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FLOW SIMULATION OF MCNT BLENDED DIESEL FUEL IN THE NOZZLE OF A DIESEL INJECTOR[*]

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Abstract

Multi-walled carbon nanotubes are regarded as promising diesel fuel additives to improve engine performance and emission characteristics. The density and viscosity of multi-walled carbon nanotube blended diesel fuel were analyzed. Flow simulations in the nozzle of an injector Spray A of Engine Combustion Network were performed by using the CFD program Fluent to investigate the effect of introducing multi-walled carbon nanotube to diesel fuel on the characteristics of the internal nozzle flow. The addition of multi-walled carbon nanotubes increases the averaged turbulent kinetic energy of diesel fuel at the orifice outlet in the stabilized injection stage. The presence of multi-walled carbon nanotubes has an insignificant influence on the rate of injection and velocity distribution in the nozzle.

Keywords: nozzle flow, diesel injector, diesel fuel, carbon nanotube

1. Introduction

Recently, the use of different ways for improving compression ignition engines (CIEs) performance and reduce emissions has received considerable attention, for example, (Agrawal et al., 2019; Markov et al., 2019c)

The effect of introducing carbon nanotubes (CNTs) to diesel fuel and biodiesel fuels on engine performance and emission characteristics has been researched in many works. Ooi's group reported a reduction of the ignition delay period during dispersing single-walled carbon nanotubes (SWCNTs) into ultra-low sulfur diesel fuel (DF) with a dose level of 50 ppm (Ooi et al., 2018). The addition of multi-walled carbon nanotube into biodiesel and biodiesel blended DF might increase brake efficiency and decrease specific fuel consumption (Najafi, 2018). El-Seesy's group investigated the emission characteristics of a direct injection

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diesel engine fueled with biodiesel blended DF (B20D) and its blend with multi-walled carbon nanotubes (MCNT) (El-Seesy et al., 2017). It has been found that the emissions of unburned hydrocarbons (CH) decreased at all the tested load range. A significant decrease in exhaust smoke during adding MCNTs to diesel fuel at a dose level from 125 to 500 mg/L was obtained for a diesel-generator test (Markov et al., 2019a). The experimental test of a diesel engine running on biodiesel blended DF and its mixture with MCNTs indicated that the addition of MCNTs to biodiesel blended DF could decrease the emissions of nitric oxides (NOx) and carbon monoxide (CO) (Karthikeyan et al., 2016). However, the opposite results of the influence of MCNTs on the emissions of CO, CH and NOx have also been reported (Tewari et al., 2013). Therefore, in order to clarify the effect of the presence of MCNTs on the combustion process in the engine combustion chamber, first of all, it is necessary to study the influence of MCNTs on the fuel flow in the injector nozzle, which has a significant effect on the fuel atomization, fuel evaporation and fuel-air mixture formation, which may further affect the performance of diesel engines. An increase in the viscosity of MCNTs blended fuels has also been reported in (Sunil et al., 2020). However, so far, little research has been done on the flow behaviors of MCNT blended fuels in fuel injector nozzles.

The objective of this study is to investigate the transient flow characteristics of MCNT blended DF in the nozzle of a diesel injector during the injection progress. Based on the result in (Markov et al., 2019b), the MCNT content in DF was set to be 0, 250, 500 and 1000 mg/L.

2. Materials and methods

2.1. Properties of the studied fuels

In this study, XFM04 MCNTs (XFNANO, China) are dispersed in petroleum DF of grade L in content levels of 250, 500 and 1000 mg/L and the obtained blended fuels are named DF250MCNT, DF500MCNT and DF1000MCNT, respectively. These MWCNTs have an average external diameter of 10 nm, an average length of 2 μm and a wall number of 4.

