

The combustion properties analysis of various liquid fuels based on crude oil and renewables

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Abstract. The paper presents results of investigation on combustion properties analysis of hydrocarbon based liquid fuels commonly used in the CI engine. The analysis was performed with aid of the CRU (Combustion Research Unit). CRU is the machine consisted of a constant volume combustion chamber equipped with one or two fuel injectors and a pressure sensor. Fuel can be injected under various both injection pressure and injection duration, also with two injector versions two stage combustion with pilot injection can be simulated, that makes it possible to introduce and modify additional parameter which is injection delay (defined as the time between pilot and main injection). On a basis of this investigation such combustion parameters as pressure increase, rate of heat release, ignition delay and combustion duration can be determined. The research was performed for the four fuels as follows: LFO, HFO, Biofuel from rape seeds and Glycerol under various injection parameters as well as combustion chamber thermodynamic conditions. Under these tests the change in such injection parameters as injection pressure, use of pilot injection, injection delay and injection duration, for main injection, were made. Moreover, fuels were tested under different conditions of load, what was determined by initial conditions (pressure and temperature) in the combustion chamber. Stored data from research allows to compare combustion parameters for fuels applied to tests and show this comparison in diagrams.

1. Introduction

The combustion properties of the fuel determine suitability of the fuel for the power applications. By power applications one can understand that the fuel can be used to supply any power machines like internal combustion engines (IC). Several basics properties of the fuel ought to be determined before it is applied in practice. The simple and effective way to determine whether a fuel is suitable for the IC engine are measurements performed on the combustion research unit (CRU).

Various types of the fuel in both liquid and gaseous phase can be used for the combustion engine. The preparation of a potential fuel to be implemented in series production requires lot of tests that allow to check whether the fuel can be used not only from the energetic point of view but also regarding to chemical properties and mechanical contamination. Due to restrictive regulations for engine exhaust gas emissions as well as the need of use renewable fuels, the basic test stands are important especially for industrial engine manufacturers and end-users. The tests should answer the question on fuel usability to the specific engine. Such approach allow to save the time and money during the engine R&D and manufacturing process.



The liquid fuels commonly used in industrial combustion engines are as follows LFO (light fuel oil), HFO (heavy fuel oil), and different types of biofuels like jetropha oil or rapeseed oil (RSO). Further, it is often mentioned on use of the glycerol as a fuel for the IC engine. All those above-mentioned fuels are in use for engines with compression ignition commonly known as diesel engines.

2. Test stand description

The CRU is an instrument based on CVCC (Constant Volume Combustion Chamber), which can measure fuel combustion parameters. The CRU makes it possible to do combustion tests on the different types of liquid and gaseous fuels for SI as well as for CI engines.

The purpose of this machine is to simulate the combustion process in the piston engine in which the dynamic aspects of its nature are neglected (piston movement, valve movement). It allows to focus only on differences that result from the fuel properties. Mainly the CRU device can be divided into three depended systems: hydraulic, pneumatic and electronic ones. The hydraulic system is responsible for providing the proper pressure in injection system. The pneumatic system is responsible for flushing and venting procedures while the fuel sample is changed from previously tested to a new one. The electronic system is responsible for steering both the hydraulic and the pneumatic systems, to communicate with a computer and to read out the measurements from CRU sensors. Test rig view is presented in figure 1.

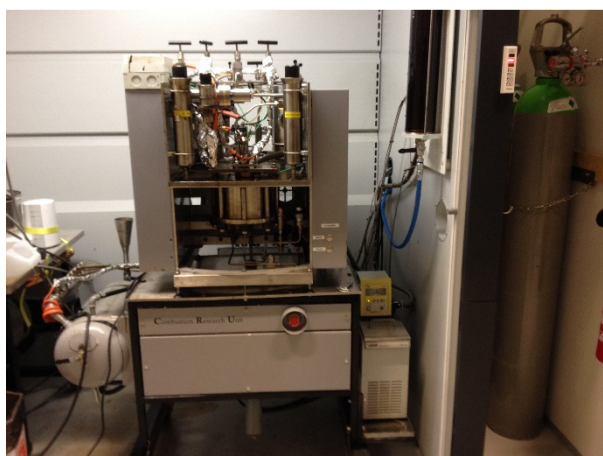


Figure. 1. CRU test rig overall view.

