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Fuel and Combustion Stratification Study of Partially Premixed Combustion

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Abstract— **Relatively high levels of stratification is one of the main advantages of Partially Premixed Combustion (PPC) over the Homogeneous Charge Compression Ignition (HCCI) concept. Fuel stratification smoothens heat release and improves controllability of this kind of combustion. However, the lack of a clear definition of “fuel and combustion stratifications” is obvious in literature. Hence, it is difficult to compare stratification levels of different PPC strategies or other combustion concepts. The main objective of this study is to define the fuel and combustion stratifications based on the fuel tracer LIF and OH* chemiluminescence images, respectively. A light duty optical engine has been used to perform the measurements. Four experimental points are evaluated, with injection timings in both the homogeneous and the stratified regimes. Two-dimensional Fourier transforms of fuel distribution and chemiluminescence images provide the range of spatial frequencies in these images. This method gives the opportunity to separate a specific range of frequencies related to fuel and combustion stratification. The signal energy content in this range is used to define the stratification, using an appropriate normalization procedure. The results indicate that this new definition is a promising method to compare the level of stratification between different experiments.**

I. INTRODUCTION

The Partially premixed combustion (PPC) relies on a specific amount of ignition delay to achieve a partially premixed charge [1-3]. PPC is a promising combustion concept which reduces both NOx emission and soot while providing a high efficiency. The amount of premixing can be controlled in various ways, for instance by tuning the injection timing. Control of premixing is necessary to implement PPC combustion strategies in a transient mode and to improve the emission formation over the full load range [4].

Combustion stratification as a result of fuel stratification can be defined as the opposite of combustion homogeneity, for instance HCCI combustion. However, there is no quantifiable definition. For the PPC combustion concept, the fuel stratification is one of the main parameters affecting the combustion and it improves the controllability of this combustion in comparison with HCCI combustion [5]. OH* chemiluminescence imaging is known as an indicator for the heat release rate [6-9] and can be used to evaluate the combustion stratification [10]. On the other hand, fuel tracer LIF method can be used to measure the fuel distribution and investigation of fuel stratification [11].

This paper proposes an advanced stratification analysis based on the frequency domain and signal energy of combustion and fuel distribution images. Two-dimensional Fourier transform of OH* chemiluminescence images in a cylindrical coordinate system is used to determine a specific range of frequencies related to the combustion stratification. The same method is applied for the fuel tracer LIF images to find the level of fuel stratification. Finally, the relation between the fuel and the combustion stratifications is investigated as the main goal of this study.

II. EXPERIMENTAL SET-UP

A. Optical Engine and Operating Conditions

A VOLVO D5 light-duty DI engine is used in this study. The engine is adjusted for optical access according to a Bowditch design [12]. One of five engine cylinders is equipped with a cylindrical quartz liner with a height of 25 mm while other cylinders are inactive. A flat optical quartz piston is used for experiments. The advantage of a flat optical piston over a bowl rim is that the image is not affected by any distortion. Distortion correction of the piston bowl is challenging for chemiluminescence imaging, since spatial position inside the cylinder along the line-of-sight of the camera is unclear.

Engine specifications and operating conditions are based on the previous study [10]. To investigate the effect of stratification, the CA50 is kept constant at 8 CAD aTDC for four different single-injection timings (different ignition delays) by tuning the intake temperatures. These injection timings and intake temperatures are detailed in Table 1 and for all cases the amount of injected fuel is approximately 16 mg/cycle at an injection pressure of 600 bar. The intake pressure is also held constant at 1.2 bar (absolute).

