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Short Communication

Estimation of Air Velocity for Levitation of Microparticles for Air Quality Control

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Abstract

Using Newton's first law of motion and geometrical analysis, we performed an estimation of force balance on a microparticle to figure out the conditions for dust levitation and ventilation. The dust particle is assumed to be a sphere pushed by a uniform upward airflow. The gravitational force pulls it downward. The velocity-dependent drag force is assumed to be zero. The results show that the minimal speed of air is proportional to the square root of both the particle mass density and size. To visualize the formula, five samples of dust have been used involving hazardous PM2.5 dust. The minimal speed for PM2.5 dust at room temperature is ~22 cm/s, which is just 10% higher than the "breeze" speed of air commonly known in the industry. This analysis could be adopted to other more complex shapes of microparticles, such as ellipsoids and cylinders corresponding to various kinds of dust. The result could also help figure out optimal and effective ventilation and filtration systems toward saving energy in air quality control.

Keywords: microparticle, airflow, ventilation

Introduction

Affection of microparticles and bioaerosols on human health receives has seen important interest in recent years [1-4]. Arising from industrial zones, motor vehicles, or living activities, these particles float and are inhaled, causing negative effects on human health [3-7]. Studying to reduce these affects, beside examining the origin, moving laws, and distribution of microparticles in various regions, their direct filtration is also crucial for a cleaner indoor environment. As a result, filtration systems are widely adopted in working and living spaces.

The physics of micro-sized particles floating in ambient air are important in both fundamental physics and application. The chaotic behavior is usually described by the Brownian motion of a particle under random affections of external forces that result from the floating force of air or liquid, the collisions of nearby particles, gravitational force, or even electrostatic force if the particle is not electrically neutral. On practical applications, the density and kinetics of these particles

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are of interest, especially for air quality control in factories and living spaces [2, 7] – especially the PM10 [7] and PM2.5 [8-13] dusts that could have hazardous effects on human health.

There are several forces exerted on a floating particle that affect its motion. Gravitational force pulls it to the ground while the buoyancy force levitates it up. In static air with negligible air fluctuation, it gradually builds up on the ground. However, due to the thermal fluctuation of the external environment and human activities, the particles continuously collide. In spaces where the passive cooling is adopted, a ventilation fan and a filtration system are usually equipped.

The structure and effectiveness of filtration systems have been examined in many studies [1, 2]. In this work, we examine the role of the speed of air on the particle levitation for ventilation. Newton's first law of motion is adopted on the microparticle to figure out the force balance on it. Then an estimation on minimum speed of airflow will be shown. The speed should reach some value v_0 to maximize the levitation and filtration effectiveness. The obtained formula presents a dependence on the particle size and mass density of the speed squared.

The formulation is general and could be applied to any shape of microparticle. In such cases a more complex geometrical analysis should be used. Therefore, this simple analysis is basic for studying the motion of microparticles.

Calculation Model

To derive a formula showing the force that airflow exerts on the particle, these assumptions are adopted [Fig. 1]:

- The dust shape is a sphere with radius r, mass density ρ, and mass m_d with $m_d = (4/3)\,\pi r^3\rho$.
- The airflow has a density ρ_0, moving continuously and uniformly with velocity v_0.
- The airflow exerts a uniform pressure P on every area element (perpendicular to the flow direction) of the hemisphere, i.e., $P = dF/d\mathrm{s} = F_{\mathrm{air}}/S$ where $S = \pi r^2$ (as shown in Fig. 1a).

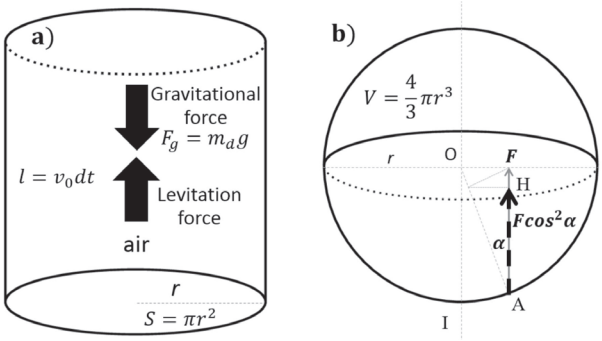

Fig. 1. Forces exerted on a microparticle that is assumed to be a sphere.

- The drag force, which is proportional to the velocity of microparticles [14], $F_{\mathrm{drag}} \propto F_{\mathrm{drag}}v$, is negligible.

For the particle to be levitated, the upward acceleration must be positive, i.e., from Newton's first law of motion:

$$\vec{a} > 0 \Leftrightarrow \sum \vec{F} > 0 \Leftrightarrow F_{air} - F_g > 0 \tag{1}$$

A Rough Estimation

A particle of mass m_d suffers a gravitational force [see Fig. 1b)]:

$$F_g = m_d g = \frac{4}{3}\pi r^3 \rho g$$

…where $g \approx 9.8$ m/s^2 is the gravitational acceleration and an airflow levitation force (see Fig. 1a)):

$$F = m\frac{|d\mathbf{v}|}{dt}$$

…where dv is the velocity change of the air element. We assume that the initial velocity of the air element is v_0 and after colliding and transferring momentum to the dust, its final velocity is $v_f = 0$. Therefore, $|d\mathbf{v}| = v_0 - v_f$. m is the mass of the air volume that passes through cross-section S within the time interval dt:

$$m = V\rho_0 = Sv_0 dt\rho_0$$

Then,

$$F_{\mathrm{air}} = m\frac{|d\mathbf{v}|}{dt} = Sv_0 dt\rho_0 \frac{v_0}{dt} = Sv_0^2\rho_0 = \pi r^2 v_0^2 \rho_0 \tag{2}$$

