Modeling the mechanics of particle motion in the air purification apparatus

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Abstract. The paper presents the description of the new high-performance design of the inertial air flow purification system for cooling systems of radio-electronic equipment. The two-stage design of the apparatus is proposed; the first stage is centrifugal-shock and the second is inertial there. Discharge of solid particles, which are dangerous for the cooling system, is carried out in the lower part. The processes modeling was carried out based on a probabilistic approach. An expression for the differential function of number distribution of elements of polluted flow on dimensionless parameter is obtained; equations for calculating statistical averages are proposed. The obtained theoretical dependences can be applied to determine the main modes of operation of cooling systems, at which the ingress of solid particles into the air ducts of radio-electronic equipment and the destruction of its elements are prevented. The spatial 3-D pattern of the structure of gas flows in the apparatus is built using computer simulation methods; it allows to calculate the necessary parameters of the developed model and to assess the presence of stagnant zones and eddy currents, which adversely affect the performance and throughput of the device. It was proposed to increase the wall thickness of the internal elements to 2÷4 mm in order to reduce the hydraulic resistance and the speeds of air flow in the central part.

1. Introduction

Air cooling is one of the main ways to reduce the temperature of electronic equipment [1–9]. Air cooling has practically superseded other types of cooling in this field due to the constructive simplicity of the equipment and high efficiency. High-speed air flows interact with radiator elements and their fins at operating the electronic devices. The intensity and efficiency of cooling depends on air movement speed. However, impact and abrasive destruction of the elements of the cooling system and the failure of the electronic equipment itself can occur if solid particles are present in the gas stream, for example, at air bleeding in dusty places. Thin-walled finning elements, contacting with high-speed turbulent air flow, and parts of the air blower, in particular, the blades and guides, especially are susceptible to wear. It is advisable to put at the input to the system a gas-cleaning equipment with simple design and low hydraulic resistance for reliable operation of electronic devices at dusty conditions. Despite the existence of sufficiently large number of gas-cleaning devices, almost all of them are not suitable for use in cooling systems for electronic devices. Filters and cyclones have high hydraulic resistance; electrostatic precipitators create significant interference, preventing the normal operation of the equipment.
This article is devoted to the development of a device design that has the above-described characteristics and a mathematical model of the processes occurring in it, which is necessary for the development of engineering calculation methods for the main operational and design parameters.

2. Research method
A new design of two-stage inertial apparatus for cleaning the air of the cooling system of electronic equipment, having compact dimensions, high cleaning efficiency and not significant hydraulic resistance, was proposed by the authors of this article (Figure 1).

![Figure 1. The principal scheme of apparatus, where 1 is housing of apparatus; 2 is input fitting; 3 is fitting for discharge of coarse fraction of dust; 4 is sloping bottom; 5 is fitting for discharge of the average fraction of dust; 6 - receiving cylinder of the second stage; 7 is screen of cylindrical form; 8 is receiving cylinder of the third stage; 9 are fixed blades; 10 is output fitting; 11 is sloping bottom; 12 is fitting for discharge of fine fraction, 13 is reflective plate.](image)

The cleaning stages are arranged coaxially in this apparatus. It can significantly reduce the device size. The first stage is a centrifugal shock. Here the main cleaning step takes place, when the largest amount of solid particles is emitted from the swirling gas stream. The solid particles are pressed against the wall of the apparatus and are concentrated in the near-wall layer due to the centrifugal inertial forces that occur at the flow is twisted. The condensed peripheral flow interacts with the fender body in this device in order to increase the intensity of cleaning the gas flow for the cooling of electronic equipment in contrast to the numerous cyclone designs. Solid particles are reflected from fender at the process of impact interaction; coarsely cleaned gas flow flows around it and moves to the next stage.

The protrusion of the fender element from the shell is chosen equal to the thickness of the wall layer containing the largest amount of solid phase. It procures an effective impact interaction, providing the extraction of solid phase from the gas stream with next directing the unloading device of the solid phase due to reflections, does not hinder to the movement of purified gas flow under the influence centrifugal forces; it slightly increases the hydraulic resistance compared to cyclones of countercurrent and straight-through types.

An inertial transition is made between the first and second stages, which makes it possible to prevent the ingress of large particles of fine cleaning into the internal (second) stage, which are reflected from the fender element. An additional device of unloading the solid phase from the gas stream, was made in
the zone of this transition. The second (internal) stage is inertial with a rosette swirler of countercurrent type, which provides the final stage of purification. The smallest particles are separated from the gas stream, previously cleaned in the first stage here.

The gas cleaning processes, implemented at the second stage, have been studied quite well [10–11]. The centrifugal shock interaction of the gas-dust flow at the first stage requires careful study and obtaining the calculated dependences, allowing to evaluate the efficiency of trapping solid particles, especially with abrasive properties. A stochastic mathematical model was developed for it.

