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Influence of exhaust residuals on combustion phases, exhaust toxic emission and fuel consumption from a natural gas fueled spark-ignition engine

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A R T I C L E I N F O

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A B S T R A C T

Exhaust gases remaining inside the engine cylinder after the exhaust stroke premix with fresh air-fuel combustible mixture and affect combustion process in the engine cylinder. Due to significantly higher temperature of these exhaust residuals (ExR) compared to the external exhaust gases recirculation (EGR), their impact on the in-cylinder combustion process is also different from impact of EGR. To control amounts of ExR independent of engine working parameters, the variable valve timing was introduced. It is known that variable valve timing affects not only volumetric efficiency and performance of the internal combustion reciprocating engine but also influences the amount of exhaust residuals remaining in the engine cylinder. These exhaust residuals impact combustion rates, combustion stability, knock and also play crucial role on exhaust toxic emissions. In this manuscript, the effect of variable valve overlap was studied on A. exhaust toxic emission (NOx, CO and THC), and B. combustion phasing and engine performance on a spark ignited natural gas fueled engine.

The investigation was carried out in a single cylinder research engine at constant load. The engine was equipped with high authority dual independent cam phasors for both intake and exhaust values, but for the purpose of this study, the exhaust valve timing was fixed and intake valve timing was changed to vary the amount of exhaust residuals remaining in the engine cylinder. The correlation between valve overlap and exhaust residuals were determined. It was observed that correlation in the positive overlap range between 55 and 85 deg was almost positive linear. Regarding toxic exhaust emission, increase in exhaust residuals from 9.6 to 12.3% (change by 28%) caused reduction in NOx by 67% and increase in both CO and THC by approximately 75%. Additionally, it did not significantly affect the engine's specific fuel consumption. Summarizing, strong correlation between in-cylinder exhaust residuals and toxic emissions, and combustion phases exists in the methane fueled spark ignited engine equipped with VVT.

1. Introduction

It is known that, there exists some amount of exhaust gases that remains inside the engine cylinder after exhaust stroke and takes part in the next combustion event [1]. Although the impact of external exhaust gases recirculation (EGR) on both engine combustion process and exhaust emissions is well known [2–11], the similarity of it when compared to the impact of internal exhaust residuals (ExR) on engine output parameters is debatable. The exhaust gases trapped in the cylinder and premixed with fresh air-fuel combustible mixture play important role in diluting the mixture and influence the combustion process, exhaust emission, and engine performance. However, internally trapped exhaust residuals in the engine cylinder cannot be considered as the same as exhaust gases directed to engine cylinder from the exhaust manifold through external recirculation, because temperature of the gases differs from one another. It has been established that EGR reduces pumping loses, NOx emissions [3,7–11] and potential for combustion knock occurrence [12–14] in an engine. There have been some studies on implementation of EGR and its potential benefits to engines working on gaseous fuels such as LPG, hydrogen, biogas and natural gas [2,14–18]. In earlier studies, a negative correlation between exhaust emissions and EGR was observed [2,15,16]. Also, positive impact of EGR on engine overall efficiency was demonstrated in the works [17,18]. From this point of view, the hypothesis is that ExR might play similar role as EGR. Therefore, the experimental work presented here is conducted to demonstrate the impact of ExR on

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engine performance and exhaust emissions and determine whether its effects are similar to EGR. However, unlike EGR, in-cylinder ExR are difficult to control. ExR amounts depend on several engine parameters including: engine volumetric efficiency, throttle position, engine load, back pressure at the exhaust manifold etc. As known, the most crucial parameter, which strongly affects ExR is valve timing. Hence, technologies such as Variable Valve Timing (VVT), Variable Valve Actuation (VVA) are most effective in controlling ExR. Although there is a considerable number of literature presenting the influence of VVT on engine performance and exhaust emission [19–21,24,26], very few of them focus on exhaust residuals. This manuscript introduces new knowledge on correlations between ExR and combustion phases as well as exhaust toxic emissions. Moreover, the literature survey shows that R &D activities are mainly focused on gasoline and diesel fuel combustion in the IC engine and very few studies are available on natural gas engine.

There are also several works presenting the impact of exhaust gases premixed with in-cylinder fresh charge to control combustion process under homogeneous charge compression ignition (HCCI) mode [22–24]. In the paper by Kozarac et al. [22] a numerical study focused on the influence of combustion products (exhaust gas residuals) trapped inside the chamber on combustion timing and combustion duration in a biogas fueled HCCI engine. The results show with increase in concentration of combustion products, the intake temperature, to maintain the same combustion timing, have to be increased. Rothamer et al. [23] investigated the spatial and temporal variation of exhaust residuals and temperature with aid of planar laser-induced fluorescence (PLIF) imaging. Their results illustrated that exhaust retention can result in significant stratification in the temperature and exhaust residual distributions, and as such may be capable of altering combustion phasing, duration for kinetically controlled combustion strategies. In the study [24], the effect of non-typical variable valve timing strategy on the gas exchange process and exhaust residuals was computationally investigated. It was found that non-typical intake valve timing significantly affects the volumetric efficiency and exhaust residuals.

