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EXAMINATION OF BURNING PROCESSES OF REGENERATIVE LIQUID FUEL AND ALCOHOL MIXTURES IN DIESEL ENGINE

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Abstract

In the article we would like to introduce our research areas, which are running at our Department (Budapest Univerity of Technology and Economics, Department of Energy Engeneering) in the field of regenerative diesel fuels. We introduce the measuring system which is based on an ASTM-CFR F5 cetane method diesel fuel-rating unit. In the course of measuring, we analysed the influences of different alcohol-rape seed oil mixtures to their burning processes and emission.

Keywords: biofuel, renewable energy, cetane number.

1. Introduction

Europe and our country too, have to take some steps in the field of regenerative fuels, because of the increasing severity of the regulations of environmental protection and considerably high dependence upon import. One of the most important application areas of regenerative fuels is transport and decentralized energy supply, which would be more significant in the future.

The fuels of internal combustion engines can be interchangeable with regenerative fuels. We investigated 17 alcohol-rape seed oil samples (5, 10, 20% 1-butanol, 2-butanol and rape seed oil mixtures; 5, 10, 20% isobutanol and rape seed oil mixtures; 5, 10, 20% 1-propanol, 2-propanol and rape seed oil mixtures; 95, 90% rape seed oil, 2.5, 5% 2-butanol 2.5, 5% ethanol mixtures) and the natural rape seed oil sample. In this paper we introduce our measuring system, the results of measured parameters (cetane numbers, and differences of peak firing pressure in the cylinder) and the emission of the samples.

1.1. Introduction of Measured Samples

1-propanol. It is a higher alcohol. It is a clear liquid; its vapour has alcoholic smell at laboratory temperature. Much less water can be mixed with 1-propanol than lower alcohol (like ethanol or methanol). Fields of application of 1-propanol are in the paint industry, pharmaceutical industry, for cleaning and antibacterial sterilization.

2-propanol (isopropanol). It is the lowest secondary alcohol. It has mildly sweet smell. Field of application of 2-propanol is like as an antifreeze component in screen cleaner liquids, cosmetic industry etc.

Butanol. It is a higher alcohol with four carbon atomic nucleus. The butanol has four isomers [1]. It has typical smell; it is a clear liquid.

The higher alcohols can be produced by biological degradation, with fermentation (for example butanol), or by indirect hidradization from CO and H_2 in synthetic way with carbon-hydrogen distillation.

In *Table* **??**, the relevant parameters of higher alcohols are summarized.

Table 1. The physical parameters of the used alcohols

	1-propanol C3H7OH	2-propanol C3H7OH	Isobutanol C4H9OH	1-butanol C4H9OH	2-butanol C4H9OH
Density [g/cm^3]	0.8035	0.785	0.8027	0.8098	0.8065
Molar mass [g/mol]	60.1	60.1	74.1	74.1	74.1
Melting point [°C]	−126.2	−88.5	−108	−89.3	−115
Boiling point [°C]	97.2	82.4	107.9	117.7	100
Flare up point [°C]	15	11.7	25	29	24
Self-ignition temp. [°C]	371	456	415	345	406

2. Principles of the Experimental Work

2.1. Overall CFR-F5 Rating Unit Description

The model CFR-F5 Cetane Method Diesel Fuel Rating Unit is a packaged version of the single cylinder, four-stroke cycle CFR Engine designed for compression-ignition testing of diesel fuel samples. The complete unit is known as the "ASTM-CFR Engine" and is marked by American Society for Testing and Materials and the Coordinating Fuel Research Committee [5]. An unique cylinder/cylinder head assembly with variable compression ratio and an indirect injection system assembles on the basic CFR-48D crankcase, which is mounted on a bedplate. The engine flywheel is belt connected to an electronic synchronous-reluctance type motor. This acts to start the engine, and maintains constant engine speed [1] [2].

[1]Isomers: they have same atomic formulas, but they are different structured molecules. The sequence of the atomic connection or the spatial situation of the atoms can be different.

2.2. The Test Method Engine

The cylinder head incorporates a cylinder pre-combustion chamber (*Fig. 1*) that is connected to the main combustion chamber by a turbulence passage. The injector nozzle sprays fuel into this chamber from one end while a variable compression plug controlled by a hand wheel mechanism blocks the opposite end. This plug can be moved in and out of the pre-combustion chamber to cause changes in compression ratio whilst the engine is in operation.

Sample fuels and reference fuels are introduced to any of three fuel tanks mounted above the inlet port of an injection pump through a selector-valve. The selected fuel is delivered from injection pump to the pre-combustion chamber of the engine through an injector nozzle assembly. The injector pump has its own adjustable fuel flow-rate mechanism so that engine fuel consumption can be varied. An adjustable timing device, integrated with the injection pump, permits controlled variation of the time of injection.

