Langmuir Probe Response to Velocity Fluctuations of Weakly Ionized Gases

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Theme

THERE are so many problems concerning turbulent or unsteady flows of weakly-ionized, high-density gases, that an electrostatic probe is frequently used for the electrical property measurements in such gas flows. In the present study, the variation of the current-voltage characteristic of a negatively-biased, cylindrical probe with the gas velocity fluctuation has been explored experimentally by using potassium-seeded, propane-air combustion gas flows. By vibrating the probe in a uniform combustion gas flow, the only relative velocity between the probe and combustion gas was made to fluctuate. A brief dicsussion on the use of an electrostatic probe for the measurements of the velocities or velocity fluctuations of high-temperature gas flows has also been carried out.

Contents

The ion current j_+ to a negatively-biased, electrically-thin conducting cylinder immersed in a weakly-ionized, high-density gas flow can be considered to depend on: the cylinder potential ψ_p; the ion density X_{io} (mole fraction) in the freestream gas; the freestream gas velocity U; the probe diameter d_p; and the probe length L_p [1-4] i.e.,

$$j_+ = j_+(\psi_p, X_{io}, U, d_p, L_p) \tag{1}$$

The fluctuation of U can be expected to cause that of j_+. j_+ and U are decomposed into their mean parts and fluctuating parts, and are, respectively,

$$j_+ = \bar{j}_+ + j'_+, \quad U = \bar{U} + U' \tag{2}$$

where the bars denote time average values and the primes represent fluctuations around these means. In such a case, the following equation is derived using the assumption that the fluctuations are small compared with the average values, so that quadratic and higher terms in the fluctuations may be neglected:

$$j'_+ = (\partial j_+ / \partial U) U' \tag{3}$$

According to the results of experimental studies on the ion current to a negatively-biased, electrically-thin conducting cylinder immersed in a steady flow of potassium-seeded, propane-air combustion gas, j_+ is proportional to L_p when the cylinder axis is normal to the flow direction, and the ion current i_+ per unit length of the cylinder can be approximately expressed by the following empirical equation:[1,3]

$$i_+ = j_+ / L_p = B(-\psi_p)^\alpha X_{io}{}^\beta U^\gamma d_p^\delta \tag{4}$$

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where B, α, β, γ, and δ are constants. From Eqs. (3) and (4), the following equation is obtained:

$$i'_+ / \bar{i}_+ = \gamma U' / \bar{U} \tag{5}$$

where $\bar{i}_+ = \bar{j}_+ / L_p$ and $i'_+ = j'_+ / L_p$. Equation (5) indicates that for the constant γ, $i'_+ / \bar{i}_+$ is directly proportional to $U' / \bar{U}$.

A weakly-ionized, high-density gas was generated by burning a potassium-seeded, propane-air mixture at atmospheric pressure. The high-temperature combustion gas (2000 to 2100 K in temperature) was led through a converging nozzle (40 mm in diameter). The measurements were made at about 20 mm from the nozzle exit, i.e., the probe wire was placed in the potential core of the combustion gas flow having uniform velocity and temperature profiles.[1] The probe wire of Pt/Rh alloy projects from a finely-drawn quartz tubing over which a water-cooled copper sleeve is fitted to keep the quartz tube as an insulator. The used probe diameters are 0.025, 0.1, 0.2, 0.3, 0.5, and 0.7 mm. The probe was placed such that the probe wire axis might be normal to the direction of freestream. The probe was vibrated using an electromagnetic vibrator. The experiments were made in the range of $\bar{U}$ from 10 to 20 m/sec, of ψ_p from -60 to -5v, and of X_{io} from 2×10^{-8} to 3×10^{-7}.

Typical records of the ion current and probe movement, which were recorded simultaneously on a cathode ray oscilloscope, are shown in Fig. 1. The sinusoidal signal representing the probe movement indicates a harmonic motion of the probe. The ion current fluctuation is also sinusoidal, the frequency of which is found to coincide with that of the probe displacement. The phase difference of the probe displacement and ion current signals is ¼ cycle. This phase difference was observed in the range of frequencies from 50 to 2500 cps, and indicates that the phases of the ion current and velocity fluctuations coincide with each other. If Δi_+ and ΔU are assumed to be the amplitudes of the ion current and velocity fluctuations, respectively, the following relations can be derived from Eq. (5):

$$\Delta i_+ / \bar{i}_+ = \gamma \, \Delta U / \bar{U} \tag{6}$$

Furthermore, the following approximate equation can be derived from Eqs. (4) and (6):

$$\Delta i_+ = \gamma B(-\psi_p)^\alpha X_{io}{}^\beta \bar{U}^{\gamma-1} d_p^\delta \, \Delta U \tag{7}$$

Equation (7) indicates the effects of ψ_p, X_{io}, $\bar{U}$, and d_p on the relation between Δi_+ and ΔU when $\Delta U / \bar{U} \ll 1$.

