High speed analysis of high pressure combustion in a constant volume cell

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Abstract
A combustion process with N₂, O₂ and C₂H₄ as fuel used in an optically accessible, high pressure, high temperature, constant volume cell for research on diesel fuel spray formation, is studied. The flame front speed \( V_{f,HS} \) is determined using high speed imaging. The pressure trace of the combustion process is used in a two-zone model to calculate \( S_{ul,0} \) and \( V_{f,TR} \). Measured and calculated \( V_{f} \) are compared and both methods used are discussed.

Introduction
Meeting increasingly stringent exhaust gas emission regulations and improving or maintaining fuel economy is the main drive for modern diesel engine development. The fuel-air mixing process inside the engine has major influence on both the combustion process and emission formation. The fuel injection equipment and the propagation of the fuel spray in the engine cylinder play an important role in the fuel-air mixing process. Modern fuel injection technology offers better possibilities to influence the fuel-air mixing process, but for optimum use of the technology fundamental understanding and research is required.

In order to study the injection process in greater detail, usually optically accessible engines or dedicated high pressure, high temperature cells are used. The latter have advantages with respect to optical accessibility, variety and controllability of conditions inside the cell. In Eindhoven therefore the Eindhoven High Pressure Cell (EHPC) is constructed and used [1].

Specific Objectives
The goal of the work presented here is to obtain more knowledge about the combustion process that is used to obtain engine-like conditions inside the EHPC. The cubic constant volume cell used here is not designed specifically for combustion research, contrary to the spherical constant volume vessels usually used in this field of research. To study the combustion process used in this setup, the pressure signal and high speed images of the combustion are used for calculating the flame front speed with aid of a model found in literature, for different combustible mixtures. Results for both methods are compared.

Experimental Setup
The EHPC (108 x 108 x 108 mm³) is an optically accessible, cubically shaped cell used to validate diesel fuel spray models, mainly for Heavy Duty diesel engines [1]. The walls of the cell can be heated up electrically to about 473 K, except for the top surface, in which the diesel fuel injector is mounted. This is cooled to 333 K to prevent premature fuel vaporisation. Optical access is obtained via up to three quartz windows of 50 mm thickness and 80 mm visible diameter. To obtain conditions inside the EHPC, similar to those inside an engine cylinder at the time of the injection of fuel, the so-called pre-combustion technique is used. With this proven technique [2, 3] a combustible mixture of (some or all of) H₂, C₂H₂, C₂H₄, O₂ and N₂ at relatively low absolute pressure (i.e. here approximately 0.5 MPa) is ignited with a sparkplug located at a rear upper corner of the cubic cell. The ignition of the combustible mixture creates a rapid rise of pressure and temperature above engine-like conditions. After the combustion, pressure and temperature decrease due to cooling, and once the desired conditions are reached the diesel fuel spray can be injected. In the work presented here the combustion process is analysed by recording the chemiluminescence of the combustion, using a Phantom v7.1 high speed CMOS camera.

Figure 1 displays a typical example of a chemiluminescence image sequence an ethylene C₂H₄ combustion.

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Figure 1: Image sequence (artificially coloured) of the chemiluminescence of C₂H₄-air combustion, \( \varphi = 1.004 \), taken from 3.20 ms until 9.01 ms after ignition. The cell temperature at ignition is 343 K.
The mixture used is created with \( \text{N}_2 \) and \( \text{O}_2 \) in a ratio equivalent to air. The employed image acquisition rate is 34.000 Hz, which gives a temporal resolution of just over 29 \( \mu \text{s} \). The images have a size of 192 x 256 pixels, 12 bit dynamic range and a spatial resolution of 0.5 mm/pixel. The combustion pressure is recorded with aid of a Kistler 7061 piezoelectric relative pressure transducer coupled to an AVL 5011B charge amplifier. Figure 2 shows an example of the output signal of the charge amplifier, which is sampled with TUeDACS data acquisition equipment at 1 MHz.

The high-speed camera and the ignition unit, which is coupled to the spark plug, receive a synchronous start trigger from the TUeDACS equipment. The pressure transducer is located at a bottom corner of the cell.

**Experimental Results**

Figure 3 displays an example of image analysis.

The intensity profile is taken over a line perpendicular to the flame front. To this end the image is first rotated over the appropriate angle, the intensity profile is subsequently averaged over 6 image rows to reduce the sensitivity for noise. The procedure is performed for every image of the image series used and the result is shown in figure 4.

![Figure 2](image2.png)

Figure 2: Absolute pressure as a function of time after ignition of the \( \text{C}_2\text{H}_4 \) combustion visualised in figure 1.

