УДК 621.436

R.V. Kolodnytska, PhD, ass. Prof.
Zhytomyr State Technological University, Ukraine

HEMP BIOFUEL FOR AUTOMOTIVE TRANSPORT. UKRAINIAN PERSPECTIVE

Ukraine takes a fourth place in the world in the technical hemp production and can use waste of hemp for biofuel (including biodiesel) production. This paper presents an analysis of cetane numbers and low-temperature properties of hemp biodiesels as well as spray and evaporation of these fuels. Two types of hemp biodiesel fuels are analyzed: Hemp Methyl esters, produced from hemp oil in Ukraine (HM1) and European Union (HM2). It was found that hemp biodiesel has smaller cetane number than traditional rapeseed or soy biodiesel. At the same time hemp biodiesel shows better low-temperature properties compared with traditional biodiesels. So, it was recommended to use the mixture of rapeseed or soy biodiesel with hemp biodiesel to optimise both the low-temperature properties and cetane number of fuel. According to modelling the spray parameters of hemp biodiesel are very close to those of soy biodiesel. Evaporation of hemp biodiesel is very close to soy biodiesel according to previous research. Therefore, mixture of soy/rapeseed and hemp biodiesels can be recommended for experimental investigation as a future fuel for Ukrainian market.

Keywords: *biofuels; biofuel production; hemp oil biodiesel; cetane number; low temperature properties.*

Introduction. According to BP Statistical Review of World Energy [1] Ukraine had 8.4 million tonnes of oil equivalent consumption in 2015 (see Table 1). The biggest share of the energy consumption of Ukraine is covered by coal, followed by natural gas and fossil oil. Ukraine has 33873 million of tonnes coal equivalent and 0.6 trillion cubic metres of gas reserve [1].

Table 1

Primary energy (Ukraine). Consumption of fuel (adapted from [1])

Million tonnes oil equivalent	Oil	Natural Gas	Coal	Nuclear energy	Hydro–electricity	Renew-able energy	Total
2014	10. 0	33.1	35.6	20.0	1.9	0.4	101.0
2015	8.4	25.9	29.2	19.8	1.4	0.3	85.1

As everyone can see from the Table 1 the majority of energy used in Ukraine is based on fossil fuels, which are non-renewable that have a major impact on the planet. The renewable energy consumption in Ukraine is less than in other European countries and even decreases in 8 % in 2015 comparing with 2014. At the same time, the renewable energy consumptions in the UK increased by 31 % (see Table 2).

Table 2

Consumption of other renewables (adapted from [1])*

Million tonnes oil equivalent	USA	Brazil	Colom-bia	Ger-many	France	Nether-lands	Poland	UK	Ukraine	Total world
2014	66.8	13.2	0.3	32.3	6.5	2.6	4.0	13.3	0.4	316.6
2015	71.7	16.3	0.4	40.0	7.9	2.7	4.6	17.4	0.3	364.9

**Based on gross generation from renewable sources including wind, geothermal, solar, biomass and waste, and not accounting for cross-border electricity supply [1]*

In 2014 global biofuels production grew by a below-average 7.4 % comparing to 2013, driven by increases in the Indonesia (+40.4 %) Argentina (+30.9 %), US (+5.6 %) and Brazil (+5.5 %) [2]. In 2015 world biofuels production increased by just 0.9%, the slowest rate of growth since output declined in 2000. Global ethanol production increased by 4.1%, the third consecutive year of growth, led by increases from Asia Pacific, South & Central America, and North America. Biodiesel production declined by 4.9 % in 2015, this was due to the decline in output from major producing regions [1] combined with decrease in oil prices worldwide. At the same time biofuel production increased in Brazil (+6.8 %), US (+2.9 %), Finland (+25.5 %) and Poland (+20.5 %) accounted for essentially all of the net increase, "partly offset by large declines in Indonesia (-46.9 %) and Argentina (-23.9 %)" (see Table 3) [1].

