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Cycle-to-cycle variations of NO emissions in diesel engines under long ignition delay conditions

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ABSTRACT

Cycle-to-cycle variations in combustion have been observed in diesel engines when operating under long ignition delay conditions. In this work, cyclic variations of NO emissions are investigated in a single-cylinder direct injection diesel engine employing a single-injection strategy under long ignition delay conditions. Two measurement sets are used to study the effect of ignition delay and amount of diffusion combustion on cyclic variations. Single-cycle NO concentration was measured using a fast NO analyzer sampling above the exhaust valve. Measurement results confirmed previous investigations reporting the presence of in-cylinder pressure fluctuations – i.e. excitation of the first radial mode of vibration of the cylinder gases by the rapid premixed combustion – which arise intermittently in cycles. The probabilities of cycles showing pressure fluctuations and the intensity of the fluctuations were shown to increase with increasing ignition delay. Pressure fluctuations were confirmed to enhance air–fuel mixing and increase diffusion combustion rate. In cases with significant diffusion combustion, cycles with pressure fluctuations showed higher-than average NO concentrations, with the intensity of fluctuation determining the increase in NO. At low charge temperature, single-cycle NO concentrations measured in cycles with the highest pressure fluctuations were ∼60% higher compared to the lowest values measured at unchanged conditions. On the contrary, measurement points where no diffusion combustion was present showed lower cyclic variation of NO, and no correlation between pressure fluctuation intensity and NO emissions. In cases with high amounts of diffusion combustion, the effect of fluctuations on average NO emissions correlated with increasing ignition delay. At conditions with short ignition delay, the discrepancy in NO concentration between cycles with low pressure fluctuation intensities and the average NO concentration of all cycles was below 0.5%, whereas at high ignition delay this increase was measured to be up to 10%. This indicates that at the latter conditions, the contribution of cycles with high pressure fluctuation intensities results in a significant increase in average NO emissions. In all, the results of this investigation underline the necessity for the determination of the contribution of single-cycles to observed emission trends in diesel engines, with significant implications on measurement and simulation best practices.

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].

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, cyclic variation of the mixture composition near the spark plug, or changes in the spark discharge characteristics, leading to differences in combustion speed or local end-gas autoignition [3–5]. These effects have been studied extensively in the past through experimental investigations [6–8] and using numerical tools [4,9–11]. Similarly, in Homogeneous Charge Compression Ignition (HCCI) engines, high cyclic variations are expected due to the high influence of small perturbations in local temperature and composition on the charge autoignition [12,13].

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

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injection primarily governs air–fuel mixing and thus combustion. Any cyclic variation in background turbulence (swirl, etc.) 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 (ID) conditions (e.g. cold start, low effective compression ratio, low fuel cetane number etc.). Koizumi et al. [14] 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 [15] 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. [16] 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 ID. Schmillen et al. [17] state that the variation in injection cannot explain the observed variation in in-cylinder pressure. In [18], studies of cold start in CI engines showed that colder in-cylinder conditions led to increased ID, which resulted in heavy cycle-to-cycle variations of in-cylinder pressure. Furthermore, in [1,2,19–22] 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 ID. 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 [1,2,21–25].

To this point, most authors reporting cyclic variations of in-cylinder pressure in diesel engines (excluding the literature where the variations were attributed to the injection system) have described the variability as random or stochastic, with no possibility of short term prediction [2,26]. Experiments in optically accessible engines have identified slight (or more significant) differences in the ignition pattern of individual sprays [17,27] as the source of the cyclic variations. Bizon et al. [28] 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. Sczomak and Henein [22] have identified the cyclic variability of ID of each cycle measured from the indicator diagram as the cause of the cyclic variation in in-cylinder pressure.

Concerning engine-out emissions, detailed studies of the cycle-to-cycle variations in NO_x emissions from diesel engines have been limited. This can be attributed to the normally limited cyclic variation of in-cylinder pressure which is encountered under conventional diesel conditions, leading to the assumption that limited variation in emissions will follow. Nevertheless, some publications have hinted to the possibility of substantial cyclic variations in emissions arising due to various reasons. Wing [15] 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 shown significant cyclic variations in emissions. In [29], fast NO measurements in a heavy duty diesel engine showed variations in the NO concentration in the exhaust at constant operating conditions. Similarly, 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 operating conditions [30–32]. 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 [33]. Wagner et al. [34] revealed that under conventional diesel combustion conditions with constant, stable injection, NO concentrations measured through sampling of the exhaust gases 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 the HRR. More recently, in measurements of in-cylinder NO concentrations in an optical engine using NO PLIF (Planar Laser-Induced Fluorescence), Verbiezen et al. [35,36] observed significant cyclic variations, attributed to local NO concentration and temperature variations, as well as variations in signal attenuation.

Prior research from the current authors [37,38] showed that cyclic variability in a 6-cylinder medium speed diesel engine and a single-cylinder research engine appears to scale exponentially with ID. The change in ID was achieved in both cases by changing the intake temperature and/or varying the Miller valve timing degree, i.e. adjusting the inlet valve closure (IVC) timing while adapting the boost pressure to keep the charge density and thus air–fuel ratio constant. In [38], measurements under low end-of-compression temperature conditions and variable charge O_2 concentration showed that in-cylinder pressure fluctuations – i.e. excitation of the first radial mode of vibration of the cylinder gases (for the calculation of the mode of vibration see [39]), caused in single cycles by the rapid premixed combustion under long ignition delay conditions – resulted in increases in diffusion HRR. The average intensity of the pressure fluctuations was shown to increase with increasing amount and reactivity of the premixed combustion. This resulted in higher cycle-to-cycle variations under these conditions, revealed by higher cyclic deviations of maximum pressure. A study of the single-cycle intensity of pressure fluctuations under long ID conditions revealed that although the average intensity of fluctuations increases with increasing premixed reactivity, even with high premixed amounts, 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, seemingly "random" effects also required to induce the pressure oscillations.

In [37], in-cylinder pressure and soot density evolution measurements, calculated through 3-color pyrometry using a specially developed optical probe, allowed the comparison between fluctuating and non-fluctuating cycles at constant charge air and injection conditions. Consecutive cycles showed significant differences in peak cylinder pressure, diffusion combustion rate and time-resolved soot concentrations in the combustion chamber. A detailed analysis of in-cylinder pressure and soot concentration from numerous consecutive cycles at long ID conditions showed that pressure oscillations of varying intensity were observed in cycles with similar ID and premixed combustion rate.

The above results indicate an increased apparent fuel–air mixing caused by the pressure oscillations within the combustion chamber, which leads to increased heat release and soot oxidation rates during the mixing-controlled diffusion combustion phase. Thus, there is clear evidence that the intermittent presence and intensity of pressure oscillations is the main cause for the observed cyclic variation in combustion rate and thus in-cylinder pressure. These findings are in line with observations arising from mixing and combustion experiments of single droplets and sprays under conditions having pressure oscillations. Blaszczyk [40] showed that