Detection of the time of injection and the start of combustion are sensed by electromagnetic pickups while two reference pickups sense the crankshaft position at prescribed points in the combustion cycle. Signals from these pickups are input to a Cetane Meter which digitally displays injection time (advance) and ignition delay in crank angle degrees.

Engine inlet air temperature is stabilized using an electric heater and a temperature control instrumentation. Electrical heater mounted under the engine crankcase and in the cylinder head jacket cooling system, maintain crankcase lubrication oil and cooling water temperature both when the unit is operating and when it is shut down [2].

2.3. Test Method for Cetan Number of Diesel Fuels

Cetane number is measure of the ignition delay characteristics of diesel fuels used in compression ignition engines. It is incorporated in the fuel specifications for these products [5].

The relationship of cetane number to full-scale engine performance is not thorough understood, however there are some correlations between the easiness of the engine to start, the combustion roughness, the misfiring and other characteristics. The test method determines the rating of diesel fuel oil using the empirical from 0 to 100 cetane number scale [2] [6].

The test method specifies the use of the CFR-F5 Rating Unit. It was manufactured exclusively by Waukesha Engine Division, Dresser Industries, Inc. The single cylinder four-stroke cycle, variable compression ratio, indirect injected diesel engine is assembled on a bedplate with a belt coupled electric power-absorption motor, suitable instrumentation and control.

The engine is operated at specified conditions of pressure, temperature, speed, etc. and three further variables are adjusted to control fuel combustion performance.

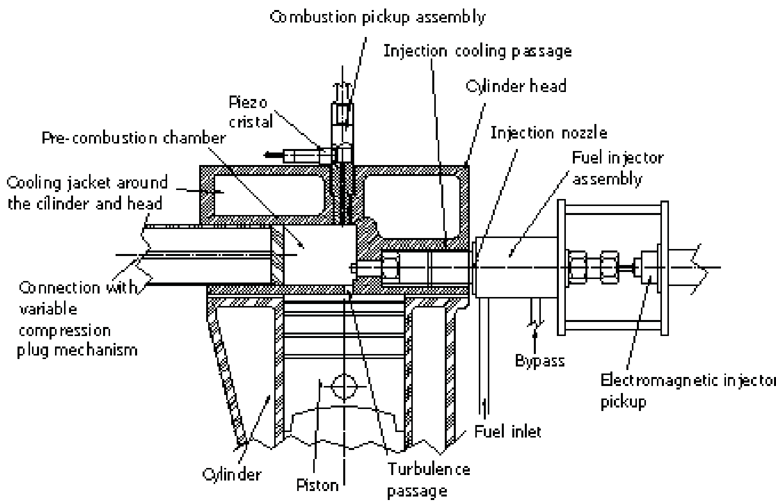

Fig. 1. CFR F-5 Diesel Combustion Chamber Assembly

These variables are:

- Fuel flow rate (13 millilitres per minute) by micrometer indicated adjustment of the injection pump rack position
- Time of fuel injection (13 crank angle degrees before top dead center) by micrometer indicated adjustment of a timing device coupled between the engine camshaft and the fuel injection pump the time of injection is sensed by a transducer mounted to detect the movement of the injector pintle as it lifts to deliver the fuel from the nozzle. The transducer signal is one input to a Cetane Meter, which displays the event as Injection Advance degrees.
- Ignition delay (13 crank angle degrees which means that combustion occurs 13 degrees after the injection of fuel into the combustion chamber). Ignition delay is affected by changes of compression ratio, which can be adjusted by rotation of a handwheel that moves a variable compression plug in or out of the pre-combustion chamber. The hand wheel has a micrometer associated with it and the position of the plug. This micrometer measurement is known as the handwheel reading. A magnetostrictive pickup exposed to the combustion chamber detects the rate of change of pressure ($\mathrm{d}p/\mathrm{d}t$) associated with the combustion chamber events including the spontaneous combustion of the fuel. This pickup signal is directed to the Cetane Meter where the trigger circuit detects the rapid rise in pressure increase gradient ($\mathrm{d}p/\mathrm{d}t$) due to combustion.

The Cetane meter displays both the time of injection (Injection Advance) and the Ignition Delay where latter represents the time from injection to the start of the combustion.

Comparing its hand wheel reading to those obtained for each of two references fuel blends of known cetane numbers is where the reference fuel hand wheel readings bracket that of the sample performs testing of sample. The operational sequence for each fuel is as follows:

- Introduce the fuel to a fuel tank
- Set the fuel flow rate
- Set the time of the injection (13 degrees before Top Dead Centre)
- Adjust the handwheel to established an ignition delay of 13 degrees
- Record the handwheel reading when engine equilibrium occurs.

