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Application of alcohols to dual – fuel feeding the spark-ignition and self-ignition engines

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ABSTRACT

This paper concerns analysis of possible use of alcohols for the feeding of self - ignition and spark-ignition engines operating in a dual- fuel mode , i.e. simultaneously combusting alcohol and diesel oil or alcohol and petrol . Issues associated with the requirements for application of bio-fuels were presented with taking into account National Index Targets , bio-ethanol production methods and dynamics of its production worldwide and in Poland.

The considerations are illustrated by results of the tests on spark- ignition and self- ignition engines fed with two fuels : petrol and methanol or diesel oil and methanol, respectively. The tests were carried out on a 1100 MPI Fiat four- cylinder engine with multi-point injection and a prototype collector fitted with additional injectors in each cylinder. The other tested engine was a SW 680 six- cylinder direct- injection diesel engine. Influence of a methanol addition on basic operational parameters of the engines and exhaust gas toxicity were analyzed. The tests showed a favourable influence of methanol on combustion process of traditional fuels and on some operational parameters of engines. An addition of methanol resulted in a distinct rise of total efficiency of both types of engines at maintained output parameters (maximum power and torque). In the same time a radical drop in content of hydrocarbons and nitrogen oxides in exhaust gas was observed at high shares of methanol in feeding dose of ZI (petrol) engine, and 2-3 fold lower smokiness in case of ZS (diesel) engine. Among unfavourable phenomena, a rather insignificant rise of CO and NOx content for ZI engine, and THC and NOx – for ZS engine, should be numbered. It requires to carry out further research on optimum control parameters of the engines. Conclusions drawn from this work may be used for implementation of bio-fuels to feeding the combustion engines.

Keywords: dual-fuel engine, alcohol, share of methanol, overall efficiency , toxicity

Introduction

Necessity of using bio-fuels results from the requirements of National Index Targets (NCW) in which a gradual rise in share of reproducible fuels in overall amount of engine fuels, is assumed. According to a Polish Ministry Council's act concerning the NCW, dated 20.07.2013, share of bio-fuel energy should reach 8,5 % in 2018, Fig. 1. It requires to introduce many changes in agricultural production industry, to rise investment expenditures for development of bio-fuel production works and to develop new fuel supply technologies for engines.

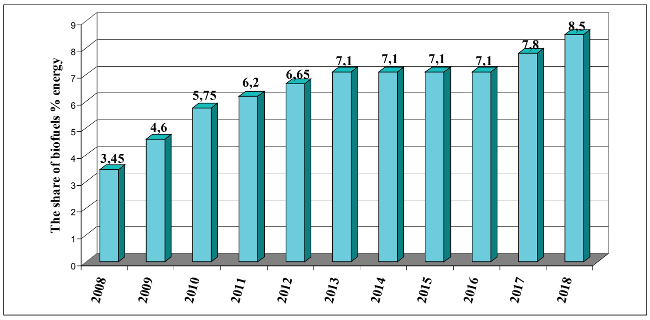


Fig. 1. Time rise in share of bio-fuels , acc. the NCW (National Index Targets)

Alcohols and esters of unsaturated fatty acids belong to the basic bio-fuels, the first group is applicable mainly to spark ignition engines and the other – to diesel engines. Primary alcohols , i.e. methanol and ethanol can be produced from bio-mass which is a reproducible source of energy available in a very large quantity. In the nature bio-mass undergoes natural decomposition into carbon dioxide (CO_2) and methane (CH_4), both numbered among greenhouse - effect gases. However, due to the fact that bio-mass decay processes are natural, emission of CO_2 and CH_4 is not considered harmful. Exploitation of bio-mass and its conversion into alcohols and then combustion in engines results in CO_2 emission to atmosphere, which is then consumed in photosynthesis process for production of biomass. In effect, use of bio-fuels may be considered a zero - emission process, in the aspect of CO_2, and that which additionally lowers natural emission of CH_4 during decay processes.

Combustion of methanol and ethanol produces in effect carbon dioxide and water and the process runs according to the reaction as follows :

$$CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2 + 2H_2O \quad (1)$$

$$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O \quad (2)$$

Mass share of carbon atoms in molecule of alcohols is lower in relation to traditional fuels and amounts to 0,375 for methyl alcohol and 0,520 for ethyl alcohol , whereas for petrol and diesel oil the ratio reaches 0,845 ÷ 0,850 approximately. However when differences in calorific values are taken into account , the gaining of the same energy amount from alcohols results in only a little lower CO_2 emission (by about 2 %) in comparison to petrol, Fig. 2. Alcohols, due to their perfect properties, first of all high octane number, high vapour heat, high combustion velocity, can be easily used both in spark ignition (ZI) engines (as only fuel or an addition to traditional fuels) and self- ignition (ZS) engines as an addition burned simultaneously with diesel oil.

This paper presents a proposal of feeding ZI and ZS engines by using a dual - fuel mode and shows some results of the tests conducted on the spark - ignition engine Fiat 1100 MPI and the self-ignition engine SW 680.

