Local Quenching Recovery Mechanisms and Flamelet Structures in a Heterogeneous Combustion

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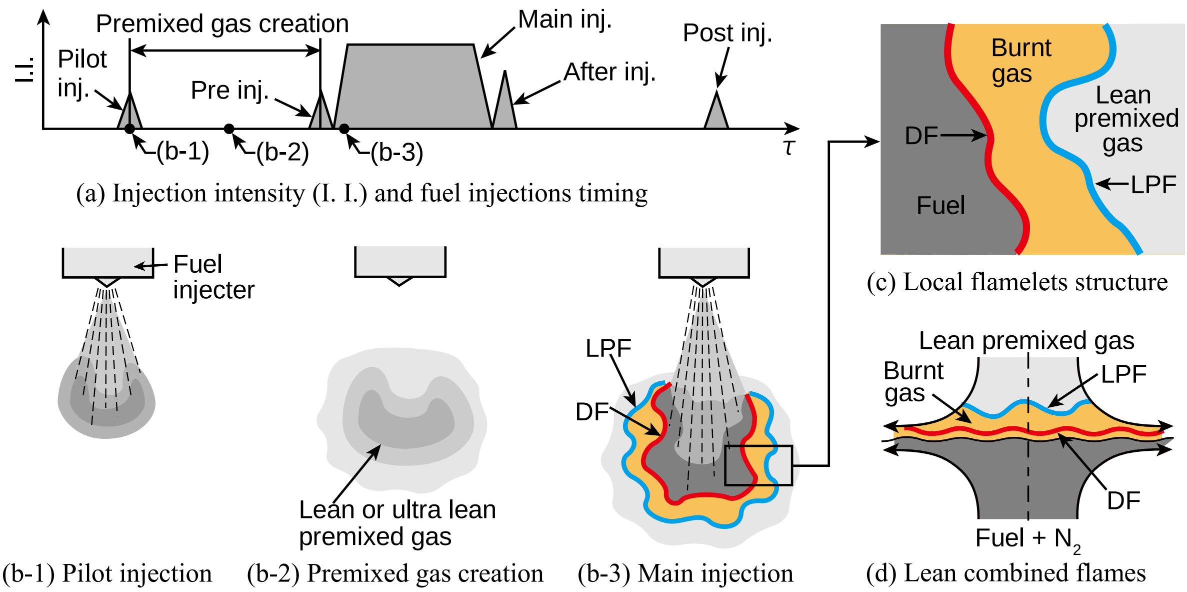
1 Introduction

In the practical combustors, the combustion phenomena operate in a heterogeneous condition rather than in a homogeneous condition. The gasoline direct injection spark ignition engines and the direct injection compression ignition engines are typical examples [1], [2]. Furthermore, in the trend of those internal combustion engines, the compression ratios of spark ignition engines (SI engines) are getting increase though compression ignition engines (CI engines) are getting decrease. One is to increase the thermal efficiency and the other is mainly to reduce the pollution in the exhaust gas. In CI engines, to reduce soot and NOx are very important issues, so CI engines are getting using a partially premixed combustion especially in the initial [3]. For example, a modern CI engine with a common rail injector



(a) Injection intensity (I. I.) and fuel injections timing

(c) Local flamelets structure

(b-1) Pilot injection (b-2) Premixed gas creation (b-3) Main injection (d) Lean combined flames by opposed flow

Figures 1. Schematic model of heterogeneous combustion in CI engine with multi injection timing common rail and our proposed flamelets structure model.

