Influence of Hydrodynamic Conditions on the Early Stage of the Development of Hydrocarbon-Air Premixed Flames in a Constant Volume Combustion Chamber

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ABSTRACT

The objective of our work is to provide well defined experimental data in order to contribute to a better understanding of the influence of the velocity fluctuation on the burning rate of a wrinkled laminar premixed flame. The results presented in this paper concern especially the very early stage of the combustion, where the burnt gas mass fraction is less than 2.5%. Investigations have been performed in a variable-hydrodynamic-condition constant volume combustion chamber (60 mm x 60 mm x 100 mm) for laminar flame velocities S, ranging between 0.19 ms\(^{-1}\) and 0.56 ms\(^{-1}\) with a constant value of the effective mixing variable \(u^* = 0.5\) ms\(^{-1}\). The ignition has been performed at the center of the chamber in order to minimize wall effects. The results show that, for an increase of \(u^*/S_1\) from 0.9 to 2.6, the relative flame velocity \(S_1/S_1\) increases only from 1.3 to 1.6 much less than that predicted by theories for fully developed turbulent flames. This tendency is in good agreement with that observed in engines.

EXPERIMENTAL CONDITIONS

For this study, a constant volume combustion chamber, called ARC-chamber, which can generate various types of flow field, has been used in its homogeneous turbulence configuration. The detail of this chamber (60 mm x 60 mm in section and 100 mm in length) was presented in COMODIA-90 (4). A quasi-homogeneous turbulent field without global motion can be created by means of premixture jets issued from one of the walls. Experiments have been performed with a fixed value of the variance of the velocity fluctuation: \(u^2 = 0.25\) m\(^2\)s\(^{-2}\). The integral length scale of the turbulence is about 5 mm. As the observation has been performed on a period less than 5 ms, which is very short before the turbulence intensity decay, the value of \(u^*\) has been considered as constant during the analysis.

Various values of the laminar flame velocity \(S_1\), raging between 0.19 ms\(^{-1}\) and 0.56 ms\(^{-1}\) have been obtained in two manners: 1) for lower flame velocities, by changing the equivalence ratio of propane-air mixture from 0.7 to 0.9 and 2) for the highest value, by using an ethylene - air mixture of an equivalence ratio of 0.9.

The range of the relative magnitude of the velocity fluctuation \(u^*\) with respect to the laminar flame velocity \(S_1\), hereafter called "effective mixing variable" \(\mu = u^*/S_1\), is therefore comprised approximately between 0.56 and 2.95.

The ignition has been realized by means of an electrical spark between a pair of fine electrodes, placed at the center of the chamber in order to minimize thermal effects of the wall on the flame. The spark discharge time has been fixed to 100 \(\mu\)s and its effective energy has been less than 5 mJ.

The pressure in the chamber has been measured by means of a piezo-electric pressure transducer, associated with a 12 bits numerical oscilloscope.

INTRODUCTION

The use of lean mixtures in spark ignited piston engines is one of the way to reduce the fuel consumption and the pollutant rejection in the environment. Two major problems arise to realize them: 1) the difficulty of the ignition, 2) the slowness of the flame propagation. The first problem can be overcome by the use of a reinforced electrical spark or a plasma jet. For the second problem, turbulence in the flow can improve the heat release rate of a given mixture (1). Nevertheless, the available results obtained in different combustion devices are not in good agreement. The results, obtained both by real engines and by theoretical analysis, suggest a strong implication of the characteristic scales of the turbulence on the flame development (2, 3).

The objective of the experimental work presented here is to reproduce the phenomena observed in engines by means of a rapid compression machine, in which the initial conditions, (mixture, velocity fluctuations, chamber geometry, for example) can be better determined than in real engines and to provide well documented experimental data in order to contribute to a better understanding of the influence of the velocity fluctuation on the burning rate of the adiabatic wrinkled laminar premixed flame, which constitutes the early stage of the combustion in real engines (1).
The temperature and the pressure at the ignition instant has been respectively 298 K and 2 bar for laminar flames and 315 K and 2.8 bar for turbulent ones.

