Extending Exhaust Gas Recirculation Limits in Diesel Engines

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ABSTRACT

This paper addresses the application of high exhaust gas recirculation (EGR) for reduced nitrogen oxide emissions from diesel engines. The research objective is to develop fundamental information about the relationship between EGR parameters and diesel combustion instability and particulate formation so that options can be explored for maximizing the practical EGR limit, thereby further reducing nitrogen oxide emissions while minimizing particulate formation. A wide range of instrumentation was used to acquire time-averaged emissions and particulate data as well as time-resolved combustion, emissions, and particulate data. The results of this investigation give insight into the effect of EGR level on the development of gaseous emissions as well as mechanisms responsible for increased particle density and size in the exhaust. A sharp increase in hydrocarbon emissions and particle size and density was observed at higher EGR conditions while only slight changes were observed in conventional combustion parameters such as heat release and work. Analysis of the time-resolved data is ongoing.

INTRODUCTION

Exhaust gas recirculation (EGR) has been used in recent years to reduce NO_x emissions in light duty diesel engines.[1-3] EGR involves diverting a fraction of the exhaust gas into the intake manifold where the recirculated exhaust gas mixes with the incoming air before being inducted into the combustion chamber. EGR reduces NO_x because it dilutes the intake charge and lowers the combustion temperature. A practical problem in fully exploiting EGR is that, at very high levels, EGR suppresses flame speed sufficiently that combustion becomes incomplete and unacceptable levels of particulate matter (PM) and hydrocarbons (HC) are released in the exhaust. This transition to incomplete combustion is characteristically very abrupt due to the highly nonlinear effect of EGR on flame speed. In a transient operating environment, it is particularly difficult to reliably approach this instability limit without occasionally producing undesirable bursts of HC and PM emissions. The result is that diesel engines must be typically operated significantly below their maximum EGR potential, thus penalizing NO_x performance.

The objective of this work is to characterize the effect of EGR on the development of combustion instability and particulate formation so that options can be explored for maximizing the practical EGR limit. We are specifically interested in the dynamic details of the combustion transition with EGR and how the transition might be altered by appropriate high-speed adjustments to the engine. In the long run, we conjecture that it may be possible to alter the effective EGR limit (and thus NO_x performance) by using advanced engine control strategies.

All experiments described here were performed on a modern turbo-charged, direct-injection automotive diesel engine. This engine was selected on the basis that it is likely to reflect the

EGR response of more advanced diesel engines proposed for automotive use. We also expect that the results of this study will be applicable to stationary CIDI engines, especially those experiencing transient load and/or speed demands.

EXPERIMENTAL METHODS

Experiments were performed on a 1.9 liter, four-cylinder Volkswagen turbo-charged direct injection engine under steady state, low load conditions. Engine speed was maintained constant at 1200 rpm using an absorbing dynamometer and fuel flow was set to obtain 30% full load at the 0% EGR condition. A system was devised to vary EGR by manually deflecting the EGR diverter valve. The precise EGR level was monitored (on a volume basis) by comparing NO_x concentrations in the exhaust and intake. NO_x concentrations were used because of the high accuracy of the analyzers at low concentrations found in the intake over a wide range of EGR levels.

In typical experiments to date, fuel flow rate and injection timing were maintained constant while EGR was increased. This operating strategy introduces a complication in the analysis because the engine air-to-fuel ratio is decreased with increasing EGR due to the displacement of intake air by recirculated exhaust gases. The effect of this decrease in air-to-fuel ratio on our observations is discussed below. In future experiments, fueling adjustments will also be made with EGR changes to keep the total air-fuel ratio constant.

Numerous steady state and crank angle resolved measurements were made for each EGR level, including in-cylinder pressure and exhaust gas constituents and PM. Measurement details are described below:

Data Acquisition Systems

High- and low-speed data acquisition systems (DAS) were used for recording engine measurements. At steady state conditions, the low-speed DAS was used to record various engine temperatures, pressures, and engine out emissions. A high-speed DAS developed by Real Time Engineering (RTE; Dearborn, MI) was used to record crank angle resolved in-cylinder pressure from three cylinders, exhaust HC concentration, and exhaust particle "density".

