

Acidic Condensation in Low Pressure EGR Systems using Diesel and Biodiesel Fuels

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ABSTRACT

Testing was performed on a 2.0 liter diesel engine with high pressure (HP) and low pressure (LP) EGR, using standard European low sulfur diesel as well as fatty acid methyl ester (FAME) biodiesel fuels produced from soy, rapeseed and palm feedstock, both neat and blended with 50% standard diesel. In the HP EGR configuration, fuel injection, air flow and EGR rate were adapted to achieve the same engine load and NO_x emissions for all fuels at the selected test points. Higher brake specific fuel consumption and lower smoke emissions were observed for the biodiesels compared to the standard diesel. In the LP EGR configuration, large reductions in NO_x and smoke were observed for all fuels compared to HP EGR. In addition, water condensed in the charge air cooler at coolant temperatures below 30°C. This condensate was collected and analyzed, finding similar volumes and acidity for condensates from all the diesel and biodiesel fuels.

INTRODUCTION

Diesel engines have a large market share in Europe and have the potential to become increasingly present on the North American market. In order to continue this trend, low pressure EGR systems will be a key element to ensuring that diesel engines comply with upcoming Euro 6 and Tier 2 Bin 5 NO_x regulations. However, in this configuration, exhaust gas is introduced to the fresh air before the compressor, therefore passing through the charge air cooler. Testing has shown that under typical operating conditions, the water vapor present in the

recirculated exhaust gas can produce acidic condensation in the charge air cooler [1]. The quantity and nature of this condensation is an essential factor to be considered in the design of engine components, in particular aluminum heat exchangers.

In parallel, biofuels are becoming increasingly important in the effort to reduce greenhouse gas emissions. Biodiesel production has been developing rapidly while the US and European governments have implemented legislation to continue that growth. The chemical composition of biodiesel is considerably different from petroleum diesel and varies with the feedstock. The exhaust gas composition, and therefore the condensate composition in a low pressure EGR system, depends on the fuel chemistry. Engine components designed for LP EGR therefore need to be compatible with both standard diesel and biodiesel blends.

FUEL SELECTION

Biodiesel is produced by a transesterification process that converts oils and fats into long chain mono-alkyl esters, also known as fatty acid methyl esters (FAME). Unlike synthetic fuels produced through the Fischer-Tropsch process, the physical and chemical properties of FAME biodiesels are greatly influenced by the feedstock. Feedstocks can include animal fats, recycled cooking oils and greases, and vegetable oils such as soy, corn, rapeseed, sunflower, palm, coconut, peanut, jatropha, and even algae.

The main differences in fuel properties between feedstocks are due to the length of the fatty acid chain and the level of saturation. The longer the molecule and the more saturated it is, the higher the cetane number, cloud point, and chemical stability [2]. The higher cetane number of highly saturated long chain biodiesels improves combustion and the better stability improves storage, however the high cloud point can be a significant disadvantage in handling. It was hypothesized that these chemical differences could also produce differences in the condensates formed in the charge air cooler during operation with low pressure EGR, and so fuels from three different feedstocks were selected for test.

The majority of the biodiesel production in the USA is from soy, while most of the European biodiesel production is from rapeseed [3,4,5,6]. Therefore biodiesels from both of these feedstocks were chosen for study. The majority of the fatty acids in soy are polyunsaturated, whereas in rapeseed most are monounsaturated [2]. Therefore a third biodiesel with a high proportion of saturated fatty acids was sought. Animal fats, palm oil, and coconut oil meet this objective [5]. Palm was chosen because it is a major low-cost biodiesel source in tropical countries [6], having an extremely high yield of oil per area of cultivated land – over 5 times higher than rapeseed, and over 10 times higher than soybean [7,8].

These three biodiesels were tested neat (B100) in order to identify the most extreme differences that might arise due to fuel origin. Standard European low sulfur diesel was used as the reference, and for blending with the neat biodiesels to form B50 in order to have an intermediate value to compare to the pure fuels. Table 1 displays some of the properties measured on the pure fuels, while a more complete listing can be found in the appendix.

Table 1. Properties of diesel and biodiesels tested.

