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Simultaneous Visualization of Natural Luminosity and Chemiluminescence of Dual Fuel Combustion in an Optically Accessible Engine

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Abstract

The engine fueled with methane/diesel is a promising and highly attractive operation mode due to its high performance-to-cost ratio and clean-burning qualities. However, the combustion process and chemical reactions in dual fuel combustion are highly complex, involving short transient pilot-fuel injection into the premixed gaseous fuel charge, autoignition, and combustion mode transition into premixed flame propagation. The motivation of the current investigation is to gain an insight into the combustion dynamics in dual fuel combustion engine based on chemical radicals and thermal radiation. The chemiluminescence (CL) and natural luminosity (NL) are expected to provide specific characteristics in combustion control and monitoring. To visualize the highly unsteady combustion process in terms of OH*, CH2O* radicals and natural luminous emissions, the band pass filters with 308nm, 330nm combined with an image doubler are employed to visualize the OH* and CH2O* CL simultaneously. High speed natural luminosity imaging is adopted to illustrate the effects methane lambda and pilot ratio on the ignition delay, luminous intensity and engine performance. Spectroscopy analysis based on OH*, CH2O* and NL was performed to study the chemical reactions in dual fuel mode.

Introduction

Natural chemiluminescence is a non-intrusive optical technique widely used in combustion diagnosis [1], such optical techniques are powerful tools to analyze not only the ignition of homogeneous mixtures, but also different parameters of sprays and even exhaust emissions. Chemiluminescence from species such as CH*, C2*, OH* and CO2* often are used as a quantitative diagnostic in experimental studies of premixed combustion [2]. Natural luminosity analysis and spectroscopy have shown to be able to describe the different phases of the combustion process under dual-fuel combustion mode [3].

Electronically excited OH ($A^2\Sigma$, denoted as OH*) is one of the most common optical diagnostic techniques applied to fundamental combustion flame and optical engines. This imaging technique captures the signals (306~310 nm) from naturally excited OH* radicals when they return to the ground state [4, 5], which is relatively easy to setup and useful to identify high-temperature reaction zones of combustion flames [5] as well as to determine key parameters such as the flame lift-off-length (LOL), ignition delay, etc. However, being line-of-sight-integrated images, the drawback is that the quantitative OH* distribution in spatial and detailed structural of flames cannot be visualized. There have been number of studies report the implementation of OH* CL imaging in optical engines. OH* CL imaging has been used to evaluate the emissions in constant volume chamber [6], rapid compression and expansion

machine [7], and optical engine [8] due to the OH* CL is strictly correlated to formation-oxidation of NOx-PM. Since OH radicals exist in both the flame front and the hot postcombustion gases, OH* CL and OH planar laser-induced fluorescence (OH-PLIF) imaging are widely used to identify high-temperature reaction zones and their temporal evolution inside the engine cylinder [9-11]. Spatially-integrated OH* chemiluminescence (CL) is frequently used as a heat release rate (HRR) indicator, since it is present at flame front and in burnt gas and predominantly formed in the hot diffusion flame. Schönborn, et al. [12] studied the autoignition of propane in air by using natural OH* CL imaging. The spatial and temperal development of autoignition kenrels was studied in an optically accessible tubular section of the reactor. They found that kernel nucleation, movement and growth affected the location and movement of the subsequent autoignition sites, and resulted in stagnation of the incoming flow and flashback. M. Roder, et al. [13] correlated the HRR, which dereived from the combined LIF of OH and CH2O and from OH* CL. They conducted that in the flames investigated in the present study gross correlations exist between the spatially integrated HRR deduced from LIF and OH* CL emission intensity when stoichiometry, fuel composition and position in the flame (with respect to degree of mixing between incoming flow and recirculation zone) are varied. OH* CL imaging is also commonly used in dual-fuel combustion to visualize the combustion process, involving the two-stage ignition, the transition between short transient pilot-injection to premixed gaseous fuel mixing, and flame propagation [14-16]. Nicolas Dronniou, et al. [17] performed a wide range of equivalence ratios of the premixed charge in an optical engine to investigate the flame propagation of dual-fuel combustion.

