662.61 : 537.56.08

Effects of Probe Dimensions on the Ion Density Measurements in Combustion Gas Flows*

By Toshisuke HIRANO**

The effects of various parameters on the ion currents to Langmuir-type cylindrical probes of Pt or Pt/Rh alloy were studied experimentally. First of all, in very low ion density flows of pure combustion gases, the effects of the potential and the dimensions of the probe on the ion current were examined. In this case, an apparent increase in ion current due to thermal emission of electrons occurred when the surface temperature of a probe containing Rh became higher than 1900°K. The sheath thickness around a probe seemed to be larger than 0.5 mm.

Furthermore, experiments were conducted in combustion gas flows, the ion densities of which were increased with the addition of potassium. Besides the effects of the potential and the dimensions of the probe, those of the flow velocity and the ion density of the gas on the ion current were examined, and an empirical equation for the ion current was obtained.

1. Introduction

For a long time, the studies of high-density gases of relatively small degree of ionization, called slightly ionized high-density gases, have been conducted by a number of investigators dealing with gaseous discharge⁽¹⁾. Besides the gases ionized by the electric discharge, the gases in the vicinities of the reaction zones of hydrocarbon flames, high temperature gases in front of re-entry vehicles and the exhaust gases of rockets are generally of high density and slightly ionized. Usually, the working fluids of MHD generators, such as high temperature gases generated by nuclear reaction and alkali metal-seeded combustion gases, are also slightly ionized high-density gases. In recent years, the phenomena dealing with these slightly ionized high-density gases were observed and studied^{(2)~(4)}.

Because a Langmuir-type probe is a diagnostic tool which has good spatial resolution, it has been frequently used for the measurements of electrical properties of ionized gases. In order to predict the electron temperature and the degree of ionization from the experimentally obtained current-voltage characteristics, a rela-

tion derived from a probe theory was used^{(5)~(7)}. Most of early probe theories are available to predict the electrical properties of low pressure ionized gases⁽⁸⁾. In recent years, however, a continuum probe theory was proposed in order to apply it to the measurements of slightly ionized high-density gases. A number of these theoretical studies have been conducted, and various analyses have been tried^{(9)~(12)}. So far, a few experiments have been conducted to compare with the theories, and few studies of the effects of the important parameters in the theories, such as the flow velocity and the probe dimensions, have been made.

In the present study, uniform flow fields of alkali metal-seeded combustion gases were used because of their relatively high degree of ionization at low temperature, and the effects of the probe length and the probe diameter on the ion current to a cylindrical probe were examined. First of all, probe measurements were made on pure (not seeded) combustion gases in order to make clear the effects of the probe length and the probe diameter on current-voltage characteristics. Then, in the combustion gas flows, the ionization degrees of which were enhanced by seeding of potassium, probe measurements were made in order to make clear the effects of various parameters, such as the flow velocity

* Received 5th February, 1970.

** Assistant Professor, Faculty of Engineering, Ibaraki University, Hitachi.

and the probe dimensions, on the current-voltage characteristics. The experiment in the seeded combustion gas flow was conducted at atmospheric pressure in the ranges of Reynolds numbers from 4 to 100 and of the ion number densities from 7×10^{10} to 6×10^{11} ions/cm³.

2. Experimental apparatus and procedure

2.1 Combustor

For the experiment of probe characteristics in slightly ionized high-density gases, it is desirable that the velocity, the temperature, the ion density and the composition of used slightly ionized high-density gas flows are definite and in uniform distributions. A combustor to generate such gas flows was prepared. A block diagram of the apparatus for supplying air, propane and potassium carbonate to the combustor is given in Fig. 1. Air was supplied from a reciprocating compressor through a purifier, a pressure regulator, a control valve and an orifice to the combustor. Propane was fed from a cylinder through a pressure regulator, a control valve and an orifice to the air stream. Potassium carbonate was dissolved in water, and after atomized with a part of air, bypassed and measured, it was fed to the air stream. The concentrations of the aqueous solution of potassium carbonate were 0.01~0.5 mol/l Aq, and the quantity of the added solution was measured by the volume lost during a certain time. Air, propane, bypassed air and the aqueous solution of potassium carbonate, measured separately, were mixed, and the resulting homogeneous mixture was supplied to the combustor.

