The impact of selected biofuels on the performance parameters of the Common Rail power system in the utility engine

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Abstract. The aim of the research was to determine the impact of biofuels from waste materials of plant and animal origin on the parameters of the common rail power supply system in the utility engine. The tests included identification of power system operation parameters in the whole load range of the tested engine, taking into account the limit and diagnostic parameters of the injectors operation. Then, for certain parameters, the engine injectors were tested on the test bench: injection pressure in the range of 25-135 MPa, injection time in the range of 200-1600 µs. In the tests, as reference fuel for testing injectors were used diesel fuel and three types of methyl esters of higher fatty acids: vegetable, animal and WCO origin. The measurements for individual fuels were made in the operating temperature range 30-60°C. The tests have shown significant changes in the volume of the fuel injection rates depending on the fuel used. Particularly, visible changes concerned the power system operation parameters for high engine speeds and the maximum working pressure of the common rail system in the engine.

1 Introduction

Today, it is estimated that transport generates about 20% of global energy demand. Due to high energy efficiency, high torque, high energy density of fuel in the different means of transport, self-ignition internal combustion engines play a dominant role [1, 2]. This particularly applies to the use of internal combustion engines in heavy duty vehicles. In addition, the use of diesel engines makes it possible to use a wide range of fuels to supplement or replace diesel [3].

The growing, restrictive requirements for the emission of toxic exhaust components and the increase in requirements for improving the efficiency of diesel engines, also in the context of reducing CO2 emissions, necessitate the introduction of new design solutions (e.g. diesel particulate filters, various types of catalysts, use of high-pressure fuel systems) [4, 5] or the use of new combustion systems [6]. This causes complications in the construction of motors and significantly reduces the reliability of drive units, increases maintenance activities (e.g. for units with SCR system) [7], and consequently, leads to potential interruption of transport processes. In addition, the introduction of new constructional solutions entails a delay of several years in the exploitation practice of the vehicle and in some cases the need to adapt the transport infrastructure to them.

Regarding vehicles and means of transport in operation, it seems preferable, instead of implementing new construction solutions, to introduce fuels that have a significantly smaller impact on the environment than diesel [1, 8, 9]. The most commonly used fuels are methyl esters of higher fatty acids of various origins [10]. The most popular ones are first generation biofuels based on oils of edible plants (rapeseed [11], sunflower, soybean, or palm) [12], the use of which does not require significant modifications in usable or traction engines [13].

On the one hand, biofuels allow for the reduction in the emission of the toxic components of exhaust fumes, carbon monoxide, hydrocarbons or particulates (due to the oxygen content), and, on the other hand, to fulfill the indicative targets of individual countries regarding the use of renewable energy sources [2]. However, the level of energy demand makes it necessary to look for new sources of raw materials for the production of biofuels. The use of raw materials in the form of non-edible plant oils or waste oils (animal, frying) allows for the increase in the potential of liquid biofuels. However, fuels made from them often do not meet the requirements for fuels used in modern diesel engines, especially in common rail systems. In addition, the production of biofuels from a variety of raw materials causes a variable chemical composition of the obtained fuel and also involves changes in physical properties, especially low-temperature ones. In the case of biofuels, an important parameter is their viscosity from the point of view of controlling the injection process. On the other hand, the chemical composition, especially oxygen content and energy value of fuel have significant impact on the fuel combustion process [14, 15, 16].

The reasons mentioned for the introduction of biofuels of various origin resulted in undertaking research aimed...
at assessing the impact of pure biofuels on the performance parameters of the common rail power system in the utility engine. The tests were based on an internal combustion engine, which is used in heavy road vehicles, farm tractors or industrial engines.

2 Research focus

The aim of the research was to determine the impact of biofuels from waste materials of plant and animal origin on the parameters of the common rail power supply system in the utility engine.

3 Object and methods of research

The tests included identification of the operating parameters of the John Deere JD 4045HF285 fuel system. The basic parameters of the tested engine are shown in Table 1.