Contrary to the OH distribution, formaldehyde is confined to narrow regions close to the steep intensity rise of the OH signal on the unburned side of the flame front. The formation of the CH2O is characteristic of low temperature reaction onset for hydrocarbon fuels, and distinct low temperature chemistry is particularly important during auto-ignition [18]. Generally, both OH* and CH2O* CL imaging contribute to the experimentally detected CL signal with CH2O* representative of cool flames and reaction onset, while OH* is used for identification of high temperature reactions. However, because the electronically excited CH2O* signal is extremely low intensity during combustion, it is rarely used in practical optical engine measurement. Xin Yu, et al. [19] implemented three individual CL radicals, OH*, CH2O* and CO2* to study the detailed n-heptane mechanism in engine environment. Modeling the OH* and CH2O* CL process bridges this gap and allows experimentally-observed CL images to be compared against the results of predictive simulations. Xiao Ma, et al. [20] investigates the flame structures, intermediate species and pressure evolution during FIAI (Flame-induced auto-ignition) and SI (Spark ignition) knocking combustion using an optical engine with ultra-high speed imaging of CH2O* and OH* CL. The flame structures are analyzed together with cylinder pressure and intermediate species to understand their dynamic interactions.

Dual-fuel combustion of the pilot-fuel in a lean natural gas mixture is a highly complex process involving short transient pilot fuel injection into the premixed gaseous fuel charge, pilot-fuel autoignition, combustion mode transition, and premixed flame propagation [21]. In order to address this short transition between pilot-ignition to the premixed gaseous fuel combustion, several optical engine studies observed the influence of methane on the ignition delay and reported the strong inhibitive effect on ignition through chemical interaction [22-24]. A numerous of studies have been reported that two stage ignition in diesel combustion in constant volume chamber and optical engine [25-27]. They concluded that the thermodynamic paths traversed by the in-cylinder gases during the injection have significant implications for how much of the mixture reaches second-stage ignition. For the dual fuel combustion, the chemical reaction of the incylinder gases is more complicate due to the addition of the methane. It was found that methane has a significant effect on the lowtemperature reactivity in pilot-fuel lean regions, which is considerably retarded leading to an overall increased ignition delay and lower pilotfuel mixture reactivity [28-30]. Nevertheless, little is known about the influence of methane on the processes of the ignition and flame propagation.

This study aims at looking into further details regarding the pilot dualfuel combustion using OH*, CH2O* and natural luminosity (NL) imaging simultaneous measurements. The main emphasis in the present work is on the dual-fuel ignition process in an optically accessible engine.

The main objectives and contributions of this work are to:

1. demonstrate the influence of additional methane in the oxidizer composition on the transient stages of ignition in the dual-fuel combustion,

2. find a simple method (compare with PLIF) such as CH2O* chemiluminescence to measure the low-temperature ignition process in dual-fuel mode, and clarify the relationship between low-temperature and high-temperature ignition.

3. investigate the transition phase from the pilot-fuel ignition until the premixed flame in dual-fuel combustion,

4. identify the most sensitive parameters with respect to the IDT.

Experimental Apparatus

2.1 Optically Accessible Engine

The optical engine layout is sketched in Fig.1, and the engine specifications are detailed in Table 1. The optical single-cylinder engine is variant of an AGCO 84AWI 6-cylinder common rail diesel engine. It is a fully flexible research engine, which provides possibilities to freely vary the critical physical variables that could otherwise be restricted in normal engine operations. An electrohydraulic valve actuator (EHVA) system is employed for a camshaft-less gas exchange system in this optical engine setup, and the fully flexible variable valve actuation system allows controlling the valve lift and timing simultaneously. A Bowditch piston is applied to provide optical access to the combustion chamber. A Kistler 6125 piezoelectric transducer is adopted to measure pressure in cylinder, and the data are recorded at a resolution of 0.2° crank angle. A common rail fuel injection system controlled by a Labview system provids the

ability to control the injection timing and the quantity of the injected fuel.



Fig. 1 Bowditch-type optical engine with details of the piston elongation assembly and optical setup

Table. 1 Engine specifications

Engine type	4-Stroke diesel single-cylinder
Engine speed	1200 rpm
Bore	111 mm
Stroke	145 mm
Swept volume	842 cm3
Combustion bowl	19.7 cm3
Vol. compression ratio	17.9:1
Swirl Ratio	2.7

2.2 Fuel injection system

A special multi-fuel injection system was developed to perform dualfuel engine experiments on both liquid and gaseous fuels. Two unique systems are included: 1) a common-rail injection system, with an symmetric six-hole piezo injector was applied to pilot fuel injection, and 2) a gaseous port fuel injection system with two gas injectors mounted at the manifold near the air intake valve, providing the primary gaseous fuel, namely methane. The specifications of the pilot diesel injector and gaseous port injectors are reported in Table. 2.

