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EFFECT OF BIOFUEL E85 COMBUSTION ON FUEL CONSUMPTION IN SPARK-IGNITION ENGINES

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Abstract

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Biofuels represent an alternative source of energy that should gradually decrease our dependence on crude oil. A rapid development of their use in combustion engines is above all the consequence of their very positive balance of emissions. The possibility of use of biofuels in conventional combustion engines is given by their physico-chemical properties. Bioethanol is one of biofuels that can be used in spark-ignition engines. However, because of its lower heating value, it is necessary to change the mixing ratio fuel/air. The aim of this paper is to evaluate the effect of combustion of a mixture of bioethanol with gasoline (in the ratio 85:15) on fuel consumption in the spark-ignition engine. Experimental measurements were performed using a six-cylinder spark-ignition Peugeot engine with the overall volume of 2.946 cm^3, which was equipped with a multi-hole system of indirect injection. Obtained results indicated that the combustion of E85 biofuel markedly increased the reduction of specific fuel consumption (corrected to atmospheric conditions). As compared with gasoline Natural 95, the actual volume consumption of E85 biofuel increased under the maximum engine load in average by 30.4%. In spite of a relatively high consumption of E85 biofuel the total costs associated with running of a modified engine were lower than those of the engine combusting gasoline Natural 95.

biofuel, ethanol, fuel consumption, stechiometric ratio

The extent of air pollution with exhaust gases increases in dependence on growing numbers of automobiles driven by conventional combustion engines. These emissions show a negative effect not only on the environment but also on human health. For that reason the European Union has accepted various norms and standards already since 1992 and these define for manufacturers of motor vehicles the maximum acceptable levels of noxious gases in exhaust gases. These new legislative regulations force engine manufacturers to look for such technical solutions that would enable them to observe the defined limit values. Individual technical measures involve for example use of catalyzers, filters of solid particles, high-pressure injection devices, and/or modified combustion chambers with turbochargers of aspirated air. Another possibility how to reduce production of noxious emissions is associated with a possible change of fuel. Internal combustion engines function mostly on gasoline or diesel fuel, i.e. fuels made of crude oil. Crude oil, however, is one of non-renewable sources of energy and this fact is associated with another problem that concerns the consumption of fossil fuels and covering future needs of the world population. For that reason an increased attention has been paid in recent decades to the so-called biofuels, i.e. fuels made of various sources of the biomass.

Changes in chemical composition of biofuels or, better to say, in ratios between carbon, hydrogen, and other elements (e.g. oxygen), can significantly reduce not only the volume of noxious substances but also of carbon dioxide (CO_2) that is one of final products of the process of complete combustion. To enable the use of these biofuels in conventional engines without any extensive modifications of their construction, it is necessary that their physico-chemical properties would be as much as possible similar to those of petroleum-derived fuels and it can be said that just the bioetanol is one of those products that are the most prospective and suitable for combustion in both spark and compression ignition engines.

Bioethanol (ethyl alcohol) is the product of fermentation that belongs to the group of light alcohols. It is the final product of those fermentation processes, which transform raw materials containing biodegradable wastes and residues, e.g. simple sugars (sugar beet), starch (maize, cereals, and potatoes), or ligno-cellulose biomass (waste materials from wood-processing industry) into utility products (Demirbas, 2009).

