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USE OF BIOFUELS IN A COMPRESSION-IGNITION ENGINE – COMPREHENSIVE TECHNICAL AND ECONOMICAL ANALYSIS

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Abstract

The assessment of renewable fuels on the basis of the results of internal combustion engine's tests is not clearly good or not good. Biofuels can be a part of sustainability from energy sources, energy security and energy diversity point of view. But they cannot be assessed better compared to the fossil diesel as for their combustion and air pollution and the engine's external parameters. Comparison test series has been conducted with three different fuel and their controlled blends. These fuels were fossil diesel, the conventional, standardized biodiesel, and a new type biodiesel, which is the so-called TBK-biodiesel. These tests covered the physicochemical properties of the fuels, the engine external parameters, the combustion parameters and the exhaust emission of an internal combustion compression ignition engine. Furthermore, external costs have been calculated based on the emission results. Physicochemical properties, engine parameters, combustion parameters, exhaust emission and external costs have been observed as parameter groups, which contain many parameters. A complex evaluation could be built with the help of such kind of parameter set. On the basis of the results, it can be established that almost in the most cases the direction of the parameters' changes is negative. Thus, the evaluation's centre of gravity has been observed as shifted in the negative direction.

Keywords: *conventional biodiesel, TBK-Biodiesel, complex evaluation, Diesel engine, combustion, emission*

1. Introduction

The energy demands of transport and power generation sectors are continuously increasing considering the future. This tendency is shown for the European Union and worldwide as well [5-7]. This situation means at the same time a growth in load and pollution of the environment. Beside the conventional fuel, there are many kinds of alternative fuel. Some of them are biofuels [8, 9]. There are different reasons for introducing bio-derived fuels: (i) diversification among the energy (fuel) sources, (ii) decreasing consumption of fossil fuels, (iii) energy safety. Fossil diesel is the traditional fuel of compression ignition engines. Besides, CI engines can run on bio-derived fuels. ICE relevant physicochemical properties of renewable fuels are different from those of diesel properties because of dissimilarity in their structure. Use of renewable fuels in internal combustion engines can be more favourable regarding air pollutant and greenhouse gas emission of an engine [9,10]. Particulate matter derived from a Diesel engine as a serious air pollutant component causes damaging effect on the living being and on the built environment as well. Particulate matter can be found in the exhaust emission of a compression ignition engine running on renewable fuel as well. Harmful emission has negative economic effect.

All the topics (mentioned above) related research's results cannot be found in the literature with a high level of bio blending rate and also with pure renewable fuel investigated in internal combustion engine.

The main aim of this article is presenting our concept of complex evaluation method of biofuels investigated in a compression engine.

2. Experimental data

2.1. Tested fuels

For our comparison tests diesel fuel (D2) – corresponding to the standard [1] – purchased from a gas station in Hungary has been used as a reference fuel. The second fuel was rapeseed biodiesel meeting the standard [2]. The TBK-Biodiesel was the third tested fuel, which is also called Triglycerides of Modified Structure is a new type biofuel.

Beside the pure form of fuels, four different blends have been made in a controlled way. So the seven different fuel compositions were according to the following: pure fossil diesel, blend of both bio fuels with blending ratio of 25V/V% and 75V/V%, pure FAME and pure TBK.

2.2. Test methods for physicochemical properties

Density means the mass of unit volume. The measurements of fuel's density have been carried out with the help of aerometer on the basis of [4]. Kinematic-viscosity of the investigated fuels has been determined by an Ostwald-Fenske viscometer [22]. To determine the heating value of a fuel there many methods. One of them can be a calculation method when the elemental consumption of the fuel is known. There are two relating standards [14, 15], we used for measurements of elemental composition. Based on the elemental composition the heating value can be calculated with the help of the Boie formula [3]. Cetane number of diesel is information about inflammation tendency. Cetane numbers of the tested fuels have been determined on a CFR-F5 measurement engine according to [11]. Flash point tests have been conducted in two different ways like open and closed cup method [12, 13].

2.3. Engine

The tests series were carried out in engine type RÁBA D10 UTSLL 160, which is one of the most commonly used engine in the Hungarian bus fleet.