In-Cylinder Pressure Measurement Techniques

In-cylinder pressure data were recorded using Kistler piezoelectric pressure transducers mounted with glow plug adapters in three cylinders. Three thousand cycles of pressure data were recorded on a crank angle resolved basis for each EGR level using the RTE system. Integrated combustion parameters (e.g., work and heat release) were calculated by integrating the in-cylinder pressure data.

Gaseous Emissions Measurement Techniques

Steady state measurements were made of CO, CO_2, HC, NO_x, and O_2 concentrations in the raw engine-out exhaust using Rosemount and California Analytical analyzers. Crank angle resolved measurements were also made of HC concentration in the exhaust using a Fast Flame Ionization Detector (Cambustion HFR400 Fast FID; Cambridge, England). The HC sampling probe was located in the exhaust manifold and the data were recorded using the RTE system.

Particulate Measurement Techniques

Conventional measurement of automotive exhaust particulates requires that the exhaust be diluted. Dilution serves two purposes: it cools the exhaust and it lowers the dew point. In these experiments, the exhaust was diluted with clean, filtered air to approximately 35±5:1 by volume. Several instruments were used for characterizing particulates in the exhaust stream on a steady state (dilute) and crank angle resolved (raw) basis.

Dilution of Exhaust

A slipstream of exhaust is fed through a heat-traced 25 mm stainless steel line to a 100 mm dilution tunnel. A 250 mm blower is used to pull HEPA-filtered air through the tunnel, and samples are taken 1 m downstream of the exhaust inlet to the tunnel. This ensures uniform mixing of the filtered air and exhaust gases before being sampled by the PM instrumentation.

Particle Mass Concentration

A Tapered Element Oscillating Microbalance (TEOM model 1105; R&P Co., New York, NY) was used to measure particulate mass concentration and total mass accumulation as a function of time. A sample of diluted exhaust is pulled through a 12 mm filter to the end of a tapered quartz element. The frequency of the element changes with mass accumulation. The instrument has approximately 3 sec resolution on mass concentration.

Particle Size Distribution

A Scanning Mobility Particle Sizer (SMPS; TSI, Inc., St. Paul, MN) was used to measure the steady state size distribution of the particulates in the exhaust stream. The SMPS is the scanning version of an Electrical Mobility Analyzer which is used extensively in aerosol work. The particles are neutralized and then sorted based on their electrical mobility diameter. The range of the SMPS was set at 11 nm – 505 nm.

Rapid Particulate Mass Emissions

A Diesel Particle Scatterometer (DPS) was used to obtain rapid scattering measurements of a raw exhaust sample taken directly from the exhaust manifold. The DPS was designed and built by Lawrence Berkeley National Laboratory.[4] Under normal operation, it measures size distribution with a 1 sec response time. For this experiment, we used it to rapidly measure gross quantity of particulates by monitoring individual signals from its photomultiplier tubes so that it functioned as a fast "smoke" or particle "density" meter. The signals were acquired at each crank angle by the RTE system.

EXPERIMENTAL RESULTS

The previously discussed instrumentation was used to investigate the effect of EGR level on time-averaged and time-resolved combustion, emissions, and particulate behavior. When interpreting the discussion and data, recall that air-to-fuel ratio decreases toward stoichiometric with increasing EGR level. Also note that measured torque decreased approximately 15% from the lowest to the highest EGR level. All gaseous emissions and particulate data were measured in the exhaust stream before the catalyst.

Combustion Characterization with Cylinder Pressure

Net heat release (HR) and indicated mean effective pressure (IMEP) values were calculated for each cycle using cylinder pressure measurements according to well-established definitions.[5,6] These specific combustion parameters were selected for the initial analysis because they are widely used for engine combustion characterization. However, it is important to note that because HR and IMEP are evaluated over the entire power stroke, they represent an integrated assessment of the entire combustion event in the selected cylinder. Details of the combustion sequence such as ignition delay or the relative contributions of pre-mixed and diffusion combustion are typically not clearly revealed by HR and IMEP.

