

Engine Knock in an SI Engine with Hydrogen Supplementation under Stoichiometric and Lean Conditions

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ABSTRACT

In this work, the effects of engine operational parameters, λ , spark timing, and compression ratio, on knock tendency and intensity as well as H_2 supplementation are studied. We postulated, verified and eventually used the duration from ignition to 70% mass fraction burnt ($MFB_{0-70\%}$) as an explanatory variable to describe the knock tendency and intensity. In this manner, the physical factors and fuel factors that are introduced by the differences in test conditions can be differentiated.

Practically, in terms of percentage of knocking cycles or the spark timing at audible knock, knock tendency decreases as λ increases and increases with H_2 supplementation. However, when MFB duration is taken into account, then for the same MFB duration, knock tendency increases as λ increases and decreases with H_2 supplementation.

Knock intensity can be represented by both peak-to-peak pressure variations and integrated power spectral density of the oscillating pressure, and these are strongly correlated. By using peak-to-peak oscillating pressure as the knock index, it was found that knock intensity increases as $MFB_{0-70\%}$ duration decreases. Additionally, knock intensity only depends on the $MFB_{0-70\%}$ duration relative to the $MFB_{0-70\%}$ duration at threshold knock. The smaller is the relative $MFB_{0-70\%}$ duration, the greater is the knock intensity, and vice versa.

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INTRODUCTION

Lean-burn of an SI engine occurs when the relative air/fuel ratio (λ) is greater than unity. Under these conditions, the two factors that people are most concerned about in the automotive industry, fuel economy and exhaust emissions, are improved as the excess O_2 increases [1]. On the other hand, lean-burn generally means dilution of intake mixture and combustion instability will be significantly increased as the dilution level is increased, so the drivability of vehicles is reduced and eventually it leads to misfire [2]. These contradictory effects strictly limit the lean-burn application in a gasoline fuelled SI engine.

Alternatively, due to the sustainable nature and unique properties of H_2 , it has been considered as a substitute for gasoline and it has been widely studied in recent decades. In contrast to hydrocarbon fuels, H_2 is carbon free which will eliminate CO , CO_2 and HC emissions. More importantly, its high flame speed complements the drivability problem of gasoline fuelled engines under lean-burn conditions [3, 4]. Therefore, applying small amounts of H_2 as a supplement to enhance the performance of gasoline fuelled SI engines at lean operation conditions is attractive.

While the effects of H_2 supplementation on efficiency and emissions of an SI engine have been widely studied, the effects of H_2 supplementation on knock tendency and intensity, particularly at lean conditions, has only rarely been studied. Engine knock is recognised as an abnormal combustion phenomenon - the pressure oscillation that is caused by autoignition of the end-gas during flame propagation [5]. Due to its potential impact on the engine performance and damage of the combustion chamber, knock is meant to be avoided in engine operation.

The quantification of knock can be categorised into two subsets, knock tendency and knock intensity. Knock tendency is normally related to the possibility of occurrence of knock under given conditions and knock intensity is normally considered to deal with the pressure oscillation and its energy content while knocking. From the literature review, it was found that there are contradictions in the effect of lean-burn as well as the effect of H_2 supplementation on knock tendency. Some researchers suggest that knock tendency can be reduced by leaning the mixture [6, 7], whilst other researchers have found that lean mixtures tend to increase knock tendency [8]. Further, some researchers suggest that H_2 is more resistant to knock than gasoline and as a supplement it can decrease knock

tendency [8, 9, 10], while others have found the opposite trend [11]. These differences in knock tendency with lean-burn as well as with H_2 supplementation are mainly caused by different test conditions. For example, achieving the same relative λ can be done either by reducing fuel flow or by increasing air flow. Reducing fuel flow will hold inlet pressure constant, but the torque output of the engine will be reduced; increasing air flow may increase torque output, or hold it at constant, inlet pressure will be increased. These two examples will create two totally different physical situations for the end-gas, and the divergence in conclusions could be the result of analysing the knock behaviour under these two different conditions.

In this work, we try to explain the effect of lean-burn and H_2 supplementation on knock tendency and intensity. We will postulate, verify and eventually use mass fraction burnt (MFB) as a new explanatory variable to describe the knock tendency. In this manner, the physical influences on the end-gas (and therefore the knock tendency) that are introduced by the difference in test conditions can be eliminated.

APPARATUS SETUPS AND METHODOLOGY

Experiments were performed on a Ricardo E6 single cylinder variable compression engine. Due to the nature of engine knock, an encoder with 3600 pulses per revolution was used. Pressure was therefore recorded at the high resolution of 0.1 crank angle degree (CAD) with the external clock. This ensured that the pressure oscillations introduced by knock could be accurately captured.