The CRU provides a wide range of parameters that can be adjusted during research to obtain the best results, accuracy and repeatability of the measurements. The basic parameters of the CRU unit are presented in table 1.

Table 1. Basic CRU parameters [4].

Chamber	
Fuel type	Diesel Fuel
Chamber temperature	Max 610°C
Chamber pressure	10-75bar
Chamber volume	385cm ³
Fuel injection	
Fuel pump and injection nozzle	BOSCH CR injector Electronic control of timing, opening period, pressure
Injection pressure	400-1600bar
Instrumentation control	
Chamber heating	2 heaters/2 sensors
Chamber pressure	Air and exhaust valve / pressure sensor
Combustion pressure sensor	Piezoelectric pressure sensor
Fuel pressure sensor	Piezoelectric pressure sensor

The CRU unit used in this research was modified to provide a possibility to use all possible fuels that could be combusted in the CI engine. For high density fuels a heating system for fuel lines were used to provide a proper kinematic viscosity during tests.

3. Tests configuration

The tests performed on the CRU were done for the four different fuels: LFO (Light Fuel Oil), HFO (Heavy Fuel Oil), RSO (Rape Seed Oil) and Glycerol. During the tests for the each fuel parameters concerning initial conditions in the combustion chamber (pressure and temperature), injection parameters (pressure and injection duration) and fuel parameters (fuel temperature – kinematic viscosity) were adjusted. In all cases during the measurements three to four injections were done for one set point. The research were done in six stages.

In first stage the kinematic viscosity as a function of temperature for HFO, RSO and Glycerol was determined by use of the rheometer. Because the LFO has low kinematic viscosity of 4,15 cSt in temperature of 20°C as Corsini et al. [2] wrote. The characteristic of this parameter against temperature wasn't determined. Afterwards, one value of kinematic viscosity for all fuels was selected to further tests. In this research, the kinematic viscosity value was $v \approx 23$ cSt for all fuels except LFO. The detailed measurement matrix is presented in table 2.

Table 2. Tests matrix.

Initial conditions of combustion chamber		Tested fuel (LFO, HFO, RSO and Glycerol)					
		Pressure of injection p_{inj} (bar)		Injection duration inj_{time} (μs)		Kinematic viscosity v (cSt)	
p (bar)	T (°C)	55bar/550°C	70bar/590°C	55bar/550°C	70bar/590°C	55bar/550°C	70bar/590°C
55	550	500		500 (1500 Glycerol)		15 (23,5 HFO)	
62,5	570	750		Optimal ^a		23 (30 HFO)	
70	590	1000		1500(2500 Glycerol)		40 (40 HFO)	

^aThe injection duration that provides 10 bar increase during the fuel sample combustion for 70bar/590°C initial conditions of the combustion chamber.

In the second stage determination of optimal injection parameters were done. For injection pressure $p_{inj}=1000$ bar the injection duration $inj_{duration}$ was modified to achieve increase in combustion pressure, for initial conditions for the combustion chamber (70bar/590°C), of 10bar.

In the third stage for fixed injection parameters (optimal) the measurements of pressure and ROHR were performed as a function of pressure and temperature that prevailed in the CRU combustion chamber (initial conditions in combustion chamber).

In the fourth stage the pressure of injection was changed during the research. The measurements were performed for two states of initial conditions in the combustion chamber 55bar/550°C and 70bar/590°C. The time of injection was set as the optimal one determined in a second stage of this research.

In the fifth stage the injection pressure for each fuel was constant $p_{inj}=1000$ bar and the injection duration $inj_{duration}$ was changed during the measurement according to table 1. The measurements were performed for two states of initial conditions in the combustion chamber 55bar/550°C and 70bar/590°C as well.

In the last stage the injection parameters were set optimal for each fuels and the kinematic viscosity was changed. Change in kinematic viscosity was done by change in temperature of fuel which was in the fuel line. Similarly to previously done measurements this one was also done for two states of initial conditions of combustion chamber 55bar/550°C and 70bar/590°C.

4. Results and discussion

The first measurements were focused on determination of the kinematic viscosity by use of the rheometer. The results of the measurements for HFO, RSO and Glycerol are presented in figure 2.

