Experimental Investigation of the Effect of Electrodes on the Ionization Current during Combustion

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The effects of the geometry and polarity of electrodes on the ionization current during combustion were experimentally investigated using compressed natural gas (CNG) as a fuel in a constant volume combustion bomb. Spherically, expanding flames are measured using the schlieren photography technique to establish the relationship between the initial flame kernel development and the waveform of ionization current. The study shows that the parameters, including the polarity and the size of electrodes, have little impact on ionization current waveform. The information on combustion in ionization current, such as ignition, front flame, and post flame, are fully observed and clearly identified. Another aspect of this study is to attach a disk either at the anode, cathode, or both electrodes to increase the surface area of the disk or to change the location of the disk. The experiments shows that the first peak position of ionization current is mainly related to the flame kernel development at which stage the ions and electrons are produced by chemi-ionization processes, while the location and area of the disk have a slight influence on its peak position. Large amounts of ions and electrons during both chemi-ionization and thermal ionization are collected if the surface area of electrode is large, and more important is the anode area. It is also found that the peak values of both front flame and post flame as well as their integral values reach the highest values when the distance of the front flame kernel to the electrode is 5 mm, which is considered as the optimum distance for detecting the ionization current during combustion. However, the electrode parameters have an insignificant effect on the interval from the ignition to the second peak and the durations of front flame and post flame.

1. Introduction

To decrease the emissions and increase thermal efficiency of spark-ignition (SI) engines, combustion diagnosis becomes important. For this purpose, the spark plugs can be effectively used as an ionization sensor to obtain the information related to the combustion behavior. Examples of applications are misfire detecting, knock detecting, cam phase determination, air/fuel estimation, pressure estimation, and peak maximum pressure position estimation.[1–12] In addition, successful applications were reported in ignition control and close-loop combustion control in SI engines.[8–15] The technique for this increased interest of ionization sensor is quite simple, because the spark plug directly contacts with the flame and gives the direct information to the combustion process. Meanwhile, the spark plug detection does not require any modification to engine block or cylinder. Therefore, this technique can simplify the traditional measuring and control system and is considered an effective approach in combustion diagnosis and control.

It is well-known that the ionization current contains rich information about the combustion process; here, the electrode configuration and its location will play an important role. They may result in a difference in contacting between flame front and the electrode surface, and the gas flow conditions near the electrodes may differ. Previous investigations reported the impact of the configuration of electrode on the ionization current. Franke et al.[16] performed the experiments on the effect of in-

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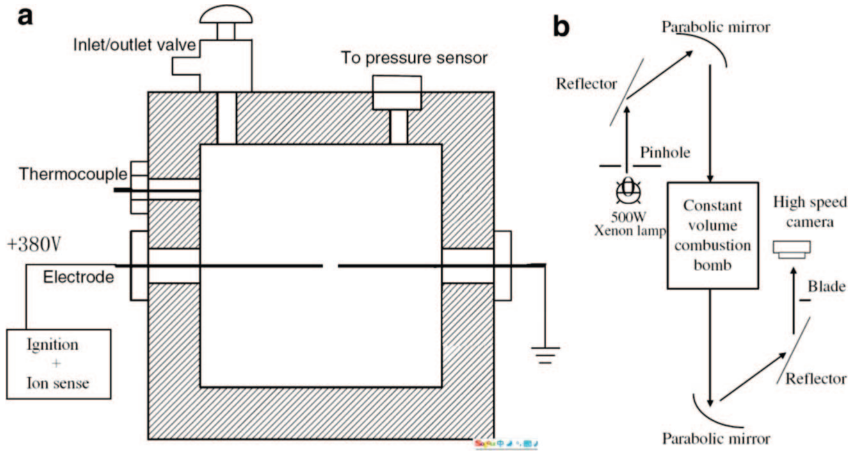

Figure 1. Schematic diagram of the experimental system.

cylinder gas flow on the ionization sensor signal and found that the shape of the combustion chamber and the location of the spark plug strongly influenced the ionization current. Vressner et al.[17] simultaneously measured the ionization current by placing seven spark plugs in different locations of the combustion chamber in a homogeneous charge compression ignition (HCCI) engine. The present study indicates that the timing of the ionization current and the amplitude are dependent upon the spark plug locations. Some report[18,19] showed that the first peak produced by chemi-ionization shifts into the second peak produced by thermal ionization when the ionization sensor is far from the spark plug. This will lead to a loss of information about the combustion process if the two peaks, reflecting the information related to the chemi-ionization and thermal ionization, are hardly distinguished. The ionization current is reflecting local information, which is different to the pressure in the combustion.