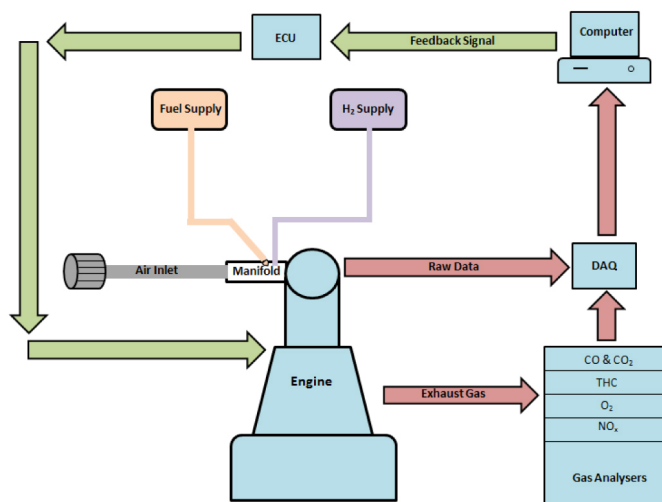


Figure 1. Schematic drawing of the Ricardo engine system.

A schematic drawing of the apparatus setup is shown in Figure 1. Further details can be found in the work of Baral and Raine [12]. Commercial gasoline with 91 octane number (ON) was used as the primary fuel in these experiments. As a supplement, H_2 was supplied in the manifold at a constant mass flow rate. The flow of H_2 was controlled by a needle valve

and measured by a Micro Motion D6 mass flow meter. Part of the exhaust gas was streamed into an emissions bench which consisted of a wet HC and a series of dry inorganic gas analysers, and λ was calculated online based on these emissions data by using the methodology that suggested by Heywood, J.B. [5]. This guaranteed the repeatability of experiments and the accuracy of results. Recorded data were post-analysed by using MATLAB.

The experimental procedure is summarised as follows, and engine operation conditions are given in Table 1:

1. After the engine had been warmed up, λ was set at stoichiometric with 30% throttle opening. H_2 that is equivalent to 12.5% of the total energy is supplemented to gasoline. λ was slightly affected by supplementation of H_2 , which was then adjusted back to stoichiometric by moving throttle position slightly. The effect of this on manifold pressure is negligible.
2. Spark timing was adjusted to the angle where the knock is just audibly detected. This spark timing is defined as low knock spark timing. Spark timing that is 2° retarded and advanced from this low knock spark timing is defined as knock limited spark timing and high knock spark timing, respectively. For each spark timing (or knock condition), data of approximately 450 combustion cycles were recorded.
3. Both gasoline and H_2 flow rates were reduced while throttle position was fixed for leaner operation conditions. For each λ , Step 2 is repeated.
4. For the gasoline only, the spark timing of each condition was set to the same spark timing that was used in gasoline with H_2 supplementation. Gasoline flow rate was reduced while throttle position was fixed for leaner operation conditions.
5. For each λ , the energy flow rate of gasoline is the same as the energy flow rate of gasoline with H_2 supplementation.

Table 1. Engine operation conditions.

Engine Speed (RPM)	1500
Throttle Position (%)	30
Compression Ratio	10 and 12
Spark Timing ($^\circ$ BTDC)	10 to 56
Relative Air/Fuel Ratio	1 to 1.3 with 0.1 increment
Inlet Air Temperature ($^\circ$ C)	19.5 to 20.5
Hydrogen Fraction	12.5% of total energy

Since the priority of these experiments was to compare knock behaviour between gasoline and gasoline with H_2 supplementation under lean-burn conditions, all conditions are performed on the same day for the same compression ratios (CR) in order to reduce day-to-day variation.

Knock

It is well-known that for a knocking cycle, there will be a pressure oscillation near to the time of peak cylinder pressure. In this work, knock index (KI) is used as the benchmark to distinguish knocking and normal cycles. To define KI, the recorded pressure data are firstly filtered by a Chebyshev Type II filter with high-pass cut-off frequency of 3 kHz in order to remove the combustion pressure [13]. Figure 2(a) shows a normal cycle (non-knocking) and a high knocking cycle. For the normal cycle, due to electronic noise, high-pass filtered pressure data oscillates constantly over the time with very small amplitude (blue colour in Figure 2(c)); on the other hand, due to the nature of knock, high-pass filtered pressure data of a knocking cycle oscillates with very large amplitude (relative to the normal cycle) and decays over time (Figure 2(b)). KI is defined as the maximum peak-to-peak pressure of the high-pass filtered pressure data.

