Testing of the fleet of the vehicles with diesel engines fed by BIOXDIESEL fuel

The paper presents results of testing of the fleet of the parcel delivery vehicles, equipped with the Diesel engines fed by biofuel BIOXDIESEL, manufactured on the way of the ethanol esterification process of the waste vegetable and animal fats, with the addition of the standard diesel fuel and pure ethanol. The comparison results of the vehicles test bed on the beginning of the testing and at the end of the testing, when vehicles were fueled with standard diesel and testing biofuel. The results of the testing at non-stationary states are also presented. The paper presents also results of the drivers evaluation of the performance of the vehicles based on the questionnaire. Presented results show that the BIOXDIESEL fuel is fully replaceable to the standard diesel fuel.

In the USA, Brasil and India the methyl or ethyl esters are not distinguished in the standards, which are describing fuel parameters. The biofuel just has to meet standard requirements, eg. ASTM D6751 in the USA, ANP 42 in Brasil or IS15607:2005 in India.

Table 1 presents selected quality parameters of the BIOXDIESEL fuel (results obtained by the authors) compared with PN-EN 590 and PN-EN 14214+A1.

| Parameter | Units | Properties of BIOXDIESEL fuel | PN-EN 590.2013 requirement | PN-EN 14214+A1 requirement |
|-----------|-------|-------------------------------|-----------------------------|-----------------------------|
| Cold Filter Plugging Point | °C | –17 | Season dependent | Season dependent |
| Cetane number | | 51.9 | 51 | 51 |
| Density at 15°C | kg/m³ | 868 | 820 | 845 | 860 | 900 |
| Flash point | °C | 24 | 55 | 101 |
| Viscosity at 40°C | | 2.33 | 2 | 4.5 | 3.5 | 5 |
| Calorific value | MJ/kg | 38.5 | 42.8 | 38 |

The fatty acid ethyl esters were obtained on the way of transesterification of the waste animal (pork and poultry) fats, waste vegetable fats, eg. used frying oils and small addition of fresh rapeseed oil with bioethanol in the presence of alkali catalyst (KOH). The selection of feedstock for production of FAEE used for BIOXDIESEL fuel is described in [6].

The application of waste animal fats as a feedstock for biodiesel production is a subject of an intensive research also around the world, eg. [2, 3].

The BIOXDIESEL used for feeding the engines of the fleet vehicles used for the testing is a blend made of about 70% of biocomponents (FAEE and bioethanol) and about 30% of diesel fuel with additives.
3. Description of the fleet vehicles used for testing

The fleet used for testing consisted of 15 parcel delivery vehicles. The vehicles have been used on different duty cycles: 5 vehicles were operated in the cities, 5 in long distances and 5 vehicles in the mixed duty cycles. Table 2 describes the fleet vehicles and their engines.

Table 2. Description of vehicles and engines used for fleet testing

| Make, model     | Year of build | Engine displacement [ccm], no of cylinders | Max engine power [BHP] | Max engine torque [Nm] |
|-----------------|---------------|--------------------------------------------|------------------------|------------------------|
| Citroen Jumper  | 2011          | 2200, 4 cyl                                | 100                    | 250                    |
| Citroen Berlingo| 2011          | 1560, 4 cyl                                | 75                     | 185                    |

4. Testing procedures of the fleet vehicles fed with BIOXDIESEL fuel

The vehicles have been thoroughly examined before start of the testing.

On the day of fuel replacement, the engine performance was evaluated on the vehicle test bed, when vehicles were fed with standard Diesel fuel. Also the engine performance in non-stationary condition was measured according to the procedure described in [1] and [5].

Just before filling the vehicles’ fuel tanks with BIOXDIESEL fuel the oil, oil filters and fuel filters were replaced with the new ones.

Then the vehicles were tested with in non-stationary conditions according to [1] and [5] again with the experimental diesel fuel. Also the vehicles engine performance was tested on the vehicle test bed.

In the middle of the test the vehicles engine performance was measured in non-stationary states.

Then at the end of the test vehicles were tested in non-stationary conditions and on the vehicle test bed with BIOXDIESEL fuel and after replacement with standard Diesel fuel.

4.1. Description of the testing in non-stationary conditions

The testing procedure is described in details in [1] and [5]. The testing in non-stationary conditions consists the set of rapid acceleration and deceleration of the engine from idling to maximal speed, back to idling. The engine is loaded by the moment of inertia of moveable parts of the engine.