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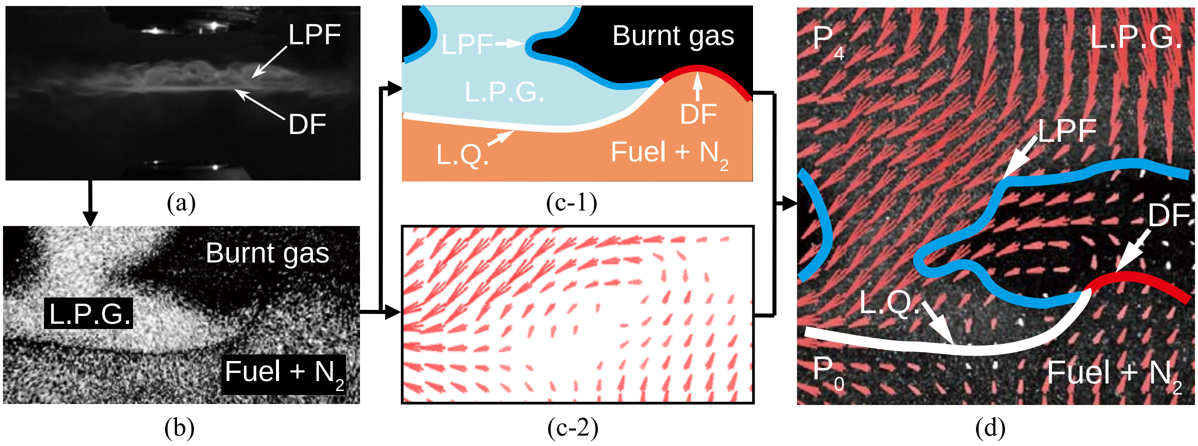


Figures 2. Procedure of the combined image of two dimensional instantaneous velocity vectors and flame fronts. (a) direct photograph. (b) two dimensional tomografic image. (c-1) visualized lean premixed flame (LPF), diffusion flame (DF) and local quenching zone (LQ) by image processing. (c-2) instantaneous two dimensional velocity vectors by cross correlation PIV. (d) local flamelet structure.

has been operated with multi fuel injection mode [3]. Especially, near the lean operating conditions, the flame may locally quench though it is globally active [4], [5]. The local quenching induces global extinction or unburnt gas emission. Those are one of the causes of the cycle to cycle variations. Figures 1 show the schematic model of heterogeneous combustion in CI engine with multi injection timing common rail and our proposed flamelets structure model. The multi injection timings are consisting with pilot-injection, pre-injection, main-injection, after-injection and post-injection as shown in Fig. 1 (a). The pilot-injection creates a premixed gas to encourage ignition and reaction speed as shown in Fig 1 (b-1) and (b-2). The combustion will start after pre-injection (Fig. 1 (b-3)) then the reactants and oxidizers are distributed in a heterogeneous condition. In the microscopic of view, the different structures reacting flows of lean premixed gas and vaporized fuel are locally interacting. Then, the combined flamelets structure created. As one of the possible combined flame structure, we proposed lean premixed flame (LPF) and diffusion flame (DF). In order to create the combined flame in lab scale, an opposed flow is one of the suitable geometry for the fundamental modeling of the heterogeneous combustion on the turbulent flow since the reactants compositions and turbulence conditions of each burner can be controlled individually [4].

However, up to now, the combined combustion phenomena of LPF and DF have not been performed in experimentally. In the present study, therefore the local quenching recovery mechanism and flamelets structure in a heterogeneous combustion are investigated for an opposite turbulent flow burner by using the time series particle image velocimetry (PIV).

2 Experimental Setup

The burner system consist two symmetrical nozzle type burners placed in line vertically. The exit diameter of both nozzles (*d*) is 40mm and the nozzles separation distance (*L*) is set to 80mm. The mean velocity of each nozzle is set at up to 2.0m/s. The turbulence generator, namely P_4, is used and it can be installed between the converging nozzle and the straight tube. Then the generated turbulent intensity is 0.37m/s and the turbulence Reynolds number ($Re_0=u'_0l_0/\upsilon_0$) is 52, where l_0 is the integral length scale, and υ_0 is the kinematic viscosity of air at room temperature. The flow condition in the present study is in the wrinkled laminar flame regime. P_0 means that no perforated plate is used and laminar stagnating flow is formed. The experiments are conducted for 2 flow combinations; one side is a laminar flow while the other side is a turbulent flow (P_0/P_4 or P_4/P_0). The CH_4 and air premixed gas flow is supplied from the upper side burner and the CH_4 diluted with N_2 non-premixed gas flow is issued from the lower side burner. Ring shape N_2 flows are supplied with same velocity of main flow from both burners to minimize the shear turbulence and to extinguish secondary combustion of the unburned fuel. The coordinate y is defined as the upward direction from the lower nozzle exit.