Other investigations[18,20–22] showed that the ionization current was also changed if the polarity or surface area of the electrode was different. Some interesting conclusions were reported in their study. Franke et al.[20] observed that a disk attached to the anode only had little change to the appearance of the current compared to the bare electrodes. Attaching a disk to the cathode produced a pronounced current during the main combustion. Yoshiyama et al.[21] performed the experiments in both a constant-volume bomb and an engine and observed that the insulating parts of the cathode decreased the current and that connecting cathode and cylinder wall led to a more pronounced current during main combustion, whereas the second peak produced by thermal ionization vanished when they interrupted this connection. This seems to contradict the findings from Shimasaki,[22] who performed experiments in an engine and revealed that the surface area of the center electrode (anode) was proportional to the amount of ionization current when its surface area was 3.65, 6.47, and 8.83 mm. Another interesting phenomenon was reported by Wilstermann et al.[18] The special spark plugs, which diameter was varied between 1 and 11 mm in steps of 2 mm, were mounted on the center electrode. They showed that a larger surface area of the center electrode would collect larger amounts of ionization current during chemi-ionization and remained for longer time with the propagating flame front using an alternating current (AC) sensing voltage.

Using different geometries and positions of electrodes in the engine is inconvenient. To clarify the phenomena of the ionization current during the flame kernel development, the experiments in a common electrode with a simplified yet flexible electrode geometry was studied in a constant volume combustion bomb using the schlieren photography. Nature gas was used as a fuel. The study is expected to clarity the characteristics of ionization current influenced by the electrode poles.

2. Experimental Section

Figure 1 shows the schematic diagrams of the constant volume combustion bomb and the optical system used for recording the flame growth. The combustion bomb is a cubic chamber with the inside side 108 × 108 × 135 mm as shown in Figure 1a. Two sides of this bomb are transparent, which make the optical accessible, while the other four sides are mounted with a heated coil to adjust the bomb temperature. Thermocouples with accuracy of 1 K is used to measure the initial temperature of the chamber charge. The inlet/outlet valve is used to prepare the charge. No gas motion is generated in the combustion chamber. A 12 bit, 544 × 544 pixel REDLAKE HG-100K high-speed camera, recording at 5000 pictures per second with a schlieren optical system (see Figure 1b) is used to record the flame development. The quartz glass windows are a round shape with a diameter of 80 mm, and thus, the spatial resolution of the flame image is 0.147 × 0.147 mm.

Figure 2 shows the measuring system. In this system, the gas sources are the compress natural gas (CNG), the oxygen (O_2), and the nitrogen (N_2). Those gases were well-mixed to become a homogeneous mixture in the mixing chamber. The quantity of each gas in the mixing chamber was adjusted according to the partial pressure of each component. A vacuum pump was used to draw out the gases from the chamber. The initial pressure in the combustion bomb was measured by a mercury manometer with the pressures accuracy of 1 mmHg. The pressure during the combustion was recorded by a piezoelectric absolute pressure transducer, model Kistler 4075A, with a resolution of 0.01 kPa. The initial temperature and pressure were set at 293 K and 100

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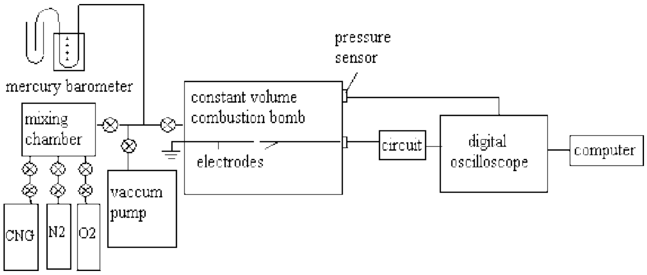

Figure 2. Measuring system.

