

Analysis of flame kinematics and cycle variation in a Port Fuel Injection Spark Ignition Engine

Katarzyna Bizon, Gaetano Continillo, Simone Lombardi
Dipartimento di Ingegneria, Università del Sannio, Benevento, Italy

Simona S. Merola, Paolo Sementa, Cinzia Tornatore, Bianca M. Vaglieco
Istituto Motori CNR, Naples, Italy

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ABSTRACT

This paper reports on the analysis of flame kinematics and cycle variation in port fuel injection (PFI) spark ignition (SI) engine. The engine was equipped with a four-valve head and with an external boost device. Different operating conditions were considered. Cycle-resolved digital imaging was used to investigate flame motion and the effects of an abnormal combustion due to the firing of fuel deposition near the intake valves and on the piston surface. Various algorithms are applied to the acquired images. Coefficients of Proper Orthogonal Decomposition (POD) were computed and used for a statistical analysis of cycle variability. The advantage is that the analysis can be run on a small number of scalar coefficients rather than on the full data set of pixel valued luminosity. POD modes are then discriminated by means of normality tests, to separate the mean from the coherent and the incoherent parts of the fluctuation of the luminosity field, in a non truncated representation of the data.

INTRODUCTION

In the last decade the fields of energy and transport have been influenced by increasingly stringent restrictions on the pollutants emission and by the request of reduction in fuel consumption and emissions of greenhouse gases like CO₂. The market needs high-performance engines and the community requires low fuel consumption and low environmental impact. This scenery has supported major changes in internal combustion engines technology, but a further

optimization is still possible. With particular reference to spark ignition engines, there exists ample room for improvement with phenomena such as cycle variation, pollutant emissions and fuel consumption [1].

Technological solutions such as fuel lean operation or increased dilution rates of the fresh charge by exhaust gas recirculation lead to a reduction in emissions of CO₂ and nitrogen oxides. However, these measures lead to a decrease in the laminar flame speed, which critically affects the flame propagation in the cylinder and may increase the magnitude of cycle variations [2]. In this context cyclic variability may be seen as a major nuisance which can considerably limit the range of operation of new engine combustion concepts. Predicting and controlling cyclic variability is thus an issue of prime necessity for today's engine designers.

Cyclic variability phenomena have been intensively studied over the last decades and a number of causes for their occurrence have been identified in SI engines [1], i.e. variations of: spark discharge characteristics, of in-cylinder mixture (overall fuel/air ratio and fraction of diluents), spatial mixture distribution near the spark plug, turbulence intensity, mean flow speed and direction in the spark plug vicinity, overall in-cylinder flow pattern. However, the relative importance of these factors is not yet well established. All these phenomena are strongly coupled, they depend on the engine geometry and engine operation, and thus they are difficult to predict at the stage of engine design. This is a major difficulty for automotive manufacturers since the unstable nature of an engine is often detected only late in the design cycle, when the costs of countermeasures become high. At this

stage, experimental techniques allow identification and understanding of the origins of cyclic variability – but only as a *posteriori* analysis.

From the experimental point of view, the engine cycle-to-cycle variations can be characterized by measuring selected thermodynamic quantities [3]. For example, pressure sensors allow real time cycle analysis with high temporal resolution. However, due to the complexity of the phenomenon, it is impossible to understand the specific role and weight of different factors that

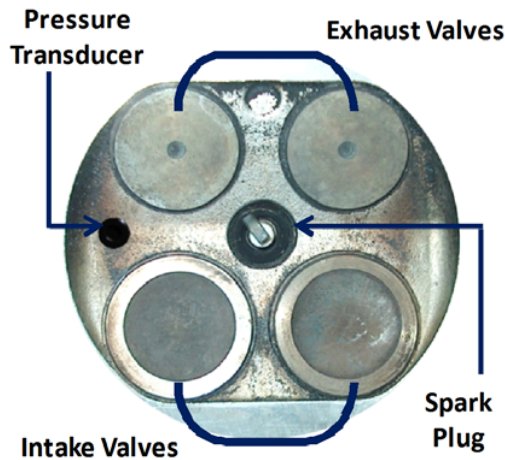


Figure 1. Sketch of the bottom field of view of the combustion chamber.