Let’s consider the process of separation (purification from solid impurities) of the gas flow at the first (centrifugal-impact) stage of the device. Extraction of solid phase from the gas stream with next direct ion to the unloading device at moving under the action of centrifugal force and in the process of impact interaction with the fender body. However, part of the solid (small) particles is carried away from this stage by the gas stream, which enters into the next zones of the apparatus further.

To describe the structure (fractional composition) of particles captured at the first stage, we will use the probabilistic method [8–11], as one of the most effective in modeling the mechanics of disperse systems flows.

The purpose of the used method is to obtain a differential distribution function of the number of particles in some parameters, in our case, on sizes. It will be possible to determine the separation efficiency on the basis of the obtained dependence and to estimate the fractional composition of the dust caught at the first stage.

According to the probabilistic approach, the volume of the phase space during the formation of the flow, reflected from the fender, can be given by a set of random speed of the dust particle \( v \), its size \( D \) (we consider, the particles to be spherical) and the angular velocity of its rotational motion \( \omega \). The random component of the angular velocity has a significant effect on the probability of particle entrainment by the flow, since the Magnus effect occurs during rotation [12], the presence of which leads to a significant change in the trajectories of particles in the air flow, and in this case:

\[
dG = dvDd\omega.
\]

(1)

The distribution of the number of particles of the solid phase, retained in the first stage \( dN \) in the element of the phase volume, is described by the Equation:

\[
dN = A \exp\left(-E \cdot E_0^{-1}\right)dG.
\]

(2)

By making the normalization condition, the value of the constant factor \( A \) can calculate, and the energy balance equation \( E_0 \) can calculate from [8–11]. Stochastic energy \( E \) in the Equation (2) contains three components: kinetic energy and interaction energy with the air flow according to the mechanism of decomposition of the initial gas-dust flow, reflected from the fender and carried on the second stage. The rotation of particles with a random angular velocity \( \omega \) will take into account in compiling the expression for the kinetic energy:

\[
E = \frac{mv^2}{2} + \frac{J(\omega - \omega_0)^2}{2} + C \cdot D \cdot v,
\]

(3)

where \( J \) is particle inertia moment; \( m \) is its mass; \( C \) is coefficient of hydraulic resistance [8-11].

Transition to dimensionless quantities is feasible for convenience of calculations:

\[
D = \frac{D}{D_0}, \quad V = \frac{v}{v_0}, \quad \Omega = \frac{\omega}{\Omega_0},
\]

(4)

where \( D_0 \) is the maximum size of the solid phase particles in the gas stream (it determines experimentally), entered into the air cooling system of electronic equipment; \( v_0 \) is the initial velocity of the gas flow in the entrance into the first stage of the air purification device; \( \Omega_0 \) is the angular speed of
the flow in the first stage of the apparatus in the zone of placement of the fender element ($v_0$ and $\Omega_0$ are calculated by the computer model, shown in Figure 3).

The Equation (3) is written in the following form for energy taking into account dimensionless representations (4):

$$E = \frac{\pi}{12} D^2 D_0^3 V^2 v_0^2 + 8.5 \cdot 10^{-3} \pi D^3 D_0^3 \rho (\Omega \Omega_0 - \omega_0)^3 + C \cdot D \cdot D_0 V v_0^3.$$  

To obtain the differential distribution function of the number of dust particles by the D value in the reflected flow of the first stage, the reduced phase volume is denoted as $dG'$, taking into account the introduction of dimensionless quantities; it is determined from the Equation:

$$dG' = d\Omega dV.$$  

The differential distribution function of the particle number over the dimensionless parameter $D$ is given in this case by the expression:

$$f (D) = 9.4 A b_1 b_2 b_3.$$  

The values $b_1 \div b_6$, included in (7), are given by the expressions:

$$b_1 = (ND_0^3 \Omega_0 D^3) \frac{1}{2}, \quad b_2 = 0.16 D_0^3 D_0^3 \rho \frac{E_0}{D \cdot D_0 \rho E_0}, \quad b_3 = 31 D_0^3 D_0^3 \rho \exp\left(0.96 C^2 D_0^3 D_0^3 E_0^{-1} \rho^{-1}\right),$$

$$b_4 = \exp\left(0.1 b_1 D_0^3 D_0^3 \rho^{-1} (b_3 V^2 + 60 C)\right) - \exp\left(0.1 b_1 D_0^3 D_0^3 \rho^{-1} (b_3 V^2 + 60 C)\right),$$

The energy constant $E_0$, corresponding to the measure of energy in the Equation (2), can be found from the energy balance of the incoming air flow into the apparatus and the flow at the outlet of the first stage, taking into account the losses:

$$E_n = E_o + E_u + E_{pot},$$

where $E_n$ is free-stream energy; $E_o$ is reflected flow energy; $E_u$ is the energy of entrained particle flow; $E_{pot}$ is energy expended to overcome the resistances in the first stage of the apparatus. The required velocity values in the internal volume of the apparatus can be calculated using a computer model (Figure 3).