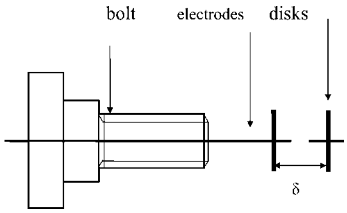

Figure 3. Schematic diagram of the electrodes arrangement.

kPa. The initial condition was strictly controlled in the experiments to realize the same initial pressure and temperature. The influence of the wall temperature on the mixture temperature can be avoided by providing enough time between each experiment. In addition, to make the data useable, five experiments were made for the same case, and the averaged values of pressures and ionization current signals were used. Thus, the uncertainties data were less than 5%.

A standard capacitive discharge ignition system with ignition energy of 45 mJ was used. A pair of electrodes with a simplified geometry were located in the central line of the bomb. The straight threaded stainless-steel electrodes with a diameter of 4 mm and sharp tip were used. The threads provide a convenient and flexible way to attach additional disks with different size and location to the electrodes. The detailed electrode arrangement is given in Figure 3, with a disk diameter of 10, 15, and 20 mm, and the different distance (δ) between two disks were used in this experiment. An electrical field between the two electrodes was set up by DC power supply with 380 V after the ignition discharge.

3. Results and Discussion

3.1. Correlation between the Flame Development and the Waveform of Ionization Current. The typical trace of the ionization current, pressure, temperature, and mass fraction burned obtained in the experiment are shown in Figure 4a. The instant flame photographs are used to visualize the relation between the flame position and the ionization current, and definition of characteristic value of ionization current are illustrated in Figure 4b. During the flame development, a sequence of six flame photographs were recorded starting from the photo of 2.5 ms after ignition. A cylindrical disk of stainless steel with a diameter of 10 mm and a thickness of 2 mm was attached to both the anode and cathode in the study. The mass fraction burned (ω_b) and temperature (T) were calculated on the basis of the pressure data, Rassweiler−Withrow method,[23,24] and two-zone quasi-dimensional model,[23] respectively.

Figure 4 shows the relationship between the current and flame ball during combustion. When ignited, a spike of the ionization current with a higher value appears with a duration less than 2.5 ms. Shortly after the discharge, the ionization current drops to near zero over a period of time (frame 1). The current remains at a low level as the flame front passes along the straight electrode. This phase is called ignition stage in this paper, and duration t_0 is defined.

When the flame front reaches the disk (frame 2), where the diameter of flame kernel is about 12 mm, the current increases remarkably and reaches the peak value (global maximum, frame 3) with a small rise of pressure and the mass fraction burned just increases by 0.78%. When the flame front passes over the disk, the current returns to a level (frame 4) and drops continuously for a period of time until the frame 5, which gives a slightly higher value than the one prior to the peak. During this time, the flame propagates fast and its diameter is over 50 mm, and the mass fraction burned closes to 30%. This peak is called first peak (I_1) during front flame development, and the time t_1 during this stage is defined.

As the flame develops along the straight electrode, more mixture gas is burned and the pressure and mass fraction burned increases rapidly. The burned gas surrounds the electrodes and the current starts to raise gradually (frame 5). When the mass fraction burned closes to 87.08% and pressure closes to the maximum value, the peak value (local maximum, frame 6) of ionization current occurs and the diameter of flame is up to 80 mm. Simultaneously, the current decreases to 0 with a much slower rate compared to the first peak. This peak refers to the fully developed flame and is called second peak (I_2) during post flame, and the time t_2 during this stage is defined. From the front to post flame stages, the pressure and mass fraction burned increase rapidly, reaching the maximum pressure and completing the combustion. This suggests that most of chemical reactions will take place within the interval of the first to second peaks, and the burning rate is very fast during this period. This is also consistent with the behavior of slow flame velocity at the initial stage of the flame development and fast after the flame kernel is fully developed.

It is well-known that the radical ions, such as CH_3^+, CHO^+, $C_3H_3^+$, and H_3O^+, are founded during the combustion using compressed natural gas (CNG) as the fuel. The signal of front flame is related to the flame kernel that is present in the vicinity of the electrode at the beginning of flame development.[4,21,25,26] The ions are produced by the chemical reactions in the propagating flame zone; thus, the chemi-ionization is the predominant ionization at this stage. The front flame only remains for a limited time in the region where the ionization current could be detected. Because of the thin thickness of laminar flame, which is less than 0.1 mm,[23] the flame front leaves from the electrodes and the ionization current decreases quickly.