Significant advances in spark ignition engines could be possible by understanding the microscopic details of the developing flame kernel and flame front propagation. Spark ignition involves the deposition of a localized source of energy in a flammable gas mixture to produce a small plasma. The plasma energy propagates by initiating exothermic chemistry involving fuel and oxidizer, resulting in a local overpressure and elevated temperature that induce flame kernel inception. The early flame kernel is fragile because the surface area of the expanding flame kernel increases rapidly (i.e., flame stretch). The heat generated by combustion must increase proportionately to maintain flame ignition temperatures, otherwise the flame extinguishes. As the flame kernel expands and the flame curvature decreases, propagation becomes more stable. In spark ignition engines, the flame front generally moves across the cylinder volume in an almost uniform way. When cycle-resolved visualization of the combustion process is available, for each acquired image, parameters characterizing flame geometry and kinematics can be computed [7, 8]. These parameters describe the evolution of burned gas and provide information about flame kernel growth, flame front propagation and the possible effects of abnormal combustion. In order to describe the flame propagation in the combustion

determine cyclic variability from the time series of a single scalar variable.

On the other hand, optically accessible engines enable to perform time resolved analysis of the engine cycle providing both lumped and distributed information [4]. At the same time, the use of optical engines shows many difficulties in terms of control and stabilization, and is currently feasible for a limited range of engine operating conditions [5, 6].

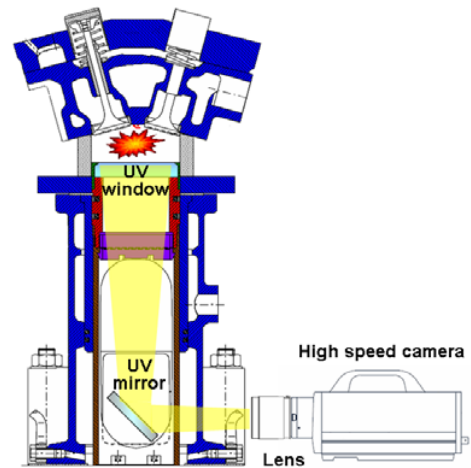


Figure 2. Sketch of the optical engine and experimental setup for the cycle resolved digital imaging.

chamber, the motion of the luminosity centroid can be used [9, 10].

Another technique that can be successfully used in a versatile *a posteriori* analysis of 2D and 3D combustion measurements is Proper Orthogonal Decomposition (POD). One of the first applications in the field was done by Palacios [11], who used the decomposition to identify the dominant structures and their temporal evolution in the optical combustion data collected from a premixed burner. Development of experimental systems in internal combustion engines resulted in further studies involving the application of POD, mostly in cold flow analysis. Druault et. al [12] attempted to analyze the velocity field in spark ignition (SI) engines: By coupling POD with simple time interpolation of the modal coefficients, continuous space-time description of the flow was recovered from the discrete measurements data. Subsequently, the same technique was used in cyclic variability analysis both in SI [13,14] and Diesel engines [15]. Roudnitsky et. al [13] proposed a filtering approach, based on POD and statistical moments, and applied it to the analysis of cold flow PIV (Particle Image Velocimetry) measurements in a SI engine. However, highly expensive computations for statistical analysis were required. Modification of the approach, with the limitation of the statistical analysis only to a small

number of POD modal coefficients, was proposed later. This filtering approach, allowing characterization of the cyclic variability in terms of coherent and incoherent components, was then successfully used to extract coherent/incoherent fluctuation of the luminosity field in SI [14] and Diesel [15] engines.

In this work, in-chamber flame luminosity images detected in an optically accessible PFI SI engine, both for open valve and closed valve injection, are used to study flame kinematics and to analyze flame structure by means of POD decomposition.

