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THE POSSIBILITY OF USE A WASTE PRODUCT OF BIOFUELS PRODUCTION-GLYCEROL AS A FUEL TO THE COMPRESSION IGNITION ENGINE

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Abstract

The article presents results of tests performed in a combustion research unit (CRU) with the two following fuels: light fuel oil (LFO) and glycerol. The CRU is a constant volume combustion chamber machine equipped with an injection system based on that used in common-rail diesel engines with electromagnetic injectors. This machine allows to compare various combustion properties between fuels for specified parameters of injection and a combustion chamber as well. As it is known glycerol is a substance which is obtained from several technological processes such as production of biofuel thus in this way it can be treated as an alternative renewable fuel. The glycerol is characterized by low heating value of 16MJ/kg and relatively high density of 1261 kg/m3. However, its heating value by volume is higher if compared to other liquid fuels. From that reason decrease in energy that can be delivered with fuel is smaller which is approximately 16% lest than for LFO. The parameters measured during this research were: pressure increase, rate of pressure increase (ROPR), ignition delay (ID), main reaction delay (MRD), main combustion period (MCP), end of main combustion (EMC), end of combustion (EC), position of max ROPR (PMR) and max ROPR. The tests were performed with different injection parameters such as injection pressure, injection duration and injection delay as well as under various conditions in the CRU combustion chamber expressed by pressure and temperature. On the basis of these tests the comparison between LFO and glycerol was done. The results were presented in diagrams. The research shows that glycerol used as a fuel, to obtain the same output power, should be injected at higher amounts. Glycerol as a fuel cannot ignite itself, hence to provide combustion the pilot injection of another fuel have to be applied.

Keywords: *glycerol, alternative fuel, diesel engine, combustion properties*

1. Introduction

One of the major problems in engine industry is reducing the exhaust gas emission which leads to improve the environmental protection. To obtain this goal engine manufacturers not only work on their engine construction, control systems but also they have been looking for new fuels which could be replace fossil fuels based on crude oil. The EU established regulations under Directive 2009/28/EC where is written that 20% of total energy production will be from renewable sources and in this 10% for transport needs [2]. For power plants fuelled with different type of fuels the emission regulations are specified in Directive 2010/75/EU where one of a statement is that the European Commission will update at least every 7 years the best available technology (BAT) [3] for this purpose, what is also strongly related with alternative fuels development. As it is mentioned the alternative fuels are cleaner in combustion compared to their fossil counterparts and are more beneficial for growth of the agricultural sector [12]. Corsini et al. [1] during their research compared the emissions of exhaust gases compounds between rapeseed oil and diesel fuel. According to their results for not modified engine the emission of NO_x was lower than for diesel fuel, though the emission of CO_2 was at the same level. Because of these advantages many engine manufacturers are interested in use it in their engines. Also blending fossil fuels as diesel fuel with biofuels gives good results in decrease in emission of toxic exhaust gases compounds as nitrogen oxides (NO_x), greenhouse gas CO_2 and soot. According to Tutak at al. addition of methanol to diesel fuel contributes to decrease in soot emission and increase in NO_x emission under the fixed injection timings [18]. The fuel in this case was formed as a blend of diesel fuel and methanol with energetic share respectively 20% and 50% of methanol. For the engine fuelled with diesel fuel as a base fuel and the E85 as an additional fuel, injected to the intake port, the decrease in emission of NO_x and soot were also observed what is probably related with high evaporation heat and additional oxygen chemically bonded in the E85 [15, 16]. In some cases where the conditions of combustion are not favourable increase in NO_x may occur, what is happening especially with high content of alcohol in a LFO-alcohol blend what cause the increase in combustion temperature. In that case use of over-expanded cycle in an engine could bring some benefits regarding to lower combustion temperature what shown in their work Grab-Rogalinski et al. [4-6]. The blends of diesel fuel and ethanol were tested in a direct injection diesel engine by Tutak et al. and under this studies for 45% fraction of ethanol by volume they achieve lower emission of CO for both types of fuel supply system [16]. The use of alternative fuel such as various types of oils or alcohols received from plants allows to be independent from the petroleum industry, which is better solution especially for smaller country, which access to fossil fuels can be limited and more expensive.

