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ALTERNATIVE FUELS AND TECHNOLOGIES FOR COMPRESSION IGNITION INTERNAL COMBUSTION ENGINES

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Abstract

The traditional use of fossil-based fuels is now widely considered unsustainable because of depleting their natural resources. Potential substitutes of fossil fuels are oils of renewable origin such as various vegetable and non-edible oils. The aim of using these oils or their methyl esters (biodiesel) is to establish and maintain a balance between agriculture, economy and environment protection. However, realizing the increasing demand of raw materials currently used can be achieved not only by increasing the production area but also by introducing new materials or technologies. The article presents and evaluates modern raw fuel components that are currently being investigated. Furthermore, the article deals with the dual fuel combustion technology in detail, with which the processed fuels are becoming available for use in Compression Ignition (CI) engines, where conventional blending is difficult or their use exclusively in diesel engines is economically unjustified. In case of dual fuel engine systems, the primary fuel, such as (wet)ethanol, methanol, LPG, H_2 etc. is injected into the intake manifold of the engine and the premixed mixture simultaneously produced is ignited by the pilot diesel fuel as secondary fuel injected directly into the engine cylinder. This technology can significantly reduce exhaust emissions and can slightly increase engine efficiency. The achievements in this field and recently obtained results by the author and his research group are also presented. Exhaust emissions, performance and combustion characteristics were measured and analyzed with respect to several operating parameters as follows: premixed ratio (rp), pilot timing and engine load.

Keywords: *alternative fuels, air pollution, environmental protection, dual fuel technology*

1. Introduction

According to the International Energy Agency (IAE) the current trends in energy storage and use are economically, environmentally and socially unsustainable. Without decisive action energy-related greenhouse gas (GHG) emissions will grow more than double by 2050 and the increased oil demand will heighten concerns over the security of supplies [1]. To avoid this problem the European Council endorsed a mandatory target of a 20% share of energy from renewable sources in overall Community energy consumption by 2020 and a mandatory 10% minimum target to be achieved by all member states for the share of biofuels in petrol and diesel consumption for transportation purposes by 2020. There are several biofuel production methods with various raw materials, nonetheless a number of improvements are required to meet the above targets. The greenhouse gas emission savings of the present biofuel production technologies will be at least 35% following the directive 2009/28/EC of the European Parliament. Furthermore, from 1 January 2017, the greenhouse gas emission savings from the use of biofuels and bioliquids will be at least 50% and the GHG emission saving of biofuels will be at least 60% from 1 January 2018.

This directive also provides rules for calculating the greenhouse gas impact of biofuels, bioliquids and their fossil fuel equivalents. According to this directive the typical greenhouse gas emission savings of the traditional – first generation type – renewable diesel fuels are between 36-62%, the savings of waste vegetable biodiesel GHG are at 88% and the savings of hydrotreated vegetable oils are between 40-68%. Savings could be even higher, but it has to be certified by a fuel company. In comparison the typical greenhouse gas emission savings of the sugar beet ethanol are at 61%, the savings of a non- specified process of wheat ethanol are at 32% and the savings of wheat ethanol with straw as processed fuel in a CHP plant are at 69%. The estimated GHG savings of wheat straw ethanol are at 87%, the savings of other technologies of waste wood ethanol are between 76-87% and the savings of biogas as compressed natural gas emission from different sources are between 80-86%.

2. Alternative feedstocks of biofuels

In case of compression ignition engines biodiesel is a commonly used biofuel, which features several advantages. Biodiesel is an efficient, clean alternative to fossil fuels. Its advantages can be highlighted as follows [2]:

- safe to use in all conventional diesel engines,
- non-flammable and non-toxic,
- reduces exhaust gas emissions,
- low sulphur and aromatic (benzene derivatives) content,
- biodegradable [4].

