The Visualization of Flame Temperature from Combustion of Hydrous Ethanol under CI Engine Condition

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ABSTRACT
This paper investigates the flame temperature of hydrous ethanol under CI engine condition via the two-color method. Tests have been performed in the rapid compression and expansion machine (RCEM) equipped with a high-pressure fuel injection system. Tested fuels are hydrous ethanol with 5% by weight water and 1% by weight Lauric acid (Eh95) and hydrous ethanol blended with commercial additive (ED95). The results revealed that hydrous ethanol with commercial additive (ED95) showed differences, not only in flame temperature, but also KL factor (i.e. soot concentration) from hydrous ethanol with 5% water by weight and 1% Lauric acid by weight (Eh95). Both tested fuels have two peaks in flame temperature history. The first peak is the effect of the intensity of premixed combustion. The second peak is the effect of increasing of combustion rate due to increased entrained air into spray. KL factor is over combustion periods, but higher generation rate of KL factor occurred at the end of combustion.

INTRODUCTION
Regarding to the environmental and public health concerns, regulations for emissions from internal combustion engines have become more stringent. In some countries, energy security has drawn increasing attention. The possibility of simultaneous reduction of exhaust emissions, substantial improvement of thermal efficiency and sustainable energy can be achieved by the use of alternative fuels. Ethanol is a promising alternative fuel in spark ignition (SI) engine, but the usage of ethanol in compression ignition (CI) engines, (replacing diesel and reducing combustion emissions, especially particulate matter and NOx) [1-4]) is not prevalent. Ethanol has been widely used in Brazil and Sweden [5].

As part of a government project ethanol buses have been used for public transportation in Sweden since 1985. The state facilitated the continual development and improvement of ethanol buses and trucks. From 2006 to 2009, a European project named BioEthanol for Sustainable Transport (BEST) promoted the use of city buses equipped with commercial ethanol CI engines fuelled by commercial ethanol fuel (ED95, composed of approximately 95% hydrous ethanol and 5% commercial additives by volume). The project proved that ethanol can be substituted for a significant percentage of the fossil fuels used for transport in Europe and Brazil. In 2010-2011, a similar demonstration project was launched for public transportation in Thailand, further contributing to the development of sustainable fuels.

As is known, using pure ethanol in CI engines produces poor ignition due to difficulties in simultaneously achieving suitable concentration and temperature for self-ignition in a spray mixture formation [5]. Main factors for poor auto-ignition of pure ethanol include a low stoichiometric air/fuel ratio and large latent heat of evaporation which strongly influences concentration and temperature in spray mixture for auto-ignition [6]. Two solutions to this problem exist: major engine modification; and fuel improvement using ignition improvers. Engine modifications such as pilot fuel injection [4] and spark assistance [7], can improve ethanol ignition characteristics with additional equipment. Ignition improver fuel additives are a more practical solution with minor engine modifications required to achieve viable engine output. Ignition improvers must be miscible substances which readily dissolve in ethanol without separation. Other important properties include cetane number, auto-ignition temperature, density and viscosity. In early 1980, a number of ignition improvers were tested in unmodified diesel engines of compression ratio 17:1 [1, 8]. The results concluded that nitrate-based additives have a
strong effect on the ignition of alcohol. However, use of nitrate-based improvers has some disadvantages including potential for increased corrosion; possibility of explosion; toxicity; wearing; and NOx emission. More recently, an additive for ED95, developed by SEKAB Biofuels & Chemical AB, has been used comprising components to act as lubricant, corrosion inhibitor and ignition improver (namely glycerol ethoxylate). Munsin et al. [9] showed that the ignition delay for ED95 is much shorter than that of hydrous ethanol with 5% water by weight (Eh95). This result is considered acceptable for real diesel engines over a wide range of operating conditions. However, further understanding of combustion characteristics of ethanol under CI engine conditions requires investigation, especially temperature and soot distribution in spray flame. This is because the formation and extinction of soot, HC, CO and NOx depend strongly on the flame temperature during combustion. Therefore, this study investigates combustion characteristics of hydrous ethanol under simulated CI engine conditions using two-color method. Although the combustion of ethanol provides low luminosity of soot (because the oxygen content in ethanol contributes combustion), low luminosity is still useful and sufficient to find flame temperature and KL factor by two-color method.

**METHODOLOGY**

**TWO COLOR METHOD**

The two-color method for measuring true flame temperature and optical thickness of soot (KL factor) has become a common diagnostic tool for the evaluation of engine designs and technologies. The measurement of true temperature and soot by the two-color method was initially proposed by Hottel and Broughton [10], who used two-color optical pyrometer to determine the true temperatures and total radiation from luminous gas flames. This technique was then applied to measure true flame temperature and soot in the combustion chamber of engines by Uyehara et al. [11], and Matsui et al. [12]. Two-color method has expanded over a number of engine studies such as the study of injection timing [13], injection strategies [14-15] injector nozzle characteristics [16] and fuels [17-18]. The principle of the technique has been well summarized [19-21]. Therefore, a brief overview of the technique will be provided presently.

