Investigation of mechanical processes of submicron aerosol formation

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In this paper we present a review of experimental studies of mechanical processes and the materials involved in that yield the production of submicron aerosols. The processes of pouring in and out, rolling, breaking, severance, and hit have been investigated. We present characteristics of the aerosols that are being produced in different processes and from different materials. The mechanism of aerosol generation during sand interspersing is examined in a more detail. This process is shown to be a source of a significant amount of submicron aerosol in arid zones.

Introduction

Atmospheric aerosols are widely involved in the exchange processes occurring on our planet. The question on the sources of atmospheric aerosol is being arisen practically in every paper in this field. With the advances achieved during recent years in the development of theoretical and experimental methods an increased attention of the researchers has been given to submicron aerosols that make up the main bulk of particles present in the atmosphere. Combustion and photochemical processes are traditionally considered to be the main sources of submicron aerosol over the continents.[1] In this case no attention has been given to a large number of mechanical processes that also can yield submicron particles.[2] The lack of knowledge in this field has stimulated us to study experimentally some of the most widespread mechanical processes that can yield submicron aerosol particles.

Results and discussion

The first step to accomplish the above-mentioned task was the creation of the necessary experimental base. Some setups were designed and assembled to study the processes of pouring in and out, rolling, fracture, break, and impact. A wide range of processes and materials was tested. Table 1 shows the characteristics of aerosol obtained as an outcome of different processes.

As is seen from Table 1 practically all the processes listed lead to formation of aerosol particles of less than one micron in size. In some cases (paper, steel) the aerosol particle size distribution is bimodal in the diameter range below several tens of nanometers. The process of aerosol formation in pouring sand can, for example, be of the environmental significance.

Table 1. Characteristics of aerosol formed as a result of different mechanical processes

Material	Output (pieces)	Parameters of particles	Process
Rubber–brass	$1.4 \cdot 10^5$ cm^{-2}	10–15 nm	Impact
Rubber	$3 \cdot 10^3$ cm^{-2}	10–25 nm	Rolling
Getinaks	$3 \cdot 10^3$ cm^{-2}	10–15 nm	Rolling
Paper	$6 \cdot 10^6$ cm^{-1}	< 3 nm, 15–20 nm	Break
Glass	$2 \cdot 10^9$ cm^{-2}	5–20 nm	Fracture
Graphite	$7 \cdot 10^8$ cm^{-2}	0.4 μm	Fracture
Steel	10^{10} cm^{-2}	< 3 nm, 20 nm	Fracture
Sand	40 cm^{-2} · s^{-1}, at 15 cm/s*	0.4 μm	Pouring
Silica gel	140 cm^{-2} · s^{-1}, at 15 cm/s*	0.4 μm	Pouring

*15 cm/s is the speed of surface moving in our experiments.

The formation of aerosol in free-flowing sand

The next step following the establishment of the fact of aerosol formation is the assessment of its practical significance and the development of a model of the process under study. At present the process of aerosol formation in free-flowing sand has been studied best of all.