The combustor consists of a diffuser, a settling chamber, a multiple burner, a combustion chamber with a nozzle exit and a duct as a test section (Fig. 2). It was intended that the generated combustion gas flow had uniform distributions of velocity, temperature and ion density at the test section. Two screens of 100 mesh were placed in the diffuser and the settling chamber to improve the profiles of the mixture

Fig. 1 Schematic diagram of supply system

flows. One of the sections was cooled by water to prevent flames from flash-back due to over-heat of the burner port. The multiple burner is a flat plate having 55 ports of 6 mm in diameter. The insides of the combustion chamber and the duct were coated with alumina so that the heat loss might be decreased and the temperature of the combustion gas flow might be kept as high as possible. In order to conduct the experiments in a wide range of flow velocities, two different combustion chambers, the nozzle exits of which were 40 mm and 28.3 mm in diameter, were used, and the test sections were made 100 mm long.

The duct was separated into 5 pieces of 20 mm long. When measurements were conducted at a section of the duct, the downstream parts of the duct were removed.

2.2 Langmuir-type probe measurements

For ordinary Langmuir-type probe measurements in flames or combustion gases, a screen of a large area is placed as a reference electrode in the downstream of the combustion gas flow, and a current-voltage characteristic is obtained between the screen and a probe. In such a case, it is necessary that the saturation electron current to the probe is much less than the saturation ion current to the screen⁽⁶⁾. If this condition is not satisfied, the electron current to the probe is limited by the ion current to the reference electrode, so that a true Langmuir-type probe characteristic will not be obtained for a positive probe potential. In order to examine the characteristic of a positively biased probe, a screen, which is at least 1000 times as large

Fig. 2 Combustor

in surface area as the probe, is necessary. It seems, therefore, that actually such a condition is hardly satisfied in ordinary experiments. However, if only a negative probe, biased with respect to the screen, is used for the probe measurement, the effect of the area of a reference electrode on the probe characteristics seems to be negligible, and the difficulty to prepare a large reference electrode is eliminated. In the present experiment, only the current-voltage characteristics of the negative probe ($0 \sim -20V$) were examined.

When a potential is applied to the probe with respect to the screen of this system, the potential of the screen is considered to be close to the floating potential at the screen position⁽¹⁰⁾. The measured probe potential, therefore, may represent the probe potential with respect to the floating potential at the screen position. In the case treated in the present study, the floating potential may be presumed to be lower than the plasma potential by less than $1V^{(10)}$, and the difference of plasma potentials between the positions of the screen and the probe may be less than a few tenths volt, so that the measured probe potential with respect to the screen may be lower than that with respect to the plasma potential at that position by less than $1V$. In the situation of the present experiment, the measurement of the plasma potential is difficult intrinsically, so that the potential of the probe with respect to the screen is used as the probe potential.

The structure of the Langmuir-type probe used in the present experiment is shown in Fig. 3. The probe wire projects from a finely-drawn quartz tubing over which a water-cooled copper sleeve is fitted to keep the quartz tube as an insulator⁽⁶⁾. In the present experiment, the probes of Pt and Pt/Rh alloy wires were used. Such probes are electrically conductive and hardly oxidized in high temperature gases, and have been usually used in flames or in combustion gases. The used probe diameters are

Fig. 3 Probe

0.1, 0.2, 0.3, 0.5, 0.7 and 1.0 mm. A list of the probe diameters, the quartz tube diameters and the water-cooled copper sleeve diameters is presented in Fig. 3. The probe was placed such that the probe wire axis might be normal to the direction of free stream.