Table. 2 Common rail and gas injector specifications

Injector type	Bosch CR12
Number of holes	6 (symmetric)
Include Angle	148°
Hole diameter	0.09mm
Injection pressure	1000bar
Injection timing	8 BTDC
Gas injector	Bosch NGI2
Gas injection pressure	8 bar
Gas injector number	2

2.3 Engine operating conditions

The aim of this investigation is to assess the effects of CH4 lambda (λ_{CH4}) and pilot ratio (R_{pilot}) on dual-fuel combustion. In order to observe these effects, the dual-fuel optical engine was run at middle load ~10 bar IMEP, charge air pressure 1.1 bar, pilot injection pressure 1000 bar and engine speed 1200 rpm. A skip-fire strategy was implemented due to the limitations of the mechanical properties of the optical window and the stabilities of the charge air system. A total of 70 cycles for each test point with 10 fired-cycles were recorded to analyze the combustion process at individual condition. High-purity methane (purity is 99.99%) was fueled as primary fuel, and the pilot was fueled with commercial diesel fuel (EN590). Two gas injectors were applied to inject CH4 into intake air manifold with pressure 8 bar at -345 CAD ATDC. The λ_{CH4} was controlled by the mass flow rate of methane and charge air, and the charge air mass flow rate was stabilized with PID control. In this study, the charge air mass flow is set to 70kg/h. The methane-air mixture was inducted into the cylinder through the intake valves along with the intake air. A six-hole piezo diesel injector was applied for pilot fuel injection at SOI = -8 CAD ATDC. Table 3 outlines the test parameters for the study of the effect of methane lambda, pilot fuel ratio and charge air temperature on dualfuel combustion. It should note that the pilot fuel ratio was defined as the percentage of the pilot diesel energy in total energy. e.g., $R_{pilot} =$ 5% means 5% energy from pilot diesel. Case A was defined as the effect of λ_{CH4} on dual-fuel combustion, λ_{CH4} was varied from 2.2 to 1.8, with interval 0.2, while keeping t_{pilot} constant (0.2 ms). This resulted in different total energy in the system due to the addition of the CH4 during combustion. In this case, we keep the water cooling as ambient temperature T_{cooling} =300K. Case B examined the effects of the pilot fuel ratio on dual-fuel combustion. The engine was heated to 350K in terms of the cooling water was heated to $T_{\text{cooling}} = 350$ K. The duration of tpilot was adjusted to control the pilot fuel ratio, while keeping λ_{CH4} =2.2. In this case, the injection pressure was kept constant with 1000 bar, and the corresponding mass flow rate of the pilot diesel can be seen in Table 3.

	Case A			Case B		
ṁair, kg∕h	70	70	70	70	70	70
Tcooling, K	300	300	300	350	350	350
λ_{CH4}	2.2	2	1.8	2.2	2.2	2.2
$t_{\rm CH4}$, ms	10.5	11.5	13	10.5	10.5	10.5
<i>ṁ</i> _{CH4} , kg/h	1.845	2.03	2.25	1.845	1.845	1.845
<i>t</i> _{pilot} , ms	0.2	0.2	0.2	0.176	0.225	0.355
SOI _{pilot} , BTDC	8	8	8	8	8	8
$\dot{m}_{ m pilot}, m mg/cc$	6.035	6.035	6.035	3.15	6.69	15.01
R _{pilot}	9.1%	8.4%	7.6%	5%	10%	20%
T _{air} , K	298	298	298	298	298	298
Total Energy, MJ/h	101.57	110.81	122.05	97,12	102.52	115.34
λ_{Global}	2	1.83	1.67	2.09	1.98	1.77

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2.4 Fuel Properties

The standard EN590 was used as a pilot fuel, which provided a strong benchmark. The methane was provided by AGA Industrial Gases (Finland) with purity of 99.9%. General properties of the methane and EN590 are listed in Table 4.

