepsilon=0.3 \div 0.4$.

The initial data were the properties of gas and liquid, the PRA parameters, the gas and droplet velocity components, and the device radius $R_o$. The initial values for air velocity components in the zone of the spray torch were taken in the form:

$$U_r=0; \quad U_\theta=0; \quad U_z=\frac{\Delta P}{4\mu} \left(\frac{R_z^2-R_i^2}{\ln(R_z/R_i)}\right) \ln(r/R_i) - \left(r^2 - R_i^2\right).$$

For air speed of 2\div40 m/s the $\Delta P$ value was taken equal to 10\div300 Pa.
The calculated trajectories of droplets of different diameters moving from the PRA-400 in a cross-flow are shown in figures 13 and 14. Calculations show that only large droplets \( d_d \geq 300 \, \mu m \) are able to reach the device walls and separate at significant velocities of blowing air flow \( U_z < 30 \, m/s \).

**Figure 13.** Trajectories of droplets of \( d_d=204 \, \mu m \) in axial cross-flow (longitudinal cross section of device): 1– \( U_z =5 \, m/s; 2–10 \, m/s; 3–20 \, m/s; 4–30 \, m/s; 5–40 \, m/s \) \( (\varphi=10\%, R_1/R_a=0.08; n=6000 \, rpm) \).

**Figure 14.** Trajectories of droplets in axial cross-flow at \( U_z=20 \, m/s \):
1 – \( d_d=52 \, \mu m \); 2 – \( d_d=108 \, \mu m \); 3 – \( d_d=210 \, \mu m \); 4 – \( d_d=312 \, \mu m \) \( (\varphi=10\%, R_1/R_a=0.05, n=6000 \, rpm) \).

It can be seen from figures that, due to a rapid decrease in the speed of motion, small droplets with \( d_d <50 \, \mu m \) acquire the flow velocity and move parallel to the air flow lines (device axis) starting from a distance of \( l_0 = l/R_a = 0.2 \) \( (l <100 \, mm) \) from PRA.

As a parameter characterizing the detaching ability of droplets of different diameters, we can propose the critical radius \( R^* \) for which the radial component of droplet velocity either completely decays or reaches a value less than a certain small value. The droplets for which the critical radius \( R^* \) is smaller than the device radius \( R_a \), do not touch walls and do not separate. In our numerical experiments, we determined the relative critical radius \( R^*/R_a \). The obtained relationship between \( R^* \) and the volume of droplets \( V_d \) at different velocities of gas cross-flow \( U_z \) in device is shown in figure 15.

**Figure 15.** The relationship between the critical radius \( R^* \) and the droplet volume \( V_d \) for \( T_c=20^\circ C, \varphi=50\% \).
Approximation of the calculated values gives the following expression:

\[ R^* = (0.0005U_z + 0.224)\ln \frac{R^*}{u_0} - 0.0055U_z + 1.24. \]  \hspace{1cm} (21)

Eq. (21) can be used to select the geometrical characteristics of the contact zone of atomizers with PRA with axial air cross-flow.

*Trajectories of droplets in a swirl cross-flow.* To determine the local values of components of air velocity during its vortex motion in device (with tangential input), the following expressions were used:

\[ u_r = 0; \quad u_z = \text{const}; \quad u_\phi = u_{\phi_{\max}} \frac{r \cdot r_0}{r^2 + r_0^2}, \]  \hspace{1cm} (22)

where \( r_0 \) is the radius of maximum location of the tangential component of gas velocity \( u_{\phi_{\max}} \) (figure 16).

![Figure 16. The scheme of velocities and relative motion of a droplet in a swirl gas flow in a device with PRA.](image)

The calculated droplets trajectories have the form of a spatial helix of variable curvature radius (figures 17 and 18). The geometry of this line and, accordingly, the critical radius \( R^* \) and the contact time of gas and liquid phases in the contact zone of device \( \tau \) depends on the direction of PRA rotation, the magnitude and direction of the peripheral and axial (longitudinal with respect to the device) air velocity. Decrease of air velocity at the inlet to device leads to a longer phase contact. An increase in the axial component of velocity leads to an increase of the contact time.