A constant potential or a variable potential of saw-tooth wave was applied between the probe and the screen placed at the downstream of the combustion gas flow, and the current-voltage characteristic was recorded by an oscilloscope. The circuit for measurements is illustrated in Fig. 4. The potential drop due to current measurement was kept less than $1/100$ of the applied potential throughout the experiment. The potential of the probe holder was kept nearly the same as the probe potential by inserting a resistance between the water-cooled copper sleeve and the power supply system, so that the electrical disturbance was avoided as far as possible. A typical current-voltage characteristic of the probe is shown in Fig. 5. When the applied potential is 0, the current is positive on the illustrated characteristic. Such a characteristic has frequently been observed in the probe measurements in flames or combustion

Fig. 4 Circuit for measuring probe characteristics

Fig. 5 Typical current-voltage characteristic of the probe used in potassium-seeded propane-air combustion gas flow

gases⁽⁶⁾. Furthermore, in order to examine the effect of the thermal emission of electrons from the probe surface⁽¹³⁾⁽¹⁴⁾, the surface temperature of the probe was measured by an optical pyrometer.

2.3 Combustion gas flow

The flame stability diagram of the multiple burner in the combustor is shown in Fig. 6. Uniform and stable flames were observed under the conditions expressed as the stable region. As the mixture ratio was decreased at a constant over-all flow rate, the flames lacked uniformity, and as the mixture ratio was decreased further, the flames were blown out completely from the nozzle. In Fig. 6, the non-uniform flame region is defined as the region of the volume flow rates and mixture ratios when the flames lacked uniformity but remained in the combustor, and the blow-off region is defined as the region of the conditions when the flames were blown out completely from the nozzle. As the volume flow rate was decreased at a constant mixture ratio, the flames propagated against the gas stream into the burner ports. The flash-back region was defined as the region of the conditions when the flames propagated upstream. In the flame stability diagram of the combustor, besides the flash-back region and the blow-off region observed with ordinary combustors, there is an oscillation region. In this region, the flames oscillated and stable flames

were not observed. In the remaining region, the flames were stable and used in the experiment. The experiment was conducted on 6 conditions of equivalence ratios of 0.8, 0.9, 1.0, 1.1 and 1.2 at a volume flow rate of 115 l/min, and an equivalence ratio of 1.0 at a volume flow rate of 140 l/min, as shown in Fig. 6. Under these conditions, flow velocities from 10 to 30 m/sec could be obtained in the duct by changing the combustion chamber and the duct.

To clarify the properties of combustion gas flows generated by the use of the combustor, the flow velocity, the temperature and the ion current distributions were examined. For measuring the velocity of the combustion gas flow, a Pitot tube and a static tube were used, and both of them are water-cooled. The velocity was confirmed by using the particle tracer technique, and the errors were found to be less than several percent at most. The temperature was measured by using a Pt—Pt/Ph 13% thermocouple, and the error due to radiation was corrected by the heat balance relation. The temperature was also confirmed by Na D line reversal method, and the difference between the temperatures measured by the two different methods was found to be less than ± 1.5 percent (30°C). The ion current was measured by the probe as a measure of the ion density. Typical velocity, temperature and ion current distributions in each section of the duct are shown in Fig. 7. In Fig. 7, x and r are the distances of axial and radial directions of the duct from the center of the nozzle exit, respectively (Fig. 2). The uniform ranges of the velocity, temperature and ion current distributions become gradually narrower toward the duct exit, but at the exit, the uniform range is found to be still wide. Most probe measurements were made at $x = 10\text{ mm} \sim 30\text{ mm}$.

In order to use a probe as a diagnostic tool for slightly ionized high-density gases, it is necessary to find previously the correlation of the ion current with the ion density. The ion density in the combustion gas was calculated on the assumption that all of the seeded potassium carbonate, dissolved in the atomized mist, was mixed in the combustion gas under the equilibrium condition^{(15)~(17)}. The details of the calculation are given in reference (17).

