A NOVEL APPROACH TO DETERMINE THERMAL CONDUCTIVITY OF MICRON-SIZED FUEL PARTICLES

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Introduction

Predictions of burning rate of coals and chars in combustion environments depend strongly on the particle temperature history. Particle temperature transients depend on the thermal properties of the particle and the surrounding gases. Extensive efforts have been made to determine thermal properties of bulk coal and char samples. Until recently there were no methods to evaluate thermal properties of single micron-sized particles. The electrodynamic chamber (EDC) [1] has been shown to be a powerful tool for studying physico-chemical processes of micron-sized particles, due to its ability to suspend a single particle in well defined conditions. The EDC has been applied to determine thermal conductivity of a char particle from indirectly measured particle photophoretic force (PPF) when the particle was irradiated from the bottom [2]. It was shown that the results have large uncertainties [3]. The objective of this communication is to present a new method enables to directly measure the absolute value of PPF, thereby determine the absolute value of the particle thermal conductivity.

Methodology

Experiments were conducted in an EDC. Detailed descriptions of the EDC are well documented in the literature [1]. A schematics of the EDC is shown in Fig. 1. The EDC comprises a pair of vertical endcap dc electrodes to balance vertical forces and a ring ac electrode to provide dynamic stabilities to a suspended particle. By inserting x- and y-dc electrodes into the ac ring electrode, Zhang and Bar-Ziv [4] successfully imposed x- and y-electrical forces on the particle, and consequently developed a 3-D position controller. The EDC with a 3-D position controller, which is illustrated in Fig. 1, includes the chamber and systems for electric circuits, position measurement (by photodiode arrays), laser heating (by a CO_2 laser beam), imaging (by a CCD camera through a microscope), and data acquisition. When a suspended particle is heated by laser radiation, PPF is imposed on the particle opposing the radiation direction while free convective force (FCF) upwards.

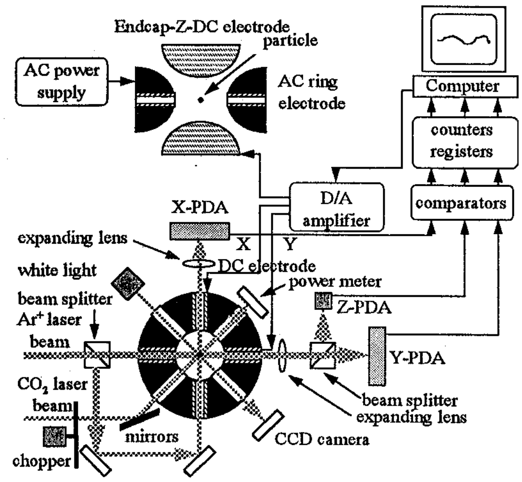

Figure 1. Schematics of an electrodynamic chamber (EDC) with associate systems.

During the experiment, the particle was heated horizontally so that PPF was induced horizontally while FCF vertically. We deal here with two basic conditions of suspended particles in a typical experiment of this study: (1) Laser-off period -- only gravity is applied, balanced by vertical electric force. (2) Horizontal irradiation of the particle that forms two new forces -- one is PPF opposite to the radiation direction and the other is the upward FCF. Here, two balancing electric forces are required, one horizontal for PPF and the other is vertical for the sum of FCF and gravitational force. In the experiments, conditions 1 and 2 were switched alternately by modulating the laser beam with a chopper. At these conditions, the equations for calculating PPF and FCF are

$$\mathrm{FCF} = \frac{V^z - V_o^z}{V_o^z}\,mg\,, \qquad (1)$$

$$\mathrm{PPF} = \frac{\sqrt{(\Delta V_x c_x / c_z)^2 + (\Delta V_x c_y / c_z)^2}}{V_o^z}\,mg\,. \qquad (2)$$

Note that PPF is determined from x- and y-dc voltage, measured by the 3-D position controller. The 3-D chamber constant c_x/c_z and c_y/c_z are essential to determine PPF and FCF. For present chamber, c_x/c_z and c_y/c_z are 0.168 and 0.138 [5], respectively.

Based on the expression for the PPF on a nonvolatile particle irradiated by electromagnetic radiation and heat balance of the particle [1], PPF can written as,

$$PPF = 16\pi K_{sl} (\frac{\mu^2}{\rho_g})(\frac{T_p - T_\infty}{T_p}) \frac{\bar{k}_g}{k_p(T_p)} \frac{J}{Q_{abs}}, (3)$$

where ρ_g is the gas density at the particle surface, and k_p is the thermal conductivity of the particle. J is an asymmetry factor describing the asymmetry of absorption of radiation within the particle. K_{sl} is a coefficient of thermal slip that was estimated to be 1.17. From equation 3, $k_p(T_p)$ can be determined.

Results and Discussions

Results of thermal conductivity for six synthetic char (Spherocarb) particles determined from Equation 3 is plotted in Fig. 2 as a function of particle temperature for particles of diameters in the range 150-250 μm and densities in the range 869-1016 kg/m^3.

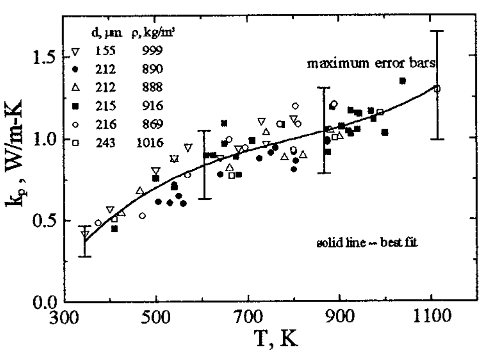

Figure 2. Thermal conductivity of six particles of diameters 155-243 μm and densities 869-1016 kg/m^3, as a function of particle temperature. Error bars were set for maximum uncertainty.

The results of all six Spherocarb particles exhibit a quite uniform trend that thermal conductivity of this char class increase from about 0.4 W/m-K at 300 K to 1.2 W/m-K at 1000 K. The value of thermal conductivity of graphite is much larger (130-170 W/m-K at room temperature, Touloukian [6]) and decreases with temperature. In summary, the thermal conductivity of these chars is much lower than that of graphite with an opposite dependence on temperature. The present results may suggest that graphitization and crystal ordering has strong impact on thermal conductivity and its temperature dependence. It can be speculated, therefore, that with the increase of the extent of graphitization, thermal conductivity will increase and its dependence on temperature will drift gradually from increase to decrease. Therefore, development of in-situ measurement of the extent of graphitization is of great interest in understanding carbon oxidation mechanisms. To evaluate extent of graphitization from thermal conductivity, more experimental and modeling work is required.

Conclusions

A novel method for the determination of thermal conductivity of micron-sized particles as a function of temperature, has been developed. The method is based on imposing a temperature differential, within a particle that is suspended in an electrodynamic chamber, and generating a photophoretic force from which thermal conductivity is backed out. Measured thermal conductivities for different highly porous char particles (Spherocarb) showed that the thermal conductivity of particles increased with temperature, opposite to the behavior for pure graphitic materials.

Acknowledgment

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