Injection and Atomization of Diesel Fuel and Rapeseed Oil in Diesel Engine

Vladimir Markov¹, Sergey Devyanin², Bowen Sa³,⁴ and Vsevolod Neverov¹
¹Piston Engines Department, Bauman Moscow State Technical University, 105005 Moscow, Russia
²Tractors and Cars Department, Russian State Agrarian University - Moscow Timiryazev Agricultural Academy, 127550 Moscow, Russia
E-mail: ¹vladimir.markov58@yandex.ru, bowensa@yandex.ru⁴

Abstract. A comparative analysis of properties of petroleum diesel fuel and rapeseed oil is carried out. Numerical studies of the influence of fuel properties on the injection process of fuel are carried out by using ANSYS Fluent. The steady flow of these fuels in the flow channel of an injector nozzle for a 4-stroke turbocharged diesel engine D-245.12S (with cylinder bore-to-stroke ratio 11/12.5) was simulated at the maximum injector needle lift of 0.32 mm. The flow characteristics of petroleum diesel fuel and rapeseed oil - mass fuel consumption, injection velocity, turbulent kinetic energy at the nozzle hole outlet, and the total volume concentration of fuel vapors in the nozzle hole were obtained. The relationship between the turbulent kinetic energy at the nozzle hole outlet and the parameters of the fuel spray fineness is studied. Numerical studies of the relationship between the spray cone angle and the turbulent kinetic energy at the nozzle hole outlet and the parameters of the fuel spray fineness is studied. A correlation between fuel spraying parameters and the turbulent kinetic energy at the nozzle hole outlet was proposed.

1. Introduction

One of the effective ways to achieve the required emission targets of exhaust gases for diesel engines is to use different alternative fuels [1]. Among the most widely used biofuels in diesel engines, it is worth highlighting vegetable oils and their derivatives - methyl, ethyl, and butyl ethers [2, 3]. Despite the problems arising during the operation of diesel engines fueled with vegetable oils, the studies of their operation on these biofuels and their mixtures with other fuels, mainly with petroleum diesel fuel (DF), have been continuing [4-8].

To use vegetable oils as an independent fuel is difficult due to the differences in the physical and chemical properties between vegetable oils and petroleum DF. It is accompanied by problems coming out when diesel engines are fueled with vegetable oils. These problems include the poor quality of the injection and atomization processes of vegetable oils caused by their high viscosity and density.

The injection process in diesel engines running on vegetable oils and vegetable oil-based fuels has been investigated in a lot of research. The features of the fuel injection and mixture formation in diesel engines fueled with fuels obtained from vegetable oils and the direction of improving these processes have been analyzed in work [3]. Franco Z and Nguyen Q analyzed the properties of vegetable oils and their mixtures with petroleum diesel fuel and investigated flow parameters of these fuels in the elements of a diesel fuel system [9]. Ra Y et al. are dedicated to the questions of the physical properties of diesel fuel and its mixtures with biodiesel fuels and the working process of the diesel engine operating on these fuels [10]. The group of Graboski M and the group of Grimaldi C developed
mathematical models to simulate the processes of fuel injection, droplet breakup, and air-fuel mixture formation in diesel engines running on methyl ether of sunflower oil and its mixtures with petroleum diesel fuel [11,12]. Suh H et al. experimentally investigated the internal flow of petroleum DF and the biofuel produced from vegetable oil in the nozzle hole of a diesel injector and observed the occurrence of cavitation [13].

Although the abovementioned works have been focused on the study of the properties of biofuels and their application in diesel engines, up to now, the features of the internal flow process of these fuels in nozzles of diesel injectors and their atomization have not been well studied. Besides, the processes of injection and atomization of vegetable oils predetermine the characteristics of the subsequent processes of mixture formation and combustion. Therefore, these processes have a significant impact on the fuel efficiency and exhaust emissions of diesel engines.

In this regard, it is necessary to carry out numerical studies and a comparative analysis of the flow parameters of petroleum diesel fuel and vegetable oil through the nozzle channels of a diesel injector and their correlation with spray characteristics. As rapeseed oil (RO) and its derivatives are currently considered as one of the most promising biofuels [3], rapeseed oil was chosen as the biofuel to be studied.

