Is gasoline the best fuel for advanced diesel engines? - Fuel effects in "premixed-enough" compression ignition (CI) engines

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In diesel engines exhaust particulates and NOx can be controlled by promoting premixing of the fuel with air and combustion at a low temperature. However, conventional diesel fuel is very prone to auto-ignition and will ignite soon after injection starts, before the fuel and air have had a chance to mix. Indeed most of the advanced technology used in diesel combustion systems is aimed at countering the low ignition delay of diesel fuel either by slowing down the chemistry or by enhancing mixing. Even then low-smoke, low-NOx combustion is only possible at low loads. Engine experiments show that fuels that are more resistant to autoignition, such as gasoline, improve such combustion processes very significantly. These findings have important implications for fuels for future CI engines

Introduction

In conventional compression ignition (CI) engines – diesel engines - it is difficult to control particulates and NOx emissions. After-treatment systems to control them are being developed but are expensive, complicated and might reduce fuel economy and thus reduce the primary advantage of diesel engines. Moreover, regulations on emissions from diesel engines are becoming more stringent in all parts of the world. Hence there is a great deal of interest to develop engine combustion systems that offer the efficiency of a diesel engine, but with low smoke and low NOx.

We define diesel fuels here only in terms of their auto-ignition quality, as those with Cetane Number (CN) > ~ 30 and gasoline fuels as those with CN < ~30 or Research Octane Number (RON) > ~ 60 [1]. In practice, diesel fuels are significantly less volatile than gasoline fuels [1]. Auto-ignition is determined by chemical kinetics [2], which depend on the pressure and temperature development, mixture strength and chemical composition of the fuel. Typical, practical diesel fuels have CN > ~40 and will auto-ignite very quickly before the fuel and air are mixed sufficiently. If the mixing is accelerated or if the chemical reaction is slowed down, auto-ignition can be made to occur after the fuel and air are better mixed and soot levels can be reduced. NOx levels can be reduced by reducing combustion temperature by either running lean, pre-mixed or using EGR, exhaust gas recirculation.

Several operating strategies have been employed to promote pre-mixed and low-temperature combustion in CI engines. In homogeneous-charge compression-ignition (HCCI) the fuel and air are fully premixed as in a spark ignition engine and compressed till the charge auto-ignites. In modern direct-injection (DI) diesel engines with common rail injection systems, HCCI combustion can be obtained by injecting the diesel fuel very early in the cycle, giving it enough time to mix completely with air. However, with HCCI, there is no in-cycle control over the phasing of the heat release, which will be determined by the initial conditions of the mixture at the start of the compression stroke and the auto-ignition characteristics of the fuel. Hence HCCI combustion is very difficult to control. Practical CI engines always need fuel injection near top-dead-centre (TDC) to control combustion phasing.

However, when a conventional diesel fuel is injected near TDC, it ignites very soon after injection starts. Most of the fuel at higher loads is injected after the start of combustion and burns in a diffusion flame. In fact, most of the high technology used in advanced diesel engines, which makes them complicated and expensive, is required by the necessity to overcome the propensity of diesel fuel to auto-ignite easily in order to promote premixed combustion. Thus high injection pressures and high swirl are used to increase mixing rates while high levels of cooled EGR are used to delay combustion; this in turn requires higher boost pressures to achieve the required loads. Even then, with conventional diesel fuels, low NOx and low smoke with partially premixed CI combustion is possible only at low loads. Modern engines now require after-treatment systems to further reduce NOx and particulates, making them even more complicated and expensive.

Running a diesel engine on a gasoline fuel

Fuel auto-ignition quality effects on partially premixed diesel combustion have recently been studied in two different single cylinder research engines – one with a displacement of 2 litres [3,4] and a compression ratio (CR) of 14 and another with a displacement of 0.54 litres and CR of 16 [5]. Both these engines could be run on gasoline-like fuels. If gasoline is injected near (but before) TDC, it ignites much later than diesel fuel and combustion occurs when fuel and air have had more chance to mix [3,4,5]. If the same amount of gasoline is injected early at the same conditions i.e. with fully premixed, HCCI conditions, ignition might

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not occur at all. Thus the inhomogeneity is essential for combustion to occur but the high ignition delay makes combustion happen when fuel and air are better mixed – fuel and air are **"premixed enough**" but must not be fully premixed. This mixture stratification, which enables control of the phasing of combustion through injection timing, is easily achieved simply by relatively late (compared to HCCI) injection. Much higher loads can be achieved at low smoke and NOx levels with gasoline compared to diesel while retaining control over combustion.