There are also some disadvantages of biodiesel blends. These fuels loosen deposits causing them to block fuel filters. The acid-based components, free fatty acid content, as well as gum formation due to oxidation and polymerization during storage and combustion, carbon deposits and the thickening of lubricating oil are serious problems [2]. From the alternative fuels' point of view not only the GHG emission reduction potential is important, but the demand for biofuels and land demand as well [3]. Year by year biofuel production systematically increases. In 2010 it was 1855.648 thousand barrels per day. The main biofuel producers are North America (914.42 TB/D), Central & South America (588.25 TB/D) and Europe (248.31 TB/D). The main biofuel refineries in the EU were Germany (25%), France (22%), Spain (10%), Italy (7%) and Belgium (5%). The other countries produced less than 5% in 2010 [5].

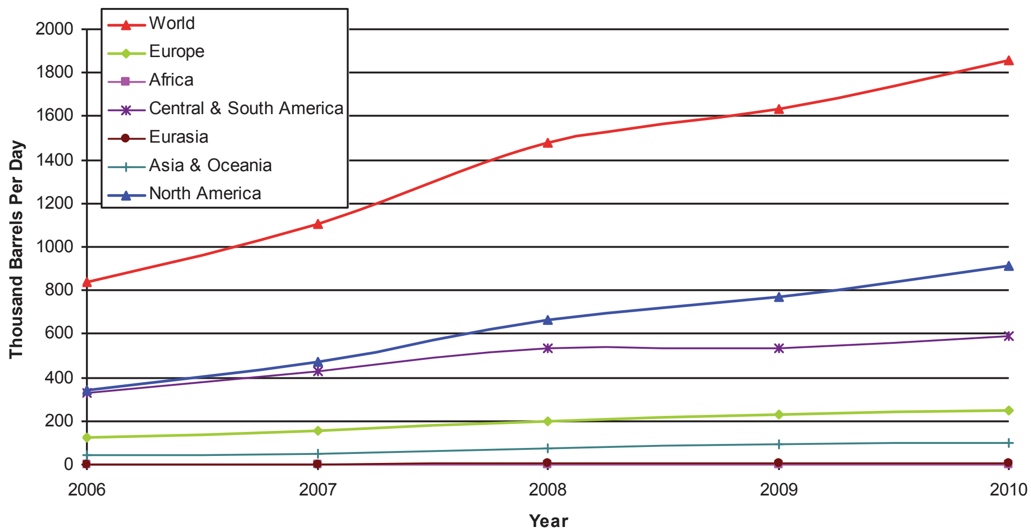

Fig. 1. Annual Biofuel Production by Regions [5]

The common biofuel feedstocks have different yields, consequently the conventional biodiesel feedstocks have different –average– yields. The palm oils' yield is the highest 3600-5300 litres/ha, rapeseed has around 800-1700 litres/ha. In order to compare them it is worth mentioning that the nominal ethanol biofuel yield of the sugar beet is ~4000 litres/ha, sugar cane yield is ~4900 litres/ha and the corn yield is just ~2600 litres/ha. The land demand in 2010 was 30 Mha and in 2020 can be 50 Mha. [1]. The significant part of biodiesel production is that feedstock comes from edible oils, because these raw materials and their production technology are well known. There is an intensively increasing demand for the feedstock for food and fuel, therefore the sustainable raw materials of biofuels should be derived from renewable and non-food biomass sources. [6]. Based on the above mentioned it is important to identify the possible and potential raw materials for diesel fuel production (Tab. 1).

Tab. 1. Comparison of different biodiesel feedstock [7]

Plant source	Seed oil content [%wt oil biomass]	Oil yield [l. oil/ha year]	Biodiesel prod. [kg /ha year]
Hemp (Cannabis Sativa L.)	33	363	321
Soybean (Glycine Max L.)	18	636	562
Jatropha (Jatropha Curcas L.)	28	741	656
Camelina (Camelina Sativa L.)	42	915	809
Canola/Rapeseed (Brassica Napus L.)	41	974	862
Sunflower (Helianthus L.)	40	1070	946
Castor (Ricinus Ommunis)	38	1307	1156
Palm oil (Elaeis Guineensis)	36	5366	4747
Microalgae (medium oil content)	50	97,800	86,515

It can be set out, that the currently used feedstock has low yield, except palm oil, because its yield is 4747 kg/ha which is as high as the yield of sugar beet or sugar cane.

