ENGINE WITH FORCED AIR INTAKE SYSTEM AND 100% HVO FUEL

Edgars Kolins[1], Maris Gailis[1, 2]
[1]Riga Technical University, Latvia;
[2]European Sustainability Science Laboratory, European University of Technology, European Union
edgars.kolins@inbox.lv, maris.gailis@rtu.lv

Abstract. The paper develops a theoretical installation of a forced air inlet system in an atmospheric engine using diesel fuel and hydrogenated vegetable oil (100% HVO) fuel. The experiments were carried out on an instrumented research CFR engine (compression ignition engine IDT 69 with adjustable compression ratio), equipped with a forced air intake. A Kistler piezoelectric pressure sensor was used to determine the pressure in the engine combustion chamber. During the experiments, the turbocharger pressure was increased 5 times (1.0 bar; 1.1 bar; 1.2 bar; 1.3 bar; 1.4 bar). For diesel and HVO fuels, the fuel nozzle opened at 500 bar and the injection duration was 1 m. Initially, diesel fuel was tested and then experiments were carried out with HVO fuel, keeping the same air inlet pressures. The aim of the work was to study the ignition and combustion characteristics of diesel and HVO fuels when the air intake pressure rises. The proposed study is based on measurements of field engine parameters (pressure) and experiments in the laboratory on a research engine. Effects of inlet air pressure and temperature increase on combustion parameters such as ignition delay and combustion phasing are evaluated by analysis of the cylinder pressure data. At the end of the study, data were collected on diesel and HVO fuels, comparing ignition characteristics and combustion characteristics. The study will provide information on whether it is necessary to change the nozzle injection advance angle of a tractor engine equipped with forced air intake and using HVO fuel.

Keywords: 100% HVO, injection advance angle, turbocharger.

Introduction

According to Article 194(1) of the Treaty on the Functioning of the European Union (TFEU), one of the objectives of the Union's energy policy is to develop the various forms of energy from renewable sources [1]. Hydrotreated vegetable oil (HVO) is one of the fuels produced from waste, which is a renewable energy source and can also be produced from algae and micro-organisms. Nowadays, more and more HVO is produced from waste and food processing residues [2].

HVO fuel outperforms conventional diesel in several areas. HVO fuels are mainly paraffinic and do not contain any aromatics, oxygen or sulphur. Cetane number and higher heating value are comparatively higher [3]. HVO fuel has a lower turbidity temperature, and lower viscosity. The above results in faster ignition of the fuel. HVO fuel allows it to be blended with other diesel fuels to form fuel blends such as 5% HVO, 20% HVO, etc. [4]. Field experiments show that HVO fuel can be diluted with oil and that HVO fuel does not degrade lubricants, and that it has several advantages in terms of ecological standards compared to fossil diesel. In 2017, for example, Neste renewable fuels reduced global climate warming emissions by 8.3 million tonnes, equivalent to the annual emissions of 3 million cars [5].

HVO fuel can be used in all types of vehicles with compression ignition engines. A single-cylinder diesel engine was used in this study, fuelled with HVO fuel (made from 100% renewable raw materials). In this paper, the fuel injection angle of HVO fuel will be investigated and compared with diesel fuel.

Materials and methods

In the field experiments, the forced air inlet pressure of the MTZ-82 tractor was measured. Experiments were carried out in a laboratory environment, simulating the MTZ-82 tractor D245 engine on the experimental engine IDT 69. The IDT 69 engine was run on diesel and HVO fuels during the experiments. The turbo pressure was provided by a compressor.

For the D245 engine the air inlet pressure was measured which was generated by the turbocharger. A WIKA barometer was installed immediately after the cold section of the turbocharger to record pressure changes. The engine speed was increased 10 times to the maximum at which point the pressure was read. In between increasing the engine crankshaft speed, the engine was allowed to reach the original crankshaft speed while maintaining the accuracy of the measurement. For the measurements taken, the standard deviation and standard error of the mean were determined, as well as the confidence interval.

Experiments were continued on the experimental engine IDT 69. Technical parameters of the IDT 69 engine are shown in Table 1 below.

Table 1

Technical parameters of IDT 69 experimental engine [6]

Parameter	Value
Engine type	4 stroke, single cylinder, pre-chamber, compression ignition
Air supply	Forced air inlet
Cooling system	Liquid-cooled
Bore and stroke, mm	85 × 115
Cylinder volume, cm3	652
Compression ratio	16
Fuel injector opening pressure, bar	500
Fuel is injected	7° BTDC

During the experiment, the engine was fuelled with diesel and HVO fuels (the main diesel and HVO fuel parameters can be seen in Table 2).

