Thermophoretic effect on soot particle behaviour –influence of particle morphology–

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1 Introduction

Soot is a main pollutant emitted from combustion devises. It is important for appropriate emission control of combustion devises to understand the behavior of soot particles in combustion fields. If the size of a particle is smaller than the mean free path of the ambient gas, the particle under a temperature gradient experiences a force toward the colder region. This phenomenon is called thermophoresis, a mass transfer phenomenon induced by the temperature gradient. Soot is a very small particle formed near a combustion field, where a very steep temperature gradient exists. In order to appropriately understand the soot formation process in a combustion field, the effect of thermophoresis must be taken into account. Some researchers proposed that the thermophoretic effect on soot formation was significant [1-3]. However, the effect cannot be analyzed in detail because of the lack of basic information and data concerning the thermophoretic effect on soot particles. Only few studies [4-11] have been conducted to quantitatively evaluate the thermophoretic effect.

In our previous study, Ono et al. measured the thermophoretic velocities of soot particles produced in flames under microgravity conditions [9]. It was found that the measured thermophoretic velocities were much greater than those expected by the sizes of the aggregated soot particles; with a given temperature gradient the measured velocities were almost constant (regardless of particle size) and equal to that evaluated by the theory for the freemolecule regime. These results suggested that the thermophoretic behavior of soot particles was different from that of solid spherical particles. Suzuki et al. also measured the thermophoretic velocities of carbon black [10]. In the study, the new optical system was developed to measure the thermophoretic velocities and the sizes of aggregated particles simultaneously. It was found that the measured thermophoretic velocities were almost proportional to $v\nabla T/T$. No clear dependence of the thermophoretic velocity on the size of aggregated particles was found. These results suggest that thermophoretic velocities of an aggregated particle must be governed by not the aggregate size but the primary particle size. For the aggregated particles such as soot, also the morphological factors must affect the thermophoretic behavior. However the effect of particle morphology has not yet clarified in detail.

	the size of primary	the bulk	the DBP	the true	Kn of primary
	particles(nm)	density	absorption	density(g/cm3)	particles
#40	24	0.14	110	1.788	40
#44	24	0.18	78	1.807	40
#45	24	0.19	53	1.814	40
#30	30	0.13	113	1.807	33
#33	30	0.16	76	1.809	33

Table. 1 The characteristics of carbon black

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In this study, we examined the effect of particle morphology on the thermophoretic behavior of aggregate carbon particle in detail. In the measurements, five kinds of carbon black samples have been used, whose morphological characteristics vary each other.

2 Experiments

Soot particles are aggregates of smaller primary carbon particles of nano-scale sizes. In this study, the effects of morphological factors(such as the bulk density which represents the whole degree of aggregation and the DBP (Liquid Dibutyl Phthalate) absorption which represents the surface area measured in the liquid molecule size level) and the size of the aggregated particles were examined to understand the effect of particle morphology on thermophoresis. Five different samples of carbon black particles were used. Each carbon black sample was specially produced to have primary particles of a uniform size. The characteristics of them are shown in Table 1. Each sample is different in morphological characteristics. The size of aggregated carbon particles is varied in the range from 10 to 180 µm because the size of aggregated carbon particles cannot be controlled.

The thermophoretic velocity was measured by the experimental setting shown in Fig. 1 [9]. In the experiments, each particle was observed individually between two aluminum plates (90 mm \times 90 mm, gap distance 2 mm); each plate was set to be at a different temperature. A heater was used to heat up the upper plate. The temperature gradient of each experiment can be determined by measuring the temperatures by thermocouples at two locations at different heights from the plate. The temperature gradient was varied from 0 to 20 K/mm. The natural

gradient was varied from 0 to 20 K/mm. The natural convection can be well suppressed by this experimental setting in this range of temperature gradient [11]. In the measurements, the carbon black particles on the mesh were introduced into the field of observation between the two plates by carrying them with air blown into the field. The carbon black particles were observed by a backlight using a microscope (resolution: about 3-4 μ m) and recorded by a digital video recorder. This microscopic observation can realize the simultaneous measurement of the size and the moving behavior of aggregated carbon particles. The observation area was at the center of the field between the plates. Immediately after a carbon black particle is carried into the observation area under a temperature gradient, it starts to move toward the lower plate (colder plate). The velocity of the moving soot particle reaches a constant terminal

velocity within a sufficiently short period of time. This constant terminal velocity is the summation of the thermophoretic velocity and the gravitational falling velocity of the particle. Therefore, the thermophoretic velocity can be calculated by subtracting the gravitational falling velocity form the measured terminal velocity.

