OVERVIEW OF EMERGING CLEAN DIESEL ENGINE TECHNOLOGY

JOHN W. FAIRBANKS
U.S. DEPARTMENT OF ENERGY
WASHINGTON , DC

BACKGROUND

Diesel engines are the most realistic technology to achieve a major improvement in fuel economy in the next decade. In the US light truck market, i.e. Sport Utility Vehicles , pick-up trucks and mini-vans, diesel engines can more than double the fuel economy of similarly rated spark ignition (SI) gasoline engines currently in these vehicles. These new diesel engines are comparable to the SI engines in noise levels and 0 to 60 mph acceleration. They no longer have the traditional "diesel smell." And the new diesel engines will provide roughly twice the service life. This is very significant for resale value which could more than offset the initial premium cost of the diesel engine over that of the SI gasoline engine. So why are we not seeing more diesel engine powered personal vehicles in the U.S.? The European auto fleet is comprised of a little over 30 percent diesel engine powered vehicles while current sales are about 50 percent diesel. In France, over 70 percent of the luxury class cars i.e. Mercedes "S" Class, BMW 700 series etc., are sold with the diesel engine option selected. Diesel powered BMW's are winning auto races in Germany. These are a typical of the general North American perspective of diesel powered autos. The big challenge to commercial introduction of diesel engine powered light trucks and autos is compliance with the Environmental Protection Agency (EPA) Tier 2, 2007 emissions standards. Specifically, 0.07gm/mile Oxides of Nitrogen (NOx) and 0.01 gm/mile particulates (PM). Although the EPA has set a series of bins of increasing stringency until the 2007 levels are met, vehicle manufacturers appear to want some assurance that Tier 2, 2007 can be met before they commit an engine to a vehicle.

OXIDES OF NITROGEN (NOx) REDUCTION - IN CYLINDER

In mid-2001 there are strategies for NOx reduction that can be divided into 2 basic categories, in-cylinder and after treatment. Most diesel engines are turbo charged to increase the number of air molecules in the engines intake stroke. This number can be further increased by cooling the turbo charger compressor output. Formation of NOx is primarily a function of time at high temperature. The lag in the turbo charger output response during an acceleration can be reduced by a variable geometry turbine which is a classical example of Bernoulli's Principle wherein the velocity of the exhaust gas is increased by decreasing the cross-sectional area of the nozzle that directs the exhaust gas to the turbine. Reciprocating diesel engines require air in a linear relation as power is increased. However the output of the turbo charger is exponentially related to power. Thus there is an inherent mismatch of the turbo charger and the diesel engine over a wide operational power range. The hybrid system with the engine running in a narrow power range can be matched with a more efficient turbo charger. Air charging can be split between 2 turbo chargers each optimized for appropriate power range. The first turbo charger would be used for low power and idling. As power is increased the second turbo charger is also cut-in. This arrangement requires very clever piping to fit under the hood and controls to prevent hysteresis effects. This system is referred to as “sequential turbo charging.”

The most significant advance in modern diesel engine development is in fuel injection equipment (FIE). Microprocessor control has enabled precisely measured amounts of fuel introduced at predetermined crank angle position into the combustion chamber at pressures approaching 40,000 psi. The fuel is forced through a series of extremely small holes in the injector tip which finely atomizes it. The microprocessor allows fuel to be introduced by rate shaping as a function of crank angle. Pilot injection, a form of rate shaping , minimizes the high thermal spikes characteristic of combustion in older FIE, thereby contributing to lower levels of NOx formation. Work a decade ago in Switzerland on a medium speed engine with a 10 percent pilot injection produced a 45 percent reduction in NOx emissions. This pilot injection also dramatically reduces diesel combustion noise to the level of SI gasoline engines and in the process it reduces most of the hydrocarbons (HC). Hydrocarbons in the tailpipe exhaust are responsible for the "diesel smell." The FIE microprocessor can also further reduce NOx by controlling the amount of exhaust gas recirculation (EGR) into the combustion chamber. This EGR should be cooled for best effect on NOx reduction. Considerable promise is emerging with the homogeneous-charge compression-ignition (HCCI) FIE. The HCCI system produces a low-temperature, even-burning combustion process that yields good fuel efficiency along with low NOx and PM levels. The problem with HCCI is that as the load is increased more fuel has to be introduced thereby raising the combustion temperatures which increase both NOx and PM. Currently HCCI is limited to about 20 percent power with the higher power requiring the more conventional FIE (1). However a dual mode system incorporating 20 percent power level HCCI is being developed by a number of companies including 2 on DOE contracts.

