Applied Energy 171 (2016) 120–132

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Cycle-to-cycle variations in diesel engines

Panagiotis Kyrtatos *, Clemens Brückner, Konstantinos Boulouchos

ETH Zurich, Sonneggstrasse 3, 8092 Zurich, Switzerland

HIGHLIGHTS

- Cycle-to-cycle variations are examined in a heavy duty diesel engine.
- Effects of ignition delay on diffusion combustion are studied.
- Randomly occurring cylinder excitation leads to increased diffusion combustion rate.
- Intermittent increased diffusion combustion rate is found to cause cyclic variation.
- Extreme cycles are found to influence the averaged cycle significantly.

ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form 3 March 2016
Accepted 5 March 2016

Keywords:
Cycle-to-cycle variations
Diesel combustion
Ignition delay
Pressure fluctuations
Diffusion combustion

ABSTRACT

Cyclic variations in diesel engines are undesirable since they are understood to lead to lower efficiency and higher emissions, as well as power output limitations. This work aims to improve the understanding of the source of cycle-to-cycle variations of in-cylinder pressure in conventional diesel engines and the implications these have for measurement and simulation best practices. Measurements in a single-cylinder diesel engine employing single injection, under low temperature end-of-compression conditions and variable charge O_2 concentration have shown that in-cylinder pressure fluctuations – i.e. excitation of the first radial mode of vibration of the cylinder gases, caused in single cycles by the rapid premixed combustion – result in increases in diffusion heat release rate. The average intensity of the pressure fluctuations was shown to increase with increasing amount and reactivity of the premixed combustion. This results in higher cycle-to-cycle variations under these conditions, revealed by greater cyclic deviations of maximum pressure.

A study of the single cycle pressure fluctuation intensity under long ignition delay conditions revealed that despite the increase of average intensity of fluctuations with increasing premixed reactivity, even under these conditions some cycles exhibited no pressure fluctuations. This indicates that the high premixed combustion rate is not in itself a sole prerequisite for the onset of the resonance of cylinder gases, with other, "random" effects also required to induce the pressure oscillations. Finally, under low temperature charge conditions the difference in peak pressure between the average cycle and cycles showing low fluctuation intensity was measured to be >3 bar (>3% of the peak). In all, these results underline the need for further understanding of the source of the pressure fluctuations and the effect of these cyclic variations on single-cycle and average emissions. The effect of the highly fluctuating cycles on the average cycle should lead the scientific community conducting measurements and simulations on such engines to reconsider the best practices for acquiring, evaluating and interpreting measured data. In addition, the community should acknowledge the contribution of extreme cycles when averaged data is used for simulation validation.

1. Introduction

Cycle-to-cycle variations in reciprocating internal combustion engines, where the in-cylinder pressure varies significantly on a cyclic basis, have been a subject of increased interest in the past decades. Cyclic variations are generally undesirable since they are understood to lead to lower efficiency and higher emissions, as well as power output (drivability) problems [1,2]. In addition, in cases where the peak pressure is the limiting factor for maximum power output, cyclic variations of peak pressure limit the power density of an engine. They are also expected to hinder the applicability of emission reduction strategies which only function

* Corresponding author at: Sonneggstrasse 3, ML L13, 8092 Zurich, Switzerland.
E-mail addresses: kyrtatos@lav.mavt.ethz.ch (P. Kyrtatos), brueckner@lav.mavt.ethz.ch (C. Brückner), boulouchos@lav.mavt.ethz.ch (K. Boulouchos).

http://dx.doi.org/10.1016/j.apenergy.2016.03.015
0306-2619/

within very limited operating windows (this includes most novel strategies such as PCCI, HCCI, LTC), since small changes in the cycle can lead to significant changes in emissions [3,4] (e.g. around the limit of PCCI, where small changes in the spray formation and combustion can lead to soot formation, which will subsequently not fully oxidize, rather than soot-less combustion).

Cycle-to-cycle variations are most commonly observed in Spark Ignition (SI) engines, where they are caused by changes in the burn rate for each successive cycle. This variation can have numerous root causes; cyclic variation in the cylinder gas motion, cyclic variation in the amount of fuel, air and exhaust gases present in the cylinder, or cyclic variation of the mixture composition near the spark plug, leading to differences in combustion speed or local end-gas autoignition [5,6]. These effects have been studied extensively in the past using experimental [7–9] and numerical tools [6,10–12] and are considered to be well understood. Similarly, in Homogeneous Charge Compression Ignition (HCCI) engines, high cyclic variations are expected due to the high influence of small perturbations in temperature and composition on the charge autoignition [13–15].

Significant cycle-to-cycle variations are less common in conventional Compression Ignition (CI) diesel engines. This is due to the nature of dominantly non-premixed CI combustion, where fuel injection primarily governs air–fuel mixing and thus combustion. Most high-speed modern diesel engines employ multiple pilot injections which aim to reduce main injection ignition delay, resulting in mostly diffusion-dominated combustion. Any cyclic variation in background turbulence (swirl, etc.) is minimal and will not affect the combustion rate significantly during the injection, since its intensity is multiple times lower than the injection-sourced turbulence. Nevertheless, there exist cases where CI combustion also exhibits cyclic variability; the root cause of this variability has usually been connected to instabilities in the fuel injection system or to prolonged ignition delay. Koizumi et al. [16] reported that the cyclic variation observed in the indicated mean effective pressure of an indirect injection (IDI) diesel engine was caused by variations in the injected mass. Similarly, Wing [17] found that cyclic variations observed in a rotary fuel-pump injected diesel engine were due to variations in the injection timing between cycles. More recently, Zhong et al. [18] and Yang et al. [1] have also attributed the observed cyclic variations in diesel engines to variations in the fuel path.