In the post flame stage, the flame is propagating to the whole chamber and burned gas surrounds the electrodes. At this stage, the ionization process is governed by the thermal ionization at high temperature in the bomb[4,22,26] because most violent exothermic chemical reactions are ended. Meanwhile the major contributor to the ionization current is NO^+ because NO molecules are easily ionized and have lower ionization energy (9.264 05 eV).[1,4,22,26,27] Therefore, the ionization current is determined by the excited state of NO at the elevated temperature and the current disappears when the temperature is low.

3.2. Correlation between the Position of the First Peak of Ionization Current and Initial Flame Kernel Development Together with Position of the Disk. From Figure 4, it is showed that the first peak development is very sharp. Clearly,

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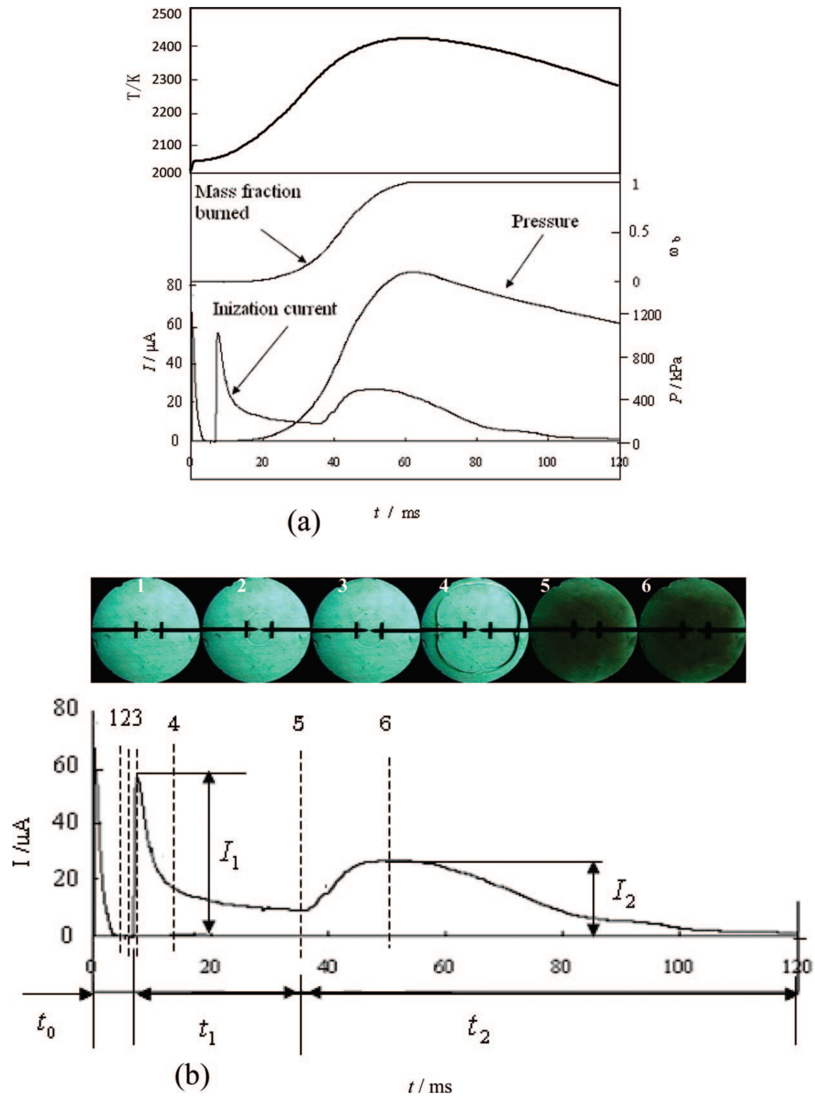

Figure 4. Ionization current with flame photographs, pressure and mass fraction burned in the constant volume combustion bomb.

the position of first peak has relationship with both flame kernel development and disk position. However, which one is more important? For an answer this question, the 12 experiments were performed. Figure 5 shows the flame images when the ionization current reaches the first peak. The experiments conditions are as follows: (1) bare electrodes with a diameter of 4 mm, (2) disk with a diameter of 10 mm at either the anode only or cathode only, $\delta/2 = 2.5$, 5, 10, and 15 mm, and (3) disks with a diameter of 10 mm at both poles, $\delta/2 = 2.5$, 5, and 10 mm.