Calculation of the sample result involves linear interpolation of the sample hand wheel reading in relation to those of the reference fuel blends; then using the same proportion to determine the sample cetane number in relation to the known cetan numbers of the reference fuel blends [2].

3. The Indicating and High Speed Data Acquisition System

We could investigate 3 channels in our measurement. The electric signal of the magnetostrictive pickup (dp/dt), piezo crystal (*Fig. 2.*) and the injector pintle transducer get to the SSH (Simultan Sample and Holding) A/D card.

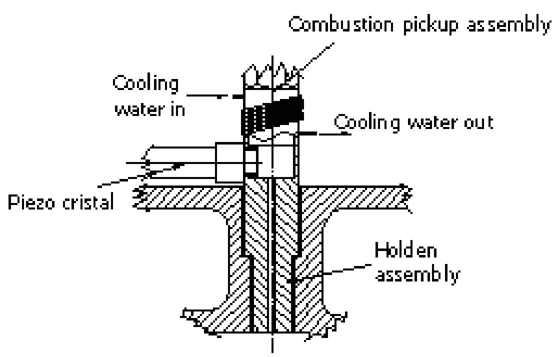

Fig. 2. The installed piezo crystal in the pre-combustion chamber

For the sake of accuracy the measurement is started by the encoder on crank axis (1024 signal/round). Our results are saved in ASCII code, in simple format of numbers and letters (txt file). It is easy to process by a simple spreadsheet programme. The indicating system can be seen in *Fig. 3.*

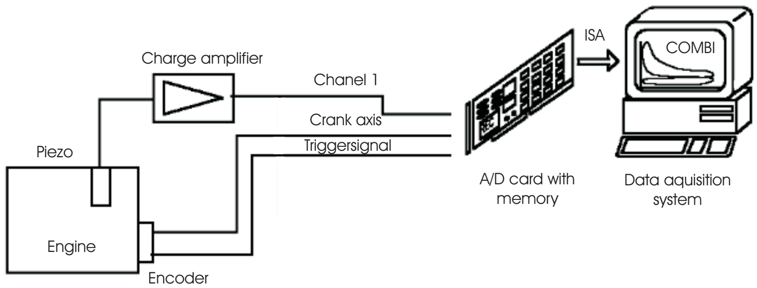

Fig. 3. The structure of the indicating system

4. Emission Measuring System

During the investigations wide measuring ranged, up-to-dated, good qualified emission measuring system was used (see *Fig. 4*). The measured emission parameters were NO/NO_2/NO_x (by system using chemiluminescent principle), CO/CO_2 (by IR principled system), O_2 (by paramagnetic principled system), SO_2 (by PFA fluorescent principled system), THC (by FID principled system).

The analysed sample or the calibration gases go through the electromagnetic valves and then pass to the sample-preparating unit.

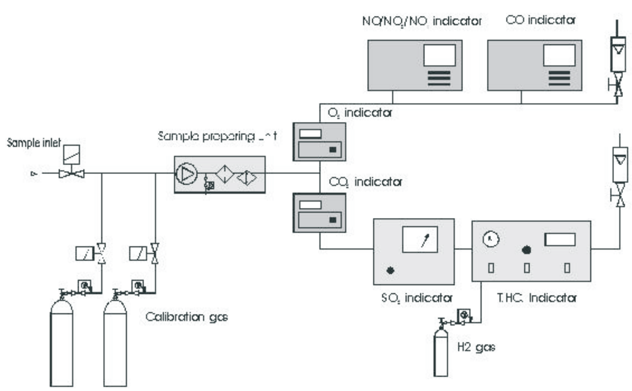

Fig. 4. Emission measuring system

AVL 415 Smoke Meter measures the smoke. The used measure is FSN (Filter Smoke Number). The Smoke Meter device set by an AVL sample collecting equipment to the un-cooled exhaust pipe of Cetane Method Measuring Unit.

5. Measured Results

5.1. Cetane Number Changes

The cetan number (CN) of the diesel fuel sample is equal with the volumetric cetane content of primary reference fuel (cetan and alpha-methylnaphthalene) mixture. Due to the high prices of the primary reference fuel components new cheaper and easily storable secondary reference fuels were developed. The cetane number of upper secondary reference fuel sample (T fuel) is around 73-75 CN while the lower secondary fuel (U fuel) has 20-22 CN. Based on a volumetric mixing table (according to the instruction of the producer) the reference fuel blends can be easily mixed in simple laboratory environment. In our researches three reference fuels were used with different cetane numbers. These cetane numbers were 32.4, 36.4 and 40.3.