The averaged intensity profile is plotted as a function of image time. It can be clearly seen that in this way the moving flame front can be visualized for the region of interest. The flame front position is determined by the location where the gradient of the intensity profile exceeds a given level. The actual value is determined by the mixture composition used. Sub-pixel interpolation is used to improve accuracy. To obtain a smooth signal a third degree polynomial is fitted to the data. From this polynomial the flame front speed is derived.

![Figure 4](image4.png)

Figure 4: Averaged intensity profiles, as determined similar to figure 3, as a function of image time, of the \( \text{C}_2\text{H}_4 \) combustion shown in figure 1. The flame front moves from \( x = 222 \) to \( x = 177 \).

![Figure 3](image3.png)

Figure 3: Rotated and artificially coloured chemiluminescence image of the \( \text{C}_2\text{H}_4 \) combustion visualised in figure 1. The region of interest is located between pixels 151 and 157.

![Figure 5](image5.png)

Figure 5: Flame front position as a function of time after ignition of the \( \text{C}_2\text{H}_4 \) combustion visualised in figure 1.
Figure 5 shows the resulting position of the flame front, derived from 315 successive images, starting 2.47 ms after ignition. The flame front speed, derived from the fitted position found in figure 5, is shown in figure 6.

![Flame front speed and absolute pressure as a function of time after ignition of the C₂H₄ combustion visualised in figure 1.](image)

Figure 6: Flame front speed and absolute pressure as a function of time after ignition of the C₂H₄ combustion visualised in figure 1.

It can be clearly seen that inside the EHPC the flame front speed decreases as pressure rises.

**Model for Data Comparison**

The measured pressure trace of the combustion can be used to determine the laminar burning velocity $S_{ld}$. The method used here is the so-called thin-flame model [4, 5]. This two-zone model is based on the assumption that the flame zone is infinitely thin and a sudden transition occurs from unburnt to burnt mixture.

Normally the thin-flame model is applied to retrieve flame front speeds from large pressure vessels (typical volume 20 to 1000 litres) with hardly any pressure rise [5]. Because of this and assumptions like point ignition in the centre, it is interesting to verify whether or not the model is applicable for the current relatively small setup where pressure rises significantly and ignition occurs in a corner.

The thin-flame model is based on the following approximate expression for the pressure gradient as function of the mass consumption rate [4]

\[
\frac{dP}{dt} = -\frac{P_{\text{max}} - P_0}{m_{u,0}} \frac{dm_u}{dt},
\]

where $P_0$ is the initial pressure and $P_{\text{max}}$ the maximum pressure. $m_u$ is the unburnt mass and $m_{u,0}$ the initial unburnt mass. The mass consumption rate is described by

\[
\frac{dm_u}{dt} = -4\pi r_{\text{flame}}^2 \rho_u S_{ld}.
\]

The expression shows that the mass consumption rate is determined by $S_{ld}$, the radius of the spherical flame $r_{\text{flame}}$, and the density of the unburnt mixture $\rho_u$. The latter, assuming adiabatic compression, is determined by

\[
\frac{\rho_{u,0}}{\rho_u} = \left( \frac{P_u}{P} \right)^{\gamma/(\gamma-1)}
\]

with $\rho_{u,0}$, the density of the initial unburnt mixture, $\gamma$, the ratio of specific heats, and the measured pressure $P$. Equation (1), (2) and (3) finally result in the following expression for the time-derivative of the pressure [4]

\[
\frac{dP}{dt} = \frac{3}{2} \left( \frac{P_{\text{max}} - P_0}{P} \right)^{\gamma/2} \left( \frac{P_{\text{max}} - P}{P_{\text{max}} - P_0} \right)^{\gamma/2} \left( \frac{P}{P_0} \right)^{\gamma/2} S_{ld},
\]

The calculated pressure gradient is fitted to the actual time derivative of $P$, by tuning of $S_{ld}$. The radius of the vessel $R_{\text{vessel}} = 0.0675$, being the radius of a sphere with the inner volume of the EHPC. $S_{ld}$ is determined using the adiabatic laminar burning velocity $S_{ld,0}$ at atmospheric conditions and the fitting parameter $\alpha$ according to the next correlation [4]

\[
S_{ld} = \left( \frac{P}{P_0} \right)^{\alpha} S_{ld,0}.
\]

Both $S_{ld,0}$ and $\alpha$ are obtained. The values found for $S_{ld,0}$ show good agreement with data found in literature [6], as is shown in figure 7.

![Laminar reference burning velocity of C₂H₄ as a function of equivalence ratio $\phi$ for $S_{ld,0}$ obtained from the thin flame model (this work) and 2 references found in literature [6,7,8].](image)

Figure 7: Laminar reference burning velocity of C₂H₄ as a function of equivalence ratio $\phi$ for $S_{ld,0}$ obtained from the thin flame model (this work) and 2 references found in literature [6,7,8].