Table 2

Main parameters of tested fuels [7]

Parameter	Test method	Diesel	100% HVO
Density (ρ) at 15 °C, $kg \cdot m^{-3}$	LST EN ISO 3675	827.3	778.9
Viscosity at 40 °C, $mm2 \cdot s^{-1}$	LST EN ISO 3104	2.402	2.884
Cetane number by IQT-analyser	LST EN ISO 5165	51,4	74.7

First, the engine was powered by diesel fuel and the forced-air inlet pressure was set at 1,0 bar (the inlet air temperature was 65°C), provided by a compressor (start-up and deceleration were not controlled) with an accumulator reservoir to reduce the impulses generated by the engine. Pressure rise in the combustion chamber by a Kistler piezo electromagnetic pressure sensor was able to read and send it to the National Instrument computer. The information is further collected in the Labview development environment. The IDT 69 engine setup can be seen in Figure 1.

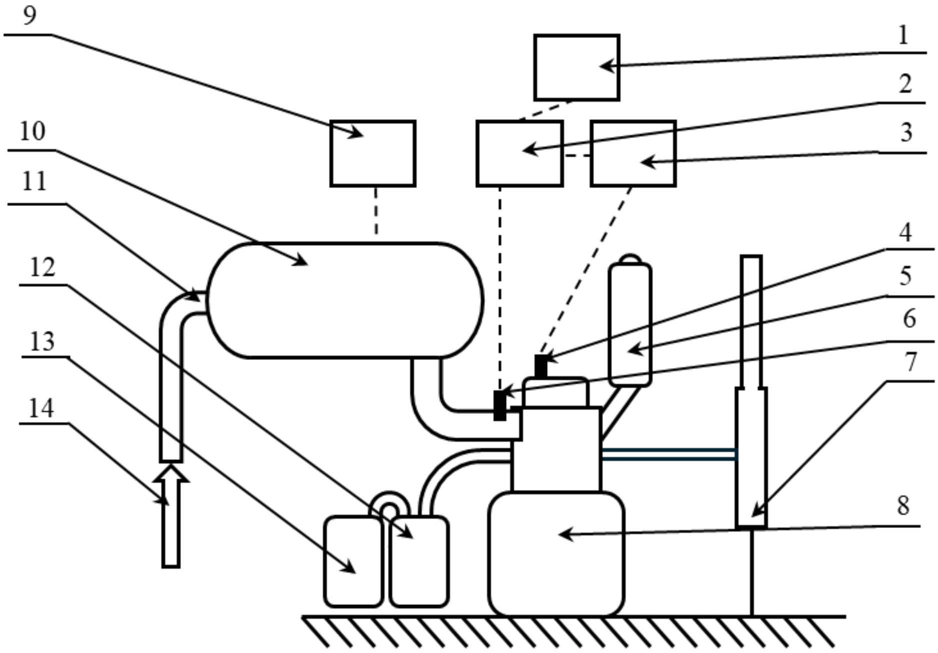

Fig. 1. **IDT 69 engine setup:** 1 – host PC; 2 NI 9068 chassis; 3 – charge amplifier Kistler 5018A; 4 – pressure sensor Kistler 6061B; 5 – cooling system condenser; 6 – inlet air temperature sensor;

7 – exhaust surge tank; 8 – cylinder block with cylinder head; 9 – engine control module; 10 – inlet air reservoir; 11– inlet air heater; 12 – high pressure fuel pump; 13 – fuel reservoirs; 14 – forced air inlet

In this way, 5 measurements were taken at an inlet pressure of 1.0 bar and the pressure in the combustion chamber was 35,9 bar. The same was done using diesel fuel at 1.1 bar (the pressure in the combustion chamber was 36 bar); 1.2 bar (the pressure in the combustion chamber was 39 bar); 1.3 bar (the pressure in the combustion chamber was 43 bar); 1.4 bar (the pressure in the combustion chamber was 47 bar).

