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Effects of Transient Valve Timing on Particulate Emission Concentration of a Homogeneous Charge Compression Ignition Engine

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Abstract

To quantify the particle emissions from a Homogeneous Charge Compression Ignition (HCCI) engine, a fast-response differential mobility spectrometer (DMS) is used during transient operation to measure momentary changes in particle concentration and size distribution. The DMS has a time response of 500 ms (10-90% rise time) and a sample rate of 2 Hz is used while the engine is operated at approximately 820 rpm or 7 cycles/s. A single cylinder engine with electromagnetic valves is used to test the effect of changing valve timing on particle emissions. During steady-state operation of the single cylinder engine at both 60° and 180° of symmetric negative valve overlap (NVO), average particle emissions of 6.0×10^7 and 5.7×10^7 cm^{-3} respectively are measured. These values agree well within error. The geometric mean diameters (GMD) of both tests are also comparable at 15 nm and 16 nm, respectively. Particulate emissions are then recorded while switching the valve timing between 60° and 180° NVO in order to see the effect of a change in engine operating conditions. An order of magnitude increase in particle concentration coincides with the valve timing changes. These concentration spikes range from 1×10^8 to 3×10^8 cm^{-3}. This variability is attributed to the time response limitation of the DMS causing some samples to be taken during the first cycle after the valve timing change versus some being taken during subsequent cycles. After a spike in particle concentration due to a timing change, the value quickly returns to steady-state levels. The GMD remains at 15 nm throughout the test, suggesting that while the particle concentration increases due to timing changes, the mechanism for particle formation does not change.

1. Introduction

In Homogeneous Charge Compression Ignition (HCCI) a fully mixed fuel and air charge auto-ignites at a high compression ratio. Because of this, HCCI can provide significant improvements in both efficiency and emissions over that of conventional internal combustion engines. Engine efficiency is improved with increased compression ratio [1,2]. The homogeneous charge prevents a region of rich combustion, which reduces the formation of solid particles [3]. Often, in HCCI engines, the peak in-cylinder combustion temperature is lower due to a lean mixture and this results in much lower levels of nitrous oxides [3,4].

In automotive applications, the engine speed and load often change quickly to accommodate the demands of the driver. In order to understand the particle emissions from HCCI engine operation, it is important to consider the effect that changing engine operating conditions has on particle size and concentration. To be able to observe these transitory effects, it is necessary to measure the particle emissions with fast-response equipment. Previous work has been done to measure the particle emissions from gasoline HCCI engines [5-9], but no work has been done to measure the transient particle emissions for such an engine. It is important to consider particle emissions from HCCI engines because automotive particle emissions are regulated. Diesel engine particle mass has long been regulated, however, Euro 5/6 standards introduced particle number regulations for diesel vehicles, as well as particle mass regulations for gasoline vehicles. Beginning in 2014, particle emission number regulations will also be applied to gasoline vehicles [10].

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2. Experimental Setup

A single-cylinder Ricardo experimental engine with fully-variable electromagnetic valves [11] is used and is schematically depicted in Figure 1. The valves allow cycle by cycle switching of the engine operating conditions. The engine is operated at approximately 820 rpm (7 cycles/s) with valve timings of both 60° and 180° of symmetric negative valve overlap (NVO) [12]. NVO causes the exhaust valve to close before the intake valve is opened. To increase the negative valve overlap the exhaust valve closing timing is advanced and the intake valve opening time is retarded. This causes more hot residual gases to be trapped, which advances the combustion timing and the peak combustion pressure. Cylinder pressure traces as a function of crank angle for both operating conditions are shown in Figure 2.

A fast-response differential mobility spectrometer (DMS) is used to measure the particle emissions created during engine operation. The DMS measures the particle size distribution from which the total particle concentration can be calculated. The DMS has a response time of 500 ms (which is on the same order as the engine speed) and the sampling rate is set to 2 Hz. Engine emissions are sampled immediately downstream of the exhaust valve in order to reduce particle losses due to diffusion or thermophoretic deposition. The sampling line utilizes a line controller in order to heat the exhaust gases to 70°C and dilutes the mixture at the sampling head by a ratio of 5. This prevents diffusion and thermophoretic deposition, as well as particle formation through nucleation or accumulation. Once the exhaust gases reach the DMS, they are further diluted by a ratio of 6 before being sampled, giving a cumulative dilution of 30 (except during the 60° NVO steady-state test where the second stage dilution is set to 1).

