ВЕСТНИК ТУРИНСКОГО ПОЛИТЕХНИЧЕСКОГО УНИВЕРСИТЕТА В ГОРОДЕ ТАШКЕНТЕ

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The effect of different regimes for premixed turbulent combustion to the burning speed inside the combustion chamber of a 2 liter 4 in-line cylinder spark ignition ICE.

Umidjon Usmanov
Department of Mechanical and Aerospace Engineering
Turin Polytechnic University in Tashkent,17, Little Ring Road street, Tashkent, Uzbekistan
Email: usmanovumidjoni@gmail.com

Abstract– This article describes different regimes for premixed turbulent combustion in gasoline internal combustion engines and the way they enhance the burning speed of a turbulent flame comparing with a laminar combustion. For this reason, we classify different regimes and summarize them in a single diagram called Borghi plot where it is possible to distinguish them and separately analyze depending on the characteristics of the turbulence. Finally, we can determine the effect of each regime to the turbulent burning speed of a premixed flame.

Key words– turbulent combustion, combustion diagnostics, premixed combustion, flame corrugation, Borghi plot.

I Introduction

In SI engines the time for premixed combustion scales almost linearly with a rotational speed of an engine due to the effect of turbulence, so on a crank angle basis the duration of a combustion is almost constant which is the reason of why SI engines can reach a much higher rotational speed compared to CI engines[1]. It is interesting to notice that while some scales of turbulence are able to enhance the burning speed of a premixed turbulent flame, others can even worsen or destroy the flame front[2]. Analysis starts with a definition of a burning speed S_b and making a comparison with a laminar burning velocity S_l. The question that worth making the focus on is whether the burning speed is locally laminar and the enhancement due to the turbulence occurs due to the flame corrugation effect or there are some modifications in the chemistry of the transformation of reactants to the products inside the corrugated flame front, so altering the local burning speed, which becomes different from laminar one. During this analysis, we will try investigate this phenomenon. Main engine specifications are provided in the following table.

Table 1: Engine specifications

Parameters of the engine	Property
Bore	84 mm
Stroke	90 mm
Compression ratio	10.35
Cylinder number	4
Displacement	1995 cm^3

II Burning speed in ICE

Burning of a premixed air fuel mixture in internal combustion engines occur not under laminar condition due to the corrugation of a flame front by the turbulence[3]. The black wrinkled line indicates the corrugated by turbulence flame front area and is indicated as A_{corr} (Figure 1). In order to define burning speed S_b, we introduce a new hypothetical area, called burning area A_b (Figure 1), such that the volume of burned and unburned gas above and below both areas are equal[2]. By assuming that locally burning speed is laminar, which works only in specific scales of turbulence, we can write

$$[\frac{dm_u}{dt}] = \rho_u S_l A_{corr} = \rho_u S_b A_b \quad (1)$$

Where ρ_u-density of unburbed gas, S_l-laminar burning speed, S_b-turbulent burning speed.

From this relation the turbulent burning speed is

$$S_b = S_l \frac{A_{corr}}{A_b} \quad (2)$$

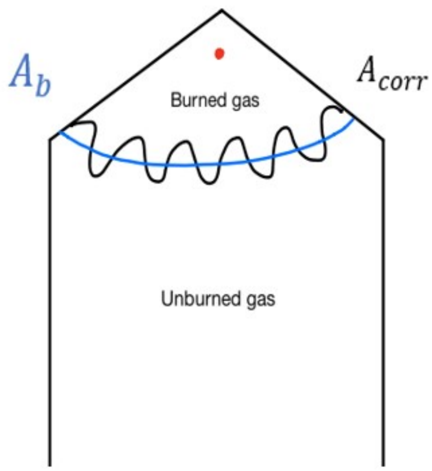

Fig. 1: Premixed combustion

The burning speed is enhanced by the turbulence by a factor which is proportional to the ratio of corrugated and burning areas by assuming that locally flame propagates with laminar burning velocity [3].