The image recording by schlieren method has been realized by means of our standard high repetitive rate laser beam generator, associated with a 60 mm wide film mounted on a drum camera. On this device the repetition rate and the exposure time can be selected individually, thanks to an acousto-optical beam deviator. For this study, the exposure time has been less than 3 μs in order to freeze the flame images.

RESULTS AND DISCUSSIONS

Global distortion of the flame

Fig. 1 gives several images of laminar and turbulent flames obtained with different mixtures. It can immediately be noticed that the geometry of the laminar flames, obtained in initially quiescent mixtures, are similar, while that of the turbulent flames are different to each other. The distortion of the flame contour is much pronounced for mixtures with lower flame velocities. The flame distortion has been characterized by means of a distortion factor:

$$\lambda = L_{\max} / L_{\min}$$  \hspace{1cm} (1)

in function of the burnt gas mass fraction $m_n/m_t$. $L_{\max}$ is the maximum length of a straight line which joins two points on a flame contour by passing the ignition point and $L_{\min}$ the minimum one. The burnt gas mass fraction is here given by the relative pressure gain:

$$\Pi = m_n/m_t = (p-p_p)/ (p_{\infty} - p_p)$$ \hspace{1cm} (2)

where $p$ is the current pressure, $p_p$ the initial pressure and $p_{\infty}$ the theoretical final pressure of an adiabatic constant volume combustion. This approximation is justified by the fact that our analysis is limited only on the early stage of the combustion, where the thermal effect of the wall on the flame is negligible.

Fig. 2 shows the results of the analysis performed on the turbulent flames of the four mixtures for $0<\Pi<0.025$. As is mentioned above, even in a very early stage, behavior of the ethylene flame is similar to the laminar one. The $\lambda$ value of the flames of two slower ($\phi=0.7$ and 0.8) propane-air mixtures decreases from about 1.7 for $\Pi=0.005$ to about 0.12 for $\Pi=0.015$. The behavior of the propane-air mixture with $\phi=0.9$ is intermediate of these two tendencies: for $0<\Pi<0.005$, its $\lambda$ value increases as the mixtures of the first group, then it continues to increase up to about 1.4 for $0.005<\Pi<0.013$, before merging the $\lambda$-evolution of the mixtures of the second group and decreases again.

Relative flame surface area

The influence of the turbulence on the flame development has been examined in terms of the relative flame surface area $\Sigma = A_t/A_n$ between turbulent and laminar flames, in function of the value of the effective mixing variable $u^/'S_t$. Two different methods have been used: 1) fractal-like analysis of the flame contour images obtained by schlieren method, and 2) analysis of the pressure signals. As the schlieren method gives an integral image of the phenomena which are present on its optical path, the flame contour thus obtained maximize the zone affected by combustion.

First, for each mixture, the length of the turbulent flame contour $L(e)$ has been measured in function of the scale $e$ for two values of $\Pi$ comprised between 0.005 and 0.025. Enlarged images have been used in order to decrease the lower limit of $e$ to 0.5 mm. Fig. 3 gives an example obtained by the Propane-air mixture ($\phi=0.8$) in ln-ln coordinates. In the fractal theory, the contour length $L(e)$ varies with the scale $e$ in the following manner: $L(e)$ is constant up to inner cut-off scale $e_c$, then it decreases with a constant slope in ln-ln coordinates, which gives the fractal dimension $D_f$ of a curve. For $e$ larger than the outer cut-off scale $e_o$, $L(e)$ becomes constant again. Neither the higher plateau of the maximum value of $L(e)$ corresponding to $e<e_c$, nor the lower one for $e>e_o$ has been clearly determined during our investigations. The first is due to the limit of the resolution of schlieren images, and the second is due to the sudden decrease of $L(e)$ which occurs when $e$ approaches the flame size. Nevertheless, the measured variation of $L(e)$ in function of $e$ for $e<e_c$ is qualitatively in agreement with that given by a fractal regime. Besides, this feature can be related to the transition of the flame from Euclidean to fractal forms (5).