The first attempts to use bioethanol as a fuel in piston combustion engines can be dated back to the end of the 19th century. In Czechoslovakia, a compulsory addition of 20% of ethanol into gasoline was ordered by law already in the decade of 1926–1936. Before the World War II, the engine fuel called DYNAKOL (50% of ethanol, 30% of benzen and 20% of gasoline) was available in the domestic market, mainly due to a shortage of gasoline. An increasing efficiency of crude oil extraction (that took place at the beginning of the 20th century) enabled a gradual replacement of ethanol by gasoline. The use of ethanol-gasoline mixtures ceased in 1950s, mainly due to a still cheaper production of gasoline (Trnavský, 2011). At the beginning of the 21st century, however, the launching of the EU biofuel programme resulted in a comeback of ethanol-gasoline mixtures. The approval of the Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 (on the promotion of the use of biofuels and other renewable fuels for the transport) resulted in a creation of preconditions for a gradual re-introduction and increase in the content of biocomponents used in existing conventional fuels. In the Czech Republic, a compulsory addition of 4.1% of ethanol into gasoline was ordered by the Act No. 172/2010 Coll., of 29 April 2010. According to data published by the Czech Association of Petroleum Industry and Trade (ČAPPO), it is now allowed in the European Union to add as much as 5% of ethanol into the gasoline (ČAPPO, 2010). Pure ethanol (or fuel mixtures containing predominantly this light alcohol) are nowadays used only extraordinarily, mainly due to some different properties of this type of car fuel. As compared with gasoline, alcohols themselves have some distinct and indisputable properties that consist in their high octane number and better evaporability. A major disadvantage of light alcohols consists in the fact that (at lower temperatures) they are not sufficiently volatile and this fact significantly influences the starting properties of internal combustion engines. When using pure ethanol, a cool start is possible only at temperatures above 7 °C. This shortcoming is usually solved in such a way that this fuel is mixed with light hydrocarbons or with gasoline. The cold-start capability is than improved and shifts to the zone of start temperatures below zero. In some countries, fuel mixtures containing 85% of ethanol and 15% of gasoline are used under the trade name biofuel E85 (hereinafter mentioned only as E85). To be able to mix it with gasoline, the bioethanol must be either water-free or may contain only small amounts of it (Matějovský, 2005; Vlk, 2006). Properties of denatured spirits used for production of car gasoline's are defined in the standard ČSN 65 6511.

A low fuel efficiency is another disadvantage of lower alcohols. As compared with gasoline, the fuel value of bioethanol is lower by approximately 30% (Tab. I) and this is the reason why it is necessary to change (i.e. increase) the amount of injected E85 into the engine cylinder if we want to preserve a proper course of the combustion process in engines optimized for combustion of petroleum-derived fuels. According to Park *et al.* (2009), the stechiometric ratio of E85 is 1:10 (i.e. 10 kg of air per 1 kg of fuel); this means that the overall need of air is by 4.7 kg lower than in the case of gasoline combustion.

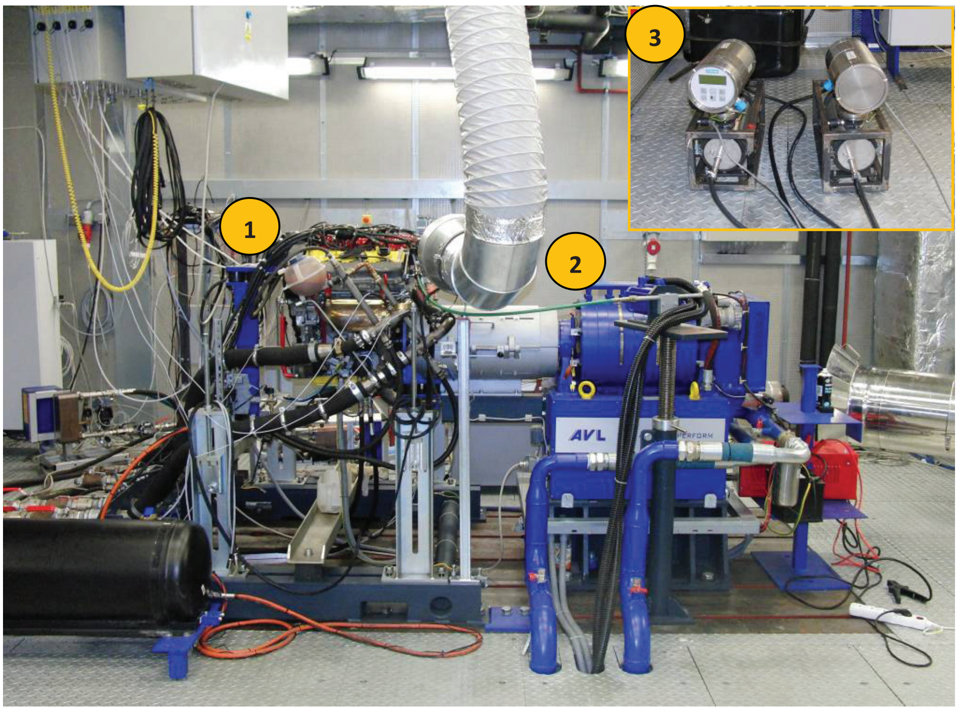
The main objective of this paper is to analyse and evaluate the effect of combustion of E85 on fuel consumption in spark-ignition engines. Basic characteristics of biofuel (E85) and gasoline Natural 95 (hereinafter mentioned only as BA95) are presented in Tab. I.