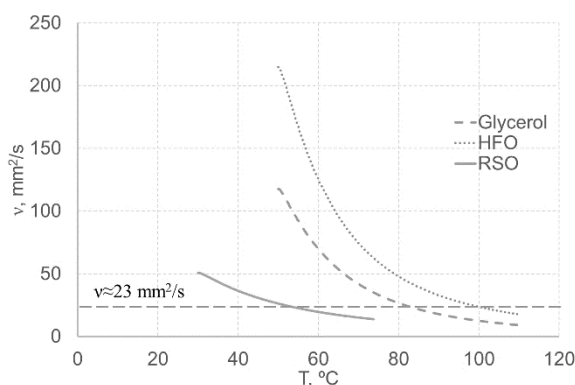


Figure 2. Kinematic viscosity vs. temperature for tested fuels (HFO, RSO and Glycerol).

As seen, these fuels are characterized by high kinematic viscosity at normal condition and use of them could be very difficult without pre-heating. The most intensive heating is required to the HFO. To obtain preliminary assumed kinematic viscosity it should be heated up to 100°C. The lowest heating up temperature is for RSO and it is about 55°C. For Glycerol the heat up temperature is approximately 82°C.

The results for optimal injection duration for these tested fuels at injection pressure of 1000bar, are presented in table 3.

Table 3. Injection duration for tested fuels.

Fuel	Inj _{duration} (μs)
LFO	1000
HFO	1075
RSO	1150
Glycerol	1900

The values were obtained during the tests with 10bar increase in combustion pressure for the each fuel. As seen, for the same kinematic viscosity for HFO, RSO and Glycerol the injection duration increases what is related with lower heating value (LHV) of these fuels compared to LFO. The lowest heating value is for Glycerol LHV=16 MJ/kg [5] what means that to obtain the same energy content in an air-fuel mixture, more fuel has to be injected. It also can be seen that RSO has a lower LHV (37,6 MJ/kg [2]) compared with HFO (42,8 MJ/kg [3]) or LFO (43,2 MJ/kg [3]).

In figure 3 the comparison of combustion pressure for different initial temperature and pressure are shown. As presented, for LFO increase in combustion pressure is the same for all cases under optimal initial pressure that corresponds to proper combustion process of this fuel and good atomization and evaporation during injection. For the initial temperature change, it can be observed that with lower temperature, the pressure starts to increase later what is correlated with ignition delay (ID) which lasts longer with lower temperature and it shortens with temperature increase. In this case the ignition delay is caused by much worse evaporation in lower initial temperature.

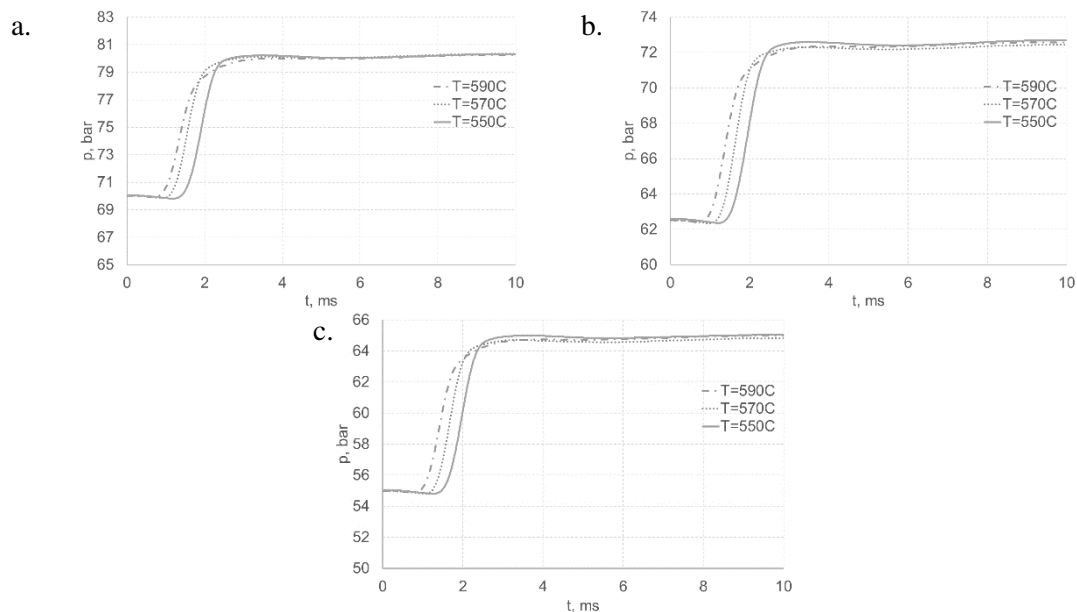


Figure 3. Comparison of combustion pressure for various internal temperatures of combustion chamber for initial pressure a) 70bar, b) 62,5bar, c) 55bar.