Page 3 of 9

Items	Unit	EN590	Methane
Molecular formula		$C_{10}H_{20}$ to $C_{15}H_{28}$	CH4
Lower heating value	MJ/kg	≈43.1	50
Cetane Number		52.6	0
Stoichiometric air- fuel ratio		14.5	17.19
Density at 15°, 1 atm	kg/m ³	820-845	0.656
H/C ratio	mole/mole	1.91	4
Viscosity at 40 °	mm ² /s	2.0-4.5	18.72

2.5 Optical setup

Natural luminosity imaging is performed by using a high-speed Complementary Metal Oxide Semiconductor (CMOS) color camera (Photron FASTCAM SA-Z) through a fixed 45° mirror, which is placed inside the piston extension, provides a view of the combustion chamber from below. The maximum resolution 1024×1024 pixels can be achieved with the exposure 33.33μ s at frame rate 20000 fps. The color camera has a high sensitivity over a wide visible range, which enables recording the color information of spectral emissions during combustion. The electronic sensors of the camera record the spectrum of colors into three channels, one dominated by red, and the others by green and blue. The spectral response of the color camera, which describes the sensitivity of the photo-sensor to optical radiation of different wavelength, can be seen in Fig. 2. A Nikon lens (Nikon AF Nikkor 180mm f/2.8) is mounted at the front of the camera, which realizes a spatial resolution of 16.4pixels/mm.



Fig.2 Relative spectral response curves of color-chrome camera

A high-speed monochrome camera (Phantom V2012) combined with high-speed intensifier (Lavision high-speed IRO) and image doubler is applied to detect the OH* and CH2O* signal simultaneously. It should note that, the image doubler is designed to double the image of an object and to project the two images on the left and right side of one camera. This allows to capture OH* and CH2O* CL simultaneously with a single camera. The result is that the resolution for each signal is half of the full resolution (640*800). To improve the image quality, a UV-enhanced lens 100mm/f2.8 (Sodern Cerco >90% transmission in UV range 250-410nm) is adopted for CL imaging. Two band pass filters with wavelength 308nm±10nm and 330nm±10nm are applied for OH* and CH2O*, respectively. A short-pass dichroic mirror, which spectrally separate light by transmitting (220-400nm) and reflecting (400-700nm) light as a function of wavelength is adopted to separate the NL and CL signal. The detailed optical specifications are shown in Table 4.

Device	Technical specification	Application
High-speed	High-speed CMOS	Natural Luminosity
color camera	(Photron SA-Z)	imaging
High-speed monochrome camera	High-speed CMOS (Phantom V2012)	Chemiluminescence imaging (OH*, CH2O*,CH*)
Intensifier IRO	High-speed intensifier	Image-intensified
Image Doubler	Double Viewers	Double image the signal by two filters
UV-enhanced Lens	100mm/f2.8 Usable wavelength: 220nm-900nm Optimized wavelength: 250 - 410nm (T>90%)	Enhance the signal located in UV region
BP 308 filter	wavelength 308nm±10nm	OH* CL
BP 330 filter	wavelength 330nm±10nm	CH2O* CL
Dichroic Mirror	Trasmission: 220- 400nm@ >80% Reflection: 400- 700nm@ >80%	Separate the NL and CL signal

Results and discussion

Effects of Lambda on Dual-Fuel Combustion

Typical simultaneous OH*, CH2O* and natural luminosity images for varying crank angle at λ_{CH4} =2.2 and 8% pilot ratio are demonstrated in Fig. 3. The field of view of these images is limited by the optical window. At about 2.8° CA ATDC, NL, OH* and CH2O* are detected simultaneously in the vicinity of the spray axes. The location of the OH* and CH2O* are similar, which is different with the previous studies [32, 33] that cool flame (CH2O) and hot flame (OH) are separated. This difference is caused by the differences of chemiluminescence imaging and PLIF image. Chemiluminescence imaging is easy to setup and effective inproviding a temporal evolution of diesel flames. However, the line-of-sight-integrated image misses details of turbulent flame structures and can be affected by broadband emissions. As shown in Fig.3, the locally high OH*/CH2O* ratio indicates that OH* and CH2O* generally form complementing spatial distributions, indicating that CH2O is consumed locally during the hot combustion. In general, OH indicates the burnt gas regions, while CH2O is found within the reactants and is often used as an indicator of the preheat region in premixed methaneair flames [15]. The margin difference of IDT of low- and hightemperature IDTs can be interpreted by two reasons. On the one hand, the short injection duration of pilot fuel injection and inhibitive effect of CH4 on the ignition delay (ID) leads to a long IDTs, results in well mixing between pilot diesel and CH4-air mixture. When the ignition takes place, the difference of low- and high-temperature combustion start almost simultaneously. On the other hand, the low temperature at the beginning of the ignition leads to huge quenching and less photon emission. Due to the low temperature combustion at this point, the flame of the NL is blue, and the intensity of the OH* and CH2O* are similar. With the temperature in cylinder increasing, the luminous of sooty flame gradually increasing, the color of the NL flame gradually turns to bright yellow. The intensity of the OH* has the similar trends with the intensity of NL, where the high intensity region of OH* and NL locate in the same region. The comparison of the OH* and CH2O* can be represented by the OH*/CH2O* ratio. It can be observed that after start of the ignition, there is margin difference in OH*/CH2O* Page 4 of 9