III Premixed turbulent regimes diagram

We will consider regimes of premixed turbulent combustion in terms of velocity and length scale ratios proposed by Borghi (1985) [4].

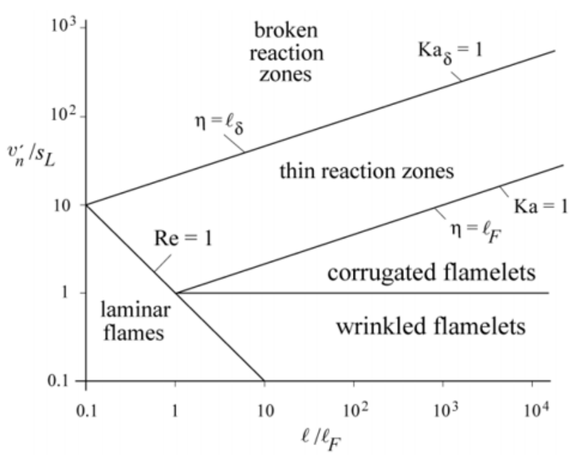

Fig. 2: Borghi plot

This diagram (Figure 2), where x axis indicates the ratio of integral length scale of turbulence and length scale of flame front $v_n^{'}/S_l$ and y axis indicating the ratio of velocity at integral scale and laminar burning speed l/l_F , distinguishes 4 different regimes for premixed turbulent combustion: wrinkled flamelets, corrugated flamelets, thin reaction zones and broken reaction zones. The laminar flames regime is out of consideration for combustion in ICE. In order to study the effect of turbulence, it is important to analyze each regime separately.

1 *Wrinkled flamelets regime*

In the wrinkled flamelets regime, the velocity at integral scale $v_n^{'}$ is lower than the laminar burning speed S_l (Figure 3).

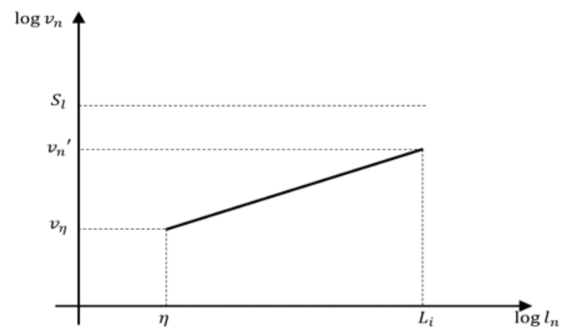

Fig. 3: Inertial subrange for wrinkled flamelets

Where η–Kolmogorov length scale, L_i – integral length scale, v_η – Kolmogorov's velocity scale.

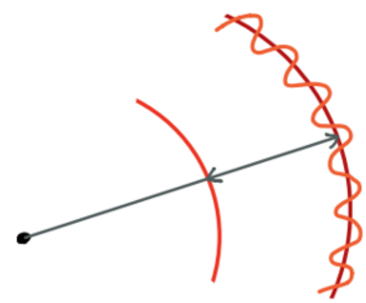

Fig. 4: Wrinkled flame front

Provided higher turbulence content, the fast revolutions of the eddies tends to corrugate the flame front (Figure 4), but the intensity is not enough that he only effect is a wrinkling of a flame front. Still, the combustion is locally laminar and the enhancement of the burning speed is almost negligible [5]. Thus, in the wrinkled flamelets regime, the turnover velocity of the largest eddies is not enough to compete with the advancement of the flame front. Laminar flame propagation dominates over flame front corrugation by turbulence.