Figures 2 show the procedure to obtain time series particle image velocimetry (PIV). A typical flame image for the combined flames formed in the opposed flow shows in Fig. 2 (a). In conditions, the lean turbulent premixed gas is issued from the upper nozzle while laminar N_2 diluted CH_4 is issued from the lower nozzle. Initially, two dimensional tomografic images are visualized by seeded particles and a thin laser sheet (Fig.2 (b)). Fine alumina particles about 1 μ m are used as scattering particles added via both nozzles. A Q-switched YLF laser having 10mJ pulse energy at 1kHz and 527nm wavelength (Photonics Industries DM 10-527) is used as a light source. The images are taken by a high speed camera Photoron Fastcam-1024PCI 100K having 1024×1024pixels resolution at 1000 frames/sec. Then, the measurement field of each frame is 40mm×40mm. In the next step, LPF and DF are identified by image processing (Fig. 2 (c-1)) and two dimensional velocity vectors are obtained by cross correlation PIV analysis (Fig. 2 (c-2)). Finally, the flamelets structure is obtained from the combined those images (Fig. 2 (d)).

3 Results and Discussions

Local quenching recovery modes

Four different local quenching recovery modes, passive local quenching recovery mode (P-mode), active local quenching recovery mode (A-mode), eddy transportation local quenching recovery mode (E-mode), and local quenching develops to global extinction mode (G-mode) are observed. Figures 3 show the one of the examples of four different local quenching recoveries mode. In cases of P, A, and E modes (Fig.3 (a), (b) and (c)), the turbulence generator is set on the upper burner, while the lower approaching flow is laminar. In the only G-mode (Fig. 3 (d)), turbulence generator sets in the opposite side of former conditions. In these figures, L.Q., LPF, and DF correspond as local quenching area, lean premixed flame and diffusion flame, respectively. In the frames, the indicated minimum velocity point is identified by PIV data and seems to be stagnating points. In the turbulent opposed flow the stagnating stream line moves three dimensionally near the center axis of the flow. Therefore, it is difficult to correctly identify the stagnating point from the 2D flow data so we use the minimum velocity point; the stagnating point will probably be located near there.

