ABSTRACT

Current spray studies in the Aalto university focus on comparison between alternative biofuel and crude oil based fossil fuel. The emissions of modern diesel engines are essentially related to spray combustion. Therefore is vital to know how the different physical properties of fuels affect the fuel spray. To develop low emission combustion technologies for renewable fuels in internal combustion engines the global fuel spray characteristics are essential to know. If the spray characteristics of fuels differ substantially combustion chamber must be redesigned or injection parameters must be re-optimized.

In recent studies, renewable hydrotreated vegetable oil (HVO) was compared with crude oil based EN 590 diesel fuel (EN590). HVO is produced from vegetable oils and animal fats using hydrotreatment. HVO is used in diesel engines without any engine modifications or changes to fuel distribution systems. In Finland, HVO is produced by the brand name NExBTL. European standard EN 590 describes the physical properties that all automotive diesel fuels must meet if it is to be sold in the European Union, Iceland, Norway or Switzerland.

Cetane number of HVO is very high and HVO contains neither aromatic hydrocarbons nor oxygen. Physical properties of HVO differ from EN590 as well. Density and viscosity are slightly smaller with HVO than EN590. Density and viscosity have effect on fuel spray characteristics. According to previous studies, the use of HVO enables
reductions in exhaust gas emissions and in engine smoke without any changes to the engine or its controls. The combustion related properties of HVO are mostly better than crude oil based fuel. Advantageous combustion related properties of HVO allow more advanced combustion strategies than has been possible with EN590. Advanced combustion strategies enable to reduce emissions even more. Optical measurements of fuel sprays were performed in a pressurized test chamber in non-evaporative conditions. The fuel injection was arranged with a modern common rail fuel injection system and all injection parameters such as injection pressure and time were completely controlled. The fuel spray measurements were made with high speed backlight photography based on short laser pulse and digital image processing.

**Keywords:** Biofuel, Renewable diesel, Biodiesel, Hydrotreated vegetable oil, HVO, BTL, NExBTL, Injection, Nozzle, Spray, Fundamental spray characteristics, Spray tip penetration, Spray angle, Spray tip velocity, Optical measurements, Backlight imagining

**1. INTRODUCTION**

The present trend of internal combustion engine development is focused on emissions reduction. Common concern of environmental issues, such as air pollution, global warming and decreasing oil reserves, has increased. Emission limits have tightened and will be tighten even more by Euro 5 and Euro 6 standards [1]. Under directives of European Commission Europe established the goal of reaching a 5.75 % share of renewable energy in the transport sector by 2010 and 10 % by 2020 [2]. Emission limits and regulation have done renewable fuels increasingly interesting option for crude oil based fossil fuels. Modern paraffinic fuels such as Fischer-Tropsch fuels or HVO fuels may be renewable and reduce emissions considerably without compromising fuel quality and engine operation [3].

The focus of this paper is to report methods and results of recent diesel fuel spray studies in the Internal Combustion Engine Research Group of Aalto University. In recent studies was compared renewable hydrotreated vegetable oil (HVO) and crude oil based EN 590 diesel fuel (EN590). According to several studies, the use of HVO or other similar paraffinic diesel fuels enables reductions in particulate matters, carbon monoxide, total hydrocarbon and nitrogen oxide emissions, and in engine smoke without any changes to the engine or its controls. With optimized fuel injection parameters for HVO, even more significant reductions in emissions can be achieved. [3, 4, 5]

The emissions of modern diesel engines are essentially related to spray combustion. Therefore, is essential to know fundamental spray properties to develop low emission combustion technologies. If the spray characteristics of fuels differ substantially combustion chamber must be redesigned or injection parameters must be re-optimized. The knowledge of spray characteristics gains more information from the combustion phenomena and influence of injection parameters. This reduces the amount of engine tests in parameter optimization and supports the computational studies. Density and
viscosity are slightly smaller with HVO than EN590 diesel fuel. Density and viscosity have fundamental effect on fuel spray characteristics [6, 7, 8, 9].

Influences of the global fuel spray characteristics are widely studied with traditional fossil diesel fuels and first generation biodiesels [10], [11]. However, only limited amount of fuel spray measurements with HVO have reported [12]. Other paraffinic fuels such as Fischer-Tropsch and gas to liquid fuels have similar properties with HVO and studies with other paraffinic fuels are able to compare with HVO. In studies with Fischer-Tropsch and gas to liquid fuels, have been reported some similarities and some differences compared with crude oil based traditional diesel fuel [7, 13, 14].

Hydrotreated vegetable oil (HVO) is modern paraffinic diesel fuel for engine use. HVO is produced from vegetable oils and animal fats using hydrotreatment. HVO is used in diesel engines without any engine modifications or changes to fuel distribution systems. HVO is produced by the brand name NExBTL in Finland and NExBTL was used in the recent studies. NExBTL is produced by Neste Oil Corporation.

