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CFD modelling of flame stretch in SI engines

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Abstract

The flame stretch is a phenomenon that affects the combustion initial stage in premixed charge Spark-Ignition (SI) engines with consequences on the laminar burning velocity, so its correct description is fundamental to predict the further turbulent flame development.

In the context of a Computational Fluid Dynamics (CFD) investigation, two different flame stretch models were implemented. The first one is obtained starting from the equations and assumptions proposed by Bradley, Lau and Lawes. The result is a flame stretch expression that takes into account the influence of flame curvature, turbulence intensity, thermal and fresh mixture diffusivity (Lewis number), activation energy of the overall combustion reaction and flame thickness. The second one is already proposed by Herweg and Maly and takes into account the same parameters mentioned before. To assess the behaviour of these two models numerical simulations on combustion inside a simplified chamber were performed at different equivalence ratios and turbulence intensities. All simulations are carried out with the open-source platform OpenFOAM, involving a 3-D finite volume discretization using RANS turbulence modelling.

Although no comparisons with experimental findings were performed, the achieved results show a good response of both stretch models with respect to theoretical considerations.

Keywords: Flame stretch; SI engines; CFD; OpenFOAM.

1. Introduction

A correct description of combustion initial stage in premixed charge Spark-Ignition (SI) engines is fundamental to predict the further turbulent flame development and, consequently, fuel consumption and pollutant emissions, whose reduction represents the current main target of SI engines design.

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After the spark discharge, which occurs between the spark-plug electrodes, and the effects that the generated plasma channel produces on fresh mixture, a laminar flame kernel starts to expand radially. This initial stage is affected by the flame stretch, with consequences on the laminar burning velocity.

The first studies on this phenomenon were performed by Karlovitz [1] and Markstein [2] then continued over the years with further developments proposed by Buckmaster [3] and Matalon [4] until Abdel-Gayed [5], Bradley, Lau and Lawes [6]. After this last period, applications of the available theoretical results were published more frequently than before: one of the most interesting results is the stretch model proposed by Herweg and Maly [7] to describe correctly the flame kernel development in a premixed charge SI engine.

However, thanks to the always decreasing computational costs, numerical simulations can be useful to improve the capability of flame stretch description by testing the already proposed models or by implementing, with some mathematical manipulations, equations and assumptions available in literature.

In the context of a Computational Fluid Dynamics (CFD) investigation, to describe laminar flame stretch phenomenon two different models were implemented: the first one is obtained starting from the equations and assumptions proposed by Bradley, Lau and Lawes [6]. The result is a flame stretch expression that takes into account the influence of flame curvature, turbulence intensity, thermal and fresh mixture diffusivity (Lewis number), activation energy of the overall combustion reaction and flame thickness. The second one is already proposed by Herweg and Maly [7] and takes into account the same parameters mentioned before.

To assess the behaviour of these two models numerical simulations of propane-air premixed charge inside a simplified combustion chamber were performed at different equivalence ratios and turbulence intensities, assuming a unitary Lewis number and neglecting the turbulence wrinkling effect on flame to focus only on stretch phenomenon. All simulations are carried out with the open-source platform OpenFOAM, involving a 3-D finite volume discretization; turbulence is described through a RANS approach by means of the k-ε model.

2. Modelling of the flame stretch in premixed charge SI engines

The laminar burning velocity S_{l0} can be predicted, as only function of fuel type, equivalence ratio, temperature and pressure of unburned mixture, by correlations available in literature [8, 9, 10]. However this estimation does not take into account that a curved flame which develops in a turbulent flow is stretched and, hence, its propagation speed is influenced.

2.1. Flame stretch described with Bradley, Lau and Lawes equations and assumptions

As a consequence of flame stretch phenomenon, the laminar burning velocity S_{l0} changes to a value of S_l through this expression [6]

$$\frac{S_{l0}-S_l}{S_{l0}}=\frac{1}{A}\frac{dA}{dt}\frac{\delta_l}{S_{l0}}Ma \tag{1}$$

where A is a flame surface area, t is the time, δ_l is the laminar flame thickness and Ma is the Markstein number.

