The effect of use E85 ethanol fuel on a five-stroke engine

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Abstract. The article presents the analysis of the impact of the use of E85 ethanol fuel on operating parameters and toxicity of exhaust gases of a spark ignition engine with an additional expansion in a separate cylinder. Such an engine in literature most often referred to as five-stroke was developed at the Cracow University of Technology (CUT). The use of additional exhaust expansion was aimed at achieving high thermal efficiency when working with an average high load. The engine developed in CUT is equipped with a turbocharger and direct fuel injection, hence the use of fuel with high ethanol content was aimed at the effective use of these attributes. The obtained results indicated an improvement in the brake thermal efficiency of the engine when fuelling with E85 in relation to the gasoline of 98 octane rating normally used for this engine. On the other hand, the efficiency of the conversion of the catalytic converter has deteriorated somewhat. Directions for further activities and research in the subject were also determined.

1. Introduction

The dynamic development of the motorization over the past few decades has caused high environmental pollution and was not without impact on climate changes caused by, among others greenhouse gas emissions, mainly carbon dioxide. Efforts are currently being made for wider use of electric propulsion systems for automotive vehicles which gives zero emissions at their place of use. However, the obstacle to the development of electromobility is the relatively low capacity for energy storage in currently available batteries, which in addition are expensive [1]. For this reason, it is estimated that internal combustion engines will be used to drive vehicles for the next several decades. This is the motivation to constantly search for solutions limiting the nuisance of combustion engines for the environment. One such solution is the use of various types of renewable fuels instead of traditional fossil fuels [2].

In the case of spark-ignition engines, high hopes for limiting global CO2 emissions caused by motor vehicles are associated with the use of bio-ethanol [3]. A better CO2 balance for bioethanol than for gasoline (petrol) has three main causes. Firstly, due to the more favourable proportion of hydrogen to carbon, ethanol combustion gives more water and less carbon dioxide than gasoline. Secondly, due to the properties of alcohol fuel, the engine powered by it usually gains a slightly higher efficiency than when running on petrol. Thirdly, part of the carbon dioxide emissions that arise during combustion is balanced by the demand for this gas for plant growth of which ethanol is manufactured [4]. On the other hand, one of the main disadvantages of pure alcohol as a motor fuel is its low vapour pressure at low temperature, which makes it difficult or impossible to start the engine even at approx. 10 °C [5, 6]. For this reason, in most countries where bioethanol is used as fuel, it is mixed with a
petrol and sold under the E85 designation with a content of 70 to 85% (V/V) of ethanol [7]. Another very widespread use of ethanol is its addition to classic petrol. In this situation, the percentage of alcohol component in gasoline usually does not exceed 10%.

The paper presents a comparative analysis of operating parameters, exhaust toxicity and efficiency of conversion of the three-way catalyst of the engine with an additional exhaust expansion in a separate cylinder (the so-called five-stroke engine) fuelled with classic petrol and E85 ethanol-petrol blend.

2. Methods

2.1. Motivation for the research

The five-stroke engine developed at the Cracow University of Technology [8] was created as a modification of a four-stroke in-line four-cylinder engine, in which a classic four-stroke cycle takes place in the outer (fired) cylinders. The two inner cylinders are joined into one bigger volume in which the process of additional (second) expansion of exhaust gases from fired cylinders takes place. This design is intended to achieve high engine efficiency at the expense of limiting its performance. Due to the principle of operation (high overall expansion ratio of the charge), the operation of the five-stroke engine is reasonable at high loads. The engine is equipped with a direct fuel injection system and a forced induction system using a turbocharger, hence the use of fuel with a high ethanol content resulting in high latent heat of evaporation giving a high octane number can result in improved engine operating indicators in the range of high load. The motivation to undertake the presented work was the desire to verify and quantify the above thesis. The basic technical data of the five-stroke engine developed in CUT and used for research is given in Tab. 1.

| Parameter                    | Value/Unit/Description                                      |
|------------------------------|-------------------------------------------------------------|
| Number of Cylinders          | 2 fired / 2 low-pressure for additional expansion           |
| Displacement of Cylinders    | 0.992 dm$^3$ - both fired / 0.992 dm$^3$ - both low-pressure |
| Bore x stroke                | 82.5 x 92.8 mm                                              |
| Number of Valves             | 4 per cylinder                                              |
| Compression/Expansion Ratio  | 10.5/21(overall)                                            |
| Engine Management System     | Electronically Controlled, Direct Fuel Injection            |
| Induction Method             | Forced, Turbocharger with a Variable Nozzle Turbine         |
| Aftertreatment System        | Three-Way Catalytic Converter, Closed-loop Operation        |