2. Materials and methods

2.1. Object of study
An FDM-22 injector manufactured by Noginsk Fuel Equipment Plant (NZTA) fitted with a nozzle no. 171.07.00 from the Altai Plant of Precision Products (AZPI) was selected as the object of the study. Fig. 1 shows the structural schematic of the investigated nozzle and its hydraulic characteristics. Some design parameters of this nozzle are given in Table 1 and Table 2.

![Figure 1. Structural schematic of the AZPI nozzle no. 171.07.00 (a) and the dependence of the total effective flow area of the nozzle assembly \( \mu_{nf} \) on the needle lift \( h_n \) (b): 1 – nozzle hole; 2 – sac; 3 – needle valve; 4 – injector needle.]

| Manufacturer, serial number | Diameter of nozzle holes \( d_n \), mm | Number of nozzle holes \( i_n \) | Maximum needle lift \( h_{n,\text{max}} \), mm | Total effective flow area of the nozzle assembly \( \mu_{nf} \), \( \text{mm}^2 \) |
|-----------------------------|-------------------------------------|------------------|-----------------------------|-----------------------------|
| AZPI 171.07.00              | 0.35                                | 5                | 0.32                        | 0.270                       |

Note: the values of \( \mu_{nf} \) are given at the maximum lift of the injector needle \( h_{n,\text{max}} =0.32 \text{ mm} \); here are the average values of \( h_n \) and \( \mu_{nf} \) obtained from a set of nozzles.
Table 2. Hole location of the AZPI nozzle

| Nozzle number | Angular position of the hole relative to the locating pin, degree | Inclination angle of the hole relative to the nozzle axis, degree |
|---------------|---------------------------------------------------------------|---------------------------------------------------------------|
| 1             | 8                                                             | 62                                                            |
| 2             | 90                                                            | 70                                                            |
| 3             | 172                                                           | 62                                                            |
| 4             | 237                                                           | 52                                                            |
| 5             | 303                                                           | 52                                                            |

In the internal flow simulations within the nozzle, petroleum DF and RO are investigated. Some physicochemical properties of the investigated fuels are given in Table 3 [3].

Table 3. Physicochemical properties of DF and RO

| Properties                                      | Petroleum DF | RO          |
|------------------------------------------------|--------------|-------------|
| Conditional composition formula                | C₁₆H₁₈.₅     | C₅₇H₁₀₁.₆O₂  |
| Molecular mass                                  | 223.3        | 883.04      |
| Density, kg/m³:                                |              |             |
| - at 20 °C                                     | 830.0        | 909.8       |
| - at 40 °C                                     | 822.7        | 896.3       |
| Kinematic viscosity, mm²/s:                    |              |             |
| - at 20 °C                                     | 3.8          | 75.0        |
| - at 40 °C                                     | 2.4          | 41.5        |
| Dynamic viscosity, mPa·s:                      |              |             |
| - at 20 °C                                     | 3.15         | 68.24       |
| - at 40 °C                                     | 1.97         | 37.20       |
| Surface tension coefficient σ at 20 °C, mN/m   | 27.1         | 33.2        |
| Cetane number                                  | 45           | 37          |
| Lower calorific value, kJ/kg                   | 42500        | 37300       |
| Specific heat C_{p}, kJ/(kg·K):                |              |             |
| - at 20 °C                                     | 2.1          | 2.3         |
| - at 40 °C                                     | 2.2          | 2.5         |
| Thermal conductivity, W/(m·K):                 |              |             |
| - at 20 °C                                     | 0.127        | 0.162       |
| - at 40 °C                                     | 0.123        | 0.160       |
| Saturation pressure, kPa:                      |              |             |
| - at 20 °C                                     | 2.7          | Close to zero |
| - at 40 °C                                     | 4.8          | Close to zero |

2.2. Numerical models of nozzle internal flow

Computational studies of the internal flow within the nozzle for the investigated fuels were carried out by using Fluent CFD software. Fluent CFD software has been a part of Ansys software packages since 2006 and is regarded as one of the best CFD simulation softwares. Fluent CFD software can be used to simulate single-phase and multiphase flow.

In the computational studies, a steady flow of petroleum DF and RO was simulated in the nozzle flow path at the maximum lift of the injector needle h_n = 0.32 mm. The pressures at the inlet to the computational domain p_{in} are taken equal to 51.5, 40, and 20 MPa. These values correspond to the fuel
pressures before nozzles in the serial fuel injection system at different operating modes of the diesel engine D-245.12S (4 ChN 11/12.5) [3]. The pressure at the outlet of the computational domain is 8.878 MPa, which corresponds to the pressure in the engine cylinder at the start of injection. The fuel temperature is taken constant and equal to 40 °C. In order to limit the calculation time, a symmetric element of the nozzle flow space with one nozzle hole is applied (Fig. 2, a). Hexahedral structured grids are meshed for the computational domain by using CFD ICEM, as shown in Fig. 2, b.