Many feedstocks have low yield potential but they are favourable from environmental management and technology's point of view [6].

Algae are one of the best renewable feedstock of biodiesel, because they have several properties considering them as a good source for bio-fuel production. They grow quickly, have high polyunsaturated fatty acids with double bonds and contribute to rapid biomass production. Within 24 hours micro algae can double their biomass weight. The oil content is high, in weight terms, more than 80% of the dry biomass and it has high yield, thus from economical point of view it can be treated as an effective source of biofuel.

Castrol is a shrub with the height of 10 metres. This plant usually grows on tropical and sub-tropical areas and it requires low humidity and a temperature between 15-38°C. The most castrol oil is produced by India, China and Brazil. The productivity is about 470 kg oil per hectare. Castrol seeds contain 46-55% oil by weight. The plant's seeds are poisonous to human and animals as they contain ricin acid.

Jatropha is a small tree with height of 5 metres that can prevent and control erosion. This plant tolerates unbalanced climatic conditions. The annual yield of plant is 2-5 tonnes of dry seeds per hectare. The seeds of the plant contain 30% oil by weight. Jatropha is a potential source for biodiesel, because it produces non-edible oil, furthermore it can be used for diesel substitute or extender.

Moringa is a small tree with the height of 5-12 metres and its fruit is 50 cm. The seeds contain 33-41% oil. This plant grows quickly, it can tolerate the soil with the pH levels of 5.0-9.0 and rainfall range. Moringa seeds have edible oil that has similar fatty acid composition to olive oil, thus it is used to substitute olive oil.

Croton is a shrub or small tree with a flower, its fruits are about 2 cm that contain a single seed. This typical African plant produces 25-50 kg of seeds annually with a 30-56% of oil content. The oil is yellow, orange or brown, depending on the age of the plant. Because of its alkaloid ricinine content it has toxic characteristics so it belongs to the non-edible renewable fuel source group. The growth of trees improves the soil's organic matter [10].

The parameters of different biodiesels comply mainly with the requirements of the EN 14214 standard (Tab. 2.)

Tab. 2. Comparison of main parameters of different biodiesels

Property	Biodiesel from microalgae	Jatropha methyl ester	Soybean methyl ester	Sunflower methyl ester	Palm oil methyl ester	Croton methyl ester	Moringa methyl ester	Castor biodiesel	EN 14214
Density [kg/l]	0.864	0.884	0.885	0.86	0.88	0.8796		0.904	0.86–0.9
Viscosity at 40°C	5.2	4.40	4.0	4.1	4.16	4.16	4.83	10.75	3.5–5.0
Flash point [°C]	125	163	178	183	164	104.5		160	>101
Solidifying point (pour point) [°C]	–12	0	–7	–2	15	N.D.	17	–45	Summer < 4.0, Winter < –1.0
Cold filter plugging point [°C]	–11	–1	–4	2	12	–11	N.D.	N.D.	Summer < 0, Winter < –15
Acid value [mg KOH/g]	0.374	0.48	0.15	0.20	0.24	0.702	0.39	0.35	<0.5
Lower heating value, [MJ/kg]	41	36.1	33.5	33.5	33.5	36.28	N.D.	30.4	
cetane number	52 min.	51.6	45	49	62	56.39	67.07	42	>51
Refs.	[8, 9]	[10]	[11]	[11]	[12]	[10]	[13]	[14-16]	

It is only not biodiesel that can be used in CI engines, with blending the use of alcohols is also possible. Ethanol-fossil diesel fuel blends can be formed only with the aid of an emulsifying agent, but bioethanol-biodiesel-fossil diesel oil emulsions can be used without any agents [17]. Fossil fuel – (n)-butanol blends were investigated as well as a possible solution of GHG saving and emission reduction both in SI engines [18] and CI engines [19]. In case of these blends the GHG friendly production of butanol is a key point. [20]

Biofuels for CI engines could be other non-conventional fuels as well, such as H_2, biomethane and biogas, which have high greenhouse gas emission saving potential, or methanol produced by several technologies (farmed or waste wood), or wet-ethanol, which is investigated in our research. These fuels are not usable for blending but with dual-fuel technology they became usable in diesel engines.