When the engine is operating under knock conditions, some cycles lie between normal and knocking cycles, that is, when the high-pass filtered pressure of these cycles are compared with pressure data of the normal cycle, there are noticeable pressure oscillations which decay over time; however, visually there is almost no difference in the unfiltered pressure data between these kind of cycles and normal cycles (black colour). These cycles probably have minimal potential to damage the engine unlike severe knocking cycles. Therefore, a threshold is chosen to separate knocking cycles from normal cycles and those cycles lying between them - in this work, a cycle to be considered as a knocking cycle is defined as when KI is greater than 0.4 bar. Although different researchers use different peak-to-peak KI in their work, such as $KI > 2$ bar used by Mittal *et al.* [14], KI for the threshold knock of each engine system should be unique as the knocking pressure received by the pressure transducer is strongly dependent on the geometry of the engine and the location of the pressure transducer [15].

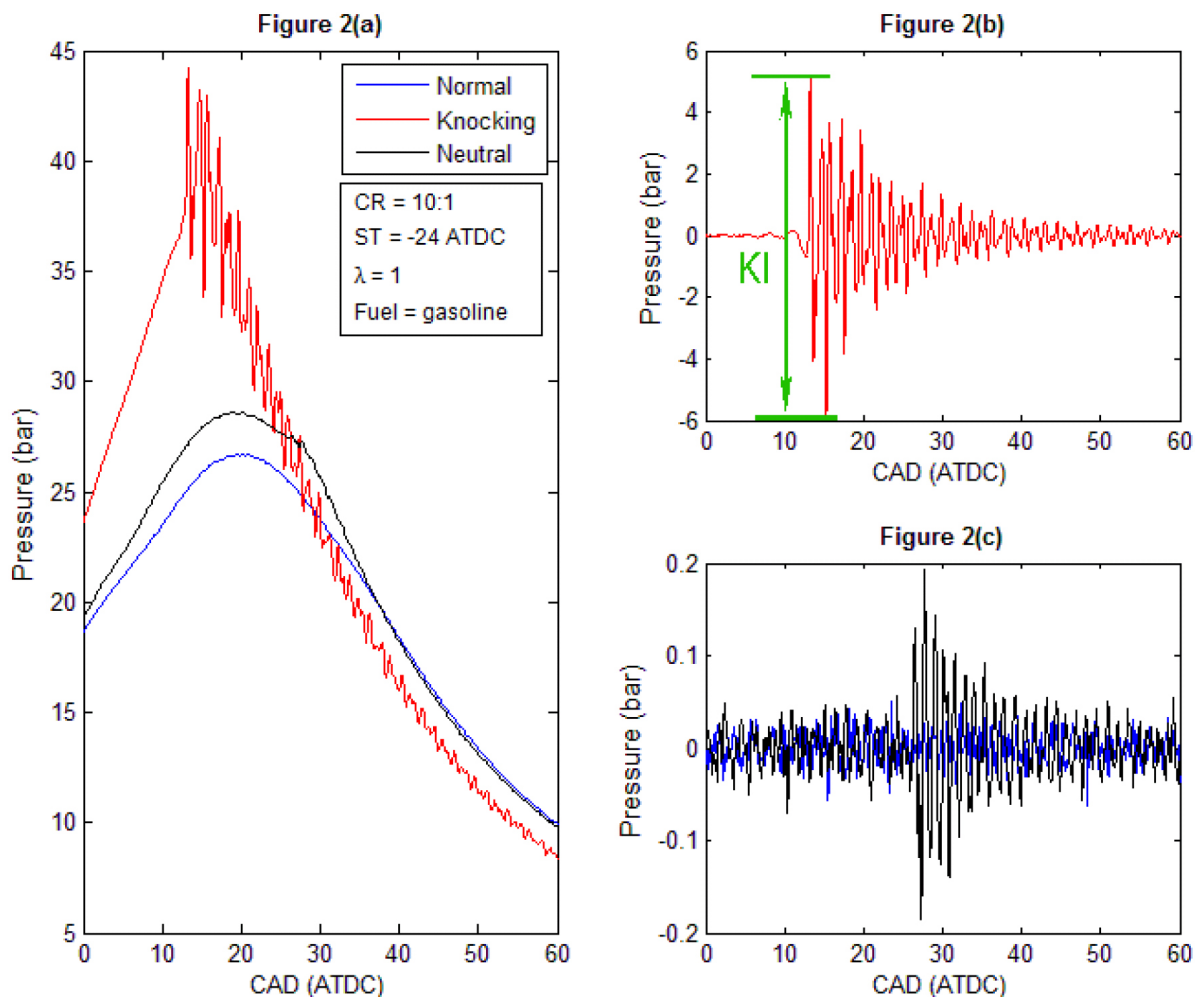


Figure 2. Example of a normal cycle (non-knocking), a knocking cycle, and a cycle that lies between the normal and knocking (named as "Neutral" in the figure) cycle over the time; (a) is the recorded pressure; (b) and (c) are high-pass filtered pressure. Normal cycle, knocking cycle, and neutral cycle are represented in blue, red, and black colour, respectively; KI is marked as the green colour. All cycles are collected at the stoichiometric condition, CR=10, ST = -24° ATDC. Fuel: gasoline.

