



## ETHYL ALCOHOL AS A FUEL FOR CONTEMPORARY INTERNAL COMBUSTION ENGINES

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### Abstract

The article presents the conditions for the use of ethyl alcohol as a component and a sole fuel for internal combustion engines. Methods of ethanol production, its properties and the benefits and risks associated with using it as engine fuel have been described. The variants of commercial ethanol fuels allowed by law have also been presented. Ecological aspects of the use of ethanol fuels for modern internal combustion engines were presented. The opinion was expressed that although ethanol is used in bulk as a component of gasolines, its use as a self-contained fuel is and probably will continue to be small in the near future.

Keywords: ethyl alcohol, combustion engines, motor fuels

### ALKOHOL ETYLOWY JAKO PALIWO DO WSPÓŁCZESNYCH SILNIKÓW SPALINOWYCH

#### Streszczenie

W artykule przedstawiono uwarunkowania stosowania alkoholu etylowego jako składnika oraz samodzielnego paliwa do silników spalinowych. Opisano metody produkcji etanolu, jego właściwości oraz korzyści i zagrożenia związane ze stosowaniem go jako paliwa silnikowego. Zaprezentowano dopuszczalne prawem warianty handlowych paliw etanolowych. Przedstawiono ekologiczne aspekty stosowania paliw etanolowych do współczesnych silników spalinowych. Wyrażono opinię, iż mimo, że etanol stosowany jest masowo jako komponent benzyn silnikowych, to jego zastosowanie jako samodzielnego paliwa jest i prawdopodobnie w najbliższej przyszłości będzie niewielkie.

Słowa kluczowe: alkohol etylowy, silniki spalinowe, paliwa silnikowe

## 1. INTRODUCTION

The concept of using ethanol as a motor fuel appeared as early as at the beginning of the automotive development. Henry Ford built his first vehicles and fuelled them with ethanol in the eighties of the nineteenth century. Early Ford T models had a carburetor that could be adjusted for either gasoline or ethanol. In the interwar period and during World War II pure ethyl alcohol was occasionally used to power spark ignition engines. In 1928 started first ethanol based Polish fuel production which was blend of 30% ethanol and 70% gasoline [2]. Alcohols were used as components of fuel mixtures: gasoline-alcohol and gasoline-alcohol-benzene for many years after the war. In these mixtures, alcohol served primarily as a component increasing the fuel octane number, and its role as an energy carrier was secondary. In the nineties of the twentieth century, an additive of 5% ethanol for motor gasolines began to be used in Poland. The main purpose of using ethanol was to reduce the content of tetraethyl lead which was used at the time to increase the octane number of gasolines. However, some favorable changes in the composition of exhaust gases caused

by the addition of ethanol were also noted, namely the reduction of CO emission by about 20% in the ECE cycle [4].

Currently, when fuel injection systems and catalytic aftertreatment systems are commonly used in spark-ignition (SI) engines, the importance of ethanol as a gasoline additive that reduces exhaust toxicity has decreased. Ethanol still plays an important role as a mean to increase the octane number of gasolines, especially due to restrictions on the content of aromatic hydrocarbons in fuel. It is used in its pure form and serves as a substrate for the production of high octane ethyl-tert-butyl ether (ETBE). However, the most important reason for the growing use of ethanol as an engine fuel today is the fact that it can be mass produced from biomass (bioethanol), i.e. as an environmentally friendly renewable fuel [7]. Ethyl alcohol can also be produced on industrial scale from ethylene, methanol or from synthesis gas [8, 19]. However, taking into account the previously mentioned environmental aspects, and partly also social, economic and political factors, the most beneficial is the production of ethanol through biomass fermentation.

## 2. ETHYL ALCOHOL PRODUCTION

Industrial production of ethanol by fermentation is a multi-stage process and includes: initial raw material preparation, hydrolysis and saccharification, detoxification (in the case of lignocellulosic biomass), fermentation, distillation and rectification, ethanol dehydration/drying, as well as the management of by-products and waste (Figure 1).

The enzymes produced by yeast in the process of alcoholic fermentation facilitate the decomposition of carbohydrates into ethyl alcohol and carbon dioxide. For example, the alcoholic fermentation of glucose proceeds according to the reaction:



A mash with alcohol concentration of up to 18% is obtained in the fermentation process (the yeast perishes at higher concentration). The concentration of alcohol is modified by distillation, the product of which is 90% ethanol is referred to as raw spirit, which is then rectified to obtain an azeotropic mixture of water and ethanol, with about 96% ethanol concentration. Ethanol used as a fuel component should not contain more than 0.3% of water, however, due to the formation of an azeotropic mixture, it is not possible to obtain anhydrous alcohol by conventional distillation. Removal of water from the azeotropic mixture is carried out using adsorption methods on molecular sieves and by pervaporation. The water content in dehydrated ethanol is 50 to 2000 ppm, depending on the process conditions.

