Investigation of ecological parameters of four-stroke SI engine, with pneumatic fuel injection system

W Marek¹ and K Śliwiński¹

¹Cracow University of Technology, Institute of Automobiles and Combustion Engines, al. Jana Pawła II 37, 31-864 Krakow, Poland
E-mail: wmarek@pk.edu.pl

Abstract. The publication presents the results of tests to determine the impact of using waste fuels, alcohol, to power the engine, on the ecological parameters of the combustion engine. Alternatively fuelled with a mixture of iso- and n-butanol, indicated with "X" and "END, and gasoline and a mixture of fuel and alcohol. The object of the study was a four-stroke engine with spark ignition designed to work with a generator. Motor power was held by the modified system of pneumatic injection using hot exhaust gases developed by Prof. Stanisław Jarnuszkiewicz, controlled by modern mechatronic systems. Tests were conducted at a constant speed for the intended use of the engine. The subject of the research was to determine the control parameters such as ignition timing, mixture composition and the degree of exhaust gas recirculation on the ecological parameters of the engine. Tests were carried out using partially quality power control. In summary we present the findings of this phase of the study.

1. Introduction
Exploration and use of new fuels for combustion engines, is an important objective of scientific and economic reasons, leading to the rationalization of the use of different energy sources. Some of unconventional fuels are not suitable from various reasons, for use in traction vehicles, but can be used in power applications. For this type of fuel can include various types of combustible substances, which is a waste product of some industrial processes. One such fuel is butyl alcohol. Typically, this kind of waste fuels is most used for heating, but often irretrievably lost by burning for open space. Their development for low-energy systems seems to be a reasonable solution, the more that this type of systems allows for flexible adaptation the type of energy to current needs. This corresponds, to the modern trend, to diversify energy sources. Suitably adapted, the piston internal combustion engine, cooperating with a power generator, can be both - a heat source and a source of electricity. This publication is a next of cycle [1] [2], in which will be presented the results of studies indicating areas of possible uses, proposed by Professor Jarnuszkiewicz concept of the pneumatic injection by means of hot exhaust gases. In this publication will be presented, the results of research of ecological parameters of using liquid waste fuels, in an internal combustion engine for the conversion of chemical energy to useful work, for the production of electricity and useful heat energy.
2. Purpose and methodology of research
The main aim of the research was to determine by laboratory measurements, the impact of supply the alcohol waste fuel, on ecological parameters of the combustion engine. It became necessary to recognize, the new problems arising from the use of pneumatic injection system according to the concept of Professor Jarnuszkiewicz, as adapted to the modern mechatronic systems [3]. All measurements on engine test bench, of the toxic exhaust components, was carried out at a constant engine speed.

These conditions correspond to the operation of the engine in the power generator. The study tested the specificity of the pneumatic injection system, and therefore the selection of the rotational speed was not bound, as in typical solutions, by the operating parameters of the electrical machine. The criterion was a task - use a qualitative adjustment of power, corresponding to the energy demands of the load, with minimum values of rotation of the crankshaft of the engine. Under these conditions, the converters of mechanical energy into electrical energy, are used in the form of inverters. Among the control parameters of the test engine, which had to be matched to the type of examined fuel were primarily:

- ignition timing,
- coefficient of excess air,
- recirculation value of exhaust injection dose.

These parameters have a very significant impact on the process of combustion in the cylinder, which then results both, the value of generated energy parameters and toxic exhaust emissions. Especially in the case of qualitative power control, these parameters directly influence on the location in time, and duration of the combustion process. This influence is reflected very intensively in this case in particular, on the emission of toxic components of exhaust gases. For this reason, for the examined fuel, and for each operating point of the engine load, these control parameters were individually set.

Measurements of the concentration of toxic exhaust components, was conducted by the measuring apparatus, in accordance with the applicable current standards, in which is equipped, the Engine Laboratory of Cracow University of Technology. Was studied and recorded the value of concentration: carbon monoxide CO, hydrocarbons THC, NO nitrogen oxide, and carbon dioxide CO₂ and oxygen O₂. In addition, was studied and recorded, the impact of the examined fuel, on the other engine parameters such as torque and power, the specific fuel consumption, the total efficiency, the coefficient of air excess and the exhaust gas temperature [2].

3. Test bed investigation of the SI engine
Research of engine fed with a mixture of alcohol and the gasoline separately, were carried out on a special test bed in the Laboratory of Combustion Engines, Cracow University of Technology, whose essential elements are as follows:

- two-cylinder, four-stroke spark ignition engine,
- engine brake generator MEZ,
- AVL fuel mass flow meter , AVL Type 4210,
- the measuring systems for determining: exhaust gas temperature, ambient pressure and humidity of the intake air by the engine, the excess air ratio.

As a research object was prepared a two-cylinder four-stroke spark-ignition engine 126 000 A1, equipped in the pneumatic-fuel injection system using the hot exhaust gases, according to the concept of Professor Jarnuszkiewicz, which in the factory configuration, was carburettor equipped.

In this configuration, the engine was characterized by the following working indicators [4]: rated power on petrol 17.7 kW/4500 1/min., the maximum torque of 42 Nm/ 3000 1/min, the minimum specific fuel consumption of 300 g/kWh. Embodiment of multi-fuel supply system of such an engine, require the design and building a pneumatic injection system and the supply fuel system, which the configuration similar to a conventional, low pressure injection supply system [5] [6]. Pneumatic injection system has been designed based on the concept of Professor Jarnuszkiewicz, described in an article on his achievements, in connection with the jubilee of Conference Konmot 2016 [1].
functional model of designed and mounted on engine, prototype system of pneumatic injection, was shown in Figure 1.