2.2. Density of the studied fuels

The density of the MCNT blended DF can be described by the classical formula developed for the traditional blended particle-liquid system with the assumption that carbon nanotubes are well dispersed in the base liquid:

$$\rho_{BF} = \rho_{DF} \cdot (1-\phi)+\rho_{MCNT} \cdot \phi, \qquad (1)$$

where ρ_{BF} – the density of blended fuel, ρ_{DF} – the density of diesel fuel, ρ_{MCNT} – the density of MCNT and ϕ – the volume concentration of MCNT. In the modern fuel supply system, the injection pressure usually exceeds 100 MPa and even reaches up to 300 MPa. In this case, the fuel's compressibility must be considered and the following formula can be used (Grekhov et al., 2015):

$$(\rho_{DF}/\rho_{DF,0T})^{\chi} = (B+p)/B,$$
$$B = 222.3 - 1.26(T - 293) + 0.62 \cdot (\rho_{293} - 825) \text{ [MPa]},$$
$$\chi = 7.49 + 0.0086 \cdot (T - 293), \qquad (2)$$

where ρ_{DF}- the density of DF at temperature T [K] and pressure p [MPa], ρ_{293} – the density of DF at 293 K and 0.10325 MPa, $\rho_{DF,0T}$ – the density of DF at temperature T [K] and 0.10325 MPa. There is ρ_{293} = 830 kg/m^3 for DF of grade L and the relationship of density with respect to temperature at 0.10325 MPa is described as following (Grekhov et al., 2015):

$$\rho_{DF,0T} = -0.365 \cdot T + 936.945 \quad (3)$$

The density of MCNTs can be calculated as a function of their characteristics (inner diameter, outer diameter and the number of walls) with the assumption that each CNT layer is a rolled graphene plane without suture and the distance between adjacent atoms is the same and equal to 0.1421nm; all CNT layers are located concentrically with an interlayer distance of 0.3400 nm (Laurent et al., 2010). Thus, the calculated density of XFM04 MCNTs is 1091 kg/m^3. Based on the described approach the density of DF, DF250MCNT, DF500MCNT and DF1000MCNT at temperature 300 K and pressure 0.10325 MPa is 827.445, 827.505, 827.565 and 827.686 kg/m^3, respectively

2.3. Viscosity of the studied fuels

Various nano-liquids can be identified as Newtonian fluid or non-Newtonian fluid according to their rheological behavior. A study of rheological properties of diesel fuel with MCNTs showed that the carbon nanotube dispersed diesel fuel is a Newtonian fluid as the mass concentration of MCNTs in DF is less than 0.5%. As a Newtonian fluid system, the effective viscosity of MCNT blended DF can be determined as a function of the volume concentration by using phenomenological and hydrodynamic equations. This equation is expressed as:

$$\mu_{NF}/\mu_F = 1 + 250 \cdot \phi, \quad (4)$$

where μ_{NF} – the dynamic viscosity of the nano-fuel, μ_{DF} – the dynamic viscosity of the base fuel.

Fig. 1 shows the dynamic viscosity ratio between the nano-fuel containing MCNTs and the base fuel with respect to the volume concentration of MCNTs obtained from different works (Sunil et al., 2020) and the dynamic viscosity ratio calculated by the formula (4). It's found that there is a linear relationship between the effective dynamic viscosity of the nano-fuel and the volume concentration of MCNTs.

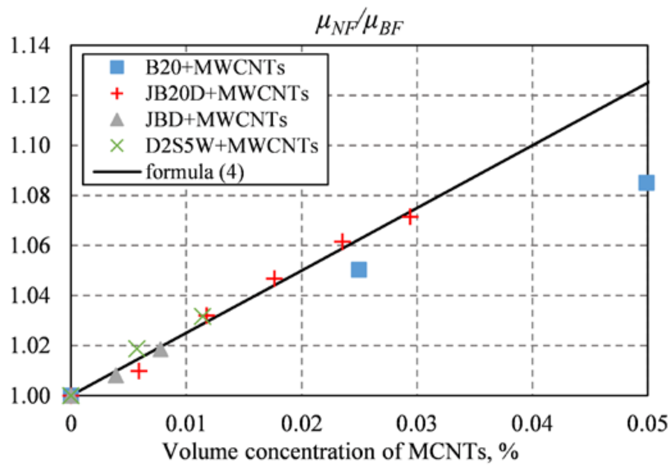

Fig.1. Relationship of the dynamic viscosity ratio μ_{NF}/μ_F between the nano-fuel with MCNTs and the base fuel with respect to the volume concentration of MCNTs in the base fuel.