The five-stroke engine developed at the Cracow University of Technology is based on a turbocharged EA113 Volkswagen direct injection engine with a displacement of 2.0 dm$^3$ and a maximum output power of 147 kW (200 HP) [9]. Due to the high compression ratio for a supercharged engine, just like the base engine, also a five-stroke engine requires fuel of a research octane number (RON) equalled 98. Engine operation with 95 RON petrol is possible, but a lowered knock limit for this fuel causes that at high load a significant ignition delay is required which leading to a reduction in the brake thermal efficiency of the engine.

Fig. 1a and 1b respectively show the concept of a five-stroke engine developed at the Cracow University of Technology (a) and its general view attached in the test stand (b).

The engine load on the test bench is carried out by means of an electronically controlled eddy-current dyne. During the tests, the exhaust gas composition was measured using Arcon Oliver K-4500 analyser. Fuel consumption measurement was carried out using the gravimetric method, and K-type thermocouples were used to determine the temperature in the selected engine points.
2.2. Fuels

The five-stroke engine was made with the intention of achievement the highest brake thermal efficiency possible, hence in the vast majority of tests they were conducted using petrol of 98 octane rating. Also in the case of the tests described in this manuscript, premium petrol with RON equalled 98 compliant with EN228 standard was used as reference fuel. A special feature of petrol used in the tests is the relatively high content of Ethyl Tertiary Butyl Ether (EETB) of 12.5% (V/V). The use of EETB allows the required high octane number to be obtained [10]. On the other hand, this gasoline is practically free of the addition of bioethanol (below 0.2% V/V), the content of which in ordinary petrol (RON 95) most often reaches the maximum value of 5% allowed in the European Union [11]. Although the EN228 standard allows for a 10% share of bioethanol in gasoline sold in Europe, then such fuel must be sold from separate, specially marked distributors, which is rarely used.

As a fuel with a high alcohol content, in the main part of the study used a blend of ethanol with gasoline called E85 available commercially in selected European countries [12, 13]. According to the guidelines set out in CEN/TS 15293:2011, E85 fuel is a mixture of ethanol, usually of plant origin, and petrol compliant with EN228 standard [7]. The content of ethanol ranges from 70 to 85% (V/V), the rest is petrol [14]. A larger share of petrol is used for the fuel composed for the winter period, lower for the summer period. Increasing the percentage of gasoline in the E85 fuel for the winter period is intended to facilitate its evaporation at low temperature to enable engine starting. The basic properties of E85 fuel assuming the maximum permissible ethanol volume concentration are presented in tab. 2.

| Parameter                              | Value/Unit                |
|----------------------------------------|---------------------------|
| Composition                            | 0.85 Ethanol and 0.15 Gasoline (V/V) |
| Density                                | 790.4 kg/m³ (at 15°C)     |
| Lower Heating Value (LHV)              | 29.1 MJ/kg                |
| Research Octane Number (RON)           | 106.8                     |
| Lubricity (ISO 12156-1)                | 636 μm                    |
| Volatility Index                       | 234                       |
| Vapour Pressure                        | 32.5 kPa                  |
| Latent Heat of Evaporation             | ~764 kJ/kg                |

As the E85 mixture is not currently distributed in Poland, commercially available fuel gained in the Czech Republic was used for the purposes of the research covered by this study. Unfortunately, the fuel seller did not provide a fuel composition specification, so the actual ethanol content of the fuel was not known. This is a crucial parameter due to the comparison of the brake thermal efficiency of the engine with the result obtained with petrol of RON 98. For this reason, to determine the volume
concentration of ethanol in the fuel, a Continental SV7 alcohol sensor applied in Flex-Fuel engine management systems was used. Sensors of this type operate on the principle of measuring fuel resistance and dielectric constant, which are significantly different for petrol and ethanol [17]. The result of measuring ethanol concentration in gasoline is temperature compensated.

When measuring the volume concentration of ethanol in the E85 fuel used for the tests, the result 0.76 (V/V) has been obtained. The density measurement of the blend indicated a result of 769 kg/m$^3$. Assuming that the lower heating value of petrol used to compose fuel was 43 MJ/kg, and the lower heating value of pure ethanol is 26.8 MJ/kg [16], the calorific value of the ethanol - gasoline mixture was determined to be 30.35 M/kg.