Table 1. Specification of the tested engine.

| Parameter                  | Engine                                      |
|----------------------------|---------------------------------------------|
| Engine type/model          | automotive variable speed 4-stroke engine/4045HF285 |
| Application                | diesel truck, tractors, industrial motors   |
| No. of cylinders           | 4                                           |
| Compression ratio          | 19:1                                        |
| Rated speed, rpm           | 2400                                       |
| Rated power, kW            | 74 @ 2400 rpm                               |
| Rated torque, Nm           | 353 @ 1600 rpm                              |
| Displacement, cc           | 4530                                        |
| Aspiration system          | turbocharged without Intercooler            |
| Fuel delivery system       | common rail                                 |
| Fuel Injection Pump        | Denso HP3                                    |
| Maximum fuel pressure, MPa | 105                                         |
| Minimum fuel pressure at   | 40                                          |
| idle speed, MPa            |                                             |
| Injector type/model        | CR/Denso 095000-6310                         |

The engine is equipped with a common-mode Denso power supply system and an electronic control system that allows for the reading and recording of fuel injection pressures in the system. The engine was mounted on a dynamometric test bench coupled with an electro-spin brake and Automex AMX data control and archiving system. In order to determine the fuel pressure level, the engine was loaded with a torque system. In order to determine the fuel pressure level, the brake and Automex AMX data control and archiving dynamometric test bench coupled with an electro-spin power supply system and an electronic control system that allows for the reading and recording of fuel injection pressures in the system.

The aim of the research was to determine the impact of biofuels from waste materials of plant and animal origin on the parameters of the common rail power supply system in the utility engine.

The tests were conducted for reference fuel (Calibrol), commercial diesel oil and three biofuels in the form of methyl esters respectively: rapeseed oil – BIO 1, animal fats – BIO 2, plant waste cooking oil – BIO 3. The chemical composition and basic properties of the tested fuels are presented in Table 2 and 3.

Table 2. The chemical composition of the tested biofuels.

| Common name of fatty acid methyl ester | BIO 1 | BIO 2 | BIO 3 |
|---------------------------------------|-------|-------|-------|
| Myristic C14:0                        | -     | -     | 0,12  |
| Palmitic C16:0                        | 0,32  | 20,8  | 6,51  |
| Palmitoleic C16:1                     | 4,1   | -     | 0,35  |
| Stearic C18:0                         | 1,58  | 6,3   | 3,7   |
| Oleic C18:1                           | 62,04 | 44,6  | 63,7  |
| Linoleic C18:2                        | 19,81 | 15,7  | 21,27 |
| Linolenic C18:3                       | 8,97  | 0,85  | 1,2   |
| Arachidic C20:0                       | 0,77  | -     | 0,27  |
| Eicosenic C20:1                       | 1,16  | -     | 0,65  |
| Others                                | 1,25  | 11,75 | 2,23  |

The density of fuel was determined by the hydrometer in accordance with PN-EN 3675 at 30, 40, 50, 60°C. The kinematic viscosity of the studied fuels was determined by capillary according to PN-EN ISO 3104 at temperatures of 30, 40, 50 and 60°C (Table 3). The composition of the various methyl esters was determined in accordance with PN-EN 14103 (Table 2), due to the significant impact of different types of esters on the physicochemical property of fuel.

All fuels were tested at temperatures from 30 to 60°C, at fuel pressures ranging from 25 to 135 MPa. Injectors opening time varied from 200 to 1600 μs. Therefore, the extreme values of injection parameters were also checked, which were determined by the manufacturer in points P1 (injection pressure 25 MPa, injector opening time 600 μs) and P2 (injection pressure 135 MPa, injector opening time 850 μs). On the basis of the obtained fuel injection quantities for individual parameters (pressure and injection time), the active flow cross section was calculated. For this purpose, the effective injection time was determined as the ratio of the amount of fuel injected at the test stand to the time of injection. The effective time was calculated as the difference between the injector coil feeding time and the time determined by extrapolation to the ordinates of the curve formed on the basis of the injection values at a given point at constant pressure. The active flow cross section identified is directly proportional to the volumetric flow rate of the injected fuel and inversely proportional to the square root of the ratio between the value of twice the product of the differential pressure before and after the injector and the density value of the tested fuel. A detailed definition of the active flow cross section is presented in [17].