During production of biofuels one of the by-products is glycerol. Glycerol is a colourless and odourless liquid. It is a side product during the esterification process in biodiesel production using a homogenous catalyst method [11]. The production of glycerol lately increases because of increase in biofuel production, it is said that for every one quantity of biodiesel one tenth is a glycerol [9, 10 14]. Because glycerol is produced with biofuels, from that point of view it can be considered that it is also a biofuel. Combustion of a glycerol is more difficult than combustion of diesel fuel in CI engine because of its viscosity. The glycerol viscosity at normal pressure-temperature condition is several times higher than for diesel fuel. For example the dynamic viscosity for glycerol at 20°C is 1.5 Pa·s [12], kinematic viscosity is 450-750 cSt at 25°C [9, 13] compared to diesel fuel which kinematic viscosity is 4.15 cSt at 20°C [12]. Glycerol is also characterized by lower value of the lower heating value (LHV) which is 16 MJ/kg [8, 14]. But because of its high density which is 1260-1261 kg/m^3 [9, 14] the reduction of energy content calculated by volume is smaller. Glycerol in normal condition is non-toxic and very stable which mean that it is not possible for it to be self-ignited and therefore it can be easily stored. The glycerol can be soluble with water and alcohols [14] therefore it can attract and hold moisture from the air but it cannot be altered by the contact with air. That makes a glycerol an environmentally friendly fuel.

2. Test rig description and experimental setup

The research presented in this paper was done on the Combustion Research Unit (CRU). The CRU is a constant volume combustion chamber with possibility of regulation the internal parameters such as pressure and temperature. In specification used for this research the experimental fuel was injected to the combustion chamber by electromagnetic injector which was similar to those used in common-rail injection systems. To collect data during the measurements the CRU is equipped with pressure sensors which measure injection pressure and pressure inside the combustion chamber. Also to provide stable thermal conditions, for air and fuel, the CRU is equipped with a heater for the combustion chamber and a fuel line as well as thermocouples to control the temperature of individual elements in this system. The overall view of used CRU is depicted in Fig. 1.

Control of the unit and data acquisition is realized by a LabView based control program which allows to adjust all needed parameters such as pressure and temperature of the combustion chamber as well as the parameters for injection as injection pressure, injection duration, injection delay (time between pilot and main injection) and temperature for fuel line elements. The data recorded during the measurements were stored in a PC computer.

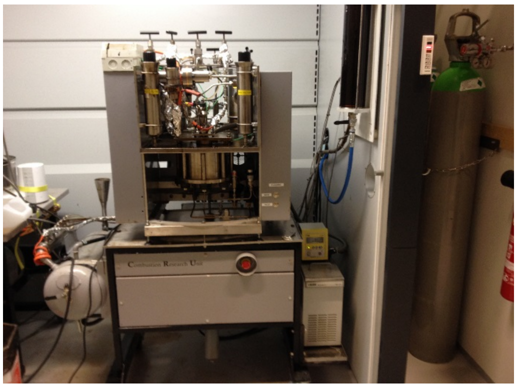

Fig. 1. CRU test bed

During the measurements increase in combustion pressure was recorded and on that basis such parameter as rate of pressure increase (ROPR or dp/dt) was calculated. The rate of pressure increase was calculated as the time based derivative of pressure history according to equation 1:

$$ROPR = \frac{dp}{dt}\left(f_{(p,t)}\right), \quad (1)$$

On a basis of recorded and calculated data the following parameters are determined:
- ID – ignition delay (dp=0.1 bar),
- MRD – main reaction delay (0.1 max PI),
- EMC – end of main combustion (0.86 max PI),
- EC – end of combustion (0.95 max PI),
- PCP – pre combustion period,
- MCP – main combustion period,
- ABP – after burning period,
- AR – area under ROPR curve,
- PMR – position of max ROPR,
- Max ROPR – maximum value for ROPR.

Table 1 presents test configuration during researches.

Tab. 1. Test matrix

(LFO, Glycerol)			
Pressure of injection p_{inj} (bar)		Injection duration inj_{time} (μs)	
55 bar/550ºC	70 bar/590ºC	55 bar/550ºC	70 bar/590ºC
500		500 (1500 Glycerol)	
750		Optimal[a]	
1000		1500 (2500 Glycerol)	

Injection parameters for the 10 bar increase in pressure during combustion in initial parameters of the combustion chamber (IPoCC) 70 bar and 590°C.