Quality of HVO is as good as crude oil diesel fuel or even better. The combustion related properties of HVO are mostly better than crude oil based fuel. With HVO, flammability is good, boiling ranges lower than with normal diesel fuel and the cold operation characteristics are adjustable. HVO contains no aromatics or oxygen. Although the lubricities of the fuels are poor, they can be easily improved with additives. Density and viscosity are slightly smaller with HVO than EN590 diesel fuel (table 1). [3, 12]

Table 1 – Some fuel properties of HVO and EN 590 that were used in the fuel spray experiments.

<table>
<thead>
<tr>
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<th>EN590</th>
<th>HVO</th>
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<tbody>
<tr>
<td>surface tension</td>
<td>29 mN/m</td>
<td>28 mN/m</td>
</tr>
<tr>
<td>density (15 °C)</td>
<td>837.3 kg/m³</td>
<td>779.9 kg/m³</td>
</tr>
<tr>
<td>viscosity (40 °C)</td>
<td>3.587 mm²/s</td>
<td>2.985 mm²/s</td>
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</table>
2. Methods of spray studies

Optical measurements of fuel sprays were performed in a pressurized test chamber in non-evaporative conditions. The fuel injection was arranged with a modern common rail fuel injection system and all injection parameters such as injection pressure and time were controlled. The fuel spray measurements were made with backlight imaging (Fig. 1) based on short laser pulse. Digital images were analyzed with computer program.

2.1 Backlight imaging

Backlight imaging method (Fig. 1) enables to take quality spray images (Fig 2). Fuel spray is injected to measurement chamber. Short laser pulse lights measurement chamber for defined time after the start of injection signal. Camera is set to the opposite direction of laser light and spray is injected between light and camera. Spray is shown darker than the background in the figure (Fig 2). The duration of the laser pulse is so short, only 5 ns, that it is able to freeze all the motion of spray.

The laser beam passes thought the diverging lens, fluorescent class and diffusor milk class. While originally green laser light is shot to a fluorescent plate, the light is phase shifted to white light which is even and planar. The light was further smoothed with a milk glass diffusor. The phase shifting (fluorescence) is used to disturb laser coherence to give a uniform backlight for a small area.

![Figure 1. Schematic picture of back-light imaging.](image-url)
2.2 Measurement Backlight image analyzing

Before the spray imaging, dimensions of the image are defined with calibration object that has well known dimensions. Calibration objective defines size of pixels in digital image. Defined dimensions are saved on computer memory. After calibration camera and injector are not moved.

Backlight images are analyzed with algorithms of computer analyzing programs. The “border” or “edge” detection of a spray is one of the main algorithms of the analyzing process. It is used for the calculation of the spray angle and spray tip penetration. The algorithm works on horizontal pixel lines of an image. The number of all pixels with intensities above the defined threshold are counted and defined as inside the spray region and all other pixel with larger numbers as outside. At the end, the algorithm finds a right and a left spray border for a given horizontal pixel line. The spray tip penetration is defined as the distance between the injector and the leading edge of the spray. The algorithm finds the penetration radius of a circle with center the injector orifice position.

Figure 2. Fuel spray images with different injection pressures 0.6 ms after start of injection signal when inner delay of nozzle was 0.34 ms.
3. Test apparatus
Measurement equipments were installed at the test rig (Fig.2). The most important measurement equipments are laser based backlight imaging system, fuel injection system and pressurized test chamber.

![Test rig, spray chamber and measurement equipments.](image)

3.1 Laser based backlight imaging system
Laser based backlight imaging system is composed of laser, camera and control computer systems. The spray measurement laser was a double pulsed Nd:YAG laser. Nd:YAG laser produce wave length of 1064 nm (infrared, invisible) fundamental beam which was frequency doubled under second harmonic generation to wave length of 532 nm (green, visible). Laser beam was directed to the pressurized test chamber (Fig 4). Double-frame photographing was utilized with double-pulsed laser to measure spray tip velocities. The camera is capable of taking two sequential images with one CCD-chip with time intervals as small as 200 ns. For each velocity measurements, two consecutive images were taken at defined time intervals. Spray tip penetration difference between both consecutive pictures were analyzed and velocities were calculated. The resolution of camera was 2048x2048 pixels (four megapixels) with dynamic range of 12 bit. The optic was 105mm teleobjective. The area of view was approximately 40x80 mm and pixel resolution was approximately 40 μm. Half of pixels were not in area of the view due to
the chamber design. More details of this and similar test rigs and pressurized spray chambers have reported at previous publications (15), (16).

3.2 Pressurized test chamber
Measurements of fuel sprays were performed in a pressurized test chamber in non-evaporative conditions in room temperature. According to earlier studies, ambient temperature has not significant influence on nonevaporative spray formation (9). Instead, ambient density has considerable influence on spray formation. Therefore, ambient density is kept constant by controlling inflow of pressurizing gas and ambient chamber pressure while temperature was not constant. Ambient density in the test chamber was 35 kg/m² which is close to the real engine conditions of heavy-duty diesel engines at the end of compression stroke. Pressurizing gas is nitrogen which is non-flammable mixture with diesel mist.

