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A study on the influence of burning rate on engine knock from empirical data and simulation

Yu Chen, Robert Raine [*]

Department of Mechanical Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

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A B S T R A C T

There is contradictory literature about whether faster combustion may increase or decrease the likelihood of knock in spark ignition (SI) engines. Faster combustion allows less time for end-gas autoignition to occur, but also increases the end-gas pressure and temperature, which may reduce the time required for autoignition. By using the duration from ignition to 70% mass fraction burnt ($MFB_{0-70\%}$) as an explanatory variable, the hypothesis that “knocking cycles are the cycles with shorter MFB duration when they are compared with normal cycles” is proposed. In the experimental work, $MFB_{0-70\%}$ duration of normal cycles is calculated by the conventional method. For knocking cycles, which have non-uniform pressure, this conventional method cannot be used. Instead, it has been demonstrated that the $MFB_{0-70\%}$ duration can be estimated by a sine wave estimation (SWE) method with negligible errors. This $MFB_{0-70\%}$ duration is then used to represent the burning rate of knocking cycles. The proposed hypothesis is verified by the relationships between $MFB_{0-70\%}$ duration and the maximum rate of change of pressure. In the simulations, a multi-step adiabatic constant-volume zero-dimensional (MACZ) model is developed using Cantera software. In the model, the most recent detailed mechanism for gasoline surrogate, developed at the Lawrence Livermore National Laboratory (LLNL), is used. The MACZ model simulates the chemical kinetics of unburned air–fuel mixture from the start of compression stroke to the end of expansion stroke based on the recorded in-cylinder pressure. The simulation results match the experimental results fairly well. The simulation results suggest that increasing burning rate will promote knock, which is in agreement with the experimental results presented here. The contributions of burning rate to the knock are categorised by two factors described as “pre-dominant” steps and “post-dominant” steps. It is found that both factors have significant influences on the knock mechanism, even though the chemical reactions occurring in the pre-dominant steps are of low exothermicity.

1. Introduction

It is common knowledge that engine knock is a barrier limiting the performance of SI engines. Although knock has been widely studied over the past century, it is still not fully understood. In this work, this phenomenon has been considered as the autoignition of end-gas ahead of the flame front [1,2]. In the past decades, technologies such as the high turbulence flow that is introduced by the modern design of the combustion chamber and the gasoline direct injection system are developed for the purposes that are more or less related to the “anti-knock” [3–8]. The common ground of these technologies is: knock is suppressed while the burning rate is increased. Hence, the question arising here is: Does an increase of burning rate assist the suppression of knock under a typical engine operation condition? From the literature review, it was found that there are disagreements on this question.

It is well-known that the burning rate is increased by introducing turbulence. With increasing burning rate, the end-gas will be consumed by the flame front at a faster rate so there is less time for the end-gas to autoignite, and hence knock is suppressed [9,10]. In addition, hydrogen (H_2) has been considered as a supplement to the spark ignition (SI) engine to inhibit knock in recent years [11–15]. Despite the fact that H_2 inhibits knock by lengthening ignition delay of the end-gas, many researchers claim that the knock suppression benefit from H_2 supplementation in an SI engine is partly attributable to its fast flame speed [11,13,16], which is favourable to the perspective of Refs. [9,10]. However, others believe that increasing burning rate will also increase the temperature and pressure of the end-gas substantially, and hence reduce ignition delay. Thus, knock is more likely to occur [17–21].

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[*] Corresponding author.
E-mail address: r.raine@auckland.ac.nz (R. Raine).