2 *Corrugated flamelets regime*

The borderline separating wrinkled and corrugated flamelets is characterized by $v_n^{'}/S_l = 1$. Therefore only integral scale turbulence is able to substantially corrugate the flame front. Above this line the ratio is $v_n'/S_l > 1$ and the Karlovitz number $Ka < 1$. From the difinition of Karlovitz number, we have

$$Ka = \frac{t_f}{t_\eta} = \frac{l_F^2}{\eta^2} = \frac{v_\eta^2}{S_l^2} \tag{3}$$

By summarizing all the equations, we have

$$\begin{cases} \dfrac{v_n'}{S_l} > 1 \\ Ka < 1 \end{cases} \Longleftrightarrow \begin{cases} \dfrac{v_n'}{S_l} > 1 \\ \dfrac{v_\eta}{S_l} < 1 \\ \dfrac{l_F}{\eta} < 1 \end{cases} \Longleftrightarrow \begin{cases} v_n' > S_l > v_\eta \\ \eta > l_F \end{cases} \tag{4}$$

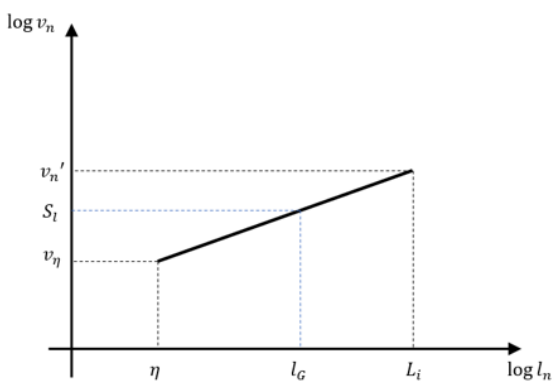

Fig. 5: Inertial subrange for corrugated flamelets

Where l_G is the Gibson length scale, above which there are vortices that are faster than flame front and below which there are vortices that are slower than flame front. However, Kolmogorov length scale is larger than the thickness of the flame front (Figure 5).

Since $\eta > l_F$, the entire reactive-diffusive flame structure is embedded within eddies of the Kolmogorov scale, where the flow is quasi-laminar. Although the eddies larger than the Gibson length scale cause a substantial corrugation of the flame front, the flame structure is not perturbed by turbulent fluctuations and does not change it's structure.(Figure 6) Therefore, the flame front locally propagates with laminar burning velocity, and the enhancement occurs only due to flame front corrugation [5].

3 Thin reaction zones regime

Thin reaction zone regime is characterized by $Ka > 1$ and $Ka_\delta < 1$. Therefore

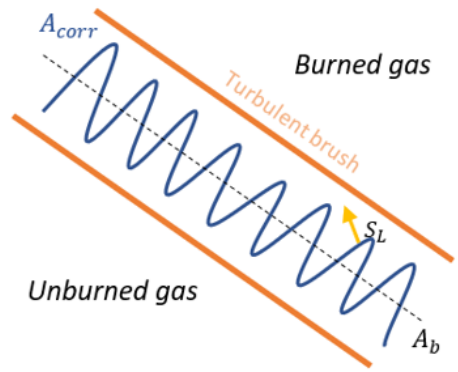

Fig. 6: Corrugated flame front

$$\begin{cases} Ka > 1 \\ Ka_\delta < 1 \end{cases} \Longleftrightarrow \begin{cases} \dfrac{v_\eta}{S_l} > 1 \\ \dfrac{l_F}{\eta} > 1 \\ \dfrac{l_\delta}{\eta} < 1 \end{cases} \Longleftrightarrow \begin{cases} v_\eta > S_l \\ \eta < l_F \\ \eta > l_\delta \end{cases} \tag{5}$$

Where Ka_δ is the second Karlovitz number, l_δ – thickness of inner layer of reaction zone.

Velocity at Kolmogorv Scale is larger than laminar burning velocity, therefore any scale of turbulence can substantially corrugate the flame front (Figure 7). Moreover, Kolmogorov scale is less than flame thickness and higher than the thickness of inner layer of reaction zone. As a result, eddies can enter into the preheat zone and increase mixing of radicals. These eddies during their turnover time might interact with the advancing reaction front and transport preheated fluid from a region in front of the reaction zone over a distance corresponding to eddy size. In addition, the heat transfer is enhanced from inner layer to preheated zone of flame

