BIOdiesel Tech NOTES

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Biodiesel Emissions

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When biodiesel was first introduced in the United States, one of the major advantages that could be used to justify its higher cost was its beneficial effect on exhaust emissions. Biodiesel provided substantially lower emissions of particulate matter, carbon monoxide, and unburned hydrocarbons. Oxides of nitrogen increased but for blends the amount of the increase was frequently small enough that it couldn't be measured accurately. As time has passed, and biodiesel has gained more consumer acceptance, its exhaust emissions are mentioned much less often.

Part of the reason for the decreased emphasis on exhaust emissions is that the Renewable Fuel Standard has provided a pathway for biodiesel to be priced comparably with petroleum-based diesel fuel. So, there is no longer a need to emphasize lower emissions to justify higher price. However, biodiesel's favorable effect on life cycle greenhouse gas emissions is still emphasized as one of biodiesel's advantages.

The main reason for the decreased emphasis on exhaust emissions is that regulations have required new diesel engines to have much lower emissions and engine manufacturers have made technological improvements to the engine in order to meet these requirements that make the effect of the fuel less important. Biodiesel still has a beneficial effect on older engines, but they represent a constantly shrinking portion of the transportation fleet. This TechNote will describe the processes that create diesel emissions and the changes that have been made to modern diesel engines that have reduced the effect caused by using biodiesel.

Under ideal circumstances, all of the carbon in the diesel fuel will burn to carbon dioxide (CO_2) and all of the hydrogen will burn to water vapor. In most cases, virtually all of the fuel follows this path. However, during the actual combustion process, small amounts of fuel carbon will remain as carbon monoxide (CO), unburned hydrocarbon, and particulate matter. In addition to these fuel-based products, nitrogen from the air will combine with oxygen to form nitric oxide and nitrogen dioxide, which are known as oxides of nitrogen (NOx).

Carbon monoxide and unburned hydrocarbon emissions are usually quite low for diesel engines compared with gasoline engines and most engine manufacturers have little difficulty meeting the regulatory requirements for these pollutants. Oxides of nitrogen and particulates are a greater challenge. Traditionally, engine manufacturers were able to use late injection timing, cooling of intake air after the turbocharger compressor with air-to-air heat exchangers, and exhaust gas recirculation to control NOx. Particulates were controlled by limiting engine power through reduced fueling levels to ensure there was an adequate amount of excess air.

With the exception of some oxidation catalysts, diesel engines traditionally did not use exhaust after-treatment for emission control. The three-way catalyst technology that is widely used for spark-ignited vehicles is not suitable for use on diesel engines because it requires a fuel-air mixture that is near the chemically correct ratio to obtain simultaneous reductions in CO, unburned hydrocarbons, and NOx. Diesels always operate with excess oxygen; thus, the reducing catalyst required to eliminate NOx cannot operate. The oxidation catalysts provided on some diesel engines are able to reduce particulate levels by oxidizing some of the adsorbed hydrocarbons from the soot particles, but they do not operate at high enough temperature to reduce the solid portion of the particulate and they do nothing to reduce NOx.

Diesel Emission Controls

There are two basic strategies that have been used to eliminate diesel particulate emissions: in-cylinder controls, which are intended to minimize the amount of particulate released from the cylinder and aftertreatment, which operates on the particulate after it leaves the engine cylinder but before it is released to the environment.

In-cylinder controls

Requirements for lower emissions and continued demands for improved fuel economy have driven the engine industry to technical advances that incorporate state-of-the-art electronics and manufacturing technology. A particular challenge for engine manufacturers was that design changes implemented to reduce particulate emissions tend to increase NOx and vice versa. This effect, known as the NOx-particulate tradeoff, limits the emission reduction that can be achieved with in-cylinder measures. Common rail fuel injection has pushed the limits for fuel injection pressures to >2500 bar. The rapid mixing provided by the high spray velocity resulting from this extreme injection pressure provides low particulate formation while allowing the retarded injection timing settings needed for reduced NOx.