The injection duration during the measurements was determined for 10 bar increase in combustion pressure for initial parameters of the combustion chamber (IPoCC) equal to 70 bar and 590°C for all tested fuels. For the each measured point several injections were performed to obtain good repeatability of measurements and calculations.

3. Result and discussion

Under the first tests the injection of glycerol without pilot injection was done. The tests were performed for two states of initial conditions of combustion chamber 55/550 and 70/590. As can be seen in Fig. 2 and 3 the combustion did not occur.

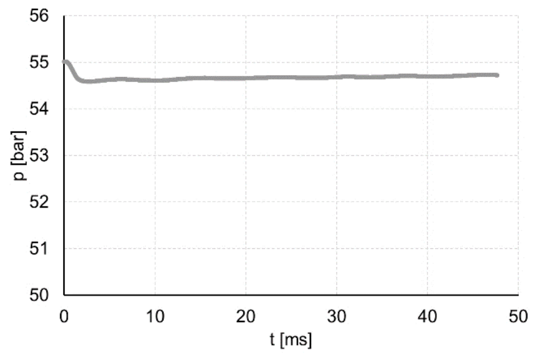

Fig. 2. Pressure increase for Glycerol (55 bar & 550 C)

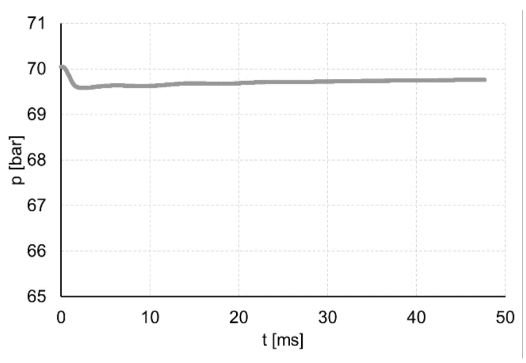

Fig. 3. Pressure increase for Glycerol (70 bar & 590 C)

The only observed phenomenon was the decrease in pressure caused by the evaporation of the injected glycerol in both cases of initial parameters of combustion chamber. Because of very difficult ignition of glycerol what is related with its low value of the cetane number (CN=0-10 [10, 19, 20]) the two methods can be applied to start the combustion. The first is based on two stage injection where at first, the pilot injection of fuel with high cetane number is applied and then injection of the glycerol takes place by the second injector. The second method is to heat up air delivered to the engine as it is described by McNeil et al. [10]. Because the CRU is not the IC engine and there is no systems for heating up the income air to the unit, the second method was chosen to perform the tests.

Figures 4 and 5 present the comparison of increase in combustion pressure for various injection pressure between diesel fuel (LFO) and glycerol for internal parameters of combustion chamber equal to 55 bar and 550°C.

From this comparison it can be seen that combustion of LFO lasts shorter than for glycerol. It can be also seen that the pressure increase slope is much steeper for LFO than for glycerol especially at the end phase of combustion. Such behaviour may be caused by much worst atomization, which depends on fuel viscosity, injection parameters [7] and evaporation of injected fuel especially if an amount of injected fuel will be taken into account. The injection duration for LFO to obtain 10 bar increase was 1000μs and for glycerol was 1900 μs, which means that to achieve the same pressure increase during the combustion, almost two times much fuel is needed what is related with LHV of the fuels.

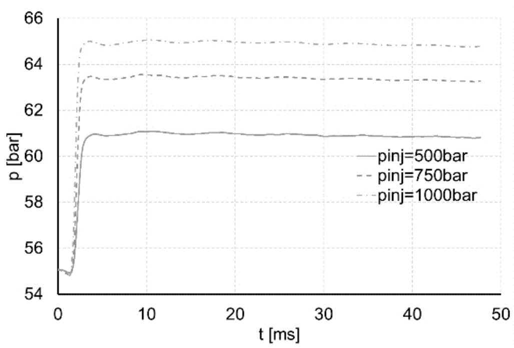

Fig. 4. Combustion pressure increase for various injection pressure (fuel LFO, 55/550)

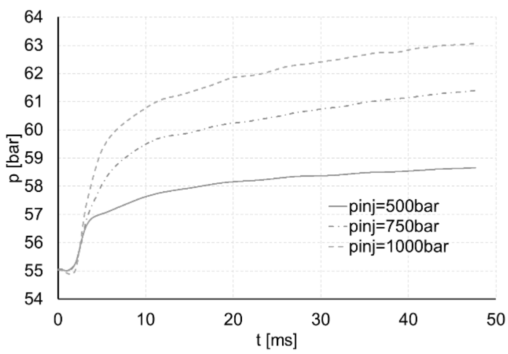

Fig. 5. Combustion pressure increase for various injection pressure (fuel glycerol, 55/550)

