Appropriate Use and Basic Characteristics of Electrostatic Probes

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1. Introduction

Electrostatic probes are promised diagnostics for combustion measurements because of excellent time and spatial resolution of those. Using those, we have obtained lots of information on combustion phenomena, especially of turbulent premixed flames, such as flame front movements (Suzuki et al., 1979), local reaction zone thickness (Furukawa et al., 1994), burning velocities of flamelets (Furukawa et al., 1998), and so on. However, only limited researchers have successfully used electrostatic probes to obtain the above meaningful information, although many combustion researchers have tried to use those. Most of the researchers, who have failed to use electrostatic probes, have not enough knowledge on the appropriate use of those. They could get only ion current records of less spatial and time resolution or under influence of high level noise or disturbance currents. Despite of their lack of knowledge on electrostatic probes, they would have doubted if the data presented by other group using those are reliable and have given up to use the electrostatic probes. If they would have appropriately used the electrostatic probes, they could obtain data what they wanted and contribute the progress of combustion science to a further extent.

The objective of this paper is for helping combustion researchers to resolve the issues that they face at the use of electrostatic probes. Thus, in this paper, we present fundamental knowledge for appropriate use and basic characteristics of electrostatic probes on the basis of currently available information. Unfortunately, only limited researchers have performed basic studies on this subject, so that the reader would doubt the appropriateness of citation. For such readers, we recommend trying to realize the validity of the contents of this paper by providing an electrostatic probe described later.

2. Control Mechanisms of Ion Behavior Surrounding the Probe

For a long time, electrostatic probes have been used for measuring combustion phenomena because chemi-ionization occurs at the hydrocarbon combustion (Calcote and King, 1955; Lawton and Weinberg, 1969; Hirano, et al., 1976; Suzuki et al., 1979; Furukawa et al., 1991). The ion density at the reaction zone of a hydrocarbon flame is extremely high compared to the vicinity (Tsuji and Hirano, 1970). However, the degree of ionization at the reaction zone is much lower than usual plasma established by an electrical spark. Also, the gas density at the reaction zone under atmospheric pressure is much higher than the plasma investigated by physicists in the earlies. Thus, the gas at the reaction zone of a hydrocarbon flame can be categorized as a slightly ionized high-density gas in the plasma physics. To appropriately use an electrostatic probe for measuring combustion phenomena, we should know the details of ion correction by a conducting body in a slightly ionized high-density gas (Hirano, 1970). When an electrically conducting body with a negative potential of a few volts is inserted in a slightly ionized high-density gas, an ion diffusion region, an electric sheath and an ambipolar diffusion region are formed around the body (Fig. 1) (Hirano, 1972). Ions in the free-stream move through the ambipolar diffusion region, the sheath, and the ion diffusion region and corrected by the body. The thickness of the ion diffusion region is of an order of the mean free path, which is less than 0.1 μm in the reaction zone of a hydrocarbon flame and much smaller than a usually used electrostatic probe diameter. It is clear that the thickness of the sheath depends on the potential of the body. Figure 2 shows the experimental results obtained by Hirano et al. (1981). It is seen that the probe potential does not influence the flame front thickness detected be an electrostatic probe of 0.7, 0.4 and 0.1 mm in diameter in the region of probe potentials from –1 to –20 volts. In this case, the relative velocity of the probe and flame is 5 m/s. This result means that the sheath does not influence the ion correction by an electrostatic probe biased less than –20 volts in the vicinity of reaction zone of a hydrocarbon flame moving in a velocity less than 5 m/s. The behavior of ions in the ambipolar diffusion region is much the same as usual molecular diffusion. The ambipolar diffusion coefficient D_a can be determined on the basis of the diffusion coefficient D_i of ions and that D_e of electrons as follows (Hirano, 1972):

$$D_a = 2(1/D_\mathrm{i} + 1/D_e)^{-1} \tag{1}$$

Since D_e is much larger than D_I, D_a is approximately equal to 2 D_I.

When the electrostatic probe of 0.1 mm in diameter is used for measuring a premixed hydrocarbon flame moving a few m/s, the Reynolds number based on the probe diameter and surrounding gas flow is an order of unity. This situation is much the same as that of a hot wire anemometer for turbulence measurement in a cold airflow at atmospheric pressure. The structure of ambipolar diffusion region can be considered very close to that of thermal diffusion region surrounding the sensor of a hot wire anemometer. In the case of the electrostatic probe, the ions collected by the probe lose the charges at the surface of the probe sensor to immediately become electric current. This situation is the same as that of a hot wire anemometer exactly kept at a constant temperature. The reliability of the electrostatic probe appropriately used is the same as that of the hot wire anemometer.

3. Probe Structure and Electric Circuit for Ion Collection

A typical structure of an electrostatic probe is shown in Figure 3 (Suzuki and Hirano, 1983). This particular electrostatic probe has two sensors. Each sensor projects from a finely drawn quartz tube over which a water-cooled copper sleeve is fitted to keep the quartz tube as an insulator. In so many cases, the users of an electrostatic probe have misunderstood that the good insulator at room temperature is still effective in an elevated temperature gas. Most of ceramics become good conductors at flame temperatures. The cooling of the insulator is indispensable except for the case of the use of an electrostatic probe for measuring a propagating flame or by instantaneously passing a stationary flame. Only short ejection of the tip of the quartz tube from the water-cooling sleeve results in large effects on the ion current and spatial resolution. To avoid the oscillation caused by the electric circuit and to reduce the response time are also important for recording appropriate ion currents. Figure 4 shows a typical electric circuit for an electrostatic probe. The capacitance and impedance of the circuit should be kept as small as possible. To reduce noise is another issue to resolve for obtaining accurate ion current records. For reducing the noise, to earth the positive side of the buttery is effective. The reason is as follows:

