Distribution of Particle Number Density near an Iron Dust Flame

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Introduction

Prevention of accidental dust explosions is an important subject for safety management in industrial processes, in which combustible powders are handled. Once a dust explosion happens in the processes, it will cause serious harms. To appropriately prevent accidental dust explosions and suppress the damages, it is important to properly understand dust explosion phenomena. That is, it is essential to understand how a flame is formed and propagates in a combustible dust cloud. However, such basic aspects have not been clear yet, because combustion in a dust cloud is a complex phenomenon taking place in heterogeneous system. Most of previous studies about dust explosions have been focused on only practical subjects, such as the minimum ignition energy, explosion concentration limits, rate of pressure rise, and explosion pressure [1, 2].

Table 1 Flammable lean limit (equivalence ratio) of gas and dust [1, 2, 3].

Fuel gas	Lean limit (Equivalence ratio)	Dust	Lean limit (Equivalence ratio)
Methane [3]	0.50	Adipic acid [1]	0.28
Ethylene [3]	0.40	Poly-ethylene [1]	0.17
Propylene [3]	0.44	Sulfur [1]	0.10
Toluene [3]	0.52	Aluminum [2]	0.29
Methanol [3]	0.46	Iron [2]	0.35

Flammability lean limits are of practical importance for prevention of dust and gas explosions. Some of the measured results of flammability lean limits are shown in Table 1 [1-3]. In this table, concentration is indicated in equivalence ratio (calculated on the assumption that all combustible solid vaporizes), it is found that the lean limits of combustible dusts are one-second or one-third smaller than that of combustible gases. It expresses the dangerousness of combustible dust clouds, however, the reason of this feature has not been clarified yet.

In our recent study [4], behavior and structure of an iron dust flame have been examined in detail, and the structure of the combustion region and particle behavior near the flame have been clarified. It was found that particle velocity differs from gas flow velocity. In this kind of flame propagation (velocity is less than a few ten cm/s), the density of gas ahead of combustion region (preheat zone) is almost constant. If particles exactly follow the gas flow movement, number density of particles becomes constant in the region ahead of the combustion zone. However, as mentioned above, the particle velocity differs from the gas flow velocity, therefore, particle number density varies as the particle approaches to the combustion zone. This phenomenon must influence the flammability lean limits.

In this study, distributions of particle number density and particle velocity were measured near a flame propagating through an iron particle cloud. Measured distribution of particle number density was compared with that estimated by the velocity distribution.

Experimental Apparatus

Schematic of experimental apparatus is shown in Fig. 1. Sample of iron particle was set on the bottom of the combustion chamber. It was dispersed into the chamber by air blow and an iron dust cloud was formed. Just before ignition, the movable tube moved downward and an open field test section was appeared. The particle cloud was ignited at the center of the open section by an electric spark. This chamber is suitable for examining the flame propagation behavior because a flame propagates in an open field free from influence of walls. The flame propagation process and behavior of particles were recorded by a high-speed video camera (recording speed is 1,000-2,000 frames/s) with a microscopic optical system. The particles were illuminated by laser light beam from an argon ion laser.

The used particle is iron particle (purity: 99.5%). The diameter of particles and its distribution were measured by using a scanning electron microscope. It was observed that the iron particles were almost spherical. The measured diameter distribution is shown in Fig. 2. The diameters of the particles are distributed mostly from 2 to 4.5 μm. In this study, iron particle cloud concentration is set to be 1.05 kg/m^3.