At low loads, when the global mixture strength is lean, the higher the ignition delay, the leaner are the mixture packets where heat release occurs by auto-ignition and NOx is reduced very significantly [3,5] and the maximum heat release rate and hence the maximum pressure rise rate are also reduced [5]. This is illustrated in Figure 1, where Indicated Specific NOx (ISNOx) and Maximum Pressure Rise Rate (MPRR, open symbols) are both plotted against IMEP for a European Diesel fuel of 56 CN (Cetane Number) and a gasoline of 84 RON. The engine was running at 1200 RPM without any EGR and the injection timing was varied – further details about the operating conditions can be found in [5].

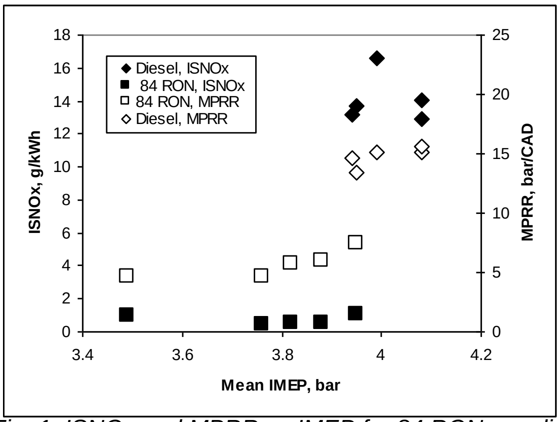

Fig. 1: ISNOx and MPRR vs IMEP for 84 RON gasoline and diesel fuel for the same engine operating condition. 1200 RPM, no EGR, no boost, 650 bar injection pressure. From Fig.s 5 & 6 in [5]

As load is increased, NOx goes up even for gasoline but, unlike with the diesel fuel, NOx can be reduced using EGR without really increasing the smoke. This is illustrated in Figures 2 and 3 where ISNOx and FSN smoke are plotted respectively against IMEP for the diesel fuel and a gasoline of 95 RON. In these tests the engine speed was 2000 RPM, the intake pressure was 2 bar abs. and the load was varied while holding the EGR level and the combustion phasing fixed. As IMEP is increased, exhaust CO_2 concentration increases and so does the intake CO_2 level, and ISNOx decreases. With ~32% EGR the reduction in ISNOx with IMEP is similar for both the diesel fuel and 95 RON gasoline. However, for gasoline, even at around 12 bar IMEP, FSN is below 0.1 (Figure 3). Increasing the EGR level to ~41% brings down the NOx significantly for gasoline without really increasing the smoke. Of course such an increase in EGR level would increase smoke even above the levels shown in Figure 3 for diesel fuel.

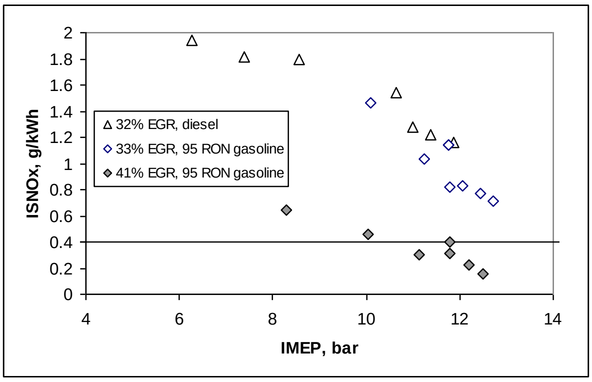

Fig. 2: ISNOx vs IMEP for 95 RON gasoline and diesel fuel at fixed EGR level. 2000 RPM, 1 bar boost, From Fig.11 in [5]

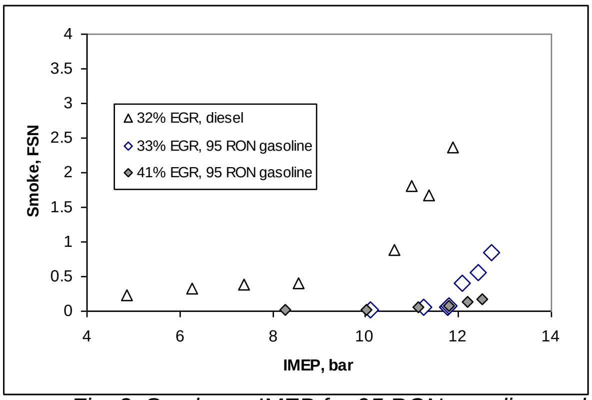

Fig. 3: Smoke vs IMEP for 95 RON gasoline and diesel fuel at fixed EGR level. 2000 RPM, 1 bar boost. From Fig.12 in [5]