The resulting $S_{ld}$ is used for calculating the flame front speed $V_f$

\[
V_f = (1 + \tau) S_{ld},
\]
in which \( \tau \) the coefficient of expansion is determined by

\[
\tau \approx \frac{T_b - T_u}{T_u},
\]

(7)

with \( T_u \) the temperature of the unburnt mixture and \( T_b \) the temperature of the burnt mixture. \( T_u \) is calculated using the cell temperature and the adiabatic compression approximation. The temperature of the burnt mixture is calculated with the equation for the adiabatic flame temperature and conservation of specific enthalpy,

\[
\sum Y_{i,a} h(T_u) = \sum Y_{i,b} h(T_b).
\]

(8)

The \( Y_i \) are the mass-fractions of the components in the mixture and \( h_i \) denotes the specific enthalpy of component \( i \). With aid of the high-speed images the results for \( V_f \) from the model can be compared.

**Comparison of Results and Discussion**

Figure 8 shows a comparison of \( V_f \) calculated with the thin-flame model and \( V_f \) as it is derived from the image analysis of the chemiluminescence.

![Figure 8: Comparison of \( V_f \) as determined from the thin-flame model and the recorded flame front position as a function of time after ignition of the \( \text{C}_3\text{H}_4 \) combustion visualised in figure 1.](image)

Another comparison between \( V_{\text{THS}} \) and \( V_{\text{TF}} \) can be made by changing the equivalence ratio of the mixture by adding more or less \( \text{C}_3\text{H}_4 \) to the \( \text{O}_2 - \text{N}_2 \) (air equivalent) mixture. As found in earlier the adiabatic burning velocity found for these cases agree well with the reference data. The flame-speeds measured, however, show an interesting difference in behaviour between the three cases. Both experiments with \( \varphi > 1 \) are convex whereas \( \varphi = 0.894 \) is concave. It might be tempting to attribute this to a Lewis number effect of the most deficient species, i.e. \( \text{C}_3\text{H}_4 \) for the lean case and \( \text{O}_2 \) for both other two cases. However, in contrast to methane/air combustion, here both fuel and oxidiser have Lewis numbers larger than one, viz. \( \text{Le}_{\text{C}_3\text{H}_4}=1.3 \) and \( \text{Le}_{\text{O}_2}=1.1 \).

**Conclusions**

Ethylene premixed with \( \text{O}_2 - \text{N}_2 \) (air equivalent) combustion is studied in an optically accessible high pressure, high temperature constant volume cell. With the aid of high-speed images of the chemiluminescence from the combustion it is possible utilizing relative straightforward methods to determine the position of the flame front as a function of time with an estimated error of \( \pm 0.5 \text{ mm} \). Due to noise, fitting the data with an \( n^\text{th} \) degree polynomial is used to determine \( V_{\text{THS}} \). This results in a local \( V_{\text{THS}} \) accuracy that is determined in part by the polynomial used. The movement of the centre of better comparison. Since stretch is also not incorporated in the thin-flame model it is surprising that the found values for \( S_{a,b} \) are so close to be the reference data.

Figure 9 shows that the near stoichiometric combustion has a slightly higher \( V_{\text{THS}} \) and a clearly higher \( V_{\text{TF}} \) compared to the combustion shown in figure 8. Using the exact same mixture composition and mass, the lower cell temperature (295 K) results in a lower initial pressure, which in turn leads to a larger \( V_f \) of the measurements shown in figure 9.

![Figure 9: Comparison of \( V_{\text{THS}} \) and \( V_{\text{TF}} \) as a function of time after ignition and mixture equivalence ratio \( \varphi \) for three \( \text{C}_3\text{H}_4 \)-air explosions. The cell temperature at ignition is 295 K.](image)
the spherical flame and the effect of that movement on the \( V_{f,HS} \) remains to be investigated.

The pressure traces of the experiments are used in a two-zone model, the so-called thin-flame model, to calculate the \( V_{f,TF} \), \( S_{ad} \), and \( S_{ad,0} \). The latter shows good resemblance to values found in literature [6,7,8].

The calculated \( V_{f,TF} \) is clearly lower than \( V_{f,HS} \) in the first part of the combustion. As flame stretch is not included in the thin-flame model, the predicted \( V_{f,TF} \) and \( S_{ad} \) can be too low for ethylene in the first part of the combustion.

More experiments will be performed to determine the behaviour and reproducibility of both \( V_{f,HS} \) and \( V_{f,TF} \) as a function of equivalence ratio. Also other fuels like hydrogen, methane and acetylene will be used to investigate flame stretch effects.

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References