MATERIAL AND METHODS

Experiments were performed using a six-cylinder spark-ignition Peugeot engine. Technical parameters of the engine are presented in Tab. II.

I: *Fuel properties (Aleiferis et al., 2010)*

Property/Fuel	BA95	E85
Specific density (kg/m^3)	752	784
Energy density (MJ/kg) (25°C)	42–45	28.94
Boiling point (°C)	30–190	84.8
Reid vapour pressure (kPa)	54–60	53.6
Research Octane Number (RON)	95	109.1
H:C	1.86–1.92	2.657
O:C	0	0.411



1: *Laboratory of the engine testing station of the Department of Engineering and Automobile Transport, Mendel University in Brno, 1 – tested engine Peugeot 605 SV 3.0e V6, 2 – dynamometer AVL Alpha 240, 3 – mass flowmeters Coriolis Sitrans FC MassFlo Mass 6000*

II: *Technical parameters of the tested Peugeot engine (manufacturer's data)*

Parameter	Specification
Make	Peugeot
Model	605 SV 3.0e V6
Engine output	142.6 kW at 5,500 rev/min
Engine volume	2,946 cm^3
Bore x stroke	87.0 × 82.6 mm
Compression ratio	9.5
Number of cylinders	6
Cylinder arrangement	V6 60°
Number of valves	24
Injection system	Indirect multi-hole injection

Measurements were performed in the laboratory of the engine testing station of the Department of Engineering and Automobile Transport, Mendel University in Brno (Fig. 1). Measurements were performed according to the ISO 1585 method.

As already mentioned in the Introduction, the stechiometric ratios of engines combusting E85 and BA95 are different. For the sake of a proper course of the combustion process it was therefore necessary to modify the supply of injected fuel by means of different injection nozzles. Because of insufficient flow characteristics of valves occurring at high revolutions, it was necessary to increase at first the fuel pressure from 0.3 to 0.5 MPa. The next step consisted of engine tuning by means of a programmable control unit. Adjusted values involved also the amount of fuel injected into the cylinder at given values of RPM and opening of the throttle valve. The supply of both BA95 and E85 was adjusted in such a way that the engine operated with an air surplus coefficient $\lambda = 1$. Other control variables (e.g. the spark advance setting) remained unchanged and were the same as those of the engine combusting BA95. The programmable control unit was manufactured by the company Magneti Marelli.

To estimate specific consumption values of both fuels under study under different operational regimes of the test engine, graphs of their complete characteristics were elaborated. To do this, measurements of 10 partial characteristics were carried out at different settings of the throttle valve opening (ranging from 10% to 100 %). These measurements were done at different engine revolutions (ranging from 1,500 to 6,000 RPM). Measured values were recorded after 500 revolutions and the measurements were carried out under a static regime (using an eddy current dynamometer); the engine was gradually loaded up to reach the required revolutions and, after the stabilization of measured values, the result was stored in the memory of the computer. Technical data of the dynamometer are presented in Tab. III.

