MEASUREMENTS OF THE TERMINAL VELOCITY OF RELATIVELY COARSE PARTICLES

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Abstract

Terminal velocities of relatively coarse particles were measured by suspending the particle in an upward air-flow in a vertical tube. Both the appropriate length of the vertical tube in which the particle was suspended and the suitable construction of a gas distributor were determined based on the measurements of the air velocity distribution in the tube. Observed terminal velocities of spherical glass particles coincided very well with the calculated values. In the case of corn particle, an example of irregular-shaped particle, observed terminal velocity agreed well with that obtained by dropping the identical particle.

The method proposed in this paper is useful to measure the terminal velocity of coarser particle for which the use of the dropping method is inappropriate since it requires very long travel distance.

Introduction

Terminal velocity of solid particle falling in the air is an important factor which controls the movement of the particles in a certain kind of gas-solid contact system[1]. In the case of spherical particles, the terminal velocity can be exactly calculated by the use of the dynamical similarity. That is to say, we can use the relation between drag-coefficient and Reynolds' number which has been confirmed experimentally by many workers. However, the terminal velocity of irregular-shaped particle can not be easily calculated. In order to estimate the terminal velocity by using the dynamical similarity, we often measure the terminal velocity in the water, for instance, changing the Reynolds' number over the wide range. In such cases we must prepare the various-sized many particles of geometrically similar shape. However, it is difficult to prepare these particles in the case of irregular-shaped particles. If only an identical particle is dropped in the air and in the water, the Reynolds' number of the particle falling at terminal velocity is not the same in both cases and therefore the dynamical similarity can not be applied.

The measurement of terminal velocity is very important in the case of irregular-shaped particles. However, it is difficult to measure the terminal velocity of coarse particle with a diameter of a few milimeters by simply dropping it. Because the coarse particle must travel very long distance before its velocity reaches the terminal velocity. For example, a spherical glass particle of 2mm in diameter required the travel distance of about 20m, as far as we calculated the travel distance required to reach 97 per cent of the terminal velocity.

From this point of view we have attempted to measure the terminal velocity of the coarse particles by suspending the particle in an upward air-flow.

1. Measuremests of the Terminal Velocity by Suspending a Particle in an Upward Air-Flow

A cylindrical glass tube was set up vertically as shown in Fig 1. A particle was put into the vertical tube and air was let upward in the tube at a uniform velocity. When the solid particle was just suspended in it, the superficial air velocity was measured. If the tube diameter is enough large to eliminate the wall effect the superficial air velocity coincides with the terminal velocity of the particle. The upper end of the tube was enlarged in diameter so as to prevent an entrainment of the particle. At the lower part of the tube stages of 100-mesh screens were introduced as a gas distributor. We investigated to find out the appropriate number of stages of screen and the appropriate length of the tube in which the particle was suspended, based on results of the measurement of gas velocity distribution.

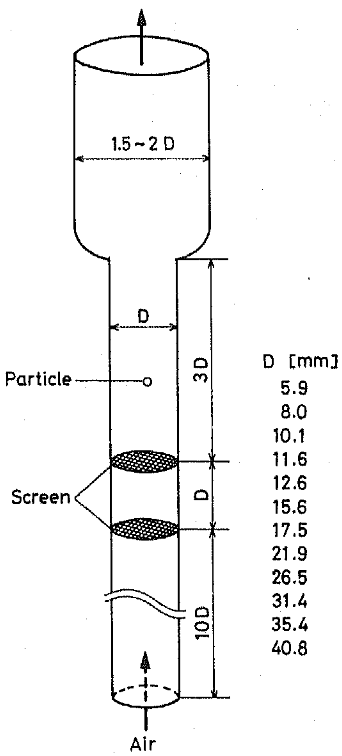

Fig. 1 Equipment for measuring the terminal velocity by suspending a particle in upward air-flow

1.1 Velocity distribution of the upward air-flow

We adopted 100-mesh screen as the gas distributor because the pressure drop was relatively small when the gas flowed through it at a high velocity. First we tried to determine the appropriate number of stages of screen. We measured the velocity distribution of gas which passed through various number of stages of screen. The results are shown in Fig. 2. The distance between adjacent screens was chosen as the same as the inside diameter of the glass tube D. The gas velocity distribution was