Therefore, the formula (4) is appropriate to describe the effective dynamic viscosity of MCNT blended DF. At the same times, the dynamic viscosity of DF of grade L can be determined by the following logarithmic relationship (Markov et al., 2016):

$$ln(\mu_{DF}/\rho_{DF}) = 5.7066 - 11.3262/(T\text{-}273.15) - 0.0163T \quad (5)$$

The calculated results about the dynamic viscosity of MCNT blended DF by using the abovementioned approach were plotted in Fig. 2. It's noted that the addition of MCNTs leads to an increase in the dynamic viscosity of DF. With increasing the MCNT content in DF, the dynamic viscosity of DF increases. Increasing temperature reduces the effect of MCNTs on the dynamic viscosity of DF.

2.4. Computational-physical Models

The dynamic flow of DF and MCNT blended DF was simulated using CFD software Fluent for an injector Spray A210675, which is a Bosch diesel injector with a single nozzle orifice proposed by Engine Combustion Network (ECN). This injector with the Common Rail system is intended for fundamental research of the injection and combustion processes in modern diesel engines. Some parameters of the nozzle for this injector are given in Table 1.

Fig. 3 presents the hexahedral structured meshes of the nozzle that were established in ICEM CFD when the needle lift is 50 μm. The nozzle geometry was built based on the data about the axial diameter profile (Markov et al., 2017). Meshes at the zone of the orifice were refined with a base size of 2 - 3.5 μm and the height of the first layer of near-wall mesh was set to be 0.3μm and in the other zones the maximum mesh size was kept no more than 35 μm. The total number of mesh elements was 0.51 million at a needle lift of 7 μm (corresponding to the starting moment of simulation) and 3.52 million at the peak needle lift of 466 μm.

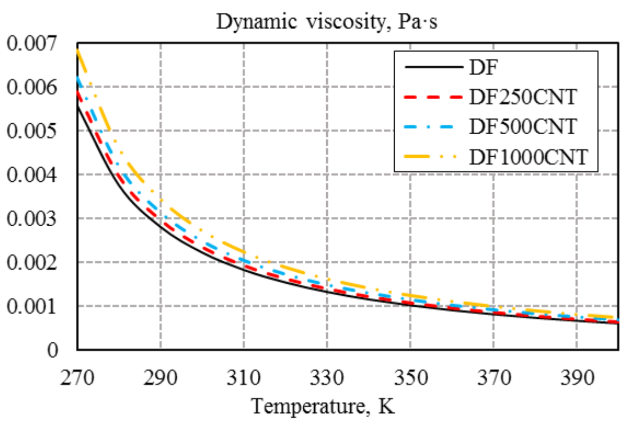

Fig.2. Calculated dynamic viscosity of MCNT blended DF at different temperatures.

Table 1. Specification of the nozzle in the investigated injector A210675 (ECN)

Orifice outlet diameter	***0.0894 mm***
Nozzle K factor	1.3
Inlet radius	25 μm
Number of orifices	1
Orifice orientation	Axial

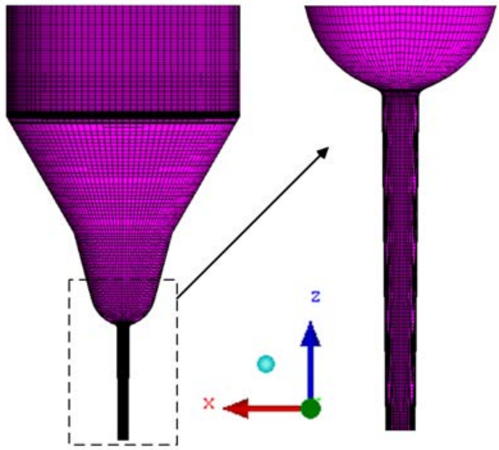

Fig. 3. Hexahedral structured meshes of the nozzle of the injector A210675

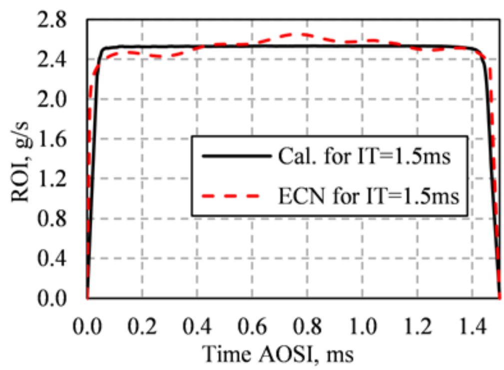

Fig. 4. Comparison of the calculated ROI of n-dodecane with the recommend ROI in ECN for the IT of 1.5 ms.