![Figure 17. Trajectories of droplets in a swirl cross-flow (cross-section of device): a – opposite direction of PRA rotation; b – the directions of PRA peripheral velocity vector and air coincide (\( \varphi=50\% \), \( n=6000 \text{ rpm} \); \( R_1/R_s = 0.1; \ u_\varphi = 40 \text{ m/s}; \ u_z = 5 \text{ m/s} \).](image)
Figure 18. Trajectories of droplets in a swirl cross-flow (longitudinal cross section of device):
a – opposite direction of PRA rotation; b – the directions of PRA peripheral velocity vector and air coincide ($\varphi=50\%$, $n=6000$ rpm; $R_1/R_a=0.1$; $u_\varphi=40$ m/s, $u_z=5$ m/s).

Figure 19 shows the calculated relationships between the droplet flight time before a contact with device walls $t$ and the droplet volume $V_d$ for two situations, when the directions of PRA peripheral velocity vector and air coincide, and when they are in the opposite direction.

Figure 19. The flight time of a droplet with a volume $V_d$ until a critical radius $R^*$ is reached:
a – opposite direction of PRA rotation; b – the directions of PRA peripheral velocity vector and air coincide (PRA-400, $\varphi=50\%$, $n=6000$ rpm; $R_1/R_a=0.1$, $u_\varphi=5$ m/s, $u_z$, m/s:
1 – 10; 2 – 20; 3 – 30; 4 – 40).

The figure shows that when PRA rotates in the opposite direction relative to the vortex air motion (figure 19a), the time $t$ before a contact with device walls can increase by 20%. The increase of $t$ is explained by the increase in the length of the droplet flight trajectory. This information must be used to select the geometrical characteristics of the contact area of atomizer devices with PRA with a swirl cross-flow.
4 Conclusions
The use of porous rotating atomizers in wet gas cleaning devices can significantly increase their efficiency. Such atomizers create a thin and almost monodisperse spray, which provides intensive and controlled contact of droplets with the gas being cleaned. However, the technologists and manufacturers of gas cleaning equipment still have little information about the capabilities of this class of atomizers. In this work, we theoretically and experimentally obtained the relationships between droplets size in spray and trajectories of their motion, and the geometrical and technological parameters of atomizers made of abrasive materials and porous filtering ceramics.

The following main results were obtained:
- The droplet sizes when detached from PRA spherical granules were numerically and experimentally determined, depending on the magnitude of centrifugal acceleration, filtration rate and granule size;
- The limiting angular velocity in the monodisperse mode of droplet formation for PRA of various geometry, porosity and granularity was obtained;
- The model that allows one to numerically calculate the motion of droplets when spraying liquid using PRA has been developed. It is based on a joint solution of equations of droplets motion in a centrifugal field, taking into account the droplets evaporation for various conditions of gas motion in device;
- The basic laws of droplet motion were established depending on their size and gas kinematics in the device;
- The relationship between the relative critical radius and the volume of droplets formed in the droplet mode of PRA spraying for various speeds in the device with an axial flow of gas in the device with PRA was obtained;
- The dependence of the expansion range of the droplets on their volume was obtained, which took into account the droplets evaporation along the motion trajectory.

The data on the dispersion of spray and the calculated trajectories of droplets in devices with different inlets of the treated gas suggest that, by adjusting the PRA rotational speed, it is possible to set the phases contact time, the axial displacement of droplets, and, consequently, the contact surface in the device. A numerical analysis of droplets trajectories in the transverse and longitudinal sections of devices with PRA makes it possible to identify zones of increased motion intensity and zones of maximum speed indicators, to select the optimal set of technological parameters and geometrical characteristics of a device with PRA.

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