Abstracts

Session 7 – Combustion and HCCI Regimes

DIESEL ENGINE ALTERNATIVES

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ABSTRACT

There are basically three different modes of combustion possible for use in reciprocating engines. These include: diffusion burning, as occurs in current diesel engines; flame propagation combustion, such as is used in conventional spark ignition engines; and homogeneous combustion, such as is used in the Southwest Research Institute homogenous charge compression ignition (HCCI) engine.

Diesel engines currently offer significant fuel consumption benefits relative to other powerplants for on- and off-road applications; however, costs and efficiency may become problems as the emissions standards become even more stringent.

This presentation presents a discussion of the potentials of HCCI and flame propagation engines as alternatives to the diesel engines. It is suggested that as the emissions standards become more and more stringent, the advantages of the diesel may disappear.

The potential for HCCI is limited by the availability of the appropriate fuel. The potential of flame propagation engines is limited by several factors, including knock, exhaust gas recirculation tolerance, high BMEP operation, and throttling. These limitations are discussed in the context of the potential for improvement of the efficiency of the flame propagation engine.

EXPLORING LOW NO_X AND LOW PARTICULATE MATTER COMBUSTION REGIMES

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ABSTRACT

We are investigating nontraditional combustion regimes for improving engine-system efficiency and reducing the performance requirements of post-combustion emissions controls. Combustion regimes of interest exhibit simultaneous low engine-out NO_x and particulate matter emissions. These regimes are realized through a combination of high EGR rates and/or fuel injection parameters.

In this study, we performed detailed emissions characterization for improved understanding of the combustion process as well as the environmental impact of operating in these regimes. Advanced techniques were applied for speciation of hydrocarbon (HC) emissions and particulate matter (PM).

HC speciation has thus far revealed the presence of many short chain hydrocarbons and partial oxidation products that were not present in the fuel. PM characterization revealed that a significant percentage of the PM in these nontraditional regimes is soluble organic, which may be treated with a simple oxidation catalyst. We are also investigating the possibility of increasing the speed/load envelope of these nontraditional regimes as well as evaluating their applicability to regenerating NO_x adsorbers and diesel particulate filters.

ADVANCED RESEARCH IN DIESEL FUEL SPRAYS USING X-RAYS FROM THE ADVANCED PHOTON SOURCE

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ABSTRACT

The distribution and degree of atomization of fuel in the combustion chamber is a primary factor in determining the emissions from diesel engines. A number of diagnostics to study sprays have been developed over the last 20 years that are primarily based on visible light measurement techniques. However, visible light scatters strongly from droplets on the periphery of the spray. This prevents quantitative measurements using these techniques, particularly in the dense near-nozzle region.

For this reason we developed the X-ray technique to study the properties of fuel sprays. X-rays have a very low probability of scattering from droplets in the spray, which allows them to be used to make quantitative measurements of the fuel distribution. These measurements are particularly effective in the region near the nozzle where other techniques fail.

We will present the results of our work measuring the mass distribution and density of sprays from heavy- and light-duty common rail diesel injectors, as well as our most recent work studying sprays under higher ambient density conditions.

NEW DIESEL COMBUSTION REGIME: PARTICULATE ANALYSIS WITH THE SINGLE-PARTICLE LASER ABLATION TIME-OF-FLIGHT MASS SPECTROMETER

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ABSTRACT

To meet the new exhaust gas emission laws, most new diesel engines will be using exhaust gas recirculation (EGR). EGR technology has been shown to be very effective means of reducing NO_x emissions; however, typically any change in engine operating parameters to reduce NO_x emissions results in an increase in particulate matter (PM) emissions, which in the case of diesel emissions is of particularly serious concern because of its known carcinogenic effects. Hence, traditionally the point defined as the ultimate EGR limit was delineated by a sudden increase in HC (hydrocarbons) and PM.

Very recently a few studies have suggested that by further increasing EGR, it might be possible to push the engine into a novel low-temperature combustion regime (NLTC) that, unlike the "classic NO_X-PM tradeoff," simultaneously reduces both PM and NO_x emissions. None of the studies have presented any information about the composition and properties of the particulate mass in this combustion regime.

We will present the results of a recent study investigating this NLTC regime. In this study, diesel exhaust particles generated by the Mercedes A-Class 1.7L diesel engine under the entire range of EGR conditions were sampled and characterized by the Pacific Northwest National Laboratory Single Particle Laser Ablation Time-of-Flight Mass Spectrometer (SPLAT-MS). The instrument's extremely high sensitivity to small particles made it possible to detect and characterize individual particles down to 50 nm, demonstrating SPLAT-MS's utility for studying diesel PM emission.

