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Surface pre-ignition measurements of fuel components and their mixtures

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ABSTRACT

A closed loop temperature controlled glow-plug has been used to control the incidence of surface pre-ignition of n-pentane, iso-pentane, n-heptane, iso-octane, ethanol, cyclohexane, ethyl-benzene, toluene and xylene, and four representative mixtures of these components. Statistical data on the incidence of pre-ignition compared with spark ignition has been derived from the in-cylinder maximum pressure, and the glow-plug temperature has been characterised on a cycle-by-cycle basis.

The alkanes and alcohols were found to be rather susceptible to surface pre-ignition, with the straight chained molecules having a higher pre-ignition tendency than branched chain molecules. The pre-ignition tendency of ring-structured components depends on the length of the attached chain, with shorter side-chain molecules (xylene, toluene) being less susceptible to pre-ignition than longer side-chain molecules like ethyl-benzene; cyclohexane was more susceptible to pre-ignition than any of the aromatic fuels. A higher glow-plug temperature was found to be needed for pre-igniting stoichiometric or rich mixtures, and this was attributed to the weaker mixture having a higher compression index and a lower specific heat capacity.

1. Introduction

Pre-ignition means ignition prior to the occurrence of the ignition spark, and in the past this was only associated with surface ignition. However, now it often refers to ignition in the bulk of the compressed unburned mixture, caused by the auto-ignition of, for example, a lubricant droplet. A recent comprehensive review by Wang et al. [1] discusses this form of auto-ignition and the related phenomenon of ‘super knock’. Conventionally, pre-ignition referred to the ignition of the fuel/air mixture by a hot spot such as a part of the spark plug, combustion deposits or an exhaust valve, so this is termed ‘surface pre-ignition’ in the title here, so as to avoid any ambiguity. The maximum pressures observed during pre-ignition are higher and occur earlier than during normal combustion as the earlier start of the combustion compresses the end gas more [2,3]. Evidence that different mechanisms are involved in surface pre-ignition and auto-ignition in the bulk gas is provided by the absence of a correlation between octane rating and surface pre-ignition ratings [4].

Combustion analysis of surface pre-igniting cycles has shown that flames appeared before the spark ignition timing, and this has been confirmed in optical and flame ionization studies. The rate of the heat release is in the same range as during normal spark ignition experiments which is significantly below the heat release rate during auto-ignition that is associated with combustion ‘knock’. This also shows that surface pre-ignition and auto-ignition are distinct phenomena [3–5]. The high rate of heat release rate during auto-ignition is because with ‘knock’ a significant quantity of mixture has been compressed to a high temperature and is at the point of combusting.

The increased pressure during surface pre-igniting cycles leads to magnified negative work during the compression stroke, and this can reduce the efficiency of an engine. The earlier ignition means that all pressures during combustion are increased, so the pressure in the unburned gas will be higher along with its temperature. The raised unburned gas temperature can lead to auto-ignition of the remaining unburned gas and a very rapid pressure rise that leads to audible knock. The rapid pressure rise is also associated with an increased heat flux so component temperatures will rise. If the auto-ignition was a consequence of pre-ignition, then the higher component temperatures will mean earlier pre-ignition and thence earlier and more intense auto-ignition. This leads to runaway knock and the likelihood of structural damage to the engine; turning off the spark ignition will, of course, have no benefit.

Surface pre-ignition can only occur if two criteria are met: the ignition criterion and the propagation criterion. The ignition criterion states that there must be a source of ignition present in the engine. The initiation criterion dictates that after ignition, a flame must grow to a critical size in order to propagate further when the ignition source (e.g. the hotspot) has disappeared. The hot spot has to provide enough

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energy for the flame kernel to reach this critical size. If the flame size is too small, the rate of heat loss to the surroundings outweighs the rate of heat release from the chemical reaction and the flame extinguishes. The influence of the pressure and temperature on the laminar burning velocity and how these impact on pre-ignition have been discussed comprehensively by Kalghatgi [4], who concludes that slow burning fuels are less prone to pre-ignition.

The most comprehensive data on the pre-ignition properties of pure fuel components is the work of Downs and Theobald [3] who tested 21 components. This work is now over 50 years old and did not have the benefit of modern data acquisition systems that allow statistical analysis of data from many engine cycles. As pre-ignition is a highly stochastic process, then this placed high demands on the test operator in determining a threshold for pre-ignition. This work also ranked the resistance to pre-ignition in terms of the heat input to a glow-plug, which then makes comparisons with other data very difficult. They also provided data on the temperature of their heater which will be discussed later. Recent work by Budak et al. [6] have also used a heater plug but in a boosted gasoline direct injection engine with an emphasis on testing biofuels. Their threshold for pre-ignition was set at 2 per cent of cyces pre-igniting with their thermocouple temperature measurements being mean values.

There are different ways of inducing surface pre-ignition and reporting the susceptibility of a fuel to surface pre-ignition. Guibet and Duval [7] used two methods: a heating element, and spark plugs with different temperature ratings, and in both cases temperature was used to characterise the pre-ignition ratings. A particular interest was how the metallic additives in oil and fuel led to deposits that catalysed pre-ignition, and these effects were quantified by how long the engine had to be run before pre-ignition occurred.