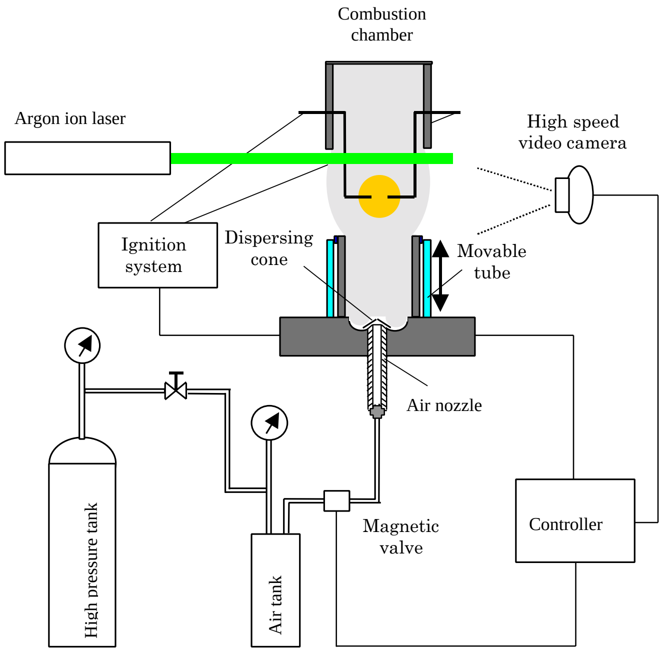


Fig. 1 Experimental apparatus.

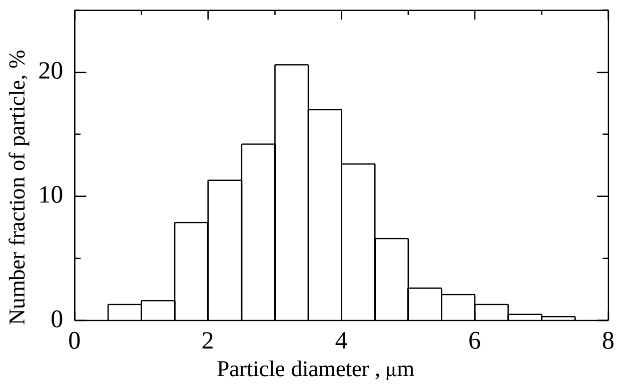


Fig. 2 Diameter distribution of iron particles.

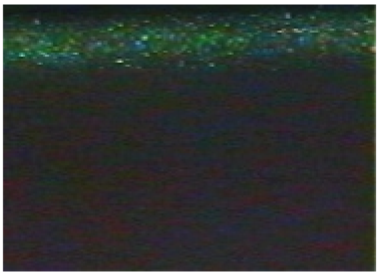
Results and Discussions

Distributions of number density and velocity of iron particles near the flame

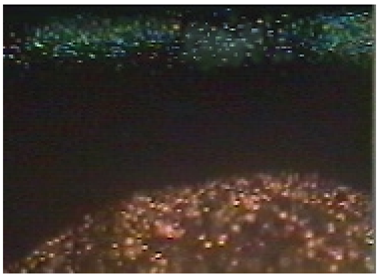
Figure 3 shows a typical series of photomicrographs, which represents upward propagating process of a flame through an iron particle cloud and laser light scattering images of particles. Green luminous points seen in the laser light path at the upper part of the photomicrographs are the laser light scattering images of iron particles. White luminous zone seen at the lower part of the photomicrographs, which is composed of luminous iron particles, are burning iron particles. Flame propagation through an iron particle cloud is observed as a propagation of a combustion zone of 3-5 mm in width, which consists of luminous particles without gas phase flame [4]. In this experiment, the propagating velocity of the combustion zone is almost constant (25.0 cm/s), and the propagation phenomena can be considered as steady state.

It is seen in the high-speed photomicrographs that number density of iron particles varies with the distance from the combustion zone. The number density N (number of particles per unit spatial volume) of iron particles was measured by using laser scattering images of iron particles. The measurements were performed at the position in laser light path sequentially as the combustion zone is approaching to the measuring area to obtain the distribution of particle number density. When the combustion zone comes into the measuring area, number density can not be measured because of strong emission from burning particles. Figure 4 shows the measured distribution of iron particle number density with the distance x from the leading edge of the combustion zone. The positive value in x means the distance in the direction of the flame propagation. When the distance x is larger than about 11.0 mm, the iron particles number density is almost constant. At the region of $0 < x < 11.0$ mm, the particle number density increases with the decrease of distance x. At the distance $x = 0.60$ mm, the particle number density becomes maximum. The maximum number density is about 2.7 times larger than the number density at the position $x > 11.0$ mm. Behind the leading edge of the combustion zone, the number density decreases quickly. This decrease might be caused by the expansion of gas with temperature rise.