3. Dual-Fuel Diesel Engines

In case of the dual-fuel diesel engine the -knock-resistant- fuel as the primary fuel is injected into the intake manifold of the engine. At the end of the compression stroke, the homogenous mixture is ignited by diesel fuel as secondary fuel injected directly into the combustion chamber.

Dual-fuel technology has become more and more popular in these days. The two following solutions are known. The more frequently used one is when the engine management is not disturbed, and a secondary fuel supply system is built in. An accessory control unit measures the speed and load – with the aid of pressure or air mass flow rate measurement – and controls the injection. The advantage of this system is the relatively low cost, but with these systems the primary fuel can be injected only in case of low or medium loads. This solution is commonly used in case of LPG-diesel fuel systems.

In the case of the other solution, which is investigated in our research, the main goal is to increase the proportion of the primary fuel as much as possible. However, in case of these systems a completely new engine management is required.

Several renewable fuels were investigated during our research from ethanol and methanol having various water to LPG ratio. In this paper selected results of wet-ethanol are included.

Dual-fuel diesel engines can be operated with ethanol with high thermal efficiency. Noboru et al [21] investigated the performance and combustion characteristics of the indirect injection dual-fuel engine with 99.5% ethanol. However, the maximum premix ratio they used was 38%. They found out that knocking could be problematic especially at high loads. To avoid this problem they used retarded injection timing in dual-fuel mode.

Lu et al. [22] conducted a study evaluating the emissions and combustion characteristics of a direct injection dual-fuel engine fuelled with biodiesel and anhydrous ethanol. The overall equivalence ratio was varied between 0.45 and 0.68 and the premixed ratio was varied between 0% and 65%. According to their results, ignition delay and the peak value of heat release rate increases with increase in the premix ratio. CO and HC emissions are higher than those of diesel mode but NOx and smoke emissions simultaneously decrease remarkably. However, they did not consider the injection advance.

Several studies have showed that dual-fuel diesel engines with different gaseous fuels such as methane or LPG suffer inferior performance and emission characteristics at low load. This is because at low load the homogeneous mixture is too lean to provide stable flame propagation that means the mixture located proximity to the pilot flame is able to propagate [23–25]. Based on the above review, in the present study emissions, performance and combustion characteristics of dual-fuel diesel engine fuelled with wet ethanol were experimentally investigated especially at high loads and high premixed ratios.

3.1. Investigation of the Dual-Fuel Diesel Engine

An experimental investigation was carried out on a dual-fuel diesel engine fuelled with wet ethanol. Exhaust emissions, performance and combustion characteristics were measured and analysed on a wide range of operating parameters.

Usage of ethanol fuel based on renewable resources has several advantages. In general, it decreases CO_2 emission depending on technology and row material [26]. Supply security is supported by ethanol fuel as well. In the agriculture sector, producing ethanol affords possibility to sell the unmarketable stock, reduces unemployment and promotes keeping people in the country. Recent technologies use anhydrous ethanol, which has poor overall energy gain. For example U.S. corn based anhydrous ethanol has a net energy gain of only 21 percent including the co-products. Using wet ethanol instead of anhydrous one can increase the energy gain remarkably. The same corn based ethanol fuel containing 5% water has a 35% gain including the co-products [27, 28].

Experiments were carried out on a generator set, which involves an IVECO AIFO 8031 three-cylinder, naturally aspirated direct injection diesel engine, a MARELLI M8b 160 synchronous generator and the required controlling systems. The synchronous speed was 1500 RPM. The measured power and efficiency values had to be divided by the efficiency of the generator (which is 0.9 according to its manual) to achieve effective values.