3. Results of research

3.1. Research plan

As part of comparative research on the behaviour of the five-stroke engine when running on petrol and E85, the following three tests were performed:

- with variable engine load at constant engine speed $n$ and constant rel. AFR,
- with variable ignition timing $\alpha_{\text{ign}}$ at constant rel. AFR, engine speed $n$ and throttle opening $\alpha_{\text{thr}}$,
- with variable rel. AFR at constant engine speed $n$, ignition timing $\alpha_{\text{ign}}$ and throttle opening $\alpha_{\text{thr}}$.

During the tests, basic engine operating parameters (torque, rotational speed, fuel consumption), exhaust gas temperature between fired cylinders and additional expansion cylinders, upstream from the turbine, downstream from the turbine (upstream from the catalytic converter) and downstream from the catalytic converter were measured. The composition of the exhaust gas upstream from the catalytic converter and downstream from the catalytic converter was also measured. This made it possible to determine the efficiency of the exhaust gas aftertreatment system depending on the fuel used, which was done for tests with change of relative Air-Fuel Ratio (rel. AFR).

In previous work, it was found that the engine in the current configuration, with a turbocharger with variable nozzle turbine, obtained the highest efficiency in the range of 2400 rpm [18], hence the tests described in this study were carried out at this value of rotational speed.

3.2. Variable load

First, the five-stroke engine tests were performed on gasoline. The throttle opening was gradually increased from 7% to 100% with maximum opening of variable nozzle vanes in the turbocharger. After reaching the maximum throttle opening, the boost pressure was increased by varying the position of turbine nozzle vanes so that the highest load was obtained at the boost pressure of 0.4 bar. The stoichiometric fuel-air mixture (rel. AFR = 1.0) was maintained for all operating points. The ignition timing was adjusted to obtain maximum brake torque (MBT) at a given operating point. After conducting a series of tests of the engine running on petrol, under exactly the same conditions, tests of the engine running on E85 blend were carried out.

Fig. 2 presents the ignition timing for individual operating points (a) and a comparison of the brake specific fuel consumption and brake thermal efficiency when fed with both considered fuels depending on the engine load (b).

In the right part of Fig. 2 a) the values of the boost pressure maintained for the last three measuring points were shown, which was increased by changing the position (closing) of the variable nozzle of turbine. Analysis of Fig. 2 b) indicates that for the same throttle opening at individual operating points, the engine fed with the E85 blend obtains a slightly higher torque. The increase in the engine performance by several percent for the same AFR is due to the increase in volumetric efficiency, which is the result of higher heat of evaporation of the fuel with high ethanol content. Obviously, due to the significantly lower stoichiometric AFR and lower heating value of the E85 blend, the brake specific fuel consumption is clearly higher than for petrol. Nevertheless, in comparison to brake thermal efficiency, which takes into account the lower heating value of fuel, reasonably higher values were obtained with E85 fuel. This can be explained by an increase in the indicated thermal efficiency
(mechanical efficiency remains the same), which is the result of reducing of the heat losses by shortening the combustion process of a fuel with a high ethanol content [19, 20]. The author's further research on the subject will include measurements of pressure in the engine cylinder with E85 fuel supply, which will allow unambiguous verification of the above statements.

**Figure 2.** Ignition timing $\alpha_{\text{ign}}$ in the function of throttle opening and boost pressure (a) as well as comparison of Brake Specific Fuel Consumption and Brake Thermal Efficiency for the operation on both considered fuels in the function of engine torque (b).

Fig. 3 presents the results of comparing the CO, CO$_2$, HC and NO$_x$ concentrations in the exhaust gas upstream from the catalytic converter when the engine is fed with both fuels.

**Figure 3.** Concentrations of CO and CO$_2$ (a) and HC as well as NO$_x$ (b) in exhaust gases of the five-stroke engine in the function of engine load.

In general, the composition of the exhaust gas when feeding a five-stroke engine with both fuels shows similar variability as in the case of a classic four-stroke engine. It should be noted that CO and CO$_2$ concentrations practically do not depend on the engine load, which results from maintaining the stoichiometric composition of the air-fuel mixture for all points. Analysis of part a) Fig. 3 indicates more favourable values of the sum of CO + CO$_2$ when fuelled with the fuel with a high percentage of ethanol. This results from the increased ratio of hydrogen to carbon in the C$_2$H$_5$OH molecule than for petrol, and from more complete combustion of fuel with a high content of oxygen in the molecule [21]. The concentration of nitrogen oxides in the entire analysed range is practically the same for both fuels - part b) of Fig. 3. Due to the internal cooling of the charge by ethanol evaporation, a reduction in the peak combustion temperature could be expected, however, it should be remembered that when fuelled with E85 there was an improvement in the volumetric efficiency, which resulted in a larger portion of energy delivered at each of the analysed points. Finally, the NO$_x$ concentration is very similar in both cases. On the other hand, during the E85 fuel supply, a significantly lower concentration of
hydrocarbons in the exhaust gas was recorded, which has similar reasons as the decrease in CO concentration in the described case.