At first, experiments with no temperature gradient were performed. It was found that, for each sample, the relation between the gravitational falling velocity and the size of aggregated particle is almost one-toone correspondence. Therefore, the gravitational falling velocity can be estimated by the measured size of the aggregated particle. The estimated gravitational falling velocity was adjusted by considering the change in air viscosity due to the temperature difference.



Fig.2 The measured thermophoretic velocity

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Fig. 1 Experimental setting

3 Results and Discussion

It is known that the thermophoretic velocity of a solid spherical particle is proportional to $v\nabla T/T$. The measured thermophoretic velocities were plotted against vVT/T (Fig. 2). Figure 2 shows that the thermophoretic velocity of each sample is nearly proportional to vVT/T despite the wide range of aggregate size within the same sample (roughly 10 to 180 µm). The thermophoretic velocity reaches 0.71 mm/s at $\nabla T = 26.0$ K/mm. In our previous study [9], it was found that the thermophoretic velocities of aggregates with an opener structure almost agreed with those evaluated by the formula for the free-molecular regime proposed by Waldmann [6],

$$U_T = -\frac{3\nu}{4(1+\frac{\pi}{8}\alpha_m)} \cdot \frac{\sqrt{T}}{T} \qquad (1)$$

where v is the kinematic viscosity of surrounding gas, α is the accommodation factor. This equation is indicated by the dotted-line in Fig. 2. It is shown that the thermophoretic velocities measured in this study are also proportional to $v\nabla T/T$ even if the scale of aggregated particle is far larger than that corresponding to the freemolecular regime. The slopes on Fig. 2, which corresponds to $U_T/(v\nabla T/T)$, are different between different samples. It is thought that the value of these slopes on Fig. 2 depends on particle morphology.

The bulk density represents the whole degree of aggregation and the DBP (Liquid Dibutyl Phthalate) absorption represents the surface area measured in the liquid molecule size level. It is shown that the higher the bulk density is (i.e., the closer the structure of particles is), the slower the thermophoretic velocity is (Fig. 3). It is also shown that the greater the DBP absorption is (i.e., the bigger the surface area at liquid level is), the faster the thermophoretic velocity is (Fig. 4).

To examine the effect of the size of aggregated particles, $U_T / (v \nabla T/T)$, which corresponds to the slope of line in Fig. 2, was plotted against the size of aggregated particles (Fig. 5). In Fig.5, no clear dependence on the size of aggregated particles is found in the range of the size from 10 to 180 µm.



Fig.3 The relation between the bulk density and the slope of Fig.2



Fig.4 The relation between the DBP absorption and the slope of Fig.2



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4 Conclusions

In this study, simultaneous measurements of the velocity and the size of aggregated carbon particles were performed to examine the effect of particle morphology on the thermophoretic velocity. Five different samples of carbon black particles with well-defined aggregation characteristics were used to represent soot particles. The measured velocities were almost proportional to $v\nabla T/T$ even if the aggregate sizes were very large (200 µm). The dimensionless thermophoretic velocity, $U_T/(v\nabla T/T)$, was different between different samples. It is thought that this difference reflects the difference in particle morphology. The bulk density and DBP absorption are used to indicate morphological charactaristics. It is shown that the higher the bulk density is, the slower the thermophoretic velocity is. It is also shown that the greater the DBP absorption is, the faster the thermophoretic velocity is. These results suggest that morphological characteristic of aggregated particles is an important factor that influences the thermophoretic behavior of aggregated particles. No clear independence of the thermophoretic velocity on the size of aggregated particles in five kinds of carbon black is found in the range of the size from 10 to 180 µm.

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