CORRELATION BETWEEN VELOCITY AND SIZE OF FREE-FALLING NONSPHERICAL PARTICLES MEASURED BY LASER DOPPLER TECHNIQUE

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Abstract

The velocity and the size of free-falling volcanic ashes, i. e. nonspherical particles with 60-120 μm sieved size, were measured by using the differential laser Doppler techique, in which the size was estimated from the visibility of a Doppler signal. Correlation between the measured velocity and the measured size agreed with the theory for a spherical particle within experimental errors. It is suggested that the effective diameters of nonspherical particles can be measured by the laser Doppler technique provided that correlation between the velocity and the size of free-falling nonspherical particles agrees with the theoretical correlation for a spherical particle.

1. Introduction

Noncontact particle size measurements utilize the Mie scattering theory, which is recognized as a powerfull means in many scientific fields. Laser Doppler technique offers an alternative method of particle size measurements, that has widely been treated theoretically and experimentally [1-5]. This method takes advantage of extracting both velocity and size information respectively from the frequency and the visibility of a Doppler signal obtained by a differential laser Doppler techique. In this case, size estimation from visibility values is based on the theory for a spherical particle and good agreement between the theory and experiment has been shown under various experimental conditions.

In this paper, correlation between the velocity and the size of free-falling nonspherical particles was measured by this method and compared with the theory for a spherical particle, in order to investigate availability of this method to nonspherical particles.

2. Experimental

The experimental arrangement is shown in Fig. 1. The beam from a 5mW He-Ne laser was guided by two mirrors M_1 and M_2, and split by a half-mirror HM to provide two beams of the same intensity, which lay in a plane parallel to the YZ-plane. These beams crossed at an angle of γ, the bisector of which was parallel to the Z-axis, to form a probe volume for a differential Doppler technique. A particle fell plumb down parallel to the Y-axis to pass the probe volume formed within a glass cylinder, the function of which was to avoid disturbance from the ambient air flow. The scattered light from the particle was collected by a lens L into a multiplier phototube PM provided with a pinhole plate A. The light collecting optical axis lay in a plane parallel to the XZ-plane, making an angle of θ with the bisector of the two crossing beams. The output of the multiplier phototube was fed to a digital memory after it was amplified by a preamplifier.

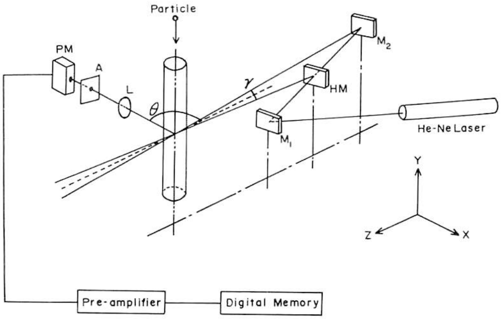

Fig. 1 Experimental arrangement for measuring velocity and size of free-falling nonspherical particle.

The experimental arrangement had the following three features:

(1) Any lens for focusing the laser beams and forming a probe volume of high space resolution was not used.

(2) The distance from the center of the probe volume to the position, where particles were first at rest and started to fall, was appropriately long, so that particles passed the probe volume with terminal velocities determined by acceleration of gravity and resistance of air viscosity.

(3) The lens in the light collecting optics focused the center of the probe volume onto the pinhole in front of the multiplier phototube, in order to collect the light scattered only from a particle that passed through the center of the probe volume.

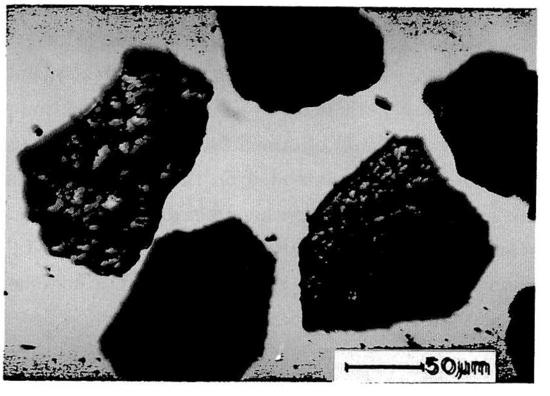

Fig. 2 Photomicrograph of particles of volcanic ashes with 80-120 μm sieved size.