After the end of the diesel fuel experiments, it was switched to HVO fuel. Diesel fuel was removed from the fuel supply system, allowing the engine to run fully on HVO fuel. 5 repeats were conducted with an air inlet pressure of 1.0 bar (the pressure in the combustion chamber was 35,9 bar), then 5 repeats of 1.1 bar (the pressure in the combustion chamber was 36 bar), then 5 repeats of 1.2. bar (the pressure in the combustion chamber was 39 bar), then 5 repeats of 1.3 bar (the pressure in the combustion chamber was 43 bar) and the final pressure was 1.4 bar (the pressure in the combustion chamber was 47 bar), for which 5 repeats were also conducted.

After the experiments in the laboratory, data collection and calculations were started on a Jupyter Notebook. All calculations, bar and curve figures were generated using Python script. For each of the pressure trials, a curve-type graph was created separately, where it was possible to observe whether there was a repeat from repeat. Data processing was carried out by averaging the repetitions of each cylinder pressure and plotting them on a curve. Five curves (1.0 bar; 1.1 bar; 1.2 bar; 1.3 bar; 1.4 bar) were obtained for the diesel fuelled engine and 5 curves for the HVO fuelled engine.

The induced mean effective pressure (IMEP) was determined in the following calculations. For the calculations, $IMEP_{net}$ was chosen, which covered a larger part of the engine cycle (720 CAD). The formula for calculating $IMEP_{net}$ is shown below (1).

$$IMEP_{net} = \frac{\oint PdV}{V_d}, \tag{1}$$

where $\oint PdV$ – work carried out in a gas engine during one cycle;
V_d – displacement volume.

The calculations were continued with an analysis of the combustion process. It is necessary to calculate the pressure differential (2).

$$\frac{d_{p\theta}}{d\theta} = \frac{P_{\theta(i+n)} - p_{\theta(i-n)}}{\theta_{(i+n)} - \theta_{(i-n)}}, \tag{2}$$

where i – data point (pressure and CAD at a point in the engine duty cycle);
n – differentiation spline.

Apparent heat release rate (*AHRR*) was calculate using the following formula (3).

$$AHRR = \frac{dQ_{out}}{d\theta}, \tag{3}$$

where dQ_{out} – changes in the amount of heat released, resulting in a modification of the combustion engine;
$d\theta$ – cycle angle changes.

Results and discussion

The diesel fuel showed a scatter at the maximum values of each engine combustion chamber pressure within 1 bar, except for the inlet pressure of 1.3 bar where the dispersion was within 1.4 bar. The slight dispersion when the inlet pressure was 1.3 bar occurred because the inlet pressure was adjusted mechanically by a lever which had to be turned by hand.

The HVO fuel graphs showed similar results with dispersion at maximum combustion chamber pressure reaching 1 bar, except at 1.1 bar inlet pressure where the dispersion between all trials was within 2 bar. The slight dispersion when the inlet pressure was 1.1 bar occurred because the inlet pressure was adjusted mechanically by a lever which had to be turned by hand. When running the engine on

HVO fuel at inlet pressures of 1.1 bar; 1.2 bar; 1.3 bar; 1.4 bar, the mean values and the confidence interval are shown in Figure 2.

