Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 October 2020 doi:10.20944/preprints202010.0096.v1

Article

Effective combustion of glycerol in the compression ignition engine equipped with a double direct fuel injection

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Abstract: The paper presents results from investigation focused on toxicity content in the exhaust gases emitted by the internal combustion compression ignition engine fueled with glycerol-ethanol blends at ratio of 50/50% by volume. Innovative issue of this engine is application of 2 high pressure injectors for glycerol-ethanol blend and diesel fuel direct injection at high pressure over 200 MPa. As known, glycerol is considered is by-product from biodiesel production technologies, hence its cost is relatively low to other renewable alternative fuels, which can be applied as a fuel to the reciprocating piston engines. Tests on exhaust gases toxicity were performed. It was found that the toxic components UHC, NOx and CO were below the maximal allowed limits. Both NOx and smoke emissions were strongly reduced with increase in glycerol-ethanol fraction in the fuel. Summarizing, such a fueling strategy proposed in this paper made it possible to effectively and environmentally friendly combust crude glycerol in the compression ignition engine working in a heat and power cogeneration unit. Exhaust gas emission tests conducted in this case confirmed usability of this technology to be implemented into practice.

Keywords: glycerol; combustion; internal combustion engine; exhaust emission; injection system

1. Introduction

One of potential energy source in the nearest future might be glycerol and its derivatives. Currently, significant surplus of glycerol comes from biodiesel technologies, where it is the major by-product. As Presciutti et al. [1] said the glycerol poor Low Heating Value (LHV) and its ineffective combustion reduces the interest to use it as a fuel. However, he provides promising future premises for glycerol. He concluded, that the glycerol fed oxy-combustion avoids acrolein production. Additionally, energy production from glycerol improves the biodiesel chain sustainability. Brock et al. [2] proposed to use glycerol indirectly in forms of its derivatives for combustion purposes. In general, researchers confirm that glycerol has significant potential as a fuel for thermal machinery [3,4].

1.1. Glycerol properties

Glycerol is a major by-product from production of biodiesel from vegetable oils. It yields at amount of 12% from its origin feedstock. As reported, the global production of crude glycerol in 2020 is predicted at amount of 4200 ML [5]. Hence, glycerol price dropped down approximately 6 times in the decade 2000-2010. Glycerol features with relatively low heat of combustion (it is approximately twice lower of that of fossil fuels). It is highly viscous, hence, it makes difficulties in effective spraying and atomization. Additionally, it has a high auto-ignition temperature (nearly 643 K). Physical specification of glycerol is shown in Table 1.

Table 1. Glycerol main physical properties [6-9]

	Property	Unit	Number
1.	Higher Heating Value (HHV)	MJ/kg	18
		kJ/mol	1662
1.	Lower Heating Value (LHV)	MJ/kg	16
2.	Dynamic viscosity at 25°C	Pa·s	1.3-1.7
3.	Kinematic viscosity at 25°C	m^2/s	(450-750)e-6
	and 40°C		(350-580)e-6
4.	Density at 0°C	kg/dm^3	1.26
5.	Cetane Number (CN)	-	0-10

Typical composition of glycerol produced from biodiesel technologies is presented in Table 2 [6- 9].

Table 2. Typical composition of technical glycerol [6-9]

	Component content	% (kg/kg)
1.	Glycerol	70-75
2.	Water	14-17
3.	Mineral content (ash)	6-8
4.	MONG (other organic compounds except glycerol)	5
5.	Methanol	<1

1.2. Combustion applications

A number of studies concern the combustion of glycerol in a burner with the possibility of application to heating and power boilers [1, 10-14].

