LASER-INDUCED KERNEL VISUALISATION BY OH* CHEMILUMINESCENCE METHOD

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Abstract

The aim of this work is a flame front visualisation of kernel evolution using the OH* chemiluminescence method. The ignition kernel is formed in a propane-butane-air gas mixture in position 100 mm above the outlet of the Bunsen burner. The kernel is initiated by a second harmonic from a solid-state Nd:YAG pulse laser with a wavelength of 532 nm.

Keywords: OH* chemiluminescence, Laser-initiated combustion, Propane-butane mixture

1 Introduction

Almost from the beginning, electric igniters were dominant in machines using combustion (engines, gas turbines and burners). These are relatively simple and reliable, especially in the area of spark-ignition internal combustion engines. According to [2], these lighteres have a very limited possibility of changing the position of the ignition point and significant heat loss through the electrode [10]. Tightening emission standards and requirements for higher thermal efficiency lead to the need to ignite lean mixtures. However, lean combustion is characterized by a decreasing laminar flame speed and thus a reduced engine power [3]. The reduction of output in lean combustion is compensated by increasing the pressure in the combustion chamber, for example by supercharging. However, if pressure is increased, the voltage at the electrodes needs to be increased and electrical erosion occurs more quickly [12]. It follows that increasing the voltage on the electrodes is not very possible in terms of their lifetime when using current materials. The rate of burn-through of the mixture and hence the power increasing of the combustion machine can be achieved in two possible ways when using the electrical system. The first is to create multiple ignition points and the second is to create turbulence [2]. The idea of using a different type of ignition of the mixture is based on these two variants. Currently, laser and microwave ignition variants are probably most discussed [1]. Laser ignition has a great potential especially in energy engineering, automotive, aerospace and cosmonautics engineering. This ignition method has two basic advantages over conventional methods.

The first advantage is that a good focusing of the laser beam results in a much higher energy density than conventional ignition with an electric discharge. This can lead to reduced fuel consumption and emissions, as it is possible to ignite a leaner mixture in this way. The second advantage is that the mixture can be ignited anywhere in the combustion chamber based on currently the most advantageous conditions of the internal flowing. This may, in particular, affect the smoothness of movement of the mechanical parts of the combustion engine [13].

Based on the works [12,13], an experimental measurement was performed to visualize the evolution of the ignition kernel in the flowing premixed fuel-air mixture at the outlet of the Bunsen burner. The ignition source is a focused Nd: YAG pulsed laser beam with a wavelength of 532 nm. OH* chemiluminescence recording OH* radicals were used to visualize ignition kernel evolution. For the subsequent processing of the kernel evolution, edge detection of the image from the obtained data seems to be the best method.
2 OH* Chemiluminescence

Chemiluminescence is a special case of luminescence, the meaning of which is the excess of light radiation emitted by an exciting molecule. The condition for luminescence is that the radiation must last longer than the period of light oscillations, which is in the range of $10^{-14}$ - $10^{-15}$ s. From the thermodynamic point of view, luminescence is non-equilibrium radiation and it is, therefore, necessary to supply the substance with the necessary energy, which the substance then converts to luminescence radiation. According to the method of supplying this energy (excitation), the luminescence is then divided into many different types. In the case of chemiluminescence, the molecules are excited by a chemical reaction. The released reaction heat, or a part of it, is then emitted as light \[11\]. Kathrotia [5] states that the reaction kinetics of excited molecules can be described by three types of reactions.

\[
\begin{align*}
A + B & \rightarrow C + X^* \\
X^* & \rightarrow X + h\nu \\
X^* + M & \rightarrow X + M
\end{align*}
\]

The excited molecule $X^*$ is formed together with molecule C in the forming reaction (1) of molecules A and B. The subsequent return of the excited molecule back to equilibrium state can occur in two ways. The first method is radiation decay (2) in which excess energy is emitted in the form of light. The second method is collision quenching, where the excited molecule $X^*$ collides with another molecule M and gives it its excess energy. These two reactions take place simultaneously and this is the main reason why quantitative measurement of the concentrations of excited intermediates is very difficult, as reported, for example, in [4].