To evaluate the increase of the contour length, it is necessary to determine a reference length $L_R$. In this study, $L_R$ has been defined as the perimeter of a circle given by the projection on a plane surface of an equivalent sphere, having a same burnt gas volume as that of the considered turbulent flame. In practice, the burnt gas mass has been deduced from the $\Pi$-value:

$$m_b = \Pi \cdot m_t$$ \hspace{1cm} (3)

then, the volume $V_t$ of the burnt gas has been determined by supposing an uniform distribution of the density $\rho_t$ in it. Assuming the prefect gas law, $\rho_t$ has been deduced from the measured current pressure $p$, the temperature $T_p$ and molecular weight $M_t$ of the burnt gas theoretically calculated for a adiabatic constant pressure flame.

Next the radius of the equivalent sphere $R_{eq}$ has been calculated, given a relation:

$$R_{eq} = \left( \frac{3V_t}{4\pi} \right)^{1/3}$$ \hspace{1cm} (4)

The length ratio $\Lambda$ is given by

$$\Lambda = \frac{L_b}{L_R} = \frac{L_b}{2\pi R_{eq}}$$ \hspace{1cm} (5)

where $L_b$ is the maximum measured contour length. The relative surface area

$$\Sigma = \frac{A_t}{A_l}$$ \hspace{1cm} (6)
between the surface area $A_s$ of the turbulent flame and the laminar surface area $A_l$, which is given by the surface area of an equivalent sphere, the volume of which is same as that of the turbulent flame. $\Sigma$ corresponds also to the relative flame velocity increase $S_l/S_t$ between turbulent and laminar flame, when the equivalent sphere surface is taken as the reference surface for the both. If $\Lambda$ is not very different to 1 and if the wrinkles are uniformly distributed on the flame surface, $\Sigma$ can be deduced from $\Lambda$ by the following relation:

$$\Sigma = 1 + 2(\Lambda - 1) \quad (7)$$

The relative surface area $\Sigma$ has also been investigated by means of the pressure in the combustion chamber. Based on the relation for a laminar flame:

$$\frac{dm_p}{dt} = \rho_u A_s S_t \quad (8)$$

and Eq. 2, the effective flame surface area $A$ can be written:

$$A = \frac{m_t}{P_t} \left( \frac{1}{\pi - 1} \right) \rho u S_t \frac{\mathrm{d}P}{\mathrm{d}t} \quad (9)$$

where $\pi = \frac{P_{\text{rad}}}{P_t}$ \quad (10)

As our flames developing in a turbulent flow field are of the wrinkled laminar flame regime, for a given mixture and for a given burnt gas mass fraction, the relative flame surface area $\Sigma$ can be given by the ratio of the pressure increase rates for the turbulent flame (index T) and for the laminar one (L):

$$\Sigma = C \left( \frac{\frac{\mathrm{d}P}{\mathrm{d}t}}{\frac{\mathrm{d}P}{\mathrm{d}t}} \right)_T \left( \frac{\frac{\mathrm{d}P}{\mathrm{d}t}}{\frac{\mathrm{d}P}{\mathrm{d}t}} \right)_L \quad (11)$$

where the corrective factor $C$:

$$C = 1.07 \frac{P_{\text{rad}} S_l T}{P_t S_l T} \quad (12)$$

allows to take into account the stagger of the initial conditions for the laminar and turbulent cases. The constant 1.07 corresponds to the heating effect of the gas in the chamber, when mixture jets are injected in it to generate the turbulent field. The value of $C$ has been taken between 1.0 and 1.02.

