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Experimental study on knock sources in spark ignition engine with exhaust gas recirculation

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ABSTRACT

The presented study aims to experimentally investigate the sources of influence of exhaust gas recirculation on the tendency toward knock in the spark ignition engine. The three main sources of influence of exhaust gas recirculation on the engine tendency towards knock are known. The influence on flame propagation changes the profile of combustion and therefore the end-gas pressure and temperature profile. The thermal influence changes the thermal properties of the end-gas mixture and consequently its temperature profile, while the chemical influence changes the kinetic behaviour of the end-gas mixture. The study is based on the results from experimental setup with spark ignition engine that uses cooled exhaust gas recirculation system and air heater installed into the intake manifold. Experimental tests that employ a new approach were performed, where intake temperature is varied by air heater when engine is operated with different levels of exhaust gas recirculation. In this way the end-gas temperature and exhaust gas recirculation percentage were varied while the influence on flame propagation was partially compensated by the change of spark timing. The obtained results show that there is no clear chemical influence of the exhaust gases on the tendency towards knock as the cases with low and high levels of exhaust gas recirculation are all mixed when the temperature of the end-gas is set to the same values. This leads to the overall conclusion that the predominant factor in a tendency towards knock is the end-gas temperature profile.

1. Introduction

The harmful impact of the motor vehicles on the environment and the growing concern regarding the pollution of the environment resulted with the change in development requirements of Internal Combustion (IC) engines that are now focused on the prevention of future global pollution. Greenhouse gases are proven to be one of the main reasons for global warming [1]. Therefore, there is a number of regulations that aim to reduce carbon dioxide (CO_2) emissions from motor vehicles [2]. Reduction of CO_2 emissions can be achieved by using the energy sources without carbon (electrical energy generated from renewable sources, hydrogen), by using fuels with lower carbon ratios (e.g. methane) or by reducing fuel consumption [3]. On a large scale the first and the second solution could be a long-term solution, while for the short to medium term solution the best way to reduce CO_2 is by reducing fuel consumption. Compression ignition (CI) engines have shown significant reduction of fuel consumption over the last decade, while spark ignition (SI) engines still have not reached efficiencies and CO_2 emission of CI engines. On the other hand, harmful emissions (nitrogen oxides (NO_X), particles) of CI present a significant concern which triggered a number of notifications regarding restrictions of use of certain CI engines in some city centres (e.g. Stuttgart). Therefore, further reduction of fuel consumption of SI engines while simultaneously keeping the low emissions of harmful exhaust gasses (total hydrocarbons (THC), carbon monoxide (CO), NO_X) is required.

For achieving higher efficiency in contemporary SI engines, several technologies are usually applied: turbocharging [4], optimization of combustion chamber design and in-cylinder flow, variable valve timing [5], direct injection [6], etc. Turbocharging, as one of the main technologies for achieving higher engine efficiency, reduces the ratio of friction and pumping losses by the increase of engine load. At the same time, the increase of engine load increases the tendency of the engine to knock [7]. Engine knock, which is one of the abnormal types of combustion, can cause permanent engine damage [8]. Over the years it has been accepted that knock is a consequence of auto-ignition of the gas in front of the turbulent premixed flame, called “end-gas” [9]. The end-gas is compressed not only by the piston movement but also by the expansion of the burned gases. Therefore many factors can increase the

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Nomenclature

ATDC	after top dead centre
AH	air heater
CO_2	carbon dioxide
CoV_{IMEP}	coefficient of variation of IMEP
CA50	crank angle for 50% mass fraction burned
CI	compression ignition
CR	compression ratio
°CA	degrees of Crank Angle
EGR	exhaust gas recirculation
IMEP	indicated mean effective pressure
IR	infrared
IVC	intake valve closure
IVO	intake valve open
ICE	internal combustion engine
MAPO	maximum amplitude of pressure oscillation
NO_X	nitrogen oxides
NO	nitrogen oxide
SI	spark ignition
ST	spark timing
α	degrees of Crank Angle after top dead centre

probability of knock occurrence, such as increased inlet temperature and pressure as well as elevated compression ratio. Therefore, one of the main obstacles in furtherer development of the SI engines in terms of further increase of the engine load is the occurrence of knock [10]. For that reason a development of different knock suppression strategies is being performed [8], e.g. retarding of the spark timing, enriching of the mixture, using of fuels with higher octane numbers, using of cooled exhaust gas recirculation (EGR), cooling of the intake air and enhancing the turbulence as a measure to increase the speed of normal combustion.