Property	Unit	Diesel	B100 soy	B100 rape	B100 palm
Cetane number	-	50.6	50.6	56.6	69.5*
Viscosity at 40°C	mm²/s	2.68	4.24	4.48	4.44
Density	kg/l	0.84	0.88	0.88	0.87
Lower heating value	MJ/kg	43.0	35.9	37.2	36.8
Sulfur content	mg/kg	7.4	2.8	1.7	1.9
Acid number	mgKOH/g	0.03	0.26	0.19	0.17
Pour point	°C	< -24	-6	-12	12
Cloud point	°C	-3	-1	-5	15
Distillation 10% vol	°C	195	316	323	314
Distillation 50% vol	°C	262	328	332	323
Distillation 90% vol	°C	339	334	342	330
Iodine value	g/100g	10	127	113	54
Oxidation stability at 100°C	hours	> 72	9.6	6.2	9.2

* Above the calibrated measurement range (maximum 60.8)

One of the most important fuel properties is the cetane number. The high cetane number of palm is particularly noteworthy, while the lower value for soy makes it less attractive as a cetane enhancing blend component for

the European market, where the minimum cetane number is 51 for B100 (EN14214) compared to 47 for B100 in the USA (ASTM D6751).

The viscosity is considerably higher for all the biodiesels compared to diesel, and the density slightly higher. These could potentially affect injection and combustion behavior. The lower heating value is significantly lower for the biodiesels, which directly impacts fuel consumption as more fuel is required to provide the same amount of energy.

Two properties that were hypothesized to have an impact on the acidity of the condensation that occurs due to EGR gas in the charge air cooler are the acid number and the fuel sulfur content (due to formation of sulfuric acid). Compared to the petroleum diesel, the acid number is higher for all the biodiesels, while the sulfur was lower for all the biodiesels.

The phase transitions occur in a much narrower temperature range for the biodiesels than for petroleum diesel. The pour point and the cloud point temperatures are much closer together, and the distillation curve is less than 20°C between 10% and 90% compared to over 140°C for diesel. In addition, the higher pour point temperatures for the biodiesels must be taken into account in handling and storage of the materials.

The iodine value and the oxidation stability at 110°C provide an indication of the chemical stability of the fuels. The iodine value is a measure of the carbon double bonds associated with unsaturated fatty acids, which are available for oxidation. As expected, the soy is the most unsaturated followed by rapeseed, while palm is far more saturated. The EN14214 maximum limit for the iodine value is 120, excluding neat soy as B100 for the European market. Nevertheless, the oxidation stability at 110°C of soy is higher than rapeseed and even palm, because both the number and the location of the carbon double bonds plays a role in the chemical stability. Nevertheless, both measures show that petroleum diesel is far more chemically stable than any of the biodiesels.

These properties confirm that the selected fuels have distinct characteristics covering a large range of the properties found in biodiesels from different feedstocks. If differences in these properties lead to differences in acidity of the condensates in charge air coolers, they would be expected to be observed in this test program.

EXPERIMENTAL SETUP

A four cylinder 2.0 liter direct injection diesel engine for passenger car application fulfilling Euro IV was used, with an open code ECU allowing the engine calibration to be tuned. Table 2 provides the main characteristics of the engine. The original high pressure exhaust gas recirculation (EGR) circuit was retained and a low pressure EGR system was added. Sulfur in the configuration shown in Figure 1.

Table 2. Test engine characteristics

Displacement	1998 cm ³
Bore x Stroke	85 x 88 mm
Valves	4 / cylinder
Compression ratio	18:1
Turbocharger	Garret VGT GT 1749V
EGR	High + Low Pressure
After-treatment	Oxy-catalyst + DPF
Max. Power @ speed	100 kW @ 4000 rpm
Max. Torque @ speed	320 Nm @ 1750 rpm

In the high pressure EGR circuit, exhaust gas is taken from the engine exhaust manifold, and routed to the engine intake manifold. Since the gas remains on the high pressure side of the turbine and the compressor, it is labeled high pressure EGR. The EGR cooler is placed upstream the EGR valve in order to prevent the valve electronics from reaching high temperatures which could affect their reliability. Downstream of the EGR valve, a pipe guides the exhaust gas to the intake manifold.

For the low pressure EGR circuit, the EGR gas is taken from the outlet of the DPF and routed through an EGR cooler to the compressor inlet. Since the gas is near ambient pressure as it is recirculated, it is labeled low pressure EGR. The EGR flow is controlled by the EGR valve downstream of the cooler. A back-pressure valve is placed in the exhaust line downstream of the EGR extraction point. The valve can be used to increase the pressure difference between the exhaust system and the intake duct at the compressor inlet, thus increasing the EGR rate in cases where the natural pressure difference is insufficient to supply the required EGR rates.

