IONIZATION OF IN-CYLINDER CHARGE DURING PREFLAME PERIOD IN COMPRESSION IGNITION OF MIXTURES

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Abstract

Ion formation has been detected in cool and blue flames that appear during the preflame period of mixture ignition caused in a rapid compression machine. An ionization gap was installed in the combustion chamber. Ion current level is much lower than that of normally observed in propagation flames, but highly reproducible. Ions arise at the time the cool flame degenerates, and again in the blue-flame induction time τ_2. Breakdown of electric non-conductance during the preflame period has been investigated recently using a motored premixed-compression ignition engine. An electrode gap was installed in the combustion chamber. Between the electrodes a high static voltage of 2 200 V was given, charged in a small capacitor. It has been found that the timing of discharge or breakdown during the preflame period was the time in which the cool flame began to appear. Several attempts have been made to detect ionization of low-temperature flames produced by piston compression or on a flat burner, and to obtain advanced knowledge on the role the low-temperature reactions, which perform for the onset of final hot-flame ignition.

Key Words: Internal Combustion Engine, Ignition, Low-Temperature Flame, Preflame Reaction, Ionization

1. Introduction

We have been interested in the ionization of in-cylinder charges, of which temperature and pressure were raised by piston compression. As the ionization is closely related to the soot formation, sooting tendency of the mixture will depend on the ignition processes of engine operation in diesel and premixed compression-ignition engines. During the induction period for the hot-flame establishment, low-temperature preflame oxidation reactions would proceed associated with the cool and blue flames. Various intermediates such as peroxides and aldehydes exist during the preflame period, and then when all is done, the most hydrocarbon fuel molecules are decomposed into carbon monoxide and hydrogen just before the final hot-flame onset. The timing of charge ionization is our interest.

Another interest is the interaction of ionization to the chemical reaction kinetics. Even though at the present time no ionized species are introduced into the codes such as Chemkin, it would be necessary to recognize whether or not ionized species could be neglected to estimate ignition delays or to find the ways of controlling ignition timing, something that is difficult to accomplish in piston compression engines.

We would like to see when the ionization starts and to which stages it continues. To begin with, we have tried to measure ion current of the preflame charge obtained in a rapid compression machine (1). Secondly, we have prepared low-temperature flames, composed of cool and blue flames, using a Powling stabilized flat-flame burner operated continuously under the atmospheric pressure. Equivalence of the flat burner flames to the low-temperature piston compression ignition has been corroborated elsewhere (2). The ion current measurement and sampling of soot and presoot substances were carried out using this type of burner. And then, the characteristics on breakdown of electric non-conductance during the preflame period have been investigated recently using a premixed-compression ignition engine.

2. Experimentals

1) Rapid compression machine

Using a rapid-compression machine, a lean n-heptane/air mixture, equivalence ratio 0.7, was compressed up to the temperature and pressure conditions ranging 547 to 640 K and 0.75 to 1.05 MPa, in which ion current and preflame light emissions were observed. Details about the rapid-compression machine used (cylinder bore: 65 mm, stroke: 140 mm) are given elsewhere (1). Quartz windows, an ionization probe, and a pressure transducer were mounted around the cylinder head.

The tip shape of ionization probe to detect ions and an electric circuit used to convert the ion current to voltage signal are shown in Fig. 1. Detecting tip was projected 25 mm into the chamber from the wall and DC 200 V was biased. Ion-current density was defined as the quotient of current through the probe divided by electrode surface area. Photomultipliers (RCA R928) were used to detect radiant light emissions. Interference filters with designated wavelength were placed ahead of the photomultipliers to detect emission monochromatically. Ion current and emission of active species were observed at the same time.

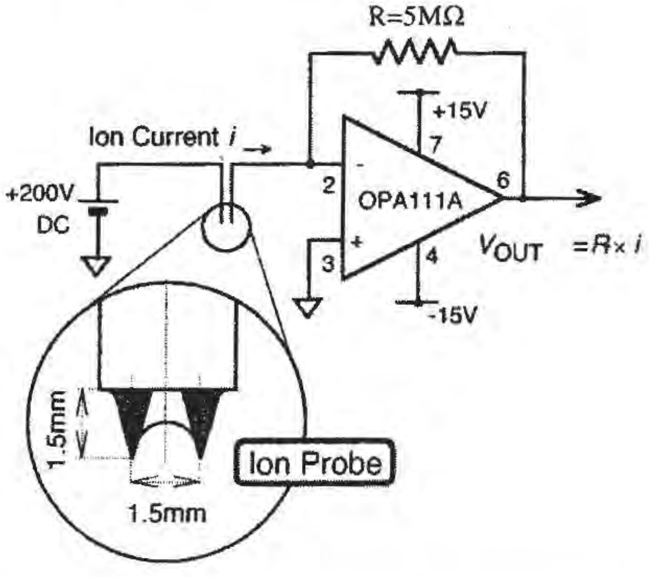

Fig. 1. Configuration of ionization probe and current-to-voltage converter for ion-current detection