Table 3

Biofuel production (adapted from [1])

Thousand tonnes oil equivalent	USA	Brazil	Colombia	Germany	France	Netherlands	Poland	UK	Finland	Total world
2014	30118	16517	654	3371	2603	1749	731	359	52	74208
2015	30983	17636	670	3130	2592	1749	882	359	65	74847

It looks like biofuel production is not large enough in Ukraine to be shown in the BP report. But it is big surprise that Ukraine has the third place after France and USA for biofuels export to the UK and contributed about 150 million litres of total supply of biofuels to the UK in 2013/2014 according British Government report [3]. At the same time the UK (i. e. Shell Company) sells diesel with biodiesel additions at higher price back to Ukraine.

Traditionally Europe uses rapeseed oil for biodiesel production. Ukraine doesn't use biodiesel as a fuel for automotive transport, however being a major supplier of rapeseed to the European market, exporting at least 1 million of crop every year. In August 2015 Ukraine's rapeseed exports are "likely to fall by 17.6% to 1.58 million tonnes in the 2015/16 season due to a smaller harvest" [4].

The 'second-generation biodiesels' have been produced from inedible oil, algae or waste (e.g. hemp biodiesel can be produced from hemp fibre production waste). Ukraine has a fourth place in the world in a technical hemp production and can use waste of hemp for biofuel production. Ukrainian hemp institute [5] is the world leader in hemp varieties. For example, the company Kinsel & Co, founded by an American enterpreneur, Andrew Kinsel, who is selling hemp seeds grown in Zhytomyr region, is among the top of twenty world leaders in terms of technical varieties of hemp. Together with partners he grows about eight hectares of hemp [5].

The potential of bioenergy production from industrial hemp were analyzed in [6, 7]. Automotive Department (Zhytomyr State Technological University) has investigation in biofuels from hemp since 2008 [8, 9]. The aim of this paper is the analysis of cetane numbers and low-temperature properties of hemp biodiesels together with spray and evaporation of these fuels.

1. Cetane number of hemp biodiesel

The investigation of the physical properties and spray of biodiesel from hemp oil of different composition was performed in [8]. Two types of hemp biodiesel fuels were considered: Hemp Methyl esters, produced from hemp oil in Ukraine (HM1) and European Union (HM2). The hemp biodiesel consists of different methyl esters molecules. Table 4 shows the physical properties, cetane numbers of the methyl esters of fatty acids and the composition of hemp oils.

Table 4

The physical properties of methyl ester of fatty acids (80 °C). The composition of hemp oils

Methyl ester of fatty acid	Density (kg/m^3) [8]	Kinematic viscosity, (mm^2/c) [8]	Cetane number [9]	Composition of hemp oil (HME1) [8], %	Composition of hemp oil (HME2) [8], %
Methyl palmitate (C16:0 M)	820	2.03	74.4	6.1	6
Methyl palmitoleate (C16:1 M)				0.3	
Methyl stearate (C18:0 M)	821	2.53	76.3	2.1	2.5
Methyl oleate (C18:1 M)	838	2.19	57.2	12	12
Methyl linoleate (C18:2 M)	845	1.92	36.8	56.9	55
Methyl linolenate (C18:3 M)	860	1.81	21.6	20.6	20
Methyl eicosanoate (C20:0 M)				0.5	1
Methyl eicosenoate (C20:1 M)					1
Methyl erucate (C22:1 M)	840	3.22	76.0	0.2	1
Methyl nervonate (C24:1 M)				0.2	1
Other				1.1	0.5

It was shown in [9] that the cetane number of biodiesel (vegetable oil methyl esters) can be predicted using its chemical composition:

$$CN = 61.1+0X_1+0.088X_2+0.133X_3+0.152X_4-0.101X_5-0.039X_6-0.243X_7-0.395X_8, \quad (1)$$

where X_1, X_2, X_3, X_4, X_5, X_6, X_7 i X_8 – the content (in percentage) of methyl esters fatty acids. Indexes show as follows 1) C12:0 M, 2) C14:0 M, 3) C16:0 M, 4) C18:0 M, 5) C16:1 M, 6) C18:1 M, 7) C18:2M i 8) C18:3 M correspondently.