As shown in Figures 1 and 2, mean HR and IMEP showed no sudden changes as EGR was increased, but instead they decreased in a manner consistent with the overall engine efficiency. Similar trends were also exhibited by the coefficients of variation (COV) for these quantities, except that the change was positive with increasing EGR. This slight increase in COV may be indicative of the onset of combustion instability. However, the small magnitude of the COV change is in sharp contrast to the behavior observed for HC, NO_x, and PM, which changed dramatically. Apparently, the flame changes that produce these emissions are relatively subtle, and such subtle details are obscured by the pressure integration process. The COV in IMEP and heat release ranged from 1.0 to 1.8% for all data sets, which is well within accepted driveability limits. Thus, one would not expect a driver to "feel" the onset of combustion events that are bad

Figure 1. Heat release and COV showed no sudden changes as EGR level was increased.

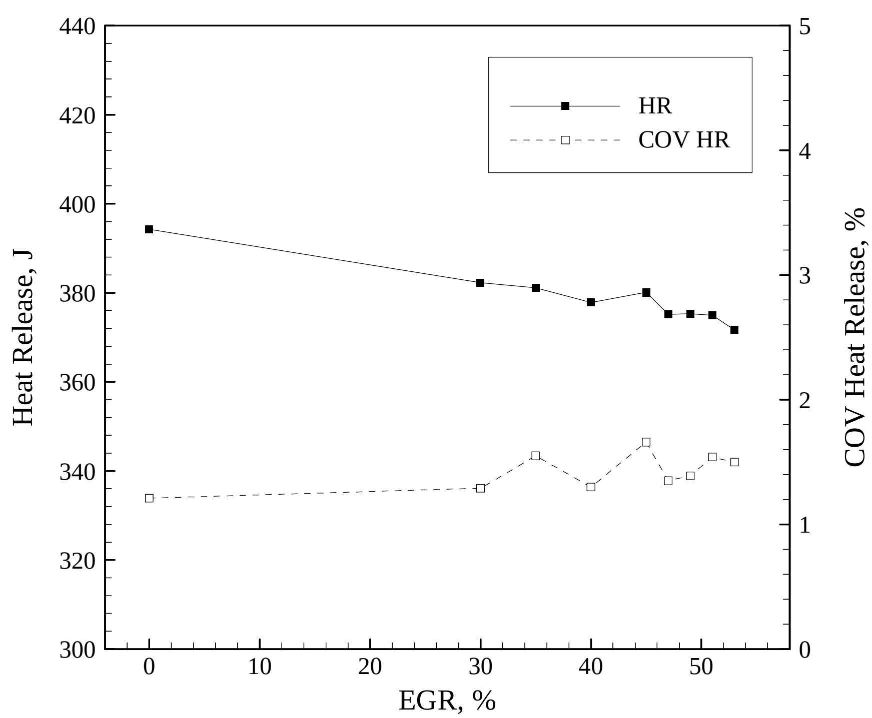
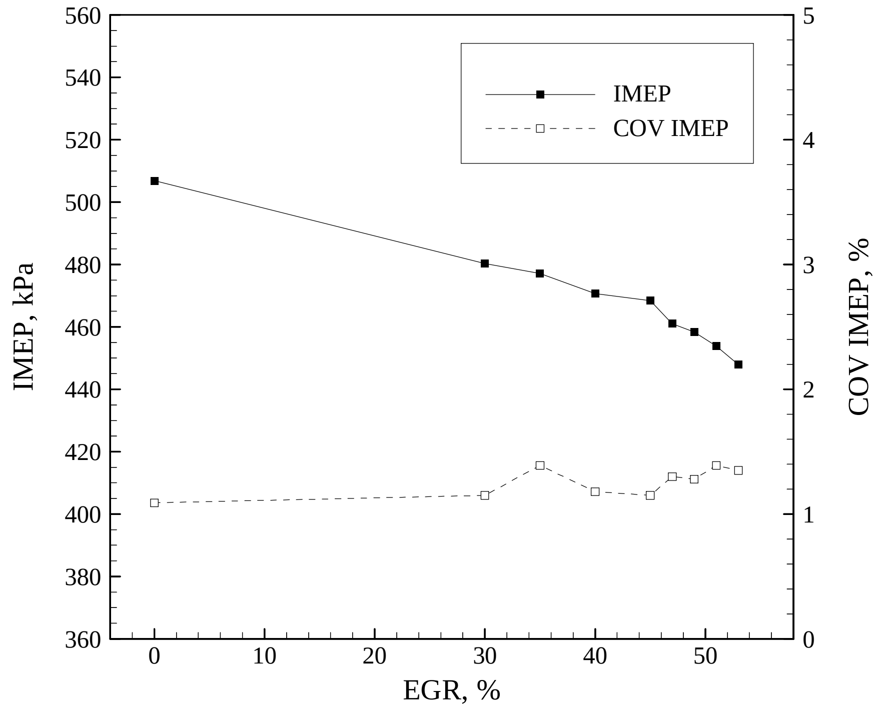


Figure 2. IMEP and COV showed no sudden changes as EGR level was increased.



enough to greatly impact emissions.