To visualize the flame front is frequently Planar laser-induced fluorescence (PLIF) used. This method is able to measure the concentration of a variety of intermediate species in the reaction zone. The molecules H, O, N, C, OH, CH, etc. can be measured [14]. The OH molecule in the form of a free radical, labeled with OH*, is the most widely used and is well detectable by the chemiluminescence method. It is a hydroxyl radical which is one of the above-mentioned intermediates formed in the combustion of hydrocarbon fuels. It is formed in the reaction zone by fast reactions, eg $H_2^+O\rightarrow OH^*+H$, or $H^+O_2\rightarrow OH^*+O$. Because the OH* radical is formed in the reaction zone and then slowly disappears, it is used to detect the reaction zone (flame front) and distinguish between burnt and unburnt areas, which can be used in strongly turbulent combustion where may be difficult to distinguish the difference between burnt and unburnt areas. The OH* radical is very well identifiable and in the case of the PLIF method, excitation using a laser sheet with a wavelength of 283 nm is used. The maximum fluorescence intensity of the OH* radicals is then approximately at the wavelength of 309 nm. The optical bandpass filter is necessary to obtain the appropriate wavelength of radiation. Another necessary component is an image intensifier, as UV light is not detectable for conventional cameras. The method for recording the chemiluminescence of OH* radicals uses a similar device with the same filter, except that the exciting laser is not used, but the natural chemiluminescence is recorded. Two important facts arise from these differences. The recorded signal for the OH* chemiluminescence method is significantly weaker than the recorded signal using the OH-PLIF method. The second and more significant difference is that for OH* chemiluminescence, the integral value of the chemiluminescence in the direction of the axis of observation is recorded compared to the cross-sectional signal that is recorded using OH-PLIF. In observing the quasi-stationary nature of combustion, this difference can be crucial, because the internal flame structures cannot be detected by the OH* chemiluminescence method. When observing the flame front propagation at the ignition of the mixture, this difference may not be as significant and it is possible to obtain very similar results with the OH-PLIF method by the OH* chemiluminescence method.

3 Experimental setup

The experimental stand was built based on the need to optimize the numerical calculation of the combustion process and adapted to the conditions of the experimental stand. The burner measuring stand is adjustable in three axes and allows wide variability in the possibilities of research of various phenomena related to combustion. In addition, the stand is fitted with a suction unit, thus allowing relatively long-term operation. A part of the stand is a spatial frame from the ALUTEC system, which
enables the convenient and effective extension of other possible measuring technique according to the needs of experimental research. The basic measurement technique and related technical equipment is the OH* chemiluminescence method supplemented by another optical PIV (Particle Image Velocimetry) method. Both of these methods are optical measurement methods and use similar components that are controlled by the same software, namely DynamicStudio from Dantec Dynamics.

3.1 Hardware
The flame front position was measured using a high-speed Olympus i-speed 3 DF camera equipped with a CMOS chip with a maximum resolution of 1280x1024 px. The maximal sampling of record at full resolution is 2000fps. In this mode, the camera is able to continuously record a process lasting about 1.25s. When using binning, it is possible to achieve up to 150,000fps, but with significantly lower resolution. The camera enables external switching using TTL (transistor-transistor logic) signal and it is possible to choose from two modes. ROC (record on command) and BROC (burst record on command). The first mode allows recording for the duration of the pulse, the second mode allows recording only one frame while recognizing the edge of the pulse. For the case of visualization of the kernel evolution, the first variant (ROC) was selected using the maximum sampling rate at full resolution.

A Quantel EverGreen laser was used to ignite the mixture. It is a pulsed, dual-chamber, solid-state Nd: YAG laser used for PIV measurement. Its output is a second harmonic frequency with a wavelength of 532 nm and output power of 200 mJ in a pulse of 10 ns. The laser was equipped with an optical assembly extending the original beam into a parallel beam of diameter approx. 25mm and then focusing to point 150mm away from the last lens. The maximum focal intensity value was calculated to be $8.15 \times 10^{11}$ Wm$^{-2}$