Figures 6 and 7 depict the ROPR for tested fuels. As can be seen the ROPR curve for LFO is very stable and with increase in injection pressure maximum value of ROPR is also increase. That phenomenon occurs because to combust more fuel in approximately constant time higher combustion speed is needed. For glycerol ROPR curves in each case has lower value compared with LFO what corresponds to less steeper slope at the pressure increase graph and it is related with fuel energy content in the injected amount, atomization of the fuel and its evaporation.

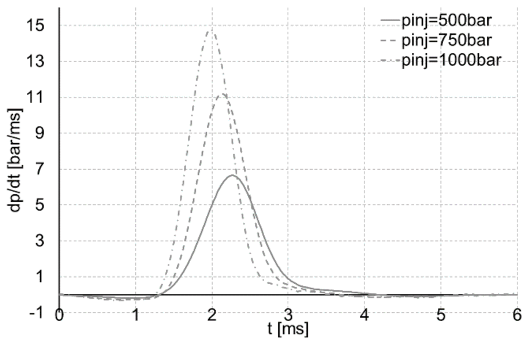

Fig. 6. ROPR (dp/dt) for various injection pressure (fuel LFO, 55/550)

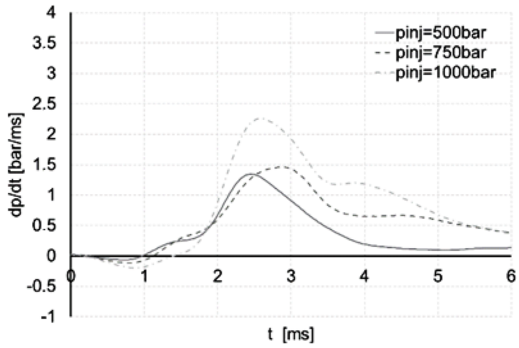

Fig. 7. ROPR (dp/dt) for various injection pressure (fuel glycerol, 55/550)

Figures 8 and 9 present pressure increase in combustion of tested fuels at higher internal parameters for the combustion chamber – 70 bar and 590°C.

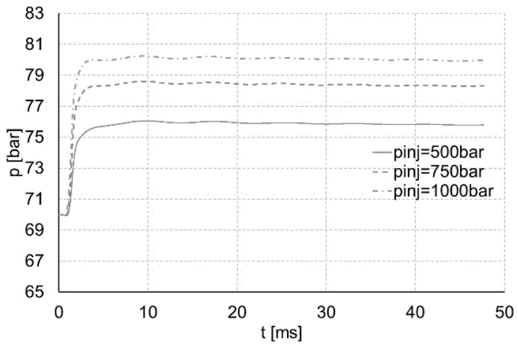

Fig. 8. Combustion pressure increase for various injection pressure (fuel LFO, 70/590)

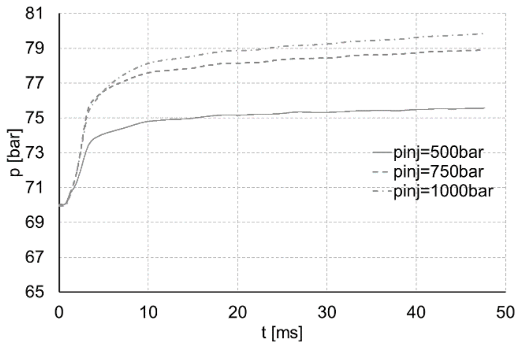

Fig. 9. Combustion pressure increase for various injection pressure (fuel glycerol, 70/590)

As can be seen for higher parameters of the combustion chamber, combustion properties for glycerol are improving compared to the LFO what is caused by better conditions for fuel evaporation during the injection and atomization what is directly related with injection pressure (Fig. 8 and 9). In Fig. 11 it is clearly seen that for all injection pressures combustion starts at the same point. It is due to the pilot injection of LFO initiates combustion. For example for LFO the reaction time, defined as an ignition delay, decreases with increase in injection pressure (Fig. 10). Because the injection parameters for the pilot injection were the same during the tests, such correlation for glycerol cannot be observed.