Literature review shows that exhaust gas recirculation, which was first implemented for reduction of NO_X emissions, might be a useful method for suppression of knock [11]. In [12] with the increase of EGR ratio to 20%, the brake specific fuel consumption (BSFC), emission of NO_X and of particle number were reduced by 7%, 87% and 36%, respectively. One of the recently developed engines described in [13] achieved an increase of efficiency with respect to its previous version by employing cooled EGR. Furthermore, [14] showed that the pumping loss gradually decreases with the increase of exhaust gas recirculation rate, while at the same time the efficiency of the high-pressure cycle increases due to the decrease of the heat transfer and exhaust gas energy loss. In [15] simple knock model coupled with a comprehensive cycle simulation of the engine showed that in addition to the suppression of knock, the use of EGR resulted with a slight increase of the brake thermal efficiency. The thermodynamic reasons for the above mentioned increase included slightly lower heat transfer and increase of the ratio of specific heat. In [16] it was shown that by using the EGR the abnormal combustion (knock) can be effectively suppressed and that the engine performance in terms of engine efficiency can be improved. It was also shown that spark timing and intake pressure need to be optimized to achieve higher efficiency when diluting intake mixture with EGR. In that optimization, generally, the intake pressure has to be increased and spark timing advanced. It was also shown that the increase of the amount of EGR enables advanced spark timings, i.e. advanced combustion phasing (with the same knock limit), through lower end-gas temperature. The advanced combustion phasing with the increased levels of EGR resulted with increased IMEP for the same input of fuel energy [16].

The levels of EGR in SI engines are limited since it was shown that the increase of EGR influences combustion stability presented by the coefficient of variation of IMEP (CoV_{IMEP}). In [17] it was shown that CoV_{IMEP} increases with higher EGR ratio and decreases with higher compression ratio and higher intake air pressure. On the other hand, in [13] it was shown that retarding of the spark timing results in an increase of CoV_{IMEP}, while [12] showed that EGR enables advanced spark timing, so the effect of increased CoV_{IMEP} with the increase of EGR is partially compensated by the advanced spark timings. However, there is a limit on the level of EGR. In [18] with 10% of the EGR and advanced spark timing the low level of CoV_{IMEP} was obtained, but further increase of the EGR resulted in an unallowable increase of CoV_{IMEP}. In [16] this limit was slightly higher. Although, at 15% EGR level the CoV_{IMEP} was slightly increased (CoV_{IMEP} = 2.5%) it was still far below the usual limits. The further increase of the EGR above 15% resulted in an unallowable increase of the CoV_{IMEP}.

In order to effectively use the EGR as a method for suppression of knock, engine designers have to understand the sources of EGR influence on knock. The EGR suppresses knock by three main factors: influence of EGR on flame speed, chemical influence on auto-ignition tendency (ignition delay) and thermal influence on the end-gas temperature [19].

The influence on the flame speed is shown as a decrease of flame speed with the increase of the EGR amount. Decrease of flame speed results with the decrease of mass burning rate and therefore pressure and temperature profiles of the end-gas change. On the one hand, slower combustion results in lower in-cylinder pressures and temperatures, therefore, reducing the tendency towards knock, while on the other hand the available time for auto-ignition increases.

Chemical influence on auto-ignition is defined as the influence of species that come from the EGR on the chemical kinetic behaviour of the mixture and therefore on the tendency towards auto-ignition. On one hand, it was shown that the CO_2 and water vapour (H_2O) that come from the EGR could reduce chemical ignition delay for the same pressure, temperature and excess air ratio conditions [20]. It was also shown that the NO_X (formed during combustion), which is recirculated back into the engine cylinder, could increase engine tendency to knock [21]. In [22] it was shown that the influence of NO_X is different for different in-cylinder pressure vs end-gas temperature (p-$T_{end\text{-}gas}$) history due to the nitrogen oxide (NO) reactivity (oxidation) at different temperatures. Reactivity of NO_X depends on whether the p-$T_{end\text{-}gas}$ history is in high, in NTC (Negative Temperature Coefficient) or in low-temperature regime. If p-$T_{end\text{-}gas}$ history is in low or NTC temperature regime, the addition of NO_X causes knock suppression, while if it is in the high-temperature regime the NO_X can promote knock.

Finally, thermal influence is defined as the influence of the EGR on the end-gas temperature level. The influence of EGR is two-folded. First, the EGR has different temperature compared to the fresh intake air, therefore the mixture of the EGR and intake air has a different temperature than fresh intake air, while the size of this difference depends on whether the EGR was cooled or uncooled. The second influence is through the thermal properties of the EGR mixture, where EGR has higher specific heat, and therefore the increase of the temperature of the end-gas caused by the compression is lower. In both thermal cases, the increase of the end-gas temperature will result in more pronounced tendency towards knock and vice versa. As it can be noticed, the use of EGR introduces various effects that are in some cases similar and in other cases are opposite.

Even though the use of EGR in SI engines has been researched over the years [23] and there are publications regarding its use, literature review showed that there is no in-depth experimental analysis of the sources of EGR influence on SI combustion with the emphasis on end-gas temperature. This study aims to bridge that gap by evaluation of the influence of the end-gas temperature, which changes with the addition of EGR, on the tendency of the engine towards knock.

The study is performed by experimental tests that employ a new