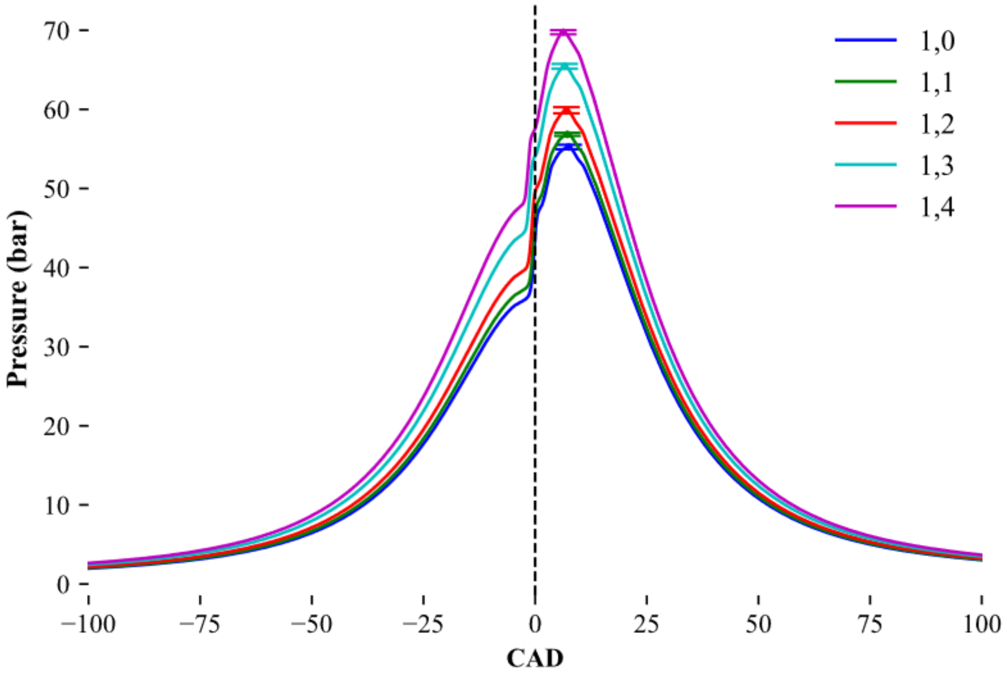

Fig. 2. **Prechamber pressure at various inlet pressure values using HVO fuel**

The next figure (Figure 3) shows the average maximum values for each inlet pressure.

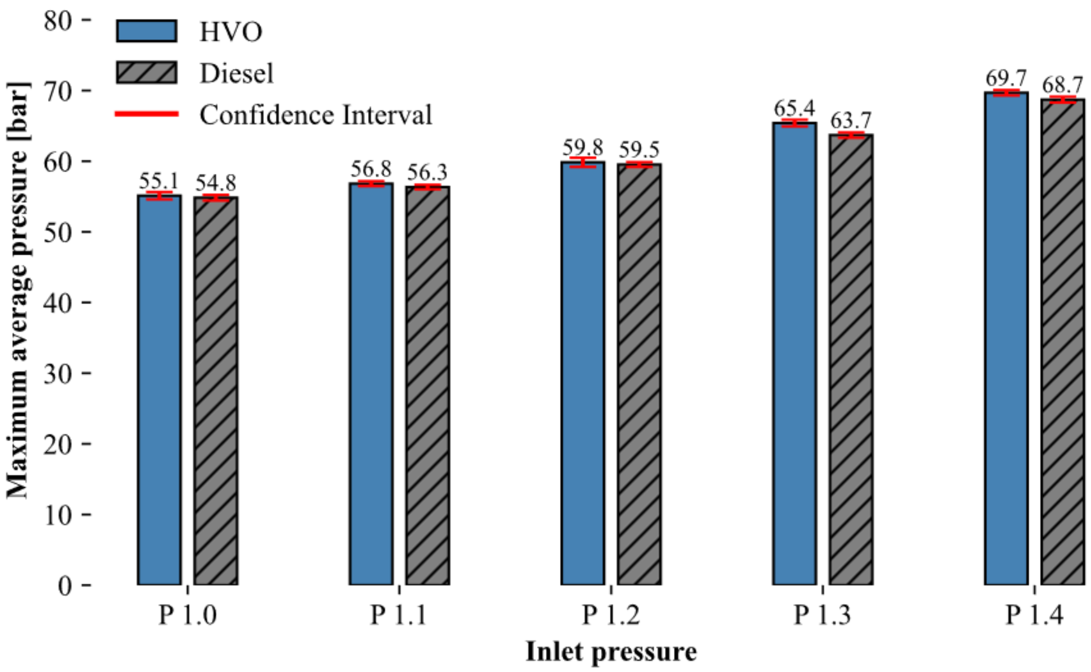

Fig. 3. **Comparison of maximal prechamber pressure for diesel and HVO fuels**

The diagram (Figure 3) shows that the experiments have been successful, as the pressure generated in the combustion chamber increases with increasing the inlet pressure.

The IMEP net at all inlet pressures was higher when the engine was fuelled with HVO than when the engine was fuelled with diesel fuel. It can be observed that HVO fuel allows a more efficient use of engine displacement. A diagram of the IMEP net values can be seen in Figure 4.

