A Novel Attempt at Eliminating Piston Compression Ignition

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ABSTRACT

A novel concept for eliminating piston-compression ignition is proposed and its validity is substantiated. The cool-flame degeneration and/or blue-flame generation would be the key factor influencing whether the final hot flame will occur or not in low-temperature compression ignition. Any early or late generation of formaldehyde other than from the fuel itself is deduced to be efficient to retard the hot-flame onset. A method devised based on this concept consists of a very small quantity of vapor addition to the mixture; a vapor of low-volatile chemical compound which has very low vapor pressure and higher boiling point than those of the fuel. Confirmation experiment is carried out using a rapid-compression machine. Silicone oil (dimethylpolysiloxane) is used as a typical source of vapor. The vapor content of silicone oil does not exceed 0.4 percent of the fuel vapor. Air, when used as the oxidizing agent, is found to efficiently eliminate hot ignition; this is not so when $21O_2/79Ar$ is used instead.

INTRODUCTION

Higher thermal efficiency in spark ignition engines is prevented by the fact engine knock will occur. If the engine knock is not associated with, fuel economy will be achieved by adopting a higher compression ratio. Alkyl-lead additives into the fuels used to be the most successful and sole measures against the engine knock. They are not accepted at present time due to their toxicity and catalyzer failure in the emission control systems. In this paper we will propose a novel concept for retarding or eliminating hot-flame ignition to be caused by piston compression, and show one of the methods to realize the concept.

Most hydrocarbon fuel/air compressed mixtures generate cool and blue flames, in relatively low compression-temperature regime before developing to hot flame. In the case of methane or benzene the blue flame would be the first and single precursor for the final hot flame. It is well known that the peroxide addition into the former fuels accompanied with cool flame will promote the engine knock, and the formaldehyde addition will eliminate it. On the contrary, for the latter fuels which start from the blue flame stage, the formaldehyde addition will act as a knocking promoter. If we could control these antithetical actions adequately, ignition would be promoted or eliminated as a free selection of the human being.

Though the cool flame itself is a formaldehyde source, the other low-temperature flame, i.e. blue flame appears only after the self degeneration of cool flame or after the formaldehyde is consumed, in the relatively low-temperature region of the compression ignition. When examined the onset and degenerate characteristics and mechanisms of the cool and blue flames, it becomes clear that the progress of the cool-flame degeneration and/or the blue-flame generation is the key factor to lead to the occurrence of final hot flames.

A different source of formaldehyde other than the cool flame of the original fuel is deduced to be efficient to retard or promote ignition, affecting preflame reactions during the induction period up to the final hot-flame onset. This is the hypothesis of ours, to set up to control the compression ignition.

Adding a very small quantity of chemical-compound vapor to the conventional fuel/oxidizer mixture is considered as a candidate procedure to substantiate the concept. Vapors of low volatile chemical compounds having very low vapor pressure and higher boiling point than those of the original fuels will have a possibility for the different sources of the formaldehyde in the preflame periods.

EXPERIMENTAL

Premixed piston-compression-ignition experiments were carried out to confirm the validity of the concept considered above using a rapid-compression machine with 65-mm bore and 140-mm stroke. The fuel used was n-heptane or n-butane, ranging from zero octane rating to the commercial-gasoline equivalent. The oxidizer was natural air in the atmosphere or $21O_2/79Ar$ synthetic air. A vaporized fuel and an oxidizer were mixed in a separate vessel, and the mixture was introduced into a cylinder of the rapid compression machine. The mixture strength was stoichiometric. The recorded pressure value at the end of compression stroke gave us the compression temperature with the aid of known values of compression ratio, initial temperature and pressure of the mixture prepared in the cylinder for the compression.

A silicone oil (dimethylpolysiloxane, Shin'etsu Silicone: KF96), a vacuum pump fluid (ULVOIL R-7), or a lubricant for spark-ignition engines (Mitsubishi Motor Oil 20W-40, SE) was used as a source of the vapor to be added. A schematic procedure for adding vapor into the mixture is shown in Fig. 1. Based on the properties of the compounds, such as the

saturated vapor pressure, the vapor of the compounds contained in the mixture did not exceed 0.4 percent of the original fuel vapor. Metering was tried using a vacuum gauge, but the strict measurement was not easy.