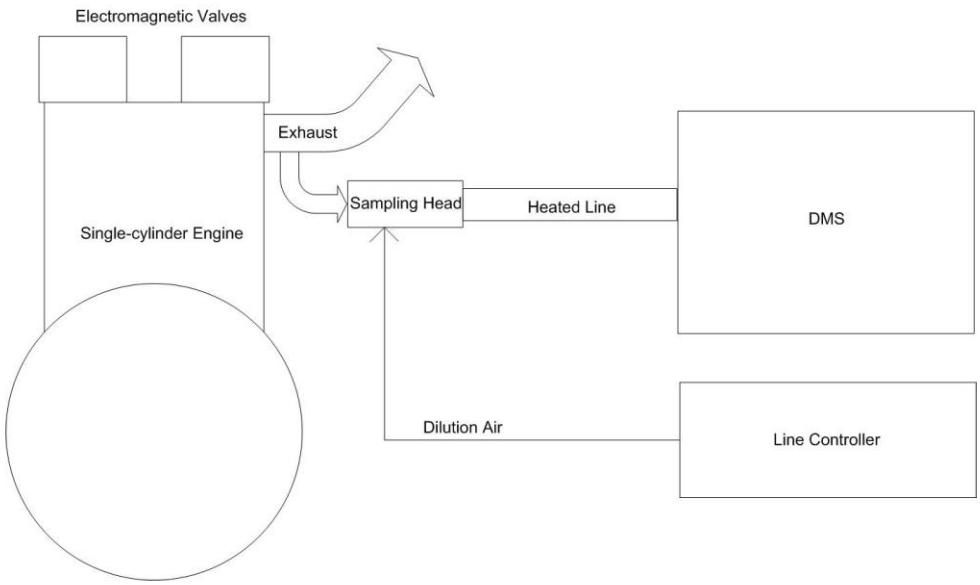

Figure 1: Single Cylinder Engine – Schematic of Experimental Setup

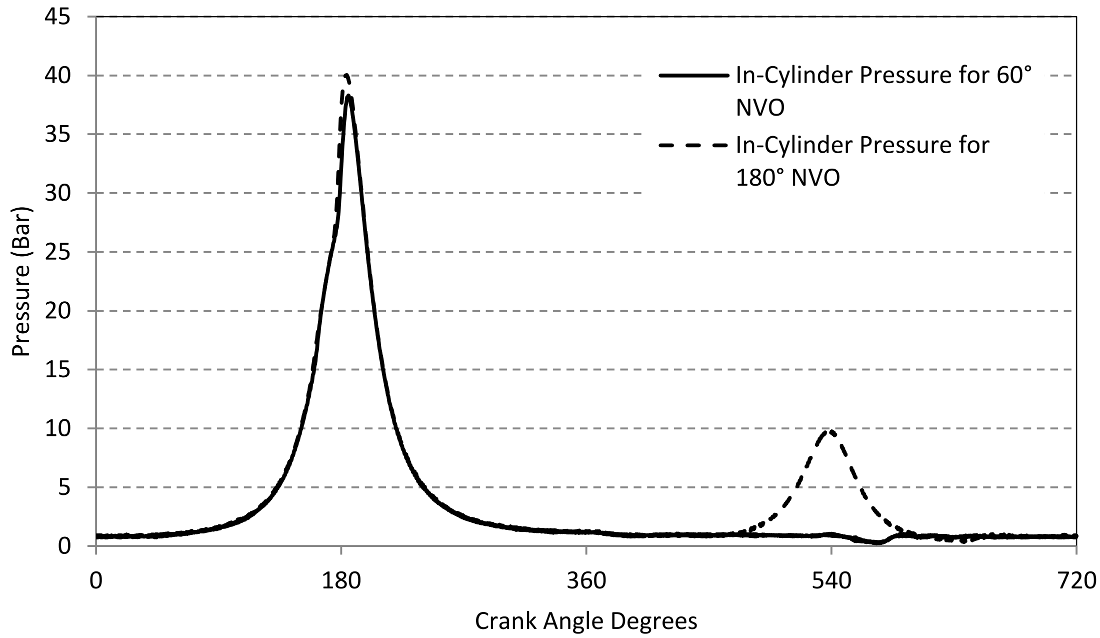

Figure 2: Representative in-cylinder pressure trace for HCCI combustion with 60° and 180° NVO.