3. Experimental results and discussion

3.1 Probe measurements in pure combustion gas

3.1.1 Current-voltage characteristics

When a sufficiently negative potential is

Fig. 6 Instability diagram of flames on multiple burner in the combustor

applied to the probe, a current due to positive ions flows from the combustion gas to the probe. Typical current-voltage characteristics obtained in pure combustion gases are shown in Fig. 8. The well known saturation current was not observed, and the ion current increased with the decrease of the potential. For the probe potential ψ_p lower than $-4V$, the ion current to the probe j_+ is expressed as follows:

$$j_+ \propto (-\psi_p)^{0.4} \dots \dots \dots (1)$$

3.1.2 Effect of probe length on ion current

Typical experimental results about the correlation of the probe length with the ion current are shown in Fig. 9. For the probe of a short length, the ion current was proportional to the probe length L_p , while for the probe longer than a certain length L_{pc} , the ion current increased with the probe length at a rate much greater than that expected to be in the proportional relation. The phenomenon seems to depend on the probe material and diameter, and also on the equivalence ratio of the mixture. In the present experiment, the phenomenon was observed only when the measurements were conducted in

the high temperature combustion gas of a stoichiometric mixture. It was observed more distinctly as the fraction of Rh in the probe increased and as the probe diameter decreased.

In order to interpret this phenomenon more precisely, the surface temperatures of the probes of various lengths were measured by means of an optical pyrometer, and the maximum surface temperatures near the probe ends were measured. The results for probes of various diameters, obtained in the combustion gas of the stoichiometric mixture, were rearranged and are shown in Fig. 10. At the same time, the length L_{pc} is represented for various probe diameters. Broken lines represent maximum surface temperatures near the probe ends. According to the results, the phenomenon seems to appear when the surface temperature of the probe containing Rt attains a value higher than $1900^\circ K$. This phenomenon is thought to be due to thermal emission of electrons, so that the quantity of the thermal emission of electrons was calculated by use of the Richardson-Dushman equation for Pt and Rh,

$$I = AT_p^2 \exp\left(-\frac{e\phi_w}{kT_p}\right) \dots\dots\dots(2)$$

where

I =thermal emission flux per unit area

A =electron emission constant

e =electronic charge

ϕ_w =work function of the material

k =Boltzmann constant

T_p =surface temperature

Although this equation is only applicable to the case in vacuum, the relation was used to predict an approximate surface temperature at which the thermal emission occurred. Using the values, $A=60\text{A/cm}^2\text{K}^2$, $\phi_w=6.3\text{V}$ for Pt and $\phi_w=4.6\text{V}$ for Rh, it was shown that the thermal emission was heavy at temperatures higher than 1600°K for Rh and 2200°K for Pt. From this result and the result shown in Fig. 10, it may be safely presumed that the phenomenon of the unproportional increase in ion current was due to thermal emission of electrons and appeared when the surface temperature of a probe con-

taining Rh attained a value higher than 1900°K .

When the effect of thermal emission of electrons on the ion current is negligible, the ion current to a probe j_+ is represented as

$$j_+ \propto L_p \dots\dots\dots(3)$$

3.1.3 Effect of probe diameter on ion current

Under the condition of a negligible thermal emission effect, the ion current to the probe varied with the probe diameter as shown in Fig. 11. In the gas, presumed to be of a small ion density ($\phi=0.8$), the ion current to the probe was constant for various probe diameters. The ion sheath, therefore, considered to be thicker than the maximum probe diameter 1 mm used in the present experiment⁽¹¹⁾, and the "effective probe diameter" did not increase with the probe diameter. In a gas of comparatively large ion density ($\phi=1.0$ and 1.1), the ion current to the probe increased with the probe diameter when the diameter was larger than a certain value. The sheath thickness seems to be about 0.5 mm in this case because the ion current increases with the probe diameter when the probe diameter is larger than 0.5 mm.