The cyclodynes are the curves drawn on the engine torque – engine revolution plane. It is possible to draw cyclodynes in the angular acceleration – engine crankshaft rotational velocity, when the information about polar moment of inertia of the engine is not known. For comparison purposes it is possible to use the angular acceleration - engine speed plane.

The cyclodynes remain loops, which positive part is drawn when accelerating and negative part during deceleration. The area of the positive part of cyclodynes is related to the energy generated by the engine during acceleration (depend calorific value of the fuel and efficiency of burning of the fuel), while negative part of the cyclodyne depends on overall condition engine and quality of lubrication oil in the engine.

4.2. Description of the on the vehicle test bed

The performance of the vehicles was evaluated in cooperation of ECU-PROJECT company, on the 4DW test bed manufactured by Dynoprotect. This test bed is able to test the vehicles with maximum power of 1000 BHP and maximum torque of 1000 Nm and results are corrected according to DIN 70020.

The torque and power vs. engine crankshaft revolution graphs have been obtained for each of the vehicles.

5. Description of the vehicles performance evaluation based on the questionnaire

The drivers of the vehicles were obliged to fill in the questionnaire describing their subjective opinion about vehicle’s performance. They had to provide their opinion about following vehicles’ performances:

- Traction of the vehicles (acceleration of the vehicles and driving with load);
- Engine performance (cold start, hot start, engine noise and exhaust evaluation);
- Vehicle’s tachometer at the beginning of each drive, date and type of the duty (urban, extra urban, mixed);
- Information about amount of the fuel filled;
- Information about the service or repair activities.

The engine and vehicle’s performance was evaluated based on the 3 grades: low, middle and high.

6. Results

The results consisted a set of data obtained on the vehicle test bed and also results of the data coming from the testing in non-stationary conditions.

6.1. Results of the vehicles performance measured on the vehicle test bed

Table 3 presents results of measurement of peak engine power and peak engine torque measured on the test bed for selected vehicles at the end of the test. It is noticeable, that the maximum power for Berlingo vehicles is about 8% lower when fueling with BIOXDIESEL fuel in comparison with standard diesel fuel. Similar trend can be observed for torque measurement. This can be explained with the fact, that the calorific value of BIOXDIESEL fuel is 10% lower than standard Diesel fuel.

Table 3. Examples of results of the vehicle test bed obtained for selected Citroen Berlingo vehicles, obtained at the end of the test

| Make, model     | Max Power [BHP] | Max engine torque [Nm] | BHP [RPM] | Nm |
|-----------------|-----------------|------------------------|-----------|----|
| Berlingo_1      | 76(3135)        | 187.7(2256)            | 69.6(3030) | 173.3(2200) |
| Berlingo_2      | 76.6(3096)      | 186.9(2255)            | 68.2(3093) | 170.6(2213) |
| Berlingo_3      | 77.9(3067)      | 193.8(2181)            | 68.8(3058) | 169.4(2173) |
| Berlingo_4      | 76.8(3080)      | 188.5(2222)            | 68.4(3049) | 167.1(2194) |
| Berlingo_5      | 74.9(3112)      | 180(2253)               | 66.9(3035) | 160.8(2243) |
| Berlingo_6      | 76.3(3087)      | 188.4(1964)            | 68.7(3033) | 166.3(2256) |
| Berlingo_7      | 76.9(3054)      | 178.7(1981)            | 66.3(3157) | 164.6(2229) |
| Berlingo_8      | 75.8(3061)      | 187.8(2005)            | 69.6(3012) | 172.6(2172) |
| Average         | 75.6(3204)      | 185.6(2177)            | 68.0(3041) | 167.8(2213) |

In Table 4 results of measurement of the peak power and torque measured on the test bed are for presented. It is
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noticeable, that the maximum power for Jumper vehicles is about 7% lower when fueling with BIOXDIESEL fuel in comparison with standard diesel fuel. Similar trend can be observed for torque measurement, the torque drop when fueling with experimental fuel is about 8% lower in comparison with standard Diesel fuel, even though the calorific value of BIOXDIESEL is lower by 10% than Diesel fuel.