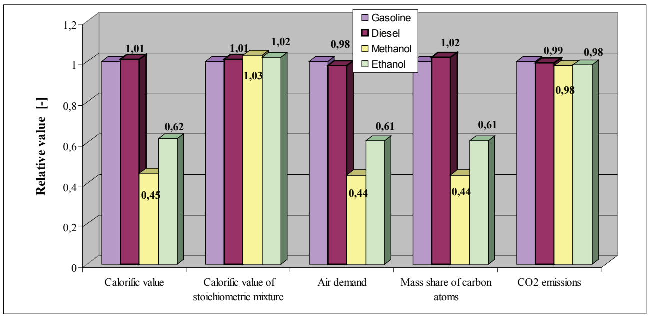


Fig. 2. Comparison of selected properties of liquid fuels in relation to petrol (gasoline) (for petrol the relative indices are equal to 1,0)

Production of alcohols

Alcohols are chemical organic compounds which contain one or more OH hydroxyl groups connected with carbon atoms. The simplest alcohols known to people for thousands of years contain one OH group and are of a general formula: $C_nH_{2n+1}OH$. The following kinds belong to this group:

- methanol CH3OH – methyl alcohol,
- ethanol C2H5OH – ethyl alcohol,
- propanol C3H7OH – propyl alcohol,
- butanol C4H9OH – butyl alcohol.

From the point of view of engine fuels, the two first, methanol and ethanol, especially the second which can be produced from biomass in large quantities by using technologies known for centuries, are most important. Anhydrous ethanol may be used as an only fuel E100 or as an addition to petrol of the kinds: E15, E20, E80. The remaining alcohols such as propanol and butanol are very rarely applied. Ethanol can be produced according to two technological methods schematically shown in Fig. 3 :

- 1st generation method – in the conventional fermentation process of such raw plant materials as corn, potatoes, sugar reed, manioc, maize,
- 2nd generation method – with the use of cellulose, straw, maize cores, and other plant residuals.

Production of bioethanol based on 1st generation process is most often applied today, and research and development projects on 2nd generation biofuels are very intensively conducted worldwide. Full mastering of this technology is expected to be reached till 2030, and 2nd generation ethanol should be more widely used to this date as raw materials for it are commonly available [8].

Ethyl alcohol is obtained in fermentation process consisting in oxygen - free decomposition of sugars by yeasts and their enzymes. In general the alcohol fermentation equation has the following form :

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 + 209{,}3kJ/mol \quad (3)$$

Heat produced during the reaction (3) accelerates this process. As a result, many by-products such as vinegar acid, higher alcohols, esters, glycerine, are obtained. Their content and amount decide on taste merits of alcohol, however it is of no importance for application to fuels because their share is very low. The raw materials used for fermentation may be split into three groups :

- Containing sugar – mellase, sugar reed, fruits, juices,
- Containing starch – potatoes, rye, barley, wheat, maize,
- Containing cellulose – wood, straw, maize cores, plant waste, garbage.

Two first groups of raw materials are used for production of 1st generation bioethanol and edible ethanol; the third group - in production of 2nd generation bioethanol.

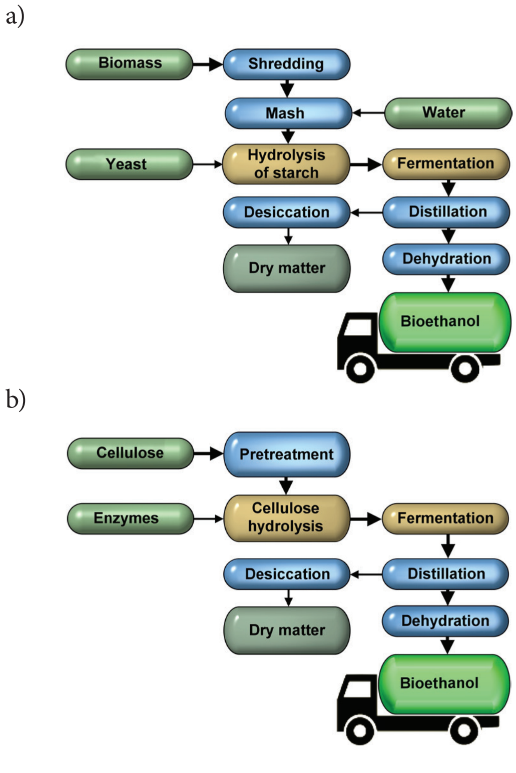
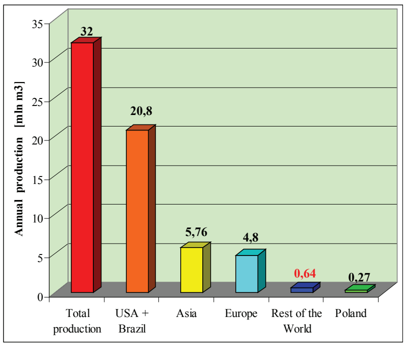


Fig. 3. Schematic diagrams of bioethanol production process: a) 1st generation bioethanol, b) 2nd generation bioethanol .

In fermentation process of 2nd generation ethanol, glucose obtained from enzymatic hydrolysis of cellulose contained in plant products, is used. They are composed of cellulose in about 60% , which, due to a large amount of biomass available worldwide, shows that significant supply of cellulose- based ethanol may be expected in the future. For this reason the 2nd generation production technologies are intensively developed in such countries as : Sweden, Norway, Finland, USA, Brazil and Canada. In present, production cost of cellulose ethanol is over twice higher than of that traditionally produced. However , development of 2nd generation bioethanol should lower the relations in a near future.