Fig. 8 Current-voltage characteristics in pure combustion gases

Fig. 9 Ion currents to probes of various lengths

Fig. 10 Maximum surface temperatures near probe ends and thermal emission of electrons. $[-O-]$ indicates the range of L_{pc} obtained by probe measurements in pure combustion gases

Fig. 11 Relationship between ion current and probe diameter in pure combustion gas flow

3.2 Probe measurements in potassium carbonate-seeded combustion gas

3.2.1 Current-voltage characteristics

The current-voltage characteristics of the probe, obtained in the potassium-seeded combustion gas flow, are shown in Fig. 12. It is seen that also in this case the saturation ion current cannot be realized and the following relation will be deduced for the probe potential lower than $-4V$:

$$j_+ \propto (-\psi_p)^{0.4} \quad (4)$$

3.2.2 Effect of probe length on ion current

The ion current to the probe was proportional to the probe length for various probe lengths (Fig. 13):

$$j_+ \propto L_p \quad (5)$$

In the potassium-seeded combustion gas, the ion current was always proportional to the probe length for various probe materials and surface temperatures. This fact seems to indicate that the effect of the thermal emission of electrons on the ion current was negligible for the seeded combustion gas which contained much higher density of ions than the combustion gas without seeding.

3.2.3 Effect of probe diameter on ion current

The ion current per unit length $i_+ = j_+/L_p$

Fig. 12 Current-voltage characteristics in potassium-seeded combustion gas

Fig. 13 Ion currents to probes of various lengths

was measured for the probes of various diameters. The results are shown in Fig. 14. It is seen that the ion current increases with the probe diameter but is not directly proportional to the area of the probe surface. The effect of the probe diameter on the ion current is approximately expressed as

$$i_+ \propto d_p^{0.43} \quad (6)$$

3.2.4 Effect of flow velocity on ion current

The ion current was also measured for various flow velocities. The results are shown in Fig. 15. The effect of the flow velocity on the ion current is approximately expressed as

$$i_+ \propto U_b^{0.43} \quad (7)$$

It is seen that the indices, indicating the effects of the probe diameter and the flow velocity on the ion current, resemble each other. The product of U_b and d_p was plotted against the ion current and the results are shown in Fig. 16.

Fig. 14 Ion currents to probes of various diameters

Fig. 15 Ion currents to probes in various flow velocities

3.2.5 Effect of ion density on ion current

The ion current necessarily changes with the ion density of the combustion gas flow. The relation between the experimentally obtained ion current and the calculated ion density is shown in Fig. 17. It is seen that this relation is approximately expressed as

$$i_+ \propto X_{i\infty}^{0.5} = (N_{i\infty}/N_b)^{0.5} \dots\dots\dots (8)$$

where $N_{i\infty}$ and N_b represent the ion and total number densities of the combustion gas, respectively.

3.2.6 Main parameters which influence ion current

When probe measurements were conducted under the condition of a negligible effect of the thermal emission of electrons, the main parameters affecting the ion current are the probe potential, the probe length, the probe diameter, the flow velocity, the ion density and so on, in the ranges of the ion densities $N_{i\infty}$ from 7×10^{10} to 6×10^{11} ions/cm³, the probe diameters d_p from 0.1 to 1.0 mm, the flow velocities U_b from 10 to

30 m/sec. The ion current per unit length of the probe placed normal to the direction of free stream is approximately expressed as follows for the probe potential lower than $-4V$:

$$i_+ = j_+/L_p = B(-\phi_p)^{0.4} X_{i\infty}^{0.5} (U_b d_p)^{0.43} \dots\dots\dots (9)$$

where B is a constant, and when ϕ_p , $U_b d_p$ and i_+ are expressed in V, m²/sec and A/m, respectively, then $B \approx 1.55V^{-0.4} m^{-1.86} sec^{0.43} A$. Furthermore, introducing the dimensionless ion current $\bar{i}_+ = i_+ / (N_{i\infty} e D_i)$, the dimensionless potential $\bar{\phi}_p = -e\phi_p/kT_\infty$ and the Reynolds number $Re = U_b d_p / \nu_\infty$, Eq. (9) becomes the following equation:

$$\bar{i}_+ = B' \bar{\phi}_p^{0.4} X_{i\infty}^{-0.5} Re^{0.43} \dots\dots\dots (10)$$

where T_∞ , ν_∞ and D_i are the gas temperature of free stream, the kinematic viscosity of the gas and the diffusion coefficient, respectively, B' is a constant and equal to about 2.3×10^{-4} . The ranges of $\bar{\phi}_p$, $X_{i\infty}$ and Re are from 22 to 110, from 1.8×10^{-8} to 1.5×10^{-7} and from 4 to 100, respectively.