2) Powling stabilized flat flame burner

An improved Powling burner at atmospheric pressure formed stabilized flat two-stage low-temperature flames of rich diethyl-ether/air mixtures in a vertically flowing laminar stream. The details are shown in our paper formerly published (3). The low-temperature cool and blue flames are stabilized within the quartz shielding tube. Fuel used for the Powling burner was diethyl ether. The equivalence ratio of mixtures was set to be 2.0 or 3.0. Temperature profiles in the two-stage flames were measured with a type K thermocouple having 50 μm in diameter, coated with SiO_2 to eliminate catalytic effects on the wire surface.

The ion current has been measured using an ionization gap, 1.5 mm, formed with two alumel-wire electrodes of 80 μm in diameter and biased with DC 240 V. Emitted light was focused onto a pinhole, and detected by a photomultiplier (1P28, 185-640 nm) through two quartz condenser lenses and a blue-glass filter (Toshiba, V-42, 320-510 nm). The spatial resolution was less than 1 mm.

3) Motored premixed-compression ignition engine

A single-cycle visualized engine modified to have extensive optical access and simple geometry, from an original Yamaha 2J2 single cylinder motorcycle engine with 87-mm bore and 84-mm stroke, was motored. Details are described elsewhere (4). The combustion chamber was a simple disc type, perfectly symmetric right circular cylinder. Valves have been replaced with an air-actuated valve located in the sidewall of the combustion chamber.

The mixture supplied was n-heptane/O_2/Ar with an equivalence ratio of 0.5. The O_2/Ar artificial air was used instead of natural air. The static initial pressure and temperature were 310 mmHg and 373 K at the top dead center (TDC), which led an expected pressure to be 0.35 MPa at TDC if the charge was inflammable.

The engine was driven by an electric motor at an engine speed of 240 rev/min (4 s^{-1}) to provide the time needed for the induction time required for the autoignition of the mixture. The compression ratio was 8.78: 1. Cylinder pressure was measured using a strain-gauge type transducer (Kyowa, PE30KF).

The mixture prepared in the storage tank, which is connected to the cylinder through a valve left open. A single cycle piston compression of the charge would start by a transfer from a continuous non-compression motoring to a regular motoring through closing valve at bottom dead center (BDC).

3. Results and Discussion

1) Ion current during in piston-compression ignition obtained in a rapid compression machine

Figure 2 is a typical example of the pressure and ion-current traces along the history up to the final hot-flame onset. Time scale is marked from the time the piston is arrested. Pressure record swings upward and ion current downwards. The first pressure rise after the arrest is due to the cool-flame appearance, and the last large one due to the blue- and hot-flame ones. Blue-flame period is the first half or foot of the latter large pressure rise. It can be seen that ions arise at the time the cool flame degenerates. Ion-current density show the maximum 200 nA/mm^2 when the ignition process has reached to the hot ignition, though the trace has swung out the figure. The maximum value during the cool-flame period is 3.7 nA/mm^2, as small as 1.8 per cent of that of hot flame. Ion current itself will degenerate very late in the cool-flame period, i.e. blue-flame induction time τ_2, just before the blue-flame onset.

In the blue-flame period the ion current is always detected more definitely. Degeneration of the ion current is often observed again late in the blue-flame period. This ion degeneration in blue-flame period has not been obtained through the emission observation.

It is possible to stop the ignited flames at the cool and blue flame level without development to the hot flame stage. It is tried to provide a special ignition process in which the ignited flames stop only at the cool flame level without development to the blue and hot flame stages. The case shown in Fig. 3 is an example under this condition, which is established by weakening the blue-flame reaction. It can be seen that the first appearing positive ions are not directly related to the cool-flame heat release. The CH and C_2 emissions were measured simultaneously. The emissions of 431.4-nm CH band and/or 516.5-nm C_2 band do not always appear at the same time ion formation reactions occur.