The same trend can be seen for rate of pressure increase (dp/dt) where with increase of ignition delay the maximum value for dp/dt is also retarded. Figure 4 presents the rate of pressure increase

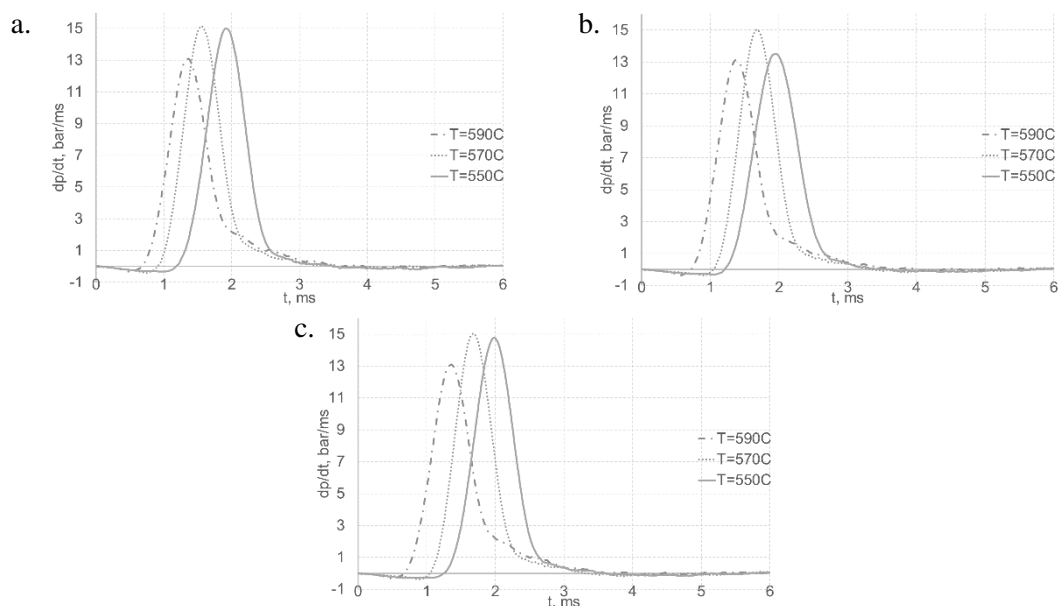


Figure 4. Comparison of rate of pressure increase for various internal temperatures of the combustion chamber at various initial pressures a) 70bar, b) 62,5bar, c) 55bar.

For LFO, no significant change in rate of pressure increase in dependence of initial combustion chamber pressure was observed. In almost all cases the time of combustion stood not changed significantly. In this case it can be seen that with longer ignition delay the combustion at its end accelerates, as concluded from figures 3 and 4. For lower initial combustion temperature the combustion slows down. All tested fuels showed the same tendency.

Figure 5 presents ignition delay for all tested fuels as a function of initial parameters for the combustion chamber.