The condition (1) to be satisfied so that the airflow could elevate the dust particle is $F_{\mathrm{air}} > F_g$. Then,

$$\pi r^2 v_0^2 \rho_0 > \frac{4}{3}\pi r^3 \rho g \Leftrightarrow v_0^2 > \frac{4}{3}\left(\frac{\rho}{\rho_0}\right) rg \tag{3}$$

This means the minimum velocity should be $v_0 \; ; \; \frac{2}{\sqrt{3}}\sqrt{\frac{\rho}{\rho_0} rg}$

A Finer Analysis

In Eq. (2) we assumed that all air elements in the area S exert the same force on the cross section of the dust particle. This could be corrected more because the levitating force that an air element exerts on the dust at position A is smaller than that at I (Fig. 1b). The net force is proportional to AH/AF = $\cos^2\alpha$, or $F_i = F\cos^2\alpha \Rightarrow P_i = P\cos^2\alpha$.

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Therefore, the force element exerting on the area $ds = r^2 \sin\alpha d\alpha d\beta$ would be:

$$dF_i = P_i ds = P\cos^2\alpha ds = P\cos^2\alpha r^2 \sin\alpha d\alpha d\beta = \mathrm{Pr}^2\cos^2\alpha \sin\alpha d\alpha d\beta \quad (4)$$

Integration over the semi-sphere with α, $\beta = [0 : \pi]$, we have:

$$F_{air} = \int dF_i = P.r^2 \int_0^{\pi} \cos^2\alpha \sin\alpha d\alpha \int_0^{\pi} d\beta = \frac{2}{3}\pi r^2 P \quad (5)$$

In comparison to Eq. (2), the force is now reduced by a factor of 2/3, i.e.: $F_{air} = (2/3)\ \pi r^2 P = P = (2/3)SP$. Therefore, the r.h.s of Eq. (3) should be modified as:

$$\frac{2}{3}v_0^2 > \frac{4}{3}\frac{\rho}{\rho_0}rg \Leftrightarrow v_0^2 > 2\frac{\rho}{\rho_0}rg \quad (6)$$

…where ρ = 1.204 kg/m^3 at 20ºC, meaning that for the dust particle to be elevated the air velocity squared must be higher than value $2(\rho/\rho_0)rg$ or $2(\rho/\rho_0)dg$, where the diameter d is commonly used for the particle size. As an example, the PM2.5 [PM10] with $d \leq 2.5$ [10] μm are of essential interest due to their direct negative effects on the human respiratory system.

Results and Discussion

The analysis in this case is simple thanks to the spherical symmetry of the dust. However, for other microparticles with more elaborate shapes, the analysis will be involved – especially the integration in Eq. (5). Hence, the minimum v_0 will correspond to the case of the particle least exposed to airflow, i.e., ellipsoids and cylinders that are vertically aligned.

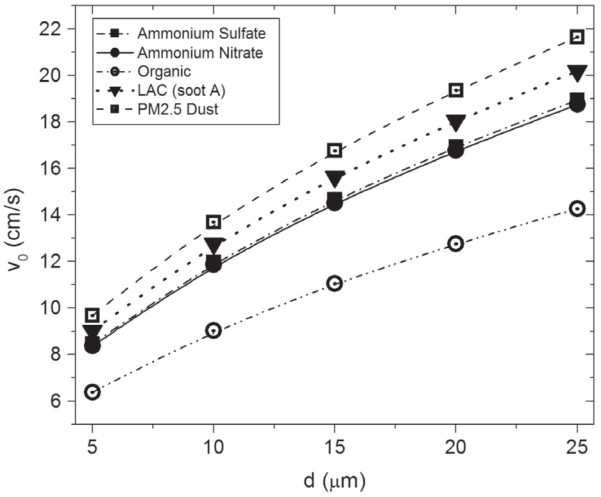

Fig. 2. Minimum speed of air v_0 from Eq. (6) to levitate the dust for five samples.

It is straightforward to visualize Eq. (6) provided that the particle parameters are known. Nevertheless, due to the diversity of dust characteristics, e.g., physical/chemical composition, specific mass, and size, it is challenging to figure out entirely the factor that is dependent on both the dust specific mass and size. Therefore, we use five samples of dust with the mass densities studied in a recent work (Ref. 15, Table 3), where ρ' = 1.0 – 2.3 g/cm^3: ammonium sulfate (1.76 g/cm^3), ammonium nitrate (1.72 g/cm^3), organics (1.0 g/cm^3), LAC (light-absorbing carbon, 2.0 g/cm^3), and PM2.5 (2.3 g/cm^3), and the estimated velocity of the airflow in Fig. 2.

The figure shows the sub-linear increase in the minimum speed v_0 (Eq. 6) with particle size. For example, v_0 should reach 22 cm/s to levitate PM2.5 dust. These values for the speed of air (v_0) from a ventilation/filtration fan help for setting up an optimal cleaning/filtration system since a high value of v_0 could attract more dust into space or excite other dust sources. These factors reduce the effectiveness of the filtration system and increase energy costs.

Conclusions

Although a simple model has been adopted, the obtained results have shown a quantitative agreement with the practical results in the experiment. The important achievement is the formula relating the minimal velocity of the airflow and the density and size of the dust. It shows that the minimum speed of air is proportional to the square root of both the particle mass density and size so that it could levitate the microparticle. The calculation has been confirmed using the data from a recent experiment and presents a consistence with the values used in practical applications, i.e., industry. The calculation method could be extended for different microparticles with various shapes and mass densities.

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Conflict of Interest

The authors declare no conflict of interest.

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