Apart from variations which were attributed to instabilities of the injection systems, studies have also shown an increase of cyclic variation with prolonged ignition delay. Schmillen et al. [19] state that the variation in injection cannot explain the observed variation in in-cylinder pressure. In [20], studies of cold start in CI engines showed that colder in-cylinder conditions led to increased ignition delay (ID), which resulted in heavy cycle-to-cycle variations of in-cylinder pressure. Furthermore, in [1,2,21–24], increased cycle-to-cycle variations were observed in direct injection (DI) diesel engines when changing the intake temperature, intake pressure (load) and injection timing parameters in order to create conditions of prolonged ignition delay. Studies concerning the variation of in-cylinder pressure using various fuels or fuel blends have shown a dependency of cyclic variation on the ignition characteristics of the fuels tested, with fuels with lower cetane number (CN) exhibiting larger cycle-to-cycle variation [1,2,23–27].

To this point, most authors reporting cyclic variations of in-cylinder pressure in diesel engines (excluding the literature where the cause was attributed to the injection system) have described the variability as random or stochastic, with no possibility of short term prediction [2,3]. Experiments in optically accessible engines have identified slight (or more significant) differences in the ignition pattern of individual sprays [19,28] as the source of the cyclic variations. Bizon et al. [29] showed that high cyclic variations are apparent in the in-cylinder luminosity level in diesel engines, but not in the pressure evolution under conventional diesel combustion conditions. Finally, Sczomak et al. [24] have identified the cyclic variability of ignition delay of each cycle as measured from the indicator diagram as the cause of the cyclic variation in in-cylinder pressure.

Detailed studies of the cycle-to-cycle variations of emissions from diesel engines have been limited in number. This can be attributed to the normally negligible cyclic variation of in-cylinder pressure which is encountered under conventional diesel conditions. This often leads to the assumption that limited variations in emissions will follow. Nevertheless, some publications have hinted on the possibility of significant cyclic variations in emissions arising due to various reasons. Wing [17] used NO emission modeling to predict the effect of cyclic variation in injection timing on NO_x emissions. The study showed an increase of the order of 5% in average NO_x emissions when a point with fluctuating injection timing was compared to a stable point, due to the higher contribution of NO_x from the cycles with advanced injection.

Under conditions where the injection is assumed to be stable, investigations have also showed variations in emissions. In [30], fast NO measurements in a heavy duty diesel engine showed significant variations in the NO concentration in the exhaust at constant operating conditions. Ultra-fast crank angle-resolved NO measurements in the exhaust stream of a marine two-stroke and a marine four-stroke engine showed variations of 20–25% and 15–20% respectively from cycle-to-cycle, at constant running conditions [31–33]. Significant cyclic variations in NO production rate which were not coupled to changes in heat release rate (HRR) were also observed in complete cylinder dumping experiments during combustion in a DI diesel engine in [34]. Finally, Wagner [35] revealed that under conventional diesel and constant injection conditions, NO concentrations measured through sampling of the exhaust showed cyclic variations of the order of 10%, while in-cylinder pressure, ID and HRR exhibited only very slight cyclic variation. Nevertheless, there was no clear correlation between variations in HRR and NO observed in this study, leading to the conclusion that variations in NO emissions were caused by random effects, possibly not coupled to HRR (i.e. combustion phasing).

In terms of cyclic variation of in-cylinder soot mass in DI diesel engines, there have been numerous studies which show significant cycle-to-cycle deviation [26,35–37]. Zhao and Ladommatos [36] argue that the large cycle-to-cycle variations in the time-resolved in-cylinder soot radiation measured using an optical probe are due to the random movement of the soot cloud, or random changes in location of the soot cloud in different cycles. On the other hand, Jakob et al. [26] argue that the observed cyclic variations in soot luminosity measured in an optical single-cylinder diesel engine are caused by combustion instabilities. This conclusion was based on the observation that the instabilities were amplified when using fuels with lower cetane number and thus longer ignition delay. Finally, investigations of soot location and intensity using soot luminosity and soot-LII (Laser Induced Incandescence) in an optically accessible engine showed high soot luminosity variations with split injection, while the measured HRR remained relatively constant [37].

Prior research from the current authors [38] showed that cyclic variability in a medium speed diesel engine appears to scale exponentially with ID. The variation in ID was achieved by varying the Miller valve timing degree [39,40], i.e. adjusting the inlet valve closure (IVC) timing while adapting the turbocharging system to change the boost pressure and keep the charge density and thus air–fuel ratio constant. In [38], the cyclic variability was shown to be connected to in-cylinder pressure fluctuations (diesel "ringing", equivalent to the similar effects observed in HCCI combustion [41,42]) arising from rapid energy release during combustion. In