OXIDES OF NITROGEN REDUCTION - AFTER TREATMENT

Three types of NOx reduction technology are emerging that potentially could enable compliance with Tier 2, 2007 emission standards. These areurea injection systems, NOx adsorbing catalyst and Non-Thermal Plasma devices. These systems have been significantly advanced but they still have problems, particularly meeting the 120,000 mile durability requirement. Long term aging data are not available.

Urea is a chemical used as a fertilizer. It is typically mixed with a liquid and which is then preheated such that it decomposes to ammonia (NH3) or an isocyanate gas (HNCO). NH3 is preferred and it reacts in the exhaust gas when the temperature is about 1500 oF to reduce NOx to it's constituent elements with over 90 percent effectiveness. Selective catalytic reduction (SCR) Catalysts or injection of hydrogen gas can reduce this reaction temperature to that of the exhaust gas. The alternative is to increase the exhaust gas temperature to 1500oF by burning fuel in the exhaust. These urea based systems have problems with ammonia slip during accelerations. Then there is the problem of establishing the urea distribution infrastructure and enforcement. Ford Motor Company has developed a dual fueling nozzle that will simultaneously dispense diesel fuel and an appropriately metered urea solution in separate streams to vehicles equipped with 2 tanks.

NOx absorber catalysts collect NOx on the Barium Carbonate catalyst surface and in 1 time period out of 30 momentarily stoichiometric conditions are periodically achieved by spraying diesel fuel into the exhaust. These conditions enable the NOx molecules to be reduced with a precious metal catalyst which doesn't work under lean conditions i.e. excessive oxygen. Unfortunately even small amounts of oxides of sulfur take sites on the Barium Carbonate catalyst that are removed by impractical high temperatures. Thus , this system needs a Sulfur removal trap before the NOx absorber catalyst. Current sulfur traps will probably need the maximum. Sulfur level in diesel fuel to be no more than 15 ppm so they are able to remove virtually all the Sulfur from the exhaust gas before it enters the NOx absorber catalyst. If 350 ppm Sulfur diesel fuel were used, the Nox absorber catalyst surface would collect enough Sulfur compounds on the catalyst surface to reduce the NOx conversion efficiency by 50 percent in less than 20 hours.

Non-thermal plasma emission reduction devices, also referred to as plasma assisted catalysts, can be designed to reduce NOx and/or PM. Most of the efforts have focused on NOx reduction. The process typically involves the plasma oxidizing NO to NO2 then reducing the NO2 to N2. The addition of hydrocarbons enhances these conversions. Laboratory work appears to favor propene as the source and it gives good results. However the realities of commercial application dictate that the reductant be derived on board from diesel fuel. Non-thermal plasma systems operate independent of temperature and fuel sulfur levels. They have an inherent self cleaning feature which suggests minimal degradation. The challenge for the non-thermal plasma developers is to build a power supply that can geometrically fit under the hood installed on current and evolving diesel engines, provide the electrical requirements and have a reasonable cost. They should not increase the engines fuel consumption by more than 3 percent. Non-thermal plasma NOx and PM reduction devices have shown considerable progress this year.

PARTICULATE AFTER TREATMENT

Particulates under 10 microns in size are respirational by humans. The smaller particles, such as the nano-particles, are thought to penetrate deeper in the lung and have a higher probability of not being exhaled. These nano-particles tend to stay airborne longer. The Environmental Protection Agency (EPA) emission standards for particulate are based on mass independent of PM sizing. This is probably because measurement of PM size is very difficult and the measuring equipment is in the advanced R&D stage. PM are also the host to nonregulated chemical compounds which are possibly harmful to human health. One group of such substances is the "polycyclic aromatic compounds" (PACs). The PACs are made from hydrogen and carbon atoms and some contain nitrogen, oxygen or sulfur atoms as well. Some of the PACs are carcinogens (substances that cause cancerous tumors in test animals) and/or muteness (substances that cause genetic damage in cells - damage that can show up as birth defects one or more generations later) (2). Recent analysis of diesel exhaust PM for 34 of the primary PAC's by the AEA group in the UK (a spin-off from Harwell now called Accentus) before and after their non-thermal plasma device, which was optimized for PM reduction, showed a virtual elimination of the PACs when the PM were oxidized (3). These results should be the same for any device that oxidizes PM.

The reduction of PM in the exhaust gas is done with PM traps, oxidation catalysts or non-thermal plasma devices. Tier 2 - 2007 will probably require PM traps. These are typically low porosity wall flow through monoliths that trap PM on these walls. Regeneration of these traps requires periodically reaching the oxidation temperature of the soot PM. Loaded trucks or busses climbing hills typically reaches this temperature at the trap. This could be a problem for light truck diesel engines. Methods being considered for regeneration include periodically micro waving , burning diesel fuel in the exhaust or periodic application of electrical resistance heating. The PM traps have demonstrated Tier 2 - 2007 level compliance but not the 120,000 mile durability requirement.