In most of the cases to use the electrostatic probe, it is easy to set the burner or sleeve as a reference electrode, and at the same time the sleeve is an electric shield of the sensor. To avoid the electric noise, we should earth the electric shield. Thus, we should earth the positive side of the buttery, which connects with the sleeve, for reducing the noise. Many researchers who do not have enough knowledge about the electrostatic probe used in a slightly ionized high density gas would have a question about the effects of the reference electrode on ion current records. They have argued that the location and size of the reference electrode would influence the ion current records because the electric circuit closes through the space between the sensor and reference electrode. The fact is that the size and location of the reference electrode do not influence the ion current records, if the electrode is set near the sensor and not so small compared to it. The ion current record completely represents the characteristics of the ionized gas at the sensor. The charged particles to the reference electrode are mainly electrons and their mobility is much larger than that of ions so that no diffusion layer or sheath is established surrounding it. By making reference to previous studies, any one can confirm the above facts.

4. Concluding Remarks

In this paper presented is fundamental knowledge needed for combustion researchers who use an electrostatic probe in their studies. The structure surrounding the sensor of an electrostatic probe is discussed. The thickness of the ion diffusion region is indicated to be much smaller than the probe dimension. Also the sheath is shown not to influence the ion current records if the probe potential is kept in an appropriate range. It is indicated that the reliability of an electrostatic probe appropriately used is the same as that of the hot wire anemometer.

To obtain reasonable ion current records with appropriate time and spatial resolution and low noise, we should appropriately determine the structure of the electrostatic probe and the electric circuit. We believe any one will be able to appropriately use the electrostatic probe for measuring combustion phenomena if he provide it as described in this paper.

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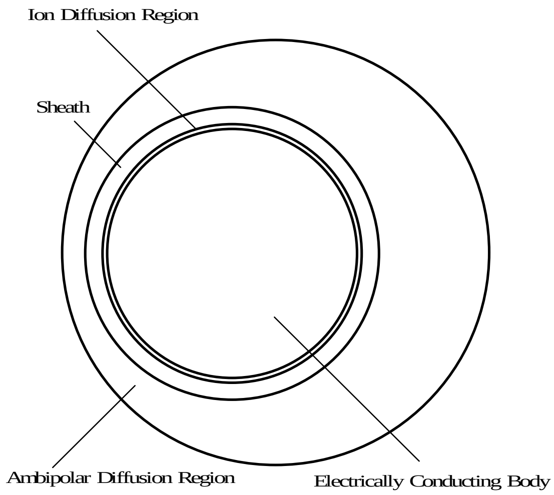

Fig. 1 Negatively biased electrically conducting body in a weakly ionized high density gas

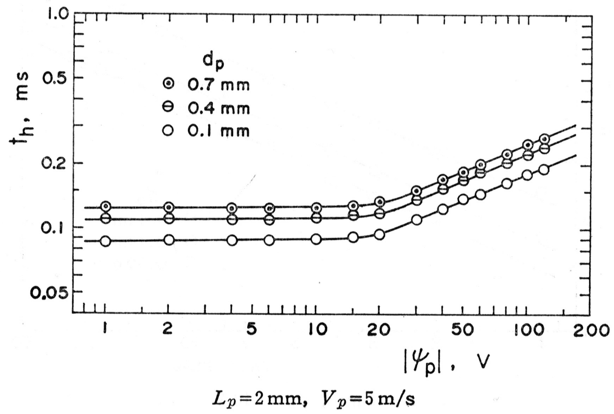

Fig. 2 Variation of half value period t_h across a laminar premixed flame front
with absolute value of probe potential

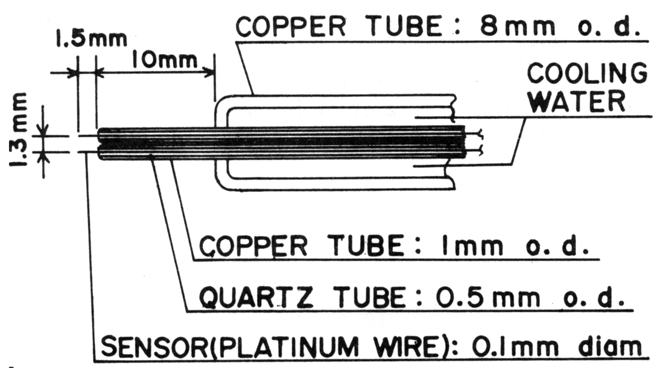

Fig. 3 Typical structure of an electrostatic probe (with two sensors)

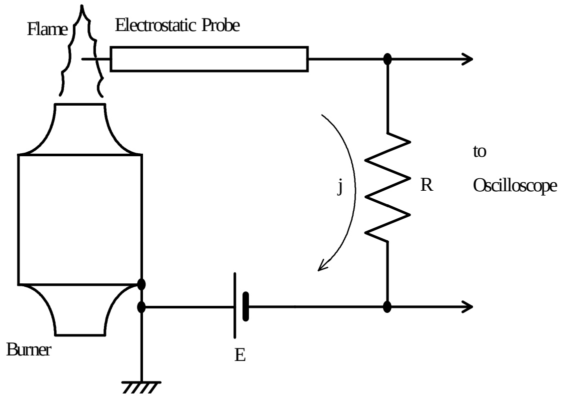

Fig. 4 Typical electric circuit for measurement using an electrostatic probe