$S_t$, for a given condition of temperature $T$ and pressure $p$, has been determined by:

$$S_t(T, p) = S_0 \left( \frac{T}{T^*} \right) ^\alpha \left( \frac{p}{p^*} \right) ^\beta \quad (13)$$

where $S_0$ is the laminar flame velocity at $p^*=1$ atm. and $T^*=298$ K. For propane-air mixtures, values of $S_0, \alpha$ and $\beta$ in function of the equivalence ratios $\phi$ have been calculated by formulae proposed by Metghalchi et al. (4):

$$S_0 = 0.342 - 1.387(\phi - 0.08)^2 \quad (14)$$

$$\alpha = 2.18 - 0.8(\phi - 1) \quad (15)$$

$$\beta = 0.16 - 0.22(\phi - 1) \quad (16)$$

For the ethylene-air mixture, $S_0=0.706$ m/s, $\alpha=1.33$ and $\beta=-0.085$, determined in our laboratory by a spherical chamber method, have been used. In the above estimation, the effects of the stretch and the curvature of the flame front on $S_t$ have been neglected, because the evaluation (7, 8) has given a reduction of $S_t$ less than 2%.

Given the fractal dimension $D_f$ from the slope of the $\ln(L)-\ln(e)$ curve, the fractal dimension $D_{f,l}$ of a surface can be deduced as:

$$D_f = D_{f,l} + 1 \quad (17)$$

For a fractal forms, the relative surface area $\Sigma_r$ can be given by (7):

$$\Sigma_r = \frac{A_f}{A_R} = \left( \frac{e_l}{e_o} \right)^{2-D_f} \quad (18)$$

The figure 4 summarize the results of the analysis. Values of the effective mixing variable $u=\mu/S$ range approximately between 0.65 and 2.8. For three propane-air mixtures, the relative surface areas $\Sigma_r$ obtained by image analysis vary between 1.50 and 1.66 except a value of 2.38 for $\phi=0.7$, $T=0.011$. For the ethylene-air mixture its value is about 1.34. The pressure analysis gives 1.3<$\Sigma_r<$1.7 for the propane-air mixtures and 1.2<$\Sigma_r<$1.4 for the ethylene-air mixture. Taking account the precision of our measurements, $S_t$ and $S_0$ can be considered as consistent. For comparison, values for fully developed wrinkled flames (10), have been estimated by means of a relationship:

$$\Sigma_{ET} = 1 + \left( \frac{u}{S_t} \right)^2 \quad (19)$$

It is noticeable that, values of $\Sigma$ obtained by this work for the very early stage of the development of wrinkled laminar flames, are quite lower than that predicted for the one developing in a fully established turbulent field.

The fractal dimension $D_{f,l}$ is comprised between 2.06 for faster mixtures and 2.11 for slower ones. Generally a value of 2.35 describes well a flame developing in an established turbulent field. The influence of the fractal dimension on $\Sigma$ has been examined by means of Eq. 18. For $D_{f,l}$, an effective fractal dimension $D_{f,e}$ proposed by Santavicca et al. (7) are used. $D_{f,e}$ defined as:

$$D_{f,e} = \frac{u}{S_t} \left( \frac{D_L + \frac{u}{S_t}}{D_T + \frac{u}{S_t}} \right) \quad (20)$$

allows to take into account the competitive feature between flame surface wrinkling process of the turbulent convection and flame surface smoothing by laminar burning. A value of 2.0, corresponding to the fractal dimension of the laminar flame, is attributed to $D_{f,e}$ while a value of 2.35, corresponding to that of the fully established turbulent flame, to $D_{f,e}$. Eq. 20 gives $D_{f,e}=2.26$ for $u=2.8$, the upper limit value of our study and $D_{f,e}=2.14$ for $u=0.65$, the lower limit value. The good agreement between these value and that determined by our
experiments indicate that the effects of the turbulence are not yet efficient on the flames studied in this work, which are in their early stage of development.

