The Study on Flame Quenching Mechanisms in a Natural Gas Pre-chamber Spark-ignition Engine

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Abstract :

This study explores the mechanisms behind flame jets quenching in pre-chamber spark ignition (PCSI) natural gas engines. Experiments were conducted using an optically accessible single-cylinder heavy-duty engine equipped with an active pre-chamber (PC). The engine was operated lean and the PC mixture was enriched to near-stoichiometry using a dedicated fuel injector. Thermodynamic and high-speed optical imaging data were processed to extract combustion metrics and visualize quenching, respectively. The results show that cycles with high peak pressure difference between the PC and MC (ΔP_{max}) were associated with a higher propensity of quenching. Additionally, cycles exhibiting symmetric jet structures demonstrated reduced quenching propensity. The findings contribute to the understanding of flame quenching phenomena and offer potential strategies to reduce cycle-to-cycle variability in lean-burn PCSI systems.

Keywords: Flame quenching, Pre-chamber ignition, Natural gas, Jet penetration .

1 Introduction

Pre-chamber spark ignition (PCSI) engines feature ignition inside a small dedicated volume termed pre-chamber (PC) which is connected to the main chamber (MC) via a set of small nozzles. Upon ignition, the PC pressure sharply rises and forces hot turbulent jets into the MC, where the jets mix and ignite the main charge. The resulting distributed ignition sites and increased turbulence accelerate the MC combustion. [1][2] However, under certain conditions, the jets may quench and fail to ignite the MC. This is a challenge since quenching leads to high cycle-to-cycle variability of combustion.

Several studies demonstrated that quenching occurs during the intense mixing between the hot jets and colder lean MC mixture.[3] However, the occurrence of quenching is stochastic and not all cycles quench. The mechanisms of flame quenching in PCSI have not yet been clearly understood, and it is not clear how the combustion process inside the PC impacts the probability of quenching. This study evaluated the key factors contributing to flame quenching, corroborated using high-speed jet/flame image analysis with thermodynamic data.

2 Methods

The experimental data was acquired in the Sandia heavy-duty, optically accessible single cylinder diesel engine which was fitted with a pre-chamber module with a spark ignition system and fueled with synthetic natural gas (NG). The pre-chamber with volume of 4.6 mL featured 8 orifices with $\varnothing 1.6mm$ and 130° umbrella angle. Both pre-chamber and main-chamber were instrumented with pressure transducers. The main fuel was fumigated into intake air at $\lambda = 1.8$, and the in-prechamber injector enriched the PC to $\lambda = 1.15$. This operating condition was selected for this analysis based on high variability of combustion.

Optical imaging of main chamber combustion was used to gain additional insights into the quenching processes. Two high speed cameras were phase-locked to engine rotation. An Infrared (IR) camera (FLIR X6900 SC) visualized hot gasses emerging from PC at 2 CAD intervals and combustion reaction propagation was captured every 0.25 CAD by a high-speed OH* chemiluminescence (CL) camera (Fastcam SA-X2). Figure 1 displays an example of a processed CL image with a blue to red color map indicating OH* intensity and a composite CL/IR image with IR intensity in black to white overlaid with OH* intensity in red hues.

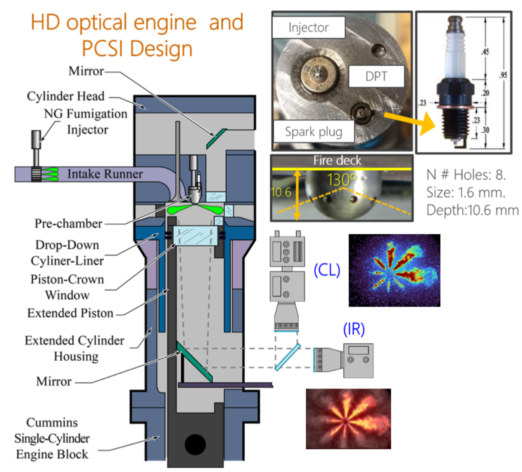

Figure 1. Schematic of Sandia Heavy-duty Optical Engine and Measurement Techniques

For each cycle, the apparent heat release metrics were calculated, and the peak pressure difference between the PC and MC (ΔP_{max}) derived. To derive the metric for quenching, the duration between 10% of heat release ($CA10$) and the timing of peak pressure difference ΔP_{max} ($CA\Delta P_{max}$) was calculated as $CA10 - CA\Delta P_{max}$. $CA10$ indicates an established flame kernel in the MC (PC is only 2% of TDC volume), and $CA10 - CA\Delta P_{max}$ marks the time when PC mixture is burning vigorously, well correlated with the time of jet emerging in the MC. Using later combustion metrics like CA50 would introduce additional sensitivity to flame propagation and kinetics effects after the jet turbulence dissipates, and was demonstrated to perform worse in tracking jet quenching. A short delay from $CA\Delta P_{max}$ to $CA10$ indicate no major lag between jet arrival and flame propagation, while a long delay suggests quenching induced lag.