The wet ethanol was injected into the intake port of the each cylinder. The installation of the injection lines needed a new intake manifold system, which was made by welding from stainless steel pipe and cut pieces that were suitable for receiving the nozzles. The fuel was atomized by the nozzles onto the intake valves to achieve less contact to the wall of the intake manifold avoiding the condensation. According to our previous investigations the wet ethanol needed to be preheated to improve atomization structure.

The wet ethanol fuel was a mixture of 95 m/m% ethanol and 5 m/m% water. The premix ratio (r_p) was defined as the ratio of energy delivered by wet ethanol to total energy that involves wet ethanol and diesel fuel.

3.2. Results of the Measurement [29]

Figure 2 shows the brake thermal efficiencies (BTE) in the function of injection advance at different premixed ratios. It can be seen that optimal injection advances for maximal BTE increase with increasing premixed ratios. This can be explained mainly with two phenomena. Firstly wet ethanol has high latent heat of vaporisation causing remarkable temperature drop of cylinder charge at the end of compression stroke. Therefore the ignition delay of pilot fuel is extended. Secondly the lean wet ethanol mixture characterizes with slow flame propagation. At high premixed ratios distinct brake thermal efficiency increment can be achieved. At optimal injection advance the BTE is 38.4% with 92% premixed ratio, which is better than the 37% with pure diesel fuel run.

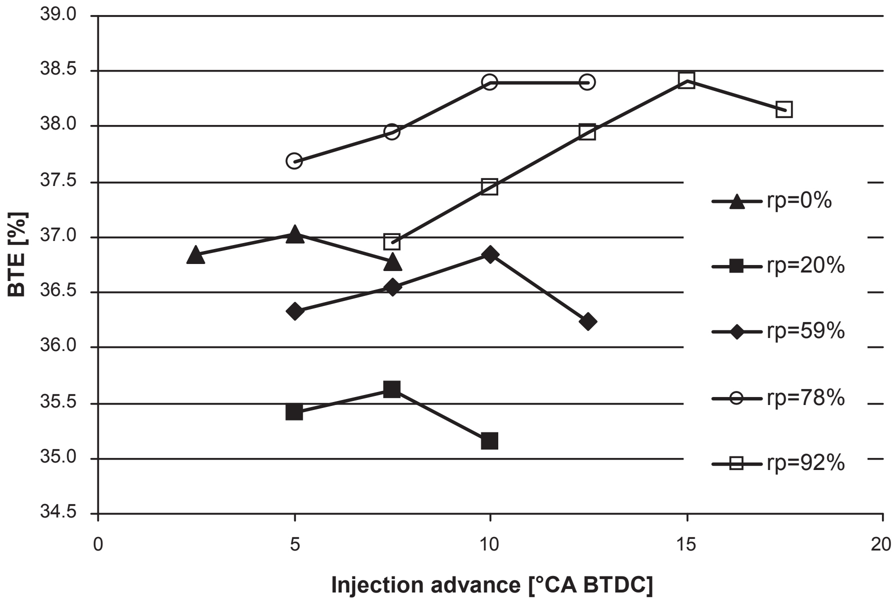

Fig. 2. Brake thermal efficiency in the function of injection advance at different premixed ratios [29]

At low engine loads – at 66% and especially at 33% – remarkable decrement of BTE and high HC and CO emissions was observed at all premixed ratios. However, NOx and PM emissions decrease with premixed ratio at these low loads as well. Fig. 3 illustrates the decreasing BTE and the rapidly increasing HC emissions below 83% load. It can be observed that in case of nearly constant diesel pilot dose the increase of load (increase of primary fuel amount) has remarkable effect on the combustion process. In case of low premix ratio the combustion process of primary fuel is not sufficient (high THC, low BTE). When increasing the amount of primary fuel there is a progress in the combustion process, thus the premix ratio is a very important parameter in dual-fuel engines, therefore it is important to investigate the combustion process in dual-fuel engines.