Presciutti et al. [1] proposed oxy-combustion of glycerol to increase flame temperature, hence to completely burn it. Zhu [10] investigated glycerol co-combustion with biochar. He found that addition of glycerol significantly reduces ignition delay time, shortens burnout time and increases burning rate of the droplets. Bohon [12] and Roberts [13] conducted investigation on fossil fuel replacement by crude glycerol in heat and power plants. His work showed that the combustion of crude glycerol could result in significant reduction of NOx emissions as a function of the high chemically bound oxygen content within the glycerol fuel. His conclusion also showed that the cost of replacing natural gas with crude glycerol requires a strong function of the market price per unit of energy for the traditional fuel. They also noticed that alkali metal content in crude glycerol presents a significant issue that needs to be addressed before crude glycerol fuels can be utilized in boilers. Coronado et al. [14] at their work discussed ecological aspects of glycerol combustion in industrial boilers. Coronado found glycerol as is a better fuel alternative than diesel fuel, fuel oil, natural gas, and LPG from an ecological point of view. Burning unblended methylated glycerol has the lowest ecological efficiency, even less than diesel fuel. Queiros et al. [11] tested combustion of crude glycerol with gaseous fuels: natural gas and hydrogen. Glycerol was sprayed by two typical air assisted atomizers under non-reacting conditions in a laboratory furnace fired by a swirl burner. He obtained results that showed the spray fineness for both atomizers increases with the atomizing air to glycerin mass ratio up to 1, CO and HC emissions reduce with glycerol ratio increases up to 1.5 and NOx emission increases as well. Finally, the most important, acrolein emissions were undetectable for all flames studied. Samoilov et al. [15] worked on glycerol oxygenated derivatives as additives to gasoline to improve its physical properties. As he wrote, the glycerol-derived oxygenates decrease the vapor pressure of the gasoline and increase its final boiling points. For the compensating of this effect the base gasoline should be enriched with the light fractions in order to save the same volatility features. Fatimah et al. [16] discussed on possibilities of upgrading glycerol to solketal to make it easier to work as fuel additive.

Summing up, there are several papers showing that combustion of crude glycerol is an inconvenient process due to the following: its low heating value, high self-ignition temperature, acrolein formation, high emissions, high emissions and salt content [14,17,18]. Additionally, high exhaust emission from its combustion to natural environment, as reported by Rodrigues et al. [17], was a challenge which motivated researchers to work out an effective method that can be implemented into combustion units for heat and power production from glycerol. Gupta and Kumar [5] stated that formation of acrolein as harmful product of glycerol combustion can be reduced significantly at high temperature combustion. Except direct combustion and solid fuel method, all the other pathways require purification of crude glycerol. Despite these problems, research is being conducted to develop an effective combustion technology that will be characterized by low exhaust gas toxicity.

1.3. Combustion in the internal combustion engine

Several important problems were reported by researchers working on applying glycerol as the engine substitute fuel. Among others, Stenhede [18] from Wärtsilä company, stated that glycerol cannot be effectively burnt in a diesel engine due to problems with its self-ignition. Hence, research team from Wärtsilä was attempting glycerol combustion using diesel fuel pilot dose. There are other papers which stated that glycerol is a poor fuel which does not burn in either spark ignited or compression ignition engines [19,20]. Other group of researchers (Oprescu et al.) proposed glycerol processing and burn its derivatives as additives to blends with classic fossil fuels [21]. Eaton et al. [22] investigated combustion of glycerol in the diesel fueled engine. He used the mixture diesel fuel – glycerol at glycerol amount of 10 and 20%, He reported problems with mixing and mixture stability, so he had to use ultrasonic blending to obtain glycerol–diesel emulsions. He found nitrogen oxides and particulate matter (PM) emissions were reduced by 5–15 and 25–50%, respectively. Indicated fuel consumption increased corresponding to increase of glycerol content in the fuel because of reduction in the emulsion energy density. Thermal efficiency improvements were observed at high loads. Beatrice et al. [23] worked on applying glycerol ethers as diesel like oxy-fuel for the automotive engine. He stated glycerol derivatives as additives to the neat diesel reduce the flash point of the blends. He tested blends with glycerol ethers of 10 and 20% by volume. He found the glycerol ethers added to neat diesel fuel affects the combustion process, mainly at low engine load through the low Cetane Number (CN) of these ethers. He also found, glycerol ethers are effective for PM emissions suppression. PM reduction is accompanied by a reduction of emitted engine raw particles. He also recommended to continue work on real engine exhaust emission to evaluate the effective impact of glycerol ethers additives on unregulated tailpipe emissions. Munsin and his group [24] conducted research on applying glycerol at small amounts up to 5% to ethanol fuel for the spark ignited engine. They found that glycerol improves ignition process and decreases injection rates by approximately 10% with respect to normal hydrous ethanol. McNeil [25] realized investigation on applying glycerol as fuel to the compression ignition engine. he and his team developed a combustion cycle that permits utilization of glycerol without the need for diesel fuel pilot or cetane improving additives. Their idea was to heat up intake air to temperature of 144°C, that was optimal for that engine type burning glycerol.