2.4. Test method for combustion and emission analysis

The three test points were chosen in relation to combustion process and the emission of air pollutants. In these three test points, the combustion process and the properties of the exhaust emission of the engine may be very different. Three points have been chosen for the tests from the speed-load range of the engine as follows:

1. 1300 rpm – 50% load,
2. 1900 rpm – 25% load,
3. 1900 rpm – 75% load,

where 50% load means 450 Nm, 25% load means 200 Nm and 75% load means 600 Nm torque.

These torque levels have been set for all kinds of the tested fuels.

2.5. Experimental setup

A complete experimental set up has been built for the in-cylinder pressure indication and for the emission measurement for indication, many sensors have been installed on the engine. Piezo signals are sent on after the charge amplifier to the data collector, from which it is transferred to a PC, which has an appropriate program to evaluate the signals. The speed signals are transmitted by the help of an opto-coupler to the data collector. The engine is coupled to a SCHENCK W 400 Eddy-current test bench. A Froude Fuel Measuring System type FG100 has been used for fuel consumption measurement. The type of the gas analyser system is Pierburg AMA 2000. The following measurement principles were used during the analysis of the gas phase components: 1. for THC Flame Ionization Detector, 2. for NO_x Chemiluminescence Detector, 3. for CO and CO_2 Non Dispersive Infrared Detector and for O_2 Paramagnetic Sensor. To measure the particle relevant emission, two different device and principles were used.

2.6. Emission derived external cost calculation

Negative externality can be the air pollution, the noise pollution, the increased travel time caused by traffic jam as well as the increased fuel consumption. The infrastructure splits the region, which situation has a negative effect on the communities live there. Furthermore, changes in our built environment, culture values, heritage as well as the deterioration in the clarity of the air can be listed to the externality [17]. Chronic diseases, increase in mortality can also be mentioned among the long-term effects. There are many types of methods, which can be used for calculation of external cost. The first type of methods is the Cost based methods e.g. replacement cost method, shadow project, cost recovery method, defence cost, production factor method, cost-benefit analysis. Secondly can mention the Revealed preference methods for which belong travel cost method and hedonic pricing method. The last one is the Stated preference methods like contingent valuation method, contingent selection method, contingent ranking method) [18].

Benefit transfer method cannot be categorized into either above-mentioned category. It can be considered as a comprehensive method, which combines all the methods. The benefit transfer method uses the results of earlier conducted researches instead of performing the introduced original surveys, assessments [19].

Calculation method used in this study was developed by us. The bases information are fuel consumption, mileage of a related bus belongs to the type of the tested engine, furthermore the emission results, and cost specific emission factors. All most important air pollutant emission component like CO, CO_2, HC, NO_x, mass of particulate matter are considered. Saving of CO_2 in case of renewable fuels is also considered [20].

3. Results and discussion

All the above-introduced parameters are needed to be used for the complex evaluation of renewable fuel's impact on the operation of a compression ignition engine. These parameters are classified into groups to form parameter groups. Using these groups, our goal is to provide a possible new approach or method for the complex evaluation of bio-derived fuels investigated in internal combustion engine. 4 different technical and 1 economic parameter group have been classified. The economic group has been derived from the fourth technical parameter group.

3.1. Parameter groups

1. Technical parameter group: group of the most important ICE relevant physicochemical parameters of fuels, which can provide information about combustion properties forward before using fuels in engine. These are pre-combustion parameters.
2. Technical parameter group: group of external parameters of the engine with using (combustion) of fuel.
3. Technical parameter group: group of combustion properties recorded during the combustion of fuel.
4. Technical parameter group: group of emission parameters, which provide us with information about the combustion afterwards.
5. Economic parameter group: group of economic parameters derived (calculated) from the air pollutant emission of the engine.

3.2. Details of each group

1. Technical parameter group (most important ICE relevant physicochemical parameters of fuels, pre-combustion parameters).

Table 1 summarizes the most important physicochemical properties of the tested fuels. These results are shown only in case of pure fuels due to the size of the study. Higher density and viscosity with more or less the same Cetane number appear firstly. Heating value of bio-derived materials seem to be also lower may be because of the higher oxygen content of the renewable fuels. Lower evaporation properties can be concluded from the higher flash points of bio fuels. As for the difference between the two-bio liquids, TBK-biodiesel has disadvantages in all cases. Based on the summarized results worse combustion and emission properties can be expected during the engine test series.

