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Understanding the relationship between ignition delay and burn duration in a constant volume vessel at diesel engine conditions

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Abstract

Experiments were performed in a constant volume vessel, with fuel sprays injected into the vessel at various different pressure and temperature conditions chosen to represent diesel engine operation at various loads.

A range of diesel primary reference fuels (i.e. mixtures of cetane and heptamethylnonane) of varying cetane number (CN) were tested, and as expected lower CN fuels have longer ignition delays. Burn period was plotted against ignition delay and two distinct trends can be seen: "mainly diffusion" diesel combustion in which burn period decreases with ignition delay and "mainly pre-mixed" diesel combustion in which burn period increases with ignition delay. There is typically a minimum in plots of burn period versus ignition delay which represents the transition between the two types of combustion mode. Higher CN, higher engine load and higher boost pressure would seem to favour "mainly diffusion" combustion whilst lower CN, lower loads and non boosted conditions favour "mainly pre-mixed" combustion.

Keywords: Diesel; Spray; Cetane number; Ignition delay; Burn duration

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1. Introduction

Diesel vehicles (both passenger cars and heavy duty vehicles) are required to meet increasingly stringent controls on particulate matter (PM) and oxides of nitrogen (NOx), whilst at the same time operating with high efficiency to minimize greenhouse gas emissions. Although exhaust gas after treatment systems remain critical to achieving the emissions norms, optimized combustion to reduce engine-out emissions also plays a pivotal role.

Engine-out PM can be reduced by improving fuel–air mixing, so that a smaller fraction of combustion occurs in ultra-rich regions. Optimized fuel injection and swirl play an important role, but some advanced diesel combustion concepts also involve injection earlier in the cycle (often

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combined with lower compression ratio) to allow more time for mixing [1–4].

Engine-out NOx reduction is usually achieved by exhaust gas recirculation (EGR) to reduce the combustion temperature. In traditional diesel combustion, increasing EGR tends to increase local mixture fraction φ, leading to higher PM emissions. However advanced diesel combustion modes with a very high degree of pre-mixing can allow a simultaneous reduction in NOx and PM [5,6]. Some workers have gone as far as to suggest that gasoline-like fuels are the best for this type of combustion system because their autoignition resistance means that they can be injected very early, thereby allowing ample time for pre-mixing [7–9].

The original Sandia conceptual model of diesel combustion [10] envisages a steady state diffusion flame in which most of the combustion occurs under very rich conditions within the head of the jet. However this model is not valid when most of the combustion takes place after injection has finished and the Sandia group have developed new conceptual approaches to describe diesel combustion modes with a high degree of pre-mixing [11].

The literature contains examples of diesel combustion systems whereby a higher pre-mixed burn fraction gives rise to a greater level of combustion noise which can be mitigated with increased fuel cetane number (CN); see Hartikka and Nuottimäki [12] for a recent example. The reason generally given is that a longer ignition delay (ID) gives more time for fuel and air to mix prior to autoignition and premixed diesel combustion is generally faster than a diffusion flame. Faster combustion causes a higher maximum rate of pressure rise and hence more combustion noise.

However the relationship between cetane number and burn rate/combustion noise is not as straightforward as commonly supposed, especially for the highly pre-mixed diesel combustion systems described by the new Sandia conceptual model [11]: In recent work Hu et al. [13] have presented results in which n-heptane and iso-octane were injected into a constant volume combustion vessel at pressure and temperature conditions representative of a diesel engine. N-heptane has a CN which is representative of a typical European diesel fuel, albeit with a much higher volatility, whereas iso-octane is extremely resistant to autoignition. Because of the long ignition delay, iso-octane was found under some conditions to have become too mixed and dilute for autoignition to occur at all. In higher temperature and pressure conditions where iso-octane did ignite, the combustion was found to be much slower than for n-heptane under the same conditions.

The objective of this work is to explore the relationship between ignition delay and burn rate in a systematic way. To this end a variety of diesel primary reference fuels were tested in a constant volume combustion vessel operated under a variety of different conditions chosen to represent diesel engine operation at various loads. Although other workers have used a wider range of techniques to investigate diesel combustion in a constant volume vessel (e.g. [14]), the novel feature of the work presented here arises from the range of fuels of different CN tested here. The relevance of the results to actual engines is also discussed.

2. Experimental

The Combustion Research Unit (CRU) in Shell Global Solutions is a constant volume vessel, manufactured by Fueltech that can mimic combustion conditions in modern diesel engines. A schematic diagram of the CRU is shown in Fig. 1.

The unit is supplied with a common rail injection system of type Bosch CRIP2 (Part No: 0445110157) and a 7 hole nozzle. Fuel is injected into the pressurized heated chamber where it mixes with hot air and ignites.

The combustion process is monitored with a pressure sensor inside the chamber whilst a needle lift sensor inside the injector monitors the injection event. The chamber pressure, chamber temperature, fuel pressure, chamber gas composition and injector pulse width can all be varied by the operator. Before the fuel is injected, the chamber is filled with high-pressure air (or another gas) from an external air cylinder and heated to a pre-set temperature via two electric heaters. Some technical parameters of the CRU are listed in Table 1.

The needle lift sensor and the two dynamic pressure sensors in the combustion chamber and fuel line all sample at a rate of 50 kHz (intervals of 0.02 ms), giving outputs including needle lift, chamber pressure and fuel pressure. The needle lift enables the measurement of the start of injection (SOI) and the end of injection (EOI). The chamber pressure is used to determine the ignition delay and burn period. The specific definitions of ignition delay and other terms used in this paper are given in Table 2.

The CRU was operated under a number of conditions to represent different points in the speed load map of a typical diesel vehicle (Table 3). The set of conditions tested in the CRU were determined from p–T curves for a non-firing cylinder for a representative light duty vehicle at different initial conditions calculated assuming adiabatic compression.

The primary reference fuels, PRFs, used for cetane measurement are cetane (n-hexadecane), which has a designated cetane number of 100, and heptamethylnonane (HMN or 2,2,4,4,6,8,8-heptamethylnonane), which has a designated cetane number of 15. Note that these are different