Striving to improve the performance, mainly the performance of the reciprocating internal combustion engine, has always been the overriding goal of several industrial and academic research centers. This article describes how to effective deliver hardly flammable fuels to the IC engine using two high pressure injectors for direct in-cylinder fuel injection. After testing, the system was used to burn those fuels which, among others, is glycerol. At the outset, it should be mentioned that the high pressure injection system with two independently working injectors is a solution that is relatively difficult to implement in practice. These difficulties are mainly come from small and limited space in which the additional injector could be mounted. Hence, such solutions are used for large engines, mainly marine engines. For this reason, i.e. due to the lack of space for a second injector, such solutions are not used in automotive engines found in cargo and passenger transport drive systems. Another reason is the economy of such a solution. The use of two injectors working independently increases the cost of manufacturing the engine. Hence, there is no need for such a solution in the case of single-fuel engines or so-called dual-fuel, i.e. engines fueled with two fuels, where the main fuel is natural gas, and the second fuel is diesel used to initiate the ignition and combustion process. The need to use a system equipped with two independently controlled injectors arose in the case of attempts to use glycerol as a fuel for the internal combustion, piston engine. Several research works [26, 27] by Chwist et al. and Grab-Rogalinski et al. were realized in this field of two injection systems in the institute where authors work. It turned out that this is a method that enables injection and combustion of large doses of glycerol, which makes it possible to use glycerol as the main fuel for the engine. Whereas the second injector is used for the injection of a diesel fuel pilot dose, which is to initiate ignition and, consequently, combustion of glycerol.

Summarizing, it can be concluded from the literature survey that such a method of feeding the engine with doubled high pressure injectors to burn glycerol has not been tested so far. Hence, this research can be considered as innovative from that point of view. Currently conducted research on combustion of glycerol in the reciprocating piston engine concerns the combustion of small amounts of glycerol (up to several percent by volume) mixed with another fuel [22-24, 28]. Such a mixture can be injected into the engine into the intake manifold or directly into the cylinder.

2. Research methodology

The methodology arrangements for the research work presented in the article were focused on the following:

- To obtain knowledge on glycerol combustion under compression ignition conditions with diesel fuel pilot for combustion initiation. As glycerol features with relatively high viscosity, ethanol was proposed to dilute it and decrease its kinematic viscosity.
- To obtain knowledge on toxicity of the engine exhaust gases. Hence, the tests were focused on exhaust gases toxic emissions as follows: NOx, CO, UHC and smoke.
- To test the dual fuel injection system with 2 independently working high pressure injectors for diesel fuel pilot and glycerol-ethanol, respectively, mounted in the engine cylinder.

2.1. Parameters varied

On a basis of the objectives presented above, studies in this field were concentrated on influence of various ratio between glycerol-ethanol blend (G+E) and diesel fuel (DF) on exhaust gases toxic emission.

The fraction of G+E mixture in the total fuel injected into the cylinder was defined as fraction by energy. Hence, energy fraction of glycerol-ethanol (G+E) in entire fuel dose was determined with equation 1.

$$Energy\ Fraction\ (G+E) = \frac{G+E}{G+E+DF}, \tag{1}$$

where:

$$G = m_G LHV_G, \tag{2}$$

$$E = m_E LHV_E, \tag{3}$$

$$DF = m_{DF} LHV_{DF}, \tag{4}$$

m_G, m_E, m_{DF}– mass of glycerol in the glycerol-ethanol mixture, mass of ethanol in this mixture, mass of diesel fuel pilot dose, per single combustion event respectively,

LHV_G, LHV_E, LHV_{DF} – lower heating value of: glycerol, ethanol and diesel fuel, respectively.

The fuel specifications are presented in Table 3.

Table 3. Fuel specifications.

Parameter	Unit	Glycerol	Ethanol	G+E (50/50)	Diesel Fuel
LHV	MJ/kg	20.3	33.4	25.8	42.5
Density at NTP	kg/dm³	1.248	0.785	1.016	0.825
Kinematic viscosity at 40°C	m²/s	226e-6	1.06e-6	3.52e-6	2.50e-6

As mentioned, the total energy in the glycerol-ethanol blend and diesel fuel pilot doses per single combustion event was maintained constant. It was achieved with diesel fuel pilot dose varied from 9.5 to 22 mg/cycle. Whereas, glycerol-ethanol dose varied from 133 to 95 mg/cycle at the same time. As shown in Figure 1, the energy fraction of G+E blend in the total fuel dose was varied from 0.68 to 0.96, whereas diesel fuel fraction changed from 0.33 to 0.05, respectively.