Table 3. Property of the tested fuels.

| Fuel property | BIO 1 | BIO 2 | BIO 3 | Diesel | Calibrated |
|---------------|-------|-------|-------|--------|------------|
| Density @ 30°C, kg/m³ | 870,8 | 862,8 | 875,0 | 832,3 | 815,0 |
| Density @ 40°C, kg/m³ | 865,2 | 856,0 | 868,4 | 825,1 | 807,6 |
| Density @ 50°C, kg/m³ | 858,4 | 849,3 | 861,8 | 817,8 | 800,2 |
| Density @ 60°C, kg/m³ | 851,7 | 842,6 | 855,2 | 810,6 | 792,9 |
| Viscosity @ 30°C, mm²/s | 5,54  | 7,09  | 6,07  | 3,65  | 3,10  |
| Viscosity @ 40°C, mm²/s | 4,43  | 5,45  | 4,80  | 2,97  | 2,55  |
| Viscosity @ 50°C, mm²/s | 3,63  | 4,49  | 3,94  | 2,5   | 2,14  |
| Viscosity @ 60°C, mm²/s | 3,05  | 3,73  | 3,30  | 2,15  | 1,81  |
4 Test results

4.1 Injection pressure of the fuel supply system

The obtained values of fuel injection pressure at different rotational speeds allowed us to distinguish between three characteristic curves of pressure curves as a function of load, which were presented in Figures 1 to 3.

In Fig. 1 for speeds of 1200-1400 rpm it can be seen that the fuel pressure rises from about 70 to 90 MPa at 150 Nm, and then remains at this level. Changes in the course of the pressure curve can be observed at a rotational speed of 1500 rpm. For 50 Nm load the pressure increases slightly, then decreases by 10 MPa at 200 Nm, after which it gradually increases to the level of 90 MPa.

Fig. 1. Fuel injection pressure in the fuel supply system at 1200-1500 rpm.

The next group of curves is shown in Fig. 2 and refers to the rotational speed from 1600 to 1900 rpm, for which the curves have a similar character. Initially, the pressure drops from 85-88 MPa to the local minimum at a load of 150 Nm, which ranges from 50 MPa to 70 MPa. Then the pressure increases to 75-88 MPa at maximum load. It should be noted that the tested engine acquires maximum torque at a speed of 1600 rpm, for which the lowest fuel injection pressure level has been recorded.

Fig. 2. Fuel injection pressure in the fuel supply system at 1600-1900 rpm.

The third group comprises the pressure curves for speeds from 2000 to 2400 rpm (Fig. 3), which have a relatively flat course. The initial injection pressure is around 90 MPa. The lowest pressure values were at 2000 rpm, where the pressure drops to 78 MPa (150 Nm), after which it increases to 90 MPa. The highest fuel pressure values correspond to the rated speed of the engine. In this case, the pressure course is a variable characteristic, it increases to 100 MPa, then drops to 95 MPa and at full load again increases to a maximum pressure of 105 MPa.

Fig. 3. Fuel injection pressure in the fuel supply system at 2000-2400 rpm.

Fig. 4 shows the dependence of the injection pressure on the rotational speed at zero load and for full engine load. In the absence of a load, the injection pressure increases with the increase of the rotational speed, the fastest being between 1300 and 1600 rpm. At full load, the injection pressure does not change to 1500 rpm and is about 90 MPa, then it decreases to a minimum of 74 MPa at 1600 rpm, after which it increases linearly to 105 MPa at 2400 rpm.

Fig. 4. Injection pressure, power output and torque characteristics in the function of engine revolutions at maximum load and idle speed.

Analyzing the entire working area of the engine, it can be concluded that the injection pressure varies with changes in the engine load in the range of 50 to 105 MPa. It should be pointed out that the minimum injection pressure for a given speed corresponded to the load, at which the air pressure generated by the turbocharger increases rapidly. For the minimum idling speed (800 rpm) the injection pressure was 40 MPa, therefore the injection pressure in the range of 40 to 100 MPa was taken into account when analyzing the discharge coefficient.

4.2 The active flow cross section

The tested fuels differed significantly in chemical composition and physical properties (Tables 2 and 3). The fuels used in the research represent the most popular types of raw materials for the production of biofuels, i.e.
1 – generation biofuel vegetable oils – BIO 1, technical animal fats – BIO 2, waste cooking oil – BIO 3. Certain values of density, viscosity or heat of combustion are close to those described in the literature [16, 19]. The lowest density and the highest viscosity was noted for BIO 2 biofuel. In contrast, the highest density and calorific value was found for BIO 3 frying oil. The obtained physical parameters result directly from the chemical composition of the fuel [16, 20]. In addition, during tests it was found out that animal fuels have a high pour point, in the case of BIO 2 the blocking temperature of the cold filter was 11°C. Analogous results for biofuels of animal origin were obtained in [16, 18, 19, 20]. This parameter is the main obstacle to the use of clean biofuels during the actual operation of internal combustion engines.