Table 4. Examples of results of the vehicle test bed obtained for selected Citroen Jumper vehicles, obtained at the end of the test

| Vehicle   | 1 ON | 2 BIOXDIESEL |
|-----------|------|--------------|
| Max Power | Max torque | Max Power | Max torque |
| BHP(RPM)  | Nm    | BHP(RPM)    | Nm         |
| Jumper_1  | 116.5(3146) | 279.4(2709) | 105.4(3350) | 244.6(2733) |
| Jumper_2  | 113.5(3050) | 252.3(2627) | 102.7(3142) | 248.5(2699) |
| Jumper_3  | 115.6(3014) | 283.5(2691) | 109.3(3000) | 270.5(2618) |
| Jumper_4  | 109.6(3208) | 266.6(2638) | 105.1(3171) | 259.3(2607) |
| Jumper_5  | 116.3(3045) | 285.5(2660) | 108.8(3253) | 259.9(2725) |
| Average   | 114.4(3092) | 279.4(2666) | 108.6(3183) | 256.6(2668) |

6.2. Results of the vehicles performance measured in non-stationary conditions

Due to shorter measurement procedure the testing in the non-stationary condition took place also in the middle of the long term test.

Figure 1 shows examples of cyclodynes obtained for one of Citroen Berlingo vehicles in the beginning of the test (start day), while figure 2 shows the results of the measurement obtained at the end of the test.

The outcome of the test in non-stationary condition is the value of the area of the positive part of the cyclodynamic loop. The area is proportional to energy conversion of the fuel. Tables 5 and 6 present the area of the cyclodynes obtained at different stages of the test for Berlingo and Jumper vehicles. One can notice, that similarly to the results of the vehicle test bed measurements, the performance of the vehicles was about 8% lower when using the BIOXDIESEL fuel than standard diesel fuel.

Table 5. Results of the testing the group of Citroen Berlingo vehicles in non-stationary conditions – area of cyclodynes

| Vehicle   | 1 ON | 2 BIOXDIESEL | 3 BIOXDIESEL | 4 BIOXDIESEL | 5 ON |
|-----------|------|--------------|--------------|--------------|------|
| P1        | P1   | P1           | P1           | P1           |
| [rad/s²]  | [rad/s²] | [rad/s²] | [rad/s²] | [rad/s²] |
| [1/min]   | [1/min] | [1/min] | [1/min] | [1/min] |
| Berlingo_1| 1316313 | 1213310     | –            | 1274083     | 1418216 |
| Berlingo_2| 1280899 | –           | –            | 1254548     | 1341255 |
| Berlingo_3| 1351733 | 1261774     | 0            | 1255458     | 1341255 |
| Berlingo_4| 1307915 | 1237558     | 1260506     | 1270063     | 1576368 |
| Berlingo_5| 1316467 | 1222883     | 1215428     | 341941      | 1462068 |
| Berlingo_6| 1328186 | –           | –            | 1189034     | 1346919 |
| Berlingo_7| 1302171 | 1182546     | –            | –           | –      |
| Berlingo_8| 1338380 | 1226060     | 1267457     | 1300205     | 1368112 |
| Berlingo_9| –     | –           | 1270899     | 1286918     | 1387675 |
| Average   | 1317758 | 1224588     | 1259959     | 1271140     | 1386535 |

Fig. 2. Results of the testing in non-stationary conditions, end of the testing; top – BIOXDIESEL fuel, bottom – standard Diesel fuel
6.3. Description of the vehicles performance evaluation based on the questionnaire

The numerical values describing maximal engine power or maximal engine torque are not giving the full image of the vehicle performance in everyday operation. It was also necessary to collect the opinions of the drivers about driving the vehicles fueled with standard and experimental fuel.

In order to make the subjective opinions comparable the drivers had to evaluate the vehicle’s performance on the base of the questionnaire:

- Traction of the vehicles (acceleration of the vehicles and driving with load);
- Engine performance (cold start, hot start, engine noise and exhaust evaluation);
- Above questions were evaluated in three grades: low, middle and high.

The questions below were additional, which helped analyzing the data:

- Vehicle’s tachometer at the beginning of each journey, date and type of the duty (urban, extra urban, mixed);
- Information about amount of the fuel filled;
- Information about the service or repair activities.

Assuming, that the ‘law’ value is scored by 0 points, ‘medium’ as 50 points and ‘high’ as 100 points, the results of the evaluation for the group of Citroen Berlingo are presented in Table 7.

