

**A KEY TO ACHIEVE IGNITION
CARBON MONOXIDE
GENERATION/CONSUMPTION IN BLUE-FLAME
PERIOD DURING HYDROCARBON COMPRESSION
IGNITION**

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Abstract. A criterion between success and failure of marginal fuel/air compression ignition was searched for using a rapid compression machine. A barely achieved ignition process was compared to a case no ignition was established due to a slightly insufficient compression pressure level. The differential on the chemical species histories during the induction periods between both cases was examined by continual different-timing gas samplings. A distinguished difference could be found only on the carbon-monoxide/carbon-dioxide ratio between the flammable and nonflammable critical conditions. The ratio increased continuously in the ignition success cases. There were no differences in other species concentration, such as gaseous water, hydrogen, formaldehyde and ethylene. At the time just before the final hot-flame onset the carbon-monoxide concentration came up to around 7 000 ppm, independent of the mixture strength. A steady carbon-monoxide/carbon-dioxide ratio was observed in the case no hot-flame onset was established. Continuous growing of carbon monoxide during the blue-flame period would be an indication for the transfer to the final hot-flame ignition.

Key Words: Internal Combustion Engine, Ignition, Low-Temperature Flame, Pre-flame Reaction, Ignition Control, Combustion Products, Spectroscopic Measurement

1. Introduction

Pre-flame reactions in the SI-engine end gas and of the CI-engine fuel are the progress of low-temperature oxidation. During the ignition processes caused by rapid-compression machines, cool and blue flames are observed before the onset of final hot-flame ignition.

Even when the cool flame has occurred, the next blue-flame stage can be suppressed, for example, by adding alkyl-lead compounds into the fuel gasoline. Once the blue flame has appeared, however, the hot flame is impossible to suppress. The blue-flame reaction is the precursor for the hot-flame ignition; preparing a trigger for developing to the final ignition.

In-cylinder ignition has long been a subject to suppress, but premixed-compression-ignition engine concept (HCCI) proposed in recent years enlightened us also on ignition promotion. It is essential to make the blue-flame reaction clear when looking forward whether to suppressing or promoting ignition.

The cool-flame is usually followed by its own degeneration, i. e., preparatory period for the blue-flame onset, another visible blue light emission and heat release. Chemical species concentration in the cool and blue flames are reported in several references; species in a piston-compression ignition process by NBS (1), and in stable flat-burner low-temperature flames (2), where the carbon-monoxide concentration is by far higher than that of carbon-dioxide. Unfortunately the former reference showed no separation between the two species. Other reports demonstrated organic components (3).

The final hot-flame onset can be recapitulated as a carbon-monoxide explosion; generation/ consumption behavior of carbon monoxide would be the key of the preflame reaction of hydrocarbon fuels in engine cylinders. The concentration histories of carbon monoxide CO, formaldehyde HCHO, carbon dioxide CO₂ and other related species will be measured during the induction periods, and spectral light-emission will be observed at the same time using a rapid compression machine, to compare between success and failure cases of fuel/air compression ignition and find a criterion for the ignition achievement.

2. Experimentals

Compression ignition was induced by rapid piston-compression of n-butane/air mixtures. The equivalence ratios of mixture were 0.4 to 1.0. The n-butane was chosen as a fuel under the background that we have a wide range of ignition delay data. Details of a rapid compression machine used (cylinder bore: 65 mm, stroke: 140 mm) are given elsewhere (4).

Quartz windows and a strain-gauge type pressure transducer were mounted at sidewalls and head of the cylinder respectively. The "blue light" and "red light" emission given forth from the preflame reactions were detected by RCA 1P28 photomultipliers coupled with color glass filters (Toshiba V-42; 320~510 nm and R-62; higher than 620 nm). The red-light emission is a reliable notification of hot flame onset. Concerning the identification of each low-temperature flame is given in our previous paper (5). Emission spectra were also measured using a monochrometer (JASCO: CT-25N; exit slit width 0.3 mm).