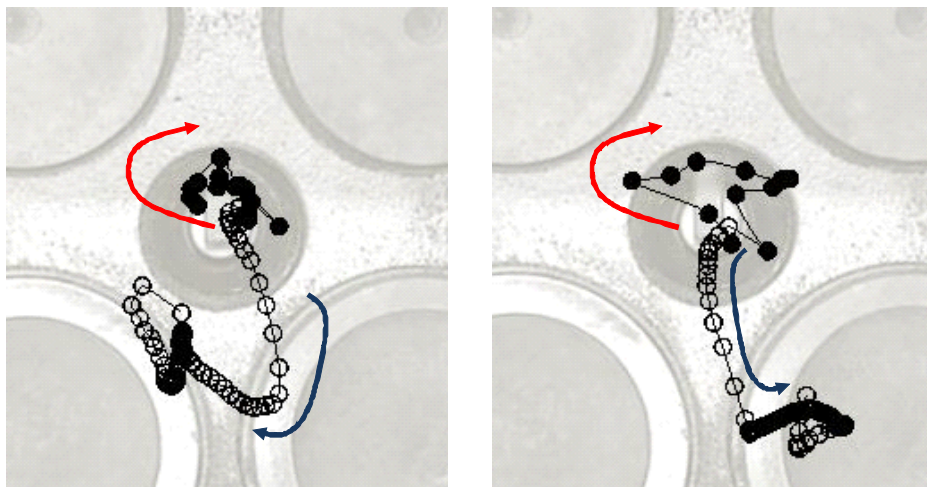


Figure 3. Trajectory of the Luminosity Centroid for open valve (a) and closed valve injection (b).

EXPERIMENTAL SETUP

An optically accessible single cylinder PFI SI engine was used. It was equipped with the cylinder head of new generation SI turbocharged engine. Bore, stroke and Compression Ratio are 79.0 mm, 81.3 mm and 10. respectively and the displacement is 399 cm³. The injection system is a ten-hole injector with 25° spray angle, 70 µm SMD, 202 cm³/min flow rate. The head has four valves and a centrally located spark plug. An external device allows the control of the intake air pressure and temperature. The bottom field of view of the combustion chamber is shown in Figure 1. A quartz pressure transducer is flush-installed to measure the in-cylinder pressure. The pressure, the rate of chemical energy release and the related parameters can be evaluated on an individual cycle basis and/or averaged on consecutive cycles.

The engine piston is flat and transparent. Its upper part consists of a 57 mm diameter quartz window. To reduce the window contamination by lubricating oil, an elongated piston arrangement was used together with self-lubricated Teflon-bronze composite piston rings in the optical section. As shown in Figure 2, during the combustion process, the light passes through the quartz window and is reflected towards the optical detection assembly by a 45° inclined UV-visible mirror. A cycle

resolved combustion visualization is obtained using 8-bit high speed camera (Optronis CamRecord 5000 – 512 x 512 pixel) equipped with a 50 mm focal Nikon lens. The spectral range of the high speed camera is 400-900 nm.

In this experiment, a camera region of interest was selected (400 x 400 pixel) to obtain the best match between the spatial and temporal resolution. This optical assessment allowed a spatial resolution of 0.175 mm/pixel and a frame rate of 6470 fps. The exposure time was fixed at 10 µs that corresponds to about 0.12 crank angle degree (CAD) at an engine speed of 2000 rpm. The dwell time between two consecutive images was around 150 µs.

FLAME KINEMATICS

In-chamber flame images were detected at 2000 rpm $\lambda=1$ and Wide Open Throttle for open valve and closed valve injection, respectively. The images showed that the first evidence of the flame occurs around 12 CAD BTDC. Then the flame front spreads with a radial like behavior. Around 16 CAD after the spark, an asymmetry in the flame front shape was observed. This was caused by the fuel film deposited in the intake manifold. Once formed in the combustion chamber, the fuel films develop dynamically under the influence of the gas flow. The heat exchange between the intake ports and the