Piston compression / ignition process of mixtures, in which one of the vapors was added, was compared with the process of conventional fuel/oxidizer mixtures with no vapor addition.

306nm-OH band, 517nm-C_2 band, blue (350 ~ 520nm) and red (590 ~ 640nm) visible light emissions were observed through the quartz windows during and after the compression to detect each of the cool, blue and final-hot flame appearances using combination of an interference filter and a 1P28 photomultiplier. The spectral sensitivity of photomultiplier and transmissivities of interference filters identifying wave length are shown in Fig. 2. Cool-, blue-, and hot-flame identification standard adopted here is described in Ref. 1. Temperature and pressure ranges prepared by piston compression were 478 ~ 730K and 0.59 ~ 1.01MPa.

RESULTS AND DISCUSSION

1. Confirmation of the validity

A conventional compression-ignition history of n-heptane/natural air mixture is shown in Fig. 3; this ignition event belongs to the one at the upper end of cool-flame-dominant temperature regime or the lower end of negative temperature-
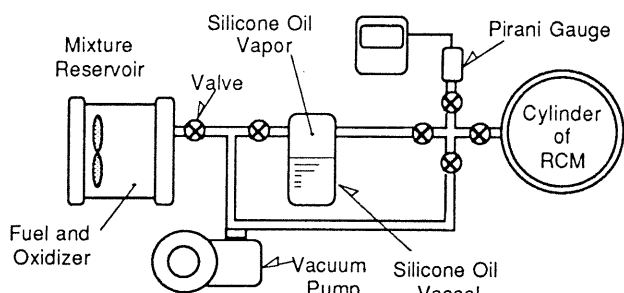
coefficient regime, where $\tau_1 \cong \tau_2$; τ_1: cool-flame delay after the end of compression, τ_2: blue flame delay after the cool-flame appearance [2]. In the figure, pressure development swings upwards and blue-light emission traces downwards. A pressure rise and emission swing followed by the typical degeneration can be found, which allows us easily to recognize it the cool-flame appearance. The final hot flame is perceived by an intense pressure jump and the full emission swing associated with.

In Fig. 4 a result is shown of the experiment the vapor of heavy compound was added into the previous mixture and compressed up to almost the same temperature and pressure. Emission detection was raised ten times sensitive. It is recognized that the first pressure rise is due to the cool-flame appearance accompanied by its self degeneration. Even though the cool flame appears earlier than in the conventional case, i.e. the cool-flame ignition delay becomes 3.8ms, almost the half of conventional 7.1ms, the blue and hot flame onsets are completely suppressed to appear.

2. Dependence on the vapor added

A case is shown above in which the silicone was used as an

Fig. 1 Schematic diagram of apparatus with which silicone vapor is added into mixture.

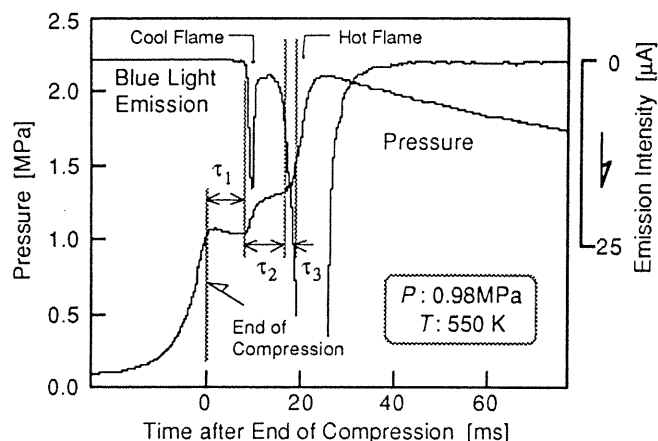Fig. 3 Pressure and blue-light emission records of stoichiometric n-heptane/air mixture ignition in cool-flame dominant regime.

