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Capturing Aerosol Particles in a Device with a Regular Pulsating Nozzle

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Abstract. The paper is dedicated to reducing the technogenic impact on the environment of using highly efficient apparatus for the complex exhaust gas treatment, operating in the advanced turbulence regime – an apparatus with a regular pulsating nozzle (RPN). Devices with on-load tap-changers are characterized by high efficiency of capturing solid particles of different dispersion (e.g., fog, dust, and smoke), the possibility of self-cleaning of contact elements from sticky dust, low material consumption, and high reliability in operation. Purpose of the study – to obtain analytical solutions for assessing the efficiency of capturing polydisperse aerosols in an apparatus with an on-load tap-changer due to diffusion and inertial mechanisms. The paper proposes a new solution for the minimum effective diameter of aerosol particles that can be captured in devices with an on-load tap-changer and can be used for a wide range of diameters of absorbing liquid droplets and their number in the volume of the apparatus. The calculations allow us to say that the minimum effective diameter of aerosol particles captured by liquid drops in an apparatus with an on-load tap-changer is less than 0.3 microns.

Keywords: high-efficiency equipment, environment, dust and gas emissions, phase contact surface, movable plug, drop, condensation.

1 Introduction

Nowadays, environmental problems of the atmosphere, which is polluted by gas emissions with fine particulate matter (aerosols), at various industrial facilities, are among the most important issues [1]. Conventional particulate removal equipment (electrostatic precipitators, cyclones, and others) is ineffective for fine particles less than a micron in size.

One of the ways to intensify the process of diffuse-inertial deposition based on the technology of “wet” gas cleaning from different types of aerosols (e.g., dust, smoke, and fog) is to carry out these processes in the advanced turbulence regime [2]. Its realization is possible in devices with a regular pulsating nozzle (RPN) [3]. Devices with regular pulsating nozzle are characterized by high efficiency of capturing aerosols of different dispersion, the ability to self-clean contact elements from various adhesive inclusions, low material consumption, and high reliability, making them effective for widespread use.

2 Literature Review

Wet dust collectors are usually used to remove fine dust particles [4]. In this case, the capture of particles is realized through various mechanisms [5]. Dust particles smaller than 0.1 μm can be effectively trapped by a diffusion deposition mechanism (Brownian diffusion). The inertial mechanism and the gripping mechanism play an essential role in removing solid particles larger than 1 micron. To a large extent, the efficiency of dust collection depends on the size of liquid droplets [6–8].

Consequently, there are particles size of 0.1 – 1.0 microns, for the effective capture of which should be considered different deposition mechanisms and the efficiency of capturing particles of different dispersed composition has a minimum value, which is called the “minimum effective catching diameter” of particles [9, 10].

The efficiency of capturing fine particles (aerosols) in wet cleaning devices is calculated by considering the pattern of behavior of a single drop, the fraction of particles that were absorbed by the volume of the considered drop during the operation of the device, and the subsequent summation of all drops per unit volume of the gas flow. The efficiency of this interaction can be determined by solving the Navier-Stokes equation for airflow around a liquid droplet. However, it is complicated to obtain a theoretical solution to the Navier-Stokes equation due to the complex flow structure considering the internal circulation of the droplets. Therefore, the approach of determining the effectiveness of the interaction of liquid droplets and solid particles of a pollutant by considering various mechanisms of particle deposition in the apparatus is of interest [11].

3 Research Methodology

3.1 General formulation

The physicochemical parameters of aerosol particles and the nature of the gas flow, which generates specific turbulent flows and pulsations in the apparatus, are one of the determining factors affecting the deposition efficiency of aerosol particles.

The droplet formation mechanism was considered in [4], where an equation was obtained to calculate the diameter of absorbing liquid droplets formed during the interaction of a vapor-gas-liquid flow in wet cleaning devices.

Based on the data of [12], for aerosol particles with a diameter of more than 0.05 μm, the overall efficiency of capturing aerosol particles in wet dust collection devices can be represented as the sum of the capturing efficiencies due to the diffusion mechanism, the particle capture mechanism, and the inertial interaction mechanism:

$$\eta_{tot} = 1 - (1 - \eta_d) \cdot (1 - \eta_{int}) \cdot (1 - \eta_{imp}), \qquad (1)$$

where η_d – the collection efficiency due to the diffusion mechanism; η_{int} – the efficiency of capturing due to the mechanism of capturing particles by a drop of liquid; η_{imp} – collection efficiency due to the inertial mechanism.

