EFFECTS OF GEOMETRICAL AND AERODYNAMIC INDUCED FLAME STRETCH ON THE PROPAGATION OF SPARK FIRED PREMIXED FLAMES IN EARLY STAGES

G. G. DE SOETE
Institut Français du Pétrole
B.P.N° 311
92506 Rueil-Malmaison
France

During early stages of propagation in the spark ignition engine, flames may be subjected to relatively strong stretch effects tending to rapidly increase their surface but also decreasing the burning velocity. Both geometrical and aerodynamical stretch may arise, the former due to fast growth of flame radius, the latter related to the existence of tangential flow velocity gradients.

An experimental study is presented on the effect of both types of stretch on flame speed and surface growth of free expanding, spark ignited flames of ethylene/air mixtures, based on fast laser shadowgraphy records.

Pure geometrical stretch effects are studied in gases at rest. Due to the existence of a spark imposed initial flame speed value, the adjustment of the latter to the value imposed by the relative stretch \( \frac{dS}{S} \frac{dt}{dt} = 2 \frac{dR}{R} \frac{dt}{dt} \) is delayed and causes almost periodic, progressively attenuated fluctuations of the flame speed in early propagation stages, roughly corresponding to the relationship \( V_p = V_p \left[ 1 - \alpha \exp(-\nu t) \right] \sin^2(2\pi \nu t) \), where \( V_p \) and \( V_p \) are the instantaneous, respectively the steady state values of the flame speed defined as the flame radius growth per unit time. \( \alpha \) and \( \nu \) are characteristics of the flammable mixture. As a general consequence the volumetric combustion rate \( \frac{dV_b}{dt} \), with \( V_b \) being the volume of the combustion products) is decreased.

Aerodynamical stretch effects are studied on flames ignited in the stagnation point of concentric opposed jet flow. In very early stages however, when flame radius is still small, aerodynamical stretch is always accompanied with the former described geometrical stretch prevailing often in that period. At later stages the flame speed approaches to an asymptotic value controlled by pure aerodynamical stretch and fairly well forecasted by the theoretical expression recently proposed by P. Clavin,\(^1\) at least for Lewis numbers close to unity. The effect of this combined geometrical/aerodynamical flame stretch on volumetric combustion rate in early stages may result as well in an increase as in a decrease of this parameter. Local flame extinction by aerodynamical stretch has been observed too.

Introduction

The propagation behaviour of the flame in the internal combustion engine, especially in early stages following spark ignition, may be seriously affected by effects of flame stretch. The initially fast increase of the surface of the spherical flame determines a "geometrical" stretch effect decreasing rapidly with the flame radius \( R \). Another type of flame stretch arises when the flame front is subjected to tangential gradients of the tangential flow component; this secondary, so-called "aerodynamical" stretch may be relatively important whenever the instantaneous flow vector is directed towards a wall, creating thus a stagnation flow characterized by important velocity gradients tangential to the wall.

With respect to the propagation of free expanding flames, stretch is a two-cutting sword: it has a negative effect on the burning velocity, eventually resulting in flame extinction; however, if the flame "survives," the increase of its total surface constitutes a positive effect. Most attention has been payed to the negative effect of flame stretch on burning velocity in the last years.\(^1,2,3\) Some experimental confirmation of the theoretical predictions has already been obtained in the case of stabilized flames.\(^4\) The present paper presents experimental results obtained on free expanding, spark fired flames in early stages of propagation, accounting for both geometrical and aerodynamical stretch effects.

1. Experimental Method

Flame speed $V_f$ is monitored as the variation of flame radius as a function of time ($dR/dt$) by laser shadowgraphy. A general view is presented on Fig. 1. The expanded laser beam (A) passes through a parallelipipedic reactor (C) equipped with windows and a central spark gap constituted by thin (0.3 mm diameter), sharply pointed electrodes (E). The shadowgraphs are photographed from the screen (S) by an electronic image-convertor camera (CIM) at the speed of $10^4$ to $10^5$ frames per second, triggered by the spark power supply (IC) over a delayed pulse generator (DPG).