As summarized in *Table 2*, we measured 17 different alcohol-rape seed oil samples, pure rape seed oil and a diesel fuel sample as a comparable value sample. As we mixed more percent of alcohol to the rape seed oil, the cetan number of the sample (ignition delay characteristics of diesel fuels) was reduced. The descending cetane number of the mixtures is explainable with the low cetan number of the alcohol components (the cetane number of higher alcohols is approximately 2).

Table 2. The measured cetan numbers

Sample	Cetane Number (CN)
Diesel fuel	56.0
100% rape seed oil	41.8
95% rape seed oil + 5% 1-propanol	40.0
90% rape seed oil + 15% 1-propanol	38.4
80% rape seed oil + 20% 1-propanol	34.0
95% rape seed oil + 5% 2-propanol	40.2
90% rape seed oil + 15% 2-propanol	39.7
80% rape seed oil + 20% 2-propanol	36.7
95% rape seed oil + 5% isobutanol	41.2
90% rape seed oil + 15% isobutanol	37.9
80% rape seed oil + 20% isobutanol	35.5
95% rape seed oil + 5% 1-butanol	41.0
90% rape seed oil + 15% 1-butanol	38.9
80% rape seed oil + 20% 1-butanol	36.2
95% rape seed oil + 5% 2-butanol	40.2
90% rape seed oil + 15% 2-butanol	38.3
80% rape seed oil + 20% 2-butanol	35.4
95% rape seed oil + 2.5% ethanol + 2.5% 2-butanol	37.6
90% rape seed oil + 5% ethanol + 5% 2-butanol	35.9

According to the regulation of ASTM (American Society of Testing and Materials) the inaccuracy of the measure can be maximum ±1.5 cetane number [3]. Each sample was measured 3 times and it can be stated that we did not find serious (more than the regulation), impermissible differences among the cetane numbers of measured samples.

In the following graphs (see *Figs. 5, 6, 7*), the CN of the measured samples are presented.

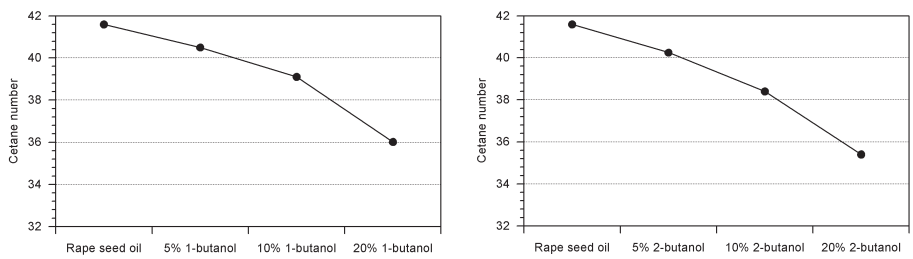

Fig. 5. The measured cetan numbers of 1 and 2-butanol mixtured with rape seed oil

In the case of 1-butanol (*Fig. 5*), the decrease of the cetane number is lower than in the 2-butanol case. When 2-butanol was used, the decrease of the cetane number was rather directly proportional to the content of alcohol component.

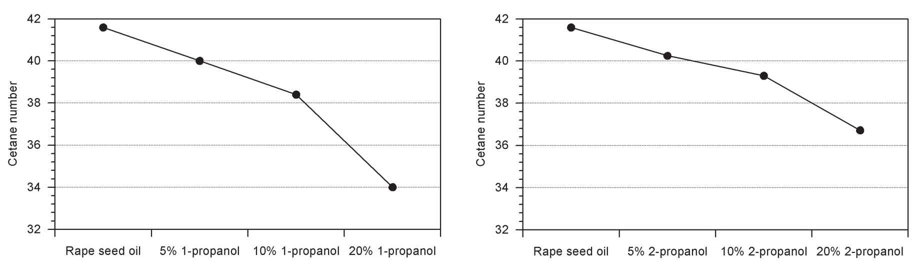

Fig. 6. The measured cetan numbers of 1 and 2-propanol mixtured with rape seed oil

In the case of 1-propanol (*Fig. 6*), the decrease of the cetane number is the highest among the measured samples. In this case the proportion was not easily provable. If the two propanol sample diagrams are compared and we consider the chemical aspects of higher alcohols, we can determine a possible small measuring failure, which is inside the acceptable measuring inaccuracy.

In the case when isobutanol was used (*Fig. 7*), the proportion was not easily demonstrable because the 5% isobutanol sample is an outlier among the other isobutanol-rape seed oil samples.