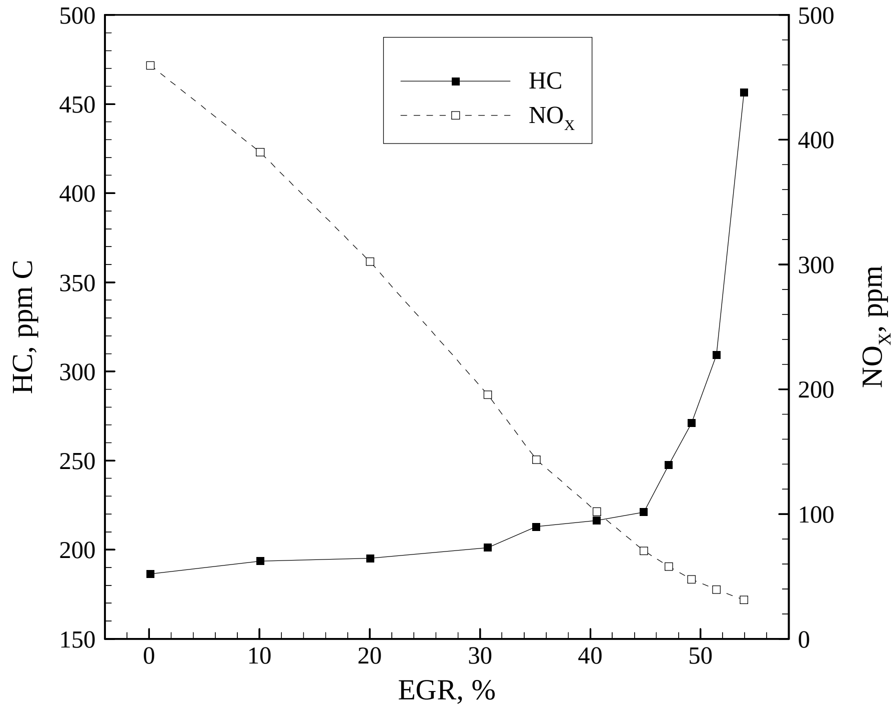
In addition to insensitivity due to integration, the HR and IMEP response may have been reduced because of the constant fueling rate in these experiments. One would expect that the corresponding decrease in air-to-fuel ratio would tend to somewhat counter the effect of dilution and help to restabilize the combustion. Additional experiments are planned to maintain constant air-to-fuel ratio while EGR is increased.

Analysis of the cylinder pressure data on a crank-angle resolved basis is still ongoing. Theoretically, it should be possible to identify specific pressure features that relate to the sudden shift in emissions described below. If such relationships can be identified, it may be possible to begin evaluating possible combustion mechanisms with detailed combustion models such as KIVA which can simulate engine pressure profiles based on fluid mechanics and chemistry.

Combustion Characterization with HC and NO_x Emissions

Time-averaged HC and NO_x concentrations in the raw engine-out exhaust are shown in Figure 3 versus EGR level. This figure shows NO_x concentration decreasing and HC increasing with increasing EGR as would be expected. Note the sudden increase in HC and leveling-off in NO_x at approximately 45% EGR, where there appears to be a significant shift in combustion chemistry. This major transition is in sharp contrast to the slight changes observed in the integrated pressure parameters, HR and IMEP. Because of the suddenness of the emissions change at 45% EGR, it is clear that dynamic engine behavior at or above this operating point will be highly nonlinear.

Figure 3. Trade-off between HC and NO_x concentration as a function of EGR level.



Thus it is imperative that any control strategies being considered should be able accommodate such behavior.