Fig. 5 shows the size of the fuel dose at the diagnostic points specified by the manufacturer for the tested injectors. The parameters of point P1 correspond to the moment of opening the injector, while point P2 determines the maximum injection pressure provided for he tested injector type. The differences in the amount of reference fuel, diesel oil and biofuels tested by the injector are clearly visible, especially in P2 point. However, all injection volume values are within the range specified by the manufacturer, i.e. for P1 points they are 3.2 ± 1 mm³ and for P2 – 60 ± 4 mm³. Taking into account the viscosity of fuels (Table 3), there was a clear dependence of the fuel doses (Fig. 5) on this parameter.

Fig. 6. Simile of the active flow cross sections of tested fuels at 30°C.

An increase in fuel temperature of up to 50°C corresponds to medium and long-term engine operation conditions. In this case, the active flow cross section (Fig. 8) in the range of 60 to 80 MPa is clearly higher for diesel and its maximum is shifted between 60 and 80 MPa. Moreover, above this point the coefficient for other fuels is higher, especially for BIO 1 fuel, which reaches its maximum again at 80 MPa. The coefficients for BIO 2 and BIO 3 are similar and reach a maximum at 100 MPa. At this temperature, the correction of the injection parameters should cover the entire tested pressure range, but their changes should be of a different nature.

Fig. 7. Simile of the active flow cross sections of tested fuels at 40°C.

Fig. 8. Simile of the active flow cross sections of tested fuels at 50°C.
In the research at 60°C, there were clear differences in the active flow cross section for diesel and all biofuels in the pressure range of 40 to 80 MPa (Fig. 9). It should be pointed out that this is an area where there is an increase in turbocharger efficiency for medium rotational speeds and medium loads. In addition, in this pressure range, the entire load characteristic for the maximum torque speed is included. Therefore, when the motor is used for a long time with high thermal loads (high ambient temperature, long-lasting operation at almost full load) it requires adjustment of the controller settings, especially at pressures of 60 MPa and 100 MPa.

![Fig. 9. Simile of the active flow cross sections of tested fuels at 60°C.](image)

5 Conclusion

The engine tests carried out on the dynamometric bench allowed us to determine the scope of the fuel supply system depending on the load and rotational speed. It was found out that fuel operating pressures range from 40 to 105 MPa, the value of which is significantly lower than the pressure levels tested in the literature [21, 22]. It has been shown that for medium loads and high level of engine recharging, fuel pressure is reduced even to 50 MPa for the maximum torque speed.

Analyzing the calculated active flow cross section it was concluded that the differences in its value for diesel oil and individual biofuels increase with the temperature of the examined fuel. For temperatures of 30 and 40°C, clear differences in the value of the coefficient occur above 80 MPa, which is related to the need to adjust the injection parameters for biofuels. Further increase of fuel temperature to 50 or 60°C deepens the differences in the coefficient for diesel oil and biofuels within the whole range of the power system operation, which is from 40 to 100 MPa.

In addition, it was found out that for BIO 1 fuel above 80 MPa, the active flow cross section has a higher value than for diesel fuel. However, for BIO 2 and BIO 3 fuels, this is the case only at 100 MPa.

References

1. K. Duda, S. Wierzbicki, M. Śmieja, M. Mikulski, Comparison of performance and emissions of a CRDI diesel engine fueled with biodiesel of different origin, Fuel, 212, 202-222 (2018)

2. S. Mishra, K. Anand, S. Santhosh, P. Mehta, Comparison of biodiesel fuel behavior in a heavy duty turbocharged and a light duty naturally aspirated engine, Applied Energy, 202, 459-470 (2017)

3. B. Sajjadi, A. Raman, H. Arandiyan, A comprehensive review on properties of edible and non-edible vegetable oil-based biodiesel: Composition, specifications and prediction models, Renewable and Sustainable Energy Reviews, 63, 62-92 (2016)

4. H. Howa, H. Masjuki, M. Kalam, H. Teoh, Influence of injection timing and split injection strategies on performance, emissions, and combustion characteristics of diesel engine fueled with biodiesel blended fuels, Fuel, 213, 106-114 (2018)