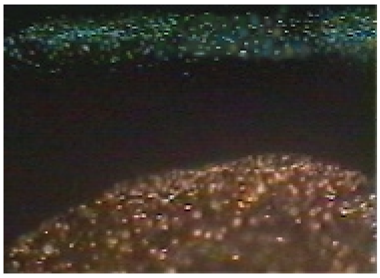
The velocities of particles near a flame propagating upward were measured to examine the mechanism of the change of number density. The measurement is done by tracking each particle on a series of photomicrographs. The velocities could be measured for only large particles because it is very difficult to track small particles. The diameter of measured particles was about 10 μm. Figure 5 shows measured velocity (relative velocity to the combustion zone) profiles of iron particles near the combustion zone. The positive value in the velocity means the velocity in the direction toward burned region. When x is larger than about 10.0 mm, the unburned iron particles move at almost constant velocity of about 35.0 cm/s (free falling). When x becomes less than 10.0 mm, the particle velocity starts to decrease. It means that particles are accelerated in the direction of flame propagation. The velocity reaches to the minimum value of about 10 cm/s at the leading edge of the combustion zone (x = 0) and then increases. The particle velocity is determined by the balance of three forces, i.e., drag force by the velocity difference of the particle from surrounding gas, gravitational force, and thermophoretic force. Therefore, the velocity difference between particle and gas will be arisen at the position ahead of the combustion zone, where gas flow is accelerated.



t=29 ms (x=12.25 mm)



t=72 ms (x=2.25 mm)



t=73 ms (x=2.0 mm)

Scale

0 2mm

Fig. 3 Series of photomicrographs. 1,000 frames/s, t: time from ignition

Evaluation of number density of particles by the velocity distribution

Distribution of number density of iron particles can be evaluated by the measured velocity distribution of particles. In this section, the evaluation of number density of particles at the region ahead of the upward propagating flame was done to examine the reason why the number density varies. In the

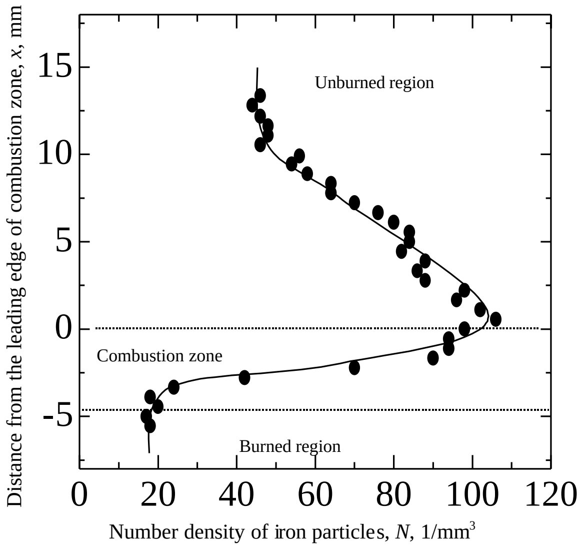


Fig.4 Measured distribution of number density.

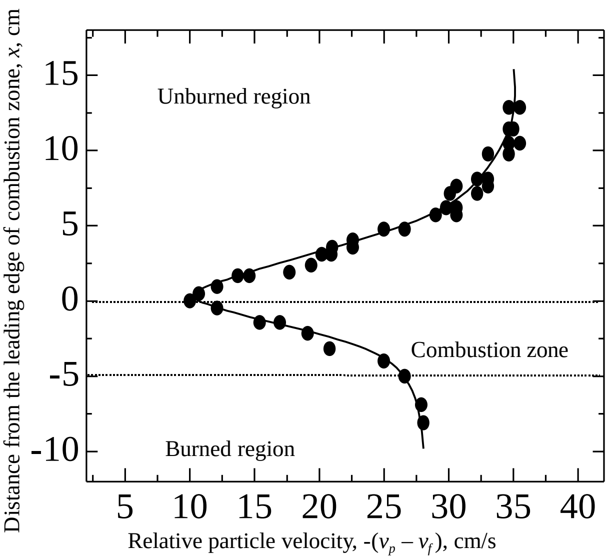


Fig.5 The relative velocity distribution of particles to the leading edge of combustion zone.