Knock Tendency

Knock tendency has been studied by many researchers. One of the explanatory variables that is most commonly used to describe knock tendency is the engine spark timing at which borderline knock occurs [6, 7, 16]. In this work, data of approximately 450 combustion cycles were recorded at each spark timing. Then, knock tendency is initially defined as the percentage of knocking cycles over the total recorded cycles. A second explanatory variable, MFB duration at the threshold knock (KI=0.4 bar), is then introduced to define knock tendency.

Inlet temperature and pressure of the air-fuel mixture can affect temperature and pressure of the end-gas significantly in an engine process. Therefore, these factors are held constantly in all experiments. From our perspective, the factors that contribute to knock tendency can be categorised into two subsets, physical factors and fuel factors.

Holding fuel factors constant (i.e. the same λ and fuel mixture), temperature and pressure of the end-gas and flame propagation rate, are commonly considered as important fundamental factors affecting knock [14]. These factors are strongly correlated. Thermodynamic considerations suggest that the more rapid is the rate of fuel combustion then the higher will be the end-gas temperature and pressure, and hence the more susceptible will the end-gas be to autoignition. Combustion duration is therefore inversely proportional to the temperature and pressure of end-gas [17]. Hence we postulate that: holding fuel factors constant, cycles with shorter MFB duration are more likely to be knocking cycles.

Thus, holding physical factors constant (i.e. the same MFB duration), for two cycles, "X" and "Y", with different fuel factors, then if knock occurs in cycle "X" but not in cycle "Y", cycle "X" is more susceptible to knock than cycle "Y". That is, we postulate that: holding physical factors constant, knock tendency is controlled by fuel factors.

In this work, MFB is estimated from the pressure and volume data by using the well-known method that is developed by Rassweiler and Withrow [18]. Adapted from their analysis, normalised pressure change due to the combustion event is:

$$\Delta p_c^* = [\beta - a]b \quad (1)$$

Where

$$\beta = \frac{p_{i+1}}{p_i} \quad (1a)$$

$$a = \left(\frac{V_{i+1}}{V_i} \right)^n \quad (1b)$$

$$b = \left(\frac{V_i}{V_{TDC}} \right) p_i \quad (1c)$$

In Eq. (1), the reference volume is the volume at top dead centre (TDC); an index of compression (n) is evaluated from pressure data half way between inlet valve close (IVC) and ignition. The MFB at the i th time step is defined by:

$$x_b = \frac{\sum_0^i \Delta p_c^*}{\sum_0^N \Delta p_c^*} \quad (2)$$

Where in Eq. (2), N is the end of combustion, defined as the point at which Δp_c^* is no longer positive.

Because the onset of knock is associated with non-uniform pressure oscillations, the validity of MFB analysis based on the pressure and volume data of a knocking cycle is unclear. Therefore, verifying the validity of MFB analysis for knocking cycles is necessary before using it in the knock analysis.

Engine knock occurs around peak in-cylinder pressures and its occurrence time is strongly correlated to its intensity. Generally, knock with high intensity occurs slightly before the peak pressure while knock with low intensity occurs slightly after the peak pressure (Figure 3(c), (e) and (g)). In order to avoid the effects of filtering (as shown by the red solid curves in Figure 3), a sine wave estimation of the pressure is made. The pressure (p_i) around peak pressure is represented by a sine wave,

$$p_i = C + A \cdot \sin(\omega t_i) \quad (3a)$$

Referring to Figure 3(a), ω is the angular frequency depending on the time period of interest; C is the pressure at the start and end of estimation. For a knocking cycle, C is defined as the pressure at which unfiltered pressure (blue) and low-pass filtered pressure (red) data start diverging; A is the amplitude of the sine wave, which is equivalent to the difference between the peak pressure and the pressure at the start of estimation. For moderate and light knocking cycles, knock normally occurs after the peak pressure, and thus A can be easily defined (Figure 3(e) and (g)); for severe knocking cycles, knock normally occurs before the peak pressure, and thus A needs to be estimated based on the unfiltered pressure data (Figure 3(c)). Furthermore, the pressure at the next time step can be represented by the same sine wave but with the phase that leads p_i by one unit time step Δt , that is,

$$p_{i+1} = C + A \cdot \sin(\omega t_i + \omega \Delta t) \quad (3b)$$