ANNALS of the ORADEA UNIVERSITY.
Fascicle of Management and Technological Engineering, Volume VII (XVII), 2008

High Efficiency Clean Combustion in a Direct- Injection Diesel Engine

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Keywords: efficiency, direct injection, diesel

1. ABSTRAC

The integration of electronic controls into diesel engine systems has resulted in substantial gains in efficiency and emissions control during the last decade. This has also introduced the possibility of exerting an increasing level of control over the combustion process itself. In the past, lowering engine-out oxides-of-nitrogen (NOX) and particulate matter (PM) emissions simultaneously was not generally believed to be possible.

2. OVERVIEW

Compression-ignition (CI) engines (more commonly known as Diesel engines) have long been recognized as highly-efficient prime movers for the transportation sector.

Electronic controls have been commonplace for spark-ignited (SI) engines since the early 1980s, resulting in continuing improvements in both efficiency and emissions performance for nearly 25 years. Electronic control of CI engines has only become widespread in the last decade and has been an enabler of the integration of more advanced technologies into CI engines. In the past, CI engines typically were not equipped with catalytic emissions control devices, and only rarely with exhaust gas recirculation (EGR). Most of these engines utilized pre-chamber, or indirect- injection (IDI) fuel systems or, more recently, high-pressure rotary pump direct- injection (DI) fuel systems. These systems generally did not permit high levels of control or adaptability over the fuel injection or combustion process, though improvements were implemented in rotary-pump systems through use of electronic controls. Today's CI engines make wide use of EGR, high-pressure common-rail DI fuel injection systems, and catalytic emissions control technologies. The implementation of electronic controls has also resulted in the possibility of exerting an increasing level of control over the combustion process itself.

Historically, the NOX and PM emissions from CI engines exhibited a trade-off behavior. That is, it was possible to reduce the emissions of one of the two pollutants, but at the expense of increasing the other. This perspective has changed in recent years. Several organizations have published work that demonstrates that it is in fact possible tominimize both pollutants simultaneously through manipulation of the combustion process. The various groups of researchers have given several names to the combustion processes in diesel engines that result in ultra-low levels of PM and NOX

The combustion process in a diesel engine is a complex process. The process begins with the injection of fuel at very high pressure (often in excess of 30 megapascals) compared with the ambient cylinder condition. The fuel jet begins to entrain air from the in-cylinder charge, and ignition first occurs in a region of the jet

that has entrained enough air to form an ignitable mixture. Burning occurs in a pre-mixed flame in this region.
Thereafter, a diffusion flame occurs at the boundaries of the fuel jet. The diffusion flame occurs at approximately stoichiometry, regardless of the overall air/fuel ratio. The combustion process then proceeds to completion as a mixing-controlled burn.
Particulate formation is believed to occur in the pre-mixed burn because of locally fuel-rich conditions caused by inadequate air entrainment. The hottest part of the flame is the near-stoichiometric diffusion flame, which is thought to be the source of most NO formation. The mixing-controlled burn is thought to complete combustion of some partially-oxidized fuel species and burning of some of the particulate.

Researchers at Nissan Motor Company have reported a combustion phenomenon they refer to as modulated kinetics, or MK combustion (2,3,4). MK combustion focuses on introducing the entirety of the fuel charge prior to the completion of the ignition delay period. This results in a combustion process that is dominated by a premixed burn condition. Particulate formation is avoided because the long ignition delay allows the premixed burn to occur at a higher equivalence ratio through a high degree of air entrainment and mixing. Accomplishing MK combustion over a broad range of conditions requires manipulating the ignition delay period so that it becomes possible to introduce the requisite amount of fuel in the time allowed. Researchers at Nissan accomplished this through a combination of high levels of EGR and through delaying the start of injection. The EGR temperature was kept constant at 30 Celsius (C) by using a large heat exchanger to remove excess heat from the EGR gases. The addition of EGR to lengthen the ignition delay also has the beneficial effect of lowering the flame temperature, which leads to low NOXemissions.

Researchers at Toyota Motor Company reported a similar approach using high levels of EGR (in excess of 50%) to reduce the flame temperature to a level that results in no soot or NOXformation. Researchers at Toyota termed this approach Low Temperature Combustion (LTC). In this approach the EGR rate was used to reduce the flame temperature and the start of injection was advanced in high-EGR regimes. The amount of EGR required for low particulate formation decreased slightly as the EGR temperature was changed from 150 C to 100 C (5).