Tab. 1. Physicochemical properties of the tested fuels [21]

Fuel	Density [kg/m^3] at 15ºC	Kinematic viscosity [mm^2/s] at 40ºC	Cetane number (ASTM-CFR method)	Heating value [MJ/kg]	Flash point (closed cup method) [ºC]	Flash point (open cup method) [ºC]
Diesel	0.837	2.98	51.1	42.12	70	90
FAME	0.877	5	51.4	36.29	201	189
TBK	0.905	6.43	50.8	34.81	221	185

1.1. parameter – *density* – is higher in case of renewable fuel compared to the fossil diesel thus worse combustion properties may be expected.
1.2. parameter – *kinematic viscosity* – is higher in case of renewable fuel compared to the fossil diesel thus worse combustion properties may be expected.
1.3. parameter – *lower heating value* – is lower in case of renewable fuel compared to the fossil diesel thus worse combustion properties may be expected.
1.4. parameter – *flash point* – is higher in case of renewable fuel compared to the fossil diesel thus worse combustion properties are expected.
1.5. parameter – *Cetane number* – is the same in case of renewable fuel compared to the fossil diesel thus the same combustion properties may be expected.
1.6. parameter – *evaporation properties* – is worse in case of renewable fuel compared to the fossil diesel thus worse combustion properties may be expected.
1.7. parameter – oxygen content – are better in case of renewable fuel compared to the fossil diesel thus better combustion properties may be expected.

Evaluation of the 1. parameter group

- Number of parameters in the group: 7.
- Resultant of parameter changes: 1 favourable, 5 unfavourable, 1 neutral.
- Number of directions of parameter changes: 3 (favourable, unfavourable and neutral).

2. Technical parameter group (external engine parameters).

The two most important economic parameters are the specific fuel consumption with a measurement unit of g/kWh and the effective efficiency of an engine. As expected the fuel consumption increases with growth of the bio-blending rate in the tested fuel. This tendency is due to the lower heating value of bio-derived fuels. The brake thermal efficiencies (BTE) of the engine are similar at one engine operating point. From efficiency point of view, renewable fuels are not worse than conventional one.

2.1. parameter – *brake specific fuel consumption* – is higher in case of renewable fuel compared to the fossil diesel, which means that combustion of renewable fuels is worse than that of fossil diesel.

2.2. parameter – *BTE* – is the same in case of renewable fuel compared to the fossil diesel. This situation occurs because of the higher amount of dose to reach the same power level with renewable fuels.

Evaluation of the 2. parameter group
- Number of parameters in the group: 2.
- Resultant of parameter changes: 1 unfavourable, 1 neutral.
- Number of directions of parameter changes: 2 (unfavourable and neutral).

3. Technical parameter group (combustion properties recorded during the combustion).

In Fig. 1, in-cylinder (indicated) pressures are plotted. They have been recorded at all operation points and for all the tested fuel species. Evaluating the effect of the biofuel on the in-cylinder pressure generally can be obtained that the pressure maximum and the pressure rising rate is higher. This is the situation also in case of the heat release rate results. Heat release rate is calculated from the in-cylinder pressure curves with the help of the first law of thermodynamics [23].

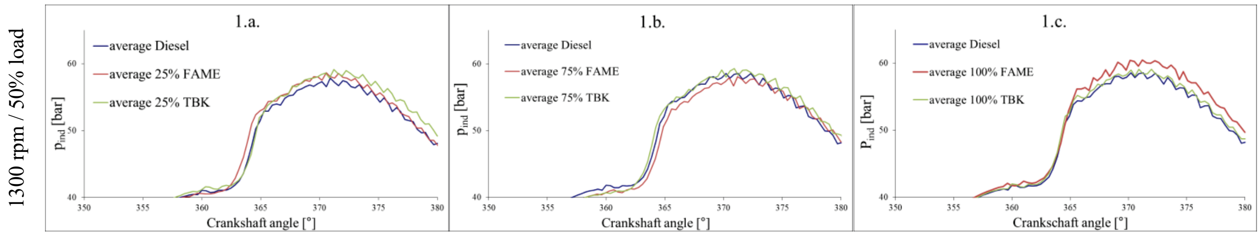

Fig. 1. In-cylinder pressure [21]

3.1. parameter – *maximum value of in-cylinder pressure* – is higher in case of renewable fuel compared to the fossil diesel, which can mean better combustion efficiency.
3.2. parameter – *pressure rise rate* – is higher in case of renewable fuel compared to the fossil diesel, which can mean worse combustion efficiency.
3.3. parameter – *maximum value of heat release rate* – is higher in case of renewable fuel compared to the fossil diesel, which can mean better combustion efficiency.
3.4. parameter – *heat release rise rate* – is higher in case of renewable fuel compared to the fossil diesel, which can mean better combustion efficiency.

