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Effects of large-scale turbulence on cyclic variability in spark-ignition engine

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ABSTRACT

An investigation is carried out into the connection between the various characteristics of the velocity field and the burning rate in a spark-ignition engine. The experiments are performed on the Leeds University Ported Optical Engine with a large skip-firing ratio; the engine allows a full optical access to the combustion chamber. Velocity fields are obtained using a Particle Image Velocimetry (PIV) and a systematic distinct averaging is performed with an account of the cyclic variability of the burning rate, that is the properties of the turbulent velocity fields are derived separately for the fast, middle and slow cycles using the peak pressure as a proxy measure for the burning rate. Even though the velocity fields are nearly homogeneous in the mean, they reveal very significant intermittency where the regions of intense fluctuations have an extent more than half the clearance height. It is shown that the variations of the burning rate are correlated with the fluctuations in root-mean-square fields of the velocity magnitude, vorticity and shear strain rate. Faster combustion is induced by the fields with larger root-mean-square values. No discernible correlation of the burning rate with the average vorticity or shear strain fields has been detected. The integral scales of the large-scale motion derived from the PIV do not show any systematic variation between fast and slow cycles.

1. Introduction

Cycle-to-cycle variability (ccv) is caused by variations in instantaneous combustion rates between different cycles while the engine operates at nominally identical operating conditions. These variations are an impediment to improving the performance of an engine [1]. This is caused by the fact that under operating conditions at the knock boundary, the octane number requirements, maximum compression ratio and spark timing are all limited by the propensity for autoignition to occur in the fastest burning cycles [1–3]. Furthermore, the spark timing for a given running condition is typically optimised for the heat release profile of the most frequent cycle, hence any deviation from this optimum will entrain penalties in terms of lost power and efficiency. Strong ccv, such that the variation in IMEP is greater than 10%, is noticeable to the driver as a deterioration in the vehicle driveability [1]. The review [4] suggests that total elimination of cycle-to-cycle variation would result in a 10% increase in brake power output for the same fuel consumption. Unfortunately, the current trend in engine design favours an increase of the amount of exhaust gas recirculation which, together with lean combustion, lead to increased cyclic variability. In particular, cycle-to-cycle variation in early flame development restricts lean operation for any particular fuel [5].

There is a number of potential sources of ccv [1,3,6], among which are the variability in: (a) charge motion and "turbulence" during combustion; (b) the trapped amounts of fuel, air, and residual and/or recirculated exhaust (c) uniformity of the mixture composition within the cylinder, especially near the spark plug, associated with imperfect mixing between the air, fuel and residual or recirculated exhaust; (d) spark discharge characteristics, such as breakdown energy and initial flame kernel random displacement. Some of the above-mentioned factors are of much greater importance than others [6]. An attempt to describe ccv in the framework of the thermodynamic modelling has been made in [6] and it has been found that imposing a 10% variation in the root-mean-square (rms) velocity at the moment of ignition allows quite a good estimation of ccv of peak pressure. Variation of the equivalence ratio of the charge has been identified as the second main cause of ccv producing a spread of values of the maximum pressure occurring at the same crank angle. At the same time, the variation of the rms velocity between the individual cycles was introduced in [6] in an ad hoc manner, in particular, no experimental evidence has so far been available to support this work. The main purpose of this work is to explore the extent of the large-scale flow variability from one cycle to another and to establish what are the main flow characteristics affecting the burning rate in an individual cycle.

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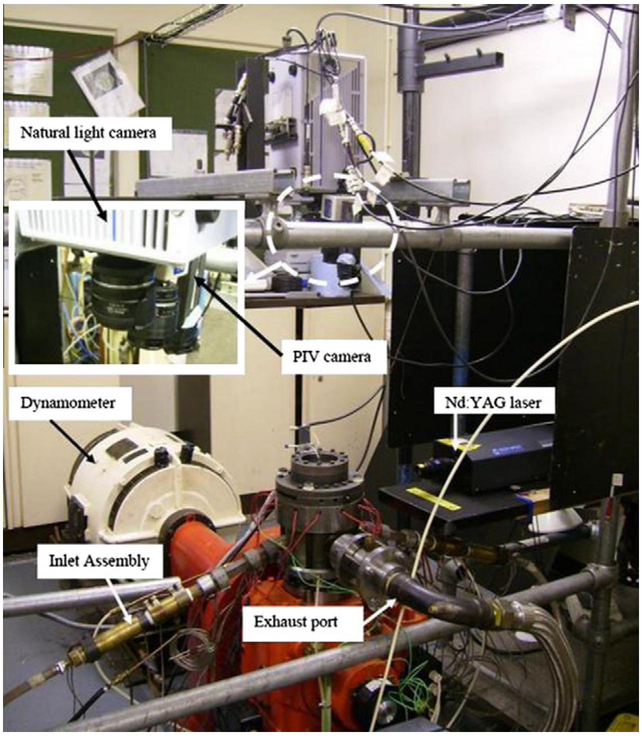

Fig. 1. Arrangement of the single cylinder LUPOE2 engine showing the details of the optical arrangements, intake and exhaust systems, positioning of the PIV system, and the dynamometer.