3.3. Combustion Process in Dual-Fuel Engine

Figure 4 presents the cylinder pressure curves and heat release rates vs. crank angle at 100% load and fixed injection advance of 7.5 CA° BTDC. The introduced wet ethanol cools down the cylinder charge, which causes noticeable pressure drop, and consequently temperature drop during compression stroke. Maximum cylinder pressure increases from r_p=0% to r_p=59% and drops remarkably at higher premixed ratios, reaching a much lower value at r_p= 92% compared to pure diesel operation. A high frequency pressure fluctuation appears at the combustion phase between r_p=0% and r_p=59% causing audible knocking noise during operation. From heat release rate (HRR) curves it can be clearly seen that ignition delay gradually increases with increasing premixed

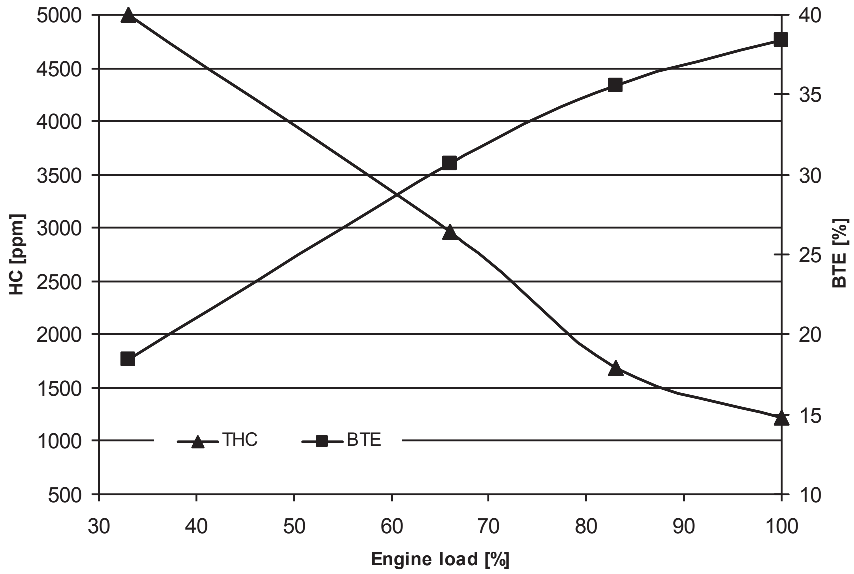

Fig. 3. HC emission and brake thermal efficiency vs. engine load at nearly constant pilot dose (0.46-0.60 [kg/h]) [29]