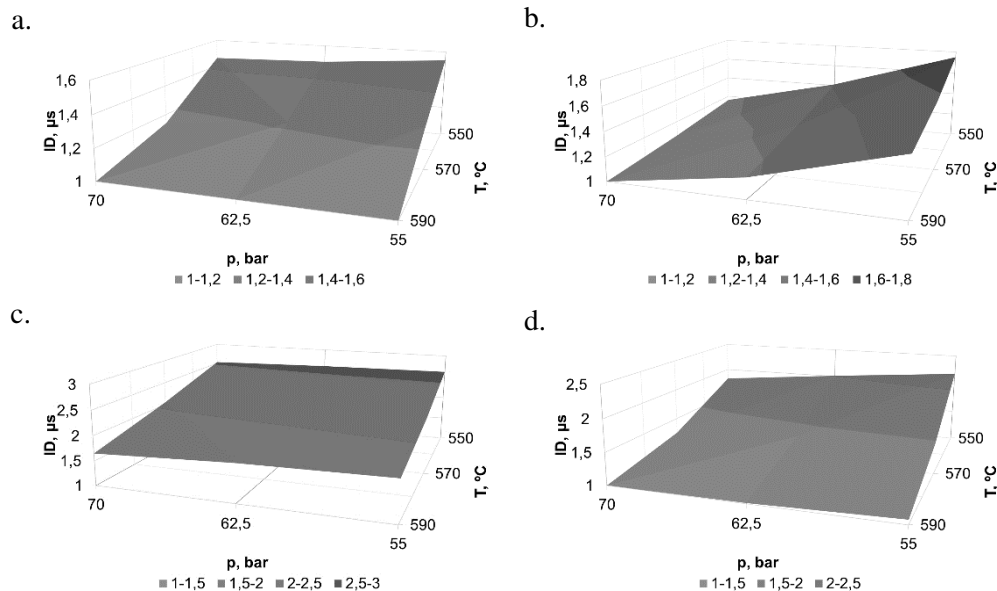


Figure. 5. Comparison of ignition delay (ID) for tested fuels, a) LFO, b) RSO, c) HFO, d) Glycerol.

For all fuels the ID has a similar tendency only for RSO more significant ID dependence of initial pressure can be observed. For LFO the major dependence on ID have an initial temperature. As can be seen, with decrease in temperature the increase in ID occurs. Furthermore, for the lowest initial combustion chamber temperature, dependence of ID and initial pressure can be observed. For HFO, Glycerol (figure 5 c and d) also for higher initial temperature the ID dependence with initial pressure can be observed. RSO however is characterized by very significant ID dependence with both initial pressure and temperature (figure 5 b). Such big difference compared to LFO can be caused by the cetane number for RSO which is 41 whereas for LFO it is above 50 according to Blin et al.[5]. HFO has a long ID which also can be related with low cetane number which is around 30 [1]. The glycerol ID is short but it is caused by pilot injection which is used to provide ignition of air-fuel mixture because pure glycerol is not able to ignite itself in the combustion engine.

As an example of the injection parameters, influence of combustion properties of HFO on combustion pressure rise is depicted in figure 6. As can be seen the combustion pressure decreases with decrease in injection pressure what is caused by two factors: worst evaporation because of larger droplets in spray and less amount of fuel injected during the injection. However for initial parameters of the combustion chamber equal to 70bar/590°C for all cases pressure increase plot is characterized by steep slope what mean that value of pressure increase rate is also high compared to initial conditions of 55bar/550°C. As can be seen in figure 6a the pressure increase slope is gentle and fuel needs more time to be burnt, what can be seen in figure 6c in which pressure increase rate has low value and lasts much longer compared to pressure release rate shown in figure 6d. This fuel is characterized with satisfied combustion properties under high initial combustion chamber conditions. For instance, LFO has good combustion properties for both low and high initial conditions. This is related with individual properties of this fuel such as the cetane number and density which affect combustion itself.