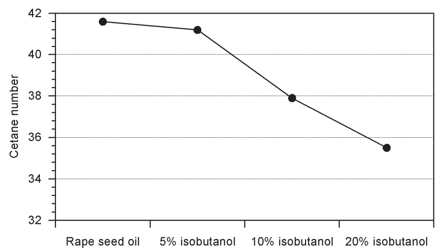

Fig. 7. The measured cetan numbers of isobutanol mixtured with rape seed oil

5.2. Differences of Compared Alcohol-rape Oil Mixtures

In *Figs. 8, 9* and *10*, the variation of the measured maximal pressure can be seen. Unlike to the cases when cetane number was changed, if we put more alcohol to the rape seed oil mixtures, we detect growing peak pressures during the combustion. Supposedly, the two components of the mixture (alcohol and rape seed oil) can burn separately. At first, when the pressure is growing, the rape seed oil component (which has better ability to flare up due to the high compression and its higher cetane number) will burn first because of the pressure. After the flame appears, the easily and heavily burning alcohol (which has absolutely low cetane number) does also flare up and causes higher pressure changing.

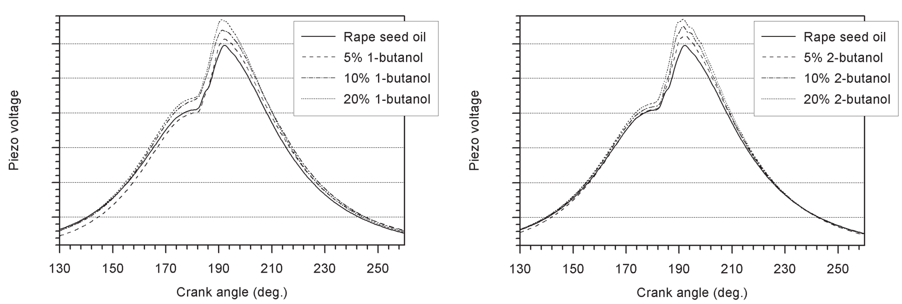

Fig. 8. Comparison of different butanol-rape seed oil mixtures

By comparing all of the diagrams (*Figs. 8* to *Fig. 10*), the alcohols seem to have the same pressure increasing effect of the mixtures burning processes except the isobutanol, which shows lower pressure increasing.

By mixing more alcohol to the rape seed oil the peak firing pressure in the combustion chambernot only increases but it takes closer the peak firing pressure to the Top Dead Centre.

The measured peak pressure values can be seen in *Fig. 11*.The evidence that more alcohol in the mixture causes proportionally higher peak firing pressure can be seen the best visible in the case of propanol mixture. The increase of peak firing

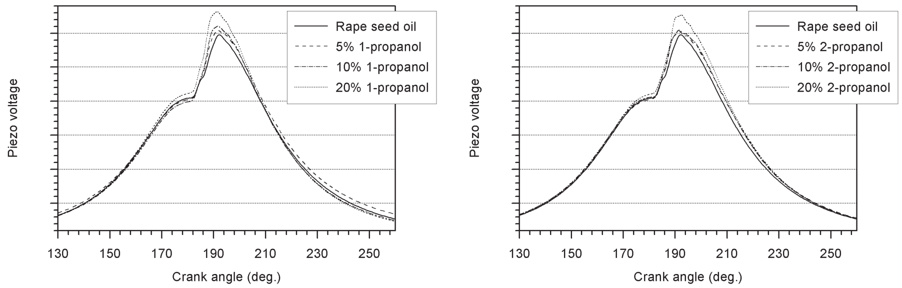

Fig. 9. Comparison of different propanol-rape seed oil mixtures

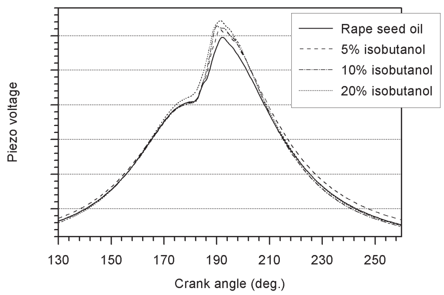

Fig. 10. Comparison of isobutanol-rape seed oil mixtures

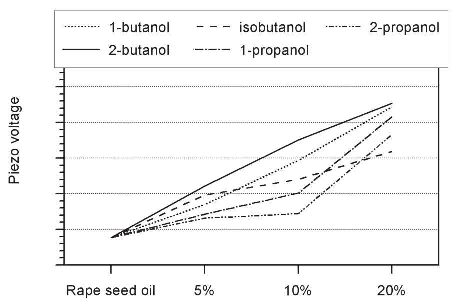

Fig. 11. Peak firing pressures over the alcohol content of the mixtures

pressure is demonstrable in every alcohol cases.