Specific fuel consumption is the same for gasoline as for diesel fuel if the combustion phasing is kept the same [3,4,5]. However, HC and CO are higher [3,4,5], as expected for a more premixed combustion in an overall lean or dilute mixture, and would need to be controlled by exhaust gas after-treatment. Also, at higher loads, as the overall mixture strength becomes richer, a more premixed burning regime will result in higher heat release and hence, higher pressure rise rates [3,4,5]. This can be alleviated by using multiple injections [4,5]. This is usually not possible with diesel fuel - double injection makes smoke and efficiency worse because, the first, early injection releases heat during the compression stroke [4]. Also with gasoline, provision has to be made for starting the engine, probably via a spark plug.

Further Work Required

Thus the fuel needs to be as much like gasoline as possible if the aim is to promote premixed combustion i.e. increase engine ignition delay in CI engines in order to control smoke and NO_x. The extent to which this is possible in practice depends on whether other critical requirements for a practical engine such as good transient and low-speed operation, low noise, low emissions and low cost can be met. The engine needs to start and run at low loads satisfactorily. A CI engine operating on gasoline through the entire range is conceivable. Such an engine could be started by using spark ignition or a powerful glow plug, run with a single injection pulse near but before TDC at low and moderate loads. At high loads the fuelling rate would be increased by additional injection pulses in the cycle. The engine will need to have an oxidation catalyst to control HC and CO emissions and a turbocharger or a supercharger. Such an engine would be very similar to HCCI / SI prototype engines that have been announced by GM and Mercedes-Benz. Those engines use gasoline, are started using a spark plug, run in HCCI mode at low load with early fuel injection and switch to SI combustion at high load though they could run in CI mode at high loads as well by injecting fuel near but before TDC. There might also be scope for improving the efficiency of the transmission system for light-duty applications by reducing the average speed since gasoline allows higher loads to be reached at any given speed with low NOx and low smoke compared to diesel fuel.

The experiments using gasoline have so far been done with a standard diesel injector. Small injector holes and high injection pressures are needed for diesel fuel in order to increase mixing rates to counter the low ignition delay. These are probably not necessary for gasoline fuels with high ignition delay. There should be further scope for optimization of this type of combustion through injector design and optimizing injector strategies. There is a lot of scope for cost saving if lower injection pressures could be used. The relative importance of fuel volatility, composition (e.g. aromatic content) and auto-ignition quality in such combustion systems needs to be studied further. However results so far suggest that auto-ignition quality is by far the most important parameter.

Implications

There has been much investment made in developing the engine and after-treatment technology using conventional diesel fuel. Hence, in the short term (< 10 years), conventional diesel fuel (CN > 40) will continue to be used in CI engines. The practical debate on fuel auto-ignition quality in CI engines is about whether future engines will require higher cetane in the 40 to 60 range, not whether diesel fuel should be replaced by gasoline. Thus should the minimum cetane specification for diesel fuel be raised in those areas where it is currently low (e.g. U.S.) compared to Europe? If future engines are designed to promote premixed combustion, higher fuel cetane number will certainly not help; it might hinder such operation. On the other hand if the strategy used to control smoke and NO_x at high loads is to promote (low temperature) *diffusion* combustion and use exhaust after treatment, higher cetane might help in reducing HC and CO emissions. Of course, other diesel quality issues such as sulphur and volatility levels and other compositional issues are also important in the debate about future fuel requirements. These will eventually have to be agreed by the different stakeholders such as the auto and oil industries, governments and regulatory bodies and environmental interests.

In the long term, fuels much more like today's gasoline rather than today's diesel fuel could be used in CI engines to great advantage. Hence components normally considered for blending fuels for SI engines, including biofuels like ethanol, could be used to make fuels for CI engines. Indeed the optimum fuel for such combustion systems could have a lower octane number and lower volatility (higher full boiling point) compared to today's gasolines. Such a fuel would maintain the advantage over diesel fuel while easing low load, high speed and high EGR operation. It might also take less energy to manufacture such low octane fuel. If such a fuel is to constitute the majority of refinery output—as a majority of the engines would be CI engines because of their higher efficiency—the consequences for fuel manufacturing, energy balances and well-to-wheel greenhouse gas emissions need to be understood.

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