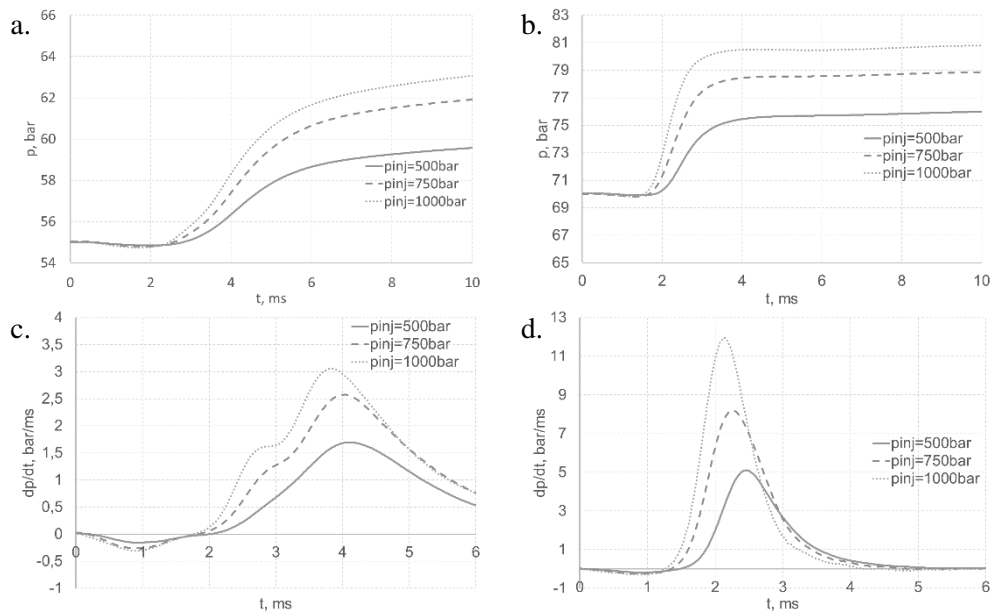


Figure 6. Combustion pressure and rate of pressure increase for different pressure of injection and initial conditions of combustion chamber (a, c – 55 bar/550 °C; b, d – 70 bar/590 °C; fuel – HFO).

Figure 7 presents ignition delay as a function of injection pressure for different initial conditions of the combustion chamber.

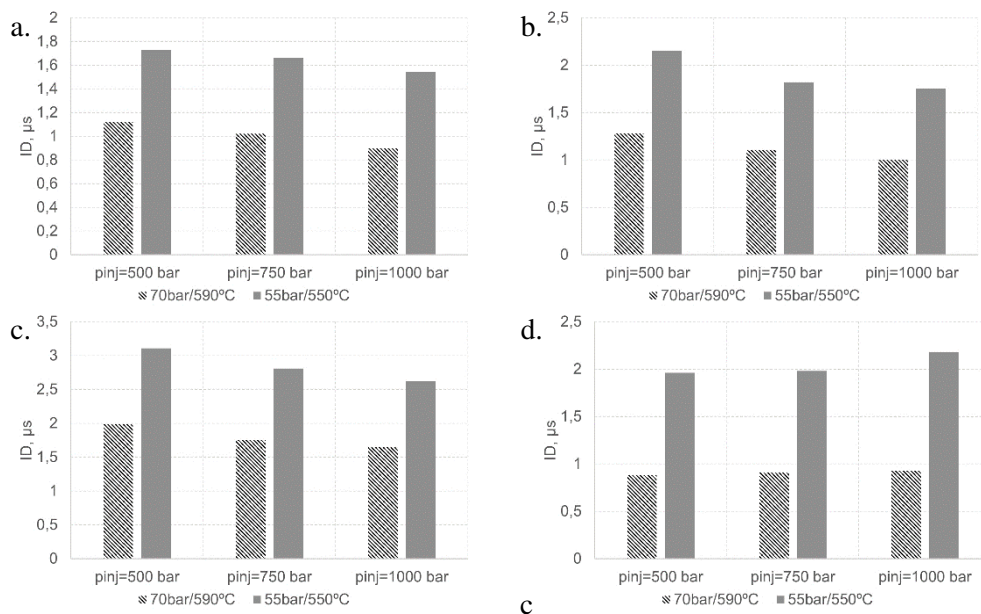


Figure 7. Comparison of ID for different injection pressure and initial conditions of the combustion chamber (a) LFO, b) RSO, c) HFO, d) Glycerol).

As plotted, for LFO, RSO and HFO there is decrease in ID with increase in injection pressure what is related with better atomization of the fuel. Additionally, it can be noticed that when the initial conditions in the combustion chamber are high the ID decreases even more. Different situation is observed with glycerol, where one can notice that for low initial conditions in the combustion chamber it is slight increase in ID especially for pressure injection of 1000bar. It may be caused by that the

glycerol is injected to the combustion chamber in high quantity therefore for low initial conditions it did not evaporate well because of its relatively high density and as a result the increase in ID occurred (figure 7d).

Figure 8 presents combustion pressure and rate of pressure increase for glycerol as a function of injection duration. It can be seen that for both cases of initial conditions for the combustion chamber both the combustion pressure and pressure increase rate plots as a function of injection duration start at the same moment.