10/19/2016

ratio (4.6 CAD to 13.6 CAD). This represents that during main combustion (from start of ignition to the end of premixed combustion) the reaction and consumption rate of OH* and CH2O* are similar. The Fig.3 also shows that where is higher OH* intensity, there is higher OH*/CH2O* ratio. This phenomenon indicates that the chemical reaction is dominated by the high temperature reaction. It has been proposed that the formation of OH radicals results from the reaction chains, induced by the auto-ignition on the fuel-rich side [34]. The chemical reaction zones of OH* and CH2O* are located in similar region in spatial which indicates that the low-and high- temperature reactions are highly dependent with the mixture fraction in spatial.



Fig. 3 Temporal sequences of NL, OH*, CH2O* and OH*/CH2O* ratio at $\lambda_{CH4}=2.2$, $R_{pilot}=8\%$

Based on the aforementioned image analysis, the effect of the λ_{CH4} on the integrated NL intensity is shown in Fig. 4. The inhibition effect of CH4 on the IDTs can be easily observed from the integrated NL intensity, which consistent with several previous studies [14, 15, 16, 24]. The ignition occurs earlier in leaner conditions than in richer conditions. The prolonged ID in the presence of methane could potentially be attributed to the increased mixture thermal capacity and to the reduced oxygen partial pressure [14]. At lean CH4 conditions, e.g. $\lambda_{CH4}=2.2$ and $\lambda_{CH4}=2$, the peak of the integrated NL intensity are similar, which means the reaction intensity and flame structure are

similar. However, when λ_{CH4} decreases to 1.8, namely, more CH4 in the cylinder, even the condition is much leaner than the stoichiometric equivalence condition, the peak intensity is about two times stronger than the peak intensity at $\lambda_{CH4}=2$ and 2.2. It seems there is a limitation of flammability for the gas phase mixture. At ultra-lean condition, the flame speed is limited, the flame area is determined by the pilot diesel distribution. Only the gas mixture around the diesel cloud can be burnt. Once the λ_{CH4} exceeds the limitation, owing to the local rich zone, more sooty flame generated and larger flame area, results in higher intensity. The high intensity duration at $\lambda_{CH4}=1.8$ sustained 30° CAD after the appearance of the signal, which is much longer than the duration at $\lambda_{CH4}=2.0$ and 2.2. It can be explained that at the lower λ_{CH4} conditions, more addition of the CH4, which provides a permissive environment for flame propagation. Meanwhile, with the total energy increasing, the combustion temperature is higher in richer condition than in leaner condition, which promote the sooty flame propagation. According to [33,35], the high-temperature sooty flame emits more visible intensity than the low-temperature 'cool-flame', the later one glows the low intensity blue light. The effect of λ_{CH4} on the NL flame color can be observe in Fig.5 easily at the 6.4° CA ATDC. It can be observed that the blue flame gradually turns yellow with the addition of CH4.