Lean ethylene/air mixtures are used throughout. The study of geometrical stretch effects is effectuated in lean flammable mixtures at rest. The study of aerodynamical stretch effects is made in the stagnation flow created by two opposed, concentric, isokinetical jets having their symmetry axes in the $x$-direction, as shown on Fig. 2. The spark is then fired in the stagnation point ($x = 0, r = 0$). In the case of the opposed jet study, the flow field characteristics are mapped using hot wire anemometry. The mean flow velocity component in the radial direction ($U_r$) is obtained with the hot wire probe placed in the position A (see Fig. 2). When placed in position B, the hot wire senses the total flow velocity ($U$). From the measured values of $U$ and $U_r$, the velocity component in the $x$ direction ($U_x$) is obtained as:

$$U_x = (U^2 - U_r^2)^{0.5}$$  \(1\)

The anemometer readings corresponding to small values of $U_r$ have been corrected in an appropriate manner to take into account the contributions of turbulent fluctuations. The tubes from which the jets are issuing have an inside diameter of 1.2 cm and are placed at a distance of 1.6 cm each from the other. The anemometric study has shown that in the central part of the flow field ($0 < r < 5 \text{ mm}$) the ideal theoretical flow conditions are obtained; especially it is found that, within that central part, the gradients $dU_r/dr$ and $dU_x/dx$ are constant and proportional to the flow rate. Outside this central part the experimentally measured values of these gradients are utilized whenever needed for calculations.

Capacity-inductance sparks are used for ignition. A constant effective spark energy of 3.5 mJ has been utilized, the corresponding spark duration being 180 microseconds.

2. Effects of Geometrical Stretch on Spark Ignited Flames in Early Stages

Stretch may be defined as the relative flame surface variation as a function of time: $dS/S dt$. In the particular case where the Lewis Number is equal (or close to) unity, the decrease of burning velocity ($V_n$) due to stretch may be expressed by the following relation according to reference 3:

$$V_n = V_{no} - e T_f \ln (T_f/T_i)/(dS/S dt)/(T_f - T_i)$$  \(2\)

where $V_{no}$ is the burning velocity of the not perturbed flame, $e$ the flame front thickness, $T_i$ the temperature of the fresh reactants and $T_f$ that of the combustion products. The values of the flame thickness have been calculated as a function of $V_{no}$, $T_i$ and $T_f$ according to Van Tiggelen:

$$e = 8\lambda c [T_i + \sigma(T_f - T_i)]/3\pi^2 T_i V_{no}$$  \(3\)
where \( c \) is the mean molecular velocity and \( \lambda \) the mean free path length; \( \sigma \) is a function of \( T_i \), \( T_f \) and of the overall activation temperature.\(^7\)

For a free expanding spherical flame of radius \( R \), the geometrical stretch is given by:

\[
\frac{dS}{S} \frac{dt}{dt} = 2 \frac{dR}{R} \frac{dt}{dt} = 2 \frac{V_p}{R} \tag{4}
\]

Solution of the system constituted by Eqs (2) and (4) allows an a priori calculation to be made of \( R \), \( V_p \) and \( dS/S \) as a function of time corresponding to the assumption of instantaneous equilibrium of each of these three parameters. An example is given on Fig. 3, where comparison is also made with the hypothetic case in which stretch would have no effect on flame speed, i.e. for \( V_p = V_{po} \) at any time.

The experimental values of \( R(t) \), \( V_p(t) \) and \( (dS/S \) \( dt)(t) \), obtained from highly time resolved, fast framing shadowgraphic records show a quite different picture as may be seen from Figs. 4, 5, and 6.

As shown on Fig. 4, the flame radius in the \( x \) direction \( (R_x) \) is larger than that in the radial direction \( (R_r) \) (for the directions of \( r \) and \( x \) see Fig. 1). This is due to non isotropic expansion of the spark kernel.\(^8\)\(^9\) The general shape of the early flame is thus that of an oblate spheroid having its small axis in the \( r \) direction (direction of the electrodes). In what follows we rather consider an equivalent radius \( R_e \) of a sphere having the same surface as the sheroidal flame. Further it can be seen that the flame radius (either \( R_x \) or \( R_r \) or \( R_e \)) is subjected to almost periodic oscillations. Careful analysis of the origin of these oscillations shows (a) that they are not due to interference of the flame front with acoustical waves