A series of experiments carried out in a constant-volume combustion vessel at Sandia National Laboratories shed light on some of the processes of both MK combustion and LTC. The experiments showed that the flame lift-off length increased as the ambient cylinder temperature decreased. (Flame lift-off length is the distance from the tip of the fuel injector to the nearest point in the fuel jet where high-heat-release reactions are occurring.) The amount of air entrained in the fuel jet was found to increase as the lift-off length increased, leading to combustion reactions occurring at leaner conditions that resulted in non-sooting conditions at 21% ambient oxygen concentration. This finding means that non-sooting conditions can be achieved at typical diesel oxygen and combustion temperature conditions if a highly mixing-controlled combustion process can be achieved, but still result in conditions ripe for NOXproduction. Decreasing the injector orifice diameter was found to allow non-sooting conditions to exist at higher temperatures. Decreasing the ambient oxygen content to simulate the use of EGR also resulted in longer lift-off lengths, but was shown to have little effect on the amount of oxygen entrained in the fuel jet at ambient oxygenlevels as low as 10% when using a 0.050 micron injector orifice. This combination allowed both non-sooting and low-NOX combustion conditions to occur

simultaneously. Conditions of very low oxygen concentrations below 10% simulated very high levels of EGR and were combined with a 0.180 micron orifice that is typical of production injectors. Under these conditions, the increase in lift-off length was no longer sufficient to offset the low ambient oxygen concentration, leading to a relatively lower amount of entrained oxygen and combustion at richer conditions. In these modes, the lack of soot is not due to enleanment of the premixed combustion due to increased oxygen entrainment, but rather by combustion events that are too cool to lead to the formation of particulate or NOX. Operation at these
low oxygen levels also had the effect of large increases in the time required to complete combustion. This is undesirable since it can lead to losses in engine efficiency.Detailed studies of the exhaust chemistry can be useful in furthering the understanding of HECC processes, but is not generally available in the literature. Studies at Oak Ridge National Laboratory (ORNL) were begun to investigate the exhaust chemistry of HECC processes in order to glean a better understanding of how these processes could be used more broadly in transportation applications. Previous studies at ORNL showed that the Mercedes engine could enter into low-NOX, low-PM combustion regimes by using high levels of EGR or by increasing EGR and retarding start-of- injection. These approaches, however, resulted in a significant efficiency penalty. The penalty arose either from the pumping losses associated with using the intake throttle to increase EGR rates or from the decrease in available work associated with retarding the start-of- injection, depending upon the approach used. The work also showed some opportunities for regaining part of the lost efficiency at some engine operating conditions by manipulating fuel injection parameters

A Mercedes-Benz 1.7 liter turbocharged 4-cylinder diesel engine was used for this study.

This engine is used in production for the A-Class vehicle in Europe, but is not used in production vehicles in the U.S. It is a modern, electronically-controlled diesel engine equipped with a Bosch high-pressure common-rail direct fuel injection system and exhaust gas recirculation (EGR). The fuel injectors are mounted centrally between the 4 valves (2 intake valves plus 2 exhaust valves). Additional details of the engine design are shown in table 1. Aflexible control system based on the Southwest Research Institute’s Rapid Prototyping Electronic Control System (RPECS) was implemented to allow flexible control of the engine. The controller is set up to closely simulate the original engine operating characteristics but also to allow departure from the baseline configuration to allow studies such as the one reported here.

An EGR cooler was added to reduce the peak EGR temperatures to a level that would not damage the thermoplastic intake manifold. The cooler is a production part from a U.S.-modelVolkswagen TDI engine. The cooler was plumbed to the engine cooling loop so that it uses the engine coolant (nominally at 100 C) as a temperature sink for cooling the hot exhaust gases in the EGR system. The EGR cooler itself is a small single-pass heat exchanger of appropriate size for a small diesel engine. Using this particular EGR cooler together with engine coolant is a realistic implementation of the technology, though it imposes limitations on the amount of heat that can be removed from the EGR gases. An intake throttle was also added to aid in increasing EGR rates whenneeded. Both components are now common on new diesel engines, but were not as common when this engine was manufactured.

Table 1. Engine characteristics.