The introduction of common rail fuel injection systems has allowed new flexibility in programming the injection event. These systems allow multiple injections within a single engine cycle. A common strategy is to start the combustion with two brief injections, called the pilot- and pre-injections. These injections produce an environment in the cylinder so that when the main injection occurs, the ignition delay will be shorter, the amount of premixed combustion will be less, and the NOx production will be reduced. These small injections that precede the main injection also reduce engine noise and vibration. Immediately following the main injection, a small amount of fuel may be injected to assist in oxidizing the carbon particles. Then, later in the expansion process a post-injection provides the elevated exhaust hydrocarbon level needed by the aftertreatment equipment. The high degree of control offered by common rail injection systems would have been useless without the use of electronic controls. The application of powerful on-board computers to diesel engines initially lagged behind their use on spark-ignition engines, but current engines have corrected this deficiency.

To improve the engine's air supply, variable geometry turbochargers have been developed to extend the engine operating range over which adequate air is provided to keep particulate emissions low. Air-to-air aftercoolers are also used to lower intake air temperatures to reduce both NOx and particulate emissions. Before 2007, in-cylinder measures were enough to meet the emissions regulations in effect to that date.

Aftertreatment

The Environmental Protection Agency (EPA) has been issuing emission standards for diesel engines since 1974. Until recently, these standards could generally be met through the use of in-cylinder controls, exhaust gas recirculation, and in some cases, exhaust catalysts. However, starting in 2007, emission regulations from the EPA dramatically lowered the allowable levels of exhaust pollutants for on-highway diesel engines. The level of particulate emissions was lowered from 0.1 g/bhp-hr to 0.01 g/bhp-hr, a 90% reduction. This reduction in particulate emissions coincided with a similarly dramatic reduction in NOx emissions, from 4.0 g/bhp-hr to 0.2 g/bhp-hr. These reductions were in addition to the reductions that had been implemented from 1974 to 2007. These emission levels could no longer be met with in-cylinder controls. To achieve these levels of NOx control, most manufacturers were required to use selective catalytic reduction (SCR), which required operators to periodically refill tanks of Diesel Emission Fluid (DEF). For particulate control, manufacturers had to start using diesel particulate filters, or DPFs. These devices are known as aftertreatment.

DPFs can be made from metal, but most commonly use porous ceramics. The filter must be ceramic to survive the high temperature in the diesel engine exhaust as well as to allow for the periodic burn-off of the collected particulate so the filter does not plug up as the particulate accumulates in the filter. This burn-off process is known as regeneration. Regeneration is a complex process because it must occur before the carbon accumulation in the DPF reaches levels that restrict exhaust flow from the engine. It requires high temperatures to oxidize the carbon but not so high as to thermally stress or melt the ceramic filter. Under high power conditions, the normal exhaust temperature of the engine may be high enough so that carbon burns off as it is deposited. But the exhaust temperature at low load conditions is too low to ignite the carbon so more active measures may be needed such as supplemental fueling, usually fuel injected during the exhaust stroke, to raise the exhaust temperature and initiate the regeneration process.

Modern diesel engines use a combination of in-cylinder controls and aftertreatment to reduce emissions to extremely low levels. Reductions in CO, unburned hydrocarbons, and particulates still occur when using biodiesel but they are of less interest because the particulate filter and the oxidation catalyst would remove them anyway. Similarly, even if NOx emissions are increased from the engine, they will be eliminated by the SCR catalyst. This is the main reason why biodiesel emissions have been deemphasized as advantages of biodiesel use. It should be noted that diesel engines have long lives and there is a large number of legacy engines that will be around for 30 years or more. These engines will benefit from biodiesel since they are not equipped with modern in-cylinder controls or aftertreatment. In addition, the reduction in life cycle greenhouse gases with biodiesel is over 80% compared with conventional diesel fuel and continues to improve each year. This is a major incentive for biodiesel use.