The gasses in the combustion chamber were sampled using an air-operated single-action valve mounted at the chamber sidewall. Container was connected to the cylinder via the valve and kept warm at 385 K. The sampled gasses were analyzed by gaschromatographs (GL Science: GC-390 DDTF, -390DDT) with Porapak Q-S and Molecular Sieve 13X columns. The target species were CO, CO₂, HCHO, H₂O, H₂, O₂, N₂, 1-C₄H₈, C₂H₂ and n-C₄H₁₀. The CO, CO₂ and HCHO gasses were converted to methane and detected with a hydrogen flame ionization detector.

3. Results and Discussion

3.1 Hot-flame onset marginally established due to weak mixture strength

The leaner inflammable limit of n-butane/air mixture is 1.8 percent by volume at the atmospheric pressure and 25 °C in temperature; the equivalence of 0.58. The piston-compression ignition limit of n-butane/air mixture is around 0.3 in the negative-coefficient temperature regime (700 to 790 K) under the compressed pressure of 1.0 MPa. A marginal but stable compression ignition is available when the equivalence ratio is raised to 4.0.

A typical pressure and blue-light emission traces of the negative-coefficient temperature regime marginal compression-ignition with an equivalence ratio of 0.4 is shown in Fig. 1 associated with a spectral emission trace of 306-nm wave length (equivalent to the OH: 306.4-nm System). The abscissa is the time elapsed after the piston is arrested at the end of compression stroke, and the light emission signals swing downwards. The temperature and pressure at the end of compression were 700 K and 0.91 MPa respectively. The τ_1 is the induction period from the end of compression to the cool-flame appearance, τ_2 the following one to the blue-flame appearance, and τ_3 the anew following one to the final-hot-flame onset, i.e. τ_3 is the blue-flame period.

The cool-flame delay τ_1 is shorter enough than the one of blue-flame delay τ_2 , which confirms that the typical ignition of the negative-temperature-coefficient regime is realized under this condition.

The cool-flame starts to degenerate at 20 ms after the finish of compression, which is recognized by a decline of blue-light emission. At the time around 140 ms the blue-light emission grows again; the blue-flame appears. At the time a blue-light emission comes up again after the cool-flame has degenerated, ultraviolet 306-nm OH system emission was frequently observed, not continuously but at intervals. Not shown here, the 330-nm (HCO: Vaidya Hydrocarbon Flame Bands) and 352-nm (O₂*: Schumann-Runge System) emissions showed a similar fashion to the 306-nm OH system emission. An observation of a near infrared (H₂O: Vibration-Rotation Bands) emission is shown in Fig. 2. This band also began at a time the blue-light emission came up again after the cool-flame degeneration. In this period fuel and oxygen were consumed and the active radicals increased; the fuel decomposition was activated.

3.2 Hot-flame onset marginally established due to insufficient pressure level

We would like to compare the normal ignition processes to the cases no ignition is established due to slightly insufficient compression pressure levels. To begin with, the temperature and pressure conditions accompanied by cool flame appearance but no ignition establishment were searched for. Secondary, the lowest pressure condition, necessary and sufficient to obtain a stable hot-flame onset was tried to find under the same temperature condition as the previous one. The pressure dependence on the blue-flame reactions is much higher than on the cool flame (6). The effect of pressure difference between the success and failure of the hot-flame ignition would be small on the cool-flame reactions with a lower pressure dependence. The most precise pressure adjustment was possible when the mixture equivalence ratio was raised to 0.65. The temperature condition was set to be about 725 K. Under this temperature condition the success and failure of the hot-flame ignition were differentiated by selecting the compression pressure to be 0.74 and 0.71 MPa.

An easily ignitable case is shown in Fig. 3A, where the compression temperature and pressure were 727 K and 0.93 MPa. The cool-flame ignition delay τ_1 was 4.5 ms and the blue-light emission appeared again at about 29 ms. At 37 ms elapsed time a red-light emission appeared which was followed by a steep pressure rise; the hot flame onset.