Number of Cylinders	4
Injection System	Bosch Common Rail
Injector Num. Holes	6
Injector Hole Dia, mm	0.169
Bore, mm	80.0
Stroke, mm	84.0
Compression Ratio	19.0
Piston Geometry	Re-entrant bowl
Rated Power, kW	66
Rated Torque, Nm	180

Oxidation catalysts have also become commonplace for diesel applications. The A-class vehicle equipped with this engine is also equipped with 2 catalytic converters, one directly coupled to the output of the turbocharger and the other in an underfloor location. The close-coupled catalyst was omitted from the setup for this study so that engine-out emissions could be more readily studied. The underfloor catalyst (1.8 liter oval shaped ceramic monolith) was mounted in a downstream position to approximate the exhaust backpressure in a realistic configuration. For the purposes of this study, all measurements were made of engine-out exhaust upstream of the catalytic converter.Standard automotive exhaust gas instrumentation was utilized to provide a basicknowledge of the exhaust chemistry. Exhaust oxygen (O2) content was monitored using paramagnetic detectors (PMDs), carbon monoxide (CO) and carbon dioxide (CO
2) were measured by non-dispersive infrared instruments (NDIRs), hydrocarbons (THC) were measured using heated flame ionization detectors (HFIDs), and oxides of nitrogen (NOX) were measured using heated photochemiluminescence detectors (HCLDs). Quickmeasurement of the particulate emissions was accomplished by using a tapered-element oscillating microbalance (TEOM) model 1105. The various temperatures and pressures were monitored using thermocouples and pressure transducers. Fuel consumption was measured by utilizing a Max Machinery 710-213 positive displacement volumetric flow measurement system. Air consumption was measured using a laminar flow element and intake mass-airflow sensors. Intake air temperature (75 F) and humidity (58 F dew point) were held constant by a combustion air conditioning system.A microdiluter device was configured to provide a dilute (non-condensing) exhaust stream for analyzing exhaust chemistry based on a design by Abdul-Khalek and Kittleson. The raw exhaust sample was routed to the microdiluter through a heated stainless steel sample line maintained at 190 degrees Celsius (ºC). The microdiluter device was heated and insulated to maintain a sample temperature of 50 ºC within the device itself.

Various samples were extracted from the diluted sample stream and trapped for off-line analysis. Dilution ratio was monitored by observing gas concentrations in the rawexhaust stream and the dilute sample and was confirmed by periodic volume flowmeasurements. Aldehyde emissions were analyzed by trapping analytes using di-nitro phenylhydrazine (DNPH) cartridges. The analytes were eluted from the cartridges with acetonitrile and analyzed by high-pressure liquid chromatography (HPLC). Gas-phase hydrocarbons were analyzed by trapping a dilute exhaust sample in a tedlar bag followed
by analysis by a gas chromatographequipped with a mass-selective detector (GC/MS).

An AVL IndiModul was utilized to examine the combustion process in the cylinders. The IndiModul recorded in-cylinder pressures for each of the 4 cylinders. The data were collected at 0.1 crank angle resolution with a known reference to top-dead-center for each cylinder. The IndiModul then produce cylinder pressure traces as well as heat-release curves and combustion statistics at near-real time speed as the engine was operated in the
test cell.An EPA certification diesel fuel was selected as the test fuel for this study. The fuel was sourced from Chevron-Phillips Chemical Company and was an off-the-shelf product. Several keycharacteristics of the fuel are shown in Table 2