Two-color method is based on the emission of soot formed in the flame inside the combustion chamber. The principal of the method is to measure the thermal radiation from soot particle at two wavelengths on the emission spectrum.

The monochromatic radiant intensity from non-black body of the flame can be expressed in equation (1).

\[
I_{(\lambda,T)} = \varepsilon_{\lambda} \frac{C_1}{\pi\lambda^5} \exp \left( -\frac{C_2}{\lambda T} \right)
\]  

(1)

As with the monochromatic radiant intensity, it can also be expressed in terms of the apparent temperature, \( T_a \), as shown in equation (2)

\[
I_{(\lambda,T)} = \frac{C_1}{\pi\lambda^5} \exp \left( -\frac{C_2}{\lambda T_a} \right)
\]

(2)

The modified equation for monochromatic emissivity of a soot cloud is given by equation (3) [10]

\[
\varepsilon_{\lambda} = 1 - \exp \left( -\frac{KL}{\lambda^a} \right)
\]

(3)

The monochromatic radiant intensity from equation (1) and (2) is equal. Replacing \( \varepsilon_{\lambda} \) by the right-hand side of equation (1), it is obtained:

\[
1 - \exp \left( -\frac{KL}{\lambda^a} \right) = 
\exp \left\{ \left( -\frac{C_2}{\lambda} \left( \frac{1}{T_a} - \frac{1}{T} \right) \right) \right\}
\]

(4)

Equation (4) is further developed to give Equation (5).

\[
KL = -\lambda^a \ln \left[ -\frac{C_2}{\lambda} \left( \frac{1}{T_a} - \frac{1}{T} \right) \right]
\]

(5)

KL representing soot concentration can be assumed to be independent of wavelength for the small variations encountered when using this method. Therefore the measurement of two radiations at two distinct wavelengths enables solution for the variables KL and T, based on equation (5).

**EXPERIMENTAL SETUP**

Experiments were carried out in a rapid compression and expansion machine (RCEM). A schematic diagram of the experiment is shown in Figure 1. Synthetic air used in this study is composed of 80% argon and 20% argon.
oxygen. The calorific value of injected fuels is kept constant by varying the amount of injected fuel. Experimental conditions are shown in Table 1. During combustion, the spray flame was imaged by high speed color camera with an infrared filter transmitting light in the visible region and absorbing light in the infrared region, (i.e. 800 to 2000 nm), to allow use of the two-color method. More experiment details can be obtained from previous study [9].

Results illustrate that hydrous ethanol with commercial additive (ED95) show similar flame shape and development. Both hydrous ethanol with 5% water by weight (Eh95) and hydrous ethanol with commercial additive (ED95) show similar flame shape and development.

Figure 1. Schematic diagram of the experiment

The tested fuels and their compositions are shown in Table 2. Lauric acid (1% by weight) was added into hydrous ethanol (Eh95) to prevent injection system lubrication failure. However, Lauric acid was not added to hydrous ethanol with commercial additive (ED95) because it contains a commercial lubricant. Properties for studied ethanol and glycerol ethoxylate which is the ignition improver for commercial additives are shown in Table 3.

**RESULTS AND DISCUSSION**

Heat release rate for tested fuels are shown in Figures 2. Results illustrate that hydrous ethanol (Eh95) with 5% water by weight and 1% Lauric acid by weight exhibited higher heat release rate in premixed combustion phase than hydrous ethanol with commercial additive (ED95). It is explained that a longer ignition delay in case of Eh95 [9] have more time to mix fuel and air prior to the start of combustion. Increased air and fuel mixing leads to a more rapid pressure rise and high heat release rate in premixed combustion phase. Heat release in premixed combustion phase accounts for 57.2% of the total heat release for hydrous ethanol with 5% water by weight and 1% Lauric acid by weight (Eh95) and 25.9% for hydrous ethanol with commercial additive (ED95).

Figure 3. (a) and (b) show both the typical direct photographs of flame obtained by high speed camera at 10000 fps and flame temperature of tested fuels obtained by two-color method at the same time during combustion duration.

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<td>Fuels</td>
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<th>Table 2. Tested fuels</th>
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<td>Eh 95</td>
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<td>ED95</td>
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<th>Table 3. Tested fuels</th>
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<td>Formula</td>
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<td>Molecular weight (g/mol)</td>
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<tr>
<td>Oxygen content (% by weight)</td>
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<tr>
<td>Stoichiometric A/F ratio</td>
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<tr>
<td>Viscosity (cP)</td>
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<tr>
<td>Density (g/cc at 20 °C)</td>
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<tr>
<td>LHV (MJ/kg)</td>
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<tr>
<td>Cetane number</td>
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<tr>
<td>Latent heat of vaporization (kJ/kg)</td>
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<td>Boiling temperature (°C)</td>
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<td>Autoignition temperature (°C)</td>
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the window. The air-fuel mixture in this zone cannot be combusted due to quenching.

In the typical flame temperature images, the range of the flame temperature was between 1600 K to 2000 K. A flame temperature of below 1600 K was designated blue, and a flame temperature of above 2000 K was designated red. The spray combustion shows non-uniform and non-axisymmetric flame temperature inside spray flame.