3.3. Variable ignition timing

The next part of the study compares the engine behaviour with both fuels and a variable ignition timing. In this test, a constant 50% throttle opening and the stoichiometric composition of the air-fuel mixture (rel. AFR = 1.0) were maintained. As before, the rotational speed was kept constant 2400 rpm.

The results of the research on the impact of the ignition timing on the operating parameters of the engine with additional exhaust expansion when fed with both considered fuels are presented in Fig. 4.

![Figure 4. Comparisons of Torque and Brake Specific Fuel Consumption (a) and Brake Thermal Efficiency and Exhaust Gas Temperature (b) of the five-stroke engine fuelled by petrol and E85 blend in the function of ignition timing.](image)

The maximum brake torque value was recorded for both fuels for the same ignition advance angle - 20.3 °CA BTDC (Crank Angle degrees Before Top Dead Centre). This is also the point of maximum brake thermal efficiency of the engine, what is natural for this relationship. As in the case of variable load tests, the five-stroke engine obtained significantly higher thermal efficiency. As the ignition advance increased, the exhaust gas temperature measured before entering the turbine also decreased. In the case of E85 fuel, overall slightly lower exhaust gas temperature values were obtained, which confirms the increase in the speed of the combustion process in this case.

Fig. 5 shows the results of comparing the exhaust gas compositions of the engine fuelled with both fuels depending on the ignition timing.

![Figure 5. Comparison of concentrations of CO and CO₂ (a) and HC as well as NOₓ (b) in exhaust gases of the five-stroke engine fuelled by petrol and E85 blend in the function of ignition timing.](image)

When the ignition timing is changed, the concentration of carbon monoxide and carbon dioxide in the exhaust gas of the five-stroke engine is practically constant. Similarly to varying the engine load, a more favourable CO+CO₂ balance was obtained for the E85 blend. As the ignition timing is advanced,
the concentration of nitrogen oxides increases. Very similar values were obtained for both fuels. A clearly lower volumetric concentration of hydrocarbons was obtained during feeding with the E85 blend, which is influenced by the fractional composition of the fuel based predominantly on ethanol.

3.4. Variable relative Air-Fuel Ratio

In the last part of the research being the subject of this study, a comparison was made of the operating parameters and the exhaust gas composition of the engine fed with E85 fuel and petrol depending on the air-fuel ratio. The throttle opening was set to 50% for both fuels. Ignition timing was adopted to ensure maximum engine performance for both fuels when supplied with a stoichiometric mixture - $\alpha_{ig}=20.3^\circ$CA BTDC. The engine torque charts when fed with both fuels and the increase in torque when fed with E85 depending on the rel. AFR is shown in Fig. 6 a), while part b) contains analogous comparisons for brake specific fuel consumption and brake thermal efficiency.

![Figure 6](image.png)

**Figure 6.** Torque and relative torque increase on E85 fuel (a) and engine BSFC and brake thermal efficiency (b) of the five-stroke engine fuelled by petrol and E85 blend in the function of relative Air-Fuel Ratio.

Research conducted with variable rel. AFR confirmed the findings described in subsection 3.2. When powered with a petrol-ethanol blend and with the same throttle opening and ignition timing, the engine achieved a torque of average 4% higher than when using pure petrol. The lowest increase in torque was recorded around the stoichiometric AFR, slightly larger for rich and lean mixture. This is due to the fact that the ignition timing, constant for all measuring points, was selected as optimal for a mixture of rel. AFR = 1.0 and petrol. Different properties of the analysed fuels mean that in the case of a lean and rich mixture due to engine performance, the ignition timing used was more suitable for the E85 blend than for gasoline.

The nature of the variability of brake thermal efficiency course is similar in both cases. The maximum thermal efficiency was recorded for a mixture of rel. AFR equal to approximately 1.1. The maximum values were 36% for E85 blend and 33.5% for gasoline respectively.