The equation describing the capture of polydisperse aerosol particles in wet cleaning devices can be represented by the following expression [13]:

$$\frac{\partial n\left(d_p, t\right)}{\partial t} = -n\left(d_p, t\right) \int\limits_{D_{d\min}}^{D_{d\max}} \beta\left(d_p, D_d\right) n_d\left(D_d\right) dD_d, \qquad (2)$$

where $n\left(d_p, t\right)$ – the aerosol particle size distribution function in the apparatus volume during t; d_p – diameter of aerosol particles, m; $n_d\left(D_d\right)$ – the function of the size distribution of the absorbing liquid droplets; D_d – diameter of droplets typical for a particular turbulent flow, m; β – mass transfer coefficient, m/s.

The equation can represent the interaction of drops of absorbing liquid and aerosol particles:

$$\beta\left(d_p, D_d\right) = \frac{\pi D_d^2}{4} U\left(D_d\right) \eta\left(d_p, D_d\right), \qquad (3)$$

where U – the speed of motion of a drop of absorbing liquid in apparatus volume, m/s; $\eta\left(d_p, D_d\right)$ – the efficiency of interaction of aerosol particles $d_ч$ with drops of absorbing liquid D_d.

3.2 Laboratory installation

Based on the general rules and laws of heuristic modeling [10], a direct flow column-type apparatus with a regular structure of the turbulizing elements is developed, which complies with the well-known principles of longitudinal sectioning and is designed to clean aerosol from gases (Figure 1).

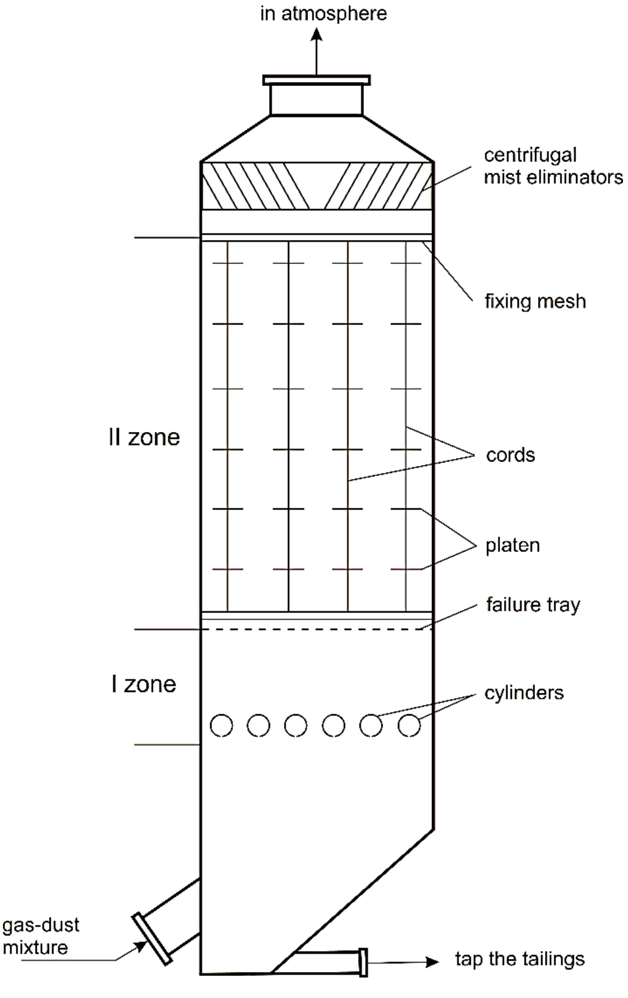

Figure 1 – Scheme of the investigated direct-flow apparatus with a regular arrangement of turbulizing elements.

The contact zone of the apparatus under study consists of two sequentially connected zones for cleaning exhaust gases from fine impurities.

In the lower part (zone I), there is an enlargement of aerosol particles captured from the gas stream due to the mechanism of condensation-coagulation deposition. The lower zone consists of a package of plane-parallel channels with turbulizing elements in the form of hollow cylinders. The cylinders have perforations in the lower part, which performs the function of steam channels (a vapor-liquid mixture is supplied). The two zones of the apparatus are separated by a failing plate, which has a hole diameter of d_o = 20 mm and a free cross-sectional area of 45 %, which ensures the maintenance of a uniform dust-gas-liquid flow into the second zone of the apparatus.

The top of the unit (zone II), intended for capturing aerosols, is a packing layer in the form of strings evenly spaced over the section of the apparatus body with plates fixed on them.

The nature of the flow and turbulent eddies during the movement of the gas flow with aerosol particles in the direct-flow apparatus, the efficiency of the interaction of the gas and liquid phases (considering the joint flow with steam), make it possible to determine the general hydrodynamic picture in the apparatus.

The movement of aerosol particles in the second zone of the apparatus after flowing around the plates occurs with pulsations and oscillations, which are inherent in the separated stream of the gas flow. In addition, during the movement of a polydisperse aerosol in the zone of a single vortex, a redistribution of aerosol fractions occurs in the vortex volume. Thus, the coarse fraction of particles under the action of centrifugal forces by inertia tends to the periphery of the vortex, and the fine inertial fraction of particles rotates in the region of the axial zone of the vortex. Thus, the vortex flow and its detached (pulsated) nature of motion largely contribute to the intensification of the enlargement processes and further sedimentation of aerosol particles.