In present, USA and Brazil, leaders in alcohol production , deliver almost 65% of ethanol amount produced in the world, Fig. 4. European countries deliver about 15% of the ethanol produced in the world , but this share has significantly increased during last years. [7].

a)



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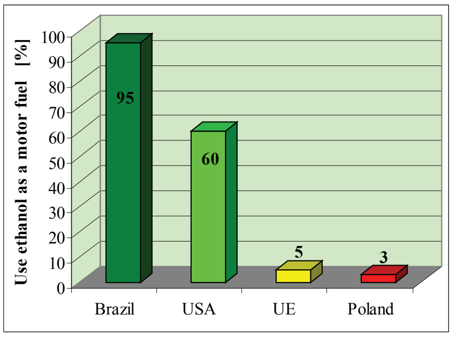


Fig. 4. Comparison of production and use of alcohols in selected countries worldwide: a) world production of ethanol in 2009 [9, 10, 11], b) use of ethanol as a fuel for engines [9, 12, 13]

In Brazil and USA a prevailing part of produced ethanol is intended for combustion as fuels (95 % in Brazil and 60 % in USA). For comparison, in European countries this part amounts to about 5 %, and in Poland to 3 % only, Fig. 4b.

Production of bioethanol in Poland does not satisfy demands of National Index Targets, and its participation in the whole quantity of used fuels is rather low, Fig. 5. Despite investments made in biofuel production industry within last ten years, rise in bioethanol production is rather low, and its level varies in particular years, Fig. 5a. It seems that without any radical change of regulations in this question and a decisive state intervention, Poland will gradually lag behind other EU countries where a big pressure is applied to production of bioethanol.

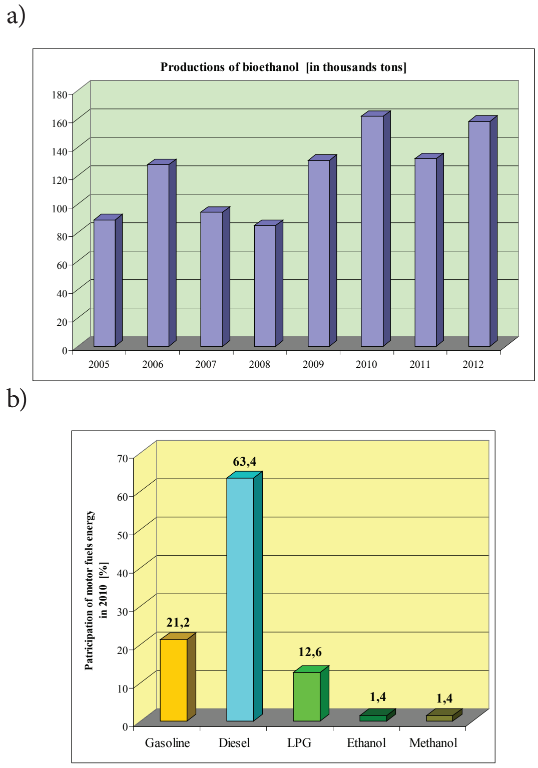
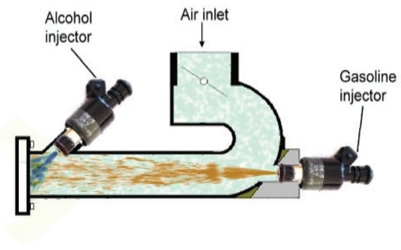


Fig. 5. Dynamic growth of bioethanol production and use of alcohols in Poland : a) production of bioethanol in Poland in the years 2005÷2012 (acc. [7]), b) energy participation of engine fuels used in Poland in 2010 [14]

Dual-fuel feeding the spark - ignition engines with the use of alcohol

In contemporary ZI engines multi-point injection of light fuels is used (indirect injection to inlet collector and direct one to combustion chamber). This injection system was assumed to select a test engine and prepare it to dual-fuel feeding mode. The tests were carried out on a 1100 MPI Fiat, four-cylinder, spark-ignition engine with multi-point fuel injection system. In order to adjust the engine to dual-fuel feeding mode a prototype inlet collector with an additional injector in each cylinder, was applied, Fig. 6a. Methanol was injected close to inlet valve through original injectors of the engine. Petrol, during work of engine in dual-fuel mode, was injected by additional injectors placed in some distance from the inlet valve. Such injection method was aimed at improving methanol evaporation, especially during engine work under low load. The applied feeding system made it possible to operate with petrol only (during starting and heating the engine), with methanol only during work under maximum load, and in dual – fuel mode at an arbitrary selected share of alcohol. The prototype feeding system was subjected to wide comparative and optimizing tests. In each work conditions the engine operated correctly and did not show any possible disturbance resulting from vibrations or indicator - controlled combustion process. Tab. 1 and Fig. 6b contain technical data of the engine.

a)



b)