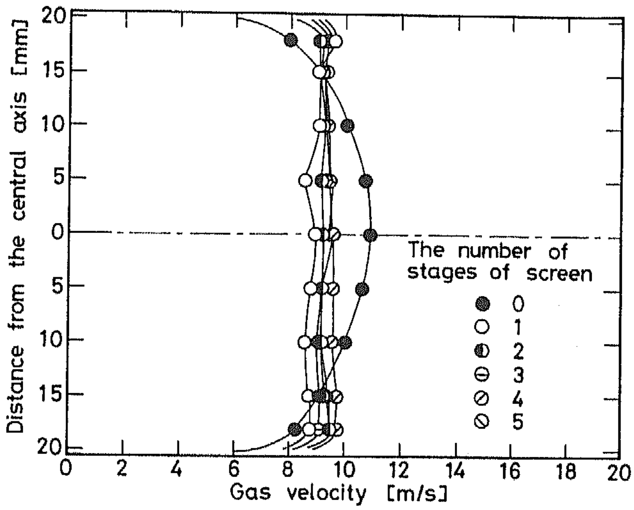

Fig. 2 Effect of the number of stages of screen on the gas velocity distribution

measured upward at the distance, D, from the top stage by the use of a modified Pitot tube. The modified Pitot tube was calibrated with a standard Pitot tube. As can be seen in Fig. 2, the distributor consisting of two stages of screens gives a more uniform velocity distribution than the single-stage distributor. There is no remarkable difference in the velocity distribution among the distributors with two or more

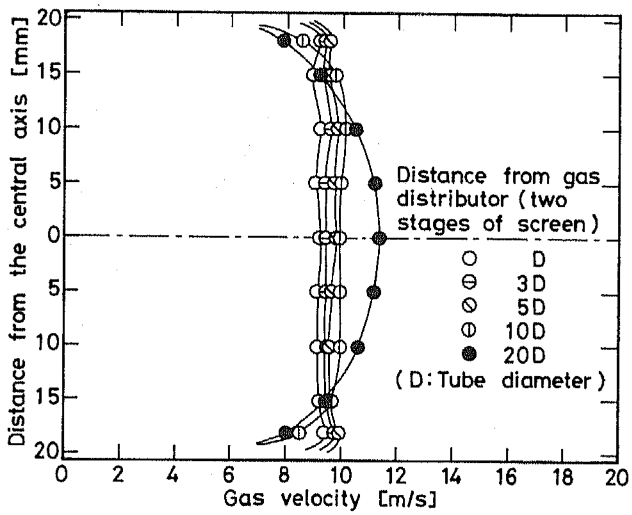

Fig. 3 Gas velocity distribution at various positions above the gas distributor

screens.

Next we tried to measure the distribution of gas velocity at various positions above the distributor consisting of two stages of screens. The results are shown in Fig. 3. It may be seen that the velocity distribution is uniform near the top of the gas distributor. The velocity distribution is still uniform at positions up to five times the tube diameter above the top stage. However, it becomes uneven at the position ten times the tube diameter from the top stage; the gas velocity decreases toward the wall of the tube. The results shown in Figs. 2 and 3 were obtained at the average air velocity of about 10m/s. The similar results were obtained when the average gas velocity was changed in the range which corresponded to the terminal velocity we measured.

From the results shown in Figs. 2 and 3 it may be said that two stages of screens are enough to get a good velocity distribution and that the length of the tube in which the particle is suspended should be limited several times the tube diameter. We thus adopted two stages of screens for the gas distributor, and made the effective tube length three times the tube diameter (see Fig. 1).

2. Terminal Velocity of Coarse Particles

2.1 Spherical particles

As described above, the terminal velocity of the spherical particle need not be measured, because it can be easily calculated by using the dynamical similarity.