observed area, particles behavior can be assumed as quasi one-dimensional. A control volume, which is moving with the coordinate fixed on the combustion zone, is introduced. It is of cross section A and height Δx. Mass conservation equation in this control volume is formulated as Eq. (1).

$$\frac{\partial}{\partial t}\left(A \Delta x \overline{m} N\right) = -A\overline{m}_{x=x+\Delta x} N_{x=x+\Delta x} u_{x=x+\Delta x} + A\overline{m}_{x=x} N_{x=x} u_{x=x}, \quad (1)$$

where $\overline{m}$ is average mass of a particle, u the particle velocity on the coordinate fixed on the combustion zone (relative velocity to the combustion zone). From Eq. (1), we can get,

$$\frac{\partial}{\partial t}\left(\overline{m} N\right) = -\frac{\partial}{\partial x}\left(\overline{m} N u\right). \quad (2)$$

In the region ahead of the combustion zone, steady state can be assumed. Therefore,

$$\overline{m} N u = \text{constant}. \quad (3)$$

Using this equation, distribution of the number density of iron particles was calculated from the measured velocity distribution of the particles. In the calculation, the average mass of a particle $\overline{m}$ is assumed to be constant.

The calculated number density is plotted on Fig. 6 against the distance x from the leading edge of the combustion zone. N is normalized by the number density N_0 at the position far from the combustion region, where N becomes almost constant. On the same figure, the measured number density is also plotted The calculated number density agrees well with the measured value. It means that the variation of the particle number density near the combustion zone can be reasoned by the velocity distribution of the particles. There is a little deviation between the calculated number density and the measured one, especially in the region just ahead of the combustion zone (x = 0 - 1 mm). Two reasons are supposed for this deviation. The first is that the average mass $\overline{m}$ is not constant. The second is that the velocity distribution used for the calculation was measured on only large particles of 10 μm in diameter, while the particle velocity varies with particle size.

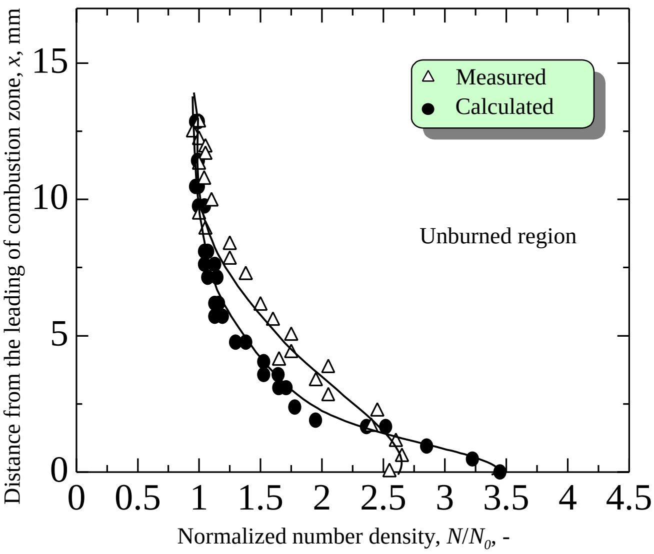


Fig.6 Comparison between calculated and measured normalized number density N/N_0.

Conclusions

Distribution of particle number density is measured near a flame propagating through an iron particle cloud. It was found that just ahead of the combustion zone the number density increases to be 2.7 times larger than that at the unburned region far from the combustion zone. This feature must influence the flammability lean limits of combustible particle clouds. The profile of particle number density estimated by the measured velocity distribution of particles agrees well with that of the measured particle number density.

References

1. Wilfred E.B. and Tang M.J., Gas, Dust and Hybrid Explosions, Elsevier. N.Y., p.247, 1991.
2. Cashdollar, K.L., .Hertzberg, M. and Zlochower, I.A., 22nd Symp. (Int.) on Combustion, p.1757, 1988.
3. Zabetakis, M.G., Bulletin 627, Bureau of Mines, 1965.
4. Sun, J-H., Dobashi, R., and Hirano, T., 27th Symp. (Int.) on combustion, p.2405, 1998.