\[
\begin{align*}
\text{FIG. 3.} \quad & \text{Calculated values of flame radius (} R \text{)}, \text{ flame speed (} V_p \text{)} \text{ and relative surface variation (} dS/S \text{ dt) of a free expanding, spherical flame in stagnant gases. Ethylene/air; equivalence ratio (E.R.) = 0.65; heavy curves calculated according to Eqs (2), (3) and (4); thin curves calculated for } V_p = V_{po} = \text{constant.} \\
\text{FIG. 4.} \quad & \text{Flame radius variation of a flame ignited in stagnant gas as a function of time. Spark gap = 0.5 mm; spark energy = 3.5 mJ; } R_x = \text{radius in the } x \text{ direction (see Fig. 1); } R_r = \text{radius in } r \text{ direction; } R_e = \text{equivalent radius of a sphere having the same surface as the sheroidal flame.}
\end{align*}
\]
Fig. 6. Variation of equivalent flame radius ($R_e$), flame speed ($dR_e/dt$) and relative flame surface evolution ($dS/S\, dt$) of a free flame propagating in stagnant gas. Ethylene/air; E.R. = 0.65; spark gap = 0.5 mm; spark energy = 3.5 mJ; $dS/S\, dt$ calculated from the experimental values of $R_e$ according to Eq. (4).

Fig. 7. Variation of $\alpha$ and $\nu$ (Eq. (5)) with equivalence ratio. Ethylene/air; spark characteristics: gap = 0.5 mm; energy = 3.5 mJ.

generated either by the spark or by the flame propagation and reflected from the reactor walls, since this phenomenon would result in much higher oscillation frequency of about $8 \times 10^3$ Hertz and (b) that they are not due to periodic transformation of the flame shape from oblate to prolate spheroids, since there is no phase shift between the oscillations of $R_e$ and $R_k$.

Differentiation of the experimental curves $R(t)$ as a function of time shows the flame speed $V_p = dR/dt$ to undergo relatively strong fluctuations, roughly between an upper value equal to $V_{po}$ and a much lower value, the oscillation amplitude being progressively attenuated. Trials to match these experimental $V_p(t)$ curves show that they may be expressed in a first approximation by the following empirical relation:

$$V_p = V_{po}[1 - \alpha \exp(-\nu t)] |\sin(2\pi\nu t)|_{ABS} \quad (5)$$

where $\alpha$ and $\nu$ are characteristics of mixture composition, as shown on Fig. 7.

As may be expected and as is shown on Fig. 6, the relative surface variation with time, calculated according to Eq. (4) from the experimental values of $R_e$ and $V_p$ is also subjected to fluctuations which experimentally show to be in phase with those of the flame speed. At a first glance this latter fact is surprising, since from Eq. (2) it is clear that the flame speed should decrease whenever the stretch $dS/S\, dt$ increases. These experimental results thus suggest the phenomena of stretch and flame speed not to be in instantaneous equilibrium.

Discussion

A tentative explanation of this particular propagation behaviour may be tried. In the case of spark ignited flames, the initial value of the flame speed can only exceptionally be in agreement with the initial value of the stretch, since the former largely depends on the spark energy. As has been shown by laser tomography studies of early flame stages, the initial value of $V_p$, especially for lean flames, may be larger than the steady state value $V_{po}$ for high spark energies and lower then $V_{po}$ for very small spark energies close to the minimum ignition energy. The first case applies for the spark energy of 3.5 mJ utilized in the present study as may be seen from Fig. 5; any way the initial value of $V_p$, imposed by the spark, is much larger than the value of $V_p$ one may calculate from Eqs. (2) and (4), the more since, for the same reason, the stretch $dS/S\, dt$ (which is proportional to $V_p$) is also larger than normal. There thus exists initially a strong disproportion between flame speed and stretch. Starting from this initial situation both flame speed and stretch will have to decrease to reach mutual equilibrium, but this simultaneous decrease even enforces the disproportion between both phenomena, the values of which becoming even smaller than the equilibrium value (compare Figs. 3 and 6); due to this "overshoot," the equilibrium required by Eq. (2) will only be reached after a number of quasi-periodic fluctuations around the equilibrium value, the amplitude of which progressively decreases with time. Moreover, the adjustment of the physico-chemical phenomenon (flame speed) visibly lags behind the physical phenomenon of stretch with a phase shift of about $\pi/2$ radians as suggested by experiment.