The cetane numbers of different biodiesels were calculated in [9] using the following formula:

$$CN = 46.3 + 5458 / SN - 0.225 IN, \quad (2)$$

where CN is cetane number; IN is iodine number; SN is saponification number.

$$IN = \sum \left(254 \times D \times A_i\right) / MW_i \text{, g J2/100g} \quad (3)$$

$$SN = \sum (560 \times A_i)/MW_i \text{ , mgKOH/g} \quad (4)$$

where A_i is a percentage of nonsaturated components; *D* is a number of double bonds (1, 2 or 3);

MW_i is a molecular weight of components.

Using Eq. (1) the cetane numbers for hemp oil biodiesels were calculated, resulting in CN = 39.8 and CN = 40.6 for HM1 and HM2 respectively. At the same time Eq. (2) gives the values of CN=40.8 and CN=42.1 for the same fuels respectively (see Table 5).

2. **The heat of combustion and ignition delay of hemp biodiesel**

The Bertrand formula was tested for higher heating value of rapeseed oil in [9]:

$$HHV(B) = 4.1868\ (11380 - IN - 9.15SN)\ \text{, (kJ/kg).} \quad (5)$$

The higher heating value of the fuel can be evaluated using Mendeleev formula that correlated with (5):

$$HHV(M) = 34.013C + 125.69H - 10.9(O - S)\text{ , (MJ/kg)} \quad (6)$$

where *C, H, O, S* are mass fracture of carbon, hydrogen, oxygen, sulfur in fuel correspondently.

The lower heating value of the fuel can be calculated using the next formula:

$$LHV = HHV - 2.512(9H + W)\text{ , (MJ/kg)} \quad (7)$$

where *W*– mass fracture of water vapour in fuel (*W* = 0).

Using data from Table 1 the composition of hemp oil biodiesel was calculated as follows: C = 77.48 %, H = 11.66 %, O = 10.86 % for HME1 and C = 77.46 %, H = 11.62 %, O = 10.92 % for HME2. Calculation of high heat values of hemp biodiesels by Bertrand formulas (5) and Mendeleev (6) gave similar values:

HHV(B) = 40.403 MJ/kg and $HHV(M)$ = 39.818 MJ/kg for biodiesel HM2

HHV(B) = 40.297 MJ/kg and $HHV(M)$ =39.754 MJ/kg for HM1.

The value of HHV for hemp biodiesel, calculated using formula (7) is also shown in Table 5.

The cetane numbers of fatty components can be determined using special IQTk test for combustion with constant volume as was shown in [9]. The ignition delay and cetane number for IQTk experiment was determined using the following formula:

$$CN_{IQT} = 83.99 \times (ID - 1.512)^{-0.658} + 3.547\ , \quad (8)$$

where *ID* is the ignition delay.

The ignition delay ID of biodiesel can be evaluated using Eq. (8) provided that cetane number is known using previous formulas (1) and (2). According to formula (8) the diesel cetane number (CN = 46.3) corresponds to ignition delay that equal to 4.3 ms. The ignition delay for ME hemp oil, according to the formula (8) is higher than for diesel fuel, and less for ME of rapeseed oil compared with diesel fuel (see Table 5). For this reason, it is possible to get ignition delay for biodiesel similar to diesel by blending HME and RME.

Table 5

The calculation results of biodiesel properties (methyl esters (ME))

Fuel/ Fuel parameters	Hemp oil ME (HME1)	Hemp oil ME (HME2)	Flax oil ME	Rapeseed oil ME (RME)	Coconut oil ME	Soy oilME (SME)
Iodine number	163.88	160.13	188.9	90.8-117.2	11.8	90-126.0
Saponification number	173.91	171.56	191.5	185.8/191.6	247.5	189.8/190.8
Cetane number	40.81	42.08	32.3/36	49.3/57.2	65.7	46.6/56.3
LHV, MJ/kg	37.67/37.13	37.76/37.18	36.92/37.03	37.15/37.82	35.34/36.29	37.13/37.55
Ignition delay. (ITQ), ms	4.95	4.78		4.03/3.49	3.09	4.27/3.54

3. **Low temperature properties of biodiesel**

The simulation of low-temperature properties of biodiesel fuels was performed in [11]. The cold flow properties of the diesel and biodiesel fuels can be quantified by using three properties: the cloud point (*CP*), pour point (*PP*) and the cold filter plugging point (*CFPP*). Cold filter plugging (CFPP) for biodiesel fuel was calculated using the following formula.

$$\begin{aligned} CFPP[^{\circ}C] &= C18:3\times(-17.860) + C18:0\times 66.075 + C18:1\times(-13.398) + \\ & C22:0\times 533.206 + C18:2(-14.958) + C12:0\times(-12.453) + C16:0\times 27.78 \end{aligned} \tag{9}$$

where $C8:0$, $C10:0$ .... $C22:1$ is percentage content of methyl esters of fatty acids.