Tab. 1. Technical data of 1100 MPI Fiat engine

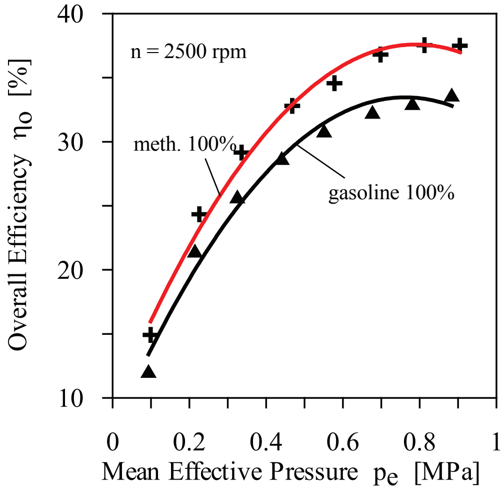
Type of engine	Fiat 1100 MPI
Cylinder bore x stroke	70 x 72 mm
Stroke volume	1108 cm^3
Compression ratio	9,6
Rated power/ rotational speed	40 kW/5000 rpm
Torque/ rotational speed	88 Nm/3000 rpm

Fig. 6. Feeding system and technical data of 1100 MPI Fiat engine used for the tests: a) Scheme of the prototype inlet collector; b) Technical data of the tested engine

Comparison of overall efficiency of the engine shown in Fig. 7 indicates that efficiency of the engine fed with methanol only was high within the whole range of changes in loading and rotational speed. Differences in efficiency grow along with engine load rising, and in the range of medium and maximum load values the absolute differences amount to 3,5%, which results in a relative rise in efficiency ranging from 10 to 16 %, deciding on operational consumption of energy. It is worth mentioning that the results were obtained without any optimization of ignition advance angle.

It seems that one of the causes of engine efficiency growth may be a greater combustion velocity of methanol, which leads to lower heat loss per cycle. The other cause is a higher evaporation heat of methanol which makes dose temperature lower during compression and at the beginning of combustion , that leads to lower mechanical losses during compression phase and in consequence to a higher efficiency. An additional reason may be a greater contraction factor of methanol in comparison to petrol (1,061 for methanol and 1,045 for petrol), which results in that from combustion of stechiometric mixture of methanol a greater number of moles of exhaust gas is produced, which additionally rises cylinder pressure and leads to torque rising. Further increase of engine work parameters can be obtained by rising compression ratio and optimizing engine control.

a)



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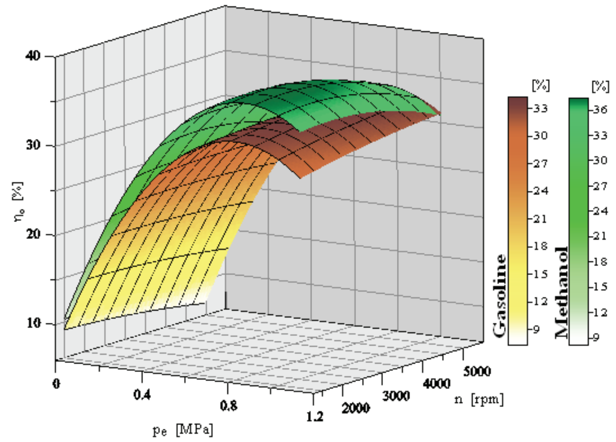


Fig. 7. Comparison of overall efficiency of 1100 MPI Fiat engine in case of feeding with petrol or methanol