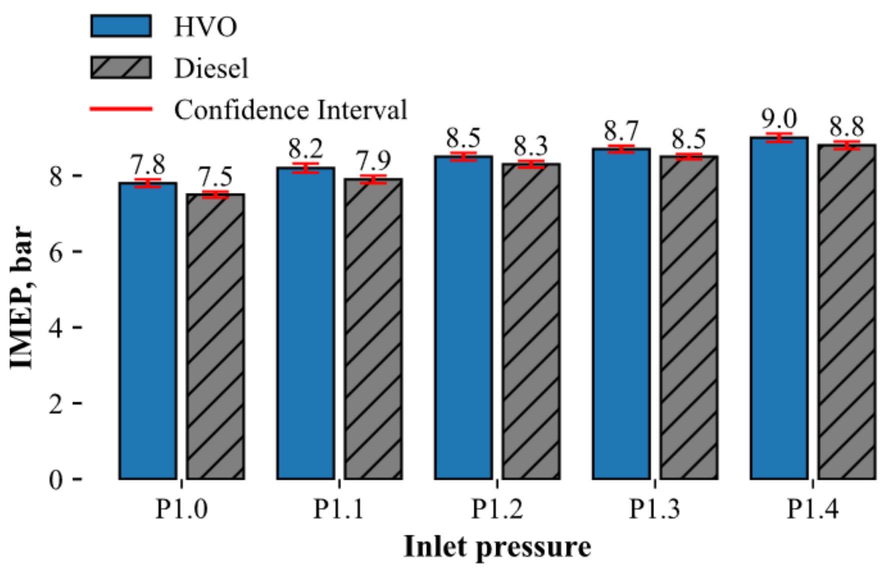

Fig. 4. ***IMEP$_{net}$* for HVO and diesel fuels**

Figure 5 shows the apparent heat release rates (*AHRR*) of HVO and diesel fuels at an intake pressure of 1.4 bar. It can be observed that the diesel fuel curve is much more impulsive and unpredictable. The HVO fuel curve allows for a more controlled and moderate fuel burn, without additional impulses and vibrations [8]. The main combustion phase is with the highest heat release rate. HVO fuel has a slightly faster heat release than diesel fuel. Premixed combustion peak of 89 J·deg^{-1} for HVO fuel and 111 J·deg^{-1} for diesel fuel. This difference is one of the factors of the chemical structure of the fuel, for example, HVO fuel is made of straight chained paraffins, so the combustion could be smoother without creating high impulsivity [9]. For both fuels, the diffusion combustion phase can be observed as the fuel gradually mixes with the air, creating a wave pattern [10]. In the diffusion combustion phase, HVO fuels show smoother AHRR. In the late combustion phase, the graph shows that the fuel continues to burn until it is completely combusted and *AHRR* is 0 J·deg^{-1}. HVO fuel and diesel fuel shows similar results in the late combustion phase.

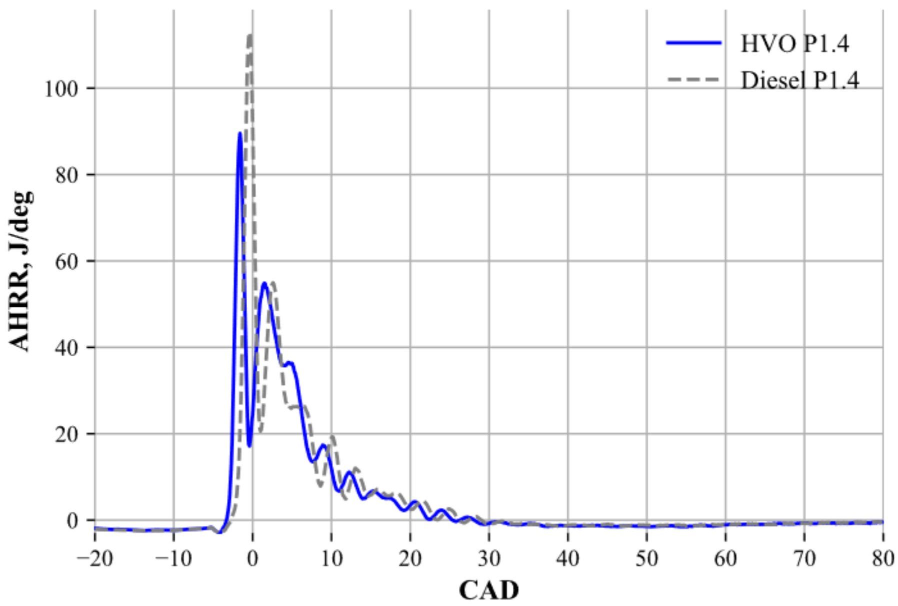

Fig. 5. **Heat release for HVO and diesel fuels**

The bottom figure shows the start of injection (SOI) for both fuels (Figure 6). In this particular engine, SOI was electronically set at 7° before the top dead centre, but in the diagram the change of

AHRR is at 5.4° before the top dead centre. Up to 0 J·deg^{-1} is the ignition delay, where the HVO fuel absorbs heat more moderately from the gases in the cylinder. Diesel fuel has a sharper and longer ignition delay. After ignition delay main combustion starts, where HVO fuel shows a more stable result with less curve bending [11].