As a further consequence of geometrical stretch and of the fluctuating propagation behaviour it imposes on spark ignited flames, the volumetric combustion rate ($dv_b/dt$) in early propagation stages is globally smaller then it would be without stretch effect. The volumetric combustion rate, expressed as the increase of the volume of burned gases with
time, depends both on flame speed and flame surface:
\[ \frac{dv_f}{dt} = S \cdot V_p \]  
(6)

or, for spherical flames:
\[ \frac{dv_f}{dt} = S \cdot V_p = 4 \pi R^2 \frac{dR}{dt} \]  
(7)

As already stated higher, the effect of geometrical stretch is negative on \( V_p \) but positive on \( S \). Figure 8 compares values of volumetric combustion rates calculated according to Eq. (7) from experimental values of \( R_e \) and \( V_p \), with those one should have if no effect of stretch on the flame speed would exist.

3. Effects of Aerodynamical Stretch on Spark Ignited Flames in Early Stages

The quasi-spherical flame ignited at the stagnation point of the opposed jet flow rapidly changes into a strongly oblate spheroidal shape, the big axis (=2 \( R_r \)) of which growing fastly under the influence of the radial velocity gradient \( dU_r/dr \), as may be seen from Fig. 9. The small axis of the oblate spheroidal flame (=2 \( R_x \)) soon reaches an almost constant value at a distance \( x \) where the axial flow component \( U_x \) and the axial flame speed \( V_p \), have the same absolute value, this at least in the case where the aerodynamical stretch does not result in flame extinction. Whenever the flame is too lean or (and) the gradient \( dU_r/dr \) too strong, the central part of the flame (close to the symmetry axis of the jets) extinguishes, an example of which is given on Fig. 9 for an equivalence ratio of 0.65.

Examples of the evolution of the flame speed in the radial direction \( (V_{pr}) \) and in the axial direction \( (V_{p}) \) as a function of time are given on Fig. 10 for different equivalence ratios (E.R. = 0.47 corresponds to a not self sustained flame in a non flammable mixture). The instantaneous values of the flame speed in the radial, respectively axial directions are calculated from the experimental values of \( R_r, R_x, U_r, \) and \( U_x \):

\[ V_{pr} = \frac{dR_r}{dt} - (U_r)_{r=0} \]  
(8)
\[ V_{p} = \frac{dR_x}{dt} + (U_x)_{r=0} \text{ ABS} \]  
(9)

At the flame apex, where \( V_{pr} \) is measured there is no positive stretch of the flame since there the tangential gradient of the flow component tangential to the flame (i.e. \( dU_r/dr \)) tends rather to decrease the flame surface. Therefore the flame speed \( V_{p} \) only senses the effect of geometrical stretch, as long as the radius \( R_r \) is small. Consequently, after an initial decrease due to geometrical stretch, the flame speed in radial direction soon reaches its steady state value \( V_{p_0} \) (or becomes even slightly

---

**Fig. 8.** Volumetric combustion rate as a function of time during early propagation stages of a spark ignited flame in stagnant gases. Ethylene/air; spark gap = 0.5 mm; spark energy = 3.5 mJ; continuous curves calculated from experimental values of \( R_e(t) \) according to Eq. (7); dotted curves calculated for the assumption that \( V_p = V_{p_0} = \text{constant} \).

**Fig. 9.** Evolution of flame radii \( R_r \) and \( R_x \) with time for flames ignited in the stagnation point of opposed jet flow. For E.R. = 0.65 the flame extinguishes in the symmetry axis region at about 1.2 ms.
larger for strong flow rates due to turbulence effects.

On the contrary, axial flame speed $V_{ax}$ is subjected to both geometrical stretch and almost constant aerodynamical stretch. The latter is proportional to the gradient $dU_r/dr$:

$$
(dS/S dt)_{aerod} = 2 dU_r/dr
$$

(10)

Only in very early stages, when the radii $R_r$ and $R_x$ are still small, will the geometrical stretch play a role, its effect prevailing then over that of aerodynamical stretch. During these early stages the flame speed will eventually and momentarily fall beneath the value determined by the sole effect of aerodynamical stretch. In later stages, for larger values of $R_r$, the effect of geometrical stretch fades out and the flame speed $V_{ax}$ progressively tends to an asymptotic value determined by the sole aerodynamical stretch. Examples of this are shown on Fig. 11 for different values of radial stretch. The asymptotic values of $V_{ax}$ may be estimated a priori from Eq. (2) upon substitution of $dS/S dt$ by its value given by Eq. (10). If this asymptotic value is negative, flame extinction occurs as shown on Fig. 11 in the case where $dU_r/dr = 1280 \text{ s}^{-1}$.