4 Results

Let us analyze the components of equation (3).

The results obtained in [14] assert that the secondary components of the efficiency of capturing aerosol particles are insignificant and simplify expression (1). The equation can represent the efficiency of interaction due to diffusion of aerosol particles:

$$\eta_d\left(d_p, D_d\right) = 2\left(\frac{\sqrt{3}\pi D_{diff}}{4D_d U\left(D_d\right)}\right)^{2/3}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{1/3}, (4)$$

where the density of the absorbing medium α is defined as the volume fraction of droplets; σ is the ratio of the viscosity of the liquid-absorbing medium to the gas phase; $J = 1-\frac{6}{5}\alpha^{1/3}+\frac{1}{5}\alpha^2$; $K = 1-\frac{9}{5}\alpha^{1/3}+\alpha+\frac{1}{5}\alpha^2$.

Aerosol particle diffusion coefficient D_d :

$$D_d = \frac{k_B T K_C\left(d_p\right)}{3\pi\mu d_p}, \tag{5}$$

where k_B – the Boltzmann constant; T – the absolute temperature, K; μ – viscosity of the gas phase, kg/(m·s); K_C – Cunningham slip correction factor, which is applied in the case when aerosol particles are less than 15 microns, otherwise it is taken equal to 1.

In the case of an aerosol particle moving along a conventional trajectory towards a liquid drop, at the moment of approaching it at a distance not less than the particle radius, a mechanism for the capture of this particle by a liquid drop is possible. The efficiency of particle sedimentation due to the capture effect [7] will be:

$$\eta_{int}\left(d_p, D_d\right) = \left(\frac{D_d + d_p}{D_d}\right). \tag{6}$$

Under the described conditions [13], the efficiency of the capture of aerosol particles by a liquid drop due to the capture mechanism is determined by the equation:

$$\eta_{int}\left(d_p, D_d\right) = \frac{1-\alpha}{J+\sigma K}\left[\frac{R}{1+R}+\frac{1}{2}\left(\frac{R}{1+R}\right)^2(3\sigma+4)\right], (7)$$

where $R = d_p/D_d$.

By quantifying the size of particles and liquid droplets in the apparatus, it can be determined that the efficiency of the capture mechanism $\eta_{int}\left(d_p, D_d\right)$ = 0.4 % at d_p = 1 μm, $D_d = 2\cdot10^{-3}$ m and the characteristic size of the plates in the vortex formation zone is 0.05 m.

For aerosol particles larger than 1 μm in size, the key mechanism for their removal in an apparatus with RPN an on-load tap changer is inertial deposition [4]. A dimensionless quantity that describes the properties of the inertial interaction of particles - the Stokes number:

$$Stk = \frac{\rho_p d_p^2 U\left(D_d\right)}{18\mu D_d}, \tag{8}$$

where d_p – the density of particles.

To estimate the efficiency of collision of aerosol particles with liquid droplets due to the inertial mechanism, one can use the equation in [15]:

$$\eta_{imp}\left(d_p, D_d\right) = \left(\frac{Stk}{Stk+0,35}\right)^2. \tag{9}$$

The overall efficiency of the interaction of aerosol particles with a drop of absorbing liquid, considering the mechanism of diffusion, interception, and inertia, can be represented by the sum of equations (4), (6), and (8). It should be clarified that the solution of the sum of these equations is a complex mathematical problem, which makes it impossible to obtain analytical dependences for aerosols of different dispersed compositions. Therefore, the primary task is to allow several approximations to assess the effectiveness of the interaction of aerosol particles and drops of absorbing liquid.

The speed of motion of drops of an absorbing liquid, considering the works [16, 17], can be determined as:

$$U\left(D_\kappa\right) = c_1 D_d^{c_2}, \tag{10}$$

where c_1, c_2 – constants that consider the operational and design parameters of the apparatus and are determined experimentally.

In [13], a study was carried out to compare the effectiveness of interaction due to three mechanisms, depending on the diameter of aerosol particles. Based on the graphical dependencies, for larger particles ($d_p > 10$ μm), the inertial interaction mechanism prevails, for smaller ones ($d_p < 5$ μm) – the diffusion mechanism.

Considering the data of [18], a promising approach to solving the problem of effective interaction of the system of an aerosol particle – an absorbing liquid droplet is to consider the diffusion and inertial mechanisms. In this case, the capture mechanism of aerosol particles of different dispersed compositions can be neglected due to the insignificant contribution to the total deposition efficiency.