Bradley, Lau and Lawes [6] suggested to consider:

1) the flame speed as the sum of the actual laminar burning velocity S_l and the fluid velocity along the flame surface normal direction
2) the flow field contribution to strain rate as the flow field stretch ahead of the flame, which, for isotropic turbulence, is of about the same magnitude of the Eulerian mean strain rate [11].

Hence, after some mathematical manipulations and considering $K = (u'/\lambda)(\delta_l/S_{l0})$ as the expression of the dimensionless Karlovitz stretch factor [5], in which u' is the root mean square turbulent velocity and λ the Taylor microscale of turbulence, the following expression of flame stretch factor I_0 can be written:

$$I_0 = \frac{S_l}{S_{l0}} \approx \frac{1 - KMa}{1 + \frac{c}{R}\delta_l Ma} \tag{2}$$

where R is the flame curvature total radius and c is the parameter that allows to adapt this formulation to the desired flame shape, in particular

1) for a spherical flame $c = 2$
2) for a cylindrical flame $c = 1$

In fact in modelling a premixed charge SI engine the flame at its very initial laminar stage can assume the shape of a sphere, if the single kernel approach is used, or of a cylinder, if the spark plasma channel formation is described.

For Eq. 2 Abdel-Gayed proposed an expression to obtain K for isotropic turbulence [12], while the Markstein number Ma can be calculated, as function of the Lewis number and the overall single-step reaction activation energy, through the relation obtained by the asymptotic analysis of Clavin and Williams [13].

2.2. Flame stretch model proposed by Herweg and Maly

Herweg and Maly, for their spherical flame kernel model, considered the flame stretch phenomenon through the following I_0 expression [7]

$$I_0 = 1 - \left[\left(\frac{\delta_l}{15L_i}\right)^{\frac{1}{2}}\left(\frac{u'}{S_{l0}}\right)^{\frac{3}{2}} + c\frac{\delta_l}{S_{l0}}\frac{1}{r_k}\frac{dr_k}{dt}\right]\left[\frac{1}{Le} + \left(\frac{Le-1}{Le}\right)\frac{T_a}{2T_{ad,f}}\right] \tag{3}$$

which is valid for a spherical flame kernel development if $c = 2$ and where r_k is the flame kernel radius, L_i the integral length scale of turbulence, Le the Lewis number, $T_{ad,f}$ and T_a respectively the adiabatic flame and the overall single-step reaction temperature.

As previously discussed for Eq. 2, in case of a cylindrical flame Eq. 3 has to be used with $c = 1$.

3. CFD investigations to assess models behaviour

In the context of Computational Fluid Dynamics (CFD) simulations, the two flame stretch models proposed in the previous section were investigated to assess their behaviour to changes in equivalence ratio and turbulence intensity, which are fundamental variables in a premixed charge SI engine.

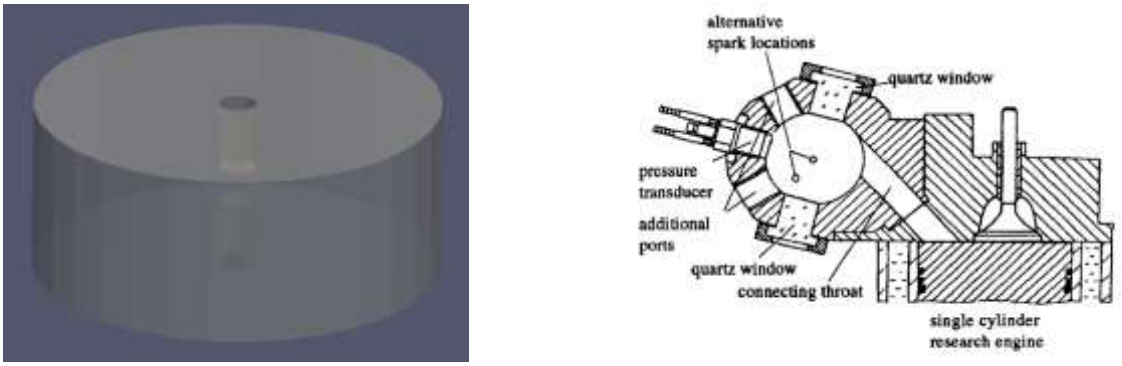
With this purpose, numerical simulations of premixed combustion were performed following the experimental setup used by Herweg and Maly. Test conditions are specified in Table 1 and calculations were carried out using the open-source platform OpenFOAM and involving a 3-D finite volume discretization. Transport equations of mass, momentum and chemical species are solved with the RANS approach and the k-ε model was used for turbulence.