It was not possible to obtain accurate HC concentration measurements on a crank angle resolved basis for EGR levels greater than 45% because the Fast FID sampling probe was fouled by particulates at the higher levels. A preliminary analysis of the Fast FID data for EGR levels less than 45% indicates no major changes in cycle-resolved HC up to that point. Additional experiments using a revised probe design are being planned.

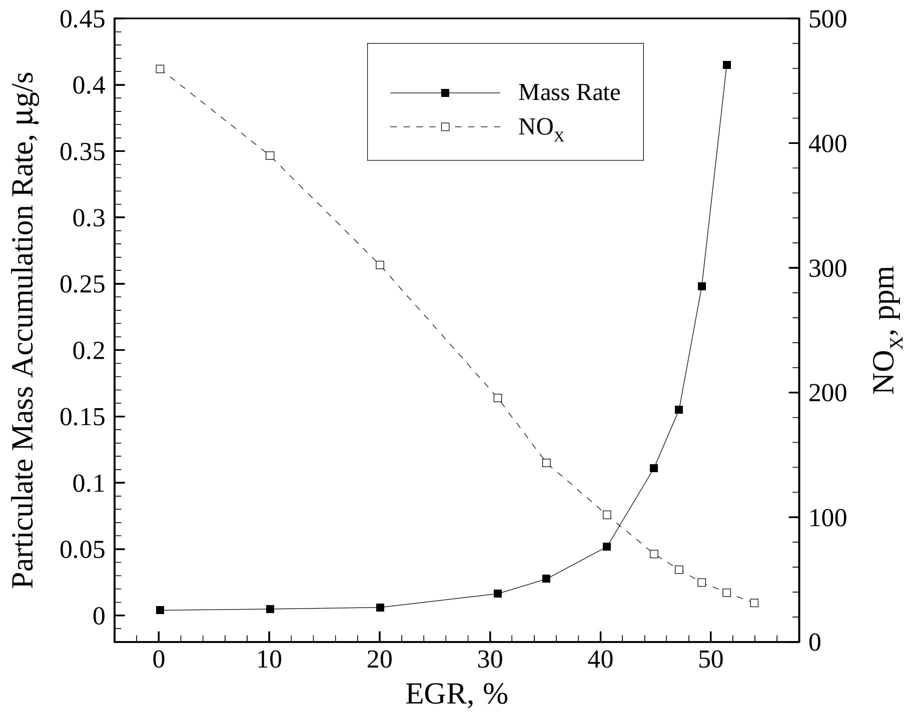
Combustion Characterization with PM

Our measurements have identified significant changes in PM emissions with EGR level as was expected. Similar to the gaseous emissions (e.g., HC and NO_x), there was a sharp increase in PM at a critical EGR level. This critical level corresponding to a sharp increase in PM was observed in mass concentration, particle size, and particle density.

Mass Concentration

Particle mass concentration and total mass accumulation were measured on dilute exhaust using the TEOM. The dilution ratio was maintained at 35±5:1. Mass accumulation rates were calculated based on over 100 mass data points and are shown in Figure 4 as a function of EGR level. Mass accumulation rates begin to increase significantly at 30% EGR and continue to increase rapidly until the maximum EGR level. The intersection of the particulate mass and NO_x curves

Figure 4. The intersection of the particulate mass accumulation rate and NO_x curves represents a region where the engine out particulate mass and NO_x concentration are minimized for this engine condition.



represents a region where the engine out particulate mass and NO_x concentration are minimized for this engine condition.

Particle Size

Particle sizing was performed on dilute exhaust using the SMPS. The dilution ratio was maintained at 35±5:1. Number concentration vs. particle diameter is shown in Figure 5 for several EGR levels. Two aspects of the data stand out. The first is the increasing number concentration with level of EGR. The second is the increasing particle size. Note that the particle size at the peak concentration increases by a factor of approximately two between 30% and 53% EGR.

The likely mechanism for particle growth is the reintroduction of particle nuclei into the cylinder during EGR. The recirculating exhaust particles serve as sites for further condensation and accumulation leading to larger particles. A significant fraction of the measured size distribution appears larger than the 500 nm upper bound of the SMPS for the highest EGR rates. This is significant because these particles contain much of the exhaust particulate mass. While exhaust dilution tunnels often are the source of artifact in the measurement of ultrafine particles, the effects are greatest for low dilution (< 15:1) and the smallest particles (< 20 nm).