**Figure 2.** The geometry of the flow space of the AZPI nozzle with one nozzle hole (a) and the mesh created for the selected geometry of the flow space (b).

In order to simulate two-phase flow within the nozzle, a multiphase equilibrium model - mixture model included in Fluent CFD software was used. The cavitation process is described by the Schnerr-Sauer model. A popular turbulent model with two equations — the k-ε model with Enhanced Wall treatment for equation ε in the near-wall boundary layers was chosen to describe turbulence flow in the nozzle. The fuel turbulence in the elements of the fuel injection system and the turbulence of fuel jets in the combustion chamber of the diesel engine have a significant effect on the quality of fuel atomization. The higher the fuel turbulence is in the flow space of the diesel injector, especially at the outlet of nozzle holes, the higher the quality of fuel atomization is. Moreover, turbulence has a great influence on flow characteristics.

To evaluate the intensity of flow turbulence at the nozzle hole outlet, it is used the turbulent kinetic energy (hereinafter referred to as k or E) - the specific kinetic energy of vortices in a turbulent flow, which is physically characterized by the average squared fluctuation (pulsation) of the fuel flow velocity:

\[
k = E = \frac{U^2 + V^2 + W^2}{2};
\]

where \(U, V, W\) - the projections of the fluctuating velocity on the x, y, and z axes.
### 3. Results

#### 3.1. Internal flow simulation in the nozzle

The steady flows of DF and RO in the flow space of the injector nozzle were simulated by using models presented in section 2.2. A uniaxial coordinate system was used to analyze the fuel flow inside the nozzle hole. The coordinate system has a coordinate \( l_{hf} \), the axis of which is fused along the axis of the nozzle hole. In this manner, the value \( l_{hf} = 0 \) mm corresponds to the inlet of the nozzle hole, and the value \( l_{hf} = 1.1 \) mm corresponds to the outlet of the nozzle hole. The following flow characteristics for petroleum DF and RO are obtained through simulations: pressure, velocity, and, turbulent kinetic energy. Based on the processing of these data by using the uniaxial coordinate system \( l_{hf} \), the values of the flow parameters averaged over the selected sections of the nozzle hole were obtained for petroleum DF and RO. The average turbulent kinetic energy on different sections of the nozzle hole for petroleum DF and RO are given in Table 4.

| Coordinate \( l_{hf} \), mm | Average turbulent kinetic energy \( E_{f,ave} \), m²/s² | \( p_{in} = 51.5 \) MPa | \( p_{in} = 40 \) MPa | \( p_{in} = 20 \) MPa |
|---------------------------|--------------------------------------------------|----------------|----------------|----------------|
|                           | DF | RO | DF | RO | DF | RO |
| 0                         | 1637.35 | 1914.69 | 1307.32 | 1236.83 | 626.25 | 1.79 |
| 0.03                      | 1710.88 | 2243.38 | 1367.69 | 1445.90 | 687.64 | 3.84 |
| 0.1                       | 1804.73 | 3070.31 | 1450.62 | 2149.03 | 764.12 | 69.68 |
| 0.2                       | 1826.49 | 3718.86 | 1467.94 | 2834.90 | 836.17 | 289.44 |
| 0.3                       | 1791.53 | 3897.49 | 1432.98 | 3002.16 | 892.58 | 448.74 |
| 0.4                       | 1753.88 | 3977.22 | 1397.47 | 2941.61 | 940.59 | 543.83 |
| 0.5                       | 1736.34 | 3891.60 | 1375.03 | 2746.15 | 965.93 | 555.86 |
| 0.6                       | 1724.25 | 3656.54 | 1374.64 | 2504.83 | 958.44 | 537.02 |
| 0.7                       | 1722.97 | 3329.64 | 1533.85 | 2248.04 | 912.98 | 498.98 |
| 0.8                       | 1743.52 | 3008.93 | 1901.21 | 2017.35 | 847.41 | 463.90 |
| 0.9                       | 1954.08 | 2707.81 | 2115.53 | 1811.71 | 771.00 | 430.75 |
| 1.0                       | 2377.49 | 2439.32 | 2136.59 | 1634.01 | 694.56 | 399.53 |
| 1.1                       | 2574.37 | 2208.06 | 2057.61 | 1483.19 | 623.43 | 371.37 |

The analysis of the presented data shows that when RO is used as an engine fuel in the diesel fuel system, there is a noticeable decrease in the injection velocity (see Table 5) and flow turbulence in comparison with petroleum DF.