There are a handful of studies [25–30] which focus on exhaust residuals in IC SI methane fueled engine. The work [25] presents the influence of exhaust residuals (referred to as Internal Exhaust Gas Recirculation - IEGR) on start of combustion in a rapid compression and expansion machine, which simulated combustion in an IC engine. In another paper [26] Xu et al. investigated fresh charge dilution by internal exhaust residuals. The aim of their study was to quantify the effect of exhaust valve timing and residual gas dilution on in-cylinder flame propagation and heat release characteristics in a spark ignition (SI) engine. Experiments were carried out in a single cylinder optical engine. Analysis based on chemiluminescence imaging showed that faster flame kernel formation in the early flame development stage could be obtained by advancing the exhaust valve timing, which shortened ignition delay and combustion duration. In the paper [27] Takei et al. found that increase in internal exhaust residuals affected the unburned mixture and made it more susceptible to autoignition in a gasoline fueled two-stroke engine. Williams et al. [28] looked into distribution of in-cylinder air-fuel mixture in a direct-injection engine with optical access using PLIF imaging. They observed that the effect of EGR on the PLIF intensity is larger than it was originally accounted for and goes beyond just diluting the air0fuel mixture with exhaust residuals. Bai et al. [29] found that internal exhaust gas residuals is an effective strategy in reducing pumping losses when compared to traditional external EGR. Grab-Rogalinski [30] proved high impact of overexpanded cycle on exhaust residuals amounts and efficiency of the biomethane fueled engine.

In summary, the literature studies show that current research does not contain detailed information of internal exhaust gases residuals on piston engine combustion phases, efficiency/specific fuel consumption and its toxic exhaust emission. Hence, investigation related to in-cylinder exhaust gas residuals and its impact on combustion and exhaust emissions in natural gas/methane fueled engines is recommended. Results presented in this paper should enrich knowledge in this mentioned field. Results of this investigation are also valuable in further investigation on stationary natural gas fueled engines for power generation.

2. Test bench setup

Experimental work was focused on evaluating the effect of internal exhaust gas residuals by variable valve overlap on engine toxic exhaust emission and fundamental engine work parameter: the indicated specific fuel consumption (ISFC) in a methane fueled spark ignited engine. Methane was used as the fuel for tests because it can be considered as the most appropriate reference fuel for natural gas. Additionally, combustion phases were determined to find correlation with overlap and further in-cylinder exhaust gases residuals. As found from literature review, the variable overlap affects exhaust gases residuals (ExR) inside the engine cylinder. Thus, investigation was focused on the influence of in cylinder exhaust gases residuals on ISFC and engine exhaust emissions viz. THC, CO, and NOx.

The tests were conducted on a single cylinder engine based on Ricardo's Hydra platform. The specifications are provided in Table 1.

The engine setup is shown in Fig. 1.

Variable valve overlap was achieved through phasing the intake valve timing by 30° Crank Angle (CA) relative to a fixed exhaust valve timing. As presented in Fig. 1, the overlap was changed by introducing variable offset in camshaft motion with respect to the crankshaft. It was achieved by applying a hydraulic servomechanism as depicted. The timing belt drives the left wheel, while the right wheel in the figure has possibility of limited rotation (± 30 CA deg) relative to the driving wheel. The valve profiles are shown in Fig. 2. The intake valve cam center line location (ICCL) varies from 90 to 120 °CA after TDC, while the exhaust valve cam centerline location (ECCL) was fixed at 95 °CA before TDC. Valve timings in detail are presented in Table 2. The test No. 3 corresponds to initial valve timings.

The valve overlap is defined as duration between intake valve opening (IVO) and exhaust valve closing (EVC). Hence, it is expressed in crank angle degrees (°CA). All the tests were performed in the following conditions presented in Table 3. The most important – spark timing for combustion events in all the tests was optimized to obtain Maximum Brake Torque (MBT).

3. Error analysis

Table 4 shows major physical quantities, instrumentation for their measurements and accuracies. Table 5 includes specifications for exhaust gas analyzer system Horiba 1600D Mexa. The accuracies for all measured quantities are below or equal 1% relative to the actual value or full scale range. The presented devices are used for research purposes due to their repeatability in ensuring credible experimental results. Accuracies for results from calculations were determined as standard

Table 1
Specifications of the single cylinder hydra engine.

Parameter	Description
Base engine	GM Ecotec GEN II LAF
Bore	86.00 mm
Stroke	94.60 mm
Connecting rod length	152.5 mm
Wrist pin offset	0.8 mm
Displacement	0.55 dm^3
Compression ratio	10.93:1
PFI injection	Methane
Cam phasing	Dual independent high authority
Engine control	Prototype for full set-point operation of throttle, fuel, spark, cams, etc.