We will use condition of the normalization [11 - 12] to determine the constant A, from which follows:

$$A = N \int_{V_{min}}^{V_{max}} \int_{D_{min}}^{D_{max}} \int_{\Omega_{min}}^{\Omega_{max}} \exp\left(-E \cdot E_0^{-1}\right) d\Omega dDdV.$$  

Let’s make the Equation to determine the average value of the particle diameter of the solid phase:

$$D_{av} = N^{-1} \int_{V_{min}}^{V_{max}} DdN.$$  

After calculating the integrals and transformations, we have

$$D_{av} = 9.4 b_1 b_2 b_3 b_4 b_5.$$  

Here the values of $b_7 \div b_{12}$ are found by the Equations:
3. Results and discussion

The differential distribution curve of the number of particles by size was constructed using dependencies (7)-(10) (Figure 2). The value of size particles, passing through the apparatus into the air cooling system, was calculated theoretically using the Equations (12) and (13). Particles larger than 0.01 mm almost do not fall into the cooling system at initial gas velocities of 15 m/s.

![Figure 2](image)

**Figure 2.** Comparison of experimental and calculated data, where dots are experimental data; solid line is a theoretical expression curve (7)-(13).

The experiments were conducted on a laboratory installation. Dust was entered into the air flow, created by the centrifugal fan using an ejector. The formed gas-dust flow, imitating the operation of cooling systems of electronic equipment at dusty conditions, entered into the input jet of the gas cleaning device (Figure 1). The flow twisted in the tangential input into the apparatus; herewith the more dense dust particles shifted to the periphery and collided with fender. Dust particles flew at high speeds from the gas flow zone into the receiving device in the lower part of the apparatus, reflecting from fender. The dust, accumulated in the receiver, was removed from the device and analyzed. An experimental distribution curve of particle size was constructed at the study of the settled dust. Particle size determination was carried out using software product and the method, developed by the authors, for its implementation. The method is based on photographing selected particles and subsequent computer processing of digital images, which allows to determine the size of the particles, including with small sizes.

Analyzing the data, presented in Figure 2, it can be concluded that there is a fairly exact match in almost the entire range (the error does not exceed 10%). The best coincidence of experimental and calculated data is observed in the zone of large values of $D$. This fact is especially important, because it is large particles that lead to the most intensive wear according to experimental studies. In addition, there is also a coincidence of the ranges of the values of the quantity $D$, which correspond to the maximum values of the differential distribution function of the number of particles. Some discrepancy of the experimental and calculated data can be explained by the presence of roughness in the apparatus and the pulsation of the air flow, generated by the fan, as well as by the dosing features.
Numerical calculation was carried out with the aim of studying the hydrodynamic situation in the internal volume of the apparatus and determining the values of flow rates (which are necessary to compile the differential distribution function of the number of particles in magnitude $D$), using software systems that implement the finite element method [13]. The distribution patterns of flow rates and pressures in the design of the apparatus were obtained being developed during the calculation.

Figure 3 shows the pattern of the distribution of velocities, obtained in the internal cavity of the apparatus using the 3D model. Bunkers for collecting the captured dust particles were not taken into account at developing the model. The thickness of the walls and other internal elements were taken from 0.5 to 5 mm.

![Figure 3. The pattern of velocity distribution in the apparatus.](image)

The solution of this problem allowed to obtain all necessary data for modeling, to evaluate the pattern of distribution of velocities and pressures, to reveal the presence of stagnant zones and internal bypasses, which negatively affect on the cleaning efficiency and increase the hydraulic resistance.

Figure 3 shows that sharp increase in flow rates is in the central part of the apparatus (by reducing the flow area and a sharp change in the direction of flow when the internal elements flow around), which can lead to rapid abrasive wear of this area. It was found at computer simulation that a reduction in flow rates can be achieved by increasing the wall thickness of the internal elements to 2-4 mm. It is possible to lower the values of maximum speeds to 10-15 m/s and reduce the hydraulic resistance of the device by 5-7% in this case.

4. Conclusion
A mathematical model of optimal heat discard in the air-liquid cooling system of radio-electronic equipment has been developed. The model makes it possible to define the parameters of air and liquid cooling systems for radio-electronic equipment with heat emission power 0.8 kW.

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