#### 3.2. Computational study of the influence of the turbulent kinetic energy at the nozzle hole outlet on the fuel atomization

The above simulation results indicate a significant effect of the fuel properties on the flow parameters at the nozzle hole outlet (see Table 4). The abovementioned parameters of the fuel flow in the elements of the fuel injection system predetermine the fuel spray fineness. Different methods are used to evaluate the fuel spray fineness [14-16]. Lyshovsky A [14] proposed a method in which the spray fineness is determined in a criterion form using the following criteria:

- **Weber's criterion**
\[ W_e = \frac{V^2 \rho_n d_n}{\sigma}; \]  
\text{- criterion } M

\[ W_e = \frac{V^2 \rho_n d_n}{\sigma}; \]  
\text{- criterion } \rho

\[ \rho = \frac{\rho_f}{\rho_a}, \]  
\text{where } d_n = 0.00035 \text{ – the diameter of the nozzle hole [m}; \mu_f \text{ – the dynamic viscosity of fuel [Pa·s]; } \sigma_f \text{ – the surface tension coefficient of fuel [N/m]; } \rho_f \text{ and } \rho_a \text{ – the density of fuel and air [kg/m}^3\text{]}, \text{respectively.}

By using abovementioned criteria, Lyshevsky A has developed the following relations for calculating the mean diameters of droplets [14]:

- arithmetic mean diameter

\[ d_{10} = 1.8d_n(\rho We)^{-0.266}M^{0.0733}; \]  
\text{- volume mean diameter}

\[ d_{10} = 2.21d_n(\rho We)^{-0.266}M^{0.0733}; \]  
\text{- Sauter mean diameter}

\[ d_{25} = 2.68d_n(\rho We)^{-0.266}M^{0.753}. \]  
\text{In work [15] Kutovoy V suggested using the average median diameter of droplets to assess the fuel spray fineness, which can be calculated by the relation:}

\[ d_M = d_n \left[ \frac{1 + \frac{d_n}{d_M}}{2} + \left( \frac{p}{p^{\text{ave}}} + \frac{p}{p^n} \frac{d_n}{d_M} \right)^{125} \right]^{1/15}; \]  
\text{where } d_M \text{ – the average median diameter of droplets [\mu m]; } d_n \text{ and } l_n \text{ – the diameter and length of the nozzle hole [mm]; } p^{\text{ave}} \text{ – the average injection pressure (in the calculations, it is equal to the injection pressures shown in Table 4); } \nu \text{ – the viscosity of fuel [mm}^2\text{/s]; constants: } d_0 = 16.5 \text{ \mu m; } d_2 = 0.30 \text{ mm; } p_i = 15.0 \text{ MPa; } \nu_0 = 5.23 \text{ mm}^2\text{/s. It is possible to use other methods to calculate the fuel spray fineness. In all of these methods, it is necessary to set the parameters of the fuel flow at the nozzle hole outlet.}
Table 5. Flow parameters at the nozzle hole outlet (at \( h_f = 1.1 \) mm) and spray fineness for different fuels and different pressures at the inlet to the computational domain \((p_{in})\).