The values of cloud point (*CP*) for biodiesels were calculated using the following formula:

$$\begin{aligned} CP[^{\circ}C] &= C18:3\times(-18.578) + C16:0\times 31.909 + C18:1\times(-11.554) + \\ & + C12:0\times(-25.653) + C18:2(-13.453) + C22:0\times(-334.926) + C18:0\times 61.230 \end{aligned} \tag{10}$$

The values of the pour point (PP) of biodiesels were calculated using the following formula:

$$\begin{aligned} PP[^{\circ}C] &= C18:1\times(-24{,}374) + C18:0\times 77{,}458 + C18:2\times(-17{,}014) + \\ & + C12:0\times(-26{,}846) + C16:0\times 44{,}137 + C22:0\times 283{,}138 + \\ & + C22:1\times(-28{,}824) + C18:3\times(-19{,}035) + C20:0\times 184{,}402 \end{aligned} \tag{11}$$

Table 6 shows the values of *CFPP*, *PP* and *CP* that were calculated for second generation biodiesel (hemp biodiesels HME1 and HME2) compared with traditional biodiesel (palm (PME) and rapeseed oil (RME) using formulas (9), (10), (11) and available experimental data on PP [11].

Table 6

The low-temperature properties of hemp biodiesels

Biodiesel from oil	*CP*, °C	*CFPP*, °C	*PP*, °C	*PP* [11],°C
Rapeseed (RME)	-9.56	- 8.405	-12.856	-12
Palm (PME)	10.60	8.197	11.506	18
Hemp (HME1)	-9.64	-10.716	-12.27	-
Hemp (HME2)	-9.06	-10.088	-9.67	-

As it is shown in Table 6, the hemp biodiesels have the lowest values of CFPP determined by the high content of molecules with double bonds (C18: 2 M and C18: 3 M) (see also [11]). Hemp biodiesel HM1 and rapeseed biodiesel (RME) have almost the same value of *CP*, although the molecules contents of these fuels are different. Important role in this plays a big difference between the coefficients that included in the formula (10) (i.e. very low value for molecules $C22:0$ M).

RME also has the lowest PP as shown in Table. 6 which is determined by a high content (60.7 %) of the molecule C18: 1 M (see. Table 1 [11]) included in the formula (1) with the largest negative factor (-24.374). As shown in Table 6, the calculated values of PP are close to those obtained from the experiment, but in order to obtain the more accurate value of this parameter additional experimental investigation is required.

4. Biodiesel ligament breakup. Length parameter (LP)

Diesel and biodiesel fuels in diesel engine are sprayed with formation of ligaments. The ligaments that are produced from biodiesel are markedly larger than for diesel fuels [12]. Figure 1 adapted from [12] shows influence of fuel type on the primary atomisation within about 2 mm from the nozzle.