Typical experimental results are collected in Fig. 2, where the relation between $\Delta U / \bar{U}$ and $\Delta i_+ / \bar{i}_+$ is shown. Except for the cases of larger values of ΔU at $d_p = 0.025$, 0.1, and 0.2 mm, the relation can be expressed by the following empirical equation:

$$\Delta i_+ / \bar{i}_+ = (0.7 \pm 0.1) \Delta U / \bar{U} \tag{8}$$

which coincides with Eq. (6) if $\gamma = 0.7 \pm 0.1$.

The values of α, β, γ, and δ obtained in the present study were: 0.45 ± 0.05; 0.5 ± 0.1; 0.7 ± 0.1; and 0.35 ± 0.05,

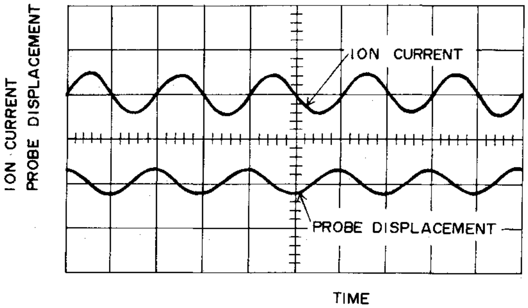

Fig. 1 Typical records of the ion current and probe movement; frequency = 100 cps, $\psi_p = -20$ v, $X_{io} = 1.0 \times 10^{-7}$, $\bar{U} = 11$ m/sec, $d_p = 0.3$ mm, $L_p = 3.5$ mm, $\Delta U = 0.6$ m/sec.

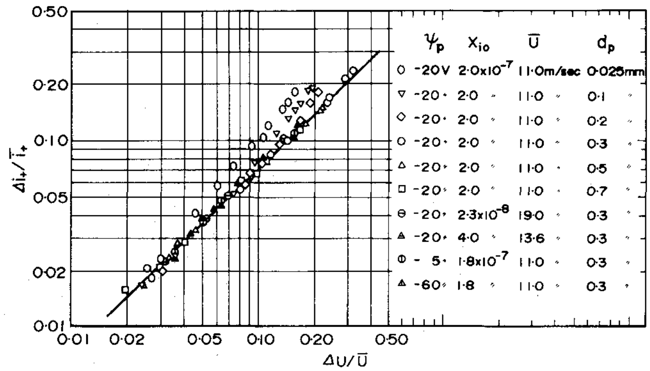

Fig. 2 Relation between $\Delta U/\bar{U}$ and $\Delta i_+/\bar{i}_+$; frequency = 100 cps.

respectively, and no much different from those obtained in the previous experimental studies.[1-3] Therefore, the ion collection mechanism in unsteady flows of weakly-ionized, high-density gases can be considered to be not much different from that in steady flows.

As shown in Fig. 2, the relation between $\Delta i_+/\bar{i}_+$ and $\Delta U/\bar{U}$ for the cases of larger values of ΔU at $d_p = 0.025$, 0.1, and 0.2 mm deviates from that expressed by Eq. (8), while any appreciable effect of ψ_p or X_{io} on the deviation was not observed in the present experiments. The Reynolds numbers for these cases were near unity. A possible interpretation for the deviation increase with the decrease of d_p is that the ion sheath and diffusion layer structure changes with d_p might be different from those at the larger Reynolds number, i.e., the values of γ and δ for these cases, which can be considered to indicate the effect of the flowfields on the ion current, might be different from those for other cases.

The response of the electrostatic probe to the velocity fluctuation can be considered very similar to that of the constant-temperature, hot-wire anemometer because the collected ion current becomes an electrical signal. The spatial resolutions of these two instruments might also resemble each other. However, there are some differences which arise from the difference of the basis of the two methods. When the hot-wire anemometer is used in a high temperature gas, many difficulties arise. A material of a high melting point should be used for the probe wire because usually the wire temperature is higher than the gas temperature. Moreover, the probe wire diameter should be made to be small enough because the heat capacity of the wire is closely related to the time resolution of the equipment. The fineness of the wire results in a short probe life time. These difficulties would not be as serious for the electrostatic probe. The temperature of the probe can be kept much lower than the gas temperature, so that a wider choice of materials is available for the probe wire. Moreover, the diameter of the probe wire need not be so small because, as mentioned previously, the ion current becomes an electrical signal. It can be expected from the relation between the ion density and gas temperature that, similar to the hot-wire anemometer, the electrostatic probe is much sensitive to the temperature fluctuation than to the velocity fluctuation.

In an actual turbulent flow, the velocity fluctuations in various directions are present, and the probe wire axis is not always normal to the mean flow direction. The velocity fluctuation in any direction can be decomposed into the components normal and parallel to the mean flow direction. If the rms values of these components are close to each other and much smaller than those of the mean velocity, it may be inferred that the ion current fluctuation is mainly caused by the normal component. The ion current to a negatively-biased cylinder inclined to the flow direction of a steady flow was already confirmed to decrease with the decrease of the angle between the probe wire axis and the flow direction.[3] Therefore, the ion current fluctuation due to a velocity fluctuation may be inferred to decrease with the decrease of the angle between the probe axis and the mean flow direction.

References

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