5. S. Ren, B. Wang, J. Zhang, Z. Wang, J. Wang, Application of dual-fuel combustion over the full operating map in a heavy duty multi-cylinder engine with reduced compression ratio and diesel oxidation catalyst, Energy Conversion and Management, 166, 1-12 (2018)

6. J. Hunicz, A. Tmar, P. Krzaczek, Effects of mixture stratification on combustion and emissions of boosted controlled auto-ignition engines, Energies, 10, 2172 (2017)

7. W. Urzędowska, Z. Stępień, Prediction of threats caused by high FAME diesel fuel blend stability for engine injector operation, Fuel Processing Technology, 142, 403-410 (2016)

8. G. Edara, Y. Murthy, P. Srinivas, J. Nayar, M. Ramesh, Effect of cooled EGR on modified light duty diesel engine for combustion, performance and emissions under high pressure split injection strategies, Case Studies in Thermal Engineering, 12, 188-202 (2018)

9. L. Lešnik, I. Biluš, The effect of rapeseed oil biodiesel fuel on combustion, performance, and the emission formation process within a heavy-duty DI diesel engine, Energy Conversion and Management, 109, 140-152 (2014)

10. C. Hayes, D. Burgess, J. Manion, Combustion pathways of biofuel model compounds: A review of recent research and current challenges pertaining to first-, second-, and third-generation biofuels, Advances in Physical Organic Chemistry, 49, 103-187 (2015)

11. G. Zając, W. Piekarski, P. Krzaczek, Comparison of an effect of FAME and FAEE addition to diesel fuel on energetic parameters of an engine, TEKA Kom. Mot. i Energ. Rol. – OL PAN, 8a, 217-223 (2008)

12. M. Bhuiya, M. Rasul, M. Khan, N. Ashwath, A. Azad, M. Hazrat, Prospects of 2nd generation biodiesel as a sustainable fuel – Part2: Properties, performance and emission characteristics, Renewable and Sustainable Energy Reviews, 55, 1129-1146 (2016)

13. V. Goel, N. Kumar, P. Singh, Impact of modified parameters on diesel engine characteristics using biodiesel: A review. Renewable and Sustainable Energy Reviews, 82, 2716-2729 (2018)
14. S. Slavinskas, G. Labeckas, T. Mickevicius, Experimental study on injection characteristics of diesel and biodiesel fuel blends with common-rail injection system, *Engineering for rural development*, Jelgava, 2134-2140 (2018)

15. M. Das, M. Sarkar, A. Datta, A. Santra, Study on viscosity and surface tension properties of biodiesel-diesel blends and their effects on spray parameters for CI engines, *Fuel*, 220, 769-779 (2018)

16. E. Giakoumis, A statistical investigation of biodiesel physical and chemical properties, and their correlation with the degree of unsaturation. Renewable Energy, 50, 858-878 (2013)

17. A. Rybak, M. Geča, P. Krzaczek, A. Mazanek, Determination of common rail injector flow characteristics with the use of diesel and biodiesel fuels, Journal of KONES, 23(4), 443-450 (2016)

18. A. Rybak, J. Hunicz, P. Krzaczek, W. Golimowski, D. Marcinkowski, Effect of different biofuels on common rail injector flow rate, Combustion Engines, 171(4), 39-43 (2017) DOI: 10.19206/CE-2017-407.

19. D. Marcinkowski, B. Rukowicz, W. Golimowski, M. Czechlowski, P. Krzaczek, W. Piekarski, Effect of selected depressants on cold filter plugging point for methyl esters obtained from transesterification of waste vegetable and animal fats, Przem. Chem, 96(9), 1927-1930 (2017), DOI: 10.15199/62.2017.9.22

20. N. Kumar, S. Varun, R. Chauhan, Performance and emission characteristics of biodiesel from different origins: A review, Renewable and Sustainable Energy Reviews, 21, 633-658 (2013)

21. L. Duan, S. Yuan, L. Hu, W. Yang, J. Yu, X. Xia, Injection performance and cavitation analysis of an advanced 250 MPa common rail diesel injector, International Journal of Heat and Mass Transfer, 93, 388-397 (2015)

22. J. Berghorson, M. Thomson, A review of the combustion and emissions properties of advanced Transportation biofuels and their impact on existing and future engines, Renewable and Sustainable Energy Reviews, 42, 1393-1417 (2015)