When the pressure was reduced to 0.71 MPa under almost the same temperature, no hot ignition was achieved as shown in Fig. 3C. A cool-flame appearance could be recognized undoubtedly from the blue-light emission and pressure traces, but this process was followed neither by a red-light emission nor a pressure rise. A compression pressure

slightly raised to be 0.74 MPa without a temperature alteration led to a stable hot ignition as shown in Fig. 3B. The average compression temperature was 725 K. The cool-flame delay τ_1 was 6.3 ms and the red-light emission grew up from about 96 ms. Even though the same compression temperature was given the reduced pressure resulted in a longer blue-flame delay τ_2 .

The incylinder gasses were sampled and the chemical species concentrations were determined. The pressure drop details when the sampling valve was actuated during the induction-time intervals were also shown in Fig. 3. A good reproducibility for the ignition events was confirmed. The species histories for each of the three pressure conditions are shown in Fig. 4 with the corresponding pressure traces and the carbon-monoxide/carbon-dioxide ratio CO/CO₂.

The species concentration up to the timing γ in the ignition failure case of 0.71 MPa is same well as the one up to the timing χ in the ignition success case of 0.74 MPa. In the ignition failure case with a pressure level of 0.71 MPa the species concentration was not advanced between the timings γ and η . In the hot-flame ignition success case of 0.74 MPa every intermediate species concentration at the timing δ in the blue-flame period was superior to those of cool-flame degenerate period except for the formaldehyde. The behavior of this kind could be seen at the timing β in the easily ignitable case with a pressure level of 0.93 MPa.

The intermediate species were generated actively in the blue-flame period except of formaldehyde. The concentrations of CO, CO₂, HCHO and H₂O have got to almost the same levels, at the timings β and δ , independent of a wide range of mixture strength from 0.4 to 1.0, though the whole results are not shown herewith. Every species is the oxide, the generation of which will be accompanied with heat releases. The amounts of H₂, C₂H₄ and 1-C₄H₈ would be an indication of fuel decomposition, a variable depending on the mixture strength. The temperature just before the hot-flame appearance is always about 900 K in the premixed compression ignition engines (7). The situation to which the blue-flame attained is almost the same in temperature and oxide concentration irrespective of the fuel and mixture strength.

In the ignition failure case of 0.71 MPa the carbon-monoxide/carbon-dioxide ratio CO/CO₂ did not increase, though both carbon monoxide and carbon dioxide were generated. The CO/CO₂ ratio increased gradually up to the hot-flame occurrence in the ignition success case with a 0.74 or 0.93 MPa pressure level. Temporary surplus oxidizing radical, such as OH, was observed periodically by emission spectrum after the cool-flame degeneration as shown in Fig. 1. The oxidizing radicals would play important roles of fuel decomposition and oxidation. As early as the cool flame degenerates surplus radicals for the preparation to hot-flame onset begin to appear. The slight difference for the oxidation preparation would exist between the success and failure of the hot-flame ignition. The CO/CO₂ ratio is considered to be a criterion and the opposite-side indication of the oxidation preparation.

4. Concluding Remarks

The blue-flame reaction is a real issue for the autoignition of hydrocarbon fuel/air mixtures in internal combustion engine cylinders. Blue flame generates carbon monoxide briskly, and is the final induction stage of oxidation up to the real hot-flame ignition.

At the time a blue-light emission comes up again after the cool-flame has degenerated, ultraviolet 330-nm (HCO: Vaidya Hydrocarbon Flame Bands), 352-nm (O₂*: Schumann-Runge System), 306-nm (OH: 306.4-nm System) and near infrared (H₂O: Vibration-Rotation Bands) emissions observed frequently. In this period more fuel and oxygen are consumed compared with during the cool-flame, and the concentration of ethylene, hydrogen and 1-butene increases rapidly. Irrespective of the mixture strength, the trends of light emission and chemical-species history behaviors in the induction periods are unchanged.