From these photographs (Figure 5), it can be seen that the first peak occurs at the flame diameter of about 12−14 mm and it occurs at almost the same time in any case of electrodes with disk or bare electrodes, and this does not exactly happen when flame contacts with the disk on electrode whenever the disk position is far from or close to the flame kernel. Slight differences in flame propagation are observed, such as the flame propagation along the electrodes have across over the contact area of disk (parts a, b, e, f, i, and j of Figure 5), just contacts with the disk (parts c, g, and k of Figure 5), or the flame does not contact the disks (parts d and h of Figure 5). This implies that the first peak position is mainly related to the flame kernel development, which includes the quantity of ions and electrons producing by the chemi-ionization processes, while both location and area of disk have a slight influence. Therefore, the flame kernel development plays key role on the first peak compared to the location and the area of disk on electrodes.

3.3. Effect of Polarity of Electrode on the Waveform of Ionization Current. To understand the influence of voltage polarity on the ionization current, the experiments with bare electrodes, with a disk on the anode or on the cathode, and with the disks on both electrodes were conducted. Typical ionization currents from the four cases are shown in Figure 6. It can be seen that the waveform of the current does not change and the three peaks, including the ignition peak, the front flame, and the post flame, are all observed and can be identified clearly in four cases. The information on combustion process exists whether using the bare electrodes or electrode with disks attached to anode or cathode or both electrodes. In addition, the higher amplitudes during chemi-ionization and thermal ionization are demonstrated when the disks are attached in each of the electrodes and anode as well. That indicated that the area of the anode electrode would play a more important role than the area of the cathode electrode. Moreover, the duration t_0, t_1, and t_2 are almost the same in the four cases. Therefore, the polarity of electrode affects both the values of I_1 and I_2 but little influence on the durations of t_0, t_1, and t_2.

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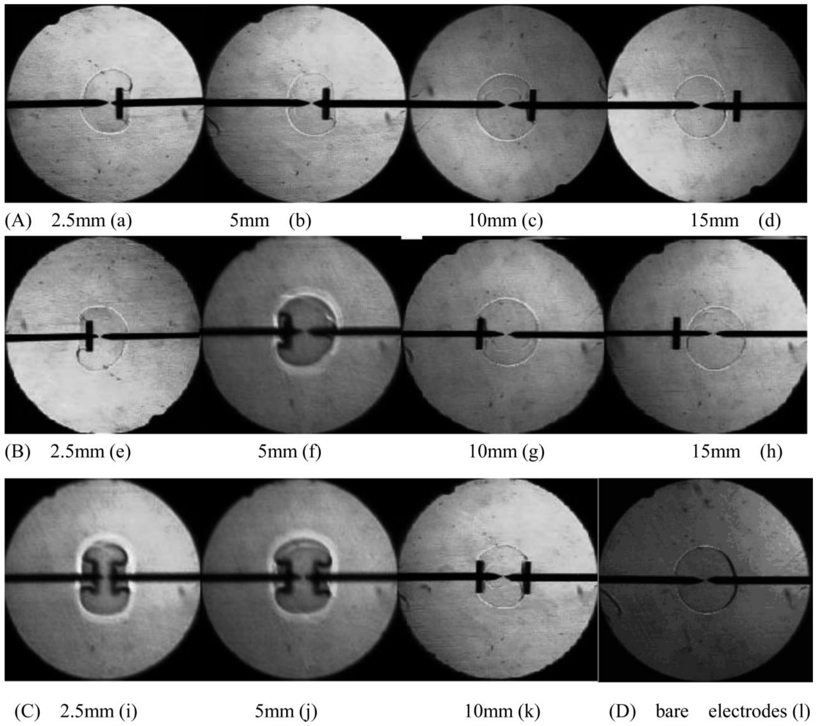

Figure 5. Flame photographs with the ionization current at the first peak in four cases of different electrodes arrangements.

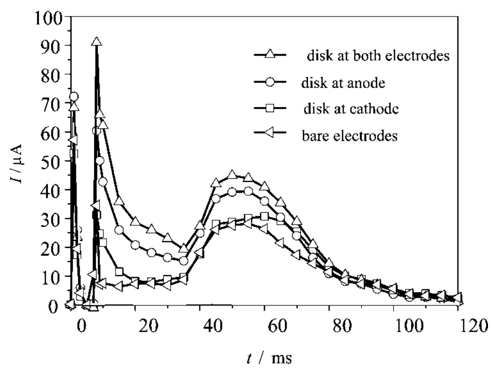

Figure 6. Ionization current curves in four cases of different electrode arrangements.