Moreover, all simulations were carried out:

1) under the hypothesis of not decaying turbulence, because of the very small time-scales that characterize the early laminar flame kernel development
2) assuming a unitary Lewis number, to focus only on equivalence ratio and turbulence variations
3) neglecting the wrinkling effect (namely the surface increase) that turbulence generates on the flame, to understand if both flame stretch models consider correctly the strain produced by turbulence
4) inside a simplified combustion chamber.

Table 1. Herweg and Maly experimental test conditions [7] used for stretch models assessment.

Characteristic	Test conditions					
	1	2	3	4	5	6
Fuel	Propane	Propane	Propane	Propane	Propane	Propane
Mixture inlet temperature [K]	298	298	298	298	298	298
Pressure at ignition timing [bar]	5	5	5	5	5	5
Relative air-fuel ratio λ	1	1.5	1	1	1	1
Engine speed [rpm]	300	300	500	750	1000	1250



(a)

(b)

Figure 1. Simplified Herweg and Maly combustion side chamber around the centered spark gap (a) and sectional view of the original one [7] (b).

This geometry (Fig 1a) is a cylindrical portion around the centred spark gap of the side chamber used by Herweg and Maly [7] (Fig 1b) and it was chosen to investigate the initial laminar flame kernel development with low computational costs and to assume a zero mean flow field velocity. On this combustion chamber volume a structured hexahedral mesh was created with 62.5 µm cell size in the cylindrical spark-gap (Fig 2a). Mesh resolution is then progressively reduced far from it (Fig 2b). Details about combustion chamber geometry and computational mesh are provided in Table 2.

In the present investigation the spark plasma channel was modelled through a set of Lagrangian particles placed along the spark-gap distance, as reported in [14]. These particles can be convected by the mean flow field velocity (here equal to zero in all test conditions because of the centred spark-gap) and grow in size because of

1. the flame speed
2. the thermal expansion, generated by the heat transferred from the electrical circuit to the gaseous mixture.

This last contribution to channel growth is computed by a sub-model that predicts current and voltage evolution inside the secondary circuit. Then, considering a cylindrical shape for the laminar flame kernel, suitable correlations can be used to initialise and to estimate the diameter and the temperature of the spark channel during its expansion (for details, see [14]).

Consequently the I_0 expressions used in this work are Eq. 2 for the Bradley-Lau-Lawes model and Eq. 3 for the Herweg-Maly one (from now on, the two models will be called with the names of the authors that proposed or suggested them) both with $c = 1$.

Table 2. Key features of the simplified geometry used for simulations and of the mesh realized on it.

Characteristic	Value/Type
Spark gap [mm]	1
Wire electrodes diameter [mm]	1
Chamber diameter [mm]	11.25
Chamber clearance [mm]	4.75
Spark location	central
Hexahedral cells [n°]	≈13000