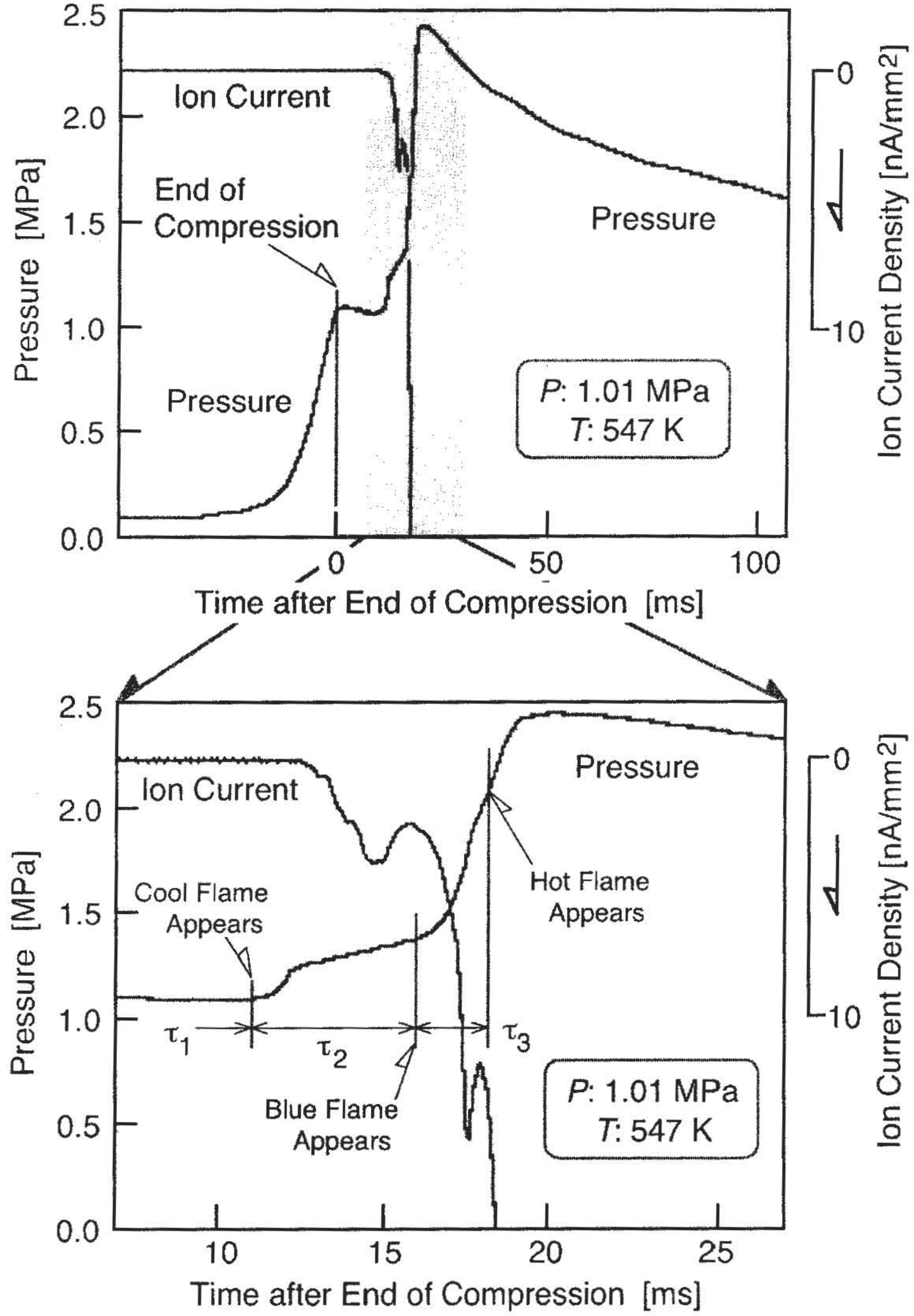

Fig. 2. Ion-current and pressure profiles in compression-ignition cool, blue and hot flame obtained in a rapid-compression machine

