INFLUENCE OF FUEL QUALITY ON MIXTURE PREPARATION AND EXHAUST EMISSIONS FROM DIESEL ENGINES WITH COMMON RAIL SYSTEM

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Abstract
The objective of mixture preparation process in Diesel engines is obtaining full combustion and minimum harmful compounds of exhaust emissions. The injection process is the most important from the viewpoint of mixture preparation process. The experimental data of fuel spray atomization and droplet velocities of three different fuels with varied viscosity are presented in the paper. The research was performed using the PIV and LDV and PDPA laser equipment. The tested fuels were Diesel oils with varied viscosity and RME. The injection pressure varied from 50 MPa to 130 MPa. The fuels were injected to test chamber with optic access in atmospherical pressure and temperature. Pressure increase caused a continuous reduction in fuel drop diameter. The fuels with higher viscosity generated bigger droplets than the fuel with lower viscosity.

1. Introduction

The objective of mixture preparation process is to assure the adequacy of physical and chemical properties of mixture for fully combustion of fuel with minimum level of exhaust emission components. It is known that external and internal mixture preparation processes are applied. Internal mixture preparation process is the standard process used for compression ignition engines. Future Diesel engines for heavy duty cars are required to have significantly low NOₓ, PM and fuel consumption performances. The high-pressure injection and multiphase injection with common rail system are main directions of development Diesel engines. They are desirable with regard to fuel consumption, NOₓ and PM reductions. The course of injection and evaporation processes are decisive from the viewpoint of mixture preparation process. A continuous reduction in limit values of toxic components and CO₂ of exhaust emissions is the reason for research concerning fuel consumption reduction and exhaust emission reduction. The challenge in development of internal combustion engines is to abate pollutants emitted while enabling efficient engine technologies applications. The development process of vehicles includes engines, fuel injection systems and fuels. Properties of fuel have substantial influence on mixture preparation process and following the performance of engines their exhaust emissions and fuel consumption.

To satisfy the performance and reliability of the engines needs, the fuels must involve meet many properties such as viscosity, density, surface tension, volatility, deposit-forming tendencies, cleanliness, and corrosives. One of the important fuel properties from the viewpoint of engine users is density, which is related to the heating value of the fuel and thus the energy available to generate power. Viscosity is important for the satisfactory operation of the fuel injection equipment, which has to meter, with high accuracy, the small quantity of fuel to be injected. As viscosity varies inversely with temperature, the tolerance range between maximum and minimum values should be kept as small as practicable. A very high viscosity at low temperature could reduce fuel flow rates resulting in smaller volume injected...
to the combustion chamber. If the fuel is very viscous, there is a possibility of pump distortion due to heat generated by the shearing action in the small clearances. The selection of fuel injection equipment and injection timing has to take into account the likely range of viscosities to be encountered as well as typical average values. The viscosity and surface tension of fuels are the most important from the viewpoint of mixture preparation process and combustion process. The viscosity and surface tension influenced on fuel atomization and a course of injection and thus the combustion process and engine performances.

The Weber Number and Ohnesorge Number enable to determine the conditions for drops breakup. The Weber Number results from assumption that the initial conditions for breakup are achieved if the aerodynamic drag is equal to the surface tension force. The Weber Number is the most common criterion of droplet disintegration.

It has been shown experimentally and has been confirmed theoretically, that the mode of drop disintegration depends on whether the drop is subjected to steady acceleration or is suddenly exposed to a high-velocity gas stream. With steady acceleration the drop becomes increasingly flattened and at a critical relative velocity it is blown out into the form of a hollow bag, attached to a roughly circular rim. On disintegration the bag produces a shower of very fine drops, while the rim, which contains at least 70% of the mass of the original drop, breaks up into larger drops. A drop suddenly exposed to a fast air stream disintegrates in an entirely different manner. Instead of being blown out into a thin hollow bag anchored to a rim, the drop is deformed in the opposite direction and presents a convex surface to the flow of air. The edges of the saucer shape are drawn out into a thin sheet and then into fine filaments, which break into drops. The Weber Number does not account the influence of liquid viscosity on drop breakup.

The Ohnesorge Number illustrates relevance of the liquid jet to the atomization process and is characterized by the ratio of the friction force to the surface tension force, where $\tau$ is the friction force per unit area.

The effect of viscosity on the critical Weber Number can be expressed by the relation of the form:

$$\text{We}_c = \text{We}_{co} [1 + f(Oh)],$$

where $\text{We}_c$ is critical Weber Number, $\text{We}_{co}$ - critical Weber Number for zero viscosity. When of viscosity liquid goes to zero, Ohnesorge Number also goes to zero and $\text{We}_c = \text{We}_{co}$.

If liquid jet emerges from a nozzle, as a continuous body of cylindrical form, the competition set up on the surface of the jet between the cohesive and disruptive forces, gives rise to oscillations and perturbations. Under favorable conditions the oscillations are amplified and the liquid body disintegrates into drops. This process is sometimes described as a primary atomization. If the drops formed exceed the critical size, they further disintegrate into drops of a smaller size. This process is known as a secondary atomization.