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Nomenclature

Abbreviations

A	maximum pressure of SWE
°ATDC	crank angle degrees after top dead centre
°BTDC	crank angle degrees before top dead centre
C	pressure at the start and end of SWE
CAD	crank angle degree
IMEP	indicated mean effective pressure
i	step index
KI	knock index
MACZ	multi-step adiabatic constant-volume zero-dimensional model
MFB	mass fraction burnt that is calculated from the pressure
$\mathrm{MFB_{SWE}}$	mass fraction burn that is calculated from the SWE
MFB duration	duration in crank angle degrees of mass fraction burnt
NTC	negative temperature coefficient
N	step at which Δp_c^* is no longer positive
n	index of compression
PRF91	primary reference fuel research octane number of 91
P	in-cylinder pressure of a cycle
P_d	pressure at the dominant point of the MACZ model
P_{exp}	experimental in-cylinder pressure data
P_{in}	input pressure of the MACZ model
P_{max}	maximum pressure. For knocking cycles, if the onset of knock occur before P_{max}, P_{max} is defined as the pressure at 1.5 CAD before the onset of knock
P_{out}	output pressure of the MACZ model
ST	spark timing
SWE	sine wave estimation
T_c	input temperature at the start of compression stroke of the MACZ model
T_d	temperature at the dominant point of the MACZ model
T_{ad}	calculated isentropic temperature (core temperature) of the end-gas
T_{in}	input temperature of the MACZ model
T_{out}	output temperature of the MACZ model
V	in-cylinder volume
V_{TDC}	in-cylinder volume at top dead centre
X_{in}	input mole fraction of species of the MACZ model
X_{out}	output mole fraction of species of the MACZ model
α	angle of a specific normalised pressure relative to the angle of P_{max}
Δp_c^*	normalised pressure change due to combustion
$\Delta P/\Delta\theta$	maximum pressure change over one unit step of crank angle
ε	percentage difference between the estimated $\mathrm{MFB_{SWE}}$ duration and the calculated MFB duration
Θ	duration of SWE in crank angle degrees
θ_d	angle at the dominant point of the MACZ model
θ_{in}	input angle of the MACZ model
θ_{auto}	angle of the simulated autoignition, which is defined as the angle at which temperature suddenly rises.
θ_{out}	output angle of the MACZ model
λ	relative air/fuel ratio
τ_d	adiabatic, constant-volume ignition delay at the dominant temperature and pressure
τ_{post}	equivalent ignition delay that reflects the contributions of post-dominant steps on the simulated knock
τ_{pre}	equivalent ignition delay that reflects the contributions of pre-dominant steps on the simulated knock

In the present work, such contradictions of the influence of burning rate on knock are studied. To achieve this, the in-cylinder pressure of an SI engine under the typical operation conditions are recorded and used to calculate mass fraction burnt (MFB) duration. The burning rate of a combustion cycle is then represented by its MFB duration. The constraint of using MFB duration to represent burning rate is that the conventional method of MFB duration calculation is not applicable for knocking cycles due to the fact that the pressure after the onset of knock does not represent the uniform in-cylinder pressure. Therefore, there is uncertainty about any conclusions on the influence of burning rate (i.e. MFB duration) on knock unless the burning rate of knocking cycles can be evaluated and correlated with the burning rate of "normal cycles".

Nevertheless, a method has been developed and verified to overcome such constraint in the present work – the sine wave estimation method (SWE). Generally speaking, SWE is a method to estimate the in-cylinder pressure of a knocking cycle as if knock did not occur. By utilising this estimated pressure, the MFB duration of a knocking cycle is calculated by the conventional method. Consequently, the influence of burning rate on knock is investigated.

A numerical model is developed to complement the experimental results. Since the so-called Shell Model developed by Halstead et al. [22], the mechanisms that describe the autoignition of hydrocarbon fuels under engine-like conditions has been studied extensively [23,24]. Generally, the mechanisms can be classified as reduced or detailed. The former requires additional calibration using engine data but is economical in the computing resources. Whereas the latter does not need additional calibration but is computationally expensive [25]. Due to the availability of computing resources for the present work, the use of a detailed mechanism is chosen. Furthermore, although knock is a very complex phenomenon as it can originate through the existence or development of inhomogeneities in the cylinder, the literature suggested that it also can be simulated homogenously [11,25–28]. In the present work, knock is assumed to be the result of homogenous autoignition. Finally, the results of simulations and experiments are matched fairly well, which provides insight into the factors that are potentially affecting the influence of burning rate on knock.

2. Apparatus setup and methodology

A Ricardo E6 single cylinder research engine fitted with a high resolution incremental shaft encoder (3600 pulses per revolution) was used in these experiments. This system allows the capturing of the high frequency spectrum of knocking combustion at very high frequency. Further details regarding the engine can be found in [18].

Table 1
Engine operation conditions.

Engine speed (RPM)	1500 ± 10
Engine load (bar)	imep ≅ 6
Compression Ratio	10: 1
Spark timing (°ATDC)	
- Knock limited	−22
- Knocking	−26
Relative air–fuel ratio	1 ± 0.02
Inlet air temperature (°C)	20 ± 1
Fuel	Gasoline (91 octane number)

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