In order to describe the internal nozzle flow of the investigated fuels under consideration of possible cavitation (two-phase flow), the Euler mechanism for homogeneous equilibrium system with a single fluid was used. In other words, the conservation equations of mass, moments and energy are solved for the multiphase mixture and the volume concentration equation is solved for the secondary phase (the primary phase is fuel liquid). The Schnerr and Sauer models were used to model the cavitation process taking into account the effect of turbulence on cavitation. To solve RANS equation, we used a turbulent model with two equations - k-ε model with Enhanced Wall treatment for equation ε. A detailed description of these models is given in our previous work (Markov et al., 2017, 2019b). In addition, in the Schnerr and Sauer cavitation model, a correction of the number density of bubbles was done for MCNT blended DF. The number density of bubbles was modified according to the number density of MCNTs: $n_{NF} = n_{DF} + n_{MCNT}$, since the presence of MCNTs increases nucleation density. The simulation was carried out in a DELL portable workstation with an 8-core Intel processor i7-6700 (maximum clock frequency 4.0 GHz). The calculation of one injection with an injection duration of 1.5 ms lasted for seven days.

The computational models were validated by comparing the rate of injection (ROI) of n-dodecane obtained from the computational models with the recommend ROI of n-dodecane in ECN at a fuel temperature of 363 K, an injection pressure of 150 MPa and backpressure of 6 MPa for the injection time (IT) of 1.5 ms. As shown in Fig. 4 the used computational models very well represented the real characteristics of n-dodecane in the nozzle and can be used for further studies.

3. Results and discussion

With the use of the abovementioned models, numerical simulations of the flow of the investigated nano-fuels in the nozzle of the injector A210675 were carried out under the following conditions, which are typical for modern diesel engines: the injection pressure - 150 MPa, the fuel temperature in the nozzle - 363 K, the backpressure at the orifice outlet- 6 MPa and the injection duration - 1.5 ms. In order to analyze the flow characteristics of the investigated nano-fuels, the distribution of the flow velocity and the turbulent kinetic energy (TKE) inside the nozzle at the moment corresponding to the peak nozzle needle lift (h=466 μm) were analyzed, as well as, the transient rate of injection and turbulent kinetic energy at the orifice outlet were investigated.

The cavitation did not appear in the nozzle for any of DF and MCNT blended DF in the whole injection progress, although the presence of MCNTs increased nucleation density. The nozzle investigated has a conical orifice (nozzle K factor = 1.3), which contributes to preventing the generation and development of cavitation. This result is in agreement with the X-ray radiography images performed for this injector nozzle (Duke et al., 2014).

Fig. 5.a shows the velocity distribution on the nozzle's longitudinal section for DF and DF1000MCNT. It was noted that there is no significant difference in the velocity distribution structure between DF and MCNT blended DF. This result can be explained by the same dynamic conditions, the same geometry and little difference in molecular when a slight amount of MCNTs are dispersed into DF. Adding MCNTs into DF increases the molecular viscosity, which increases the flow resistance in the near-wall region. However, in the region far from the wall, the turbulent viscosity plays a dominant role (the Reynolds number for the case of DF is about 38000). As shown in Fig. 5.b, the flow velocity for DF1000MCNT was lower than that for DF in the area near the wall, but there was no difference in the region far from the wall.