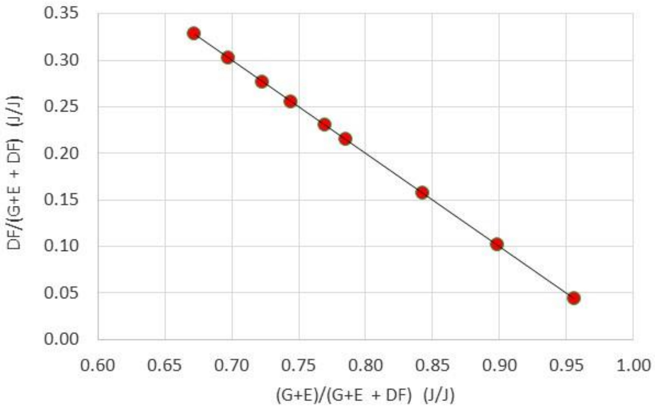

Figure 1. Correlation between DF fraction vs. G+E fraction by energy

Although, both doses were simultaneously changed to maintain fixed energy content in the total fuel dose, but for further analysis, the G+E fraction was taken as the independent parameter.

The total energy in the entire fuel dose to engine cylinder is presented in Figure 2. As depicted, total mean energy in both fuel doses (G+E and DF) per single combustion event (cycle) was maintained fixed at level of 2868±20 J. The condition of constant energy per cycle was assumed as fixed with respect of avoiding influence of energy on engine cooling and consequently on in-cylinder peak combustion temperature. Hence, it appeared simple to determine indicated thermal efficiency as well as find credible correlations of exhaust toxic emissions with G+E fraction in the total fuel dose.

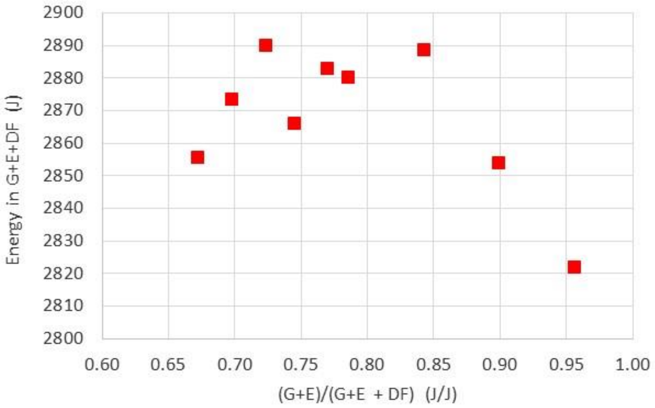

Figure 2. Energy in entire fuel vs. G+E energy fraction

2.2. *Parameters maintained constant*

The following parameters were maintained fixed during tests:

- Basic fuel was a mixture of 50% ethanol and 50% glycerol by volume. The ratio of 50/50 was determined on a basis of maximum injector flowrate capacity under acceptable kinematic viscosity. Hence, the kinematic viscosity varied in narrow range between 3.3e-6 and 3.7e-6 m2/s.
- Engine run at constant speed of 970 rpm. The speed was limited by a belt transmission from the engine to the power generator and synchronous speed of that generator.
- Injection pressures for both injectors were constant and adjusted at 2000 bar. Hence, each fuel dose was precisely adjusted by injection timing.
- Entire fuel energy per cycle was constant in the range between 2820 and 2890 J/cycle, as previously depicted in Figure 2. This condition required changing both glycerol-ethanol and diesel pilot dose. Hence, with increase of the diesel pilot dose, the glycerol-ethanol dose systematically decreased. Keeping fixed the total energy of entire fuel injected into the cylinder was important in regards to obtain knowledge on the following: engine overheating, exhaust gases temperature and thermal efficiency.
- Injection timing for the diesel pilot fuel was fixed. Start of injection (SOI) was at 26 CA deg bTDC (bTDC – before Top Dead Center). This optimal SOI for diesel fuel was determined during preliminary tests regarding the highest engine efficiency working on diesel fuel only.

With respect to glycerol-ethanol injection timings the strategy of fixed SOI was applied due to maintaining the same pressure-volume initial conditions at ignition for total combustion process. As known, combustion products among others depend on combustion initial parameters. Hence, SOI for glycerol-ethanol was fixed at 10 CA deg bTDC.

2.3. Test bench description

Figure 3 presents complete test bench with the compression ignition engine S320 (2) equipped with the double common rail system (1,7,9,10,14) for injecting a diesel fuel (DF) pilot dose and mixture of glycerol and ethanol (G+E) independently from each other. The engine specification is provided in Table 4.