Fig. 2 Spectral sensitivity of photomultiplier and transmissivities of interference filters.
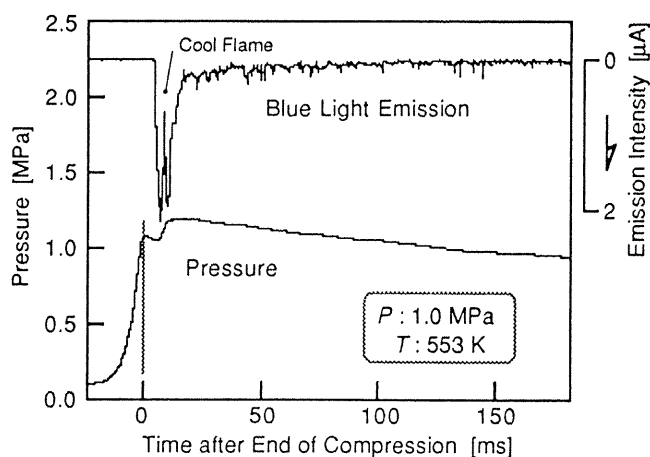

Fig. 4 Pressure and blue-light emission records when silicone vapor is added into stoichiometric n-heptane/air mixture the same as in Fig. 3.

adding vapor. The structure of silicone is very similar to the tetramethyllead, a typical antiknock additive. The obtained anti-ignition characteristics were quite similar to that of alkyl-lead compounds. The effect of molecular structure of the vapor should be examined. The silicone was replaced by a vacuum pump fluid, or a lubricant for spark-ignition engines specified in previous section as a source of the vapor to be added. Compression ignition events were repeated in the same temperature regime, and no distinctive difference was found at least among the three vapors listed.

3. Luminescence from vapor-containing air

It would be expected to explore the behavior of the compound vapor added into the mixture in the low-temperature oxidation process. A piston compression of a fuel-removed, compound vapor-containing air will give the most simple evaluation. The compression temperature is set to be about 570K; if a stoichiometric n-heptane/natural air mixture is introduced into this temperature condition , it would show a typical three-stage ignition; accompanying with/through cool, blue and hot flames one after another. This temperature is adequate to oxidize the silicone vapor as well.

The blue-light and 516.5nm (C_2) band emission records are shown in Fig. 5 associated with the pressure history, where only the silicone vapor was added into the air, and the mixed substance was compressed up to 568K.

The blue-light emission appears early just before the end of compression stroke. However, 516.5nm (C_2) band emission is very weak. The emission at 306.4nm (OH) band could not be caught, therefore is not shown in this figure. Silicone, when oxidized, will generate formaldehyde at the early stage. The blue-light emission observed here covers the Emeleus cool-flame band and is recognized to identify the formaldehyde.

When a chemical-compound vapor was added into the fuel/air mixture as shown in Fig. 4, the visible blue emission did not appear near the end of compression, but the emission was not associated till late with the cool flame onset. The formaldehyde generated from the silicone vapor was probably consumed by the pre-cool-flame reactions of the fuel itself. The fact that the cool-flame induction time τ_1 of the vapor-added mixture was shorter than of the conventional mixture
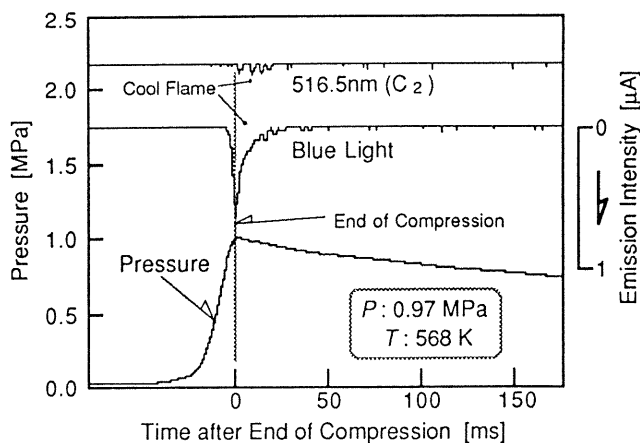
certificates the interpretation.