3. Results

To establish the baseline particle emissions, the DMS is first used to measure the steady-state particle emissions for both 60° and 180° of negative valve overlap. The average particle distribution for 60° and 180° NVO are shown in Figure 3. For 60° NVO the geometric mean diameter (GMD) is 15.1 ± 1.5 nm with a geometric standard deviation (GSD) of diameter of 1.56. The average particle concentration is $6.0 \times 10^{7} \pm 1.7 \times 10^{7}$ cm^{-3} (all uncertainties are given with 95% confidence). For 180° NVO the GMD is 16.0 ± 1.6 nm with a GSD of 1.51. The average particle concentration is $5.7 \times 10^{7} \pm 1.8 \times 10^{7}$ cm^{-3}. Operating at both 60° and 180° NVO results in similar particle distributions and total number concentration. These two operating points also agree well within the uncertainty of the instrument.

After establishing the steady-state particle emissions for both 60° and 180° NVO, the DMS is used to record measured particle emissions while the valve timing is repeatedly changed back and forth between 60° and 180° NVO. A pseudo random binary signal (PRBS) is used to switch between valve timings. This signal randomly excites the system (i.e. the engine) over a wide range of frequencies. This ensures a change in engine operation is due to the valve timing change and not a result of a natural engine frequency. It is important that the particle emissions are observed for a random selection of cycles to give a representative measurement of all engine cycles. This is achieved by switching back and forth between the two operating points a large number of times at random intervals.

The total particle concentration measured by the DMS during the transient test, as well as the time-averaged total particle concentration for the steady-state tests at 60° and 180° NVO are shown in Figure 4 for comparison. The valve overlap used during the transient test is also shown. Synchronizing (in time) the particle concentration measurements with the valve timing for each cycle, it is apparent that there is a close correlation between the peaks in particle concentration and the timing changes. However, because the DMS sampling rate is lower than the engine cycle rate, not every timing change event resulted in a visible spike in particle concentration. The particle concentration between spikes is at similar levels to the steady state operation; whereas, the spikes observed in particle concentration due to a valve timing change increase by nearly an order of magnitude. The highest concentration observed was approximately 2.7×10^{8} cm^{-3}, however, the time-response limitation of the DMS (500 ms) means that the particle concentration would be attenuated, and because of the sampling rate (2 Hz), the maximum could be missed. Thus, the actual maximum particle concentration corresponding to a change in valve timing is expected to be greater than the measured value.