Fig. 4 Effect of λ_{CH4} on the integrated NL intensity



Fig. 5 Effect of λ_{CH4} on the NL flame color

Fig.6 demonstrates the effect of λ_{CH4} on the integrated OH*, CH2O* intensity. According to [14], there is a discriminable difference of lowtemperature and high-temperature IDT can be observed from the appearance of CH2O* and OH* signal. However, this phenomenon is not able to be detected in our experiments. The appearance time of the OH*, CH2O* are similar, CH2O* shows slightly faster increasing at the beginning of the ignition. The potential possibility is related to the low intensity signal of the CH2O* at the beginning of ignition due to the low temperature and quenching. The short injection duration (0.2ms) also promotes to decrease the dwell of the low- and hightemperature ignition. It can be observed that the EOI is much earlier (5 CAD) than the ignition, when the pilot diesel have well mixed with the ambient CH4-air mixture, results in low equivalence ratio in diesel

Page 5 of 9

10/19/2016

cloud. This well mixing leads to a significant distribution of CH2O throughout the reactants in the high-turbulence conditions, while CH2O is typically observed in thin layers in the low-turbulence condition [35]. The inhibition effect of λ_{CH4} on the appearance of OH*, CH2O* signal can be observed clearly. As the previous studies [14], the prolonged ID in the presence of methane could potentially be attributed to the increased mixture thermal capacity and to the reduced oxygen partial pressure. According to Ales's study [14], low T ignition is not influenced with the addition of CH4 whereas high T is slightly retarded but to a smaller extent compared to the chemically-active CH4, indicating a chemical involvement of methane in the autoignition process. This is consistent with our experimental results (see Fig. 6), where the increase in ID when adding methane (and therefore reducing oxygen partial pressure) is considerably more pronounced than the empirical relation of Idicheria and Pickett [31] predicts for diesel spray auto-ignition (ID <[O2]-1). Except this physical effect, the low-temperature chemical reaction is also discussed in previous studies. The study from LES simulation shows that the additional CH4 influences the chemical pathways and production/consumption rates of intermediate species such as OH, CH3, HO2 and early decomposition products of diesel such as RO2 [30].

The OH*/CH2O* ratio show the same level with different λ_{CH4} . It represents that at lean CH4 conditions, the chemical reaction rate of CH2O* is proportional to OH* during main combustion. According to Paul's [26] conclusion, have shown that the product of OH and CH2O concentrations is directly proportional to the reaction rate of CH2O+OH \rightarrow H2O+HCO and, therefore, the consumption of OH and CH2O shows the same rate. However, since the longer combustion duration in richer conditions, the OH*/CH2O* ratio increases with the decreasing of λ_{CH4} during the tail combustion. Especially, at $\lambda_{CH4}=1.8$, another OH*/CH2O* ratio appears at the end of combustion, which can be related to the high-temperature residual CH4 spontaneous combustion. During the tail combustion, the high-temperature, low-oxygen ratio, which accelerates the consumption and quenching rate of CH2O*.



Fig. 6 Effect of λ_{CH4} on the integrated OH* and CH2O* intensity

To compare the influence of different λ_{CH4} on the combustion HRR, the pressure-trace based detection for different λ_{CH4} were performed to validate the thermodynamic phenomenon in dual-fuel mode, as shown in Fig.7. A two-stage ignition also can be observed in HRR. It can be

seen that there is a small peak at the beginning of ignition, which defined as the low-temperature reactivity. Unfortunately, this phenomenon can not be observed by CH2O* imaging. After the lowtemperature reactivity a distinct peak HRR occurred during the autoignition of the pilot-fuel and entrained methane. Higher peak HRR was observed for higher -CH4. At ultra-lean condition $\lambda_{CH4}=2.2$, there is no significant transition can be observed, the peak HRR gradually decreases due to the small flame propagation. With the addition of CH4 the transition from the pilot diesel to CH4 combustion can be observed. It can be seen that the HRR peak decreases and increases again. It can be seen that pressure-trace based detection of lowtemperature and high- temperature heat release rate agreed well with ignition times detected by the optical methodology. According to the HRR, the lean condition show shorter IDT and smaller peak at the premixed diesel combustion. This can be related to the less CH4 involves to the combustion at leaner condition. Meanwhile, the shorter IDT decreases the diesel mixing time, which also decreases the premixed combustion.