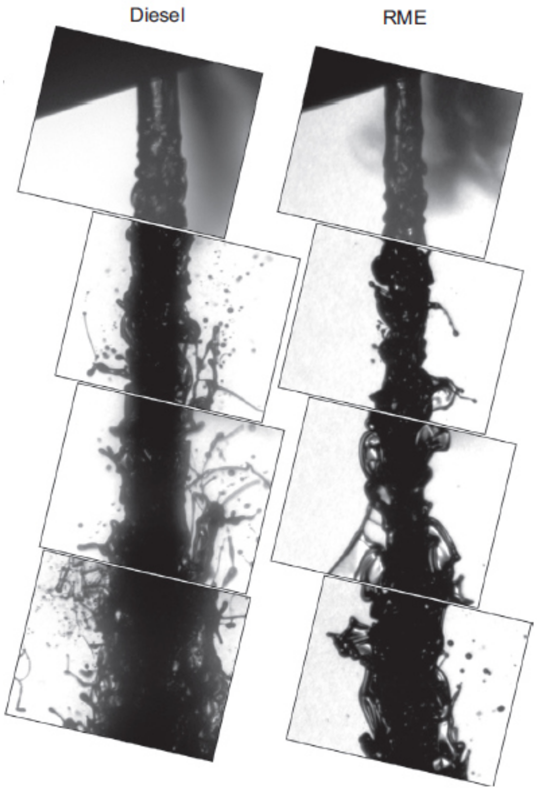

Figure 1. Influence of fuel type on the primary atomisation within the first 2.1 mm from the nozzle (left is diesel fuel and right is biodiesel (RME)).
Injection pressure is 40 MPa; gas pressure is 0.1 MPa [12]

Length parameter was introduced in [8] for modelling of average droplet spray diameter and used in [13] for spray penetration modelling. Length parameter (*LP*) took into account viscosity, density and surface tension of fuel.

$$LP = \frac{\nu_f^2 \rho_f}{\sigma} . \qquad (12)$$

LP is related to the liquid jet breakup, ligament creation, and necking. LP has a dimension of [m] and it was shown how LP could be used for modelling of average diameter (SMD) of biodiesel spray in [8]. Table 7 presents the physical properties of Hemp biodiesel (HME) compared with those for soy biodiesel (SME), rapeseed biodiesel (RME) and diesel fuel at 80 °C which were outlined in [8].

Table 7

Comparison of physical properties and LP of biodiesel and diesel fuels at 80 °C

	HME	SME	RME	Diesel
Density	845	841	841	788
Kinematic viscosity	1.96×10^{-6}	2.01×10^{-6}	2.58×10^{-6}	1.09×10^{-6}
Surface tension	27.41×10^{-3}	27.15×10^{-3}	27.82×10^{-3}	24.14×10^{-3}
LP [m]	1.18×10^{-7}	1.25×10^{-7}	2.01×10^{-7}	0.388×10^{-7}

Spray penetration is a very important spray parameter that shows the distance of the spray from the nozzle. Analysis in [13] has shown that the spray penetration of biodiesels would be proportional to the $LP^{0.1}$. The spray penetration for hemp biodiesels is very close to SME penetration that also is proven by the proximity of values of *LP* for HME and SME (see Table 5). Likewise, it was shown in [8] that average diameter (SMD) of hemp biodiesel spray is very close to SMD of soy biodiesel.

The papers [14, 15] have presented a detailed comparative analysis of transport and thermodynamic properties of biodiesel fuels (including hemp biodiesel) and components of these fuels that can be used for evaporation and combustion analysis. It was shown in paper [15] that evaporation of hemp biodiesel is very close to soy biodiesel.

Summary. The energy consumption of Ukraine was analyzed and possibility to use hemp waste for biodiesel production was shown. Two types of hemp biodiesel fuels were considered in the analysis: Hemp Methyl esters, produced from hemp oil in Ukraine (HM1) and European Union (HM2) compared with rapeseed and soy biodiesels. It was found that hemp biodiesel has smaller cetane number than traditional rapeseed or soy biodiesel. Hemp biodiesel shows better low-temperature properties in comparison with traditional biodiesels (partly the lowest values of cold filter plugging point (CFPP)). The spray parameters of hemp biodiesel are very close to soy biodiesel as modelling has shown. Akso evaporation of hemp biodiesel is very close to soy biodiesel according to previous research. Therefore, mixture of soy/rapeseed and hemp biodiesels can be recommended for experimental investigation as a future fuel for Ukrainian market.

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KOLODNYTSKA Ruslana Vitaliyvna – associate professor of automotive department, ZSTU.
Research interests:
- alternative fuels / biofuels and environmental safety of the vehicle;
- spray modelling and evaporation of fuel in internal combustion engines;
- the problem of destruction of materials ; materials based on natural fibres.

Стаття надійшла до редакції 21.09.2016