Considering high discharge voltage and small current, the phenomenon of ionization current appears close to the glow discharge. According to Baozhu,[28] in the gaseous conduction theory, the discharge current density (j) is governed by the equation

$$j = j_e + j_i = \rho_e u_e + \rho_i u_i = \rho E(\nu_e + \nu_i) \tag{1}$$

where j_e and j_i are the density of electrons flow and the density of ions flow, ρ_e and ρ_i are density of electric charge of electrons and ions, u_e and u_i are transfer velocity of electrons and ions, ν_e and ν_i are transfer velocity ratio of electrons and ions, and E is the electric field intensity. Because $\nu_e \gg \nu_i$, when E and ρ are constant, the discharge current density (j) is mainly dependent upon the density of the electric charge of electrons. Increasing the area of the anode will help increase the current.

According to the gaseous conduction theory,[28] high voltage drop across the anode is required when the area of anode is small, while low voltage drop on the anode is needed if its area is large. In the experiments, increasing the area of anode reduces the requirements of voltage drop on the anode; thus, high voltage drop across the cathode will make more ions across the gap of electrodes and finally reach the cathode. This theory also helps us understand that the area of the anode plays a key role on the ionization current comparing to the area of the cathode. The obtained results are consistent with the theory and the reported by Shimasaki[22] in the engines.

Theoretically, the electron emission in case of glow discharges will cause ionizing or exciting collisions with molecules in the gas; thus, the density of ions will increase. The purpose of increasing the cathode area can provide the emitted electrons with enough area and thus ensure a sufficient flow of ions and metastable species toward the cathode. This theory helps us in understanding an increase of the ionization current as the cathode area increases. The present results are also consistent with those reported by Wilstermann experiments[18] that larger surface area of the center electrode collect larger amounts of ionization current using an AC sensing voltage and Yoshiyama experiments,[21] that insulating parts of the cathode made the current decrease, and that connecting cathode and cylinder wall leads to a more pronounced current during main combustion.

According to the feature of glow discharge, usually the voltage is in the level of several hundreds. In our experiments and experiments reported by Wilstermann,[18] Yoshiyama,[21] and Shimasaki,[22] the voltages are all more than 300 V. Thus, the theory of glow discharge may explain these experiment results. However, in Franke experiments,[20] only voltage of 80 V is applied. Because this voltage is still less than typical values for cathode falls in glow discharge, which are of the order of 200 V, this phenomenon may be close to glow and arc discharge. Therefore, differences between our experiment and Franke's experiments are observed.

3.4. Effect of the Different Size of the Anode and Cathode. Experiments are conducting with the bare electrodes with diameters of 4 mm, and the attached disk with diameters of 10, 15, and 20 mm at both of electrodes (Figure 7a), the anode (Figure 7b), and the cathode (Figure 7c), respectively.

Although the area of the disk in the experiments is different, the information on combustion, such as ignition, front flame, and post flame, is clearly demonstrated and can be identified in

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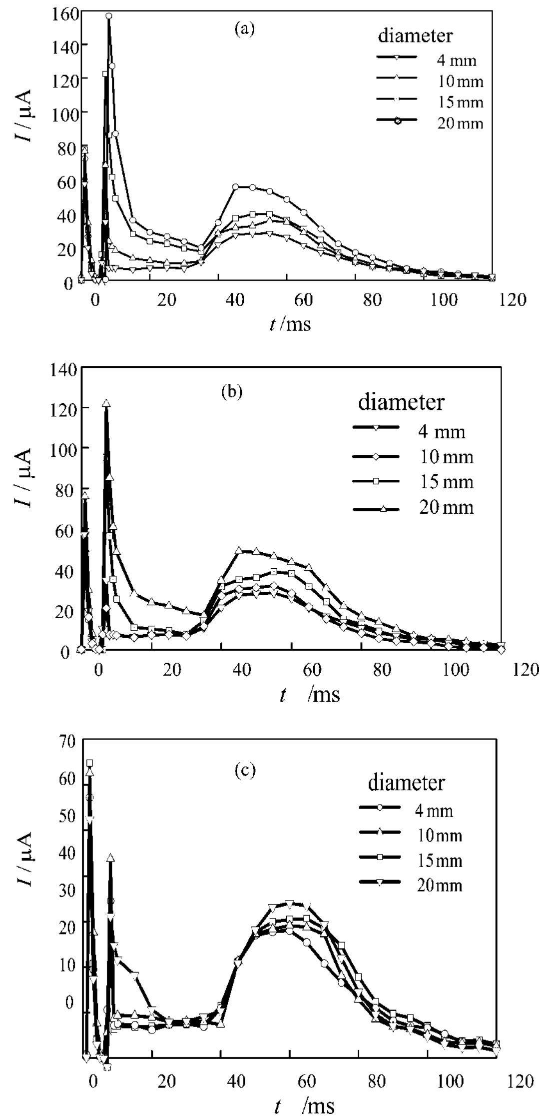