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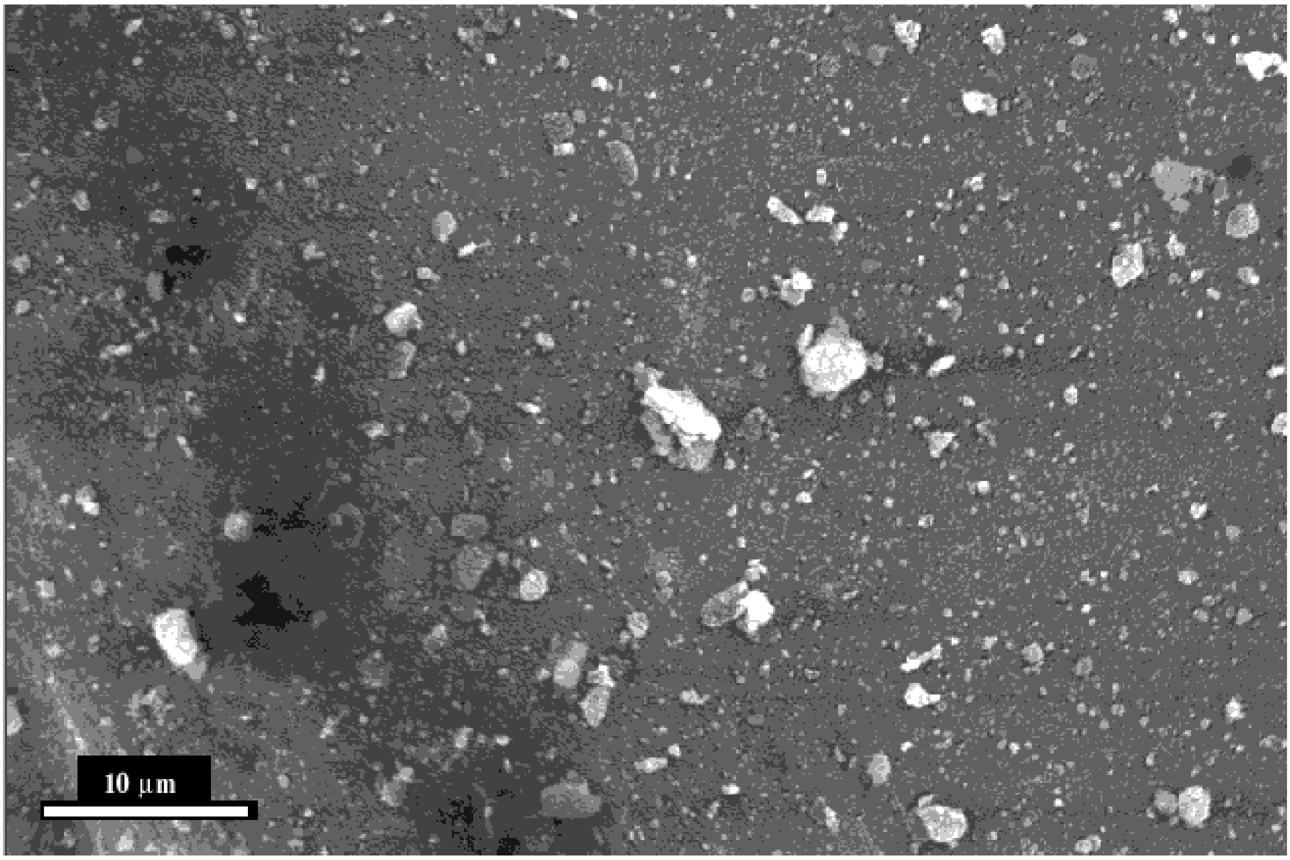

Fig. 1. Microphotograph of a sand particle surface obtained with a scanning electron microscope.

The sand transport due to the process of free flowing under the effect of wind is a natural process in a desert.[3] The formation of aerosol during dusty storms is also known.[4] In our experiment the sand is transported inside a rotating can without the effect of air current. The linear velocity of sand motion corresponds to the wind velocity of 5 to 8 m/s. The estimates show that a 2 to 3 km^2 area of a sand surface can emit (at the generation parameters indicated in Table 1) into the atmosphere the amount of aerosol sufficient for the aerosol concentration to be comparable with that of natural aerosol. Taking into account that the arid zones occupy up to 40% of dry land, this mechanism contributes significantly to the total content of continental aerosol.

Within the framework of this paper the concentration and the "sand" aerosol size spectrum were measured using a photoelectric counter (Fig. 2). The surface of sand particles was studied using a scanning electron microscope (Fig. 1).[6]

The processing of microphotographs (Fig. 1) showed the presence of small particles on the surface of sand grains. The number density of particles is about 30 per 100 μm^2 of the sand grain surface. The particle size-distribution, both in the air and on the surface, is bimodal (Fig. 2). It is possible to explain such a shape of the size spectrum if we assume that the particles on the sand grain surface are of atmospheric origin.

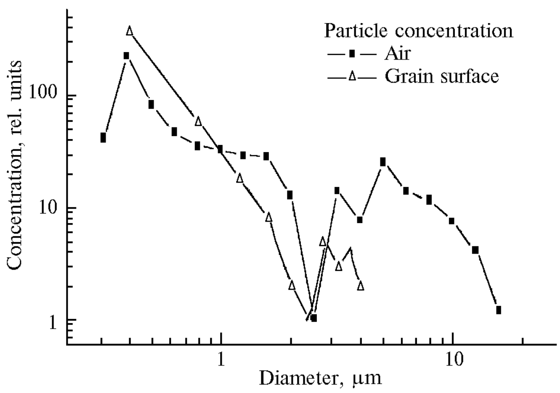

Fig. 2. Size distribution of particles observed on the sand grain surface and in the air.

To interpret the process, we propose the following qualitative model:

The initial assumptions:

1) Sand grains are assumed to have a spherical shape of the diameter $D = 10^{-1}$ cm.

2) There are small particles of the size $d = 0.4 \cdot 10^{-4}$ cm adsorbed on the surface of sand grains.

3) The van der Waals forces are responsible for the particles sticking to the sand grain surface.