While the present measurements are performed in an engine, it should be stressed that fluctuations of burning rate are common for every instance of turbulent premixed flames. In that sense, the flame propagation in an engine is not different from explosions in closed volumes or freely propagating flames. Indeed, as early as 1953 Mickelsen and Ernstein [7] in their pioneering work observed that the burning rate of a free turbulent flame in a wind tunnel was a random quantity, the distribution of which was approximately Gaussian. For stronger turbulence and for non-stoichiometric mixtures the variance of burning rate was found to increase. The variations in burning rates observed by Mickelsen and Ernstein [7] must be attributed entirely to the variation of the flow filed, because the effect of variation in the spark discharge properties and other parameters were ruled out through a carefully executed experimental arrangement. It was found that there was very little correlation between either the spark current, spark energy or spark kernel displacement and the observed turbulent flame speed [7]. Large variations in burning rate have been observed for very diverse fuels and conditions in turbulent deflagrations in fan-stirred bombs, where the charge composition was perfectly uniform and well controlled [8,9].

Table 1
LUPOE2 specifications.

Parameter	
Bore (m)	0.08
Stroke (m)	0.11
Conrod length (m)	0.232
Crank radius (m)	0.055
Inlet port opening/closure (deg. CA)	107.8
Exhaust port opening/closure (deg. CA)	101.4
Compression ratio (–)	10.6
Clearance volume (mm^3)	37,680
Volume of top land crevice (mm^3)	1450
Spark advance (deg. CA)	–17

Shen et al. [10] performed simulations of an SI engine using different sub-models to simulate variability in flame kernel convection, level of turbulence experienced by the flame kernel during the early stages of combustion and the level of turbulence experienced during the main flame propagation. They suggested that ccv in turbulence, particularly during the early stages of combustion, had the largest impact. The predominance of the fluid flow factor (more specifically, variations in the turbulence conditions experienced by the developing flame kernel) on ccv in freely propagating explosions has been demonstrated by Lipatnikov and Chomiak [11]. This work established the link between the internal intermittency of turbulence, which is manifested in the log-normal distribution for the instantaneous values of the dissipation, and the amplitude of the spread in the turbulent diffusivity defining the flame growth.

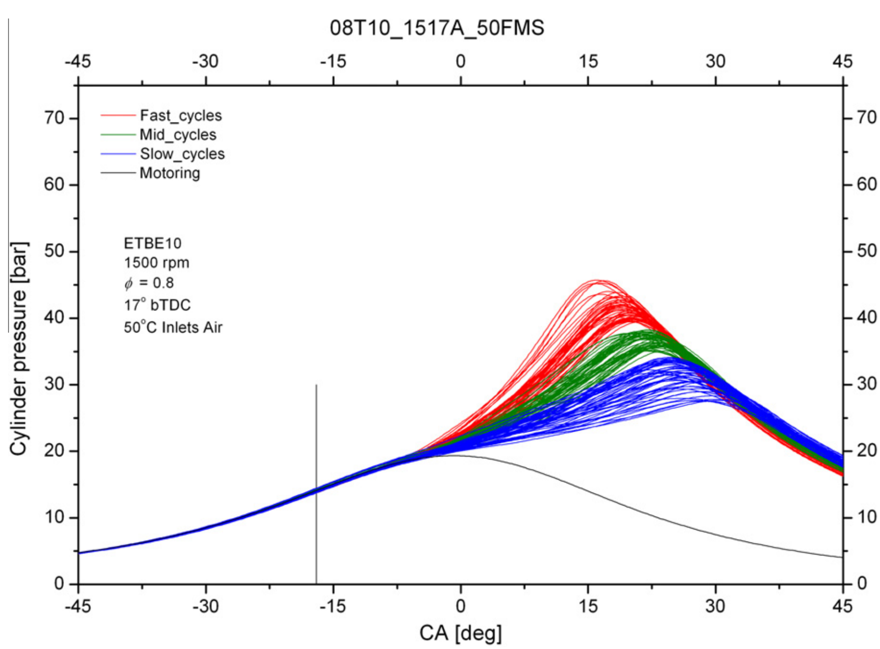

Fig. 2. Spread of the crank-resolved pressure history of the firing cycles showing fifty samples of fast, middle (i.e. average) and slow combustion events.