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Efficiency improvement of a spark-ignition engine at full load conditions using exhaust gas recirculation and variable geometry turbocharger – Numerical study

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ABSTRACT

The numerical analysis of performance of a four cylinder highly boosted spark-ignition engine at full load is described in this paper, with the research focused on introducing high pressure exhaust gas recirculation for control of engine limiting factors such as knock, turbine inlet temperature and cyclic variability. For this analysis the cycle-simulation model which includes modeling of the entire engine flow path, early flame kernel growth, mixture stratification, turbulent combustion, in-cylinder turbulence, knock and cyclic variability was applied. The cylinder sub-models such as ignition, turbulence and combustion were validated by using the experimental results of a naturally aspirated multi cylinder spark-ignition engine. The high load operation, which served as a benchmark value, was obtained by a standard procedure used in calibration of engines, i.e. operation with fuel enrichment and without exhaust gas recirculation. By introducing exhaust gas recirculation and by optimizing other engine operating parameters, the influence of exhaust gas recirculation on engine performance is obtained. The optimum operating parameters, such as spark advance, intake pressure, air to fuel ratio, were found to meet the imposed requirements in terms of fuel consumption, knock occurrence, exhaust gas temperature and variation of indicated mean effective pressure. By comparing the results of the base point with the results that used exhaust gas recirculation the improvement in fuel consumption of 8.7%, 11.2% and 1.5% at engine speeds of 2000 rpm, 3500 rpm and 5000 rpm is obtained. Additionally, by using the presented numerical methodology the influence of the specific operating parameter on the overall behavior of the complex charging system was shown.

1. Introduction

Future challenges in the internal combustion engines development consist of further reduction of fuel consumption and exhaust gas emissions including greenhouse gases, e.g. CO_2. Compression ignition engines (CI) have shown significant improvement in fuel consumption over the last decades, while for satisfying exhaust gas emissions requirements they require complex and costly exhaust gas after treatment systems. On the other hand spark-ignition (SI) engines show slower progress on the fuel consumption side, but the exhaust gas emissions, excluding CO_2, are very low. With growing concern regarding the influence of CO_2 on the climate change [1] and by acknowledging the fact that the CO_2 emission is proportional to fuel consumption, the efficiency of IC engines is becoming one of the primary development targets. Therefore, the amount of research in the field of SI engines has shown significant growth over the last couple of years.

There are numerous technologies that have been introduced to reduce fuel consumption such as variable valve timing [2], turbocharging [3] and direct injection [4], while the exhaust gas recirculation (EGR) [5] has been introduced to reduce the exhaust emissions of NO_x. The configurations of cooled EGR systems can be divided into three main groups: low-pressure EGR (LP-EGR), high-pressure EGR (HP-EGR) and mixed-pressure EGR loop [6]. In [5] the authors showed that in a SI engine LP-EGR system allows wider EGR area in turbocharger region, better knocking suppression and higher exhaust gas temperature reduction. However, they also reported that due to low differential pressure and long EGR passage it is more complicated to obtain stable EGR control in LP-EGR compared to HP-EGR strategy. Regarding CI engines, in

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Nomenclature

C_{bd}	breakdown constant $(V/\sqrt{J\,mm})$
C_{cg}	voltage constant (–)
C_{ε}	ε source coefficient for high pressure cycle (–)
C_{ε}^{UZ}	ε source coefficient for unburned zone (–)
C_{τ}	transition time constant – laminar to turbulent flame (–)
C_{00}	intake ε production coefficient (–)
C_{10}	intake ε production coefficient (bar^{-1})
E	energy (J)
f_{D3max}	maximum value of fractal dimension (–)
k_W	heat transfer coefficient (W/m^2 K)
K_1	speed constant for scaling overall knock intensity (rpm^{-1})
K_2	constant that defines the maximum crank angle at which auto-ignition produces knock (°CA)
K_3	exponent constant of knock intensity equation (–)
L	inductance (H)
n	engine speed (rpm)
r_0	assumed critical flame kernel radius (mm)
R	electric resistance (Ω)
S_{00}	intake k production coefficient (–)
T	temperature (K)
V	voltage (V)
x_B	mass fraction burned (–)