Estimation of the energy of the interactions studied

1. We assume that the collisions among the sand grains mainly cause the aerosol formation. It is supposed that at a collision the sand grain falls from a height that equals the size of a sand grain. In this case the collision energy is expressed as follows: $E_1 = \pi\rho g D^4/6 = 0.1$ erg, where $\rho = 2.5$ g/cm^3 is the sand grain density, D is the sand grain size, $g = 10^3$ cm/s is the acceleration of free fall.

2. The adhesion energy for a particle of 0.4 μm size on a flat surface can be calculated by the following formula[5]:

$$E_2 = -Ad/(12x) = 6 \cdot 10^{-12} \text{ erg},$$

where $A = 10^{-13}$ erg is the energy constant, $d = 0.4 \cdot 10^{-4}$ cm is the size of a particle, $x = 0.5 \cdot 10^{-7}$ cm (5Δ) is the gap between the particle and the surface.

3. The value of electrostatic interaction between a particle and the surface for a pair of elementary charges can be easily estimated as follows:

$$E_3 = -\frac{e^2}{2x} = 2.5 \cdot 10^{-12} \text{ erg},$$

where $e = 5 \times 10^{-10}$ CGCEq.

The particle energy at the surface can be calculated from the maximum rate of the sand grain fall V:

$$V = \sqrt{2gD} = 14 \text{ cm/s}.$$

Hence, the kinetic energy of the particle equals

$$E_4 = mV^2/2 = 8 \cdot 10^{-12} \text{ erg}.$$

In this formula: $m = 8 \times 10^{-14}$ g is the particle mass.

From the above-said it follows that the particle energy at the surface far exceeds the adhesion energy and the energy of the possible electrostatic interaction, that is, the inertial “shake off” of the particles from the sand grain surfaces is possible. Taking into account a significant kinetic energy of particles, it is assumed that the rate of particle emission from the surface practically equals the maximum rate of the sand grain fall, i.e., 14 cm/s.

Next we evaluate whether this energy is sufficient or not for a particle to overcome the viscous sublayer surrounding the same grain in the air flow.

The viscous sublayer thickness for a sand grain δ can be estimated using the following formula:

$$\delta^2 = 2\,\frac{\eta}{\rho}\,\frac{D}{V_\infty} \cong \frac{1}{4}\,\frac{D}{V_\infty} \Rightarrow$$

$$\delta \cong 4 \cdot 10^{-2} \text{ cm} = 400 \text{ μm},$$

where η and ρ are the air viscosity and density, $V_\infty = 15$ cm/s is the velocity of the ambient air flow.

Then one can easily estimate the distance l at which the particle can move off of the surface:

$$l = VV_s/g = 5 \cdot 10^{-4} \text{ cm} = 0.5 \text{ μm},$$

where $V_s = 2 \cdot 10^{-3}$ cm/s is the sedimentation rate of the particle (0.4 μm).

As follows from the above said, the particle that escapes the surface couldn’t leave the viscous sublayer itself. However, the rate of the air flow is not zero even inside the sublayer.

The velocity of the ambient air flow V_l at the distance the particle escaped at, if it is assumed that at the sublayer boundary this velocity equals $V_\infty = 15$ cm/s, is calculated as follows:

$$V_l = V_\infty\, l/\delta = 4 \cdot 10 \text{ cm}^{-2}/\text{s}$$

and if we assume that the escaped particle immediately takes the speed of the ambient air flow, it is possible to estimate the maximum time t of the particle drift from the sand grain surface in the form of the sand grain size divided by the speed of the air flow V_l:

$$t = D/V_l = 2.5 \text{ s}.$$

In this case the other possible mechanisms prove to be less efficient, namely, the diffuse penetration of the viscous sublayer requires the time

$$t_D = \sqrt{\delta^2/D} \approx 40 \text{ s},$$

where $D = 1.6 \times 10^{-6}$ cm^2 is the diffusion coefficient of a particle that escapes the layer.

Thus, qualitatively, the process can be interpreted as follows. The colliding sand grains shake off small particles from their surfaces, when freely flowing, and then these particles move inside the viscous sublayer to the distance of the order of their size and then are transported outside a sand grain by the air flow inside the sublayer. Then the ambient air flow carries the escaped particle out to the free atmosphere.

Conclusion

In conclusion it should be emphasized once more that the formation of submicron and nanometer aerosol particles in the mechanical processes, studied in this paper, can probably compete with the photochemical processes and combustion, which are the traditional sources of aerosol particles of the size less than one micron. As a result of the investigations, we recognized the potentially significant source of the atmospheric submicron aerosol for arid zones of the continent, namely, the process of the sand free flowing, for which the qualitative model was proposed.

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