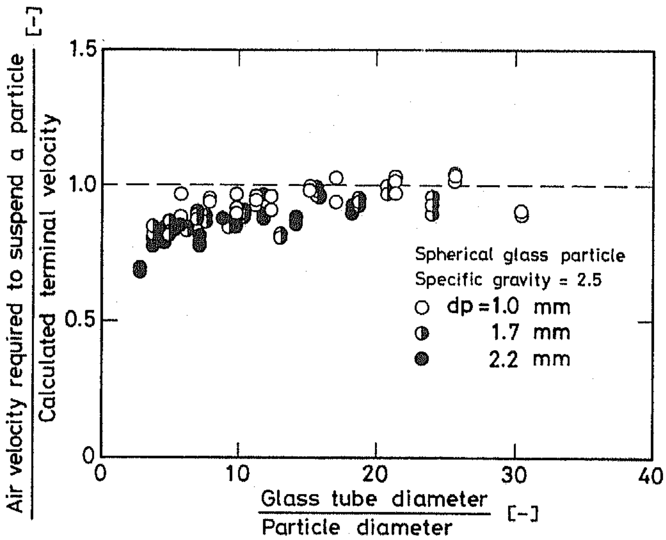

Fig. 4 Velocity of the upward air-flow required to suspend a particle

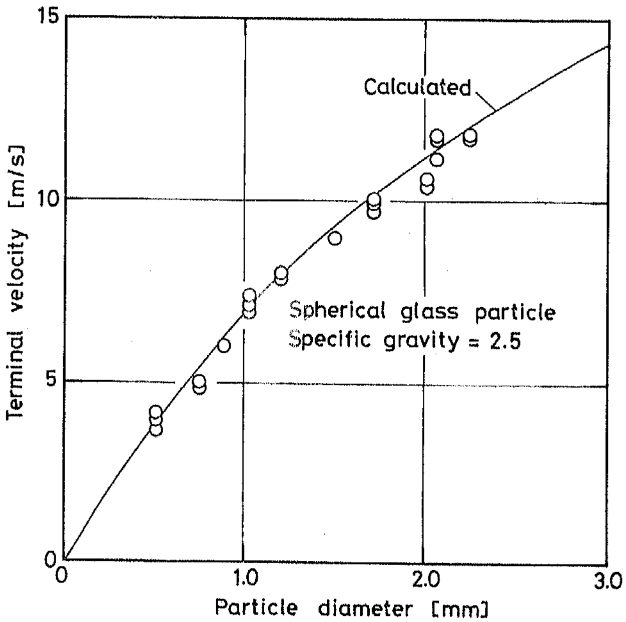

Fig. 5 Terminal velocities of spherical glass particles (D/dp>15)

However, first we measured the terminal velocities of the spherical glass particles and compared them with calculated values, to examine whether the acculate terminal velocity could be obtained or not. We used the glass particles which were almost in the shape of perfect spheres. The diameter of each particle was measured with a microscope several times, changing the orientation of the particle. Such particles of which the difference between the maximum and minimum values were less than three per cent of average diameter were used.

By the use of the glass tubes of various diameters shown in Fig. 1 we measured the superficial air velocity required to suspend the spherical glass particles of various sizes. Some of the results are shown in Fig. 4. The abscissa shows the ratio of tube diameter to particle diamter and the ordinate, the ratio of air velocity, required to suspend the particle, to calculated terminal velocity. When the tube diameter is small the wall effect arises and the observed air velocity required to suspend the particle is smaller than the calculated terminal velocity. The observed velocity gets larger as the tube diameter increases and becomes approximately equal to the calculated terminal velocity when the ratio of tube diameter to particle diameter amounts to about 15. We also measured the terminal velocity of the spherical polyethylene and polystylene particles. The similar results were obtained for the minimum ratio of the tube diameter to the particle diameter, at which the termianl velocity could be derived.

Figure 5 illustrates the observed terminal velocities of various-sized glass particles obtained on the condition that the tube diameter is more than fifteen times the particle diameter. The observed velocities coincide very well with the calculated values.

2.2 Irregular-shaped particles

The measured terminal velocity can not be compared with the calculated value in the case of non-spherical particle. So we also measured the terminal velocity of corn particle, as an example of the irregular-shaped particle, by dropping the particle in the air at rest. In the dropping method falling velocity of the particle was measured changing the height from which the particle was dropped. The falling velocity gradually increases with the dropping height, and finally it approaches approximately constant, that is, the terminal velocity. We could fortunately measure the terminal velocity by dropping the particle, because the particle was a small one.