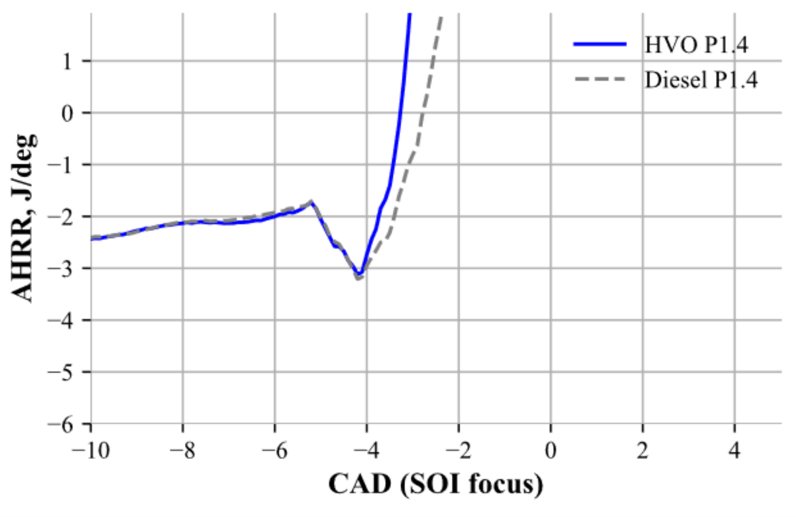

Fig. 6. **HVO and diesel fuels injection**

HVO fuels are more balanced and less impulsive in all combustion phases, allowing them to burn more efficiently.

Ignition delay is one of the most important parameters in diesel engines as it affects engine efficiency. The diagram (Figure 7) shows the ignition delay. HVO fuels show lower degree values than diesel fuels at the air inlet pressures (1.0; 1.1; 1.2; 1.3; 1.4 bar). The ignition delay is approximately 12% lower in all air pressure ranges. O. Shepe, J. Matijošius, A. Rimkus in their publication point out that the ignition delay for HVO fuel is 1° shorter than for diesel fuel [12]. HVO fuels have a higher cetane number, which causes them to ignite more quickly, producing a shorter ignition delay. Ignition delay is affected by fuel density, which is lower for HVO than for diesel fuel.

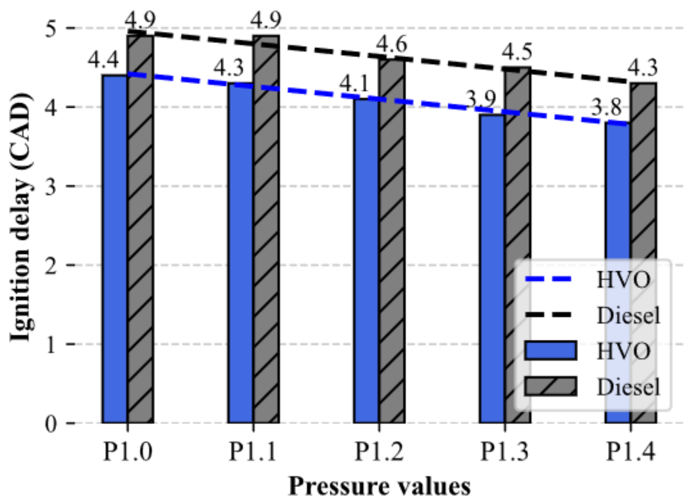

Fig. 7. **HVO and diesel fuel ignition delay**

Conclusions

1. 100% HVO fuel at inlet pressures of 1.0; 1.1; 1.2; 1.3; 1.4 bar shows higher combustion chamber pressures than diesel fuel.
2. The IMEP net values of HVO fuels at the inlet pressures of 1.0; 1.1; 1.2; 1.3; 1.4 bar show higher values than diesel fuel. Confirming that the combustion is more efficient and more complete.

3. The AHRR values of HVO fuel at an inlet pressure of 1.4 bar show smoother and faster ignition and combustion dynamics compared to diesel fuel.
4. The ignition delay for HVO fuel is lower than for diesel fuel at different air supply pressures.

Author contributions

Both authors have contributed equally to the study and preparation of this publication. Authors have read and agreed to the published version of the manuscript.

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