Figures 12 and 13 present comparison between pressure increase for LFO and glycerol for initial parameters of the combustion chamber equal to 70 bar and 590°C where the injection duration time was changed.

As can be seen in this case the pressure increase depends on amount of injected fuel what means that for all cases the parameters such as atomization and evaporation where the same because the injection pressure was the same for each injection duration.

The combustion parameters such as ID, MRD, EMC, EC, PCP, MCP, ABP and PMR for various injection pressure for tested fuels are presented in Tab. 2.

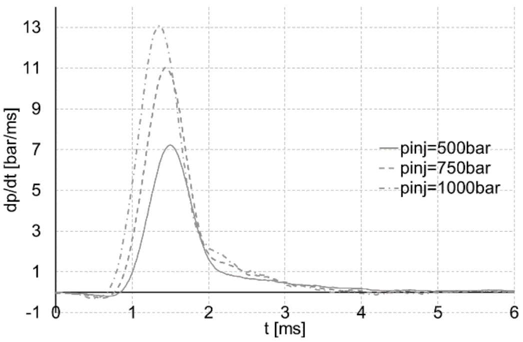

Fig. 10. ROPR (dp/dt) for various injection pressure (fuel LFO, 70/590)

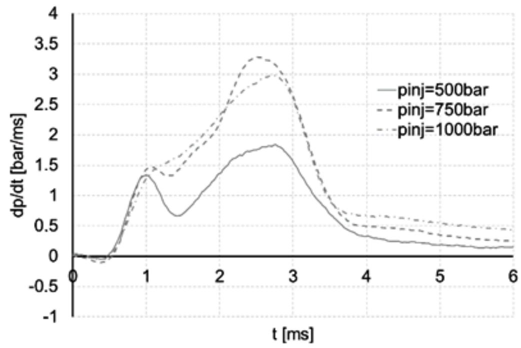

Fig. 11. ROPR (dp/dt) for various injection pressure (fuel glycerol, 70/590)

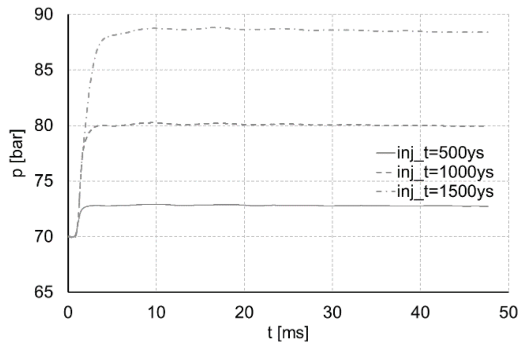

Fig. 12. Combustion pressure increase for various injection duration (fuel LFO, 70/590)

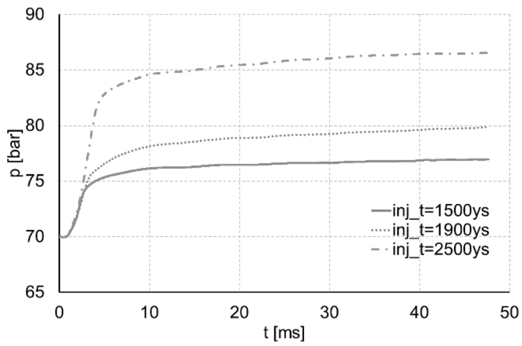

Fig. 13. Combustion pressure increase for various injection duration (fuel glycerol, 70/590)

As can be seen in all cases for LFO the ID decreases with increase in injection pressure and increase in parameters of the combustion chamber. The opposite trend can be observed for glycerol with LFO pilot injection where ID increases with injection pressure but decreases with higher initial parameters in the combustion chamber. That trend may be caused by much better dilution of the LFO pilot with evaporated glicerol. It can be noticed that each combustion parameter decreases for LFO, where the increase in glycerol amount injected to the cylinder generally causes increase of those parameters (Tab. 2).