The frequency plot in Figure 6 illustrates the disappearance of small particles and the growth of much larger particles. The divergence between the curves for particles > 100 nm and particles

Figure 5. Time-averaged size distributions as measured by the SMPS. The overall number and size of particles increases with increasing EGR.

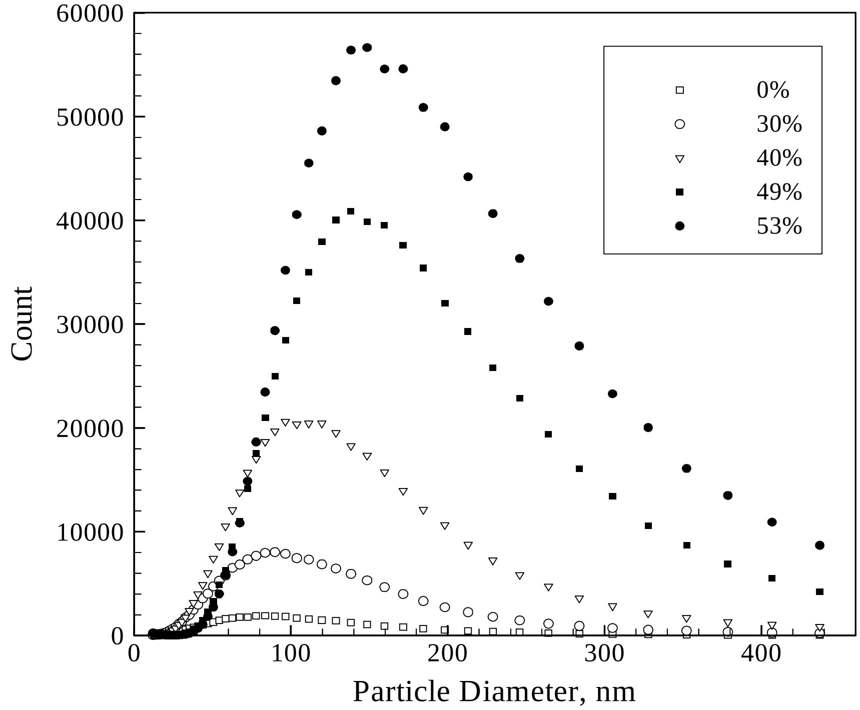
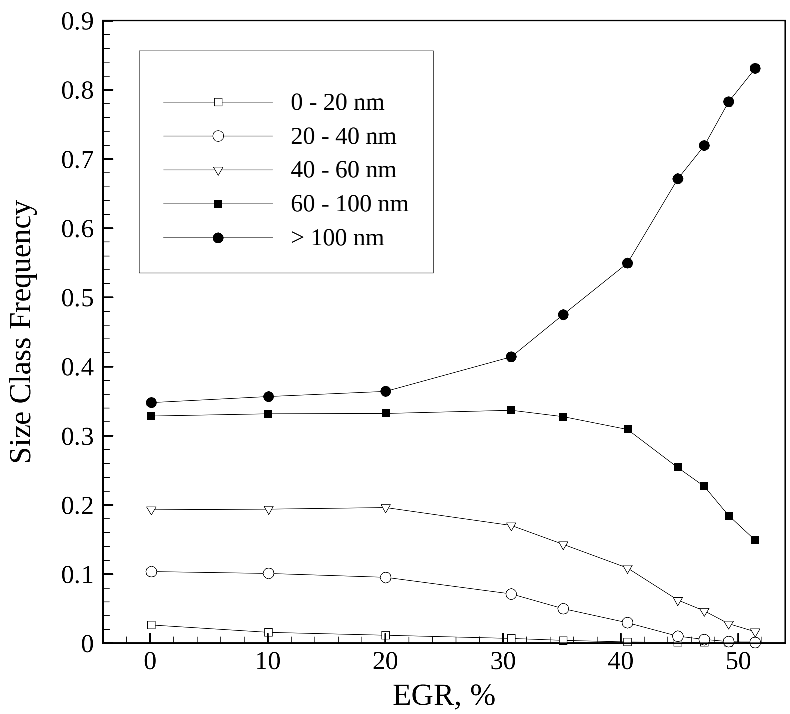


Figure 6. Frequency of occurrence of particle size classes as a function of EGR. Frequency of smaller particles decreases as the frequency of larger particles increases at higher EGR levels.