Fig. 7 Effect of λ_{CH4} on the pressure-trace based HRR

Effects of Pilot Fuel Ratio on Dual-Fuel Combustion

Typical simultaneous OH*, CH2O* and natural luminosity images for varying crank angle at λ_{CH4} =2.2 and 10% pilot ratio are demonstrated in Fig. 7. The cooling water temperature is 350K in Case B. Because the increase of the cooling water temperature, the ignition occurs at -0.36° CA ATDC, which is around 3° CA earlier than in Case A. At 2.8° CA ATDC, NL, OH* and CH2O* are detected simultaneously in the vicinity of the spray axes and all the flames can be observed at all of the spray plumes. The high-temperature sooty flame can be observed at the tip of the flame at 2.8° CA ATDC. Owing to the longer injection duration, the movement of flame is dominated by the spray guide other than charge air guide. Therefore, there is less effect of swirl on the flame movement. The OH* and CH2O* CL show the similar location and shape in cylinder, which has explained in aforementioned section. At 2.8° CA ATDC, the blue flame gradually turns to bright yellow, due to the increase of combustion temperature in cylinder. This change is much earlier than in Case A. Two reasons can be explained for this phenomenon. On the one hand, the high-temperature cooling water increase the global temperature and chemical reactivity of the mixture in-cylinder. On the other hand, the increase of the pilot fuel ratio increases the high reactive fuel and promotes more sooty flame. The signal of CH2O*, which corresponding the low temperature reaction shows less intensity than in Case A, because the high temperature combustion accelerates the consumption of CH2O*. The CH2O* is

Page 6 of 9

10/19/2016

extinguished at 15.4° CA ATDC shows a shorter combustion duration than in Case A, as shown in Fig.3. According to the comparison of Case A (Fig.3) and Case B (Fig.7), it can be assume that the signal of CH2O* is very sensitive to temperature variations, due to the fluorescence emission temperature dependence.

Calculations of the OH*/CH2O* ratio distribution for pilot-diesel dual fuel combustion shows that the intensity ratio distribution is proportional to the reaction rate, and therefore has the potential to be used as a criterion to distinguish between reaction zone and non-reaction zone in turbulent flames. Since the decrease of the CH2O* signal in higher temperature conditions, the OH*/CH2O* ratio is larger than in Case A. The OH*/CH2O* ratio distribution shows that where is higher OH* intensity, there is lower CH2O* and higher OH*/CH2O* ratio.



Fig. 7 Temporal sequences of NL, OH*, CH2O* and OH*/CH2O* ratio at λ_{CH4} =2.2, R_{pilot} =10%

The effect of R_{pilot} on the integrated NL intensity is shown in Fig.8. It can be observed that the integrated NL intensity is exponential growth with the increase of the R_{pilot} . If compare Case A and Case B, the total energy level and global lambda are similar, however, the integrated NL intensity at $R_{\text{pilot}}=10\%$ and $R_{\text{pilot}}=20\%$ are several order of magnitude larger than in Case A. As aforementioned explanation, the addition of

pilot-diesel greatly increase the high reactivity reactants, the spontaneous combustion of the high reactivity reactants in rich zone dramatically increases the local temperature and intensity of luminous sooty flame. Meanwhile, increase the R_{pilot} , also increase the flame area due to the less quenching happens in richer conditions. This phenomenon can be observed in the Fig.9. At $R_{pilot}=5\%$, the flame show dark blue and small flame area, however, at $R_{pilot}=20\%$, the flame turns to bright yellow and the bright flame occupies the whole cylinder. It can be concluded that the increase the pilot ratio can dramatically increase the local temperature and increase the soot emission.



Fig. 8 Effect of R_{pilot} on the integrated NL intensity



Fig. 9 Effect of R_{pilot} on the NL flame color

Fig.10 demonstrates the effect of R_{pilot} on the integrated OH*, CH2O* intensity. According to aforementioned analysis, there is no significant difference of low-temperature and high-temperature IDT can be observed from the appearance of CH2O* and OH* signal, which is accordance with the previous conclusion. The appearance of the CH2O* and OH* signal shows the similar IDT at different R_{pilot} . It means that the R_{pilot} has less effect on the low- and high-temperature ignition delay. However, the R_{pilot} shows significant effect on the intensity of CH2O* and OH* signal. The higher R_{pilot} increases the low- and high-temperature radicals, namely, CH2O* and OH* signal simultaneously. The potential explanation could be the addition of the high reactivity diesel promotes the chemical reaction rate exponentially. However, the difference of integrated CL signal is less compared with the integrated NL signal at different R_{pilot} . It means the increase of R_{pilot} has more contribution on the high-temperature sooty flame than the 'cool flame' and 'hot flame'. The OH*/CH2O* ratio also supports the hypothesis. At the beginning of the ignition, there is similar OH*/CH2O* ratio for all of the Rpilot due to the lowtemperature premixed combustion. With more diesel involving the main combustion, the OH*/CH2O* ratio gradually increases. It is interested that the R_{pilot}=10% shows the highest OH*/CH2O* ratio peak at 14.32° CA ATDC rather than R_{pilot}=20% at 20.44° CA ATDC. The higher R_{pilot} seems to retard the peak of the OH*/CH2O* ratio. It can be observed that after the peak the OH*/CH2O* ratio is sharply