In this study exhaust particle flow was introduced into the SPLAT-MS after dilution by a factor of 100 to 1,000 through an aerodynamic lens inlet. Each individual particle was then aerodynamically sized, and its chemical composition was characterized by using two-step, two-laser JR evaporation followed by ultraviolet ionization. The separation of the process by which ions are formed into two steps -- particle evaporation and ionization -- greatly improves the analytical capability of the SPLAT-MS and makes spectral assignment significantly more tractable.

Particle-size distributions from 3.5 to 500 nm were measured in parallel using Scanning Mobility Particle Sizer (SMPS). In addition, the NTRC group measured gas phase concentrations of NO_x, CO, CO_2, and HC's; recorded engine performance parameters; collected filter samples for gas chromatograph – mass spectrometer analysis; and measured total aerosol mass with TEOM for all EGR conditions.

Increasing EGR from 0 to 45 percent resulted in an increase (a doubling) in the particle number concentration and a shift in the average particle mobility diameter from 85 nm to 115 nm. At the same time the particle average aerodynamic diameter decreased from 97 to 74 nm, suggesting that increasing EGR from 0 to 45 percent results in a decrease of ~25 percent in particle size.

REAL-TIME SIMULTANEOUS MEASUREMENTS OF SIZE, DENSITY, AND COMPOSITION OF SINGLE ULTRAFINE DIESEL TAILPIPE PARTICLES

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ABSTRACT

Diesel exhaust particulate has been classified as a carcinogen. To understand its effect on human health, it is important to be able to characterize the composition and size of the emitted particles. We have recently developed a single-particle mass spectrometer for the characterization of size and composition of individual exhaust particles. The instrument was specifically designed to provide high sensitivity for particles in the 150- 5O nm range to cover the bulk of the particle mass that is present in the exhaust. We will present results from a recent deployment of this instrument at the National Transportation Research Center (NTRC) at Oak Ridge National Laboratory.

Our Single Particle Laser Ablation Time-of-Flight Mass Spectrometer (SPLAT-MS) was operated over the period of January 31 through February 13, 2003, and sampled exhaust particles generated by a Mercedes A-Class diesel engine. A total of approximately 0.5 million individual particles were sized and their composition characterized in real-time. The aerodynamic size distribution of the detected particles peaked at 70-100 nm, depending on engine operating conditions. The instrument's extremely high sensitivity to small particles was demonstrated by its ability to detect particles down to 50 nm.

After dilution by a factor of 100 to 1,000, exhaust particles were introduced into the SPLAT-MS through an aerodynamic lens, where each individual particle was sized and its chemical composition was characterized through a synchronous laser heating for particle evaporation followed by ultraviolet ionization. The separation of the process by which ions are formed into two steps -- particle evaporation and ionization -- greatly improves the analytical capability of the instrument and made spectral assignment significantly more tractable.

Initial studies investigated the effects of different load, revolutions per minute (RPM), and exhaust gas recirculation (EGR) conditions on particle-size distributions and composition. When EGR reached 52 percent, the engine operation became "smokeless," and the number concentration of particles dropped by a factor of 20. Studies of the effects of different loads and RPM on particle size and composition were repeated with the diesel fuel containing 15 percent alcohol.

Variation of particle composition with injection timing and sequence, the use of oil recirculation, and the presence or absence of a catalytic converter were also investigated. Very preliminary analysis of the data shows that the vast majority of the exhaust particles were composed of soot, which accounted for over 90 percent of all emitted particulates under many operating conditions. Other types of characterized particles include small amounts of oxygenated organics. Engine wear-and-tear particles containing aluminum, aluminum oxide, and iron were observed under extreme operating conditions of high RPM and low load.

DIESEL HCCI DEVELOPMENT AT CATERPILLAR

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ABSTRACT

Implementation of a practical homogeneous charge compression ignition (HCCI) engine has numerous technical challenges. Among these are proper mixture preparation, controlling combustion phasing and cylinder-pressure rise rates, and expanding the operating range to higher loads and idle/light loads. Methods to control combustion phasing include inlet manifold temperature and pressure, injection timing, valve timing and fuel properties. Recent progress on part-load HCCI operation using diesel fuel will be given.