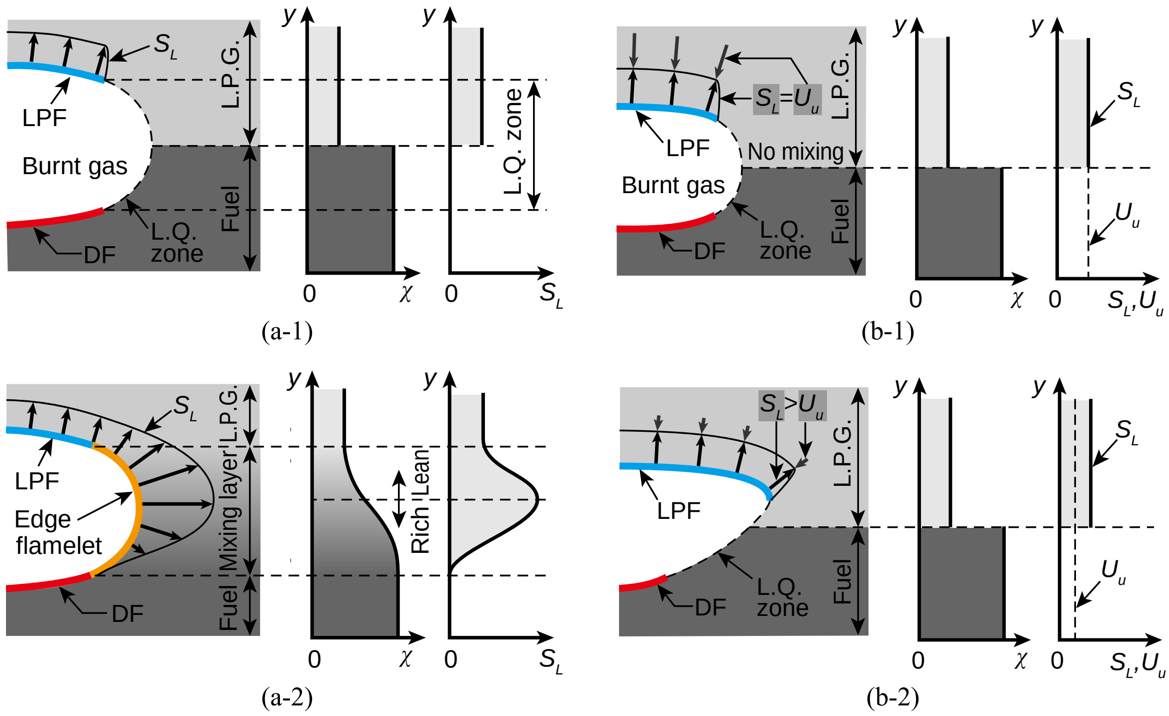
Figure 3 (a) shows P-mode. The local quenching occurs slightly outside of the minimum velocity point (see frame 0ms). In frames 4ms to 12ms, the local quenching area is developing from the outside of the minimum velocity point. In frames 2ms to 10ms, the local quenching area is drifting outward from the minimum velocity point, then the flame can automatically recover from the local quenching phenomena in accordance with the opposite flow properties (see frame 12ms). The important point of P-mode is the position of local quenching and it does not include the minimum velocity point.

Figure 3 (b) shows A-mode. In this case, the local quenching occurs at the center including the minimum velocity point (see frames 0ms~4ms). The local quenching area can spread to the whole region. The flames are active in 3-dimensional space though the flames seem globally extinguished in 2-dimensions. In fact, the LPF propagates from the right side (see frame 20ms). In the 24ms frame, a LPF island also appears. These flame fronts are spreading until reaching the quenching surface. In the 28ms frame, the recovered DF surface also appears and spreads to the whole area. Finally, the flames can be recovered from the local quenching phenomena. As the common feature of local quenching phenomena of P and A modes, it is worthwhile to pay attention that the local quenching occurs in the regions of the minimum velocity point. Without the self-propagation, the flame may not recover from large scale local quenching if the quenching occurs within the minimum velocity point. Therefore, the wrinkled flamelet propagation plays a very important role for the recovery mechanism.

Figure 3 (c) shows E-mode. In order to investigate turbulence effect on the local quenching recovery mechanism, the turbulence generator is set on the premixed gas side, while the mixture condition is set as φ_U=0.3. That is, the turbulent premixed gas does not have self-propagation. In this case, the local quenching occurs at the center including the minimum velocity point same as A-mode (see frame 0ms). Since the mixture concentration is below the self-propagation limit, self propagation

(a) P-mode (b) A-mode (c) E-mode (d) G-mode

Figures 3. Four different local quenching modes. P-mode, A-mode, E-mode and G-mode correspond as passive local quenching recovery mode, active local quenching recovery mode, eddy transport local quenching recovery mode, and local quenching develops to global extinction, respectively. The flow conditions are following: (a) and (b) P_4/P_0, φ_U=0.6, χ_L=7.8%; (c) P_4/P_0, φ_U=0.3, χ_L=22.0%; (d) P_0/P_4, φ_U=0.6, χ_L=10.0%.