| Parameters                      | \( p_{in} = 51.5 \) MPa | \( p_{in} = 40 \) MPa | \( p_{in} = 20 \) MPa |
|---------------------------------|---------------------------|------------------------|------------------------|
| Discharge velocity \( V \), m/s | 322                       | 309                    | 275                    | 264                    | 165                    | 158                    |
| Fuel’s density \( \rho_f \), kg/m\(^3\) | 822.7                    | 896.3                  | 822.7                  | 896.3                  | 822.7                  | 896.3                  |
| Surface tension coefficient \( \sigma_f \), mN/m | 27.1                     | 33.2                   | 27.1                   | 33.2                   | 27.1                   | 33.2                   |
| Dynamic viscosity \( \mu_f \), mPa·s | 1.97                     | 37.2                   | 1.97                   | 37.2                   | 1.97                   | 37.2                   |
| Dynamic viscosity \( \nu_f \), mm\(^2\)/s | 2.4                      | 41.5                   | 2.4                    | 41.5                   | 2.4                    | 41.5                   |
| \( E/\nu_f^0.5 \), m/s\(^{1.5}\) | 1661749                  | 342757                 | 1328182                | 230236                 | 402422                 | 57648                  |
| Weber’s criterion \( \text{We} \) | 1102952                  | 900301                 | 805904                 | 67831                  | 289299                 | 236145                 |
| Criterion \( M \) | 0.0005                    | 0.133                  | 0.0005                 | 0.133                  | 0.0005                 | 0.133                  |
| Criterion \( \rho \) | 0.0204                    | 0.0187                 | 0.0204                 | 0.0187                 | 0.0204                 | 0.0187                 |
| Arithmetic mean diameter \( d_{\text{am}} \), \(\mu m\) | 25                       | 41                     | 27                     | 44                     | 36                     | 58                     |
| Volume mean diameter \( d_{\text{vm}} \), \(\mu m\) | 31                       | 50                     | 34                     | 54                     | 44                     | 72                     |
| Sauter mean diameter \( d_{\text{sa}} \), \(\mu m\) | 37                       | 61                     | 41                     | 66                     | 53                     | 87                     |
| Average median droplet diameter \( d_{\text{md}} \), \(\mu m\) | 31.4                     | 48.1                   | 35.4                   | 54.3                   | 50.8                   | 77.8                   |
| Tangent of half the spray cone angle \( \tan(\alpha/2) \) | 0.234                    | 0.142                  | 0.212                  | 0.128                  | 0.152                  | 0.093                  |

Note: the density, kinematic viscosity, and dynamic viscosity of fuels are given at temperature \( t = 40 \) °C and the surface tension coefficient of the fuel is given at temperature \( t = 20 \) °C

The data on the calculated flow parameters at the nozzle hole outlet, the properties of the investigated fuels, and the calculated data on some of the above-described fuel atomization indicators are summarized in Table 5. According to the data in Table 4 and Table 5, it should be noted that the indicators of the fuel spray fineness largely depend on the turbulent kinetic energy \( E \). This is also evidenced by the data in Fig. 3. In accordance with the data in this figure, with increasing turbulent kinetic energy \( E \) from 500 to 2500 m2/s2, the average median diameter of fuel droplets by the Kutovoy’s method \( d_{\text{am}} \) (the red line) and the maximum diameter of droplets by the Lyshevsky’s methods \( D_k \) (the blue line) decrease by about half.
Figure 3. The dependence of the maximum diameter of droplets by the Lyshevsky’s methods $D_k$ and the average median droplet diameter by the Kutovoy’s method $d_M$: red and blue points are the calculated $D_k$ and $d_M$, respectively; red and blue lines are the trend line for $D_k$ and $d_M$, respectively.

With the use of the results presented in Table 4 and Table 5, the relationship between the indicators of the fuel spray fineness and the turbulent kinetic energy $E$ of the fuel flow at the nozzle hole outlet were numerically studied. The velocity of fuel discharged from the nozzle $V$ (m/s) was determined by the well-known outflow equation written in the form:

$$V = \sqrt{\frac{2}{\rho_f}} (P_{in} - P_{cc}),$$  \hspace{1cm} (9)

where $P_{in}$ – the injection pressure, Pa; $P_{cc}$ – the pressure in the combustion chamber, Pa; $\rho_f$ – the density of fuel, kg/m$^3$.

The analysis of the influence of the average turbulent kinetic energy $E$ of the fuel flow at the nozzle hole outlet and the kinematic viscosity of fuel $\nu$ on the indicators of the fuel spray fineness made it possible to assess their relationship. Through analyzing this effect, the correlation determining the average diameters of fuel droplets during fuel injection and atomization were obtained, which are follows:

- Arithmetic mean diameter $d_{10}$ and the coefficient of determination $R^2$ between $d_{10}$ and the complex $E/\nu^{0.5}$:

$$d_{10} = 165.7 - 9.85 \ln \left( \frac{E}{\nu^{0.5}} \right) \text{[\mu m]},$$ \hspace{1cm} (10)

$$R^2 = 0.9884$$

- Volume mean diameter $d_{30}$ and the coefficient of determination $R^2$ between $d_{30}$ and the complex $E/\nu^{0.5}$:

$$d_{30} = 203.4 - 12.09 \ln \left( \frac{E}{\nu^{0.5}} \right) \text{[\mu m]},$$ \hspace{1cm} (11)

$$R^2 = 0.9884$$

- Sauter mean diameter $d_{32}$ and the coefficient of determination $R^2$ between $d_{32}$ and the complex $E/\nu^{0.5}$:
Average median droplet diameter \( d_M \) and the coefficient of determination \( R^2 \) between \( d_M \) and the complex \( E/v^{0.5} \):

\[
d_m = 220.5 - 3.25 \ln \left( \frac{E}{v^{0.5}} \right)
\]

\[
R^2 = 0.9773
\]

The best correlation between the fuel spray fineness and the parameters \( E \) and \( v \) was successfully obtained by using the complex \( E/v^{0.5} \). The form of this complex is due to the fact that the fuel spray fineness is proportional to the turbulent kinetic energy \( E \) and is inversely proportional to the fuel viscosity \( v \) (i.e., the higher the viscosity is, the worse the quality of fuel atomization is). At the same time, the kinematic viscosity of the investigated fuels varies over an extensive range - \( v = 2.4 \text{ mm}^2/\text{s} \) for petroleum DF and \( v = 41.5 \text{ mm}^2/\text{s} \) for RO (at temperature \( t = 40 \degree \text{C} \)). In this regard, the viscosity term in the denominator of the complex \( E/v^{0.5} \) has an exponent of 0.5, i.e., the value \( \sqrt{v} \) is used in the denominator of the complex. This exponent provides an optimal representation of the relationship between the spray fineness and the fuel kinematic viscosity. The obtained relationships evidenced by the coefficient of determination \( R^2 = 0.977\ldots0.988 \) and as demonstrated in Fig. 4 can be used to calculate the average droplet diameters of the fuel ejected from the injector nozzle holes.

\[
d_{10} = 246.7 - 14.66 \ln \left( \frac{E}{v^{0.5}} \right) \text{ \mu m}
\]

\[
R^2 = 0.9884
\]

In addition to the considered indicators of the fuel spray fineness, the most important indicator that characterizes the coverage of the combustion chamber volume by the injected fuel sprays and the uniformity of the distribution of fuel droplets over the combustion chamber volume is the spray cone angle. This angle can be calculated according to the dependence proposed by Lyshevsky A [14]. This dependence for half the cone angle of the main section of the fuel spray can be represented as:

\[
\tan \left( \frac{\alpha}{2} \right) = D_a \beta \frac{W_{e,0.32}}{M^{0.007}}
\]

where according to the recommendation of Lyshevsky A [14], constants have the following values: \( D_a = 0.0112 \) and \( m = 0.5 \).

With the use of the data in Table 5 and the abovementioned methods, the effect of the turbulent kinetic energy \( E \) and the complex \( E/v^{0.5} \) on the fuel spray angle \( \alpha \) was calculated and investigated. Table 5 shows the calculated values of the tangent of half spray cone angle \( \tan(\alpha/2) \) for the

![Figure 4](image-url)
investigated fuels under the abovementioned injection conditions. The dependence of the tangent of half spray cone angle \( \tan(\alpha/2) \) on the complex \( E/v^{0.5} \) is given in Fig. 4.

Based on the calculated results, an empirical correlation between the tangent of half spray cone angle \( \tan(\alpha/2) \) and the complex \( E/v^{0.5} \) was obtained via regression and the corresponding coefficient of determination \( R^2 \) was calculated:

\[
\tan(\alpha/2) = 4.41 \times 10^{-3} \times (E/v^{0.5})^{0.2749},
\]

\[
R^2 = 0.9937.
\]  

Such a close correlation between the investigated parameters (\( R^2 = 0.9937 \)) allows using the obtained dependence (empirical formula) to calculate the spray cone angle through \( \tan(\alpha/2) \).

4. Discussion

The use of biofuels in diesel engines remains a pressing issue because of the need to replace petroleum engine fuels with fuels produced from alternative renewable raw materials and to reduce emissions of harmful substances from exhaust gases into the atmosphere. At the same time, one of the main problems with the use of biofuels in diesel engines is the difference in physical and chemical properties between biofuels and petroleum diesel fuels.