MIXED-MODE DIESEL HOMOGENEOUS CHARGE COMPRESSION IGNITION WITH EXTERNAL MIXTURE FORMATION

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ABSTRACT

Diesel homogenous charge direct injection (HCCI) is a combustion technology showing great promise for the reduction of oxides of nitrogen and particulate matter from diesel engines. Our implementation is a mixed-mode concept, which relies on the use of an essentially unmodified common-rail compression ignition direct injection (CIDI) engine, coupled with a highly effective atomizer for external mixture formation. With this concept, the engine can operate in HCCI mode, HCCI/DI mixed mode, or DI mode, depending on the load and with seamless, progressive mode transition.

The external mixture preparation for the HCCI mode offers a number of advantages over techniques that utilize only the DI system to perform HCCI mixture preparation. External mixture formation, with the additional residence time and very active mixing through the intake stroke, allows for better HCCI operation due to the very effective mixing and charge homogeneity when compared DI HCCI. The traditional problems of external mixture formation (wall wetting, poor cold start, etc) are largely remedied by a novel fuel atomizer with its ultra-fine atomization. Furthermore, when used in a mixed combustion mode or in pure DI mode at higher loads, the DI injectors can be optimized strictly for DI operation with respect to number, orientation, or size of injector holes.

This mixed-mode operation has been demonstrated on a single-cylinder engine (one-quarter of a recent production 2L engine) in collaboration between Ohio State University and the University of Stuttgart, Germany. The concept has demonstrated extremely low levels of nitrogen oxides (below 10 ppm) and pure HCCI operation up to an IMEP of 4.7 bars. Operation at various conditions (engine speeds, loads, boost pressures, intake temperature, exhaust gas recirculation rates from 0 to 60 percent, etc.) have shown that this technique enables HCCI operation over a wide range of engine conditions with relative insensitivity of the combustion process to operating conditions. This is probably due to the high level of charge homogeneity achieved by this technique. Furthermore, the transition from HCCI to mixed HCCI/DI to DI combustion mode is seamless, significantly enabling the controllability of such a combustion system over the entire engine operating map.

DETAILED MODELING OF HOMOGENEOUS CHARGE COMPRESSION IGNITION AND PRE- MIXED CHARGE COMPRESSION IGNITION COMBUSTION AND MULTI-CYLINDER HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE CONTROL

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ABSTRACT

This work supports the need to develop a new combustion concept that allows both high efficiency and low emissions for transportation applications. Our work on homogeneous charge compression ignition (HCCI) combustion is a synergistic combination of analysis and experimental work.

On analysis, we have developed advanced methodologies that combine chemical kinetics with fluid mechanics to analyze HCCI engines with accuracy never before achievable for other types of engines. These analysis tools have also been used to guide the experimental effort.

On experimental work we have a multi-cylinder Volkswagen TDI engine that allows us to work on balancing combustion between cylinders. This is a crucial problem with HCCI combustion that has so far precluded commercialization of these engines.

Previously, our analysis capabilities applied only to perfectly homogenized air-fuel mixtures. We have recently extended our methodologies to include mixing between zones. We have used this model to demonstrate that mixing between zones is responsible for most of the production of carbon monoxide in an HCCI engine. In addition to being an important enhancement to our HCCI engine analysis tools, this new model can be used as a framework to analyze engine operating conditions where the charge is not perfectly homogeneous (i.e., PCCI combustion).

We are also developing methodologies for controlling and balancing combustion in a multi-cylinder HCCI engine. We are using an exhaust throttle as a low-cost surrogate for variable valve timing. Our results for using an exhaust throttle in an HCCI engine show some unexpected results. Throttling the exhaust typically advances combustion in a single-cylinder engine, due to the effect of hot combustion gases on HCCI combustion. However, in a multi-cylinder engine, throttling the exhaust of a cylinder *delays* combustion in this cylinder and *advances* combustion in other cylinders. This is due to flow interactions between cylinders, as the exhaust throttle in a cylinder diverts the flow of the fresh charge to the other cylinders. Characterizing these effects is extremely important in obtaining satisfactory combustion in a multi-cylinder HCCI engine.