To evaluate $\Sigma$ by Eq. 18, it is necessary to know the values of external ($e_2$) and internal ($e_1$) cut-off scales. While the attribution of the integral scale of the turbulence of 5 mm, previously determined (4) to $e_1$, is reasonable, it is difficult to choose the value of $e_2$, because it was not possible to determine their values from our image analysis. Therefore, $\Sigma_{tr}$, has been calculated for two values of $e_1$; $e_1=0.4$ and 0.04 mm and plotted on Fig. 4. It is observed that $\Sigma_{tr}$ and $\Sigma_{ex}$, determined from our results, are found between the above 2 curves. These features show that the relative flame surface area $\Sigma$ of the flames at the early stage of their development examined in this study is unambiguously smaller than that predicted for the flame in a established turbulent field.

CONCLUSION

The work presented in this paper has shown the possibilities offered by rapid compression machines to study interactions between hydrodynamics and premixed flames which occur in spark ignited piston engines during the early stage of the development of confined hydrocarbon-air premixed flames. In spite of the reduced number of the samples, diagnostics performed by means of a fractal-like image analysis and pressure analysis in order to determine the relative flame area $\Sigma=A_{\Sigma}/A_{L}$, in function of the effective mixing variable $\mu=\Sigma/\Sigma_{m}$, have clearly pointed out that, for a burnt gas mass fraction less than 1.1%, the turbulence is not as efficient as that observed in fully established turbulent field. For $0.65<\mu<2.8$, the gain of the flame velocity thanks to the turbulence is lower than 2. It seems to be difficult to improve the early stage of the combustion of a premixture, whose laminar flame velocity is low, by means of a large value of effective mixing variable $\mu=\Sigma/\Sigma_{m}$.

NOMENCLATURES

$\lambda$: distortion factor (Eq. 1)
$\Lambda$: contour ratio length (Eq. 5)
$\mu=\Sigma/\Sigma_{m}$: effective mixing variable
$\Pi$: burnt gas mass fraction (Eq. 2)
$\rho_{b}$: burnt gas density
$\rho_{u}$: unburnt gas density
$\Sigma$: relative flame surface area (Eq. 6)
$\Sigma_{tr}$: $\Sigma$ calculated for a fully developed wrinkled flame (Eq. 19)
$\Sigma_{f}$: $\Sigma$ calculated by means of a fractal dimension (Eq. 18)
$\Sigma_{g}$: $\Sigma$ calculated by means of pressure signals (Eq. 11)
$A_{f}$: effective flame surface area
$A_{L}$: laminar flame surface area
$A_{T}$: turbulent flame surface area
$D_{f}^{(1)}$: fractal dimension of a curve
$D_{f}^{(2)}$: fractal dimension of a surface

$m_{b}$: mass of burnt gas
$m$: total mass of the mixture in the combustion chamber
$p$: current pressure
$p_{i}$: initial pressure
$p_{f}$: theoretical final pressure of an adiabatic constant volume combustion
$R_{ex}$: radius of the equivalent sphere (Eq. 4)
$S$: laminar flame velocity
$S_{f}$: turbulent flame velocity
$S_{r}$: relative flame velocity increase
$T_{b}$: theoretical burnt gas temperature for an adiabatic constant pressure combustion
$u_{t}$: variance of the velocity fluctuation
$V_{f}$: volume of the burnt gas

REFERENCES

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Fig. 1: Some images of laminar and turbulent flames (real size of the images: 100 mm x 60 mm)
Fig. 2: Comparison of the distortion factor $\lambda$ in function of the burnt gas mass fraction $\Pi$.

Fig. 3: An example of the variation of the contour length $L(e)$ in function of the scale $e$.

Fig. 4: Influence of the effective mixing variable $u'/S_1$ on the relative flame velocity increase $A_f/A_i = S_f/S_1$. 