Tab. 2. Comparison of combustion parameters for various injection pressure

IPoCC[1] [bar/C]	55/550						70/590					
Injection pressure [bar]	500		750		1000		500		750		1000	
Fuel	a	b	a	b	a	b	a	b	a	b	a	b
ID [ms]	1.73	1.96	1.66	1.98	1.54	2.18	1.12	0.88	1.02	0.91	0.90	0.97
MRD [ms]	1.73	2.90	1.66	2.41	1.54	3.76	1.12	1.69	1.02	1.58	0.90	1.57
EMC [ms]	2.71	18.5	2.49	24.7	2.29	31.0	2.64	12.5	2.16	10.3	2.01	9.43
EC [ms]	3.22	35.9	2.77	38.0	2.53	49.1	5.45	28.4	3.23	29.9	2.78	27.1
PCP [ms]	0	0.95	0	0.43	0	1.58	0	0.81	0	0.67	0	0.61
MCP [ms]	0.99	25.6	0.83	22.3	0.75	27.25	1.53	10.8	1.14	8.71	1.10	7.86
ABP [ms]	0.51	17.32	0.28	13.33	0.24	18.04	2.80	12.5	1.07	19.7	0.77	17.63
PMR [ms]	2.29	2.41	2.14	2.74	1.97	2.47	1.49	2.28	1.44	2.55	1.35	2.6

a – LFO; b – Glycerol; [1] – initial parameters of combustion chamber.

Table 3 Real combustion parameters for various injection durations and initial conditions of the combustion chamber.

Tab. 3. Comparison of combustion parameters for various injection duration

IPoCC [bar/C]	55/550						70/590					
Injection duration [μs]	500[1] (1500)[2]		1000[1] (1900)[2]		1500[1] (2500)[2]		500[1] (1500)[2]		1000[1] (1900)[2]		1500[1] (2500)[2]	
Fuel	a	b	a	b	a	b	a	b	a	b	a	b
ID [ms]	1.40	2.01	1.54	2.18	1.59	2.13	0.86	1.03	0.90	0.95	0.93	0.91
MRD [ms]	1.40	3.70	1.54	3.76	1.59	3.07	0.86	1.40	0.90	1.66	1.88	1.84
EMC [ms]	2.85	21.4	2.29	23.49	2.68	20.26	1.63	8.30	2.01	11.8	3.01	8.15
EC [ms]	7.04	38.1	2.53	37.07	3.74	33.76	2.50	25.9	2.78	31.9	4.21	23.6
PCP [ms]	0.00	1.68	0.00	1.58	0.00	0.84	0.00	0.38	0.00	0.71	0.94	0.93
MCP [ms]	1.45	17.7	0.75	20.1	1.08	17.18	0.77	6.90	1.10	10.2	1.14	15.54
ABP [ms]	4.19	16.7	0.24	18.0	1.06	13.5	0.87	17.6	0.77	20.1	1.19	15.54
PMR [ms]	1.73	2.26	1.97	6.38	2.11	3.65	1.12	2.21	1.35	2.28	1.35	3.19

a – LFO; b – Glycerol; [1] – LFO; [2] – Glycerol.

In case were the injection duration time was changed the ID parameter does not show any trend for glycerol combustion. Because the ID parameter for glycerol combustion depends on fuel injection during the pilot injection, thus, these values in this case are very similar for higher initial conditions of the combustion chamber. For lower initial parameters difference between LFO and glycerol in ID is more significant. The LFO ID for both initial conditions increases with increase in injection duration what corresponds to higher amounts of fuel injected, what revealed in temperature drop caused by fuel evaporation after injection.

4. Conclusions

Investigation presented in this paper shows possibility of the CRU use for combustion analysis of fuels that could be used in a compression ignition engine. On a basis of this research the following conclusions can be formulated:

1. Glycerol combusts much slower than LFO especially at the end combustion phase. It can be explained by higher viscosity and density which have negative influence on fuel atomization during injection.
2. For conditions provided for the CRU, combustion of pure glycerol is not possible, because of its low cetane number which is between 0 and 10.
3. Combustion of glycerol with the pilot injection of diesel fuel is possible but in this configuration the stability of it is very low. To improve combustion, increase in the pilot injection dose should be done or blend of glycerol with another renewable fuel should be applied as well.
4. Increase in evaporation of main fuel dose (increasing of injection pressure) during the injection with the pilot causes increase in the ID, but increase of main fuel dose by extending the injection duration time does not affect significantly on ID.
5. The increase in injection duration for glycerol does not significantly influence on such combustion parameters as EMC, EC where these parameters do not show any correlation with injection pressure increase in the contrary to increase in injection pressure, where EMC with increase in injection pressure lasts shorter.

Summing up, glycerol can be used as a fuel in the compression ignition engine but the implementation requires several crucial modifications in the engine injection system and the intake system should be equipped with heaters.

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