Measurements of fuel consumption were carried out using two differentially connected mass flowmeters Coriolis Sitrans FC MassFlo Mass 6000 (Fig. 1). The accuracy of measured values was 0.1% of the measured value. As far as the other measured values were concerned, the following data were recorded: mass flow of air, fuel

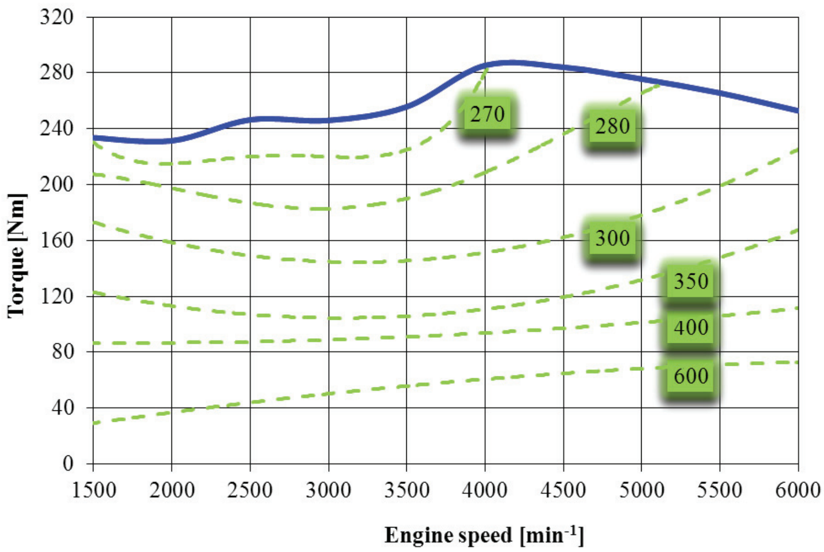
III: *Technical parameters of the dynamometer used*

Parameter	Specification
Type of dynamometer	eddy current dynamometer
Manufacturer	AVL
Name	AVL DynoPerform Alpha 240
Maximum absorption output	240 kW
Maximum torque	600 Nm
Maximum revolutions	10,000 RPM

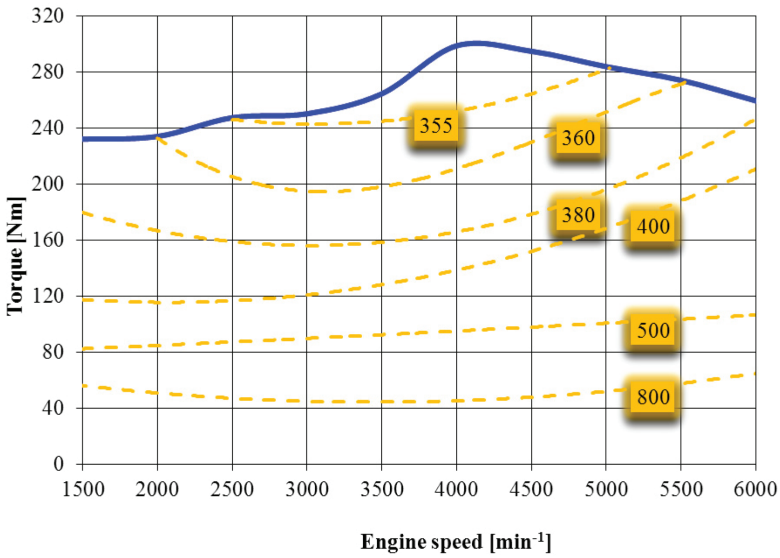
temperature, temperature of engine lubrication oil, temperature of sucked air etc. Last but not least, data about atmospheric conditions of the laboratory were recorded as well. Dyno-measured data were corrected to normal atmospheric conditions. This correction was performed in accordance with specifications of the standard ČSN 30 2008. Measured values were recorded with the frequency of 100 Hz and continuously stored in the memory of the computer installed in the testing station.

