Advances in Applied Mathematics and Mechanics
Adv. Appl. Math. Mech., Vol. **3**, No. 3, pp. 310-326

DOI: 10.4208/aamm.10-10s2-04
June 2011

Heat Transfer, Knock Modeling and Cyclic Variability in a "Downsized" Spark-Ignition Turbocharged Engine

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Received 14 January 2010; Accepted (in revised version) 18 August 2010

Available online 28 February 2011

Abstract. In the present paper a combined procedure for the quasi-dimensional modelling of heat transfer, combustion and knock phenomena in a "downsized" Spark Ignition two-cylinder turbocharged engine is presented. The procedure is extended to also include the effects consequent the Cyclic Variability. Heat transfer is modelled by means of a Finite Elements model. Combustion simulation is based on a fractal description of the flame front area. Cyclic Variability (CV) is characterized through the introduction of a random variation on a number of parameters controlling the rate of heat release (air/fuel ratio, initial flame kernel duration and radius, laminar flame speed, turbulence intensity). The intensity of the random variation is specified in order to realize a Coefficient Of Variation (COV) of the Indicated Mean Effective Pressure (IMEP) similar to the one measured during an experimental campaign. Moreover, the relative importance of the various concurring effects is established on the overall COV. A kinetic scheme is then solved within the unburned gas zone, characterized by different thermodynamic conditions occurring cycle-by-cycle. In this way, an optimal choice of the "knock-limited" spark advance is effected and compared with experimental data. Finally, the CV effects on the occurrence of individual knocking cycles are assessed and discussed.

AMS subject classifications: 76N15, 62P30, 80A20, 80A25.

Key words: Finite elements in heat transfer, internal combustion engines modelling, cyclic variability, knock.

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1 Introduction

The phenomenon of Cyclic Variability (CV) in internal combustion engines, a known issue since the end of the 19th century, is nowadays particularly relevant in the autom-

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otive research, due to the measures that are being adopted to fulfil more and more stringent legislative constraints about the pollutants emissions at the exhaust. As an example, there is a trend to a convergence between the Spark Ignition (SI) engine and the Compression Ignition (CI) engine in operating under lean mixture conditions and with high percentages of Exhaust Gas Recirculation (EGR) to increase the fuel economy and minimize the NO emissions. In these situations CV occurs with a high frequency and actually limits the potential benefits which can be derived from these operating modes.

During normal engine operation, cycle-by-cycle fluctuations are expected in the rate of heat release, hence in the amount of useful work done by a single combustion event, in the fuel consumption and the exhaust emissions. Due to its unpredictable and stochastic character, CV poses several problems to the development of optimal engine control systems [1, 2] and limits the vehicle drivability. CV is a consequence of the early flame development conditions, that deeply influence the subsequent combustion phase [3]. The flame kernel formation depends on local mixture composition and thermo-fluid-dynamic conditions at the spark plug location. These are affected by various factors, as the spatial and temporal fluctuations of the turbulent flow field inside the cylinder, the not perfectly homogeneous nature of the mixture at the spark time and the continuous adjustment of the gasoline injected mass and possible EGR amount, actuated by the engine closed-loop control system. This last, on the other hand, suffers from time delays and noise disturbances of the processed signals. Although the complex interaction of the above phenomena is not yet fully understood, it is widely recognized that CV is particularly felt at cold starting, idling, low load, and lean or highly diluted mixture operation [4], where the burning velocity is slow and the flame development is difficult. In this sense CV also limits the engine tolerance to EGR, and penalizes the fuel consumption of Variable Valve Timing (VVT) equipped engines [5], where internal EGR is realized to the aim of virtually reducing the engine displacement at low load.

Moreover, recently, a tendency is being consolidated to produce low displacement turbocharged SI engines. This design philosophy, known as "engine downsizing", allows to reduce mechanical and pumping losses at low load as a consequence of the higher operating Brake Mean Effective Pressure (BMEP). The turbocharger permits to restore the maximum power output of larger displacement engines. Additional advantages are a higher low-speed torque and a better drivability and fun-to-drive. Of course, at high loads, the spark-advance and heat transfer phenomena through the cylinder walls must be carefully controlled to avoid the knock occurrence. Even small differences of the unburned gas temperature, related to variations in the heat transfer rate and the spark-advance setting, non-linearly affect the knocking onset. For this reason, the knowledge of the heat transfer details is crucial to carefully compute the so-called "knock-limited spark timing", being a key point for the reduction of the fuel consumption drop at high loads. From this point of view, the effects resulting from CV play a fundamental role. CV mainly causes fluctuations in the heat released by the combustion process and heat losses through the walls, turning in fluctuations