Piston-compression ignition processes of n-butane/air mixtures conditioned at slightly upper and lower than the lean ignitable pressure limit were compared using a rapid compression machine to elucidate the ignition trigger to the final hot-flame appearance. The features of this paper are as follows:

- The concentration of ethylene, hydrogen and 1-butene becomes higher when the mixture strength is closer to stoichiometric. Carbon monoxide, carbon dioxide, formaldehyde and water vapor, however, are on the identical levels just before the hot-flame ignition independently of mixture strength.
- The amount of carbon monoxide is superior to of the carbon dioxide during the whole induction period even in the very lean marginal ignition processes.
- The carbon-monoxide/carbon-dioxide ratio is a main key and should increase during the induction period for the hot-flame establishment.

A small amount of carbon-monoxide brimming over during the blue-flame period would be a trigger for the transfer to the final hot-flame ignition. The temporary surplus oxidizing radicals would play roles for the growing of CO/CO₂ ratio.

References

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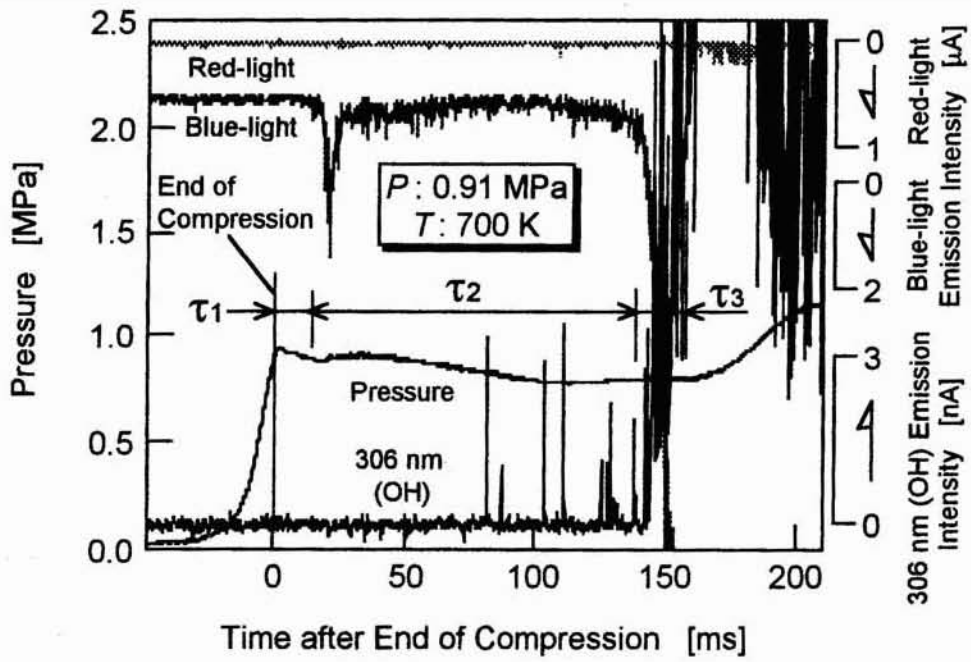


Fig. 1 Pressure, blue-, red-light and 306-nm (OH) emission histories of *n*-butane/air ignition at equivalence ratio $\phi=0.4$