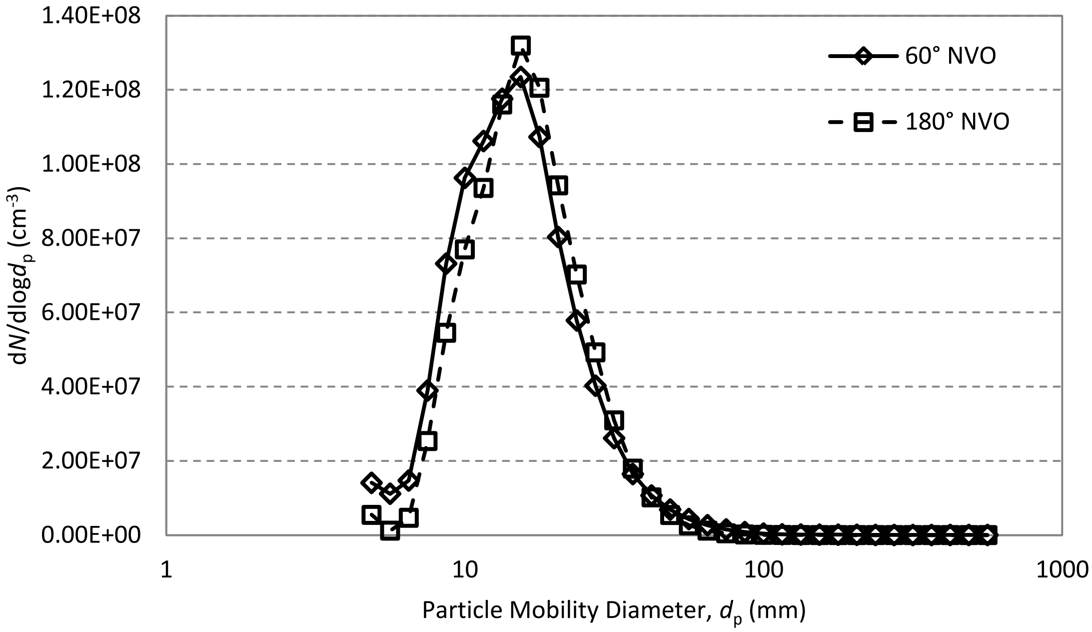

Figure 3: Particle distribution for steady-state 60° and 180° negative valve overlap.

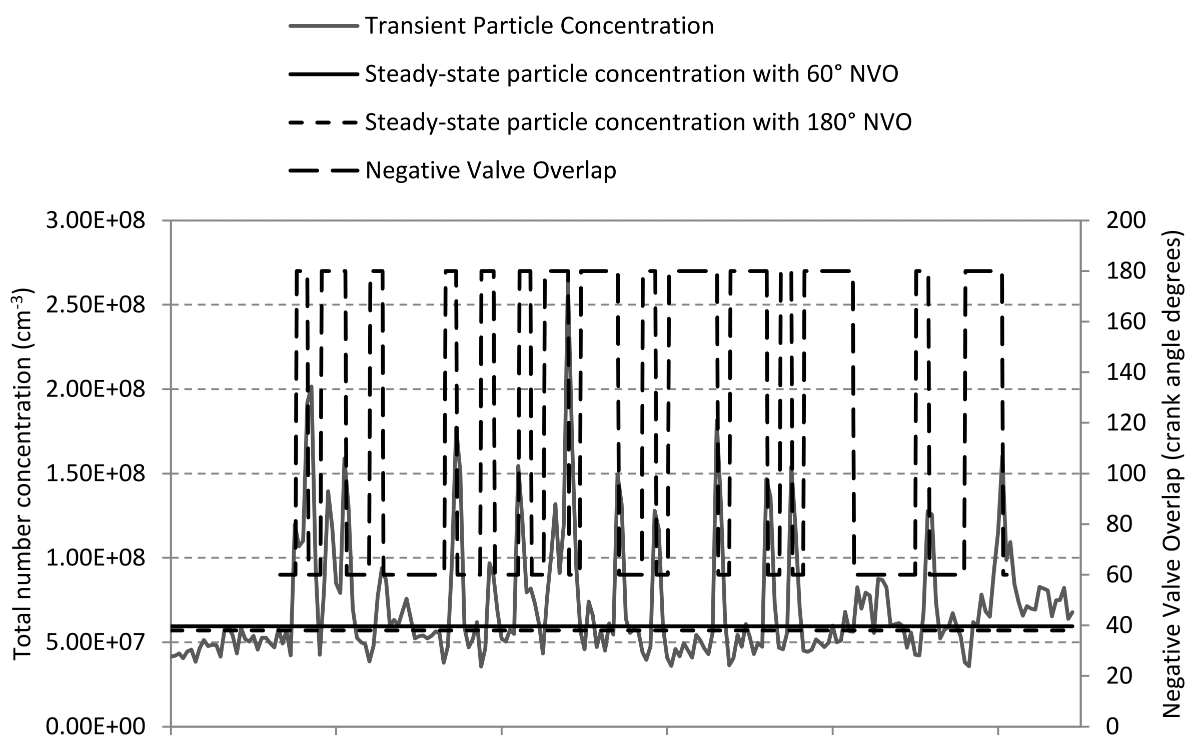

Figure 4: Particle concentration measured during transient engine operation. Steady-state particle concentrations recorded at 60° and 180° NVO are also shown, but are not a function of time and are included only for comparison. Negative valve overlap is also shown and corresponds to the secondary *y*-axis.