OVERVIEW OF DETAILED CHEMICAL SPECIATION AND PARTICLE SIZING FOR DIESEL EXHAUST, BOTH REAL-TIME AND FILTER-BASED MEASUREMENT

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ABSTRACT

EPA ambient air-quality measurement protocols have been incorporated into the exhaust measurement system of a research single-cylinder diesel engine. To allow more detailed assessment of the individual chemical components of the diesel particulate matter (PM), the exhaust dilution system includes a residence-time chamber (RTC) to allow for residence times of 30-60 seconds in the second stage of dilution before sampling. Measurements have been performed using the more normal approach of catching the particulate matter on filters and then analyzing the filters, and also using an aerosol time-of-flight mass spectrometer (ATOF-MS), which is capable of analyzing individual particles for size and composition at a rate of up to 150 particles per minute for a particle-size range from 0.15 to 5 micrometers. Additional data on particle size were obtained using a scanning mobility particle sizer (SMPS).

Samples have been collected on a range of different filters where mass loading, elemental and organic carbon (EC/OC), trace metals, sulfate ions (SO_4), volatile organic compounds, and semi-volatile organic compounds have been evaluated. Using the SMPS, particle-size distributions have been measured for the different operating conditions and for different exhaust gas residence times in the RTC.

This paper gives an overview of the results obtained with the different measurement techniques for the range of engine operating conditions covered by the CARB 8 mode test. Results show that the chemical composition and size distribution of the particulate matter are highly dependent on the engine operating conditions. There is a dramatic shift in the ratio of elemental to organic carbon and in the sulfate ions (SO4) when the engine is traversed across a load and speed range. Similarly, there is a shift in the particle-size range for which there is virtually no impact on the mass loading, and the nano-particle-size distribution, at a fixed dilution ratio and temperature, is a function of the time spent in the RTC. Trace metal concentrations in the particulate vary significantly with load and speed and are treated as indicative of oil consumption.

Results of the filter-based measurements are being compared to those obtained using the ATOF-MS, which has been widely used to study atmospheric aerosols but has only seen limited use for assessing internal combustion engine exhaust emissions. Using the ATOF-MS to make fundamental measurements of chemical composition and particle size in engine exhaust has the potential to offer unique insights into the impact of changes in engine operating conditions on the resultant changes in the exhaust characteristics.

NON-SOOTING, LOW-FLAME TEMPERATURE, AND MIXING-CONTROLLED DIRECT INJECTION DIESEL COMBUSTION

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ABSTRACT

Methods of producing non-sooting, low- flame temperature diesel combustion were investigated in an optically accessible, quiescent constant-volume combustion vessel under mixing-controlled diesel combustion conditions. Combustion and soot processes of single, isolated fuel jets were studied after auto-ignition, transient premixed combustion, and while the injector was fully open (i.e., during the mixing-controlled phase of heat release for diesel combustion).

The investigation showed that small injector tip orifices could be used to produce non-sooting, low-flame temperature combustion in two different ways. First, using a 50-micron injector tip and ambient oxygen concentrations as low as 10 percent (simulating the use of extensive exhaust gas recirculation), a fuel jet was non-sooting at typical diesel ambient temperatures (1000 K). Second, using the same injector tip at a reduced ambient gas temperature (850 K), but with 21-percent oxygen, it was shown that non-sooting, mixing-controlled combustion occurred at the lift-off length in a fuel-air mixture with a cross-sectional average equivalence ratio of approximately 0.6—suggesting that the quasi-steady combustion was fuel lean and thereby avoided the formation of a diffusion flame.

The adiabatic flame temperature with reduced ambient oxygen concentration or fuel-lean combustion was approximately 2000 K, compared to typical diesel flame temperatures that exceed 2600 K. The 50-micron injector tip results above were obtained using a #2 diesel fuel. However, using an oxygenated fuel (20 weight percent), the investigation showed that the same low-temperature combustion, either with reduced ambient oxygen concentration or fuel-lean combustion, was realized with a 100-micron injector tip.

Although these single, isolated jets do not have jet-jet interactions that would occur in realistic engines, the results are useful for understanding limiting-case behavior of single-jet mixing and combustion during an injection event. The non-sooting and low-flame temperature, mixing-controlled combustion realized using small orifice tips suggests that the use of small orifices offers the potential for a simultaneous soot and NO_x reduction in an engine, much like diesel homogeneous charge compression ignition combustion.