5.3. *Changes of Emission Parameters*

It has to be noticed, the used CFR test engine with low turbulence pre combustion chamber and low injection pressure is behind the times compared with a modern passenger or heavy-duty diesel engine equipped with high pressure injection system (for example common rail). The test engine was designed mainly to measure the cetan number of diesel fuels. Because of these parameters the following emission data has only informative meaning for the next, modern test rig measurements.

In the followings we introduce several relevant emission parameters like Smoke Number, NO_x and THC. Some other emissions were also measured like CO_2 and SO_2 due to the complex build-up of the measuring system but these were dropped out from this report. We did that because all of the investigated samples were regenerative fuels and they do not emit more CO_2 to the environment than their absorbability as a plant and they do not contain any sulphur. In these cases theoretically the SO_2 can come only from the burnt lubrication oil. The measured operating points were followed by the cetan number measurements. We measured every operating point three times and made an average value from each set of similar measurements.

5.3.1. Smoke Number Changes

The measured smoke numbers are considerably higher than a modern Euro I-IV standard engine case but they give an important hint on how the number of the emitted smoke particles change with the added alcohol percentage.

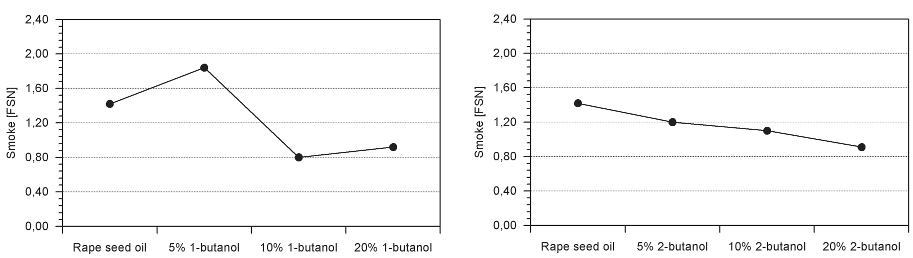

Fig. 12. The measured Smoke Numbers of butanol and rape seed oil mixtures

In *Fig. 12*, compared with the other diagrams (*Fig. 13*) one non fitting point (at 5% 1-butanol - 95% rape seed oil mixture) can be seen, which is a possible outlier among the measured points. In the 2-butanol's (*Fig. 12*) case the burning process was faster (higher temperatures) as we add more alcohol to the mixture. The carbon elements did not have enough time to merge to bigger molecules due to the higher burning speed of the mixture. Last but not least, if we use higher alcohol percentage, we can expect lower smoke emission because alcohol itself does not cause any smoke emission.

In the last figures (*Figs. 13* and *14*), the mixtures show decreased smoke at the first operating points, which was our prediction, too. Unfortunately, as we put more alcohol to the mixtures the cetane numbers were decreased. Due to the behaviour of the cetane number investigations we had to increase the compression ratios that caused worse injecting capability of samples (smaller differences between the peak

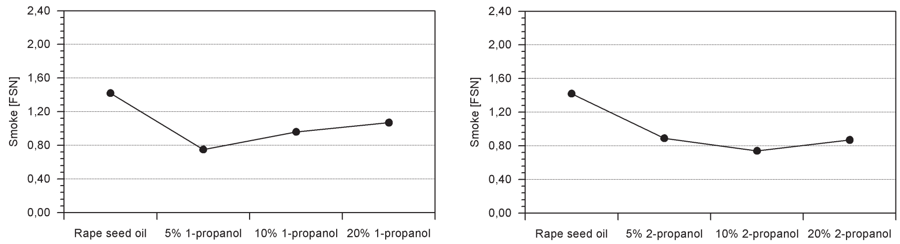

Fig. 13. The measured Smoke Numbers of propanol and rape seed oil mixtures

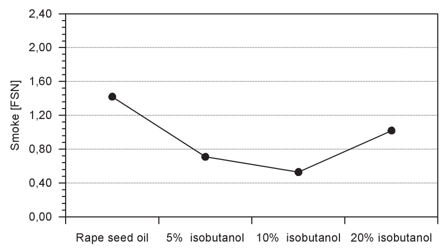

Fig. 14. The measured Smoke Numbers of isobutanol and rape seed oil mixtures

firing pressure and injecting pressure of the injector) to the combustion chamber. As a result we got more emitted smoke (can be seen at the last points of *Figs. 13* and *14*) from the rape seed oil component of the mixtures. The same procedure could be detected almost with every alcohol samples. In the *Fig. 12* the decrease is close to linear. The difference among the first 3 measured points approximately 5% each while between the 3rd and 4th points this difference is 10%. It has to be remarked that the alcohol evaporates quickly from the injected fuel, which takes to micro explosion of the fuel drops, but it has no positive influence on the degraded injection circumstances (due to the higher compression ratio).