Evaluation of the 3. parameter group
- Number of parameters in the group: 4.
- Resultant of parameter changes: 4 favourable.
- Number of directions of parameter changes: 1 (favourable).

4. Technical parameter group (emission parameters, information about the combustion afterwards)

Gas phase emission and also the particulate relevant emission of the engine have been measured during the test series. Investigated gas phase components are nitrogen-oxides, carbon monoxide, total hydrogen-carbon. Particulate mass and total particulate number means the particulate relevant emission engine in this case. These parameters have also been recorded for all fuel species investigated and at all engine operating point. From analysis, the gas phase emission results can be stated a small amount of combustion improvement, because NO_x emission increases and HC emission decreases with growing bio blending rate in the tested fuel. This tendency suits for the combustion improvement tendency concluded in the previous section.

Particulate relevant emission relevant results can be found in the Fig. 2 (upper). Mass of particulate matter shows a constantly increasing tendency with getting larger bio blending rate. It is proved to be true for all the three engine-operating points. In contrast, the total particulate number presents a changing tendency over the bio-blending rate. In case of pure investigated biodiesels, the total particulate number is at each operating point higher compared to the pure diesel's total particulate number in the exhaust gas of the engine.

4.1. parameter – *emission of hydrogen-carbon* – is lower in case of renewable fuel compared to the fossil diesel, which can mean better combustion efficiency.

4.2. parameter – *emission of carbon monoxide* – is the same in case of renewable fuel compared to the fossil diesel, which can mean unchanged combustion efficiency.

4.3. parameter – *emission of nitrogen-oxides* – is higher in case of renewable fuel compared to the fossil diesel, which can mean better combustion efficiency.

4.4. parameter – *Filter Smoke Number* – is lower in case of renewable fuel compared to the fossil diesel, which can mean better combustion efficiency.

4.5. parameter – *opacity* - is lower in case of renewable fuel compared to the fossil diesel, which can mean better combustion efficiency.

4.6. parameter – *particulate mass* – is higher in case of renewable fuel compared to the fossil diesel, which can mean worse combustion efficiency.

4.7. parameter – *particulate number* - is higher in case of renewable fuel compared to the fossil diesel, which can mean worse combustion efficiency.