Salooja [3] commented that the formaldehyde generated from tetraethyllead took a part of antiknock actions of the additive. We don't discuss here the antiknock mechanism of alkyl-lead compounds, but we have to recognize the contribution of formaldehyde on the proposed anti-ignition behavior.

4. Dependence on the fuel and temperature range

Figures 6 and 7 are an example examining whether the chemical-compound vapor addition will take effect or not to eliminate ignition at the upper end of negative temperature-coefficient regime, where $\tau_1 \ll \tau_2$ [2] as recognized in Fig 6. The temperature is more than 100K higher than the cool-flame dominant regime. The previous fuel was replaced by n-butane which has faint cool flames and a similar antiknock properties as commercial gasolines. n-Heptane is difficult to use as a fuel in this temperature range due to an extremely early ignition onset during compression stroke when being kept the compression pressure on the same level. This example is the one a lubricant for spark-ignition engines was used as a source of the vapor. The emission detection was raised more than ten times as sensitive as the n-heptane case shown in Fig. 3.
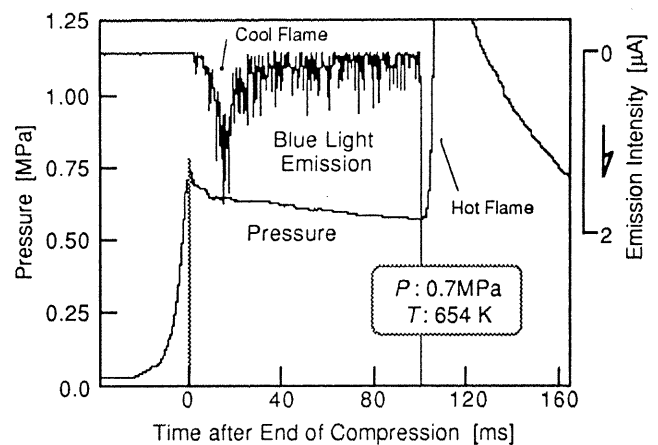
Fig. 6 Pressure and blue-light emission records of stoichiometric n-heptane/air mixture ignition in negative temperature-coefficient regime.
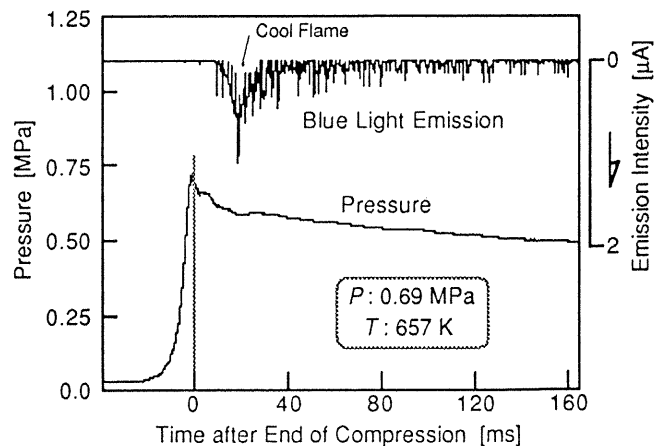
Fig. 7 Pressure and blue-light emission records when lubricating-oil vapor is added into stoichiometric n-heptane/air mixture the same as in Fig. 6.

Fig. 5 Pressure, blue-light and 516.5nm (C_2) band emission records when silicone vapor is added into air.

A very gratifying effect can be found to eliminate both blue-flame onset and hot ignition under the negative temperature-coefficient regime as well in Fig. 7 in the similar manner described above in Fig. 4.