Figure 6 shows the data obtained both by suspending and by dropping the identical particle. Physical properties of the particle are also shown in Fig. 6. The spherical equivalent diameter shown in Fig. 6 means the diameter of the sphere which has the same volume as the particle. As can be seen in Fig. 6, the terminal velocity obtained in the suspending method coincides very well with that obtained in the dropping method. This result indicates that the terminal velocity of irregular-shaped particles can be also measured acculately by the suspending method.

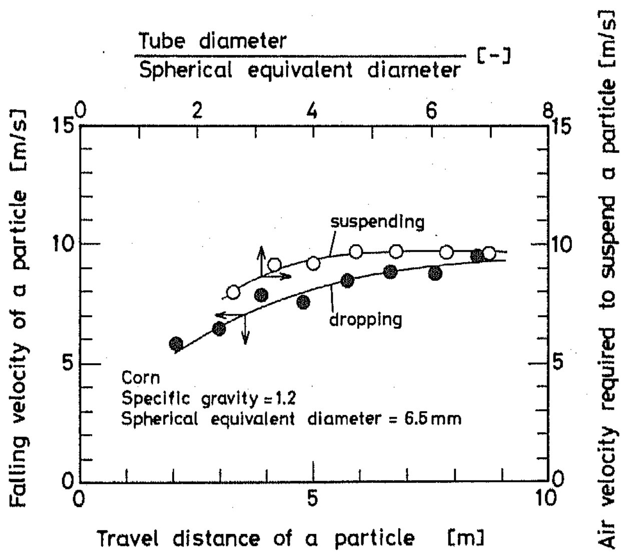

Fig. 6 Terminal velocity of corn particle measured by suspending and by dropping the particle

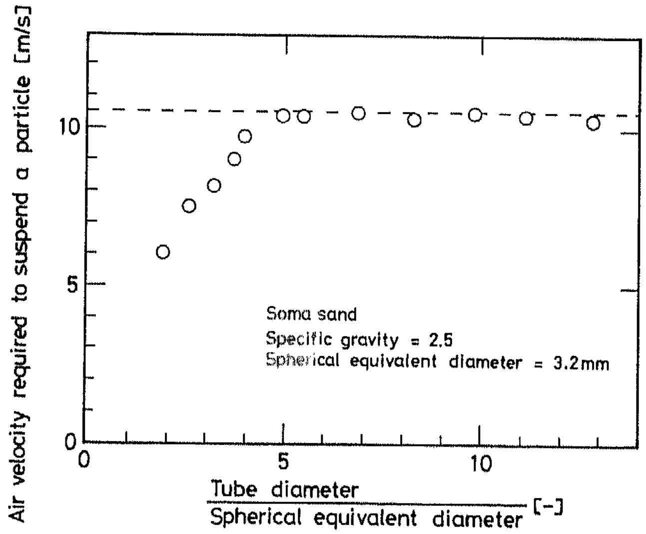

Fig. 7 Terminal velocity of Soma sand

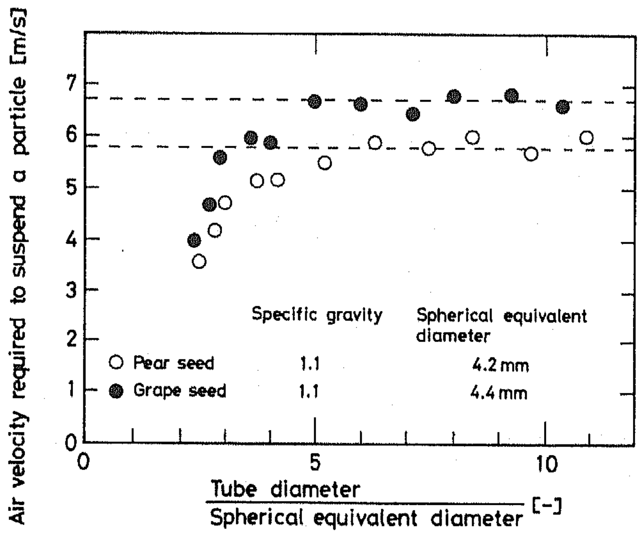

Fig. 8 Terminal velocities of pear seed and grape seed

Figure 7 shows the measured terminal velocity of the Soma sand. Figure 8 shows the measured terminal velocities of seeds of a pear and a grape. These seeds were dried naturally, being left at room temperature for many days, before they were used. As can be seen in Fig. 6, 7 and 8, in the irregular-shaped particle the minimum ratio of the tube diameter to the particle diameter, at which the terminal velocity can be derived, is smaller than that in the spherical particles. The ratio seems to