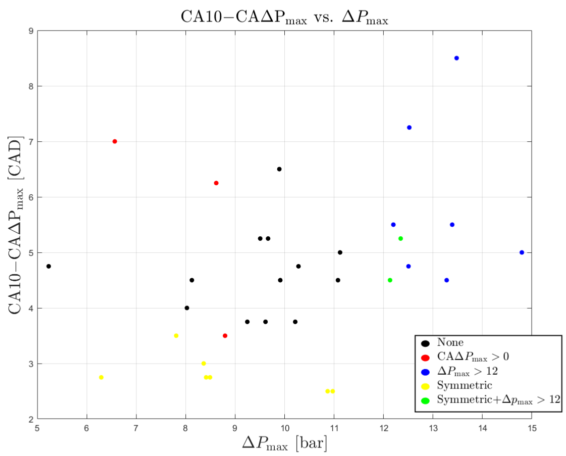

Figure 2. Correlation between $\Delta P_{\max}$ and $CA\Delta P_{max}$ for 40 cycles. Some points are color coded based on phenomenology: red indicates retarded $CA\Delta P_{max}$, blue high ΔP_{max}, yellow indicates symmetric flame pattern, green is a combination of high peak pressure and symmetric flame

3 Results

One factor for quenching is retarded ignition, which we define as when $CA\Delta P_{max}$ is reached during the power stroke. In Fig 2. several outliers lie on the ΔP_{max} end. Fig 3. collage A, the first image shows promising initial flame structure, however, it is delayed in time. Despite this, the jets quench and failed to re-ignite later in the cycle. This behavior can be attributed to slow re-ignition driven primarily by the adiabatic cooling effect during the power stroke. Due to delayed ignition (late inflammation in the PC), the hot turbulent gases mix with the cooler surroundings and further lose heat through expansion, leading to significant quenching.

Fig. 2 shows a positive though weak correlation between $\Delta P_{\max}$ and $CA\Delta P_{max}$. We can associate an increase in peak pressure in the PC with a greater propensity for quenching effects (blue markers). The analysis of individual cycle phenomenology also indicates that cycles with symmetric flame emergence (yellow dots) ignite very robustly, even at high ΔP_{max} (green dots). On the other hand, cycles with delayed inflammation in the PC (red markers, late $CA\Delta P_{max}$) show very high quenching propensity even at low ΔP_{max}.

Fig. 3 probes into the findings based on Fig. 2 by visualizing the combustion for selected cycles. In collage B, the first image shows significant IR signal (gray) indicating hot products from PC, which are leading the flame (red hues) by a significant margin, indicating that all jets quenched at the tip. As the cycle progresses, the flame jets in the bottom and left fail to re-ignite. This suggests that the increased jet momentum induced strong mixing with colder and leaner MC air-fuel mixture, suppressing the MC jet re-ignition and leading to strongly quenched cycle.

Conversely, symmetric cycles exhibited minimal to no quenching. In Fig. 3, collage C, images 1-4 show the flame effectively trailing the hot jet with minimal lag, and propagating to the cylinder wall accompanied with widespread intensity OH* signals. While the internal dynamics of the PC cannot be observed in current setup, it can be hypothesized that in this cycle the jets has similar composition and the flame in PC reached all nozzles simultaneously. This led to minimal quenching. On the other hand, cycle B shows significant asymmetry of hot jets even though the pressure difference across all nozzles is identical. This suggests asymmetric mixture or flame evolution in the PC, which lead to strong quenching.

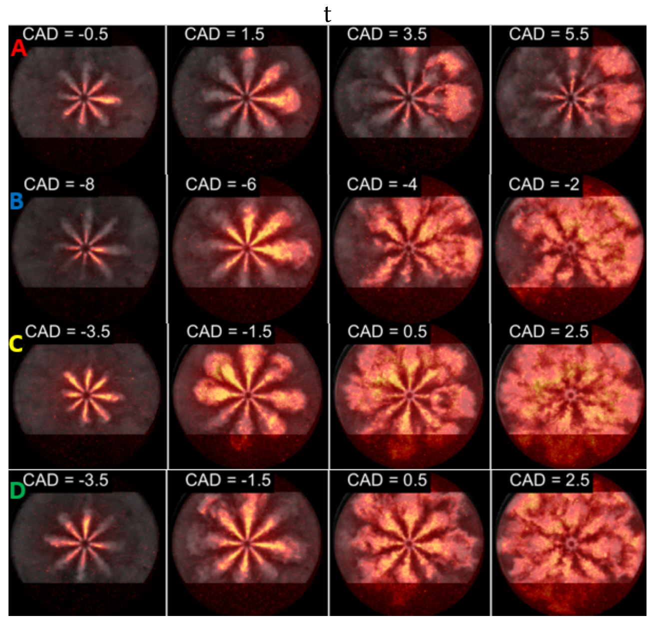

Figure 3. Collages of combustion images showing key phenomenology: A. cycles with late $CA\Delta P_{max}$, B. high $\Delta P_{max} > 12bar$, C. a symmetric flame pattern, D. a symmetric flame and $\Delta P_{max} > 12bar$.

Cycles that produced high peak pressure and displayed symmetric tendencies showed signs of quenching but also evidence of re-ignition (Fig. 3, collage D). First image resembles collage B's with the jet leading the flame by a substantial margin. Despite this, the second image shows re-ignition of several jets, with most jets showing well developed flame by the third image. It can be hypothesized that favorable composition of hot jets enable jet re-ignition despite the initial quenching resulting from high ΔP_{max}.

4 Conclusion

Flame quenching is a key mechanics in cyclic variability of combustion in PCSI NG engines and therefore, a key contributor to combustion lean limit. This work investigated the phenomenology of jet quenching in heavy-duty PCSI engine operated at $\lambda = 1.15$ and MC $\lambda = 1.8$. The results revealed a correlation of peak PC pressures and quenching propensity. The primary mechanism appears linked to excessive turbulence, which rapidly mixes hot PC products with fresh mixture, reduces local temperatures and prevents re-ignition of the jets. Retarded PC ignition also contributes to quenching as the charge expansion during the power stroke further lowers the temperatures, emphasizing the need for appropriately timed ignition. Lastly, the symmetry of combustion in the PC was shown to impact the quenching, with cycles showing asymmetric jet emergence in the MC being more prone to quenching. This suggests that optimal PC operation includes a homogeneous constitution of air-fuel mixture in the PC, a symmetric PC geometry, and a good control over peak PC pressure.

Acknowledgments

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