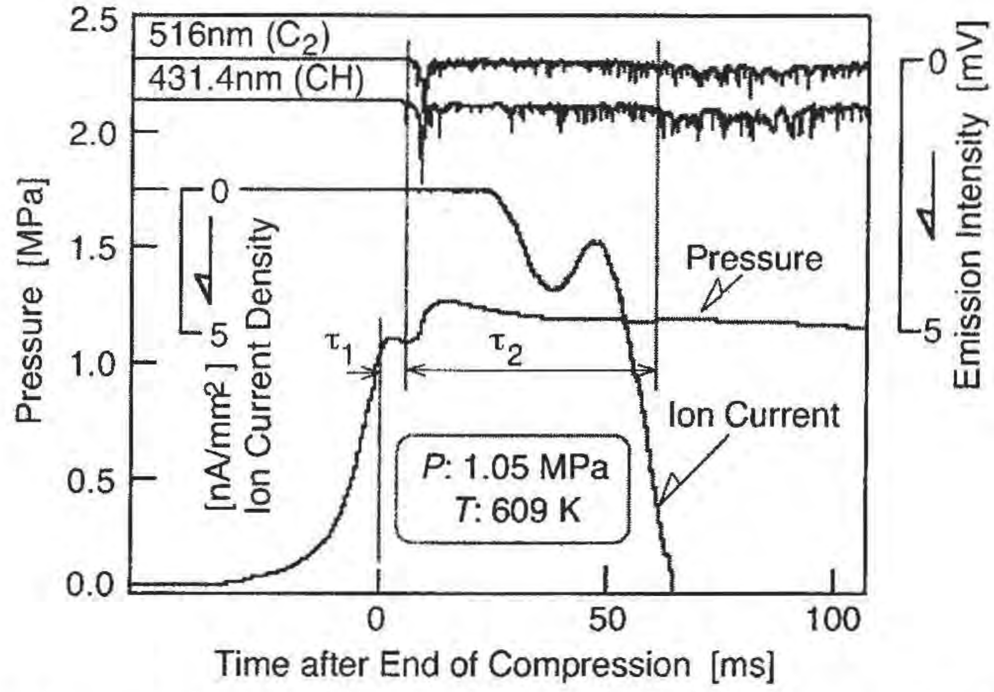

Fig. 3. Ion-current, CH and C_2 emission, and pressure profiles in compression-ignition cool flame. Blue- and hot-flame appearances are eliminated. Ions are not directly related to the cool-flame heat release and species such as CH and C_2

2) Ion current in stabilized flat low-temperature flames obtained using Powling burner

The ion formation has been measured on the laminar diethyl-ether/air premixed low-temperature flames under atmospheric pressure with reference to polycyclic aromatic hydrocarbons (PAHs) formation, to obtain an advanced knowledge of soot formation processes. It has been recognized that ion is related to soot precursor formation.

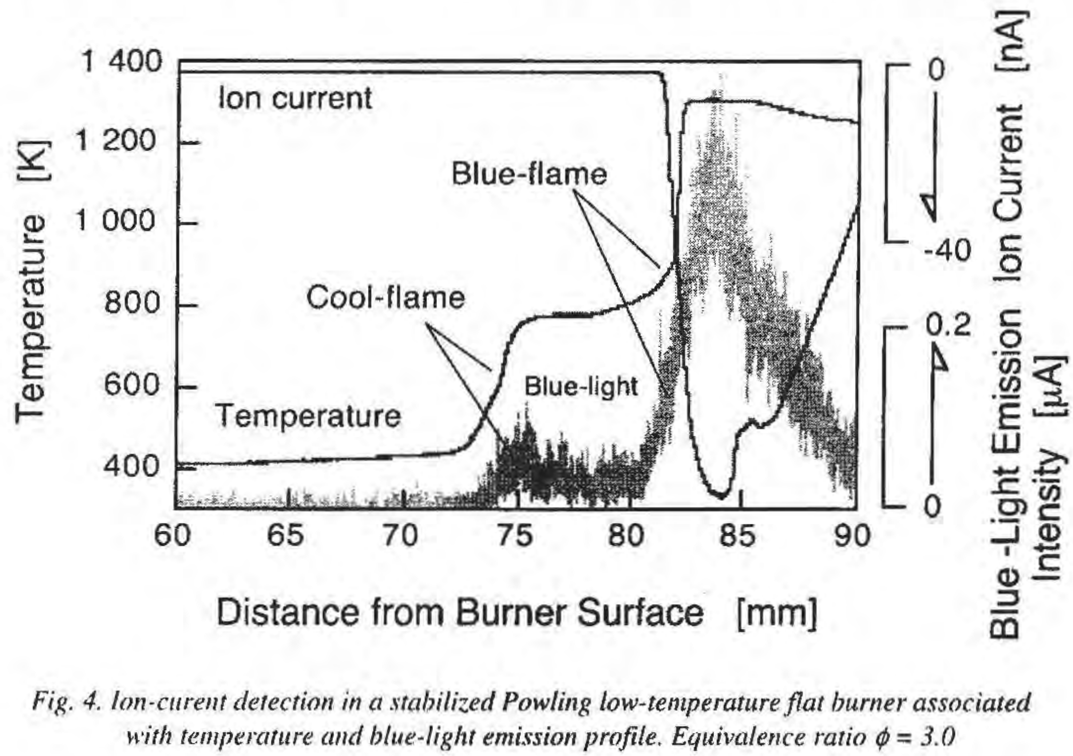

Fig. 4. Ion-curent detection in a stabilized Powling low-temperature flat burner associated with temperature and blue-light emission profile. Equivalence ratio $\phi = 3.0$