RESULTS

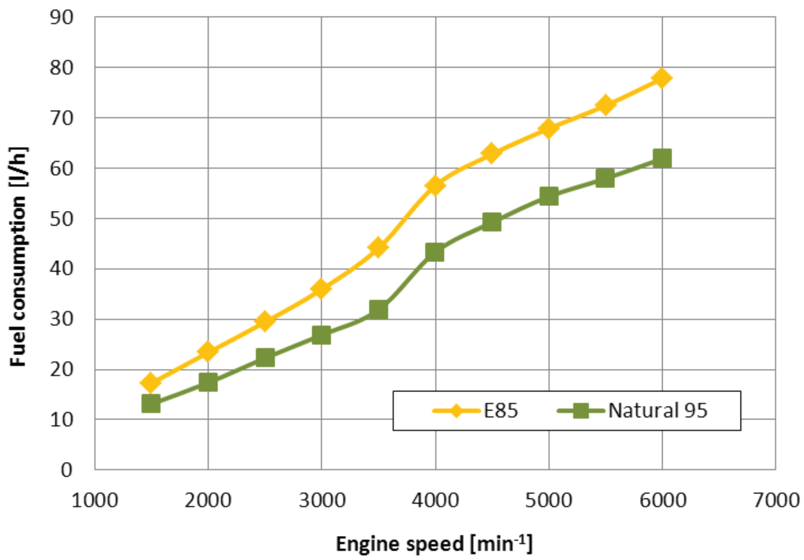
The aim of these measurements was to compare the fuel consumption in a spark-ignition engine combusting either unleaded BA95 gasoline and E85 biofuel. Measured and calculated values (corrected in accordance with provisions of the Czech standard ČSN 30 2008) were used to develop a graphical presentation of complete engine characteristics containing isolines of reduced specific fuel consumption values [g.kW^{-1}.h^{-1}]. Complete



2: *Complete characteristics of the engine combusting BA95 gasoline*



3: *Complete characteristics of the engine combusting E85 biofuel*



4: *Course of volume consumption of both types of fuel as dependent on engine revolutions at the full (100 %) opening of the throttle valve*

characteristics of the tested engine combusting either BA95 or E85 are presented in Figs. 2 and 3.

The measured values indicated that in the engine combusting E85 its torque (and thus also its output) gradually increased. With the maximally opened throttle valve and/or at the maximum torque, the average increase in engine output was 3.4 kW and 5.8 kW, respectively. As compared with BA95, this increase in the engine output was caused by a higher evaporation temperature and better anti-knock properties of E85.

When combusting E85 (Fig. 3), the reduced value of specific fuel consumption of the engine running with the maximum torque was 352 $g.kW^{-1}.h^{-1}$. As compared with results obtained in tests of the engine combusting BA95, the fuel consumption was higher by 81 $g.kW^{-1}.h^{-1}$. When using BA95 and at the maximum torque, the reduced value of specific fuel consumption was 271 $g.kW^{-1}.h^{-1}$ (Fig. 2). After conversion of the reduced value of specific fuel consumption to $MJ.kW^{-1}.h^{-1}$ (that represented the need of energy bond in the fuel per unit of produced energy), it was found out (calculated) that the gasoline/air mixture contained by 11.7% more energy than that of biofuel/air (11.38 $MJ.kW^{-1}.h^{-1}$ and 10.19 $MJ.kW^{-1}.h^{-1}$ for BA95 and E85, respectively). This result indicated that the efficiency of the combustion cycle of E85 was higher than that of BA95.

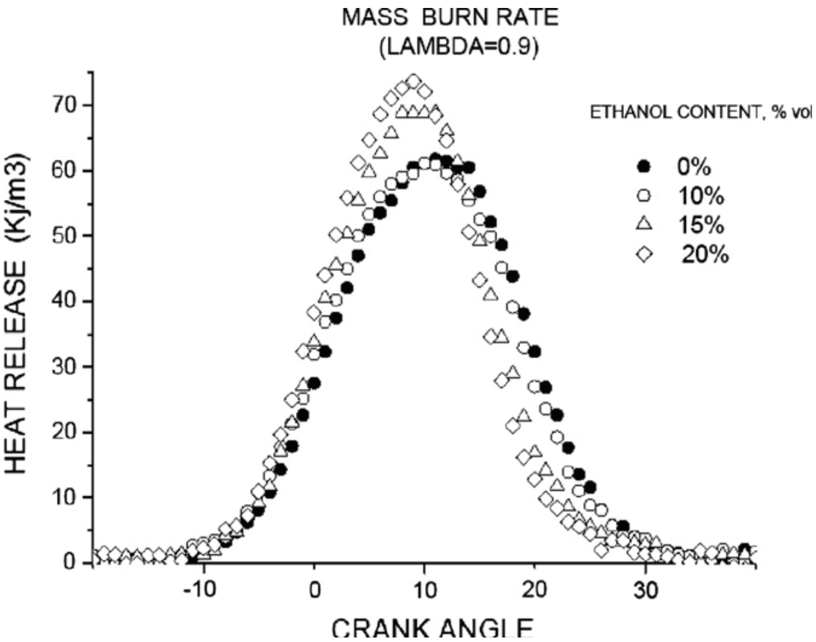
The dependence of calculated values of hourly volume consumption of both fuels on RPM of the engine with the fully (100%) opened throttle valve is presented in Fig. 4. At the maximum torque of the engine, the consumption values of E85 and BA95 were 56.54 and 43.32 liters per hour, respectively. Within the whole range of measured revolutions, the average volume consumption of E85 was higher by 30.4% than that of BA95. The specific density of both fuels, as necessary for the conversion of mass consumption values to volume consumption ones, was estimated in the laboratory using the Mohr's (Westphal) balance.