![Functional model of pneumatic injection](image)

**Figure 1.** The view of the functional model of the pneumatic injection using hot exhaust gases for liquid fuels

To control: the value of fuel dose and phase of its dosing, the angle of ignition timing, degree of throttle opening and the composition of the combustible mixture (excess air ratio), and also the value of dose of exhaust gases to blowing the dose of fuel, was designed and used a special engine controller. As the fuel was used waste mixture of iso-butanol and n-butanol alcohol, as a post-processing fuels of the chemical industry - marked ZAK and X. Both waste fuels come from different technology threads and characterized by the same calorific value, but different physical and chemical properties. For comparative purposes, was used motor gasoline.

Due to the prototype nature of fuel supply, and combustion system, the power control range was limited to medium loads.

4. **Results and analysis of investigations**

The energy benefits from the use of lean fuel-air mixture in the cylinder charge, have been known for a long time. Slightly worse on this background presents it’s the issue of achieving, a satisfactory toxic exhaust emissions, especially when it comes to nitrogen oxides. However, in the case of dual fuel supply using the alcohol liquid phase, can be a significant reduction of the concentration of the toxic compounds in the exhaust gas. It was illustrated on Figure 2 and 3.

![Concentration of nitric oxides NOx](image)

**Figure 2.** The concentration of nitric oxides NOx in the exhaust gas of engine fuelled with petrol.
Figure 3. The concentration of nitric oxides NO\textsubscript{x} in the exhaust gas of engine fuelled with the post-processing fuels.

In the case of petrol fuelling, the concentration of oxides of nitrogen to grow strongly while increasing the load of the engine, but by increasing the value of mixture enrichment and increase stage of recirculation while increasing a load, its concentration is significantly reduced. In the case of alcohol fuel supply, as the load increases we observed a sharp increase in the concentration of nitrogen oxides. This is facilitated by increasing the temperature of fuel combustion, as well as greater availability of oxygen, because as the load increases, the engine was powered by a mixture with ever increasing air excess. However, the adjusting of the value of exhaust gas recirculation, caused that the maximum concentration of NO\textsubscript{x} values, in case of alcohol fuel supply, it were smaller in relation to the petrol. This different strategy of fuel control dosage, was also highlighted, in the concentration of carbon monoxide in the exhaust gas. This is exemplified in Figure 4 and 5.

Figure 4. The concentration of carbon monoxide CO in the exhaust gas of engine fuelled with petrol.
Figure 5. The concentration of carbon monoxide CO in the exhaust gas of engine fuelled with the post-processing fuels.

In the case of a gasoline supply, to increasing the load on the engine, it was necessary to enrich the air fuel mixture. This strategy allows for an increased load, without the occurrence of the phenomenon of knock, while also decreasing the concentration of NOx. The negative result, was a large carbon monoxide content in the exhaust gases - Figure 4. The strategy used for the alcohol fuel - was used a lean mixture in the whole load range - in the case of carbon monoxide concentration, will provided very positive results. It has been reduced several times - Figure 5.

The concentration of hydrocarbons in the exhaust gas, was dependent on the value of the air excess ratio - Figure 6 and 7.

Figure 6. The concentration of hydrocarbons HC in the exhaust gas of engine fuelled with petrol.

In the case of petrol supply, an increase in the concentration level of this exhaust component (Figure 6), was mainly due, to a significant enrichment of the mixture to $\lambda = 0.83$, as the load increases.
Figure 7. The concentration of hydrocarbons HC in the exhaust gas of engine fuelled with the post-processing fuels.

In the case of the alcohol fuel supply, was observed a significant spread of concentrations - Figure 7, and the higher value in relation to the petrol supply. This is due to the phenomenon of misfire and the reduction of combustion speed, during supply of engine by lean mixture of the value $\lambda \approx 1.4$.

The figure 8 presents the impact of load of the engine fuelled by alcohol, on CO$_2$ concentration in the exhaust gases.

Figure 8. The concentration of carbon dioxide CO$_2$ in the exhaust gas of engine fuelled with the post-processing fuels.

The concentration of carbon dioxide is dependent on the composition of the mixture, also from the concentration of carbon monoxide CO and hydrocarbons HC in the exhaust gases. Because the composition of the mixture, during alcohol fuel supply, was practically solid, it also affected for stabilizing effect on the level of concentration of that component in the exhaust gases, in the final
phase of the load increases. In the case of petrol supply - Figure 9, the mixture was steadily enriched, and this is reflected in the course of variability in the CO2 concentration, in accordance with the typical regulatory characteristics of the composition of the mixture.

![Carbon dioxide concentration in exhaust gas of engine fuelled with petrol.](image)

**Figure 9.** The concentration of carbon dioxide in the exhaust gas of engine fuelled with the petrol.

Comparing the values of CO₂ concentrations for both fuels, for the corresponding load values, found distinctive differences in reported values, due to their different chemical structure.

### 5. Summary

The investigation results of the ecological parameters of the engine 126 000 A1 powered by waste fuels on alcohol base, allow to formulate the following most important conclusions:

1. Due to the relatively low concentration of carbon monoxide in the exhaust gases, with the alcohol fuel supply - relative to the petrol supply, the limitation of the control of lean mixture composition, is to prevent the occurrence of the misfire,
2. Reduction of nitrogen oxides concentration, will require more precisely determine the value of exhaust gas recirculation injection dose,
3. Was achieved positive results, which testify to the fact that the combustion of alcoholic waste fuels in the internal combustion engine with pneumatic fuel injection, is reasonable for both energy and ecological issues.

### References

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