Temperature and blue-light emission profiles of the low-temperature flames formed downstream of Powling burner is shown in Fig. 4 for the case of equivalence ratio 3.0. The abscissa is the distance from the burner surface. Temperature and emission signals are indicated as swing upward on the ordinate. Around 72-mm position a distinct heat release due to the cool-flame appearance could be found accompanied with a blue-light emission, which would degenerate later. From 80-mm position a steep blue-flame heat release would occur together with a strong emission. The ion-current profile is shown alongside in the figure. It is demonstrated that the ion current first realized at the blue flame appearance.

Though not shown herewith in details, it is indicated a possibility that the ion is generated from the exited oxygen molecules and acetylene generation due to the interrelation between ion current and light emission. It has also been found that the PAHs first appears during the cool flame period.

3) Breakdown of electric non-conductance in preflame in-cylinder charge in premixed-compression ignition engine

A gap was formed between two electrodes. The shape and configuration are shown in Fig. 5. The DC voltage was exerted between the two electrodes, which was given by a Cockcroft-Walton voltage step-up circuit with a small amount of capacitance.

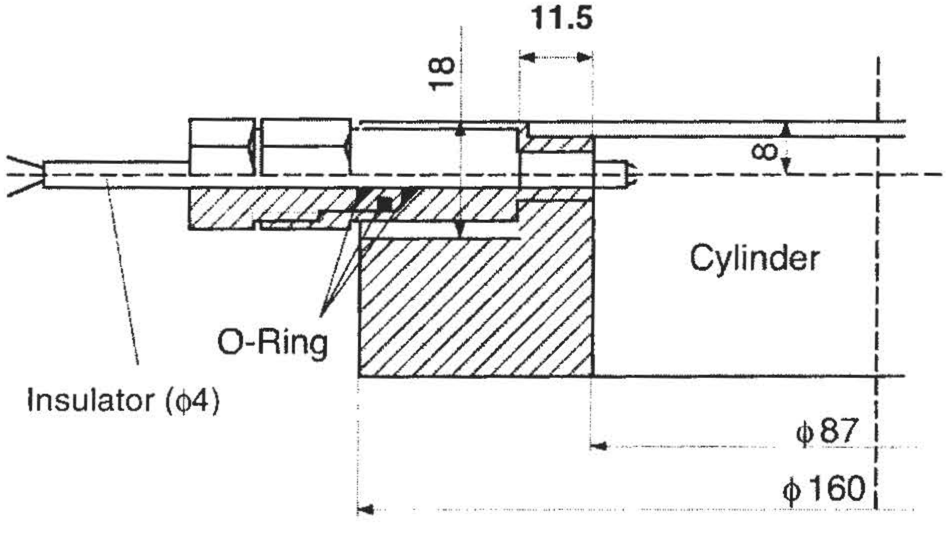

Fig. 5. Shape and configuration of excited gap. DC voltage is exerted between the two electrodes, which is given by a Cockcroft-Walton voltage step-up circuit with a small amount of capacitance.

The result is shown in Fig. 6. Almost the same pressure and light-emission records were established. Cool flame took place and was going on from 25 ms before TDC, and then the final hot-flame onset appeared at 3 ms before TDC, both at the stated time. Repeatability of the identical ignition phenomenon was fully ensured. Cool flame pressure rise could be recognized as compared to the inflammable pressure trace, synchronized with when a weak blue-light started to emit and then degenerated.

Static exciting voltage of several different levels was exerted in the gap between electrodes; 300, 750, 1 200, 1 600 or 2 200 V from bottom to top. The differential voltage history when and after the mixture was compressed was measured through a Tektronix P6015A high-voltage probe, and recorded together with pressure and light-emission histories.