SHELL GAS-TO-LIQUIDS IN THE CONTEXT OF A FUTURE FUEL STRATEGY – TECHNICAL MARKETING ASPECTS

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ABSTRACT

Liquid fuels refined from crude oil are likely to continue to dominate the transportation fuels market for the next 20 years. However, fuel properties and specifications will not stand still, with change driven by sustainability challenges of:

- Security and diversification of energy supply
- Reduced greenhouse gas emissions
- Reduced local pollutant emissions
- Affordability, availability, and customer acceptance.

In the long term, hydrogen produced from renewable sources is seen by many as the ultimate solution, combining both local and global environmental advantages. However, in the personal mobility domain, there is still a long way to go on the path to commercialization of hydrogen and fuel cells.

In the interim period, alternative fuels – such as biofuels, liquefied natural gas, compressed natural gas, and gas to liquids (GTL) fuels -- will play, in varying degrees, an increasingly important role in meeting mobility needs. Some may grow beyond niche positions depending on Government transport fuel policy.

GTL fuel offers strategic diversification of energy supply, since it is derived from natural gas, and can provide a bridge to future fuels and technologies. Its compatibility with the existing diesel infrastructure in combination with significant local pollutant emissions benefits (both as pure, 100-percent GTL and as a blend with conventional diesel) results in a more cost effective solution in reducing emissions than other alternative fuels.

This paper discusses various market development activities associated with GTL fuel and how these are often directly related to the technical attributes of the fuel. For example, the ability of GTL fuels to deliver emissions benefits when blended with conventional diesel, has recently allowed the formulation of fuels with reduced black smoke emissions in Thailand and Greece.

EFFECTS OF FUEL TYPE AND ENGINE SPEED ON REQUIRED INTAKE TEMPERATURE AND COMPLETENESS OF COMBUSTION IN A HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE

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ABSTRACT

Homogeneous charge compression ignition (HCCI) engines have shown potential for both high efficiency and low emissions of NO_X and particulates. However, as the fuel/air-equivalence ratio is reduced for decreasing engine loads, CO and hydrocarbon (HC) emissions become excessive.

In a previous study, the sources of emissions at low loads were investigated using iso-octane as the fuel. It was found that the peak combustion temperature had a strong influence on the completeness of the bulk-gas combustion reactions, particularly the CO-to-CO_2 reactions. In the engine, this peak temperature is reached by a combination of intake temperature, compression, and combustion heating. However, the intake temperature required to maintain combustion phasing near top dead center (TDC) varies with both the fuel type and engine speed. Therefore, it can be anticipated that the fuel/air-equivalence ratio for onset of incomplete bulk-gas reactions is dependent on both the autoignition characteristics of the fuel and the engine speed.

To gain a better understanding of how the onset of incomplete bulk-gas combustion changes with fuel type and engine speed, a parametric study of HCCI combustion and emissions has been conducted. Four fuels with different ignition characteristics were investigated, including: a research-grade gasoline, pure iso-octane, and two mixtures of the primary reference fuels (*n*-heptane and iso-octane) with octane numbers of 80 and 60. The experiments were conducted at naturally aspirated conditions in a single-cylinder engine (0.98 liters/cylinder) fitted with a custom HCCI piston that minimizes crevice volume. For each fuel, data were acquired at four engine speeds (600, 1200, 1800, and 2400 revolutions per minute), and the fuel loading was varied from near the knocking limit to loads at or below idle (based on typical diesel-engine fueling) at each speed. Cylinder pressure and exhaust-gas data (CO_2, O_2, CO, HC, NO_X, and smoke) were acquired for each condition.

The results show that there is a strong coupling between the ignition quality of the fuel and the intake temperature required to phase combustion at TDC. The intake temperature, in turn, directly affects the completeness of combustion for a given engine speed and fueling rate. The effect of engine speed depends on the ignition characteristics of the fuel. For fuels with little cool-flame activity (i.e., gasoline and pure iso-octane), the equivalence ratio for the onset of incomplete bulk-gas reactions is independent of engine speed. This occurs because the increased compression temperatures required to maintain combustion phasing as the engine speed is increased also increase the rate of CO-to-CO_2 conversion, balancing the shorter time available to complete combustion. However, for fuels with a significant fraction of *n*-heptane (i.e., significant cool-flame chemistry), the onset of incomplete bulk-gas combustion depends strongly on engine speed, with a shift to higher equivalence ratios at lower speeds. This is due to the strong time dependence of the cool-flame chemistry, which necessitates lower intake temperatures at lower engine speeds to maintain combustion phasing. This leads to lower combustion temperatures and a commensurate rise in CO-emissions unless the fueling is increased.