decreased and the combustion is extinguished. It can be explained that the increase of R_{pilot} prolongs the high-temperature combustion duration and reduces the CH4 slip. This can be observed in Fig.9, the higher R_{pilot} shows larger flame area in NL. Moreover, the hightemperature combustion accelerates the consumption of the CH2O*, especially at the end of combustion, the fuels are depleted, therefore the concentration of CH2O* is much lower than the OH*, which results in higher OH*/CH2O* ratio peak than main combustion.



Fig. 10 Effect of R_{pilot} on the integrated OH* and CH2O* intensity

Figure 11 presents the pressure and HRR curves for a variation of R_{pilot} . The low R_{pilot} case ($R_{pilot} = 5\%$) HRR is characterized with two small peaks: the first small peak was attributed to low-T combustion, followed by the larger peak when the second-stage ignition proceeds through the pilot-fuel cloud. After this peak, only a small HRR is observed as the last fuel-rich regions lean-out. In high R_{pilot} cases ($R_{pilot}=10\%$ and $R_{pilot}=20\%$), the first stages of combustion proceed similarly as in the low R_{pilot} case after the low-T reactivity, the distinct peak HRR occurred during the auto-ignition of the pilot-fuel and entrained CH4. Higher peak HRR was observed, and the HRR stabilized with established premixed flame. The dynamics of the HRR changes during the premixed flame propagation were much slower than during



Fig. 11 Effect of R_{pilot} on the pressure-trace based HRR

Summary/Conclusions

The pilot-fuel based dual-fuel combustion was investigated in an optically accessible compression ignition engine, analogous to the combustion process under lean CH4 conditions. The aim was to understand the influence of operation parameters on pilot-based dual-fuel combustion: CH4 lambda and pilot fuel ratio were varied. A simultaneous visualization of high-speed NL, OH*, CH2O* imaging technique was built to evaluate the combustion characteristics and ignition properties in visible range, high-temperature reaction zone and low-temperature zone.

According to the analysis of experimental results, the following conclusions can be stated:

(1) Increasing methane amount, namely, decreasing the CH4 lambda prolongs the pilot-fuel ignition delay.

(2) There is no significant difference of low- and high-temperature IDTs based on the CH2O* and OH* CL appearances. It is potentially attributed to the low temperature and quenching at the beginning, which leads to low intensity of the CH2O* CL can be detected.

(3) Pilot ratio was found to have a small influence on the IDTs. Nevertheless, it has significant effect on the NL intensity. The increase of the pilot ratio showed an exponential growth in NL intensity due to the increase of high-temperature sooty flame.

(4) CH4 lambda was found to have less effect on the OH*/CH2O* ratio during the main combustion. However, during the tail combustion (end of the combustion), the addition of the CH4 amount enhances the high-temperature reaction and leads to higher OH*/CH2O* ratio.

(5) Increasing the pilot diesel amount greatly increases high-temperature reaction zone and prolongs the diffusion combustion duration, which leads to high OH*/CH2O* ratio at the end of combustion.

(6) Increasing the CH4 has a margin effects on the premixed combustion peak-HRR, and attributed to simultaneous combustion of

Page 8 of 9

methane entrained in the spray volume. However, a later peak-HRR can be observed due to the fast flame propagation at richer conditions.

(7) Pilot-fuel injection strategy influences the premixed peak-HRR dramatically. Particularly in higher pilot ratio cases, the peak-HRR was proportional to the initiated spray-volume at ignition.

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Definitions/Abbreviations

SA	sample abbreviations		
UBT	Use borderless table ≤ 3.5 inches wide.		
test vector	Don't capitalize term unless an acronym or proper noun.		