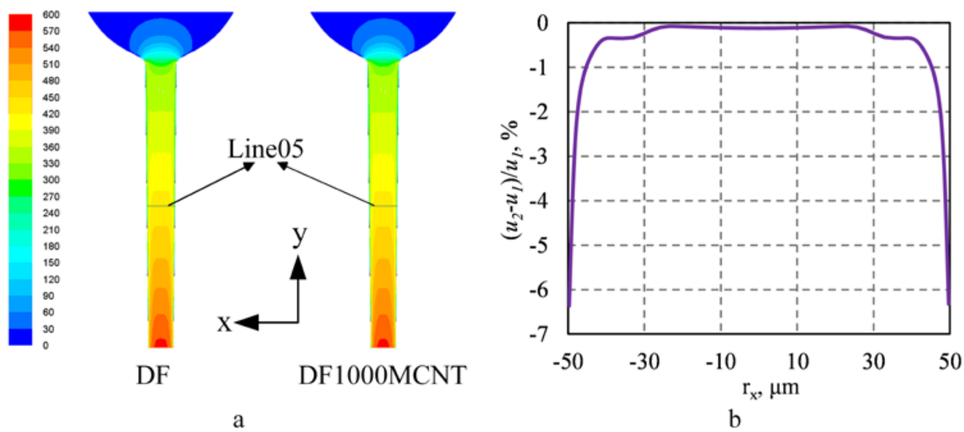

Fig. 5. Velocity distribution on the nozzle's longitudinal section at the time of the peak needle lift for DF and DF1000MCNT (a) and the velocity variation of DF1000MCNT relative to DF on the transverse line (line05) of 0.5 mm from the orifice outlet (b): r_x – the distance to the orifice axis; u_1 - the velocity of DF at r_x; u_2 – the velocity of DF1000MCNT at r_x.

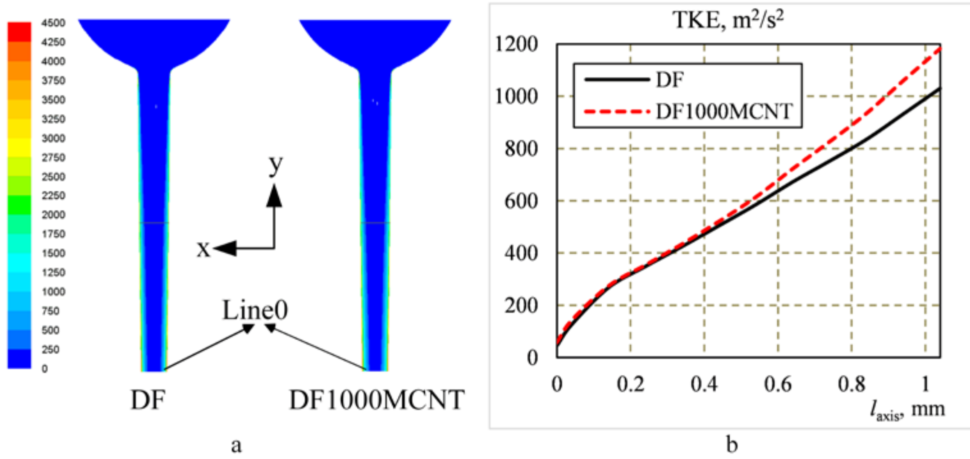

Fig. 6. Distribution of TKE on the nozzle's longitudinal section at the peak needle lift for DF and DF1000MCNTs (a) and curves of the average TKE on the cross-section of the orifice along the flow direction for DF and DF1000MCNTs at the peak needle lift (b).

TKE on the longitudinal section of the nozzle orifice was presented in Fig. 6.a. It indicates that there is the same distribution structure of TKE for DF and MCNT blended DF due to the same distribution structure of velocity. The relationship of the TKE averaged over each cross-section of the orifice with the distance to the orifice inlet (coordinate l_{axis}) was plotted in Fig. 6.b. It is obvious that the average TKE for DF1000CNT is more than the average TKE for DF, and this difference increases with closing to the orifice outlet. The reason for this result is the increased turbulence in the fully turbulent region with the presence of MWCNTs in DF caused by the increased velocity gradient between the near-wall region, mainly affected by molecular viscosity, and the central zone, mainly affected by the Reynolds number. As shown in Fig. 5.a. the flow velocity in the central zone of the orifice is the same for both fuels, but the flow velocity for DF1000MCNT in the near-wall region is lower than that for DF. Therefore, the velocity gradient between these regions for DF1000MCNT is greater than that for DF, which leads to an increase in the TKE for DF1000MCNT.