60-100 nm increases significantly at 30% EGR and continues to increase. The figure does appear to show that the smallest particles are contributing to the growth of the largest ones. The increase in larger particles is less steep than the increase in particle mass in Figure 4. The particle mass, however, increases as a function of the cube of particle diameter, and thus can be expected to increase more rapidly.

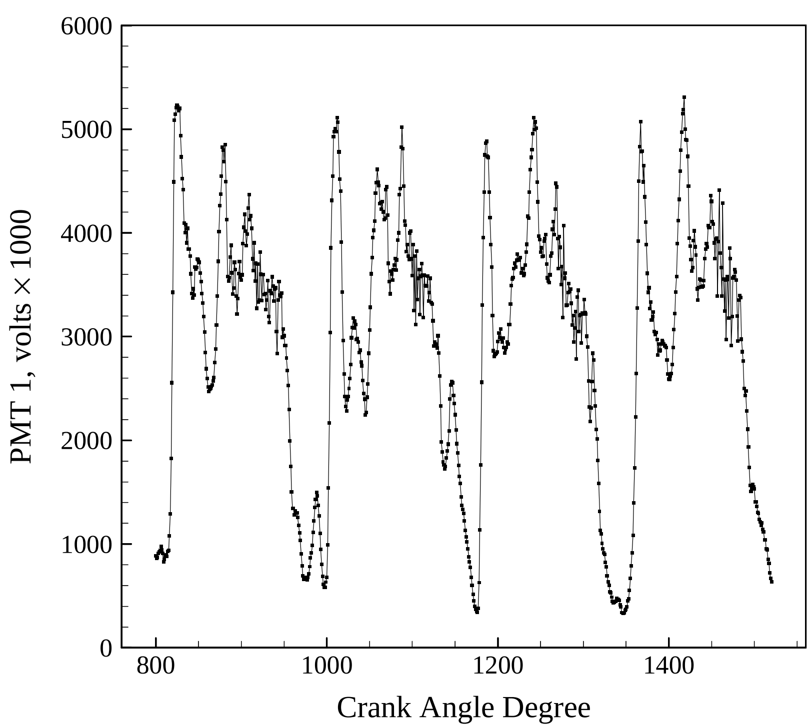
Rapid Particle "Density"

Fast particle "density" measurements were made in the raw exhaust using the DPS. Figure 7 shows an example of the crank angle resolved signal from the DPS for a single engine cycle. Recall that the photo-multiplier tube (PMT) voltage is effectively a measure of "smoke" or particle "density". PM emissions from each cylinder event are clearly visible in the figure. A preliminary analysis of the data indicates no significant cycle-to-cycle variations in mean particle "density". While the data are preliminary, this instrument in conjunction with fast emissions and in-cylinder pressure measurements is expected to be very useful for improving our understanding of PM formation. Analysis of the DPS data is ongoing and will be discussed in more detail in a future publication.

CONCLUSIONS

The results of this investigation give insight into the effect of EGR level on the development of gaseous emissions as well as mechanisms responsible for increased particle density and size in

Figure 7. Example of the crank angle resolved signal from the DPS for a single engine cycle. Particulates from each cylinder event are clearly visible.



the exhaust. The time-averaged gaseous emissions results were similar to those seen in other studies. Particle sizing data showed some of the most interesting results. The results indicate that it is possible to directly measure particle growth of the exhaust particulate mass during high rates of EGR. This growth is likely caused by the recirculating exhaust particulates serving as nucleation sites for further particle growth. The DPS fast particle "density" instrument demonstrated in this study will be used extensively in future studies with fast emissions and in-cylinder pressure measurements to improve our understanding of PM formation and growth.

The observation of only slight changes in the conventional engine combustion parameters of HR and IMEP at high EGR indicates that these integrated quantities are not adequate for monitoring the combustion processes responsible for the increased emissions. It is more likely that quantities related to specific crank-angle-resolved details of the cylinder pressure trace will be more useful.

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