Table 7. Results of drivers’ evaluation of Citroen Berlingo when fuelling with BIOXDIESEL (averaged)

| Vehicle | Acceleration | Drive with load | Cold start of the engine | Hot start of the engine | Noise | Exhaust |
|---------|--------------|----------------|--------------------------|-------------------------|-------|---------|
| Berlingo_1 | 100%         | 100%           | 100%                     | 100%                    | 100%  | 100%    |
| Berlingo_2 | 100%         | 100%           | 100%                     | 100%                    | 100%  | 100%    |
| Berlingo_3 | 50%          | 50%            | 50%                      | 50%                     | 50%   | 50%     |
| Berlingo_4 | 100%         | 100%           | 100%                     | 100%                    | 100%  | 100%    |
| Berlingo_5 | 50%          | 50%            | 50%                      | 50%                     | 50%   | 50%     |
| Berlingo_6 | 100%         | 90%            | 100%                     | 100%                    | 100%  | 100%    |
| Berlingo_7 | 51%          | 52%            | 100%                     | 100%                    | 100%  | 100%    |
| Berlingo_8 | 50%          | 50%            | 100%                     | 100%                    | 100%  | 100%    |
| Berlingo_9 | 100%         | 50%            | 90%                      | 100%                    | 88%   | 94%     |
| Berlingo_10| 100%         | 100%           | 100%                     | 100%                    | 85%   | 94%     |
| Average  | 80%          | 80%            | 89%                      | 94%                     | 84%   | 78%     |

Evaluation of the vehicles’ performance during the fleet testing was very positive. The drivers did not observe a lack of power, poor acceleration of the vehicles or excessive fuel consumption. No major problems were observed with the cold start of the engine (the test was carried from August to December), this means the end of the test took place in colder weather conditions. There were no problems with hot start of the engines. The drivers did not observe in exhaust gases smoke during acceleration or during driving with heavier load.

Table 8. Results of drivers’ evaluation of Citroen Jumper performance with fuelling with BIOXDIESEL (averaged)

| Vehicle | Acceleration | Drive with load | Cold start of the engine | Hot start of the engine | Noise | Exhaust |
|---------|--------------|----------------|--------------------------|-------------------------|-------|---------|
| Jumper_1 | 100%         | 100%           | 100%                     | 100%                    | 100%  | 100%    |
| Jumper_2 | 89%          | 94%            | 100%                     | 100%                    | 100%  | 100%    |
| Jumper_3 | 100%         | 100%           | 7%                       | 100%                    | 7%    | 100%    |
| Jumper_4 | 100%         | 100%           | 100%                     | 100%                    | 100%  | 100%    |
| Jumper_5 | 94%          | 86%            | 77%                      | 100%                    | 89%   | 78%     |
| Average  | 97%          | 96%            | 61%                      | 100%                    | 88%   | 80%     |

Table 9. Comparison of fuel consumption of the selected Citroen Berlingo and Citroen Jumper before the test (standard diesel fuel) and with BIOXDIESEL fuel

| Vehicle | Diesel fuel | BIOXDIESEL |
|---------|-------------|------------|
| Jumper  | August - December 2014 | February - July 2015 |
| Berlingo_1 | 271 | 1073 |
| Berlingo_2 | 312 | 1073 |
| Jumper_1 | 1901 | 4235 |
| Jumper_2 | 1037 | 12505 |

7. Summary and conclusions

Unlike the vehicles performance measurement on the vehicle test bed or testing the engines in non-stationary conditions, the drivers did not see a drop of performance of the vehicles when fuelling with the BIOXDIESEL fuel. The difference of the maximal engine power and torque did not influence the daily operation of the vehicles. No major maintenance problems were observed. It is worth to mention, that the parcel delivery vehicles are operated in difficult duty cycle: high number of start and stop of the engine per day, driving mainly in urban conditions.

It is worth to notice, that in case of the Berlingo’s, the maximum power of the engines appears in lower engine speed when fuelling with BIOXDIESEL in comparison with the standard diesel fuel.

Also the fuel consumption of the BIOXDIESEL fuel is not significantly different to standard Diesel fuel.
Presented results of testing the engines fueled with the BIOXDIESEL and Diesel show:

− similar efficiency engine feeding BIOXDIESEL and Diesel,
− fuel consumption, vehicles behaviour in everyday natural operation remained the same for standard Diesel and BIOXDIESEL;
− lack of linear relations between calorific value of biofuel and the peak power of the engine related to the standard diesel fuel confirms more efficient combustion of BIOXDIESEL fuel.

Analysis of presented in this paper results of the road testing, vehicle test bed measurement, testing in non-stationary conditions and evaluation of vehicle performance by the drivers in day by day operation entitle to state, that the BIOXDIESEL fuel is very advanced, and can be used as an alternative fuel for all Diesel engines.

Nomenclature

FAEE – fatty acid ethyl esters
FAME – fatty acid methyl esters

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