There is a particle size for which neither diffusion nor inertial collision effectively allows the removal of particles – the minimum particle diameter for effective interaction with a droplet of absorbing liquid. To determine the minimum diameter of aerosol particles, we use the data on the deposition efficiency due to the diffusion and inertial mechanisms.

To clarify the efficiency of the diffusion interaction, we use the approximation of the Cunningham slip correction coefficient by the following equation:

$$K_C = Max\left[1,664\left(\frac{2\lambda}{d_p}\right), 2,609\sqrt{\frac{2\lambda}{d_p}}\right]. \qquad (11)$$

Using this approximation, in [18], an analytical solution was obtained for particles of various dispersed compositions in wet cleaning devices with a predominantly fine particle size (diffusion interaction mechanism).

To assess the effectiveness of the mechanism of inertial interaction, we use the approximation from [2]:

$$\eta_{imp}\left(d_p, D_d\right) = Min\left[3,4Stk^{9/5}, 1\right]. \qquad (12)$$

Substituting equations (4)–(6), (10), and (11) into equation (2), we get a dependence for assessing the interaction of liquid droplets with aerosol particles, for which the diffusion mechanism prevails:

$$\beta_d(d_p, D_d) = Ad_p^{-1}D_p^{(4+c_2)/3}, \qquad (13)$$

where

$$A = \frac{\pi}{2}\left[\frac{c_1\lambda(1-\alpha)(3\sigma+4)}{24(J+\sigma K)}\right]^{1/3}\left(\frac{2,609k_BT}{\mu}\right)^{2/3}. \qquad (14)$$

Substituting equations (7), (9), and (11) into equation (2), we obtain a dependence for assessing the interaction of liquid droplets with aerosol particles, for which the inertial mechanism prevails:

$$\beta_{imp}\left(d_p, D_d\right) = Bd_p^{18/5}D_d^{(1+14c_2)/5}, \qquad (15)$$

where

$$B = \frac{3,4\pi c_1^{14/5}}{4}\left(\frac{\rho_p}{18\mu}\right)^{9/5}. \qquad (16)$$

To determine the minimum effective diameter of a particle that can interact with a liquid drop, it is necessary to consider the diffusion and inertial mechanisms. The interaction of the above aerosol particles and droplets can be represented by the sum of equations (12) and (14):

$$\beta\left(d_p, D_d\right) = Ad_p^{-1}D_d^{(4+c_2)/3} + Bd_p^{18/5}D_d^{(1+14c_2)/5}. \qquad (17)$$

Let us consider Eq. (16) as a homogeneous differential one and, having solved it, we obtain the dependence for determining the minimum effective diameter of the interaction of aerosol particles and a droplet:

$$d_{p\min} = \left(\frac{5A}{18B}\right)^{5/23} D_d^{(17-37c_2)/69}. \qquad (18)$$

The resulting dependence (17) makes it possible to determine the value of the minimum diameter of an aerosol particle that can be captured by a liquid drop in devices with an on-load tap changer and can be used for a wide range of the diameter of absorbing liquid drops and their number in the volume of the device. To select the values of c_1 and c_2, the characteristics of the experimental stands of wet cleaning devices were taken [19]. The calculation results for different equilibrium droplet diameters characteristic for different turbulent flow in the apparatus (D_d = 1–7 mm) and irrigation density of the absorbing liquid are presented in (Figure 2).

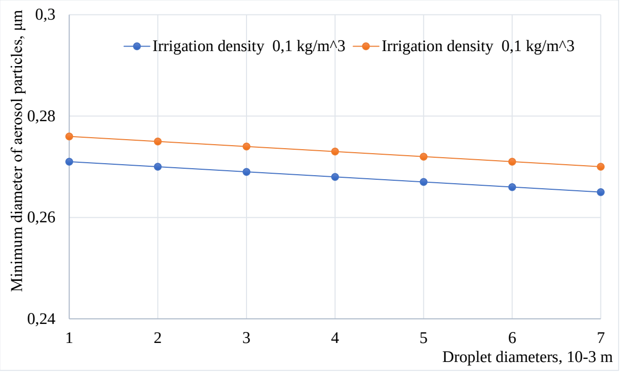

Figure 2 – The minimum diameter of aerosol particles for different droplet diameters and irrigation density of the absorbing liquid

5 Conclusions

In this work, studies of various mechanisms of deposition of aerosols capable of being captured by liquid droplets in an apparatus with RPN on-load tap changer, depending on the particle size distribution parameters of aerosols carried out.

The choice of particle deposition's diffusion and inertial mechanisms, as prevailing in the apparatus with RPN on-load tap changer, has been substantiated.

The calculations made allow us to say that the minimum effective diameter of aerosol particles that will be captured by liquid droplets in an apparatus with RPN on-load tap-changer, without considering the effects in the first zone of the apparatus, is not less than 0.3 microns, which indicates the possibility of working with fine aerosol emissions from industry.

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