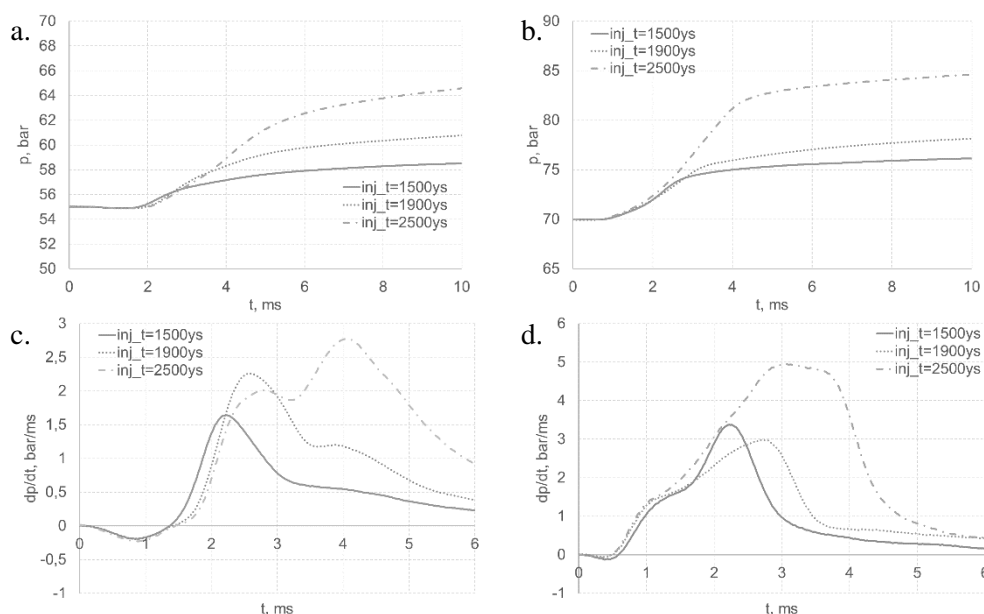


Figure 8. Combustion pressure and rate of pressure increase for different injection duration and initial conditions of combustion chamber (a, c – 55 bar/550°C; b, d – 70 bar/590°C; fuel – Glycerol).

The maximum values of the following: combustion pressure, rate of pressure increase and the time of combustion only differ from each other that is related with increasing amount of fuel injected to the combustion chamber. However, because injected fuel is the same, the changes in ID are considered as random, hence it cannot be seen any particular pattern what figure 9 presents. Most stable fuel in this case is LFO (figure 9a). As can be seen for high initial conditions ID is at the same level for different injection duration but for low initial conditions when the injection duration increases, the ID also increases what can be related to higher amounts of fuel that does not evaporate or evaporation process lasts longer before the ignition occurs.

Figure 10 presents combustion pressure, rate of pressure increase and ID as function of different kinematic viscosities for RSO in high initial conditions in the combustion chamber. As observed, in case of RSO the change in kinematic viscosity has an influence on aforementioned parameters especially combustion pressure and rate of pressure increase. With higher temperature the kinematic viscosity decreases what causes better atomization during the injection and better vaporization. As a result of this phenomenon the increase in combustion pressure occurs. The combustion for all kinematic viscosities lasts for similar time which is approximately 3ms what can be observed at figure 10b. A confirmation for this observation is figure 10c where ignition delay for all kinematic viscosities is at the same level which is approximately 1ms. For low initial conditions in combustion chamber the ID value decreases with kinematic viscosity increase which is related with better atomization of fuel, quicker evaporation and as a result advanced ignition.