DISCUSSION

The efficiency of the combustion cycle (at the maximum torque) of E85 is 35,33% and of BA95 31,63%. The larger combustion efficiency is caused by better physico-chemical properties of E85 than BA95. Particularly the basic properties affecting the efficiency of combustion cycle include the amount of heat release by burning and burn rate of fuel. The measurement performed by Schifter *et al.* (2011) (Fig.5) shows that the increasing proportion of ethanol in blend with gasoline, the proportion of released heat increases. More of the heat can be than transform into mechanical work. The fuels containing ethanol burn faster than the reference fuel (gasoline without ethanol) as well. Figure 5 shows that with the increasing proportion of ethanol, the burn rate of the combustion mixture increases. The four fuels tested at rich air-fuel ratio $\lambda = 0.9$.

The proper of combustion, particularly the combustion duration, depends on the composition and homogeneity of the mixture and on the mixture circulation and conditions (temperature, pressure) in the combustion chamber. The mixture homogeneity is influenced by the oxygen in the fuel. Due to a high percentage of oxygen in the ethanol molecule the heating value of E85 is lower than that of other fuels made of petroleum, but the ethanol mixture with gasoline are pre-oxygenation. The pre-oxygenation has a positive effect on mixture homogeneity, on burn rate.

This fact shows the possibility of using a mixture of ethanol with gasoline to improve combustion efficiency of the cycle. For ethanol contents of 15 %



5: *Heat release for four tested fuels (Schifter et al., 2011)*

and 20 % not only the combustion is significantly faster, but it has a high instantaneous heat release. For 10% ethanol, the heat release is only slightly faster than the references (Schifter *et al.*, 2011).

Measured results correspond with data published by Koc *et al.* (2009) as well. These authors used various mixtures of biofuels E50 and E85 and analysed their influence on the change in output parameters and emissions. Their measurements were performed using a single-cylinder engine with a variable compression ratio. Their results also indicated that the consumption of E85 could be markedly reduced when using engines with a higher compression ratio.

In spark-ignition engines, the application of higher compression ratios is limited by their anti-knock properties or, better to say, by the octane value of fuel. As compared with gasoline, the octane value of E85 biofuel is high (Tab. I) and for that reason it is possible to combust it in engines with a high compression ratio and a higher thermal efficiency. A modification of the engine compression ratio can be to a certain extent replaced either by the spark advance setting or (in overcharged engines) by the increased charging pressure. To be able to use the tested engine under conditions of a better course of E85 fuel consumption it would be thus necessary to set the spark advance for each measured point.

Miler *et al.* (2009) performed similar measurements with the engine Škoda Felicia 1.3 MPI; their objective was to evaluate the effect of E85 combustion on ecological and economic parameters of the tested engine. The engine tuning was performed only on the base of an extended period of fuel injection. After having measured the working characteristics of the engine in a test station, they performed a virtual simulation of two parts New European Driving Cycle (NEDC), viz. the urban driving cycle (UDC) and the extra-urban driving cycle (EUDC), as related to one kilometer of driving. Their results indicated that, under conditions of combined driving (i.e. engine operation), the volume consumption of fuel was increased by 46.4% per kilometer.