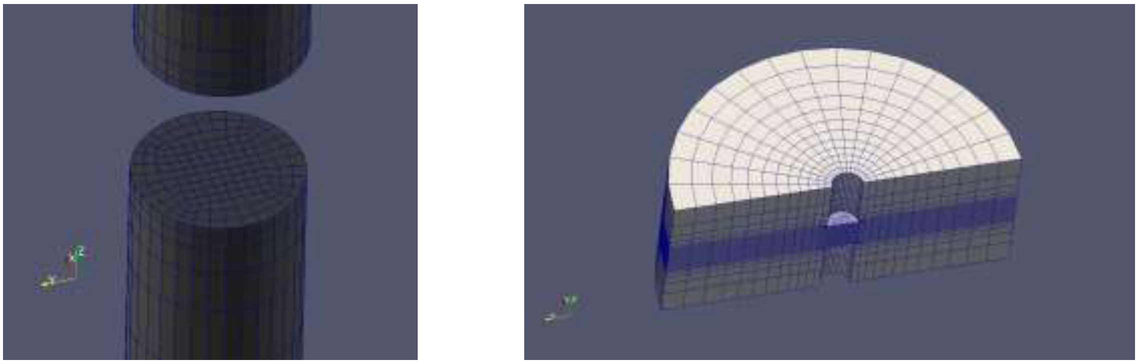

(a) (b)

Figure 2. Simplified side chamber mesh details: cubic cells in the cylindrical spark-gap (a) and hexahedra of size increasing with chamber radius (b).

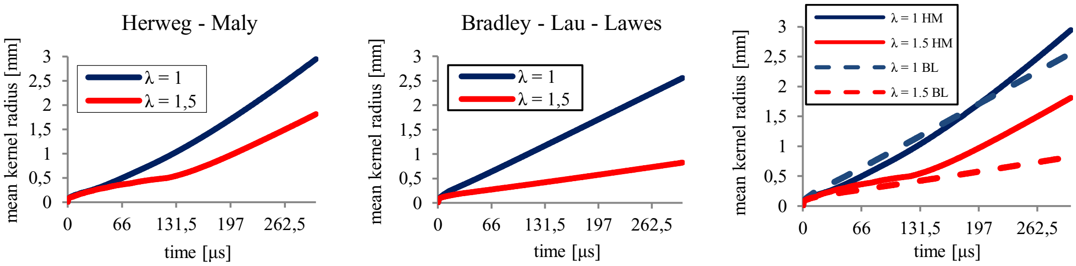
3.1. Equivalence ratio variations

The influence of flame stretch phenomenon on flame front development is strongly dependent on the air/fuel ratio of the investigated mixture.

For this reason, the first parameter that was changed to assess flame stretch models behavior is the equivalence ratio ϕ, which is defined as the ratio between the stoichiometric α_{st} and the actual α air/fuel ratio $\phi = \alpha_{st}/\alpha = 1/\lambda$. The parameter λ here represents the inverse of ϕ, so in presence of lean mixtures ($\phi < 1$) the value of λ is greater than one ($\lambda > 1$) and vice versa.

Consequently, test conditions 1 and 2 were compared (see Table 1) because it highlights only a λ-variation. Numerical simulations were performed using a 0.5 µs time-step.

As Fig 3a and 3b show, at fixed turbulence (300 rpm engine speed) with both models the laminar flame kernel development is slower if the value of λ increases, namely the laminar flame speed is reduced as the mixture becomes leaner. Consequently both models have the same trend to λ-variations, although that proposed by Bradley-Lau-Lawes is more sensitive: as Fig 3c shows, the laminar flame development predicted by this model is similar at stoichiometric mixtures ($\lambda = 1$) but slower at lean mixtures than Herweg-Maly's one.



(a) (b) (c)

Figure 3. Development of mean flame kernel radius in time at different λ values, using Herweg-Maly (HM) (a) and Bradley-Lau-Lawes (BL) (b) stretch model at constant turbulence (test conditions 1 and 2 of Table 1). Image (c) compares the results estimated by the two models.

3.2. Turbulence intensity variations

Normal operating conditions of an actual IC engine are included in a certain crankshaft speed range: this generates variations on piston speed with consequences on mean (i.e. swirl or tumble) and turbulent flow field motion inside the combustion chamber. Because flame stretch phenomenon is sensitive to turbulence intensity variations [6], this aspect was investigated in this work.