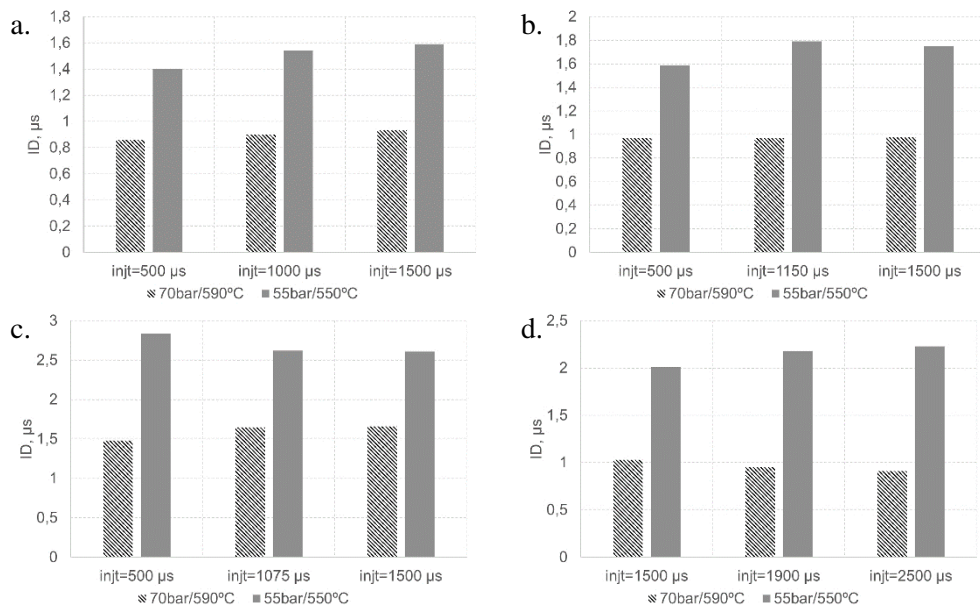


Figure 9. Comparison between ID for different initial conditions of combustion chamber a) LFO, b) RSO, c) HFO, d) Glycerol.

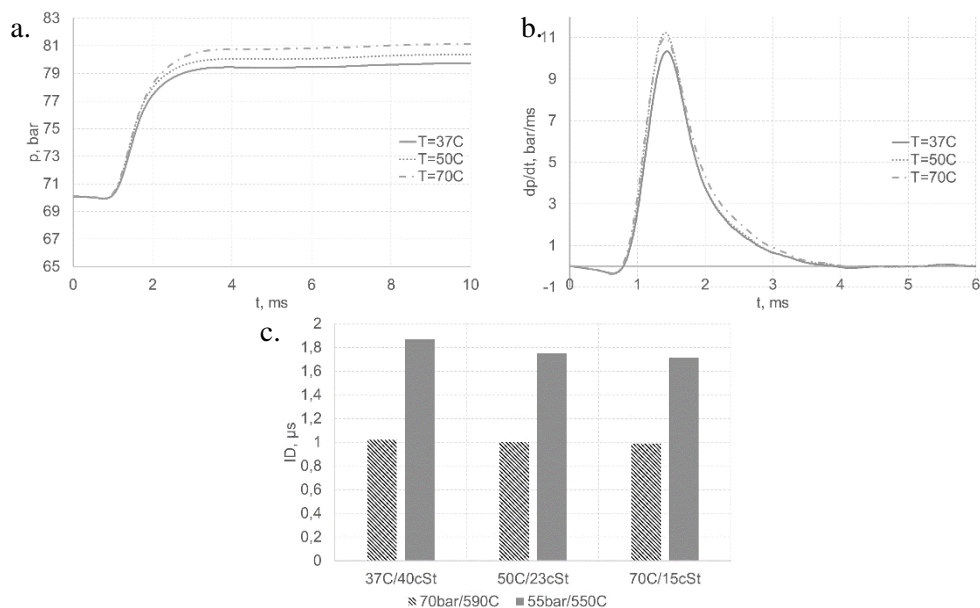


Figure 10. RSO characteristics at different kinematic viscosity a) combustion pressure, b) rate of pressure increase, c) ignition delay (ID).

5. Conclusions

The results of the research presented in this paper are a summary about possibility of use a CRU to perform fast tests for different type of fuels.

The CRU during this research was configured for combustion of the fuel that can be used in the compression ignition engine. Most advantages of this device is very fast configuration of test procedure, wide range of operational possibilities (change in combustion chamber parameters, injection parameters). This unit does not simulate real flow conditions in the engine cylinder, so there is no

possibility to demonstrate evaporation process of the fuel spray which significantly affects air-fuel mixing process.

On a basis of the performed tests the following conclusions can be formed:

- 1) Initial temperature at the injection has crucial influence on ignition delay for all tested fuels. For RSO also initial pressure affects ID. That is caused by worse conditions for vaporization with decrease in initial temperature of combustion chamber.
- 2) Ignition delay depends on the cetane number of the fuel.
- 3) Injection pressure has bigger influence on combustion properties than injection duration especially if the ID is considered as the important parameter. That is related to the atomization of injected fuel.
- 4) Glycerol as a fuel for the internal combustion engine can be used only with pilot injection. Very small amount of LFO pilot dose enriched with glycerol makes the combustion less stable, slow and depleted. To avoid this problem higher amount of pilot dose should be used. However, thanks to LFO fuel used as a major pilot dose the ID is in satisfied range.
- 5) Kinematic viscosity of all the fuels has influence on combustion parameters. With higher kinematic viscosity the property of injection decreases which affect combustion pressure and ID, especially in low initial conditions in the combustion chamber (55bar/550°C).

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