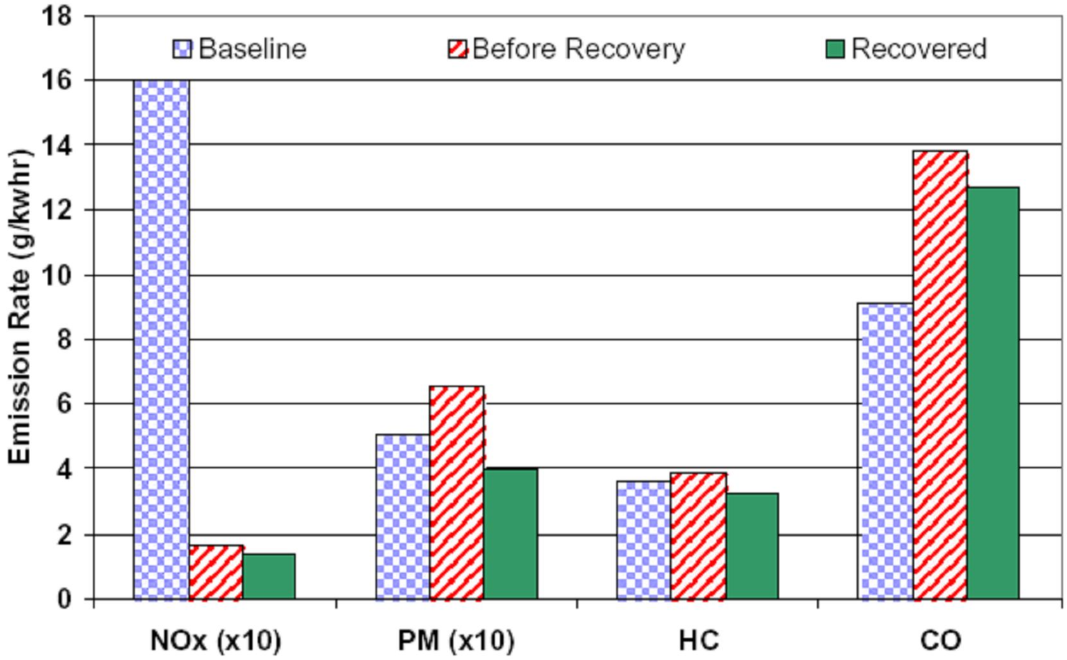
The engine was first operated at a baseline condition of 1,500 revolutions per minute (RPM) and 2.6 bar brake-mean-effective pressure (BMEP) and data were collected. This is a low-load condition that is typical for highway cruise type operation of an economy car. The baseline operating characteristics closely emulated the manufacturer's calibration for the engine at this condition. The EGR was then increased until the engine entered a clean combustion (meaning that it exhibited both low NOXand low PM emissions) condition. The fuel injection characteristics were held constant during this transition. In previous work, the engine was transitioned into the clean-combustion mode over a period of hours, owing to the time required to conduct data and sample collection at several intermediate conditions. As the intermediate points were of less interest for this study, the engine was transitioned into a clean combustion mode quickly. That is, the EGR valve was opened to its fully open conditionto produce a high level of EGR in one step change. Data and exhaust samples were again collected at this point. As in previous studies the increase in EGR caused the efficiency of the engine to decrease, resulting in a drop in the brake torque output of the engine. The fuel injection parameters were then adjusted in an attempt to regain the efficiency lost by operating at a higher level of EGR.

Table 2. Properties of the Chevron-Phillips certification diesel fuel.

Fuel Characteristic	Method	Result
Cetane Number	ASTM D-316	47.3
Sulfur, ppm	ASTM D-2622	386
Viscosity, cs 40C	ASTM D-445	2.3
Specific Gravity, 60/60	ASTM D-4052	0.8453
Carbon, wt%	Phillips	86.85
Hydrogen, wt%	Phillips	13.11
Net Heat of Combustion, BTU/LB	ASTM D-3338	18432
Aromatics, Vol%	ASTM D-1319	30.6
Olefins, Vol%	ASTM D-1319	0.8
Saturates	ASTM D-1319	68.6

The real-time combustion analysis showed that the pilot fuel injection was no longer producing significant heat release, so it was turned off to reduce unburned hydrocarbon and particulate emissions. The resulting drop in overall fuelling rate was corrected by adding both a small increase in fuel rail pressure and injection duration to the main injection event. The SOI was then advanced to regain lost thermal efficiency. The NOX, PM, HC, and CO emissions for these three cases are shown in Figure 1. Readers should note that NOX and PM emissions are shown multiplied by 10 to enhance the clarity of the figure As shown above, it is possible to reduce the NOX emissions by slightly more than an order of magnitude while also reducing PM emissions by about 20%. HC emissions were reduced slightly compared with the baseline case, but CO emissions rose significantly. The HC concentration in the exhaust increased by about 1.7x, but the overall exhaust flow rate dropped, causing a net decrease in HC emissions. The actual CO emissions rates are actually higher than shown because the CO concentration was in excess of the full-scale value for the instrument being used to measure CO

Brake thermal efficiency and volumetric efficiency data are shown in Figure 2. The data show that the NOX and PM reductions can be attained without an efficiency penalty at this particular engine condition. Increasing the EGR rate has a detrimental effect on the volumetric efficiency because it increases the temperature of the fresh charge. The temperature of the mixture of EGR and fresh air increased from a baseline level of 43 C to 129 C before recovery and 94 C at the recovered condition. In contrast to the reclamation of thermal efficiency in the recovered case, the volumetric efficiency does not return to levels comparable to baseline. Since the overall fueling rate was kept constant and the intake of EGR and fresh air mixture is lower than baseline at the recovered case, energy losses must necessarily have been reduced somewhere within the engine system. A further study of the data are necessary to determine whether reductions have been accomplished in heat losses or whether changes in the combustion process have reduced availability losses in the combustion process itself. shows the heat release rates for the three cases.