The possibility of using waste frying vegetable oils as an additive to petroleum diesel fuel was investigated in [17]. The addition of these oils was from 2 to 25%. Petroleum diesel fuel was supplied by a Common Rail fuel supply system to a DI-diesel engine with a power of about 30 kW at an engine speed of 2000 min\(^{-1}\). An increase in the viscosity of the blended fuels was noted, which affects the processes of fuel injection and atomization. It was also observed a decrease in the flammability of the blended fuels (an increase in the ignition delay period).

The work [18] is devoted to an overview of the possibilities of using mixtures of petroleum diesel fuel with various vegetable oils as diesel fuels – rapeseed oil, sunflower oil, soybean oil, palm oil, Jatropha oil, Castor oil, and, Karanja oil. It is noted that all the considered oils have a high viscosity, ranging from 30 to 40 mm\(^2\)/s at a temperature of 38 °C.

Anantha Raman L et al. investigated the performance of a DI-diesel engine running on petroleum diesel fuel, rapeseed oil, and rapeseed oil methyl ester [19]. The possibility of operating the diesel engine on petroleum diesel fuel blended with biofuels at the content from 0 to 100% has been studied. Changes in the processes of fuel injection and atomization during the diesel engine running on biofuels has been observed.

The dependence of the working process indicators of diesel engines fueled with biofuels on the fuel properties has been reported in other works. A number of works have shown that the performance of a diesel engine is largely dependent on the parameters of the fuel flow in elements of the fuel injection system, first of all, in the flow space of injector nozzles [20-23]. These parameters include mass flow rate, flow velocity, pressure, fuel vapor content, turbulent kinetic energy. The enhancement of fuel turbulence in the fuel injection system and the fuel sprays in the combustion chamber has a significant effect on the quality of fuel atomization. The higher the fuel turbulence inside the injector nozzle, especially at the nozzle hole outlet, the higher the quality of fuel atomization. And besides, turbulence has a great influence on flow characteristics.

The flow of diesel fuel in a microsac-type nozzle, including eight uniformly arranged nozzle holes with a diameter of 0.173 mm, was investigated in [24]. During the flow of diesel fuel, cavitation zones are formed in the upper area of the nozzle hole, which corresponds to the distributions of the volume concentration of diesel fuel vapor obtained in our studies.

A decrease in the diameter of the nozzle hole leads to an increase in the intensity of cavitation when other geometrical parameters and hydraulic conditions are kept unchanged [25].

The flow of diesel fuel in injector nozzles was numerically simulated in works [26-28]. At the same time, the values of flow parameters in injector nozzles are close to those obtained in our study. According to the data from works [27, 28], when the pressure at the inlet of a nozzle hole with a diameter of 0.17 mm is 30 MPa and the pressure at the nozzle hole outlet is 7 MPa, the axial velocity...
of diesel fuel through the nozzle hole is 95-110 m/s. This is in good agreement with the calculated average velocity at the nozzle hole outlet in our study, where the velocity at the nozzle hole outlet is about 90-110 m/s when the pressure at the nozzle hole inlet is 20 MPa.

5. Conclusion
A comprehensive computational study was performed to investigate the flow parameters of diesel fuel and rapeseed oil in the nozzle of a diesel injector and their atomization in the combustion chamber of a diesel engine. Important observations are as follows:

(1) During simulating the steady flow of petroleum DF and RO within the injector nozzle of the D-245.12S diesel engine, the following flow characteristics were obtained - fuel pressure, its velocity, and turbulent kinetic energy at the nozzle hole outlet.

(2) The analysis of the calculated results showed that when using RO as an engine fuel in the fuel injection system, there is a noticeable decrease in the injection velocity and flow turbulence in comparison with the use of petroleum DF.

(3) In the performed computational study of the effect of the turbulent kinetic energy at the nozzle hole outlet on the fuel atomization, the average diameters of fuel droplets and the fuel spray cone angle were considered as indicators of fuel atomization. The relationship between the turbulent kinetic energy at the nozzle hole outlet and these indicators of fuel atomization has been investigated.

(4) A complex $E/V^{0.5}$ reflecting the relationship between the indicators of fuel atomization, the turbulent kinetic energy at the nozzle hole outlet, and the fuel viscosity has been proposed.

(5) Empirical relations of the investigated indicators of fuel atomization on the turbulent kinetic energy at the nozzle hole outlet and on the proposed complex $E/V^{0.5}$ have been developed.

6. References
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