In domestic conditions, ethanol is the most often produced from grains and potatoes. In the USA, Canada and China, the primary raw material is corn. The largest amount of ethanol production in the world (about 60%) comes, however, from the processing of sugar cane. This raw material is used for example in Brazil. Raw materials for the production of bioethanol can generally be divided into three groups [1]:

- containing sucrose: sugar cane, beetroots and sugar sorghum and certain fruits,
- containing starch: wheat, rye, barley, potatoes, maize, rice, cassava,
- lignocellulosic biomass: energy crops, by-products from agriculture and the wood industry, paper and cardboard being a fraction of municipal waste.

Bioethanol from the raw materials of the last group is a 2nd generation biofuel.

## 3. PROPERTIES OF ETHANOL AS FUEL

The physicochemical properties of ethanol (Table 1), in particular the high octane number, low viscosity and low boiling point, predispose it primarily as fuel for SI engines. The use of ethanol as a fuel brings both benefits and risks (Table 2), the latter being largely related to its impact on some construction materials of vehicles not adapted to be powered by ethanol. It is assumed that the maximum safe ethanol content in gasoline intended for conventional automotive SI engines is 10-15%. The latest edition of the Worldwide Fuel Charter (2013) [20] recommends not exceeding the level of 10%. Fuels with higher ethanol content can be used for the so-called FFV (*Flexible Fuel Vehicles*), i.e. vehicles that are factory-adapted for the use of this type of fuel. These vehicles are equipped with a fuel composition sensor and can be fuelled with an ethanol-gasoline mixture with any range of changes between the content of these two components. Several European car manufacturers offer FFV versions of their passenger cars (Table 3).

Table 1. Properties of ethanol as engine fuel [5]

Parameter		Ethanol	Gasoline 95	
Density at 20°C	kg/m <sup>3</sup>	789	750	
Research octane number	–	109	> 95	
Motor octane number	–	90	> 85	
Heat of evaporation	kJ/kg	841	330	
Heating value	MJ/kg	26.8	43.5	
	MJ/dm <sup>3</sup>	21.2	31.8	
Stoichiometric air-fuel mixture	kg <sub>air</sub> /kg <sub>fuel</sub>	9,0	14,3	
Distillation	°C	78	40 – 215	
Flash-point	°C	13	– 43	
Kinematic viscosity at 40°C	mm <sup>2</sup> /s	1.2	0.5	
Elementary composition	% m/m			
		C	52.2	84.8
		H	13.0	13.3
		O	34.8	2.4

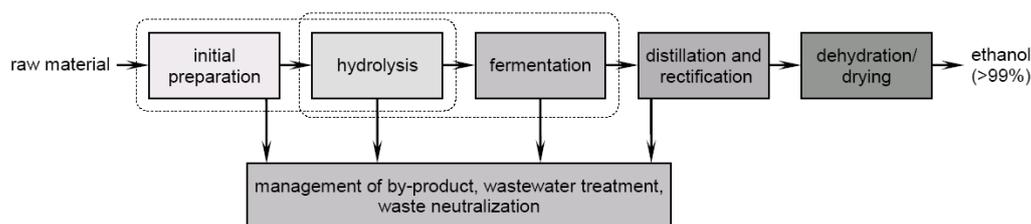


Fig. 1. Step by step processes and operations of ethanol production [6]

Table 2. Technical and operational advantages and risks associated with the use of ethanol as motor fuel [9]