CONCLUSIONS

Our experimental measurements were performed with the aim to estimate the fuel consumption in a spark-ignition engine combusting the biofuel E85. The suitability of the use of a certain type of biofuel for combustion in engines is dependent on its physico-chemical properties. The heating value is one of the most important properties of each fuel. Due to a high percentage of oxygen in the ethanol molecule, the heating value of E85 is lower than that of other fuels made of petroleum (Vlk, 2006). Oxygen contained in fuels shows a very positive effect not only on the course of the combustion process (burn rate) but also on the amount of produced emissions and just the positive emission balance represents the main reason why E85 is used as a fuel. On the other hand, however, a low heating value of this fuel requires an optimization of the combustion process. For that reason it is then necessary to modify the mixing ratio fuel/air and this modification causes an increased consumption of fuel. Our measurements revealed that the adjusting of the mixing ratio to a required value by means of an increased volume of injected fuel dose resulted in average in an increase in volume consumption of E85 by 30.4% (as compared with BA95).

As indicated by results published by some other authors, the optimization of E85 combustion should not involve only a modification of the mixture richness but also the setting of ignition advance and/or of compression ratio. An increasing compression ratio represents a base for the increasing thermal efficiency of the engine and, thus, for the reduction of fuel consumption. In naturally aspirated engines, however, this is rather difficult to set up in case that they will be used also for the combustion of petroleum-derived fuels. The combustion of various mixtures of bioethanol and gasoline is possible in the so-called Fuel Flexible Vehicles (FFV) that are capable of burning any proportion of the resulting blend in the combustion chamber because fuel injection, boost pressure, and spark timing are adjusted automatically according to the actual blend of ethanol and gasoline detected by electronic sensors. At present, there are also several firms that implement conversion (i.e. adaptation) of conventional engines to combustion of E85. In these vehicles, the engine control unit is combined with a controller, the internal algorithm of which extends the period of opening of the injection valve and, thus, modifies the richness of fuel mixture to the desired value. Other regulation algorithms are implemented by the original control system (as shown in the performed measurements). The activation of the additional regulator is performed by a switch, which is mostly localized on the car dashboard. A marked reduction of the operation cost of the vehicle adapted to running on E85 is, however, rather discutable. The savings will be dependent above all on the price of the concrete fuel used.

SUMMARY

The paper deals with the evaluation of fuel consumption of a spark-ignition engine running either on unleaded BA95 gasoline (Natural 95) or E85 biofuel. Experimental measurements were carried out in the laboratory of the engine test station of the Department of Engineering and Automobile Transport, Mendel University in Brno and performed according to the methodology of the standard ISO 1585. Measurements were performed using a six-cylinder spark-ignition Peugeot engine with the overall volume of 2.946 cm^3, which was equipped with a multi-hole system of indirect injection. Due to different properties of biofuel E85 and gasoline BA95, it was necessary to modify the stechiometric ratio. As it is usually in practice with conventional engines converted to the combustion of E85 biofuel, the modification of the stechiometric ratio was performed on the base of a change in the amount of fuel injected into the engine cylinder. The supply of both unleaded gasoline and biofuel was modified in such a way that the engine operated with the coefficient $\lambda = 1$. This change was carried out by means of the programmable Magneti Marelli control unit. Other control parameters (e.g. spark advance) remained to be the same as in case of engine running on gasoline Natural 95.

When combusting the biofuel E85, the reduced fuel consumption of 352 g.kW^{-1}.h^{-1} was recorded in the zone of the maximum torque. As compared with gasoline BA95, this fuel consumption was higher by 81 g.kW^{-1}.h^{-1}. The conversion of reduced specific fuel consumption to MJ. kW^{-1}.h^{-1}units indicated that the mixture of BA95 and air produced by 11.7% of energy more than that of E85 and air. These results indicate that with E85 the efficiency of combustion cycle was higher. As compared with BA95, the values of hourly consumption of E85 at full (100%) opening of throttle valve, and of average output of the engine were higher by 30.4% and 3.4 kW, respectively. When combusting E85, the increase in engine output was caused by a high value of evaporation heat, mass of heat release, better burn rate and anti-knock properties of the biofuel.

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