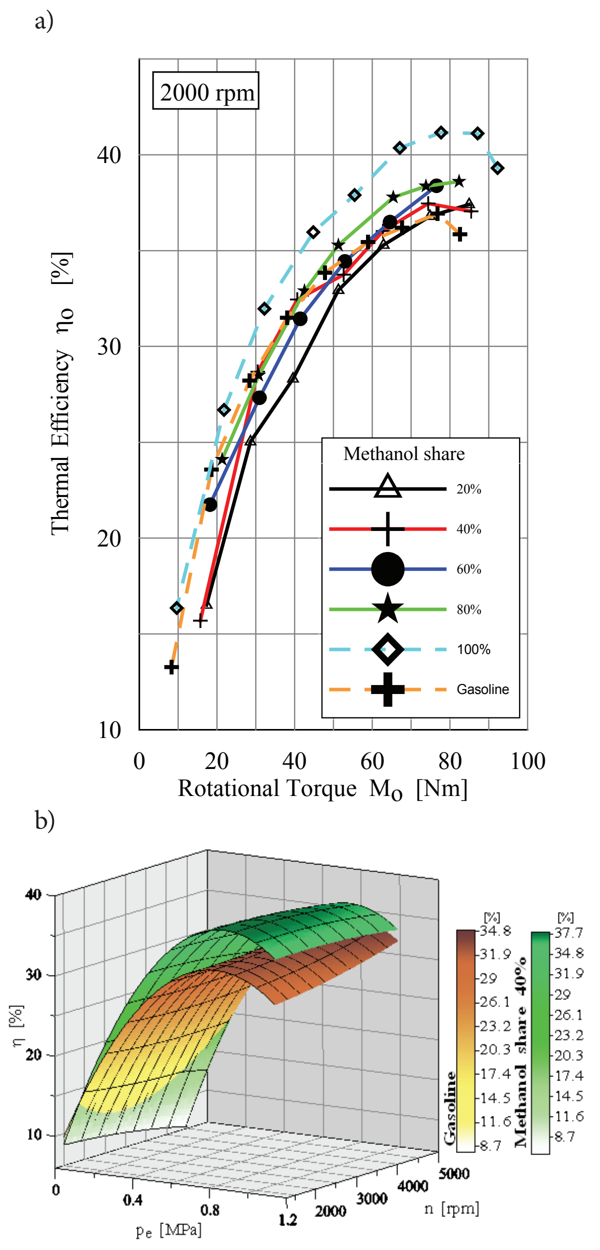


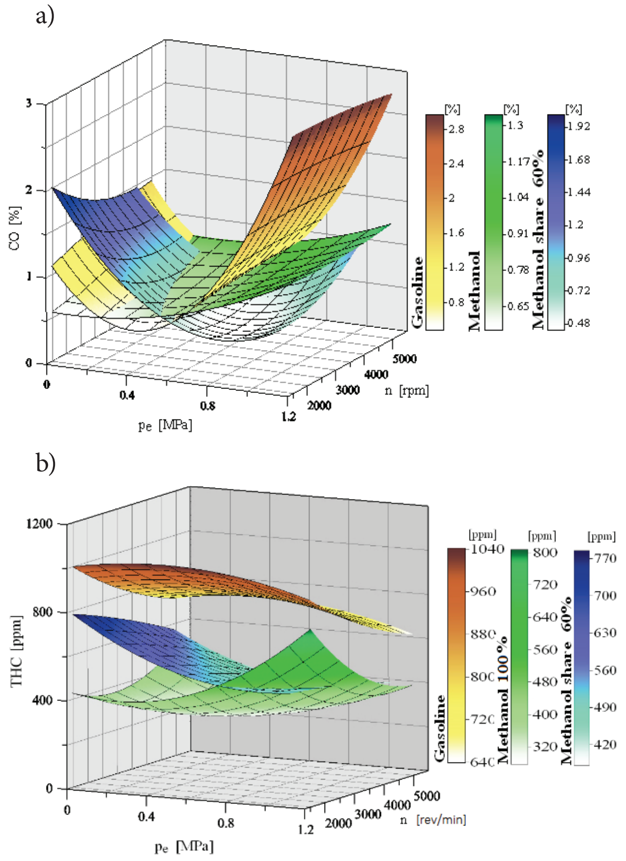
Fig. 8. Comparison of overall efficiency of 1100 MPI Fiat engine in case of feeding with petrol or two fuels at various shares of methanol

For small addition of methanol (20 % share) and low engine load the overall efficiency of the dual-fuel fed engine was lower than in case of traditional feeding, Fig. 8. It seems that the fact of petrol injection through the additional injector placed in some distance from the inlet valve, affected the obtained results. As a result, conditions for producing petrol-air mixture were worsened (lower temperature, influence of fuel film formed on inlet channel walls). It may affect work steadiness in particular cylinders and increase fuel consumption and emission of noxious components of exhaust gas. In effect, the favourable influence of combustion of methanol, proportional to its dose share , did not compensate the loss in efficiency resulting from worsened conditions for evaporation of petrol and mixing it with air. It could be probably possible to improve efficiency of engine under low load and at a low share of alcohol by applying a primary mixer of alcohol with petrol as well as by injecting the mixture through original injectors or by implementing a double injector used in dual-fuel, self-ignition engines.

At greater methanol shares efficiency of the engine was improved almost in the whole range of changes in its operational parameters, as shown in Fig. 8b. It suggests that even at unchanged compression ratio operational consumption of energy at dual-fuel feeding will be lower than that at feeding only with petrol.

Combustion of methanol, both as the only fuel and in mixture with petrol, affects content of toxic components in exhaust gas from ZI engine. The influence depends on alcohol share and engine load. At low methanol share values and low engine loads a greater content of CO was observed in comparison with that in case of feeding with petrol only, Fig. 9a. It was probably caused by decreased temperature due to presence of methanol, and worsened fuel evaporation resulting from some distance of the petrol injector. However at higher engine loads CO content, both in case of feeding with methanol only and in dual-fuel mode, was distinctly higher in comparison to that in case of petrol.

Combustion of methanol favourably affects emission of summary THC hydrocarbons, Fig. 9b. At dual-fuel feeding mode a distinct tendency to lowering THC emission may be observed and the lowering grows along with increasing share of methanol in combustion mixture. At feeding with methanol only, THC content was about 2¸2,5 times greater than in case of feeding with petrol.



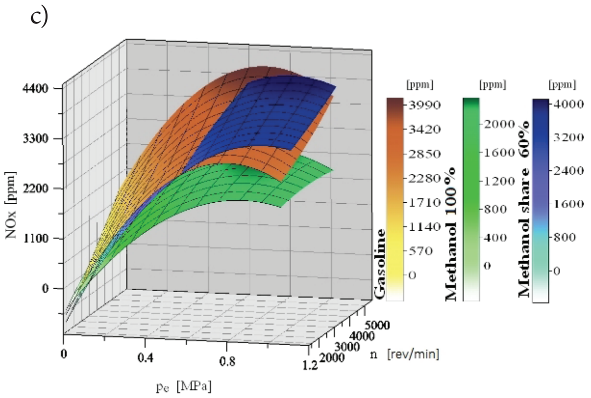


Fig. 9. Comparison of CO, THC and NOx content in exhaust gas from dual-fuel fed engine. Notation of the diagrams : for petrol – blue marked, for methyl alcohol (60% share) – bronze marked , for methyl alcohol only - green marked