DIESEL ENGINE EFFICIENCY IMPROVEMENT

If one does a control volume around a diesel engine it is apparent that the roughly 34 percent of the energy of the fuel into the engine is available energy in the exhaust gas. There are other possibilities for improved efficiency by further reducing friction and lighter weight engine block and moving parts. Utilization of this otherwise wasted exhaust gas energy could result in reduced emissions (less fuel burned and the turbo charger can be motor driven during an accel to minimize turbo lag) , a smaller engine could provide the same power or provide the electrical power for component drive of the " beltless engine " or " more electric " engine. A concept advanced by Caterpillar, Inc. The DOE is supporting development of 2 concepts of exhaust gas energy conversion to electricity. These are the addition of a motor/alternator to the turbo charger shaft, referred to as "electric turbo compounding," and thermoelectrics.

The DOE has cooperative agreements with Caterpillar and Garrett Air Breathing Systems to develop the turbo compounding concept. Caterpillar is focused on the Class 7 & 8 heavy duty track and off-highway applications. Garrett, who developed the only mechanical turbo compound system that was commercialized, is developing electro turbo compounding for the light truck and automotive applications. Both companies are in the process of selecting the motor /alternator. Both are assessing conventional magnetic field motor/alternators with advanced winding configurations. Caterpillar is also doing a comprehensive assessment of switch reluctance motor/alternators that use a computer to simulate the effects of magnet fields such that magnets are not required. Thus the switch reluctance motor/alternators have minimal cooling requirements. These systems were analyzed to provide a 6 to 10 percent improvement in fuel economy. They eventually will be mated with the emerging motor/ alternator/starter/dampers which are 92 percent efficient alternators over the full power range whereas current alternators are 69 percent efficient at low power s and 39 percent at high power operation. These systems will be in phase with the 42 volt revolution and provide the capability of engine shut-off and restart during idling at traffic lights and longer non - underway periods.

Thermoelectric modules can be connected to either convert heat to electricity (the Seebeck Effect) or for heating or cooling (the Peltier Effect). There is interest in both effects by the automotive community. DOE is sponsoring development and demonstration of a 1 kW generator for a Heavy Duty truck application. This generator has undergone iterative test and redesign mated with a Cummins engine on a test stand. The improved thermoelectric generator (TEG) has been shipped to PACCAR and installed on a Kenworth powered with a 550 horsepower Cummins engine. The thermoelectric modules are Hi-Z's latest Bismuth -Telluride bulk semi-conductors , which are about 6 - 8 percent efficient. The excitement in thermoelectric are the emerging quantum-well thermoelectric, which involve many alternate layers of a nominal 100 angstroms thickness. Test coupons have been made that can reproducibly convert 20 percent of the thermal energy to electricity with a delta T of 250oC to 50oC and these are with the N leg of bulk semi-conductor material. There are several vehicle manufacturers that are seriously reviewing the possibilities of using thermoelectric modules to augment the vehicles power or for heating/cooling applications.

LUBE OIL

Texaco recently commercially introduced a lube oil additive that reduces fuel consumption from 3 to 5 percent for any rated lube oil rating. They are working on a similar oil additive for diesel engines (4). Diesel engine manufacturers are now confronting the problem of lube oil sulfur and ashes from metallic additive packs. The engine companies would like an ash free , no sulfur lube oil that extended drain intervals, reduced friction for a 5 percent fuel economy gain with equivalent lubricity as current lube oils and at current lube oil prices.

CONCLUSIONS:

Diesel engines for light truck and automotive applications are facing requirements to comply with extremely stringent emissions regulations. The more challenging NOx standard is being addressed by 3 technologies that appear to be strong candidates at this time. These are the Urea based systems, NOx absorber catalysts and non-thermal plasma devices. They each have problems to be solved that appear solvable. Diesel engine efficiency can be improved from 5 to 10 percent with electric turbo compounding and thermoelectric. Very low sulfur, < 15 ppm , diesel fuel is necessary to meet Tier 2 - 2007. And we have to get the sulfur out of lube oil also.

References:

1) Ashley ,Steven , " A Low Pollution Engine Solution " , Scientific America , June 2001

2) anon , " Introduction : Health Effects of Combustion" , e-lab report of the Massachusetts Institute of Technology , Cambridge , MA , January - March 1988

3) Morgan , Ross, AEA , Abingdon, UK : personal communication with John Fairbanks , DOE Washington , DC , 28 January , 2000

4) Jung , Al , Texaco - Brussels , Belgium : personal communication with John Fairbanks , DOE , Washington , DC , 7 July 2001