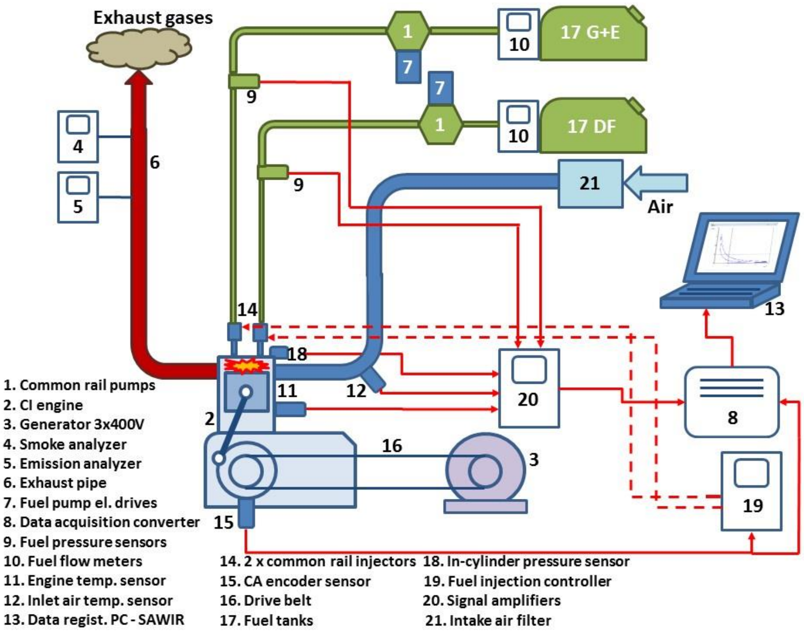

Figure 3. Test bed scheme

Table 4. Engine main specifications

Parameter	
Type of engine	four stroke compression ignition
Number of cylinders	1

Displacement	1810 cm^3
Engine rotational speed	970 rpm
Bore × Stroke	120 × 160 mm
Compression ratio	17
Max. injection pressure	250 MPa
Injection timing	26 CA deg bTDC – for DF
	10 CA deg bTDC – for G+E
Max. rated power	13.3 kW
Max. engine torque	104 Nm

The look into the engine with a power generator and two electrical motors (7 – above the engine) for driving high pressure injection pumps is inserted as Figure 4.

Figure 4. View on the engine at the test bed

The double common rail system consists of two parallel installed feeding lines for liquid fuels. The fuels can be directly injected under high pressure up to 250 MPa into the engine cylinder as depicted in Figure 5. Spraying clouds are developed in the bowl shaped piston. Original injector location is marked with G+E. Nowadays, this injector feeds the engine with glycerol-ethanol blend (G+E). The additional injector, which was used for diesel fuel (DF) was mounted nearby. Although, spraying cloud from the DF injector can reach piston surface due to non-centralized location, but such approach was justified because it only injects diesel pilot dose to initiate combustion of the main fuel G+E.

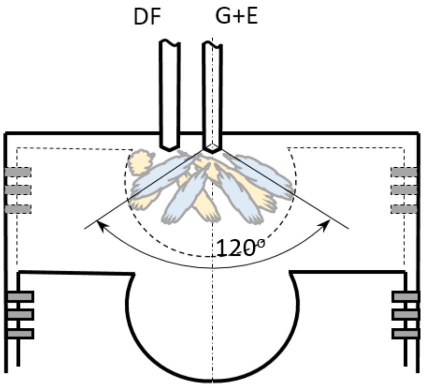

Figure 5. Location of 2 common rail injectors for glycerol-ethanol (G+E) and diesel fuel (DF).

The measurement apparatus consists of the following:

- smoke meter 415SE from AVL with measuring range to 10 FSN (filter smoke number) [28],
- data acquisition module, Measurement Computing USB-1608HS – 16 bits resolution, sampling frequency 200 kHz,
- piezo-ceramic pressure transducer, Kistler 6061 SN 298131, sensitivity: ±0.5%,
- charge amplifier, Kistler 5011, linearity of FS <±0,05%,
- crank angle encoder, resolution 1024 pulses/rev,
- signal analysis unit Tektronix MSO2014,
- air/fuel Ratio Meter LM-2 with lambda sensor, range 7.35-22.38,
- THC, CO, CO2 gas analyzer – Bosch BEA 350. (CO, CO2 and THC based on NDIR method, the measuring of the oxygen concentration based on an electrochemical cell O2)

2.4. Errors and accuracies in tests

Accuracies in measurements of the crucial parameters are shown in Table 5.

Table 5. Absolute errors and uncertainties of measured parameters.