TABLE I.
SINGLE INJECTION STRATEGIES AND OPERATING CONDITIONS

Case	Injection timing	CA50	Intake temperature	Oxygen percentage
A	-340 CAD	8 CAD	348 K	18.2 %
B	-100 CAD	8 CAD	348 K	18.3 %
C	-25 CAD	8 CAD	368 K	18.4 %
D	-15 CAD	8 CAD	398 K	18.4 %

B. OH* Chemiluminescence

OH* Chemiluminescence imaging provides spatial and temporal information of heat release during the combustion [9]. OH* chemiluminescence is recorded by using a high-speed intensified camera for each crank angle degree. The flat optical piston used in this study provides 60 mm optical access out of the 81 mm engine bore. The combustion is detected from below, by aiming the camera at the 45 degree mirror and from the side by aiming the camera directly at the quartz liner (Fig. 1).

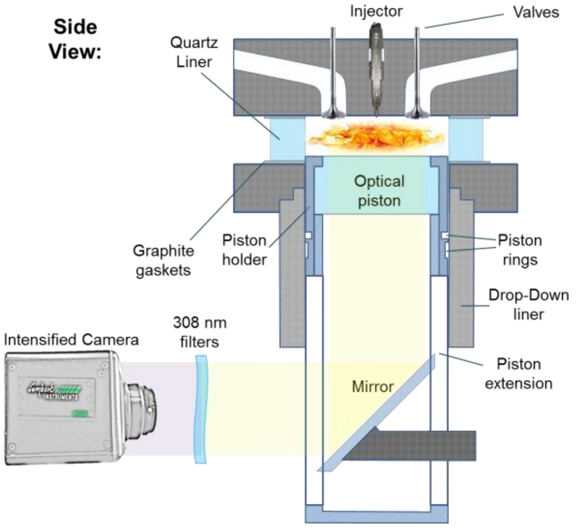

Fig. 1. Schematic of OH* chemiluminescence method.

Images are captured for 30 fired cycles using a Lambert HiCAM 5000 camera with a temporal resolution of 1 CAD and an exposure time of 25 μs. The light is recorded through a combination of a 315 *nm* bandpass filter with 15 *nm* FWHM and a 300 *nm* bandpass filter with 80 *nm* FWHM, to reject light with wavelength below 300 *nm* or above 330 *nm*.

C. Fuel Tracer Laser Induced Fluorescence

Fuel concentrations are measured using toluene fuel-tracer fluorescence in non-reactive conditions (pure nitrogen). The schematic of the setup is illustrated in Fig. 2.

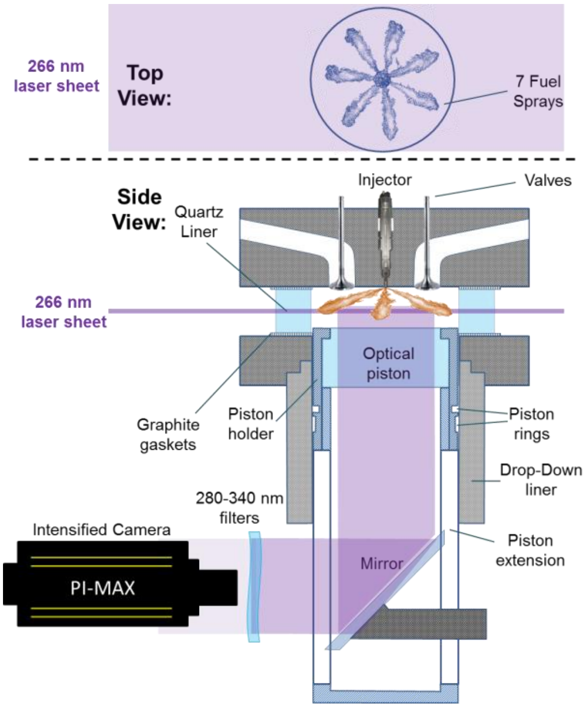

Fig. 2. Schematic of Fuel Tracer Laser Induced Fluorescence method.