While using a DMS allows for fast measurements of transient particle distribution, it would also be useful to measure the mass or number concentration in an integrated fashion to quantify the magnitude of the increase in emissions under these transient conditions. For example, the integrated mass concentration could be measured with filter measurements, but this has not yet been done.

The particle size distribution during transient operation is shown in Figure 5. This figure graphically depicts the particle concentration peaks due to valve timing changes. While the particle concentration spikes as a result of changing operating conditions, the median diameter and GSD remain fairly constant. The GMD remains at 15 ± 1.5 nm throughout the test. Also, the size distribution remains unimodal. This suggests that the mechanism for particle formation remains the same, whereas the presence of larger particles would suggest the formation of new types of particles, like soot. Previous steady-state experiments on another single cylinder engine resulted in similar size distributions and volatility experiments suggested that the particles are likely composed of unburnt lubricating oil [13]. Therefore, it is likely that the particles generated by this engine are also lubricating oil; however, this was not tested because the volatility experiments require long sampling times.

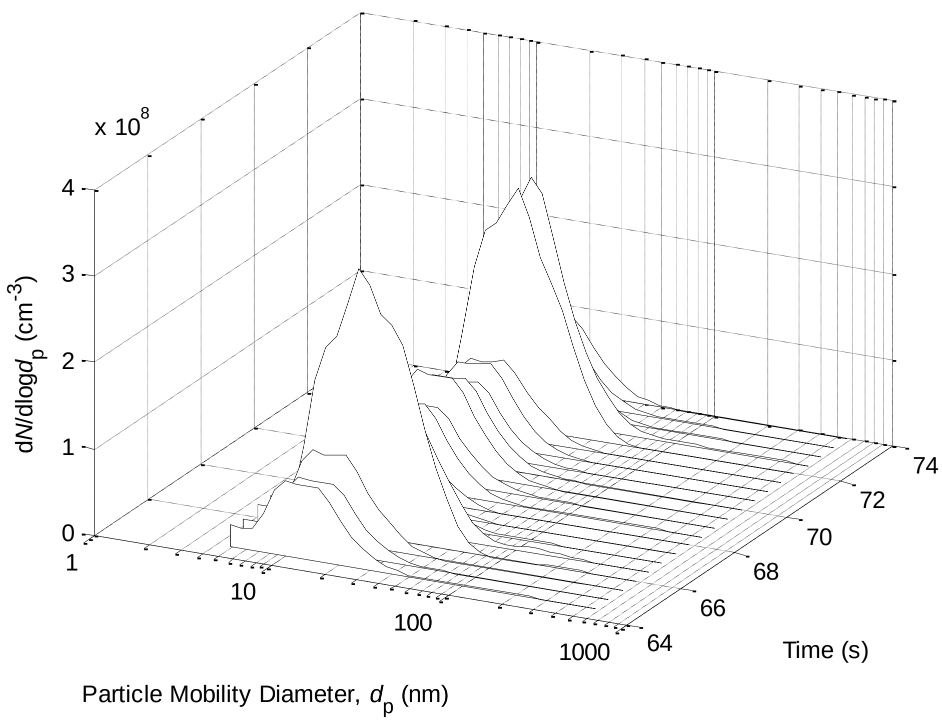

Figure 5: Size distributions from transient measurements showing concentration spikes due to changing operating conditions.

4. Conclusions

HCCI engines in automotive applications are constantly required to change loads and speeds due to driver commands. In order to quantify the particle emissions produced in HCCI combustion, a fast-response differential mobility spectrometer is used to measure the particle concentration and size distribution during steady state and transient engine operation. Electromagnetic valves that allow for cycle-by-cycle valve changes are used in a symmetric negative valve overlap strategy which results in nearly an order of magnitude spike in particle concentration. These transient changes to valve timing are followed by a quick return to steady-state levels and the size distribution indicates that while the concentration increased, the distribution remains quite similar. This suggests that the mechanism for particle formation remains the same. Previous work with steady state volatility testing indicates that the particulate emissions are volatile and are mostly composed of engine oil.

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