Figures 4. Possible flamelets structure model at the local quenching part. χ_L : fuel concentration. S_L : local burning velocity. U_u : unburnt gas velocity.

recovery mechanism does not expect. However, the local quenching area can not spread to the whole region and the local quenching region is transported to the out side of the minimum velocity point (see frame 15ms). The local quenching area is drifting outward from the minimum velocity point and is getting smaller (see frames 27ms to 37ms). Finally, in the 39ms frame, LPF and DF spread to the whole area and the flames can be recovered from the local quenching phenomena. In this case, the active flamelets may be transported by an eddy motion.

Figure 3 (d) shows typical global extinction phenomena (G-mode). In the first frame of Fig. 3 (d) (see frame -12ms), LPF and DF surfaces are formed individually. In the second frame (see frame -8ms), the convex part of the DF surface moves to upward. The local velocity of that region exceeds 1.5m/s and finally the DF surface attaches to the LPF surface (see frame 0ms). In this part, both flames are locally quenched. The local quenching area (L.Q.) is developing to outer direction as shown in frames 0ms to 32ms. Finally (see frame 40ms), the local quenching area developed to the global extinction (G.E.). The local quenching developed to the global extinction phenomena at about 30~40ms. It is worthwhile to note that the minimum velocity point does not move.

Possible flamelets structures models at the local quenching part

Figures 4 (a) and (b) show some possible flamelet recovery models at the local quenching part. As shown in Fig. 4 (a-1), at just after the local quenching, the reactive flows of lean premixed gas and fuel diluted N_2 are completely separate and gas composition profiles distribute step shape. The local burning velocities are supposed to be a constant in the active LPF zone. In next moment (Fig. 4(a-2)), the lean premixed gas and fuel will be starting to mix and to diffuse in the local quenching zone. In this created mixing zone, the concentration of premixed gas will be changing from lean to rich and finally it will become non premixed gas. The similar mixing mechanisms are observed in edge parts of the oscillating boundary layer diffusion flames and the lifted jet diffusion flames [7]. In those transition zones, the local flame propagation speed will be changed. Especially in around stoichiometric conditions, the local propagation speed would be faster than the original LPF. This intensified flamelet may become driving force for the local quenching recovery mechanisms of the A-mode. As the other possible model, Fig. 4 (b) shows flamelets recovery model with no mixing and diffusion. In the initial condition (Fig.4 (b-1)), the local burning velocity (S_L) equals the incoming unburnt reactive flow or smaller than that. If the incoming reactive flow decreases or LPF transport by eddy motion, S_L becomes faster than U_u (Fig.4 (b-2)). This is one of the possibilities of the A- or E-modes. As discussed in the local quenching recovery mechanisms, the key factor is the balance of the incoming flow velocity and the propagating speed on the flamelet edge. It is difficult to identify that the flame structure of the flamelet edge is having the premixed flame or diffusion flame. Also it is hard to measure the flamelet edge propagation speed but it is important for the local quenching recovery mechanisms.

4 Concluding Remarks

Four different local quenching recovery modes passive local quenching recovery mode (P-mode), active local quenching recovery mode (A-mode), eddy transportation local quenching mode (E-mode), and local quenching develops to global extinction mode (G-mode) are observed in the heterogeneous opposed reactive flows. Those local quenching would be frequently observed to approaching the global extinction limits. The flame may become possible to recover from the local quenching with a lot of opportunity. Then, the structure of the flamelets and incoming reactive flows are very important issues to concluding the local quenching recovery mechanisms. Especially, immediately after the local quenching even, the mixing zone creates in the quenching zone. The fuel concentration of lean premixed gas may increases from the original condition and the local propagation speed increases in the zone. This increased propagation speed may becomes driving force to the local quenching recover mechanisms. In addition, the flamelets transported by the eddy motion also helps to recover from the local quenching event.

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