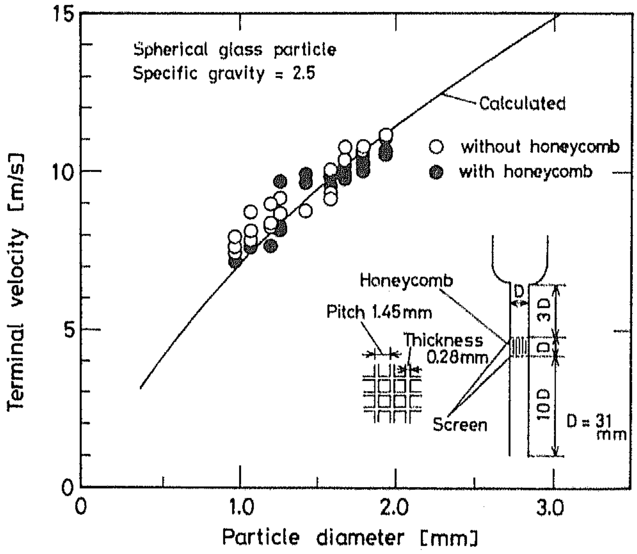

Fig. 9 Effect of the use of honeycomb on the observed terminal velocity (Spherical glass particle D/dp>15)

depend on the shape of the particle. Therefore, if we wish to measure the terminal velocity of a certain particle of irregular shape, the measurement should be repeated changing the ratio of the tube diameter to the particle diameter and the minimum ratio should be found out.

3. Effect of the Turbulence

Air motions are generally turbulent when a coarse particle is suspended in upward air-fiow. In the presence of turbulence the resistance exerted by the fluid on a particle is different from the case that the particle moves in fluid at rest. The resistance are usually greater when the fluid moves on the particle at rest[2]. Therefore, the terminal velocity measured by suspending a particle in the upward air-flow is smaller than the real terminal velocity of the particle which drops in the air at rest.

We attached the honeycomb between two stages of screen as shown in Fig. 9 so as to minimize the effect of the turbulence and measured the terminal velocities of the spherical glass particles. The results were compared with the data which were obtained by using the apparatus without honeycomb, as shown in Fig. 9. There is no remarkable difference between the measured values obtained using the apparatus with honeycomb and without honeycomb.

We adopted the honeycomb to only one apparatus of which the tube diameter was 31mm. The maximum diameter of the particle which we could measure the terminal velocity by using this apparatus was about 2mm. When the particle of such a small diamter is suspended in the upward air-flow in vertical tube, the tube Reynolds' number is relatively small. In the case shown in Fig. 9 the tube Reynolds' number ranged from 1.5×10^4 to 2.3×10^4. However, the tube Reynolds' number becomes larger when the terminal velocities of larger particles are measured. In such cases further study is necessary on the effect of the turbulence.

Conclusion

The terminal velocities of relatively coarse particles were measured by suspending the particle in upward air-flow in vertical tube. Measured terminal veoocties of spherical glass particles coincided very well with the calculated values. In the case of corn particle, a typical example of the irregular-shaped particles, measured velocity agreed well with that obtained by dropping the identical particle. It was found that the minimum ratio of tube diameter to particle diameter, at which the terminal velocity can be derived, was about 15 in the case of the spherical particle. In the irregular-shaped particle, the ratio was smaller than that in the spherical particle. The turbulence did not affect the observed values as far as we measured the terminal velocity of spherical glass particles up to 2mm in diameter, by using the tube of 31mm in diameter.

The method proposed in this paper is a convenient one to measure the terminal velocity of relatively coarse particle which can not easily be measured by dropping the particle.

Acknowledgment

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Nomenclature

D = diameter of glass tube [mm]
d_p = particle diameter [mm]

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