Fig. 7 and Fig. 8 show the transient ROI and TKE at the orifice outlet for pure DF and MCNT blended DF, as well as the relative variation of these parameters for MCNT blended DF compared to pure DF. With increasing the amount of MCNTs added into diesel fuel, ROI decreases (see Fig. 7.a and Fig. 8.a). At the time from 100 μs after the start of injection (SOI) to 1400 μs after SOI, the decrease of ROI doesn't exceed 0.74%. Only at the initial stage of needle opening and the final stage of needle closing, this decrease rises to 5.4%. The reason is that at a small needle lift, the little annular gap between needle valve sealing cone and needle seat prevents the flow of the fuel and the flow velocity is very small, where the molecular viscosity is the main factor affecting the fuel flow. The presence of MCNTs in DF has a more significant effect on flow turbulence at the orifice outlet (see Fig. 7.b and Fig. 8.b). At a small needle lift, TKE at the orifice outlet for MCNT blended DF is less than that for pure DF, but the difference is no more than 4% for DF250MCNT. From 100 μs to 1400 μs after SOI, the addition of MWCNTs into DF leads to an increase of the TKE at the orifice outlet up to 15.2% for DF1000MCNT compared to pure DF. The increased flow turbulence at the orifice outlet contributes to accelerating the primary breakup of fuel droplets and might lead to more refined fuel droplets.

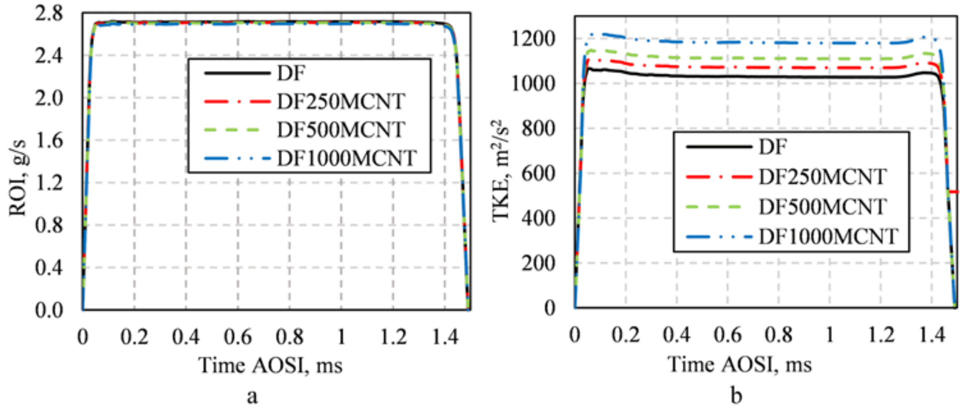

Fig. 7. ROI (a) and TKE (b) at the orifice outlet for the investigated DF and MCNT blended DF

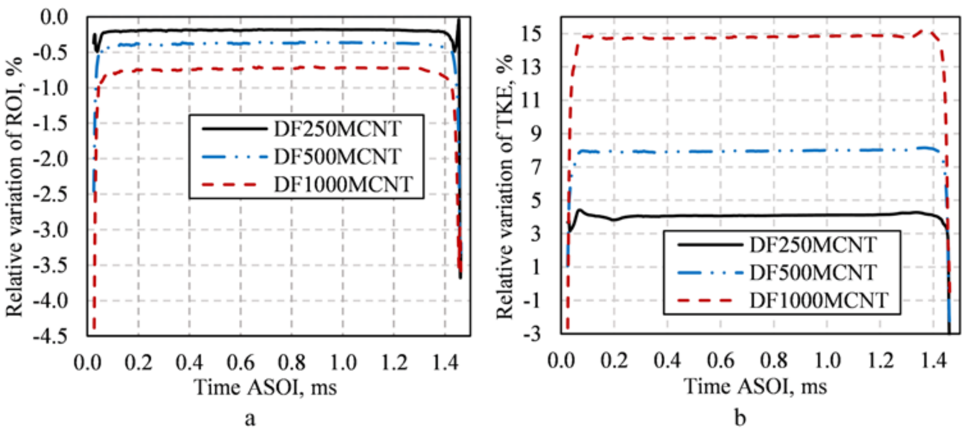

Fig. 8. The relative variation of ROI (a) and TKE (b) at the orifice outlet for MCNT blended DF compared to pure DF

4. Conclusions

Important observations are as follows:

- The presence of MCNTs in DF leads to a viscosity increase;
- The MCNTs only affect the ROI of MCNT blended DF at the initial stage of needle opening and the final stage of needle closing;
- Adding MCNTs to DF leads to an increase of TKE at the orifice outlet in the stabilized injection stage. The increased turbulence of the fuel jet contributes to accelerating the primary breakup and improving the quality of the fuel-air mixture formation, which can lead to more complete combustion and reduce the formation of pollutant substances.

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