Influence of methanol addition to fuel dose on changes in NOx content in exhaust gas is not unambiguous. During feeding with methanol only the lowering of NOx content was observed over entire working area of engine. However, during dual-fuel feeding changes in NOx content depended on engine load, Fig. 9c. In the range of low and medium load values the lowering of NOx content, but at higher loads – a rise of NOx content (by about 10 ÷ 15 %) in relation to feeding with petrol, was observed. By controlling the air excess coefficient it was revealed that at dual-fuel feeding the engine was charged with somewhat poorer mixture in relation to its content in case of feeding with petrol and methanol only. It could cause an increase in NOx content at higher engine loads.

Dual-fuel feeding the self- ignition engines with the use of alcohol

Alcohols have a high self-ignition temperature and low octane number, which makes it impossible to control their self-ignition in engine work conditions. For this reason combustible alcohol - air mixtures always require an external self-ignition source. In self-ignition engines the only possible feeding mode is a dual-fuel system for which a very good source of self-ignition is a dose of diesel oil. In this case, alcohol may serve as a basic energy source or as a small addition to improve diesel oil combustion. Alcohol for self-ignition engines may be delivered in three ways:

- in the form of alcohol vapour mixed with suck- in air (by evaporating alcohol in an evaporator using heat from cooling system or in the form of an aerosol comprising alcohol drops dispersed in air flux),
- by injecting liquid alcohol into inlet collector,
- by injecting alcohol directly to combustion chamber during final combustion phase.

Indirect delivery of alcohols to inlet collector, due to high evaporation heat of alcohols (2,5÷3,3 times higher than that of diesel oil and petrol), results in lowering temperature of suck-in dose, which may unfavourably affect lag of ignition. However, while applying direct injection, high evaporation heat of alcohols, at their high shares, may be used for lowering maximum temperature of a medium during its combustion. For this reason , this feeding mode is most advised, though it requires to apply an additional injector or dual-fuel injectors, which makes engine head construction a little more complex. Research projects on application of alcohols for dual-fuel ZS engines have been carried out by many centres worldwide, including Technical University in Radom, Poland, (see the publications of prof. Luft [1, 2] referring engine feeding with evaporated alcohol, and the publications of prof. Kowalewicz [3, 4, 5] referring application of methanol injection into inlet collector) as well as an external branch of Technical University of Łódź, Poland (see publication of this author [6] where a mixed feeding system for engines was discussed).

Selected results of the tests on a SW 680 self-ignition, slow-suction, six-cylinder engine fed with methanol and diesel oil, are presented below. Technical data of the engine are given in Tab. 2.

Tab. 2. Technical data of SW 680 engine

Parameter	Quantity
Cylinder bore	127 mm
Piston stroke	146 mm
Number of cylinders	6
Stroke volume	11,1 dm^3
Compression ratio	15,8
Rated power	141–148 kW
Rotational speed at rated output	2200 rpm
Combustion chamber	toroidal in piston, direct symmetrical injection

Even a small addition of methanol favourably affects combustion of diesel oil, a main part of energy delivered to engine. In effect, overall efficiency of the engine under full load increases by about 3 ÷ 6 % in relation to a traditionally fed engine, Fig. 10.

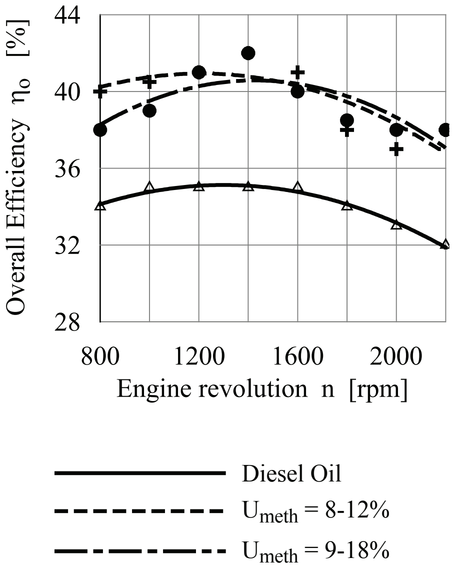


Fig. 10. Comparison of overall efficiency of traditionally- fed SW 680 engine and that dual-fuel fed by using diesel oil and methanol

Increases in overall efficiency of the engine at various shares of methanol are similar within the whole range of changes in rotational speed, while at a higher share, in the range of low rotational speeds, the efficiency increases are lower. It should be stressed that no optimization procedure of injection advance angle was conducted for the tested engine - the angle was constant and equal to 27° of single rotation before reaching upper return point, independently on rotational speed and load of the engine.

It seems that such increase in overall efficiency is associated with higher combustion rate of methanol as compared to that of diesel oil. It results in an increase of temperature of a medium in reaction zones and simultaneously in a greater number of diesel oil ignition spots. The last factor is especially important at maximum engine loads, when, at a complete biggest dose of diesel oil, initial combustion processes play significant role. The greatest changes in overall efficiency of the engine were then observed , Fig. 11.