5.3.2. NO_x *Emissions*

Generally, one of the problems to use rape seed and any other vegetable oils as a diesel fuel is the amount of nitrogen content of the oil which causes considerably high NO_x emission. Theoretically, as we add more alcohol to the rape seed oil, we get less NO_x emission in the exhaust gas because the alcohols do not contain nitrogen atoms. However, our measurements confirm this theory. Within every measurement we got dissonant values, which can be imputable to the definite failures of the sensitive measuring system.

In *Fig. 15* a possible outlier can be seen at the last sample. If we put aside from the outlier second measuring point, we can see a very light slope on NO_x emission decrease.

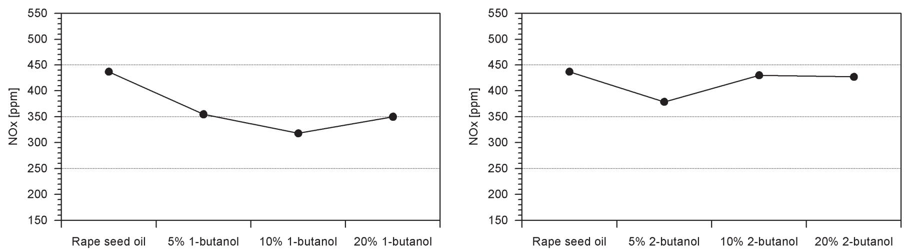

Fig. 15. The measured NO_x emission of butanol and rape seed oil mixtures

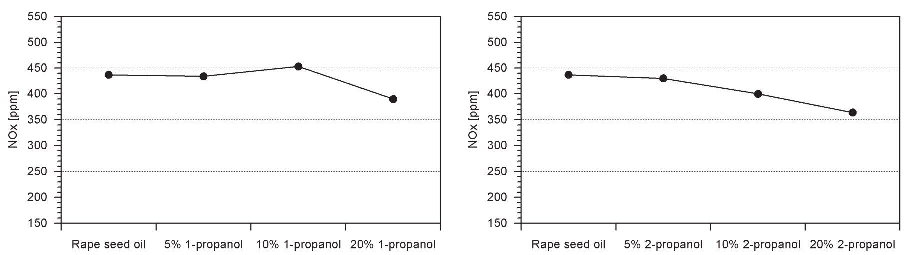

Fig. 16. The measured NO_x emission of propanol and rape seed oil mixtures

In *Figs. 16* and *17* a reduced NO_x emission can be seen as we add more alcohol to the mixtures. The proportions between the added alcohol quantities are visible. They have negative slopes.

If we compare the diagrams with butanol mixtures, it shows up, that the decrease of NO_x in the case of 2-butanol is lower than in the case of 1-butanol. In the case of isobutanol the difference can be smaller. There can be more reasons, which can cause this effect. The different alcohols evaporate with different speed from the alcohol-rape seed oil mixtures during the combustion and they burn at different temperatures. These circumstances would have influence on NO_x formation.

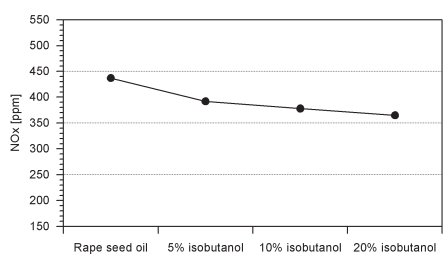

Fig. 17. The measured NO_x emission of isobutanol and rape seed oil mixtures

3 different circumstances can affect the NO_x formation in the combustion chamber: temperature, combustion length and the nitrogen content of the fuel. As

we mix more alcohol to the alcohol-rape seed oil mixture, the kinetic period of the combustion will start earlier and there is more time to the NO_x formation. Of course, more alcohol in the mixture means less nitrogen content of the fuel.

5.3.3. *THC Emissions*

Due to the fact that combustion is not perfect and that the amount of the injected fuel is not burning fully, the THC is appearing as emission in the exhaust gas.

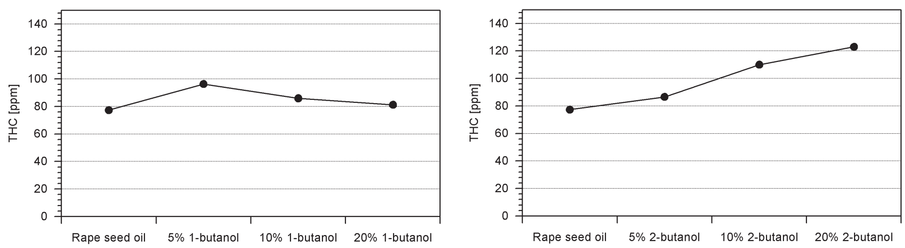

Fig. 18. The measured THC emission of butanol and rape seed oil mixtures

Our predictions were the following: increasing the alcohol content of the mixture means the emitted THC quantity will decrease. The alcohol improves the combustion quality. It burns more quickly than the rape seed oil and we take less rape seed oil into the combustion chamber because the injected fuel quantity is constant, if there were more percent alcohol in the injected fuel, it would consist less percent rape seed oil.

