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Numerical and experimental investigation on combustion characteristics of a spark ignition engine with an early intake valve closing load control

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HIGHLIGHTS

- A new intake port for a turbocharged spark ignition engine was designed and tested.
- The new port promotes turbulence by increasing the tumble motion at low valve lifts.
- Target of enhancing poor turbulence levels typical of EIVC at part load was reached.
- Full load performance targets were not reached due to the slower combustion.
- Combustion characteristics were related to in cylinder flow characteristics.

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ABSTRACT

In this paper a new intake port configuration has been designed, analyzed by means of 3D CFD simulation and experimentally tested on a turbocharged Spark Ignition (SI) engine, with the aim of addressing the issue of the poor in-cylinder turbulence levels which are typical of the Early-Intake-Valve-Closing (EIVC) strategies adopted in Variable Valve Actuation (VVA) systems at part load to reduce pumping losses. The proposed intake port layout promotes turbulence by increasing the tumble motion at low valve lifts in order to achieve a proper flame propagation speed at part load. The new layout was proved to have a significant and positive effect in improving the EGR tolerance and in shortening the combustion process, especially at the lower loads, which are the more critical for VVA systems using an EIVC strategy.

However, under full load operating conditions the new design (which enhances the tumble motion at the low valve lifts used at part load, but decreases the tumble intensity under the full lift operation used at full load) did not reach the performance targets, since the knock mitigation was not sufficient to compensate for the loss in combustion efficiency due to the slower combustion. The proposed solution could therefore be exploited only if a reduction of the engine full load performance is allowed in view of the significant benefits during part load operation.

Finally, the calculated in cylinder flow characteristics were related to the experimental combustion durations, identifying, on a quantitative basis, the relationship between the turbulent kinetic energy and the burning process durations, and thus providing guidelines for further possible modifications of the engine geometry aimed to achieve a suitable combustion speed over the whole engine operating map.

1. Introduction

A major challenge for combustion scientists and engine development engineers is to optimize engine combustion for improved fuel economy and reduced exhaust emissions while maintaining outstanding performance, durability, and reliability at an affordable price [1,2]. Spark Ignition (S.I.) engines have been gaining an increasing interest in the last years, especially in combination with downsizing and turbocharging, due to their noteworthy potential for fuel consumption and emissions reduction. Fuel consumption and therefore CO_2 emissions are being reduced by means of engine downsizing, which allows a shift of load points towards more efficient zones of the engine map, while performance are being preserved or even enhanced despite the smaller displacement thanks to high boost levels [3–5].

However, downsizing and turbocharging are not the only means to improve SI engine efficiency: technologies which can allow

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throttle-free load control such as Variable Valve Actuation (VVA) are also playing a major role. This trend was pioneered in 2001 by BMW with the introduction of Valvetronic system, that was also adopted in Europe by PSA [6].

In recent years other OEMs such as for instance Fiat, Toyota, Mitsubishi and Nissan have also introduced different types of variable valve actuation systems on production vehicles, and Toyota has recently announced that it will be converting its complete program of engines to full mechanically variable valve lift [7–10]. The capability to adapt both the valve lift and the valve timing to engine operating conditions is also a characteristic of the MultiAir system, patented by FIAT [9,10]. This system usually employs Early–Intake–Valve–Closing (EIVC) to reduce pumping losses at part load, as shown in Fig. 1 where the ideal operating cycle of the engine is represented.

However, the use of EIVC suffers from poor in-cylinder turbulence especially at low loads; the dissipation of the kinetic energy of the intake air mainly occurs from the EIVC to the Bottom Dead Center (BDC), because the intake valves are already closed during the last portion of the intake stroke and there is no energy source available to supply the viscosity losses in the trapped air charge (see Fig. 1). At low loads the EIVC is further advanced towards the Top Dead Center (TDC), because a lower amount of charge is required, and this results in higher turbulence dissipation if compared with medium–high loads. This weakness can be mitigated by means of the use of internal Exhaust Gas Recirculation (EGR) that can allow significant reductions in terms of pumping losses without the need of using a significantly advanced EIVC, as shown by the ideal pumping loops sketched in Fig. 2. However, the dilution of the charge tends to adversely affect combustion stability and to increase cycle-to-cycle variations, and a proper balance between the use of internal EGR and of the advance of the EIVC has therefore to be found, in order to minimize pumping losses while preserving an acceptable combustion quality.

Finally, further attempts to solve the issue of the turbulence dissipation caused by the EIVC can be made by means of cylinder head and piston top modifications, designed to increase the turbulence levels in the combustion chamber. However, the impact of these modifications on burning velocities should be carefully evaluated, since fastest burning engine cycles will be most likely to knock under full load operating conditions [11,12], and knocking phenomena will limit engine compression ratio, boost and downsizing ratio, thus hindering the achievement of CO_2 emissions reduction targets.