Figure 7. Histories of the ionization current in three cases.

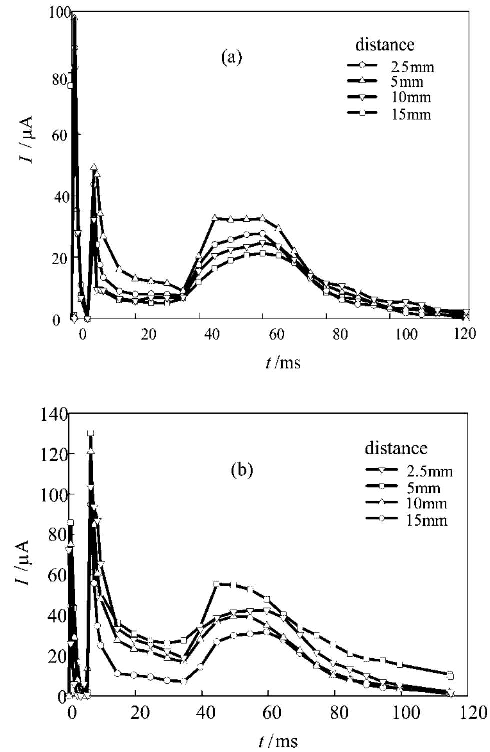

Figure 8. Histories of ionization current with different distances of the disk in two cases.

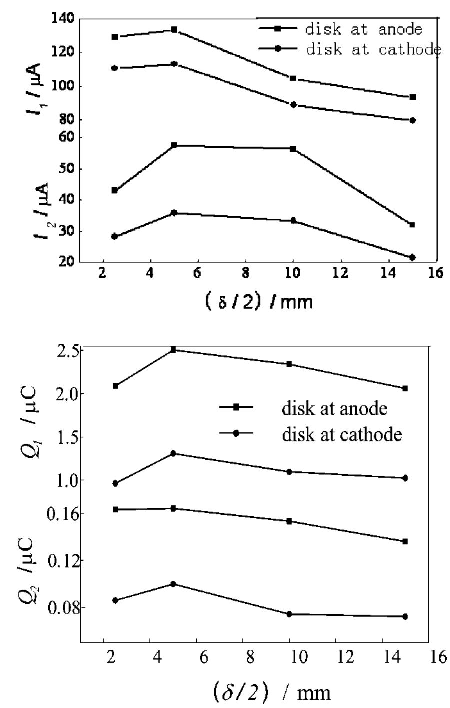

Figure 9. Relationship of ionization current features with different distances of the disk in two cases.

the ionization current. Furthermore, although large surfaces are able to stay much longer in contact with the propagating flame front, the first peak positions does not shift toward the second peak especially. This phenomenon confirms again that the first peak position is mainly related to the flame kernel development, while the contact area of the disk has a slight influence. Because three peaks are indeed distinguished from these figures, the information on combustion process does not affected by the different sizes of disk at the anode, cathode, or both electrodes. It means that the ionization current waveform and combustion information have little relationship with the size of disk at electrodes and the polarity of electrode.