Measured parameters	Absolute error	Uncertainty (%)
Rate of flow of diesel fuel	0.25 g/min	2.5
Rate of flow of glycerol/ethanol blend	0.25 g/min	0.5
Dose of diesel fuel	0.5 mg/cycle	2.5
Dose of glycerol/ethanol fuel	0.5 mg/cycle	0.5
Gas analyser		
UHC range 0 – 9999 ppm vol	12 ppm vol	
CO range 0 – 10 % vol	0.4 % vol	
NO range 0 – 9999 ppm vol	10 ppm vol	
Smoke range: 0-10 FSN	0.002 FSN or 0.02 mg/m^3	

3. Results and Discussion

As known, in-cylinder temperature is the crucial parameter which affects exhaust emission, in particular nitric oxides (NOx). During experiment temperature of exhaust gases was measured. Assuming fixed compression and expansion ratio and valve timing as well as other parameters influencing the combustion process, it can be concluded that the exhaust gas temperature is in close correlation with the average combustion temperature. Figure 6 depicts temperature Teg of exhaust gases. As seen, Teg is almost in linear negative correlation with glycerol-ethanol energy share (G+E) in the total combustible fuel charge (G+E+DF) injected into the engine cylinder. Temperature drop by 80K is observed with G+E energy fraction increasing from 0.67 to 0.96. As far as energy of the total fuel dose is constant, this temperature drop can be explained by higher amounts of glycerol and ethanol, that increases cooling effect from glycerol evaporation. Therefore, one can conclude both mean and peak in-cylinder combustion temperatures decrease with increasing G+E content, that affects NOx (here determined as only NO) formation following thermal NOx mechanism by Zeldovich [30]. As observed in Figure 7, NOx exhaust emission strongly goes down from nearly 300-400 ppm to below 50 ppm with G+E increase. Similar results on NOx emission reduction were reported by Lapuerta et al. [28], but he worked with smaller amounts of glycerol esters as the additive to diesel fuel.

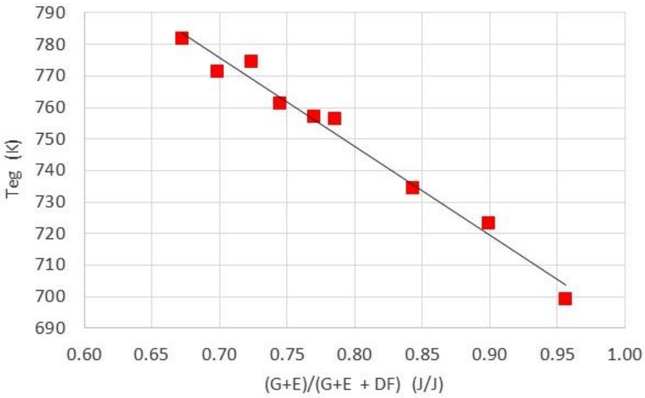

Figure 6. Temperature of exhaust gases vs. G+E fraction by energy content

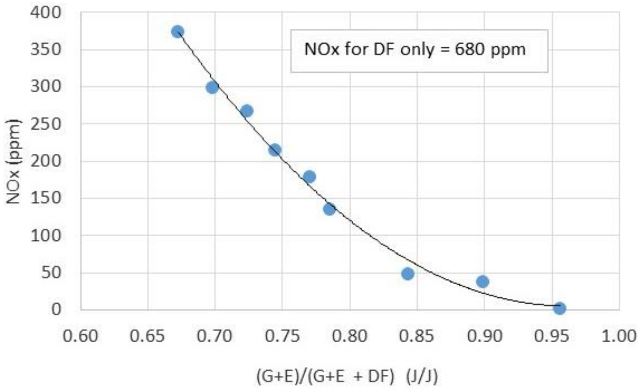

Figure 7. NOx vs. G+E fraction by energy content

Unlike NOx, unburnt hydrocarbons (UHC) increase lightly and next stabilize at level of 600 ppm with increase G+E content in total fuel as presented in Figure 8. This effect can be considered as combined effect of two phenomena affecting contrary to each other:

- cooling by higher amounts of G+E,
- and oxygenation by oxygen bounded in G+E mixture.

Unfortunately, this explanation looks not useful in CO trend with G+E increase, as depicted in Figure 9. At first, CO emission systematically decreases with G+E increase from 0.67 to 0.80-0.85. If someone assumes, that G+E delivers extra oxygen and combustion temperature is still high enough to effectively oxidize CO, therefore such a reasoning makes sense. When G+E increases over 0.8, exhaust temperature rapidly drops below 730K (so does mean combustion temperature) and it might cause rapid increase in CO even though higher oxygen in fuel is provided. As known, reaction rate for CO2 at those temperature range is relatively low, hence CO higher emission resulted from lack of time for complete oxidation CO to CO2. Total time of the expansion stroke when CO can be burnt to CO2 inside the engine cylinder is limited to nearly 30 ms at the engine speed of 970 rpm.