Greek symbols

α	crank angle (°)
δ	distance between two points that represent spark plug geometry (mm)
λ	excess air ratio (–)
σ	standard deviation of certain property
Φ	air equivalence ratio (–)

Subscripts

af	anode fall
cf	cathode fall
exp	experiment
norm	normalized
q	quenching
s	secondary electric circuit
sim	simulation
SOK	start of knock
SP	spark plug

Abbreviations

A/F	air to fuel ratio
BSFC	brake specific fuel consumption (g/kW h)
BTDC	before top dead center
CA	crank angle (°)
CCV	cycle-to-cycle variations
CI	compression ignition
CFD	computational fluid dynamics
CoV	coefficient of variation
CO_2	carbon dioxide
CP	combustion products
CR	compression ratio (–)
EGR	exhaust gas recirculation
FTDC	firing top dead center
HP	high pressure
IMEP	indicated mean effective pressure (bar)
IMEP_GE	indicated mean effective pressure of gas exchange (bar)
ISFC	indicated specific fuel consumption (g/kW h)
KI	knock integral (–)
KLSA	knock limited spark angle (°)
LP	low pressure
NO_x	nitric oxides
QDIM	quasi-dimensional ignition model
SHP	start of high pressure
SI	spark-ignition
SOC	start of combustion
VGT	variable geometry turbocharger
0D, 1D, 3D	zero-, one-, three-dimensional

[7] it was shown that LP-EGR allows higher EGR mass flow rate in wider CI engine operating range compared to HP-EGR system.

Each of the above mentioned systems can be controlled to achieve specific operation which should help in reaching targeted efficiency. This means that the number of engine operating parameters is growing. Since each individual system influences the operation of other systems and of the engine, the complexity of the overall engine operation is increasing. Therefore, finding optimal operating parameters of the engine can be challenging. Also, since all systems interact with each other, predicting overall performance of the engine in the design phase of development is difficult. Therefore, there are efforts to use numerical tools for predicting engine performance of future engines and for finding the approximate operating conditions for each specific operating point [8]. The entire engine system is usually modeled with cycle simulation models (0D/1D), which if properly calibrated offer a good tradeoff between accuracy and calculation time. Such simulation models usually predict the average engine cycle [9] which means that the influence of operating parameters on the combustion stability cannot be captured. Combustion stability becomes very important for conditions with late spark timing and large EGR fractions which are more frequently used in modern, turbocharged SI engines [10].

This study aims to investigate the influence of various control parameters of a port fuel injection (PFI), turbocharged SI engine, equipped with a HP-EGR loop on overall performance, by using a cycle simulation model with the novel approach in simulating combustion that includes modeling of cycle-to-cycle variations (CCV) [11]. The emphasis of the study is to research the influence of HP-EGR on overall engine performance and to investigate the possibility of using EGR for lowering fuel consumption at full load conditions.

The methodology consists of creating a reduced cycle-simulation model of a cylinder that corresponds to a modern four valve chamber design. The cylinder and combustion model constants are calibrated by comparison of experimental and simulation results at three different engine speeds (2000, 3500 and 5000 rpm) at full load conditions. Once the model of the cylinder is calibrated the model is extended to feature all systems of a turbocharged SI engine equipped with HP-EGR loop. The performance analysis of this new engine design is made by the parametric investigation of the influence of spark timing, air to fuel ratio and EGR on engine performance results. Overall engine performance is obtained by excluding the operating conditions that are not allowed based on the results of knock occurrence, exhaust gas temperature, excessive combustion instability and turbocharger limits (surge operation).

2. Cycle-simulation model

The cycle-simulation model of the engine that will be described later is made in AVL BOOST. This model is a 1D/0D simulation