5. Nitrogen as an inert component of air and dependence on the temperature range

An ignition when a $21O_2/79Ar$ synthetic air was used as the oxidizer is shown in Fig. 8. This is a case caused in the blue-flame dominant temperature regime [2]. The temperature was raised about 70K still further than the negative temperature-coefficient regime cases. No efficacy of vapor addition was obtained in this case in Fig. 8. Two excuses are considered; the one is the difference on temperature regime prepared; the higher one compared to the cases shown in Figs. 4 and 7, and the other excuse is the inert component between argon and nitrogen in the synthetic and natural airs. Due to the difference of specific heat ratio between them, the similar temperature and pressure condition belonging to the blue-flame dominant regime cannot be realized by using the natural air as an oxidizer. With the natural air no validity confirmation can be carried out in the blue-flame dominant regime.

In the negative temperature-coefficient regime case, however, a similar condition can be prepared either using the air and using the $21O_2/79Ar$ synthetic air as an oxidizer. With the synthetic air the efficacy was not found also in the experiments in the negative temperature-coefficient regime.

The vapor addition is examined further using a synthetic air for the ignition belonging to the cool-flame dominant temperature regime, and neither in this regime the efficacy is obtained; neither for the n-heptane nor for the n-butane. It will be obvious that the ignition elimination by this procedure mentioned here can be obtained only when air is used as the oxidizer for the fuel/oxidizer mixture.

A possibility to explain this peculiarity would be indicated in the fact, for example, that in the compression ignition the nitric oxide could be generated during the induction period up to the hot flame onset [4]. Antiknock characteristic of aromatic amine is a well known fact. Nitrogen related species would probably take part in the preflame reactions in the procedure proposed here for eliminating blue flame generation and hot ignition.

CONCLUSIONS

A hypothesis was set up to control the compression ignition; a different source of formaldehyde other than the cool flame of the original fuel should be efficient to retard or promote ignition, affecting preflame reactions during the induction period up to the final hot-flame onset. Adding a very small quantity of chemical-compound vapor to the conventional fuel/air mixture was a sample procedure deduced from the concept proposed here.

Piston-compression ignition of a stoichiometric fuel/air mixture could be completely eliminated over a wide range of octane rating fuels from n-heptane to n-butane. Even though the cool-flame onset, the first precursor to the hot flame ignition, could not be suppressed, blue and final hot flame could not appear. The vapor should have a very lower vapor pressure and higher boiling point than those of the fuel.

Silicone oil (dimethylpolysiloxane) was used as a typical example of the compounds for this purpose, but other compounds, such as vacuum pump fluid, are efficacious as well. The effect confirmed here is exhibited in a similar manner the alkyl-lead shows; which promotes the cool flame generation slightly but suppresses the blue and hot flame onsets.

Ignition elimination can be obtained only when natural air on the atmosphere is used as the oxidizer for the fuel/oxidizer mixture. When $21O_2/79Ar$ synthetic air is used instead, no eliminating effect can be found. It is indicated that the nitrogen related species take part in eliminating blue flame onset to the procedure described here.

REFERENCES

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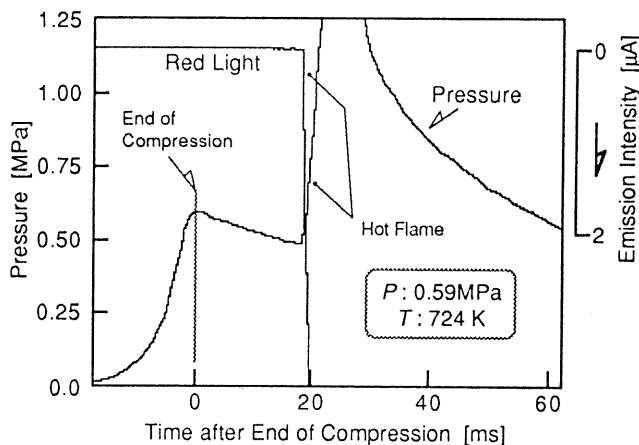
Fig. 8 Pressure and blue-light emission records when lubricating-oil vapor is added into stoichiometric n-butane/oxygen/argon mixture in blue-flame dominant regime.