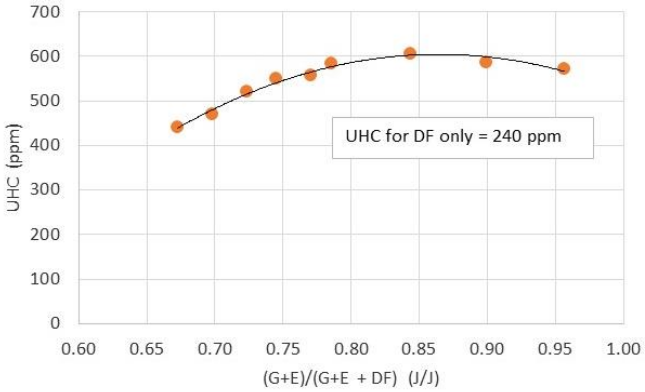

Figure 8. UHC vs. G+E fraction by energy content

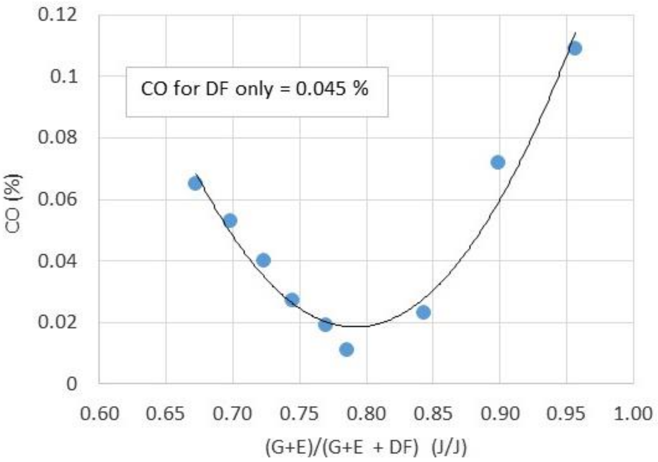

Figure 9. CO vs. G+E fraction by energy content

Smoke in exhaust gases was measured following the method by AVL [28]. This method was based on mass trapped in a special filter. Thus, smoke in numbers is considered as both soot and particle matter (PM). As plotted in Figure 10, smoke trend was negatively correlated with G + E fraction. Hence, one can conclude, that addition of glycerol-ethanol dose to the total fuel charge, that will be burnt in the engine cylinder, remarkably reduces smoke. As the smoke mainly consists of soot, it reduces soot formation and its content in the exhaust gases as well. To correctly confirm this thesis about this negative smoke trend, additional plots were performed as follows:

- smoke against glycerol-ethanol (G+E) dose (Figure 11),
- and smoke against diesel fuel pilot (DF) dose (depicted in Figure 12).

Both DF and G+E dose came from the same tests as depicted in Figure 10. The trend showed in Figure 10 is almost in line with the trend in Figure 11, presenting smoke vs. G+E dose.

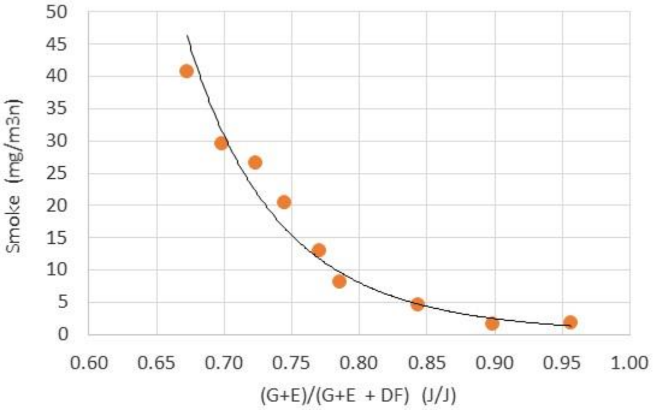

Figure 10. Smoke vs. G+E fraction by energy content.

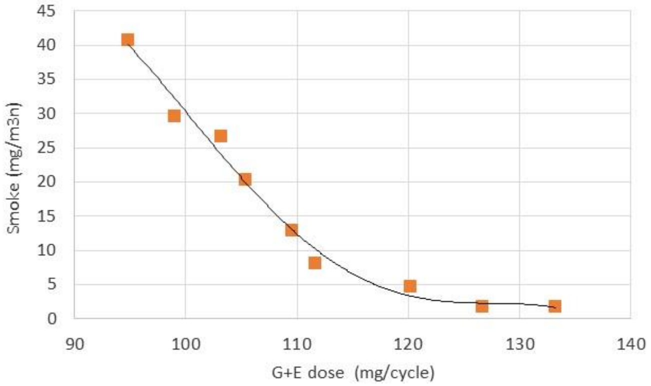

Figure 11. Smoke vs. glycerol-ethanol (G+E) dose.