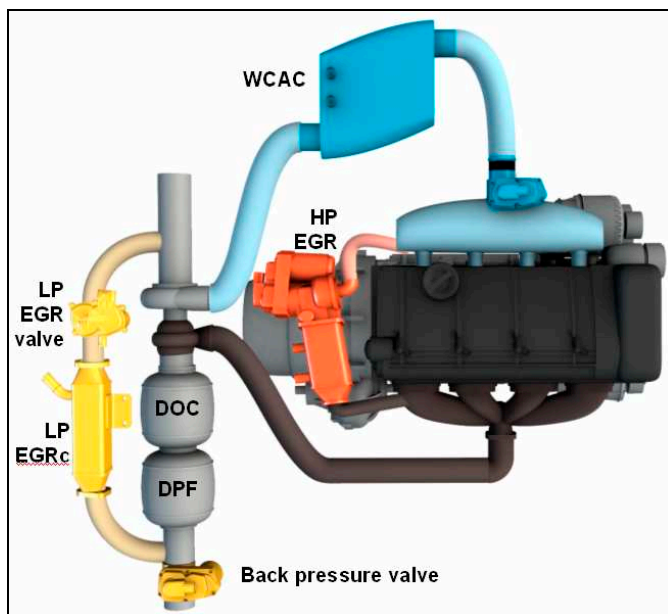


Figure 1. Test engine architecture

In both the high pressure and the low pressure EGR circuits, the EGR cooler is supplied with engine coolant at 90°C. The charge air is cooled with a high efficiency water-cooled charge air cooler (WCAC) supplied with coolant from a separate system that can be maintained at a temperature independent of the engine coolant. The condensates that form in the WCAC are collected by a sampling system underneath the outlet air tank, as seen in Figure 2.

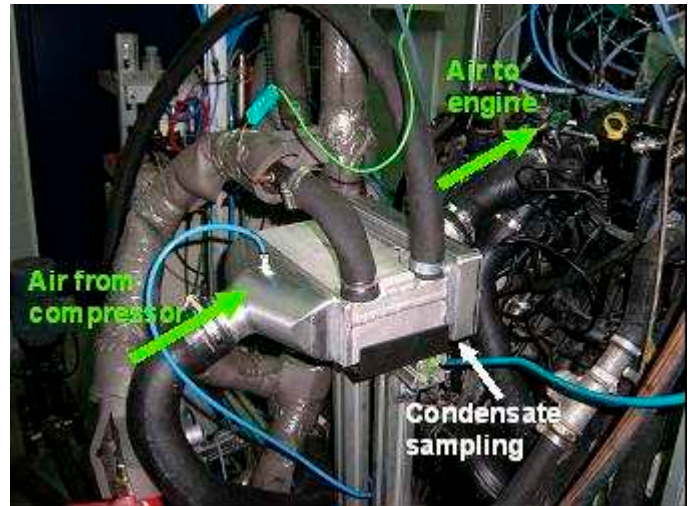


Figure 2. WCAC installation

The engine is installed in a test cell equipped with a variable frequency fast response dynamometer. A partial flow opacimeter AVL439 is placed upstream of the DPF in order to measure the engine out smoke emissions, while the exhaust gas emissions are measured after the DPF in order to have a representative measure of the EGR gas. The intake CO₂ concentration and exhaust gas emissions (NO_x, HC, CO, CO₂ and O₂) are measured by a Horiba Mexa 7100 DEGR equipped with the following detectors:

- NO_x by a Heated Chemiluminescence Detector
- HC by a Heated Flame Ionization Detector
- CO₂, CO by a Non-Dispersive Infrared Detector
- O₂ by a Paramagnetic Detector

The condensate samples are analyzed for acidity with a pH meter using a silver chloride electrode calibrated with buffer solutions at pH 2 and pH 7. Ionic Chromatography was used to measure the chloride, nitrate, sulfate, fluoride and organic acid concentrations. Inductively Coupled Plasma was used to measure the sulfur and the metal concentrations.

EXPERIMENTAL PROCEDURE

Three engine operating points from the NEDC cycle were selected for test, based on the standard Euro IV high pressure EGR configuration with diesel fuel. The points represent the 50 km/h and 100 km/h steady state operation and the acceleration in the urban cycle (Figure 3).