Fig 7. presents a graph of conversion efficiency of a three-way catalyst (TWC) depending on rel. AFR when fed with both fuels under consideration, while the exhaust gas temperature charts measured upstream and downstream from the TWC are shown in Fig. 8. The conversion efficiency of the catalytic converter for each of the considered components (CO, HC and NOx) was determined using formula (1).

$$\text{TWC Conversion Efficiency} = 100 \cdot \frac{X_{\text{upstr}} - X_{\text{downstr}}}{X_{\text{upstr}}} \%,$$  \hspace{1cm} (1)

where:
- $X_{\text{upstr}}$ - A concentration of the component measured upstream from the three-way catalyst, [% vol.]
- $X_{\text{downstr}}$ - A concentration of the component measured downstream from the three-way catalyst, [% vol.]
The TWC used in a spark-ignition engine works with the acceptable efficiency of simultaneous neutralization of CO, HC and NO\textsubscript{x} only for a mixture of air-fuel ratio close around stoichiometric composition [22]. The second very important condition for the effective operation of TWC is to obtain a sufficiently high exhaust temperature. In the case of a five-stroke engine, in which the two-stage expansion of the charge leads to a relatively low exhaust gas temperature as for the spark-ignition engine, this issue takes on special significance. The time from starting the engine to light-off the catalyst is relatively long, and in the case of too low load, the catalyst light-off temperature may not be obtained at all [23]. The analysis of Fig. 8 shows that the temperature of the exhaust gas upstream from the catalytic converter for the E85 blend supply was 15-20 °C lower for the comparable AFR than for the petrol supply. This establishes additional challenges for the exhaust gas aftertreatment system of the five-stroke engine developed at CUT.

Processes in the catalytic reactor leading to oxidation of carbon monoxide and hydrocarbons and reduction of nitrogen oxides are exothermic. The increase in exhaust gas temperature measured downstream from the catalytic converter relative to the temperature upstream from the TWC indicates the total efficiency of neutralization of undesirable components by the reactor. The maximum increases in exhaust gas temperature downstream from the catalytic converter have been similar for both fuels. In the case of petrol supply it was 110 °C for rel. AFR = 1.02, while for E85 105 °C for rel. AFR = 0.997. The discrepancies in achieving the point of maximum total efficiency result from the significantly lower hydrocarbon oxidation efficiency when fed with the E85 mixture (Fig. 7). For a slightly lean mixture, it does not increase as much as when the engine is powered by gasoline and for rel. AFR = 1.02 reaches only 28.4%, and then the efficiency of NOx reduction decreases significantly.
and amounts to only 46%. It was found in [24] that the reduction of hydrocarbon oxidation efficiency when fuelling with an increased ethanol content fuel results from the increased water content in the exhaust gas. In a five-stroke engine, this effect is further compounded by the exhaust gas temperature much lower than for a classic spark-ignition engine.

4. Conclusions

As a result of the research being the subject of this study, it was found that the engine with an additional exhaust gas expansion in a separate cylinder tolerates supply with E85 blend well. Quite obviously, in analogous conditions the engine obtained a higher BSFC, but its brake thermal efficiency taking into account the reduced lower heating value of the fuel with a large content of oxygen was clearly higher than when running on gasoline. This is the result of a more favourable combustion process and better use of the cylinder displacement by increasing the volumetric efficiency associated with in-cylinder cooling of the charge as a result of significantly higher latent heat of evaporation of the fuel with ethanol. When the ignition timing was changed, the engine response in the form of changes in performance was similar when fed with both fuels. The maximum torque for both analysed cases was obtained at the same ignition timing. The analysis of exhaust gas composition before and after the catalytic reactor revealed a clear reduction in the concentration of carbon monoxide and hydrocarbons, which results from a more favourable fractional composition of the fuel, but also confirms a more beneficial combustion process. On the other hand, a significantly lower conversion efficiency of the TWC for hydrocarbons was also noted. This was the result of the general low exhaust gas temperature of the five-stroke engine, additionally lowered by an average of 15-20 °C when fed with E85 fuel. Ultimately, at feeding with E85 TWC did not achieve acceptable total conversion efficiency, which indicates the need for searching for another TWC capable of efficiently working at reduced temperatures.

In summary, it should be stated that the obtained results are so promising that further development and studies of a five-stroke engine with a high-ethanol content fuel supply are planned. First, the concept of attachment of TWC upstream from the turbine is considered, where the exhaust gas temperature is significantly higher than downstream from the turbine, but still not too high due to the two-stage expansion of the charge. In addition, efficient reactor operation would increase the enthalpy of the exhaust gas upstream of the turbine, which could improve the brake thermal efficiency.

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