Advantages	Risks
<ul style="list-style-type: none"> <li>high octane number allowing the increase of compression ratio → engine efficiency increase,</li> <li>CO, HC and PM emissions reduced or maintained at the current level,</li> <li>reduction of CO<sub>2</sub> emissions (partial or complete closure of the CO<sub>2</sub> cycle chain),</li> <li>reduction of benzene and other aromatics emissions,</li> <li>lower ozone formation potential than for pure gasoline,</li> <li>lower toxicity than pure gasoline,</li> <li>better flammability than pure gasoline, allowing the alcohol-air mixtures to be leaner, which may result in a slightly higher overall engine efficiency,</li> <li>higher flame propagation speed (by about 20-30%), which has the same effect as above and gives the possibility of obtaining increased engine speed,</li> <li>high heat of evaporation → "internal" cooling of the engine.</li> </ul>	<ul style="list-style-type: none"> <li>high emission through evaporation,</li> <li>smaller particle sizes created in the combustion process (more harmful particles),</li> <li>lower calorific value → increased fuel consumption,</li> <li>difficult engine start at low temperatures, due to low vapor pressure and high latent heat of ethanol evaporation,</li> <li>acetaldehyde formation in the combustion process, which is suspected of having carcinogenic properties,</li> <li>low lubricity → reduced durability of fuel injection elements,</li> <li>corrosive effects on metals: zinc, lead, aluminum, brass and steel without coatings; stainless steel and bronze are sufficiently resistant,</li> <li>damaging impact on some elastomers (gaskets, fuel lines, etc.) and plastics (e.g. polyamide, PVC, etc.),</li> <li>mixture instability, it stratifies under the influence of even small amounts of water or moisture from the air, it is necessary to use stabilizers or emulsifiers,</li> <li>ethanol does not burn visibly, which increases the fire hazard,</li> <li>unburned ethanol reacts in the catalytic reactor, causing an unpleasant, acetic smell of exhaust gas,</li> <li>the mixture is electrically conductive → electrochemical corrosion, fire hazard,</li> <li>some detergent additives for gasolines do not work in the presence of ethanol or even show the reverse effect – increase in the amount of deposits.</li> </ul>

Table 3. Selected FFV models commercially available on the European market [11]

FFV Vehicle Brand	Country
Audi A3 1.6e e-power (E85) Audi A4 2.0 TFSI	Sweden
Citroën C3 Flex Citroën C4 1.6/2.0 BioFlex Citroën C5 2.0 BioFlex	Sweden, Benelux, France, Switzerland
Dacia Duster 1.6 16v (E85) Dacia Logan MCV 1.6 16v Hi-Flex (E85) Dacia Sandero 1.6 16v Hi-Flex (E85)	Sweden
Ford Focus Ford C-Max Ford Mondeo Ford S-Max Ford Galaxy	Austria, Denmark, France, Germany, Ireland, Holland, Poland, Spain, Sweden, Switzerland, UK
Peugeot 307 1.6/2.0 BioFlex Peugeot 308 1.6/2.0 BioFlex Peugeot 407 2.0 BioFlex	Sweden, Benelux, France, Switzerland
Renault Clio III 1.2 16v Eco2 Renault Mégane 1.6 16v Eco2 Renault Kangoo 1.6 16v 105	Sweden, Benelux, France, Switzerland
SEAT Leon MultiFuel 1.6 MPI (E85) SEAT Altea MultiFuel 1.6 MPI (E85) SEAT Altea XL MultiFuel 1.6 MPI (E85)	European market
Škoda Octavia MultiFuel 1.6 MPI (E85)	Sweden, Benelux, France, Switzerland
Volvo C30 1.8F Volvo S40 1.8F Volvo V50 1.8F Volvo V70 2.0F Volvo V70 2.5FT Volvo S80 2.0F Volvo S80 2.5FT	European market
Volkswagen Golf and Golf Plus Volkswagen Jetta	Germany, Sweden, Benelux and Switzerland

Ethanol is also considered as fuel for future high-performance engines [5, 16]. Its parameters, such as high octane number and a large evaporation heat, which contribute to the effective cooling of the cylinder fuel mixture, are particularly desirable in high-performance engines. An engine designed for ethanol fuel may have a higher compression ratio, thus significantly improving the overall efficiency under low and medium load, a similar effect relates to the accelerated ignition.

#### 4. VARIANTS OF USING ETHANOL AS FUEL IN POLAND

In Poland, it is legally permissible to produce and sell ethanol fuel in three variants:

- as a biocomponent of gasoline in an amount up to 5% (v/v),
- as a biocomponent of gasoline in an amount up to 10% (v/v),

(c) as a fuel component of E85, which is a mixture of motor gasoline and ethanol, in which the ethanol content ranges from 70 to 85% (v/v).

Gasolines containing up to 10% of ethanol are classified as conventional fuels. The quality requirements that apply to them are listed in the Regulation of the Minister of Economy of 9 October 2015 on quality requirements for liquid fuels. There is a separate regulation that regulates the quality of bioethanol used as a component of these fuels (Table 4). E85 fuel is classified as biofuel. The quality requirements that apply to it are described in the Regulation of the Minister of Energy of May 25, 2016 regarding quality requirements for liquid biofuels. In that regulation, E85 fuel is formally called "motor gasoline containing from 70% to 85% bioethanol, used in vehicles equipped with spark-ignition engines adapted to the combustion of this liquid biofuel". The ethanol used to produce the E85 fuel must meet the requirements set out in Table 4. Despite the legal possibilities neither E10 (with a 10% ethanol content) nor E85 fuel can be found commonly available at fuel stations in Poland.