The pressurized test chamber (Fig. 4) has four glass windows, each 100 mm in diameter. The glass windows are 30mm thick. The glass was hardened and the surfaces were ground smoothed. When windows and teleobjective of camera was combined, was found only a minor distortion to the picture. This distortion was taken into account in calibration process.

![Pressurized test chamber and the glass window of chamber.](image)

3.3 Fuel injection system
The fuel injection is imitating the modern common rail injection system (Fig. 5). The difference compared to the normal common rail is the computer based control system
where all injection parameters except geometrical issues and fuel characteristics are able to vary during the measurements. In the recent studies was used solenoid operated common rail injector. The nozzles of this size are normally used at heavy-duty diesel engines.

**Figure 5. Typical common rail injection system (Robert Bosch Inc).**

### 4. RESULTS

HVO and EN590 diesel fuels were tested with same nozzle orifice and three various injection pressures (table 2). Nozzle orifice diameter was 0.12 mm and injection pressures were 450, 1000 and 1985 bar. Ambient density in the test chamber was 35 kg/m³ that is close to the real engine conditions at the end of compression stroke. Ambient density was kept constant by controlling inflow of pressurizing gas and chamber pressure while temperature was not constant. The delay between injection signal and fuel jet exit from the nozzle orifice was 0.340-0.370 ms. This is mainly due to solenoid operation, needle inertia and fluid inertia. Delay was depended on injection pressure and fuel properties.
Table 2 – Tested measurement points. Tested measurement points are marked with X. Each point was tested with NExBTL and EN 590 diesel fuel.

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<th>1985 bar</th>
<th>1000 bar</th>
<th>450 bar</th>
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<tr>
<td>0,12 mm</td>
<td>X</td>
<td>X</td>
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This paper focuses on spray tip velocity studies. Other fundamental spray tip characteristics will be reported later. Spray tip velocity was measured with double-frame photographing and double-pulsed laser. The main purpose of velocity measurements was to find possible differences between compared fuels. Spray tip velocity results are presented as function of penetration. Injection pressure comparisons are in figures 6 and 7. Fuel comparisons between HVO and EN590 are in figures 8, 9 and 10.

Figures 6 and 7 shows expected differences between different injection pressures. The spray tip velocity of HVO seems to be slightly higher than the velocity of EN590. Acceleration, velocity maximum and deceleration region were found in all velocity figures as has been reported earlier studies (17), (18). Velocity seems to be notable low with lower injection pressure especially at the end of measurement area.

![Figure 6. Spray tip velocity comparison between injection pressures 450, 1000 and 1985 bar when diameter of injector orifice is 0.12 mm, ambient gas density is 35 kg/m³ and fuel is NExBTL (HVO).](image-url)
The Swedish and Finnish National Committees of the International Flame Research Foundation – IFRF

Figure 7. Spray tip velocity comparison between injection pressures 450, 1000 and 1985 bar when diameter of injector orifice is 0.12 mm, ambient gas density is 35 kg/m³ and fuel is EN590.

Figure 8. Spray tip velocity comparison between NExBTL (circle) and EN 590 (square) diesel fuels when injection pressure is 450 bar and diameter of injector orifice is 0.12 mm.
Figure 9. Spray tip velocity comparison between NExBTL (circle) and EN 590 (square) diesel fuels when injection pressure is 1000 bar and diameter of injector orifice is 0.12 mm.

Figure 10. Spray tip velocity comparison between NExBTL (circle) and EN 590 (square) diesel fuels when injection pressure is 1985 bar and diameter of injector orifice is 0.12 mm.
5. CONCLUSIONS

In this paper, methods and results of recent diesel fuel spray studies in Aalto University were reported. The global fuel spray characteristics between renewable hydrotreated vegetable oil (HVO) and crude oil based EN 590 diesel fuel were compared. Focus of measurements was on spray tip velocity measurements. Experimental arrangement and measurements were performed successfully.

According to the spray tip velocity measurements, in non-evaporative conditions, a clear difference was found between HVO and EN590 diesel fuels. Spray tip velocities are substantially higher with HVO than EN590 diesel fuel. Velocity difference seems to be especially clear in the beginning of spray penetration where velocity maximum was found. Velocity maximum region seems to be wider with HVO than EN590 diesel. After deceleration region, velocity difference between different fuels is not as clear. In the end of monitoring area, spray tip velocity seems to be notable lower with lower injection pressure. Although, in the real engine conditions spray is mostly vaporized momentum still remains. Low velocity may be reason for unfavourable engine combustion and higher emissions. Interesting question for further studies is how the higher velocity of spray tip penetration affects on atomization, fuel-air mixing and turbulence. The assumption is that higher velocity affects favourable combustion phenomena which lead to reduced emission formation. Presumably, higher velocity of spray tip penetration improves atomization and fuel-air mixing with same injection parameters.

6. REFERENCES


7. ACKNOWLEDGEMENTS

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