. ***Figure 1 Nox,PM,HC and CO emision rates***

The pilot injection event is evident for the baseline case and substantially suppressed for the before recovery case. The recovered condition exhibited a heat release curve very similar to the baseline condition, but the rate of increase of heat release from 0 to 10 CAD after top-dead-center was noticeably higher.The recovered condition exhibits a faster 10-50% heat release duration, 6.2 crank angle degrees (CAD), compared with baseline (7.5 CAD). However, the 50-90% heat release duration, 34.8 CAD, is much longer compared to baseline (26.8 CAD). In fact, the 50-90% heat release duration is longer than for the unrecovered case (31.9 CAD), though the 10-50% duration is shorter than the unrecovered case (12.7 CAD). The bulk in cylinder average temperature at SOI was higher for the recovered case than for baseline, owing to higher intake charge temperature that is in turn a result of increased EGR. Analysis of the average temperature of the bulk gases over the entire combustion event was not found to correlate with measured emissions. Flame temperature estimates from the data are not yet available, but are planned for future studies. A study of combustion processes in an optically-accessible engine at Sandia National Laboratory showed that the 10-50% burn
duration in similar combustion modes was rate-limited by chemical kinetics and that the 50-90% burn duration was mixing-controlled (11,12). The heat release is data from this study generally seem to support the Sandia finding, though this is uncertain because the in-cylinder charge compositions and engines were not the same for both studies.

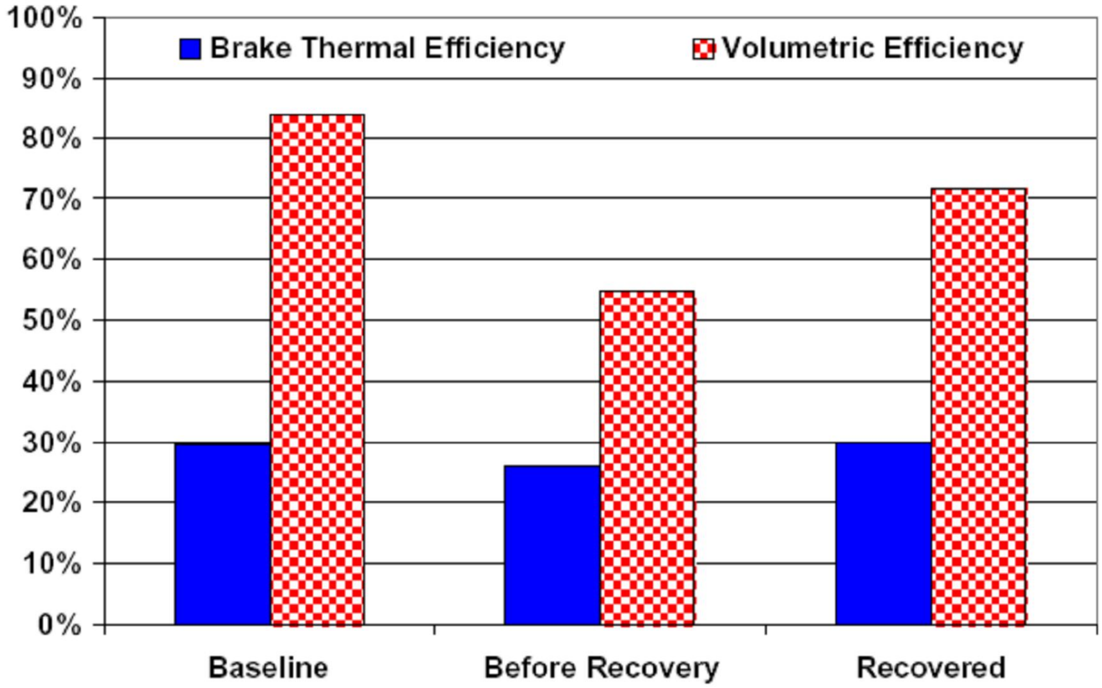


Figure 2 brake termal and volumetric efficiency result

3.CONCLUSIONS

Operation of a DI diesel engine in a highly efficient, clean combustion mode has been demonstrated at some operating conditions.

CO emissions rise substantially in HECC modes, but are generally treatable with known catalytic aftertreatment technologies.

Hydrocarbon emissions show a trend of producing olefins and aromatics but a trend of decreasing long-chain fuel hydrocarbons.

Studies of combustion together with the chemistry of the exhaust constituents can provide insights into the combustion and particulate formation processes that can aid in broader use of HECC processes in transportation and power generation applications.

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