Volcanic ashes were used as nonspherical particles. They were classified by passing them through sieves into two groups whose sieved sizes were 60-80 μm and 80-120 μm, respectively. A photomicrograph of particles of the latter group is shown in Fig. 2. The reason of using volcanic ashes was as follows:

(1) The most of their chemical components consisted of those of glass. Therefore, they were considered to have almost the same density and refractive index as those of glass.

(2) They had randomly distributed shapes and were suitable for obtaining experimental data for general nonspherical particles.

3. Results and discussion

A typical Doppler burst signal stored in the digital memory is shown in Fig.. 3. It consisted of modulated components and a pedestal. The frequency f of the modulated components relates to a particle velocity v and, as is well known in the case of a differential Doppler configuration, it is given bv

$$f = 2v \sin(\gamma/2)/\lambda \qquad (1)$$

where λ is the wavelength of the laser source. On the other hand, a particle size relates to the visibility of the signal, The visibility V was defined as usual by the following formula

$$V = (I_{max} - I_{min})/(I_{max} + I_{min}) \qquad (2)$$

where I_{max} and I_{min} are burst center values of upper and lower envelopes of the modulated signal, respectively. For a nonspherical particle, the main problem exists in the definition and estlmation of particle size. To start with, an effective diameter of a nonspherical prticle was defined and estimated by using the theory supported by experimental verification for a spherical particle. In the case of a spherical particle, the relation between the visibility V and the particle diameter d is given by [1]

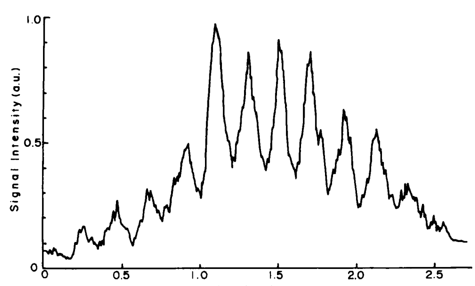

Fig. 3 Typical Doppler signal obtained with the experimental arrangement shown in Fig.1. The signal is the intensity of light scattered from a particle of volcanic ashes.

$$V = |\, 2 J_1(\pi d/\delta)/(\pi d/\delta) \,| \qquad (3)$$

where J_1 is the first-order Bessel function, and δ is the interference fringe separation in a probe volume, i. e.

$$\delta = \lambda/2 \sin(\gamma/2) \qquad (4)$$

The effective diameter of a nonspherical particle was defined as d in eq.(3).

The beam crossing angle γ was chosen to be 0.30° ane 0.20° for two groups of volcanic ashes, i. e. size of 60-80 μm and 80-120 μm, respectively. The velocity v was calculated by eq. (1) using this γ and a frequency f obtained from Doppler burst signal. The fringe separation δ became from eq. (4) 120 μm and 180 μm according to γ of 0.30° and 0.20°, respectively. Therefore, the argument π d/δ in eq. (3) remained less than the value of 3.83, which makes the visibility V given by eq. (3) a monotonic decreasing function of d free from ambiguity in determining the effective diameter d. An observation angle θ was set at 90°. Effective diameters were calculated by eq.(3) using the visibility values of the Doppler signals. In this way, velocity and effective diameter were measured from each burst signal and correlation between velocity and effective diameter for each particle was obtained.