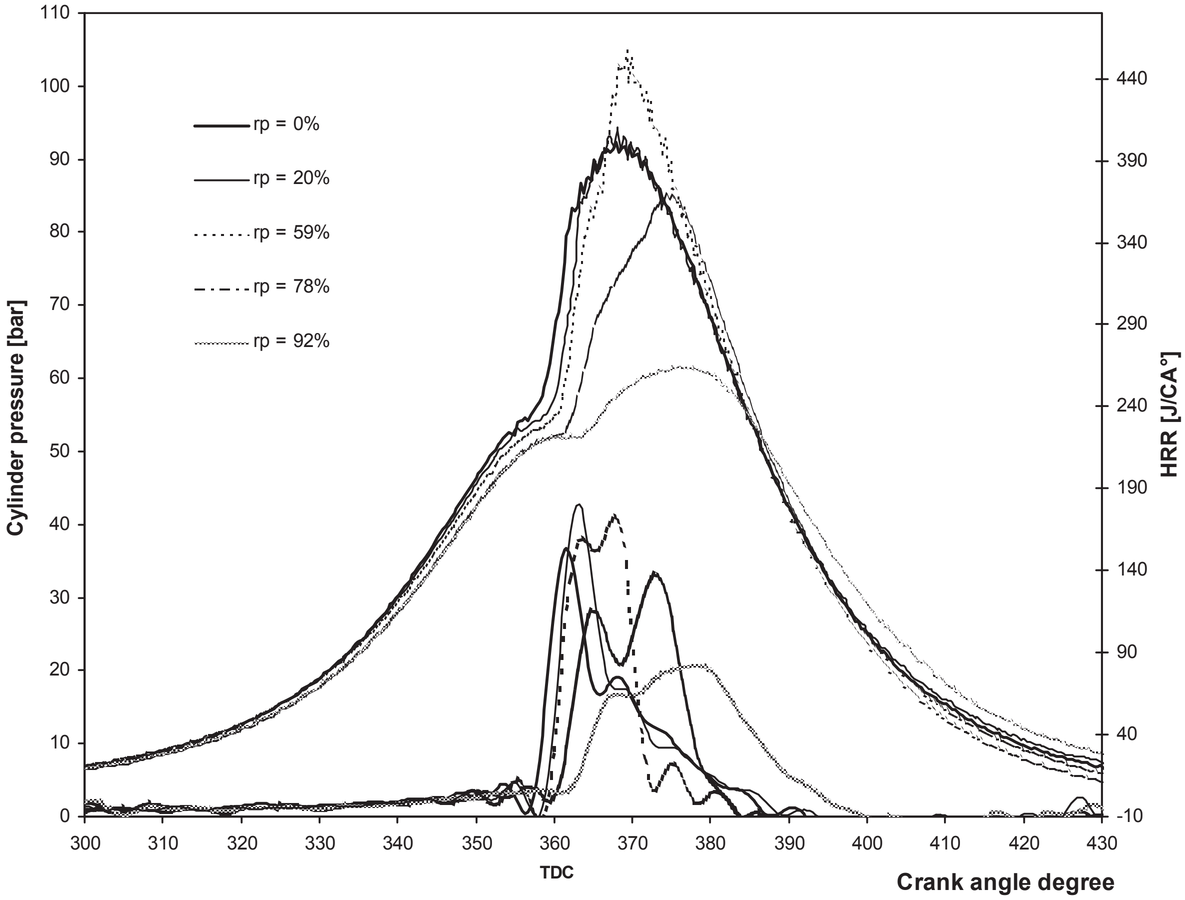

Fig. 4. Cylinder pressure curves and heat release rates in the function of crank angle at 100% load and injection advance of 7.5 CA° BTDC [29]

ratios. This is reasonable with the above-mentioned temperature drop at the end of the compression stroke. HRR curves can be separated into two distinct phases in each case, although remarkable differences can be observed. At pure diesel operation (r_p=0%) the HRR gives the well-known behaviour where the two phases are premixed and diffusion combustion. At r_p=20% the HRR is very similar to that at pure diesel operation but has higher peak value and delayed ignition start. Further increase of the energy ratio at r_p=59% and r_p=78% the first phase is followed by a short intensive second phase while peak values of both phases gradually decrease. Finally at r_p=92% the duration of second phase is much longer and the peak value is the lowest.

4. Conclusions

It is possible that the greenhouse gas emission savings from the use of biofuels and bioliquids will be at least 50 % after 2018. Waste vegetable biodiesel, sunflower oil and palm oil biodiesel or hydrotreated oil with methane capture will be taken into account as biofuel for traditional Diesel engines according to the directive 2009/28/EC. To meet rising food and fuel demands while increasing efficiency, sustainable raw materials of biofuels should be derived from renewable and non-food biomass sources.

Many biofuels can be produced from various feedstocks. Usability of biofuels in CI engines depends on parameters such as GHG saving, yield and agricultural management, etc. Some feedstocks have low yield, but can be grown on poor soil and tolerate extreme weather conditions. Other have high yield, but their production technology needs to be developed.

Alcohols provide other fuel alternatives for CI engines. Ethanol-fossil diesel fuel blends can be formed only by the help of emulsifying agent, or can be used with dual fuel technology.

Biofuels for CI engines could be other non-conventional fuels - with high GHG saving- in dual fuel CI engines with high efficiency, but the optimization of combustion process is highly recommended.

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