The image intensifier unit Hamamatsu C 10880 - 03C was selected based on [6,7,9]. It is a high-speed image intensifier unit utilizing an MCP (Microchannel plate). The MCP is preceded by a photocathode, which mediates the conversion of a photon into an electron, which releases secondary electrons as it passes through the MCP. A cluster of multiple electrons falling on the anode causes image intensification. The maximum repetition rate is up to 200 kHz due to the P46 anode phosphor screen used. The image
intensifier unit allows recording in the UV spectrum, in which OH* radicals emit at a wavelength of approx. 309 nm. In addition to the fact that their emitted radiation is very weak, especially the ability to record a signal in the UV region is the main reason for using this image intensifier. The OH* radical signal emitted at a wavelength of approximately 309 nm is also associated with another important part of the entire recording apparatus designed for the visualization of OH* chemiluminescence, which is the optics and optical filter used.

The main requirement for the optical assembly in front of the image intensifier unit is the need to pass UV radiation. Commonly used lenses have a lower transmittance limit above 309 nm. The emphasis is on transmittance in the visible spectrum. For observing OH* chemiluminescence, it is, therefore, necessary to use an objective that is capable of transmitting radiation in the UV area. One possibility is to use an optic made of silica glass (SiO2) which has a transmittance of 90% even around 250 nm. A Nikon UV-Nikkor 105mm f/4.5s lens was used to measure OH* chemiluminescence. Due to the requirement to record only OH* radicals, a band-pass filter is required. The selected filter has a maximum transmittance at a wavelength of 313 nm with an FWHM bandwidth (full with at half maximum) of 25 nm. It allows to safely record photoemissions from OH* radicals.

4 Method

4.1 Recorded data properties

The quality of the input data for the flame front position analysis was performed according to the publication [6]. The main indicators of data quality are the signal to noise ratio (SNR) and the maximum gradient of the image function. To evaluate the SNR, individual frames (i.e., image functions) \( f(x,y) \) were first smoothed using median filtering given by (4), where \( g(x,y) \) is the resulting image function in the \( x, y \) coordinate system. Used median convolution mask \( h(k,l) \) had a 5x5px matrix dimension.

\[
g(x,y) = \sum_{k=-N}^{N} \sum_{l=-N}^{N} h(k,l)f(x+k,y+l) \tag{4}
\]

The SNR is determined according to (5) as the ratio of the maximum value of the original image function and the noise component obtained by the mean difference of the original image function and the image function smoothed by median filtering.

\[
SNR = \frac{\max(f(x,y))}{|\text{mean}(g(x,y) - f(x,y))|} \tag{5}
\]

Data quality indicators were evaluated for a series of recorded images and evaluated as histograms. Figure 3 shows the histogram for SNR and Figure 4 shows the histogram of maximum gradients.

![Figure 3: Histogram of SNR. Mean value is 25.4.](image1)

![Figure 4: Histogram of maximal gradients. Mean value is 5.47 px\(^{-1}\).](image2)
4.2 Edge detection

To detect the position of the flame front, so-called edge detection is used for data acquired using optical methods. In this context, the edge is meant as a sudden change in the brightness value of the recorded image. The image is taken as a two-dimensional function $f(x,y)$. In the case of recording by a digital camera, the image is in a discrete form and the edges correspond to the pixels with just the abrupt change in brightness. The easiest way to find an edge is to use the maximum gradient of the image function. Although this method is very simple, its disadvantage is its strong dependence on noise. In the case of a weak signal such as the OH* chemiluminescence signal, this method may not be the most appropriate. For this reason, two edge detection methods were used for comparison, which are in some respects quite similar. This is the method of Canny and LoG (Laplacian of Gaussian) [7]. Both methods use a filter corresponding to the Gaussian profile in two-dimensional space to remove high-frequency noise components. This is given by (6)

$$G(x,y) = e^{-\frac{x^2+y^2}{2\sigma^2}}, \quad (6)$$

where $x$ and $y$ are image coordinates and $\sigma$ is the mean square deviation. In the case of the LoG method, the laplacian of this filter $G$ and the image function $f$ written by:

$$\nabla^2 (G(x,y,\sigma) \ast f(x,y)). \quad (7)$$

In the case of Canny edge detection, Gaussian $G$ is used to calculate the operator $G_n$ according to the relation:

$$G_n = \frac{\partial G}{\partial n} = n \cdot \nabla G, \quad (8)$$

which is a derivative of $G$ in the $n$ gradient direction. Gradient direction $n$ is then given by:

$$n = \frac{\nabla (G \ast f)}{|\nabla (G \ast f)|}. \quad (9)$$

The edge position is then the local maximum of the convolution of the image function $f$ with the operator $G_n$ in the direction $n$, where

$$\frac{\partial}{\partial n} G_n \ast f = 0. \quad (10)$$

5 Results

The result of the visualization is a series of images in Figure 5, which shows the initial ignition phase of the gaseous mixture with a time interval $t = 0.0005 \text{ s}$, captured by an image intensifier and a high-speed camera with a sampling rate of 2000 fps. In the first image, at time $t = 0 \text{ s}$, very intense radiation is seen, indicating the presence of the generated plasma. But the radiation is so strong that there is a so-called "pixel overflow" and it is not possible to say that the image of the first frame corresponds to reality. In the image at 0.0005 s, the evolving kernel with probably two vertical toroidal formations and a horizontal projection in the axis of the laser beam is already visible. The reason for this shape may be a possible combination of LAI (Laser ablation ignition) and LPI (Laser plasma ignition) ignition types. Where the first toroidal formation from the left can be caused by the collision of the laser beam with the microparticle contained in the mixture and there is the ignition of LAI and the second toroidal formation is due to LPI. The horizontal projection at the end of the core may be due to the elongated shape of the focus and the transport of the flame front due to the high velocities produced. Due to the shape of the focus, the velocities in the kernel may exhibit anisotropic character. The aforementioned pair of toroidal formations are clearly evident to the time of approx. 0.0065 s. Subsequently, the first toroidal formation is absorbed by the second toroidal formation and disappears, and the kernel evolves as a single entity. Between the states at time $t = 0.0005 \text{ s}$ to $t = 0.001$, the kernel evolution is the same in all directions. From time $t = 0.001 \text{ s}$ the influence of the flow field is apparent. Thus, over time, it is possible to discern horizontal asymmetry caused by a flowing mixture flowing upwards. The upper part of the kernel is entrained by the flow of the mixture, and the velocity of the flame front is added to the flow velocity. On the other hand, the lower part of the kernel burns upstream of the mixture and the kernel evolution is minimalized by the flowing mixture. The horizontal displacement evaluation is distorted due to a weak
signal, which has a negative effect on the edge detection capabilities. This is reflected in the overlapping of the edges in Figure 6 and the fluctuation of the evaluated displacements in the graph in Figure 7.

Figure 5: Series of images shows kernel evolution by OH* chemiluminescence method in time t= 0 - 0.007s
Figure 6: Time-dependent kernel evolution by Canny edge detection of OH* chemiluminescence.

$t = 0.0005 - 0.008 \, s$

Figure 7: Flame front displacement for each time step
6 Conclusion

The edge detection revealed that the influence of the flow field on the evolution of the kernel is minimal until \( t = 0.001 \) s. Initial conditions have a much greater effect on initial phase of kernel. These may include plasma formation and the initiation temperature field. Plasma formation at the beginning shows signs of two types mechanisms of ignition. The first mechanism is the random passage of the dust microparticle through the focussed beam. Collision of a high intensity laser beam is likely to break the particle and form the plasma. This is the so-called laser ablation ignition. The second mechanism is plasma formation due to the high focal temperature. Here, gas breakdown and plasma formation. The second mechanism is called laser plasma ignition. Both of these plasma formations have an effect on the resulting kernel shape. Combinations of spherical plasma formations with an elongated temperature field at very high temperatures can cause toroidal formations. Their presence can be estimated from the kernel visualization or very precise velocity measurement. From the evaluated data it is also possible to determine the speed of the flame front. After subtracting the flow velocity of the mixture from the vertical components, the flame front propagation velocity is \( 0.75 - 0.9 \) m\( \cdot \)s\(^{-1} \). These values will be further used as input data for numerical verification of this experiment. Based on the evaluated data, it can be argued that experimental determination of flame front propagation by OH* chemiluminescence method and Canny edge detection is applicable and the results are as expected.

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References