With this purpose the mixture was ignited at the central point of the side chamber where the mean component of the flow field velocity can be neglected [7], hence flow velocity was set to zero. Then the initial turbulence intensity u' was changed according to Herweg and Maly's test conditions at different engine speeds (300 rpm, 500 rpm, 750 rpm, 1000 rpm and 1250 rpm) [7]. Results from test conditions 1, 3, 4, 5 and 6 (see Table 1) were compared. Turbulence intensity was changed by adjusting the following parameters u':

1) the turbulent kinetic energy $k = (3/2)(u')^2$
2) the k dissipation rate $\varepsilon = (0.09k^{1.5})/L_i$

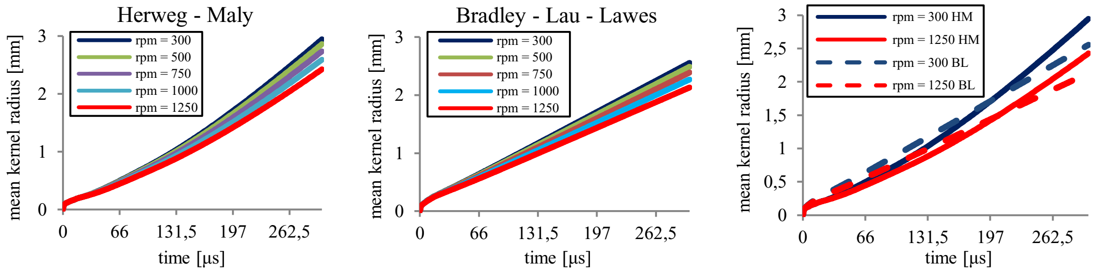
with $L_i \approx D_{sc}/10$ and D_{sc} = 45 mm, where D_{sc} is the Herweg and Maly side chamber diameter [7]. All numerical simulations were performed using a 0.5 μs time-step.

As Fig 4a and 4b show, at fixed equivalence ratio ($\phi = 1$) and with both models, a turbulence intensity increase causes a reduction of the laminar flame kernel development. This result is due to the increased flame stretch that a higher turbulence generates on the flame and that, in the context of this numerical investigation, is not counterbalanced by the wrinkling effect. In practice, turbulence affects a flame by two principal and opposing phenomena [6]:

1) the wrinkling effect, which increases the flame surface and consequently the flame speed
2) the stretch effect, which strain the flame surface and causes a flame speed reduction

but in this work, first effect was removed and only the second one was considered. Another important aspect is that, as specified before, for each test condition the hypothesis of not decaying turbulence was assumed because attention was focused on the very initial stage of combustion, whose characteristic time-scales are very small, so in these investigations the turbulent flow field is not affected by the flame front propagation.

Finally from Fig 4c, it is possible to notice that both stretch models have an almost similar behavior both at low and high turbulence intensity.



(a) (b) (c)

Figure 4. Development of mean flame kernel radius in time at different engine speed values (rpm), using Herweg-Maly (HM) (a) and Bradley-Lau-Lawes (BL) (b) stretch model at constant equivalence ratio (test conditions 1, 3, 4, 5 and 6 of Table 1). Image (c) compares the results estimated by the two models.

4. Conclusions

Purpose of this work was to investigate how different flame stretch models affects the initial flame kernel development process in SI engines. To this end, numerical simulations were carried out and two different approaches, suggested by Herweg and Maly and and Bradley-Lau-Lawes, were tested: both them can fairly predict the flame stretch phenomenon. Under the hypothesis of not decaying turbulence and unitary Lewis number they are able to estimate a laminar flame speed reduction in case both of a leaner mixture (Fig 3a and Fig 3b) and an increased turbulence intensity (Fig 4a and Fig 4b). This last result is true only if we neglect the wrinkling effect that turbulence generates on the flame to understand if the investigated stretch model consider correctly the strain produced by turbulence.

Moreover, by comparison, both of them take into account almost the same variables (Eq. 2 and Eq. 3) and have quite similar behaviours at λ and rpm-variations (Fig 3c and Fig 4c), so this result allows to assert that they are almost interchangeable.

Since flame stretch strongly affects the initial flame kernel development process, the numerical approach developed in this work can be useful to develop suitable ignition systems for diluted mixtures, which have the potential to reduce both fuel consumption and pollutant emissions in SI engines.

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Biography

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