4. Conclusions

The effects of the probe length and the probe diameter on the ion density measurements in uniform combustion gases of potassium-seeded propane-air mixtures were examined, and the following conclusions were drawn:

(1) An apparent increase in ion current due to thermal emission of electrons appears when the surface temperature of a probe containing Rh attains a value higher than 1900°K.

(2) The thickness of the ion sheath formed around a probe in pure combustion gases seems to be larger than 0.5 mm.

(3) The well known saturation phenomenon of the ion current to a probe is not observed.

(4) The ion current is proportional to the probe length.

(5) In a potassium-seeded combustion gas flow, the ion current to the probe is affected greatly by the probe diameter, the flow velocity, the ion density and so on.

(6) When probe measurements are conducted in the potassium-seeded combustion gas flows, the ion current to the probe is expressed by the following empirical equation:

$$i_+ = j_+/L_p = B(-\phi_p)^{0.4} (N_{i\infty}/N_b)^{0.5} (U_b d_p)^{0.43}$$

The ranges of ϕ_p , $N_{i\infty}$, U_b and d_p in this equation are from -4 to $-20V$, from 7×10^{10} to 6×10^{11} ions/cm³, from 10 to 30 m/sec and from 0.1 to 1.0 mm, respectively.

This study is a part of the work conducted in the graduate course of Tokyo University. The author would like to express his sincere

Fig. 16 Relationship between ion current and product of probe diameter and flow velocity

Fig. 17 Ion currents to a probe in the gases of various ion densities

thanks to Professor Hiroshi Tsuji for his valuable guidance and to the members of his laboratory.

References

- (1) Cobine, J.D., *Gaseous Conductors*, (1958), Dover.
- (2) Payne, K.G. and Weinberg, F.J., *Proc. Roy. Soc., Lond., Ser. A*, Vol. 250, No. 1269 (1959), p. 316.
- (3) Capener, E.L., et al., *AIAA Jour.*, Vol. 4, No. 8 (1966-8), p. 1349.
- (4) Mullaney, G.J., et al., *Jour. Appl. Phys.*, Vol. 32, No. 4 (1961-4), p. 668.
- (5) Langmuir, I. and Mott-Smith, H., Jr., *G.E. Rev.*, Vol. 27, No. 8 (1924-8), p. 538.
- (6) Calcote, H.F., *9th Symp. on Combustion*, (1963), p. 622, Academic Press.
- (7) Travers, B.E.L. and Williams, H., *10th Symp. on Combustion*, (1965), p. 657, The Combustion Institute.
- (8) Mott-Smith, H., Jr. and Langmuir, I., *Phys. Rev.*, Vol. 28, No. 4 (1926-4), p. 727.
- (9) Su, C.H. and Liel, R.E., *Jour. Appl. Phys.*, Vol. 37, No. 13 (1966-12), p. 4907.
- (10) Chung, P.M., *Phys. Fluids*, Vol. 7, No. 1 (1964-1), p. 110.
- (11) Kulgein, N.G., *AIAA Jour.*, Vol. 6, No. 1 (1968-1), p. 151.
- (12) Pollin, I., *Phys. Fluids*, Vol. 7, No. 9 (1964-9), p. 1433.
- (13) Chen, C.J., *Jour. Appl. Phys.*, Vol. 35, No. 4 (1964-4), p. 1130.
- (14) Wolf, R.J., *AIAA Jour.*, Vol. 4, No. 12 (1966-12), p. 2155.
- (15) Freck, D.V., *Brit. Jour. Appl. Phys.*, Vol. 15, No. 3 (1964-3), p. 301.
- (16) JANAF Thermochemical Tables, (1961), The Dow Chemical Co.
- (17) Hirano, T., *Bulletin of I.S.A.S., Tokyo Univ.* (in Japanese), Vol. 6, No. 1 (1965-1), p. 26.