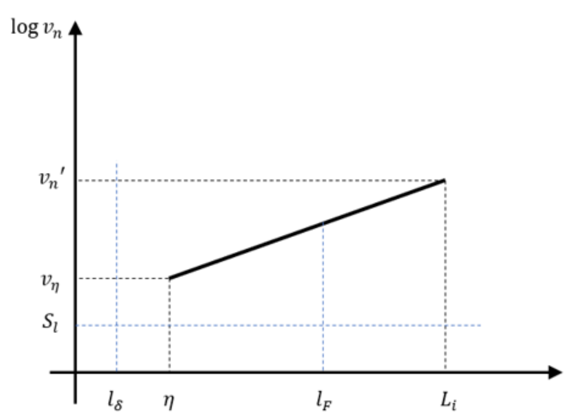

Fig. 7: Inertial subrange for thin reaction zones

front [5]. However, such eddies cannot penetrate into the inner layer because $Ka_\delta < 1$. Therefore, the enhancement of burning speed occurs not only due to corrugation effect but also due to better kinetics of chemical reactions happening in the flame front[6]. The local burning speed is no more laminar. The burning speed is now

$$S_b = S_l^{'} \frac{A_{corr}}{A_b} \tag{6}$$

Where $S_l^{'}$ - enhanced local burning speed, which is different from laminar one.

4 Broken reaction zones regime

Second Karlovitz number is less than one for broken reaction zones [7].

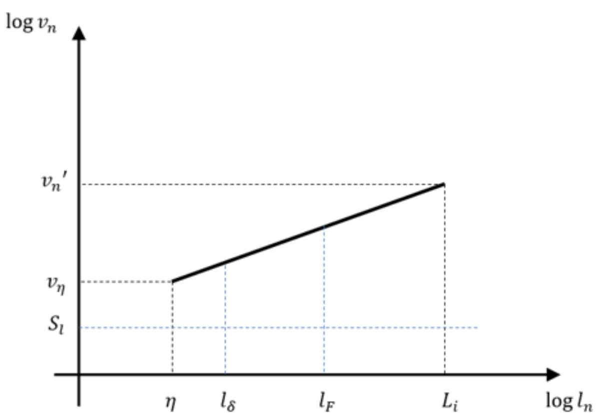

Fig. 8: Inertial subrange for broken reaction zones

$$Ka_\delta < 1 \iff \eta < L_\delta \tag{7}$$

Kolmogorov scale eddies are smaller than inner layer of flame front, so there is direct interaction between the eddies and the inner layer (Figure 8), but unfortunately this is not beneficial since the turbulent motion tends to remove the radicals within the inner layer which are essential for the chain branching reactions. In the broken reaction zones regime, mixing is faster than the chemistry, which leads to local extinction. This can cause noise, instabilities and possibly global extinction. Eddies may enter into the inner layer and perturb it with the consequence that chemistry breaks down locally owing to enhanced heat loss to the preheat zone followed by temperature decrease and the loss of radicals. Finally, flame extinguishes, fuel and oxidizer will inter diffuse and mix at lower temperatures, where combustion reactions have ceased.

IV CONCLUSION

In conclusion, turbulent flow field could be intensified through several approaches, like bowl-in piston, directed or deflected intake wall ports, helical inlet port and etc. However, although turbulence seems to enhance burning speed at any scale, it is evident that substantial amplification occurs only at corrugated flamelets and thin reaction zones regime and at a specific zone where $v_n^{'}/S_l > 1$ and $Ka_\delta < 1$. Furthermore, local speed of propagation of the flame front remains laminar in case of corrugated flamelets regime and improvement occurs at the expense of increased flame front area. Nevertheless, local burning speed becomes different from laminar in case of thin reaction zone regime due to improved chemical reaction kinetics inside the flame front. Enhancement in this case occurs both from increased flame front area and local burning speed. Finally, concerning the application field, it can be claimed that by properly tuning the turbulence level and matching the burning speed enhancement zones inside the gasoline combustion chamber across all the range of engine rotational speeds, it is possible to further increase the limit of engine revolution speed of a particular engine.

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