Menrad et al. [8] also used spark plugs with different heat ratings and materials to quantify the pre-ignition rating of different alcohol gasoline blends with a particular focus on methanol (because of its susceptibility to pre-ignition). They used the spark plug as an ionisation detector so could determine whether or not pre-ignition had occurred. They increased the temperature of the sparkplug by retarding the ignition timing and reported their results in terms of this critical ignition timing.

Another approach to identifying a pre-igniting cycle is reported by Luef et al. [9] who considered the angle of occurrence of the 5% mass fraction burned (mfb) in 200 consecutive cycles. If the observed 5% mfb is earlier than a predefined limit (which was set at two times the standard deviation of the 5% mfb point earlier than the mean value for spark-ignited combustion) then pre-ignition has occurred. The compression ratio was then adjusted to find the value that would satisfy their pre-ignition criterion. Tests with a similar pre-ignition criterion were also undertaken with a heated glow-plug and the temperature for pre-ignition was reported for a range of alcohols blended with iso-octane.

2. Experimental equipment and procedure

As with the work of Downs and Theobald [3] a Ricardo E6 variable compression ratio engine has been used for the surface pre-ignition tests; it has a bore of 76 mm and a stroke of 111 mm. The inlet valve opens 9°bTDC and closes 37°aBDC; the exhaust valve opens 41°bBDC and closes 6°aTDC. The engine (Fig. 1) has two M14x1.25 tapped holes on opposite sides of the cylinder head: one being used for a spark plug fitted with a Kistler 6051A piezo-electric pressure transducer, and the second being used for the pre-ignition glow-plug and thermocouple. An NGK Y-307R diesel glow-plug was mounted in a holder that had a lead-through for the type K thermocouple that was butt-welded onto the surface of the glow-plug. A NI USB-6525 card with LabVIEW was used to record the temperature of the glow-plug; the power to the glow-plug was regulated by a MOSFET that was controlled by a PID controller within LabVIEW

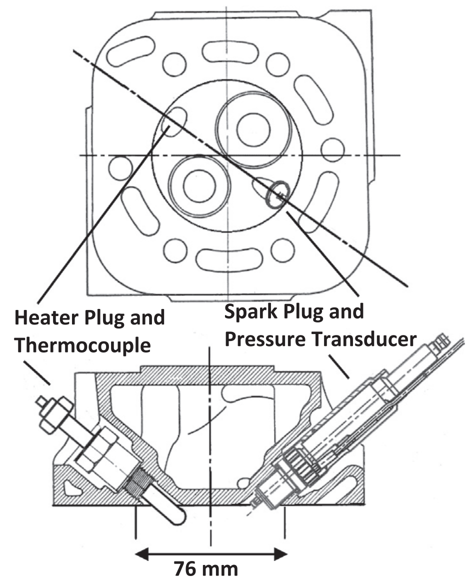

Fig. 1. Cross-section and plan view of the cylinder head showing the heater plug and thermocouple, and the spark plug with integral pressure transducer, adapted from Ricardo and Hempson [2].

The engine was comprehensively instrumented with thermocouples, flow sensors, pressure transducers and other sensors described later. The instrumentation was connected to two NI USB-6211 data acquisition cards (maximum sampling rate of 250 ksamples/s) for once per cycle and once per degree crank angle measurements. Typically over 500 cycles of data were recorded with the engine operating at wide open throttle. Data acquisition was through a LabVIEW program that also provided closed loop control of the air temperature (set at 30 °C), coolant temperature (set at 80 °C) and lambda (using the signal from an Innovate LM-1 lambda sensor system to control the port fuel injector). Data acquisition was controlled by an incremental shaft encoder (360 ppr), that also enabled the LabVIEW system to set the ignition timing. The engine was equipped with a port fuel injector and 3 fuel tanks pressurised with nitrogen; solenoid valves enabled the operation to be readily switched between the different fuels. The compression ratio was measured by an LVDT that had been calibrated against a micrometer. The engine speed was regulated to 600 rpm by the DC dynamometer and a load cell was used to measure the torque.

The pre-ignition experiments were conducted with a spark-ignition timing of 5°ca bTDC. This retarded timing was selected so that when pre-ignition occurred it would not immediately lead to knock. Various criteria based on combustion analysis derived from the pressure record were considered (such as the angle at which 50% mass fraction burned occurred or values of the heat release rate), but it was concluded that these had no advantage over the most direct measurement – the maximum cylinder pressure (P_{max}). Even with the maximum cylinder pressure there are different criteria that can be used.

Fig. 2 shows histograms of P_{max} at different glow-plug temperatures with iso-octane, operating at the stoichiometric air fuel ratio and a compression ratio of 6.

In Fig. 2 with the glow-plug unheated (and a temperature of 530 °C) there was no pre-ignition, but when the glow-plug had a mean temperature of 800 °C there was pre-ignition, and a bi-normal distribution has been fitted. The bi-normal distribution would suggest that the ratio of pre-igniting to spark-igniting cycles was 3.3 at 800 °C. However, there will be a range of pre-ignition timings, some of which will only be just prior to the spark (leading to only slightly higher maximum cylinder pressures), and indeed surface ignition just after the spark ignition will lead to a faster burn and that too will raise the maximum cylinder pressure. So for the data with the glow-plug at a mean