In *Fig. 18*, a small increae in THC emission of 1-butanol rape seed oil mixture can be seen but the tendency of the measured values is not clear. In the 2-butanol's case there is a linear dependence.

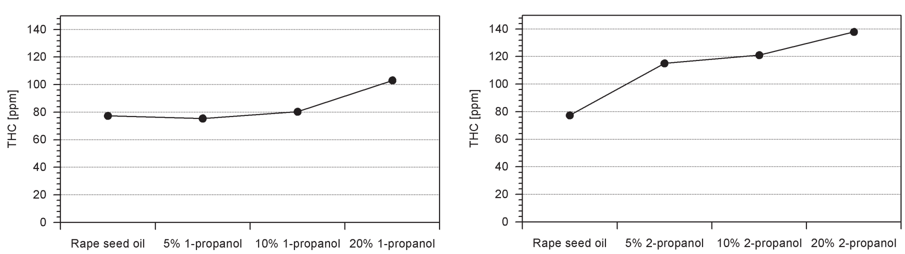

Fig. 19. The measured THC emission of propanol and rape seed oil mixtures

If we compare the 1-propanol (*Fig. 19*) and the 2-propanol butanol measurements, in the 2-propanol's case we can expect a linear correlation between the alcohol content and the THC emission while the 1-propanol shows a relation with higher order.

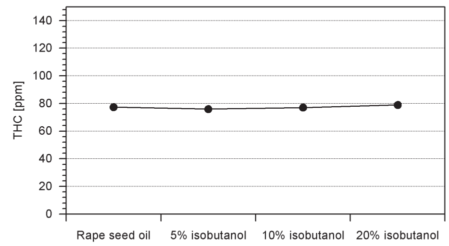

Fig. 20. The measured THC emission of isobutanol and rape seed oil mixtures

In the case of isobutanol (*Fig. 20*) there are no functional differences among the measured values. The reason why we measured higher THC emission can be that by increasing the alcohol content of the mixtures the combustion temperature increased, which was favourizing the dissociation. Due to the lower cetan number the combustion started and finished later.

6. Conclusions

- As the amount of alcohol mixed to the rape seed oil increases, the cetan number decreases.
- The peak pressure of rape seed oil is higher with increased alcohol content.
- The two components (rape seed oil and alcohol) of the mixture burn separately during the combustion.
- The sample with higher alcohol content had less smoke emission until we mixed maximum 10.
- The sample with higher alcohol content showed less NOx emission.
- When more alcohol was put to the mixture, higher THC emission was reiterated.
- One of the main advantage of the alcohol additives: the viscosity of the samples was decreased by the higher percentage of alcohol additives. It would mean better pumping ability in the diesel fuel pump.
- The cetane number decreases by higher alcohol content, until 10% of alcohol content of the mixture can be used in older diesel engines (for example agricultural heavy duty vehicles) without any other preparation of the engine (mechanical development) or the rape seed oil samples (esterification).

7. Future Plans

However the alcohols, which we used, come from the procedure of petroleum technology (secondary products), in order to justify the using of these components it can be stated that the prices of these products are considerably low at the moment and the mixtures of rape seed oil and lower alcohols are not stable under normal laboratory conditions. If we want to produce mixtures from bio alcohols (bio ethanol or bio methanol) and natural vegetable oils, we need a solvent for a good blended homogenous mixture. We did not have any of these products during our work but we would like to carry on our research programme with them. In the next step, we are planning to measure the alcohol-rape seed oil mixtures viscosity and modern diesel engine tests on up-to-dated test bed.

We have not analysed fully the possible damages in the mechanical parts of the engine (for example wears and discharges in the lubrication system and in the cylinder) which are caused by alcohol-rape seed oil mixtures. Because of these mechanical problems we would like to measure them in the future.

Pending in produce the common diesel fuels (made of petrol) these are blended with many solvents (minimum 15 different components), for example viscosity reducing components - which would be most important in the case of running engines with vegetable oils, anti wear compounds, preventive contents against of solidification and the biological degradation of the fuels, etc [4]. Further researches are needed to analyse the influence of solvents in combustion processes, emission of the engine and how the structure of vegetable oils can change by the time. If these additives can be used, the availability of natural vegetable oils in diesel engines would be better.

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