The study also shows that a larger surface area of disk will collect larger amounts of ions during both chemi-ionization and thermal ionization. The amplitude of ionization current shows a strong dependence on the contacting area of disk, and the peak values of both I_1 and I_2 increase as the area of the disk increases. However, the contacting area at the anode shows a larger influence than the area at the cathode, because the current amplitude is always large when the same size of disk is at the anode. The durations (t_0, t_1, and t_2) show little relationship with the diameter of disk. It reveals that the contact area of electrode has little effect on the duration from the ignition to the second peak and the durations for both chemi-ionization processes and the thermal ionization process.

3.5. Effect of Distances between the Disks. Figure 8 shows the experimental results of the impact of disk position. The disk with diameter of 15 mm is at either the anode or cathode, and the distances ($\delta/2$) are 2.5, 5, 10, and 15 mm, respectively. To validate the observation above, the current characteristics are presented in Figure 9 in which the definitions of I_1 and I_2 are given in Figure 4b. Q_1 and Q_2 are the integral of the ionization current during front flame and post flame.

Although the location of the disk is far from the center of ignition, three peaks can still be distinguished; therefore, the information on the combustion process is reflected. The peak values (I_1 and I_2) and their integral values (Q_1 and Q_2) also give higher values when the disk is at the anode. The positions of the first peak and the durations (t_0 and t_1 together with t_2) do not vary with the distance whether the disk is at the anode or cathode.

The unique phenomenon is that the I_1, I_2, Q_1, and Q_2 increase to the peak value at the distance of 5 mm for the cases of the disk at the anode only or at the cathode only. According to interpretation of glow discharge by Baozhu,[28] the electric field between the anode and cathode is not homogeneous. A larger electric field enhancement exists near the cathode, and a small field enhancement exists near the anode. The voltage drop near the anode is very small or nearly 0 if the distance between the anode and cathode is large enough. However, a high voltage drop near the anode is needed if the distance between the cathode and anode becomes small; thus, the electric field near the cathode becomes weakened. Hence, a few ions are obtained because of the lower cathode drop. Therefore, the ionization current decreases if the distance between the cathode and anode becomes small. The ionization current will also decrease when increasing the distance because the intensity of the electrical field diminishes gradually. Apparently, the optimum distance between two disks should exist if more ions and electrodes are collected. The optimum distance from the center of the flame kernel to the disk is 5 mm in the study.

4. Conclusions

Experimental study of the effects of electrodes on the ionization current during combustion is conducted and the following conclusions are summarized as follows: (1) The ionization current in the front flame is mainly related to the flame kernel development, which includes quantity of ions and electrons produced by the chemi-ionization processes. The flame kernel development mainly influences on the first peak position of the ionization current, while both location and area of disk slightly influence it. (2) The electrode parameters including the polarity, size, and distance do little influence on the ionization current waveform. The information on combustion in ionization current, such as ignition, front flame, and post flame, are fully demonstrated and can be clearly identified. The information on combustion maintains regardless of the variation of the polarity, size, and distance of electrodes. (3) A large amount of ions during chemi-ionization and thermal ionization can be collected if the contacting area of electrode increases. The contacting area of the anode plays a more important role than that of the cathode. (4) The duration from the ignition to the first peak (t_0), front flame (t_1), and post flame (t_2) show little variation with the electrode parameters, including the polarity, size, and distance. (5) The peak values and their integral values during front flame and post flame reach the maximum values at the distance of 5 mm from the flame kernel to electrode when the disk is attached at the anode or cathode. An optimum distance exists to detect the ionization current during the combustion.

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Nomenclature

D = diameter of disk (mm)
E = electric field intensity (V/m)
I_1 = maximum value of ionization current during front flame (μA)
I_2 = maximum value of ionization current during post flame (μA)
j = discharge current density (C m^{-2} s^{-1})
Q_1 = integral value of ionization current during front flame, $Q_1 = \int_0^{t_0+t_1} I\,dt$ (μC)
Q_2 = integral value of ionization current during post flame, $Q_2 = \int_{t_0+t_1}^{t_0+t_1+t_2} I\,dt$ (μC)
t_0 = duration from the ignition to the first peak (ms)
t_1 = duration of front flame (ms)
t_2 = duration of post flame (ms)
u = transfer velocity of electron or ion (m/s)
ρ = density of electric charge (C/m^3)
ν = transfer velocity ratio of electron or ion (m V^{-1} s^{-1})
ω_b = mass fraction burned
δ = distance between two disks (mm)

Subscript
e = electron
i = ion

EF800066V