Moreover, one can conclude, that, smoke is positively correlated with amounts of diesel fuel (Figure 12) in the total fuel charge injected into the cylinder. Hence, the conclusion on smoke emission caused by diesel fuel in the engine working on glycerol-ethanol mixture is proven. However, we cannot clearly state which: ethanol or glycerol impact on smoke is more significant. However, Eaton [22] and Beatrice [23] also confirmed that addition of glycerol to diesel fuel reduce PM, so does smoke emission.

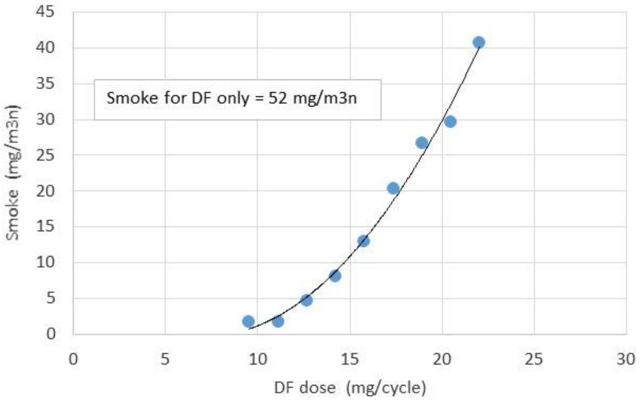

Figure 12. Smoke vs. diesel fuel (DF) pilot dose

Unfortunately, deterioration in engine indicated, thermal efficiency with G+E increase in the total fuel charge was observed as presented in Figure 13. Although combustion was complete and there were not any combustibles in the exhaust gases, but the combustion process got lengthening due to lower mean combustion temperature. Under fixed injection timings for both fuels, the maximum peak pressure was shifted far away from its optimal location towards expansion stroke. It was main reason for this drop in indicated efficiency.

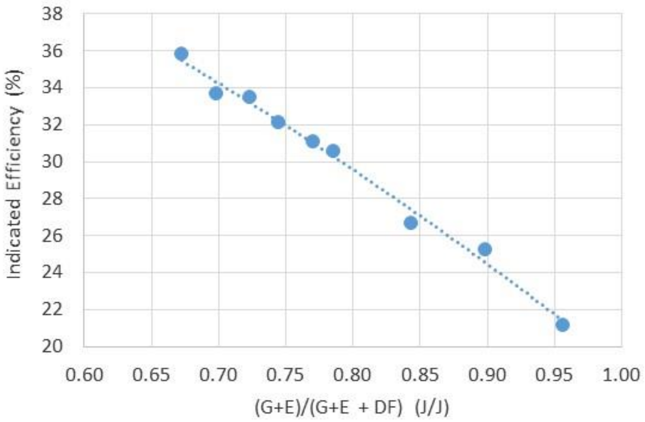

Figure 13. Indicated efficiency vs. G+E fraction by energy content

4. Conclusion

The following conclusions have been drawn from the presented analysis:

- Blending crude glycerol with ethanol at volumetric ratio of 1:1 (50/50%) is reasonable way to burn large amounts of glycerol in the reciprocating internal combustion engine with diesel fuel pilot for self-ignition. Glycerol blending with ethanol also provides mixture stability during its storage.
- The proposed injection system consisted of 2 high pressure injectors with direct in-cylinder injection can be successfully applied to the engine for effective combustion of glycerol-ethanol blend.
- Preliminary investigation on engine exhaust toxic emissions shows that both NOx, UHC and CO are at satisfactory level in comparison to emissions from the diesel fueled engine.

- The most interesting issue in toxic emissions was significant decrease in smoke with increase in glycerol-ethanol blend in total fuel charge injected into the engine cylinder. As found smoke was produced from diesel fuel pilot combustion. Blend of glycerol and ethanol reduced smoke several times from 40 to 3 mg/cycle. As concluded, it was caused by oxygen content in the G+E blend.
- The only problem reported was the combustion got longer with increase in glycerol-ethanol content in the total fuel injected into the cylinder. Under fixed injection timings, it caused the maximum combustion pressure was shifted far away from TDC location. As result, the thermal efficiency decreased.

Plans for further research: the problem with lengthening combustion was probably caused by geometry of the combustion chamber, mainly shape of the piston crown, that limited proper spraying and atomization of the G+E dose. Therefore, it is planned to do research with other piston shapes, in-cylinder swirling and various angles of injections into the cylinder.

Author Contributions: Conceptualization, G.M. and P.M.; methodology, G.M. and S.S.; Tests, G.M. and P.M.; software, G.M.; formal analysis, S.S. and S.M.; writing and draft preparation, S.S and S,M.; writing and editing, S.S.. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

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