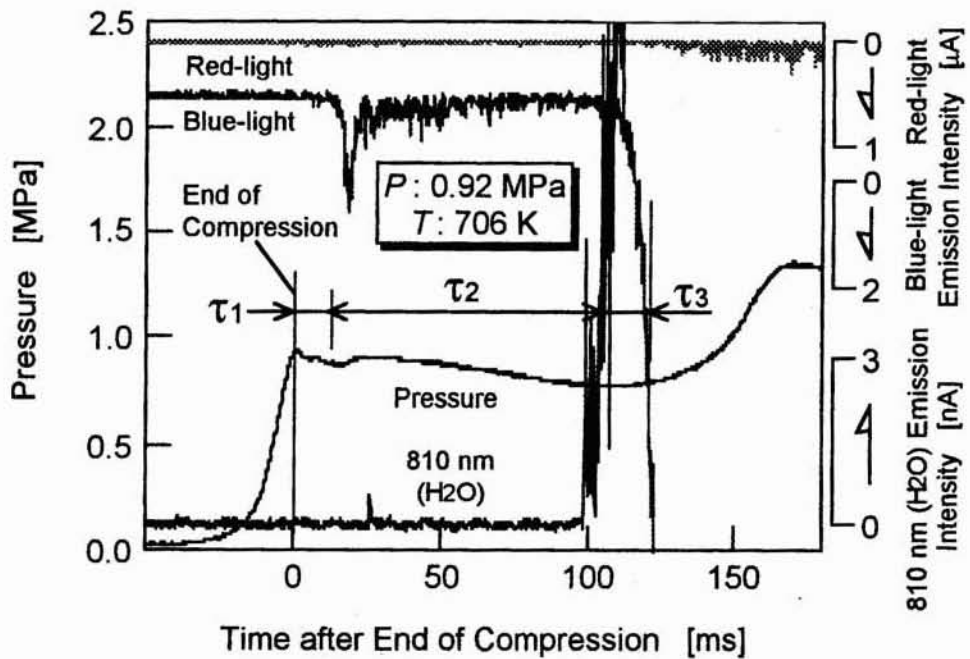


Fig. 2 Pressure, blue-, red-light and 810-nm (H_2O) emission histories of *n*-butane/air ignition at equivalence ratio $\phi=0.4$