The PRF70 fuel is doped with toluene at a concentration of 1% by volume. The toluene fluorescence is excited by the 266 *nm* output of a Nd:YAG laser. The laser beam is formed into a thin sheet with around 1 mm thickness and 60 mm width to cover whole optical access of the flat piston. A blue-optimized intensified CCD camera (PI-MAX) is used for fluorescence imaging through a bandpass filter (280-340 *nm*). The method, post-processing procedure and calibration are based on the research of Kokjohn, et al. [11]. All fuel distribution images are recorded at TDC position for 100 cycles.

III. STRATIFICATION ANALYSIS

The objective of the image processing is to find the level of stratification based on the combustion and fuel distribution images. However, the definition of stratification is a matter of debate [10]. In this section, a new method is proposed based on the spatial frequency content of the images.

The Fourier-based method basically focusses on the spatial frequencies in a certain FOV. First, the spatial domain is transformed to the cylindrical $M{\times}N$ coordinate system. Over this 2D spatial domain, the Fourier transform is applied, based on Eq. (1) (see Fig. 3), in which $I[m,n]$ represents the intensity of pixel $[m,n]$, and $F[u,v]$ represents the spatial frequency. Note that the center of the frequency domain represents the lowest frequency (DC value), while the edges represent the highest frequencies [13].

$$F[u,v] = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} I[m,n].\, e^{-i2\pi\left(\frac{um}{M}+\frac{vn}{N}\right)} \tag{1}$$

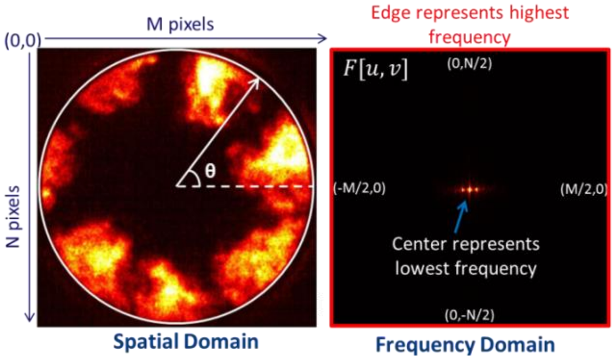

Fig. 3. Transformation from the spatial domain to the frequency domain.

Parseval's theorem can be used to relate the signal energy, E, of an $M{\times}N$ image in real and Fourier space [13]:

$$\begin{aligned} E &= \frac{1}{MN}\sum_{u=-M/2}^{M/2}\sum_{v=-N/2}^{N/2}|F[u,v]|^2 \\ &= \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}|I[m,n]|^2 \end{aligned} \tag{2}$$

Not all spatial frequencies in Fourier space are related to stratification. Low frequencies correspond to large scale variations, whereas the highest frequencies largely are due to noise. An intermediate frequency range with energies E_A, should be selected to characterize stratification, when properly normalized.

Now the aim is to find the maximum possible signal energy as a function of maximum and mean intensity of the image. Thus, the normalized stratification would be independent of the camera and intensifier settings, and allows to compare the stratification obtained from different cameras and imaging methods (or any image format as a result of numerical methods). Writing

$$I[m,n] = k_{m,n} \times I_{max} \qquad 0 \le k_{m,n} \le 1 \tag{3}$$

and using that the mean intensity of an image follows from

$$I_{mean} = \frac{1}{MN} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} I[m,n] \tag{4}$$

Eq. (2) can be rewritten as:

$$\begin{aligned} E &= \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} |I[m,n]|^2 = {I_{max}}^2 \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} |k_{m,n}|^2 \\ &\le {I_{max}}^2 \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} k_{m,n} \\ &= I_{max}(MN \times I_{mean}) = E_{max} \end{aligned} \tag{5}$$

because ${k_{m,n}}^2 \le k_{m,n}$. Eq. (5) shows that the signal energy is always smaller than a particular value, denoted as E_{max}. The normalized Fourier-based stratification, Str, can now be defined as:

$$Str = E_A / E_{max} \tag{6}$$

The relevant signal energy based on a frequency range 'A' (Fig. 5a) is calculated by