The volumetric combustion rate accounting for both geometrical and aerodynamical stretch effects may be calculated from the experimental values of $R_r(t)$ and $R_x(t)$ for oblate spheroidal flame shape by the expression:

Fig. 10. Flame speed measured in radial, respectively axial direction, as a function of time. Ethylene/air flames in stagnation flow; $dU_r/dr = 640 \text{ s}^{-1}$; Spark gap = 0.5 mm; spark energy = 3.5 mJ.

Fig. 11. Relative flame speed in axial direction measured in stagnation flow, as a function of time. Ethylene/air; spark gap = 0.5 mm; spark energy = 3.5 mJ; $V_{po} = 200 \text{ cm.s}^{-1}$. Asymptotic values calculated by Eq. (2) according to Eq. (10).

Fig. 12. Experimental values of ratio $Q$ as a function of time for different equivalence ratios and radial velocity gradients. Ethylene/air flames in stagnation flow of opposed jets. Spark energy = 3.5 mJ; spark gap = 0.5 mm.
Division of Eq. (11) by Eq. (7) yields an experimental ratio (Q) of the volumetric combustion rate accounting for both types of stretch effects and the volumetric combustion rate measured in stagnant mixtures. Values of the ratio Q measured under various stretch intensities are shown on Fig. 12.

\[ \frac{dv_b}{dt} = \frac{4}{3}(2R_e R_r \frac{dR_r}{dt} + R_r^2 \frac{dR_e}{dt}) \quad (11) \]

Conclusions

1) During early stages of propagation of spark ignited flames, geometrical stretch causes quasi-periodic fluctuations of the flame speed, the amplitude of which is attenuated progressively. The origin of these fluctuations is the fact that spark characteristics impose a well defined initial flame speed.

2) The negative effect of aerodynamical stretch on flame speed has been demonstrated experimentally during early propagation stages of spark ignited, free expanding flames. During these early stages geometrical stretch effects continue to play an important role.

3) The negative effect of both geometrical or aerodynamical stretch on flame speed, coupled with their positive effect on the growth rate of flame surface, may cause either an increase or a decrease of the volumetric combustion rate during early propagation stages.

Greek Symbols:

- \( \alpha \) pre-exponential attenuation factor (see Eq. (5))
- \( \lambda \) mean free molecular path
- \( \nu \) frequency
- \( \sigma \) proportionality factor (see Eq. (3))

Acknowledgments

The author gratefully acknowledges the financial support of the "Direction du développement Scientifique et Technologique et de l’Innovation" of the French Department of Energy, as well as of the French "Groupement Scientifique Moteurs."

REFERENCES


COMMENTS

S. R. Vosen, Sandia National Laboratories, USA.
In zero g minimum ignition energy experiments performed by P. Ronney of NASA Lewis, it has been found that the initial growth of CH₄-air flames is strongly dependent upon the supplied energy. Specifically over a range of energies, the flame will propagate and then will suddenly die, its final radius being proportional to the supplied energy. How does your study relate to zero g study?

Author’s Reply. I cannot comment on the eventual relationship between the results obtained here and the results found in the zero g experiments you are referring to. An earlier study we made in the field,* although not performed with zero g conditions, supports the findings of P. Ronney showing a strong effect of spark energy on initial flame propagation speed.

P. L. Blackshear, University of Minnesota, USA.
Is it possible to reconcile your results for the spherical flame stretching effect with the results of the preceding paper? If we follow Wu’s temperature profiles with time we can obtain your first minimum but not the succeeding oscillations. Can it be that the oscillations are a result of excess enthalpy which Wu avoided? Shouldn’t both of your results agree?

Author’s Reply. Having not had the opportunity to check the equations used in the model of Wu, I cannot answer this question at the moment.

S. Galant, Societe Bertin, France. Do you believe that your frequency and attenuation parameters in your simple “model” are: (a) only chemistry dependent, (b) only transport dependent or (c) both, say, functions of the laminar flame speed?

Author’s Reply. At the present state it is clear that frequency (v) and attenuation factor (α) of the flame propagation stretch, depend on laminar flame speed, as suggested by Figure 7. Therefore, it is likely that these two parameters depend on the intersection of both chemical and transport phenomena.

*DeSoete, G. G.—“A laser tomography study of the propagation of spark ignited flames in early stages” Central States Spring meeting, 1981.