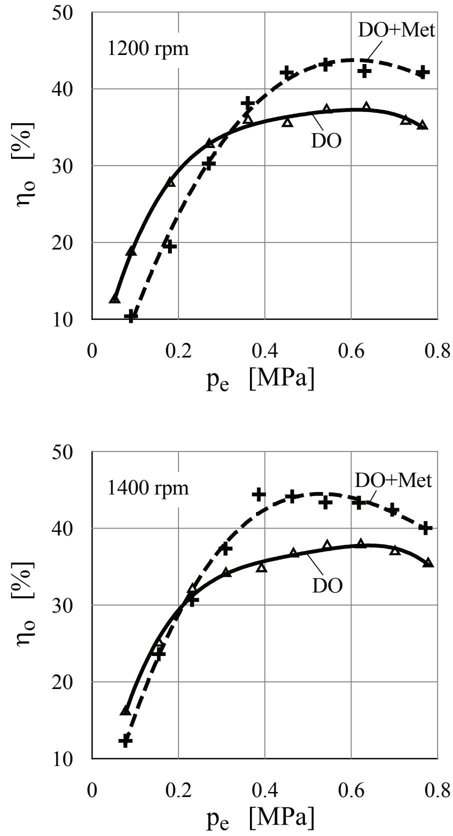
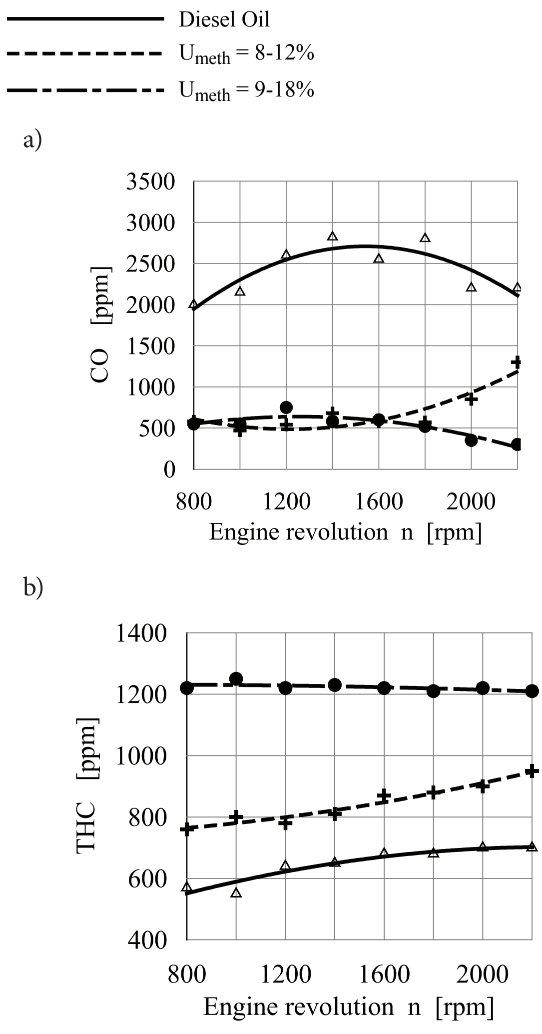


Fig. 11. Comparison of overall efficiency of traditionally- fed SW 680 engine and that dual-fuel fed by using diesel oil and methanol , presented in function of engine load.

In the presented tests a change in engine load was made by lowering diesel oil dose. At constant rotational speed, the selected control system caused methanol share increasing in total amount of energy along with engine load decreasing. In the range of low engine loads it could really affect charge temperature and decrease overall efficiency of the dual-fuel engine in relation to the traditionally fed engine. This is especially visible at the lower rotational speed of 1200 rpm (Fig. 11). For higher rotational speeds the influence of methanol, because of a higher thermal load of engine, is smaller and the overall efficiencies are similar for both feeding modes in the range of low loads. It should be mentioned that at the lowest loads the share of methanol was significant , equal to 44÷50 %, depending on rotational speed , in spite of that the methanol mixture was poor (the air excess coefficient lm > 3,8 ÷ 4,2).

It seems that for combustion of poor methanol mixtures at low engine loads, interaction of liquid fuel jet plays crucial role. This observation is proved by results of the tests presented in Luft's publication [1] where the engine was fed with methanol vapour delivered from a special evaporator placed beyond inlet system (free from fuel evaporation cooling effect on to charge).

In more developed, turbo-charged engines changes in load are usually accompanied with the lowering of charging rate, which may also significantly influence methanol combustion process. It seems that it would be possible to make use from positive effect of methanol combustion also at lower engine loads by applying an appropriate control of charging rate. Additionally, it may be possible to change, if necessary, methanol share along with engine load changing, by applying methanol injection.