$$E_A = \frac{1}{MN} \sum_{(u,v) \in A} |F[u,v]|^2 \tag{7}$$

To specify the frequency range of 'A', the signal energy as a function of frequency for different crank angle degrees of a PPC combustion event is measured, and shown in Fig. 4b. Two peaks are observed for the signal energy, the first peak for the frequency of 1 which is governed by the radial frequency, and the second peak at the frequency of 7 which belongs to the angular frequency of 7 sprays. Due to this phenomena, E_A is evaluated for the frequency range of $1 \le f_A \le 2n$, where n represents the number of injector holes. Based on this frequency range, all critical spatial frequencies of a stratified fuel distribution and combustion are covered in the stratification definition.

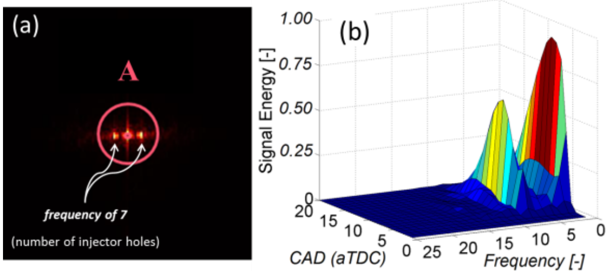

Fig. 4. Typical spatial frequency domain for a PPC combustion image at a given crank angle (a), signal energy as a function of spatial frequency for a sequence of crank angles (b).

IV. RESULTS AND DISCUSSION

OH* chemiluminescence imaging and fuel tracer LIF measurements have been performed for the same operating conditions. All the presented results in this section are the mean values over 30 and 100 measurement cycles, respectively for chemiluminescence and fuel tracer LIF measurements. High level of repeatability is observed for the experimental points, especially for the PPC points.

A. *Combustion stratification*

The results of the Fourier-based stratification analysis of OH* chemiluminescence images are illustrated in Fig. 5. It is observed that the level of stratification is indeed zero for images in which nothing is detected. It is noteworthy that the level of stratification is close to zero for the HCCI combustion of SOI -340 CAD, while for the SOI -100 CAD the combustion stratification increases by a little. For PPC combustions, the level of stratification is significantly higher. Interestingly, there is a good level of distinction between stratification levels of SOI -15 and -25 CAD (expectedly, higher stratification for later injection). Reference [10] showed that the previous stratification analysis method [7,10] couldn't well distinct between the stratification levels of PPC points, while this new Fourier-based definition gives this opportunity to compare the stratification levels of different PPC strategies.

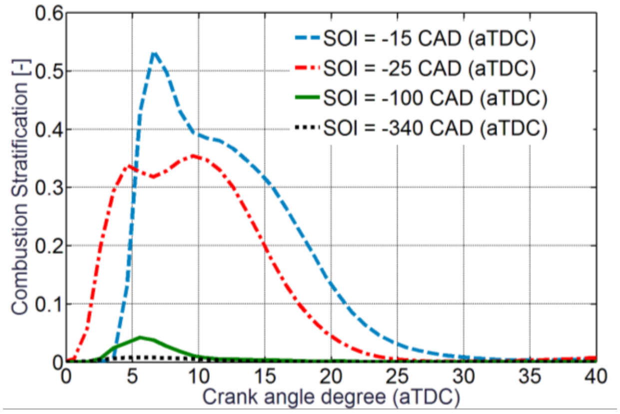

Fig. 5. Time resolved combustion stratification for different injection timings.

B. *Fuel stratification*

The fuel distributions at TDC position are demonstrated in Figure 6 for different injection timings (one random sample out of 100 images). These results are corrected for the flat field and the background but not calibrated for the temperature effect on the toluene fluorescence and this is the reason that a quantified color bar is not presented.