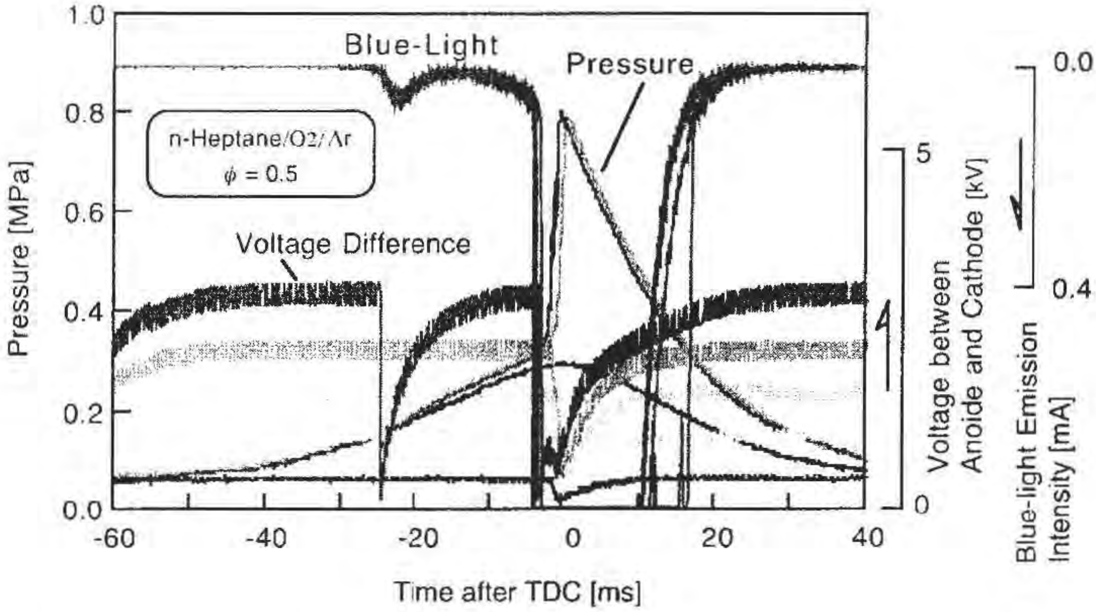

Fig. 6. Breakdown at the time of hot-flame onset. When voltage was intensified to 2 200 V, another breakdown could be found at an earlier timing, at the beginning of cool-flame appearance

Appearance of hot flame onset always led to an arrival of breakdown or capacitance discharge, as easily expected. The breakdown timing is just beginning of hot-flame onset, almost still during blue-flame period. Under the exciting voltage lower than 2 000 V, the breakdown was observed only at the time of hot-flame onset. However, when voltage was intensified to 2 200 V, another breakdown could be found at an earlier timing, at the beginning of cool-flame appearance.

It has been found that the discharge during the preflame period was the timing the cool flame first appeared. Exciting voltage for the gap was recovered within twenty milliseconds when discharged through the breakdown.

The exciting voltage is raised further, higher than 2 500 V, breakdown could be seen even when no flammable is charged, simply the artificial air is compressed.

4) Discrepancy on ionization depending on generation procedure of low-temperature flames

Several attempts have been made to detect ionization of low-temperature flames produced by piston compression and stabilized flat flame burner. Ion current is always detected when the blue flame appears in the same way in hot flames, independent on the three different preflame processes prepared herewith.

The preflame process generated in a rapid compression machine will give the ion-current signal early in the cool-flame degenerated period. However, low-temperature flame in a Powling burner will give no signals in that period. No capacitance discharge can be found at the cool-flame degenerated period during the preflame process of premixed compression ignition engine. Even tough, discharge could occur at a very early preflame stage, at the time of cool-flame appearance.

4. Concluding Remarks

Ion formation has been tried to detect in cool and blue flames which appear during the preflame period of compression ignition and in a continuously stabilized flat flame burner by two measuring techniques, ion current and breakdown of electric non-conductance. The obtained knowledge is as follows:

Ion current is always found when the blue flame appears in the same way in hot flames, independent on the low-temperature- flame generation apparatus.

The preflame process generated in a rapid compression machine will give the ion-current signal early in the cool-flame degenerated period.

Powling-burner low-temperature flame will give no signals in the cool, nor pre-blue-flame period.

Discharge or breakdown could occur at a very early preflame stage, at the time of cool-flame appearance during the preflame process of premixed compression ignition engine, if the gap is sufficiently excited. No breakdown can be found at the cool-flame degenerated period.

Further investigation is necessary to make clear the difference between observed ion current and breakdown of electric non-conductance relating to the ionization of charge in which preflame reactions are proceeded.

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