In the present work a new cylinder head was therefore designed for a MultiAir turbocharged SI engine fuelled with gasoline, and its impact on the combustion process was evaluated by means of both Computational Fluid Dynamics (CFD) simulations and experimental tests. The target of the new design was to enhance turbulence by increasing the tumble motion at low valve lifts, in order to

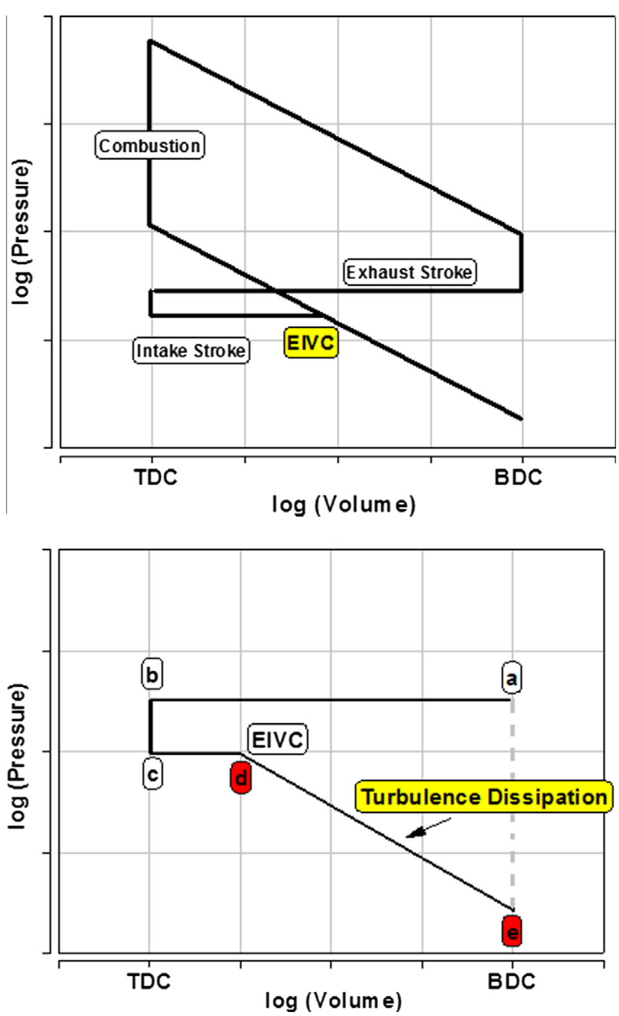

Fig. 1. Sketch of the ideal in-cylinder pressure vs. volume diagram for a MultiAir system adopting an EIVC at part load: complete cycle (top), zoom on gas exchange (bottom); log–log scales. (a–b) exhaust stroke, (c–e) intake stroke, (c–d) fresh charge intake, (d–e) trapped charge expansion.

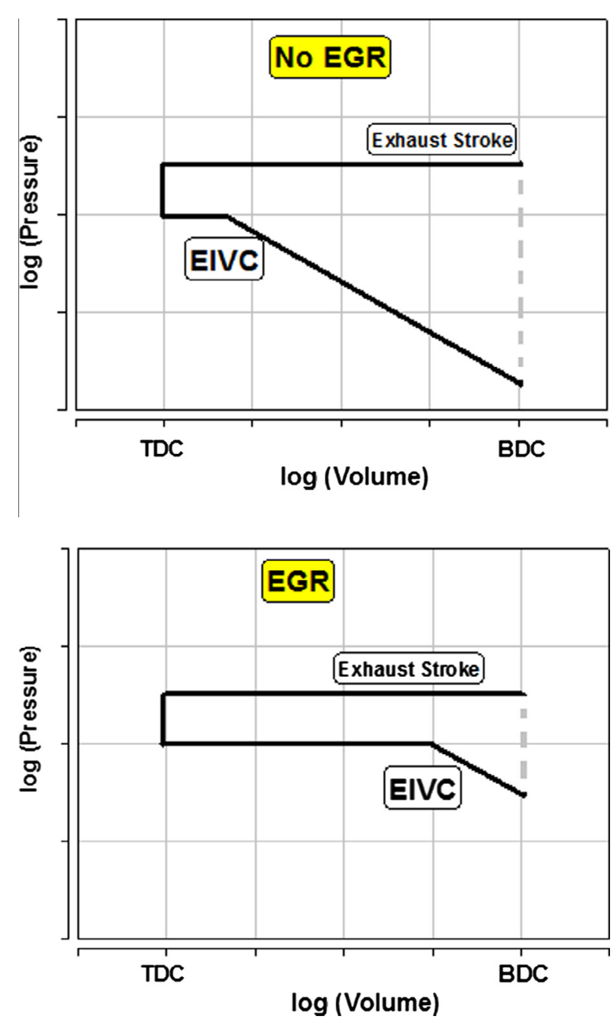

Fig. 2. Sketch of the ideal in-cylinder pressure vs. volume for a MultiAir system adopting an EIVC at part load: zoom on gas exchange without (top) and with EGR (bottom); log–log scales.