The correlation obtained in the above mentioned way is shown as open circles in Fig. 4. It is important to note that the measured effective diameters coincided well with the sizes of two sieved groups. In comparison to this, a similar experiment for spherical particles was made using glass beads of 60-80 μm diameter and the obtained correlation is shown in Fig. 4 as solid circles. The measured

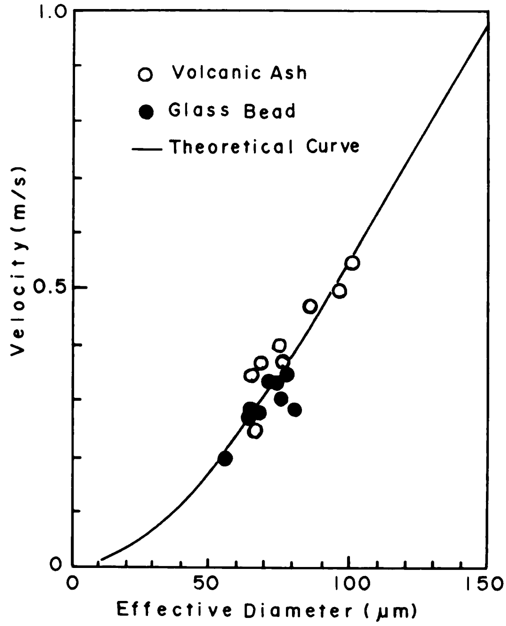

Fig. 4 Correlation between velocity and effective diameter of free-falling volcanic ashes. The results of glass beads together with a theoretical curve are also shown.

diameters coincided well with the specified size. A theoretical correlation curve between terminal velocity and size is also shown is Fig. 4 as a solid curve, calculated from the theoretical relation between terminal velocity v_t and particle diameter d, which is given by

$$v_t = \sqrt{4(\rho - \rho_0)\, g\, d/3\, \rho_0 C_D} \quad \cdots\cdots (5)$$

wkere ρ and ρ_0 are densities of particle and medium, respectively, g is acceleration of gravity, and C_D is a drag coefficient of the medium, which is a function of viscosity η of the medium[6]. For obtaining the theoretical curve shown in Fig. 4, following values were used. $\rho = 2.5 \times 10^3 kg/m^3$ (for glass), $\rho_0 = 1.21 \times 10^3$ kg/m^3 (for air) and $\eta = 1.82 \times 10^{-5}$ Nsm^{-2}(for air). The theoretical curve agreed well with the experimental values both for nonspherical and spherical particles.

There are various definitions of nonspherical particle size [6] and two typical ones are mentioned in the followings:

(1) The diameter of a nonspherical particle is defined as the diameter of a sphere which has the same projected area as the nonspherical particle.

(2) The diameter of a nonspherical particle is defined as the diameter of a spherical particle which falls in a medium with the same terminal velocity as the nonspherical particle.

The effective diameters obtained in the experiments were the same as those defined by the definition (2) and, moreover, judging from above mentioned coincidence with the sizes of two sieved particle groups, showed no discrepancy with those defined by definition(1). Therefore, it is concluded that the effective diameters of nonspherical particles can be measured by laser Doppler technique, provided that correlation between velocity and size coincides with the theory for a a spherical particle.

4. Conclusion

Correlation between the velocity and the size for free-falling volcanic ashes, i. e. nonspherical particles was measured by laser Doppler technique. Correlation between the measured velocity and the measured size agreed with the theory for a spherical particle within experimental error. The results show that the effective diameters of nonspherical particles can be measured by the laser Doppley technique, if it is checked beforehand that measured correlation between the velocity and the size of free-falling nonspherical particles agrees with the theoretical correlation for a spherical particle. The method is applicable to velocity and size measurement of moving nonspherical particles in any industrial apparatus or equipment.

Acknowledgements

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REFERENCES

1) W. M. Farmer, Appl. Optics **11**(1972)2603.
2) W. M. Farmer, Appl. Optics **13**(1974)610.
3) W. D. Bachalo, Appl. Optics **19**(1980)363.
4) W. M. Farmer, Appl. Optics **19**(1980)3660.
5) G. Laufer, Appl. Optics **23**(1984)1284.
6) T. Allen, *Particle size measurement* (Chapman and Hall, London, 1981)