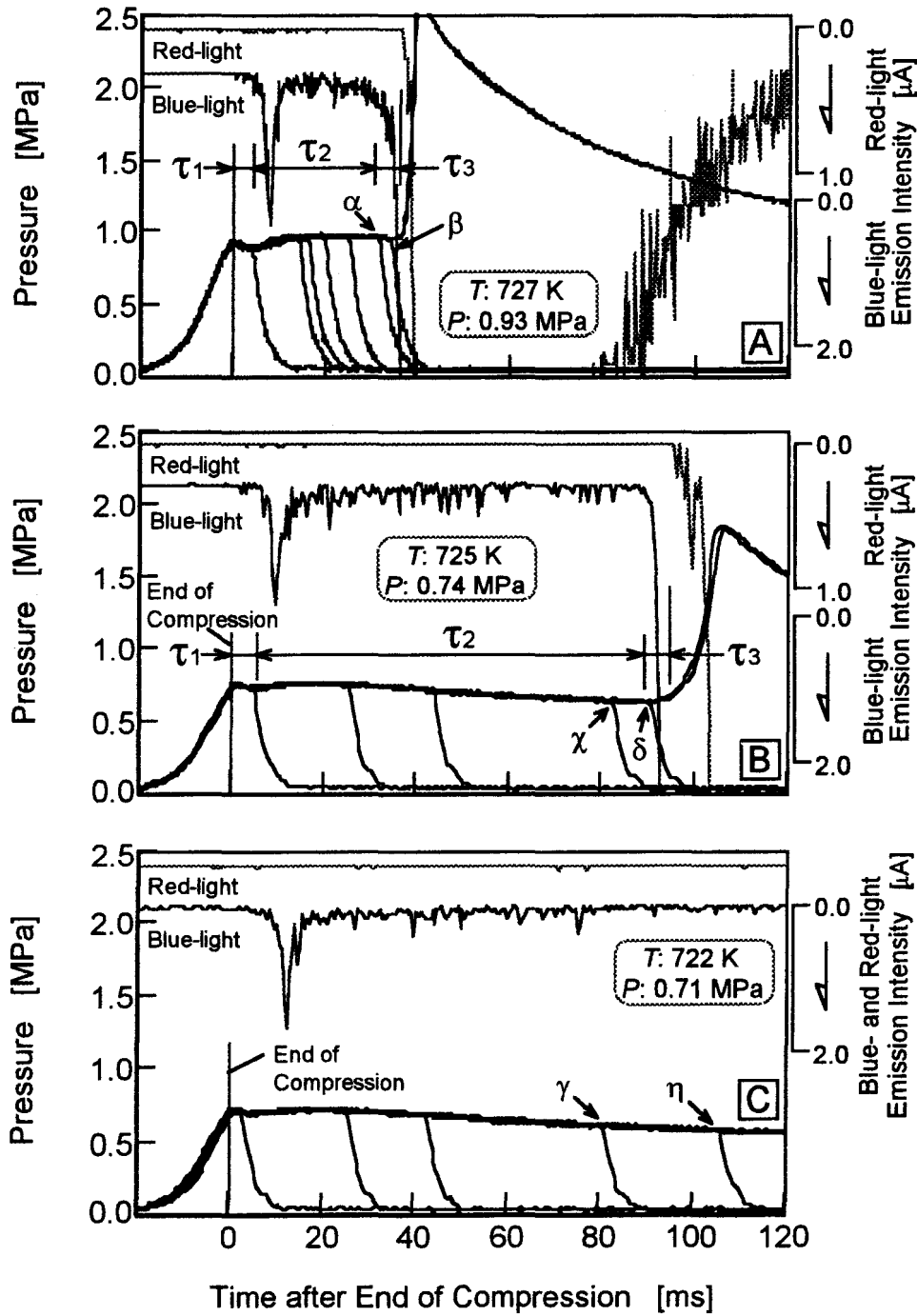


Fig. 3 Pressure, blue- and red-light emission histories under n-butane/air flammable/nonflammable critical conditions at equivalence ratio $\phi=0.65$

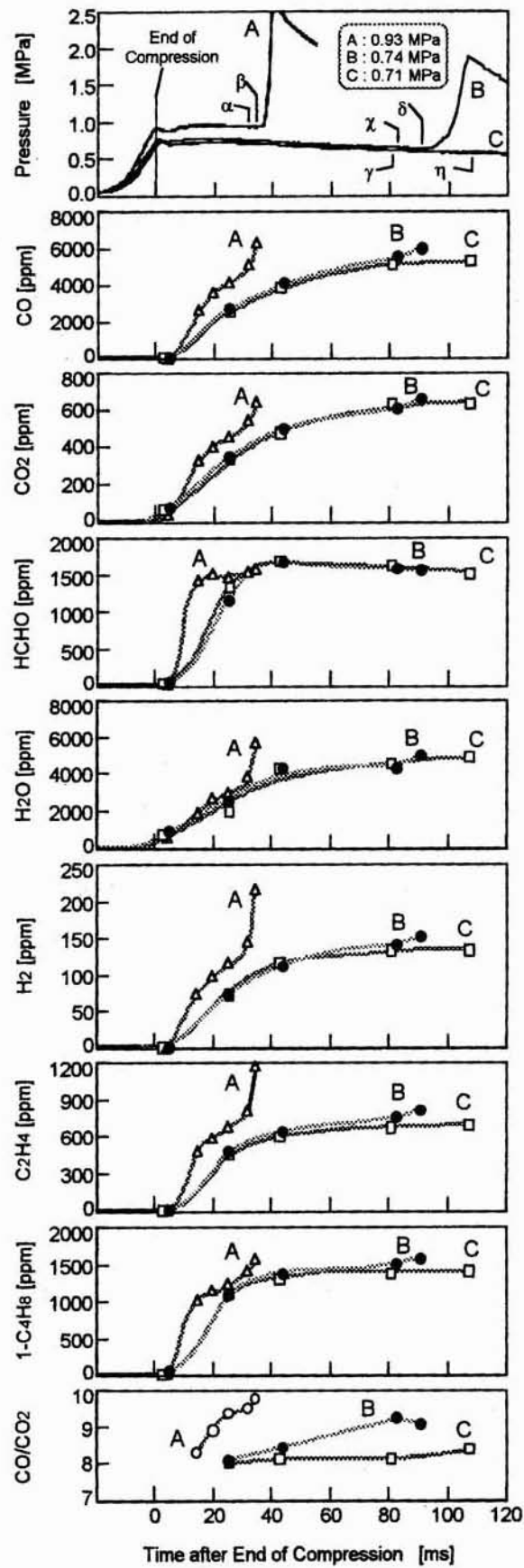


Fig. 4 Species concentration profiles under n-butane/air flammable/nonflammable critical conditions at equivalence ratio $\phi=0.65$