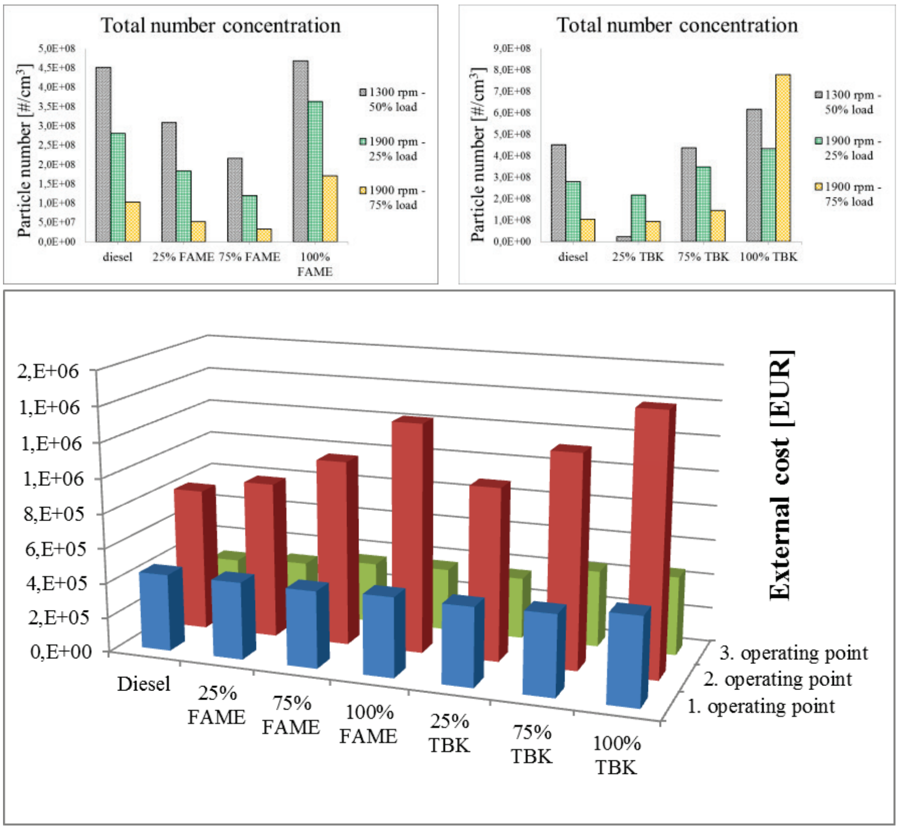

Fig. 2. Particulate number (upper two) and external cost results (under)

Evaluation of the 4. parameter group

- Number of parameters in the group: 7.
- Resultant of parameter changes: 4 favourable, 2 unfavourable, 1 neutral.
- Number of directions of parameter changes: 3 (favourable, unfavourable, neutral).

5. Economic parameter group (external costs derived from air pollutant emission)

Results of external cost calculation derived from exhaust emission components are presented in Fig. 2 (under). Calculation method contained the part calculation the CO_2 saving potential of the biodiesels. The previously established increasing NO_x emission as a combustion improvement effect is an adverse effect in the emission related cost case. Against the CO_2 saving potentials of renewable fuels – which is 45% in our renewable fuel case [10] – it seems to be a rising tendency with bio blending rate of the tested fuel. This tendency is proved to be the same at all the three operation points. It is mainly due to the particulate emission, because the particulate's cost specific emission factor is the highest among the others.

5.1. parameter – cost derived from emission of hydrogen-carbon – is lower in case of renewable fuel compared to the fossil diesel, which can mean better combustion efficiency.

5.2. parameter – cost derived from emission of carbon monoxide – is the same in case of renewable fuel compared to the fossil diesel, which can mean unchanged combustion efficiency.

5.3. parameter – cost derived from emission of nitrogen-oxides – is higher in case of renewable fuel, which can mean better combustion efficiency, but since nitrogen-oxides are dangerous components, thus higher level of emission causes higher external cost.

5.4. parameter – cost derived from emission of particulate measured with gravimetric process – is higher in case of renewable fuel, which can mean worse combustion efficiency.

Evaluation of the 5. parameter group

– Number of parameters in the group: 4.
– Resultant of parameter changes: 3 unfavourable, 1 favourable.
– Number of directions of parameter changes: 2 (favourable, unfavourable).

Tab. 2. Evaluation of external costs derived from air pollutant emissions (1. engine operating point)

No.	5.1.	5.2.	5.3.	5.4.
parameter	HC cost	CO cost	NO_x cost	PM cost
change 100% FAME	-19%	+8%	+8.7%	+16.4%
change 100% TBK	-19%	+1.4%	+9.7%	+25.1%

Conclusion of subparagraph 3.6. if parameters are compared in case of renewable fuel to fossil diesel:

– in one group of parameters there are differences in the parameters' direction of changes,
– resultants of the five-parameter groups are different.

4. Conclusions

ICE relevant physicochemical properties and effect of combustion and emission of renewable fuels and their controlled blends have been investigated. External costs were also calculated from emission values with an own our on created calculation methodology. On the basis of the results introduced in the article above the summary evaluation can be done as follows:

– (i) The use of bio-derived fuels in a Diesel engine can be observed as favourable based on certain parameters, but relating other parameters, renewable fuels can be evaluated as undesirable. Because of this situation, the assessment of these kinds of fuels is not clear if we compare these fuels with conventional fossil fuel.
– (ii), because of (i), for complex evaluation of fuels regarding their usage in a compression ignition engine it is essential to create the five groups of parameters presented above and the assessment should be carried out for considering the parameters of these five groups. A parameter group should contain many parameters.
– (iii), (i) and (ii) can also mean, that valuation according to one – any – parameter or group of parameters can give us false information whether the use of biofuels is useful or undesirable compared to fossil diesel.

– (iv) Having regard to the results it can be established that almost in the most cases the direction of the parameters' changes is negative when bio-derived fuel is a part of the investigated fuel. Thus, the evaluation's centre of gravity has been observed as shifted in the negative direction.
– A goal in the future to refine the complex evaluation method further with exact factors relating to the parameters in a parameter group.

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