Table 4. Quality requirements for bioethanol used as a fuel biocomponent [12, 13]

Properties	Unit	Range	
		minimum	maximum
The content of ethanol and higher saturated alcohols	% (m/m)	98.7	–
The content of mono-saturated alcohols (C3 – C5)	% (m/m)	–	2.0
Methanol content	% (m/m)	–	1.0
Water content	% (m/m)	–	0.300
The content of inorganic chlorides	mg/kg	–	6.0
Copper content	mg/kg	–	0.100
Total acidity (expressed as acetic acid content)	% (m/m)	–	0.007
Appearance		clear and transparent	
Phosphorus content	mg/l	–	0.15
The content of dry residue after evaporation	mg/100 ml	–	10
Sulfur content	mg/kg	–	10.0
Electric conductivity	$\mu\text{S}/\text{cm}$	–	2.5
Sulphate content	mg/kg	–	4

## 5. ECOLOGICAL ASPECTS OF USING ETHANOL AS MOTOR FUEL

The negative impact of automotive air pollution on human health has been proven in many research projects, such as for example [17]. In ecological terms, the advantage of ethanol-powered vehicles over conventional ones stems from the possibility of vehicles being partially or completely (E100) powered with a renewable fuel. The emission level of the legally limited exhaust emissions from modern FFVs is similar regardless of the fuel used (Figure 2).

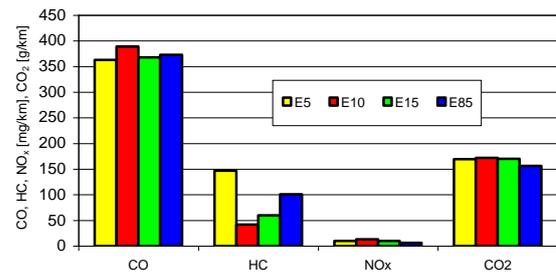


Fig. 2. Exhaust emission from an FFV Euro 5a passenger car (direct injection SI engine, TWC reactor) powered by various mixtures of gasoline and ethanol [18]

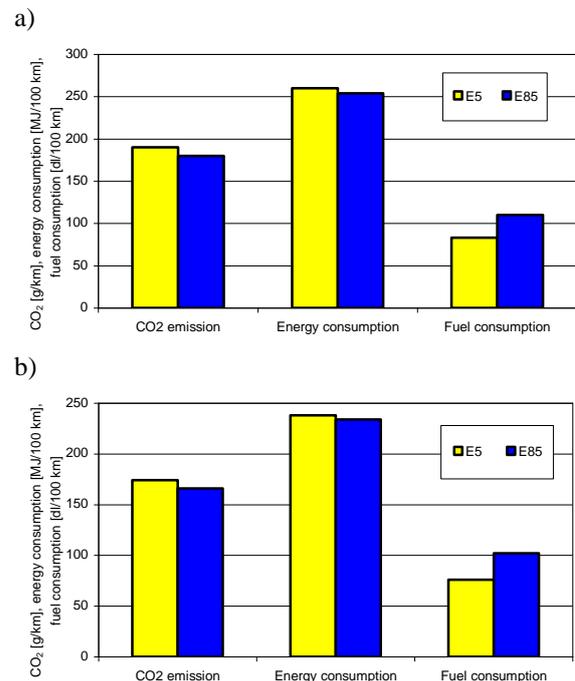


Fig. 3. CO<sub>2</sub> emissions, energy consumption and fuel consumption in the NEDC cycle for FFVs fueled with gasoline (E5) and E85 fuel; a) a Euro 5 passenger car with a 132 kW SI GDI engine, b) a Euro 4 passenger car with a 92 kW SI MPI engine [3]

Due to the lower calorific value of ethanol, FFVs fueled with E85 are characterized by about 30% higher road fuel consumption than when fuelled with conventional gasoline. However,

energy consumption is very similar when using both fuels, and CO<sub>2</sub> emissions is even lower for E85 (Figure 3) due to the more favorable hydrogen-carbon ratio in the ethanol molecule.

Extensive tests of FFVs' fuel consumption were carried out by the United States Environmental Protection Agency (EPA). The test results of these vehicles are the most comprehensive data available for the comparison of gasoline and E85 fuel efficiency. For the 2007 year, 24 different models from 5 manufacturers were designated FFVs. Within these 24 models, there were 76 different drivetrain/body-style variants tested for gasoline and E85 fuel economy. Table 6 presents these results. The mean fuel economy of E85 in city driving was 73.42% that of gasoline. In highway driving, the mean fuel economy was 73.4% that of gasoline. The EPA also produces a mean fuel economy by averaging city and highway fuel economy, with a 55% city/45% highway weighting. By this measure, the ratio of E85 to gasoline fuel economy was also 73.4% [14].