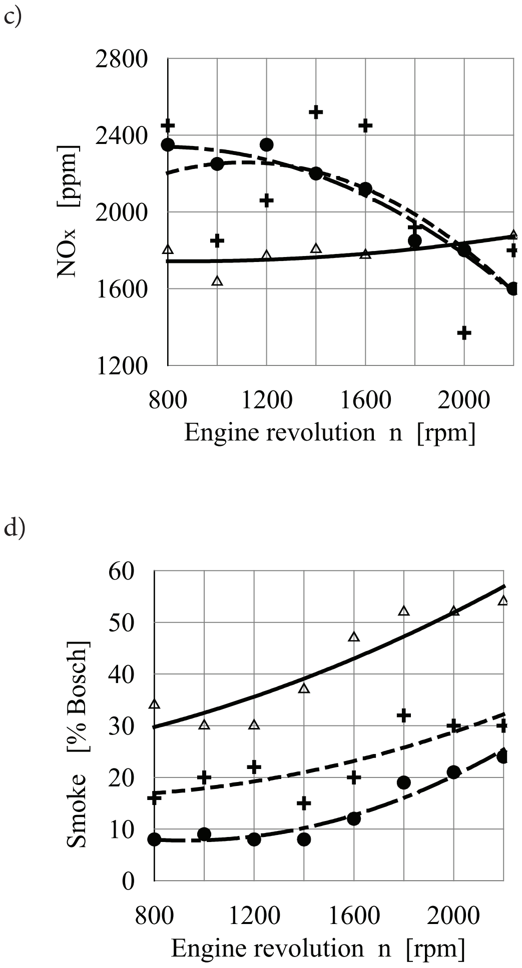


Fig. 12. Comparison of content of components of exhaust gas from SW680 engine fed respectively with diesel oil and two fuels : diesel oil and methanol [6]

Application of methanol addition to ZS slow- sucktion engines results in the significant lowering of exhaust gas smokiness and CO content at maximum engine loads, Fig. 12. However it may lead to a higher content of NOx and not fully burned hydrocarbons.

The lowering of smokiness is associated with the lowering of diesel oil dose and acceleration of its combustion by burning methanol vapour. The process depends on a methanol share in the whole energy dose delivered per cycle. For a lower share of methanol the lowering of smokiness is almost twofold in the whole range of changes in rotational speed. For a higher share of methanol the smokiness lowering was 2,6¸3,0 –fold, which may be used for the lowering of emission of solid particles from engines installed in buses operating in towns with high road traffic. It is worth mentioning that such positive effect may be already reached by a small addition of methanol (or ethanol), while cost of adaptation of engine to dual-fuel feeding mode is rather low in the case in question.

The increased content of hydrocarbons in exhaust gas at mixed feeding mode may be associated with an escape of a part of charge as a result of sheltering the valves, which may be more intensive in charged engines. For this reason, in ZS engines alcohol injection should be applied, preferably directly to cylinders. Research on this problem was carried out by prof. Kowalewicz of Technical University of Radom [3÷5]. It is also worth mentioning that methanol vapour is very toxic , which additionally makes injection systems preferable.

The increased content of NOx in exhaust gas at full engine load (Fig. 12c) is connected with an increased combustion rate of charge in dual-fuel, methanol - fed engine. The greatest differences in NOx content occur in the range of lower rotational speeds (increase by 30%), which decreases along with the speed increasing, while in the range of 2000¸2200 rpm the differences are even lower than in the case of traditional feeding.

Conclusions

On the basis of the performed tests and analyses the following general conclusions may be offered :

- Dual-fuel feeding mode for self-ignition and spark-ignition engines with the use of alcohols is an interesting alternative which makes it possible to increase share of biofuels in total consumption of engine fuels.
- In the case of self-ignition engines alcohol may constitute a basic fuel or serve as an addition to improve combustion of diesel oil. Adaptation of engine to addition of alcohol does not require any wide changes in engine construction and may be introduced both in older engines and contemporary ones. However in both the cases injection of liquid alcohol to inlet collector or directly to cylinders, is preferable.
- Dual-fuel feeding mode in spark-ignition engines makes it possible to use an arbitrary share of alcohol (within the range of 0¸100%) depending on load and thermal state of engine. Its compression ratio may be elevated this way by 1,5¸2,5 units in relation to basic engine. Moreover, at high shares of alcohol , dual-fuel feeding mode does not require to use anhydrous alcohols as it is in the case of mixtures with petrol, as a result production cost of biofuels may be lower.
- Addition of methanol favourably affects combustion process of both petrol and diesel oil and results in the improving of operational parameters and overall efficiency of ZI and ZS engines. It is also possible to reach an increase in maximum effective power and torque at comparable loads (results of the tests are not presented in this paper). The rise in overall efficiency of ZI engine without any correction of compression ratio was equal to 3¸5 % at high shares of methanol , that is equivalent to the relative increase by 10¸16 %. In ZS engine the overall efficiency rise, at maximum loads, was obtained in the range of 3¸6 %, that is equivalent to the relative increase by 8¸17 %. The high relative increases in overall efficiency may contribute to a much lower consumption of energy by engines in operation. Addition of methanol leads to distinct changes in content of exhaust gas components emitted from dual-fuel engines. The following tendencies may be distinguished:
  - concerning ZI engines: the lowering of CO content at higher loads , the significant (2¸2,5 - fold) lowering of

THC content, the lowering of NOx content at higher shares of methanol as well as its rise in some engine operation ranges.

- concerning ZS engines : the significant (2¸3-fold) lowering of smokiness of exhaust gas, the lowering of CO content, the elevating of THC and NOx contents in some engine operation ranges.

It seems that certain unfavourable consequences of methanol combustion in ZI and ZS engines may be mitigated by optimizing control parameters of the engines.

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