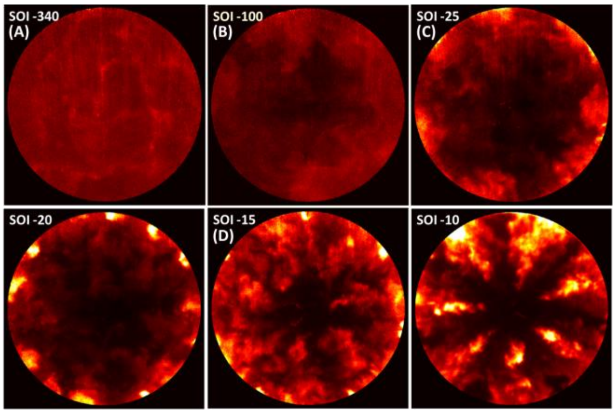

Fig. 6. Fuel distributions for different injection timings.

The behaviors of the fuel distributions in Figure 6 confirm that the homogeneity decreases by retarding the injection, especially in the PPC region. Fourier-based stratification analysis is applied on these fuel distribution images and results are presented in Figure 7 as a function of ignition delay accompanied with the results of maximum combustion stratification at similar points. Here, the ignition delay is defined as the difference between the start of injection and CA50. Small error-bars throughout the results can confirm the stability of the analysis method.

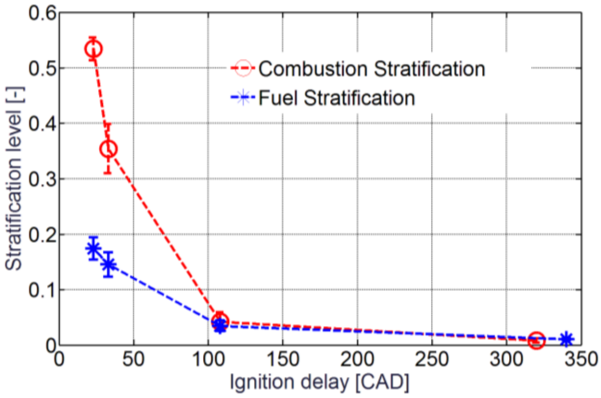

Fig. 7. Fuel and combustion stratification versus ignition delay.

Same behaviors are observed for fuel and combustion stratifications; for an increasing ignition delay, the stratification decreases. However, the combustion stratification is much higher than the fuel stratification for PPC points. This can be due to the fact that chemiluminescence images are providing the line-of-sight information across the combustion chamber, while the fuel tracer LIF method gives the fuel distribution within a thin sheet at the middle of combustion chamber. For HCCI points, the charge is the most homogeneous and hence, any sheet within that volume can be a representative of whole volume. This is why the same stratification levels are observed for both combustion and fuel stratifications at HCCI points. However, combustion inhomogeneities can be accumulated through the line-of-sight information of PPC combustions and causing the value of combustion stratification of these points to be much higher.

V. CONCLUSIONS

The objective of this study was to propose a new method to define the combustion and fuel stratification of Partially Premixed Combustion. OH* chemiluminescence measurements were performed in order to analyze the combustion in a light duty optical engine, while the fuel tracer LIF was implemented to measure the fuel distribution. The new methodology is proposed based on the spatial frequency domain of images to define the stratification. Regarding this method, the following is concluded:

- Fourier-based stratification analysis is a promising method to compare the fuel and combustion stratifications of different strategies, ranging from homogeneous HCCI combustion to stratified PPC combustion, and it clearly distinguishes those two regimes.
- Fourier-based stratification analysis provides a stratification level limited between 0 and 1, independent of imaging techniques or detection specifics. Hence, it can be used for different purposes and comparing different experiments or results.
- The Fourier-based analysis method is stable and not sensitive to the noise considering its focus on the low frequencies.
- Results confirm that fuel and combustion stratifications follow similar behaviors and they drop by increasing the ignition delay. However, comparison of them have to be done with 'caution' regarding their experimental procedures.

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