As the ethanol content in fuel increases, the content of harmful aromatic hydrocarbons in fuel decreases. Hence, decreases also emissions of aromatics in exhaust gas. According to [15] the total aromatic hydrocarbon emission is several times lower for an E85 powered vehicle than for a gasoline-powered vehicle (table 5).

Ethanol in its pure form is used very rarely as fuel for compression-ignition (CI) engines. There is in principle only one manufacturer on the automotive market that offers ethanol-powered CI engines, namely Scania. These engines have a high compression ratio (28) and require a special ED95 fuel. It is a mixture of 95% ethanol and a 5% package of additives improving, among others the ability of the fuel to self-ignite and its lubricity. The high compression ratio alone does not ensure proper ignition of the ethanol [10]. Scania's ethanol-powered CI engines are mainly used in city buses. Although this solution has been present on the market for over 20 years, less than one thousand ED95 buses have been manufactured so far, mainly for the Swedish market. In Poland, several buses powered by ED95 were operated at MZK Słupsk. After a few years, the carrier withdrew from this solution, due to high operating costs among other reasons. As shown by the data published in [10], the EEV (*Enhanced Environmental Friendly*

*Vehicle*) class bus fuelled with ED95 fuel has admittedly exhaust emissions similar to the conventional EEV bus fuelled with diesel fuel but also about 7% higher energy consumption.

Table 5. Emissions of aromatic compounds over the FTP-75 cycle for vehicles fuelled with fuels containing ethanol [15]

Nissan passenger car emissions [mg/km]				
	Benzene	Toluene	Xylenes	Total aromatics
Gasoline	4.08	5.23	5.30	18.96
E10	4.35	4.75	5.21	19.43
E45	1.14	1.20	1.44	5.05
E85	0.31	0.31	0.53	1.68
GM pick-up emissions [mg/km]				
	Benzene	Toluene	Xylenes	Total aromatics
Gasoline	1.40	3.45	3.34	11.00
E10	1.17	3.01	3.70	11.38
E45	0.51	1.40	0.99	4.08
E85	0.37	1.23	0.77	3.15

## 6. CONCLUSIONS

Ethyl alcohol has been used for many years as a few percent additive to regular gasoline. Its valuable feature, both in the past and today, is increasing the octane number of fuel. In the era of using advanced catalytic exhaust aftertreatment systems, the effect of ethanol on toxic exhaust emissions is less important. At present, the main advantage of ethanol in the environmental aspect is the fact that it is a renewable fuel that leads to a reduction in CO<sub>2</sub> emissions and lower dependence on fossil fuel resources. It is also definitely less toxic and more readily biodegradable than gasoline. Despite the legal and technical possibilities, in Poland and most other countries the market of vehicles powered with neat ethanol or mixtures with a high ethanol content is not developed. FFVs have a significant market share in only a few countries around the world. At the same time, work is being carried out on fuels for future engines, including HCCI engines, for which ethanol is also considered as potential fuel component. The production of ethanol is still mainly based on the use of raw materials from edible plants containing

Table 6. Summary statistics of EPA FFV fuel economy tests [14]

	City			Highway			Average		
	Gasoline	E85	Ratio	Gasoline	E85	Ratio	Gasoline	E85	Ratio
<b>Mean</b>	14.9	10.9	73.4%	19.8	14.6	73.4%	17.1	12.6	73.4%
<b>Minimum</b>	13.1	9.1	66.9%	16.7	12.4	67.6%	14.7	10.8	68.3%
<b>Maximum</b>	21.8	15.8	81.3%	31.2	23.4	81.5%	25.8	19.2	81.4%

Notes: Nominal values are EPA estimated miles travelled per gallon consumed. 'Ratio' is the ratio of E85 fuel economy to gasoline fuel economy. 'Average' is the average of 'City' and 'Highway' weighted 55% 'City' and 45% 'Highway'. N = 76 total vehicles tested.

sucrose or starch. The technologies of ethanol production from non-food raw materials, mainly from lignocellulosic complexes, developed for about last 20 years, have still not had a significant share in this fuel production market. Although ethanol remains a very important component of fuels for SI engines, the scale of its use as an independent motor fuel is growing slowly. It also seems that the coming years will not bring a significant change in this field.

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