At the given times, local flame temperature for hydrous ethanol with 5% by weight water and 1% by weight Lauric acid (Eh95) is lower, compared with hydrous ethanol with commercial additive (ED95).

Cause of the difference of flame temperature between Eh95 and ED95 was postulated to the effect of entrained air into the spray, which is affected from different ignition delay time [9].

![Figure 2. Heat release rate of tested fuels](image2)

![Figure 3. Typical direct photographs along with flame temperature of tested fuels](image3)
The average flame temperature and KL factor of tested fuel changed over the combustion durations are depicted in Figure 4 (a) and (b).

As shown in Figure 4 (a), the maximum average flame temperature of hydrous ethanol with 5% by weight water and 1% by weight Lauric acid (Eh95) was approximately 1830 K at 3 ms after start of injection, which corresponds with the peak of heat release rate occurred 2 ms after start of injection shown in Figure 2. At the maximum average flame temperature, it is possible to generate NOx due to thermal NOx onset when temperature exceeds 1700K.

In the later stage of combustion of Eh95, another peak temperature occurred at 5 ms after start of injection. The later peak temperature was nearly identical to first peak temperature. Afterward, the flame temperature gradually decreased.

In the case of ED95 (hydrous ethanol with commercial additive), the same tendency of flame temperature history was illustrated, but it is lower than that of Eh95 during 10 ms after start of injection. However, flame temperature of ED95 recovered at 10 ms after start of injection and stayed elevated until the end of combustion.

The first peak of flame temperature is attributed to the effect of intensity of premixed combustion. Longer premixed combustion phase of Eh95 resulted in higher temperature.

The second peak occurs just after the end of the fuel injection. It is believed that combustion rates are increased because the spray impinging after the end of injection entrained the additional air from surrounding gas, thus playing an importance role in the oxidation process [15].

KL factors representing the soot concentration are shown in Figure 4 (b). The history of KL factor can be interpreted to soot generation during combustion.

The KL factor of hydrous ethanol with commercial additive (ED95) is higher throughout combustion period compared with hydrous ethanol with 5% by weight water and 1% by weight Lauric acid (Eh95). The reasons are contributed to; i) the difference mixing time and entrained air into a spray due to the different lift-off length (the distance between nozzle tip and reaction zone in the spray flame), where almost 20% of the air required to achieve complete combustion of the injected fuel is entrained [23].

It is expected that a shorter lift-off length of ED95 due to shorter ignition delay [9] has lower entrained air into spray. ii) the lower flame temperature of ED95 obstructs high soot oxidation rate.

Both tested fuels showed the highest KL factor in the later stage of the combustion period when the flame temperatures have decreased. KL factors increased significant 5 ms after start of injection and dropped drastically after the highest points at 13 ms after start of injection. The results showed obviously that soot is generated throughout combustion duration of ethanol.

**CONCLUSION**

The main conclusions concerning the combustion characteristics of hydrous ethanol without commercial additive are that:

1. Hydrous ethanol with commercial additive (ED95) showed different flame temperature and KL factor from hydrous ethanol with 5% water by weight and 1% Lauric acid by weight (Eh95).

2. Flame temperatures for hydrous ethanol with 5% water by weight and 1% Lauric acid by weight (Eh95) is initially higher than that of hydrous ethanol with commercial additive (ED95). However, flame temperature of
ED95 recovered at later state until the end of combustion.

3. Flame temperatures for both tested fuels showed two peaks in temperature history. The first peak of flame temperature occurs after the peak of heat release rate due to the intensity of premixed combustion. The second peak occurs just after the end of fuel injection because of the increasing combustion rate due to increased entrained air into spray.

4. The KL factor of hydrous ethanol with commercial additive (ED95) is higher throughout combustion period compared with hydrous ethanol with 5% water by weight and 1% Lauric acid by weight (Eh95). Higher rate of KL factor generation occurred at the end of combustion for both fuels.

ACKNOWLEDGEMENT

The financial support of Ronnachat Munsin and Sumrerng Jugjai from the Office of Higher Education Commission and The Thailand Research Fund through the Royal Golden Jubilee Ph.D. Program (Grant No. PHD/0083/2551) is gratefully acknowledged. The research fellowship of Yossapong Laoonual in Japan from the Hitachi Scholarship Foundation is also highly appreciated. This work is supported by the Higher Education Research Promotion and National Research University Project of Thailand, Office of the Higher Education Commission. The authors also acknowledge Mr. Norihiko Takahashi for his help during the experimental work.

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DEFINITIONS
\( \varepsilon \) emissivity
\( \lambda \) wavelength (nm)
\( K \) the absorption coefficient
\( L \) the path length (m)
\( \sigma \) an empirical constant equal to 1.39 in the visible spectrum.
\( E_{\lambda,T} \) monochromatic radiant intensity of the flame (kW/m\(^2\)-m)
\( T \) true temperature of the flame
\( T_a \) apparent temperature of the flame
\( I_{\lambda,T} \) monochromatic radiant intensity emitted by a black body (kW/m\(^2\)-m)
\( C_1, C_2 \) Planck constant

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