Haenlein identified four distinct regimes of breakup in the disintegration of a liquid jet:

- **Drop formation without the influence of air.** This is the mechanism studied by Rayleigh. The term „varicose” is sometimes used to describe the appearance of the jet in this regime. Radically symmetric waves are formed by the interaction of primary disturbances in the liquid and surface tension forces. This regime is characterized by a linear relationship between the breakup time to be proportional to $d_0^{1.5}$ for nonviscous jet and proportional to $d_0$ for viscous jets.

- **Drop formation with air influence.** As the jet velocity is increased, the aerodynamic forces of the surrounding air are no longer negligible and tend to accentuate the waves formed under regime 1.
- Drop formation due to waviness of the jet. This regime is associated with increasing effectiveness of aerodynamic forces and lessened relative influence of surface tension. The term „sinuous” has been used to describe the jet in this regime.
- Complete disintegration of the jet, i.e., atomization. The liquid is broken up at the nozzle in a chaotic and irregular manner.

Although these four separate regimes can be clearly identified, there is no sharp demarcation among them.

From photographic records of jet disintegration, Ohnesorge classified the data according to the relative importance of gravitational, inertial, surface tension, and viscous forces. He used dimensionless analysis with good effect to show the breakup mechanism of a jet. It could be expressed in three stages, each stage characterized by the magnitudes of the Reynolds Number and a dimensionless number \( Z \), which is obtained as:

\[
Z = \left( \frac{w^2 \rho_L d_0}{\sigma} \right)^{0.5} \left( \frac{w \rho_L d_0}{\mu_L} \right)^{-1} = \frac{\mu_L}{\left( \rho_L \sigma d_0 \right)^{0.5}},
\]

where:
- \( \mu_L \) - liquid viscosity,
- \( \rho_L \) - density of liquid,
- \( d_0 \) - liquid jet diameter (orifice diameter).

This group is sometimes referred to as the stability number, the viscosity group, or the Ohnesorge Number (Oh).

Ohnesorge showed that the various mechanisms of the jet breakup could be divided into three regions on a graph of Ohnesorge Number versus Reynolds Number, according to the rapidity of drop formation:
- At low Reynolds Numbers, the jet disintegrates into large drops of fairly uniform size. This is the Rayleigh mechanism of breakup.
- At intermediate Reynolds Numbers, the breakup of the jet is by jet oscillations with respect to the jet axis. The magnitude of these oscillations increases with air resistance until complete disintegration of the jet occurs. A wide range of drop sizes is produced.
- At high Reynolds Numbers, atomization is complete within a short distance from the discharge orifice.

The number and variety of factors that have impact on droplet generation process, cause that theoretical dependencies are not illustration of the real phenomenon complexity but an assumptions are semi empirical formula.

During Diesel engines operation conditions of fuel injections varied, which influenced varied course of injection and the spray droplet spectrum. These complicated engine operation conditions cause that experimental methods of research of fuel spray atomization and droplet velocity in the spray assure better results.

2. Research of velocity distribution in fuel spray using PIV

The common - rail system with the possibility of changing the injection pressure from 50 to 130 MPa was used in the research. The test stand with common rail system used in the experiments is presented in Fig.1. In Fig.2 the schematic of PIV equipment and in Fig.3 the view of this equipment are shown.
Fig. 1. View of test stand

Fig. 2. Outline of PIV system

Fig. 3. View of PIV system

\[
\begin{align*}
\rho & \, [g/cm^3] \\
\mu & \, [mm^2/s]
\end{align*}
\]
The test stand includes test chamber, common rail system with injector, electronic control unit, low pressure and high pressure pumps, electric drive with regulated velocity, fuel tank, filters and valves actuated hydraulically and by hand. The electronic control unit of test stand enables realization of single injection (also multiphase) at variable pressures. Two glass windows in the test chamber allowed optical access into the spray of injected fuel. The test chamber was not pressurized and injection was performed at normal ambient pressure and temperature.

Distribution velocity in the spray was determined using PIV (Particle Image Velocimetry) laser equipment. The general technique PIV involves a multiple exposure photograph of a flow containing particles or droplets. A photographic image of the particles is obtained for a plane of particles, which has dimensions: the high of an illuminating laser sheet, the width of the image plane, and the thickness of the laser sheet. Typical dimensions are 30 mm high by 50 mm wide by 200 µm thick. The light source is controlled to allow two exposures of the particle field to be recorded on the film. The time between the exposures is controlled. Particle velocity can be obtained by measuring the magnitude and direction of the displacement of a particle between exposures. The PIV system is characterized by the possibility of carrying out measurements at 12000 points simultaneously. It also has high resolution, guarantees high measurements precision, and enables visualization of flows, which
includes the structure of turbulent flows. The important advantage of the system is the possibility of defining turbulence and Reynolds stress. Moreover, it assures quick operation in automatic cycle.

The properties of three different experimental fuels, with different viscosity, are shown in Fig.4. Two fuels (No. 1 Fuel and No.2 Fuel) in experiments with PIV were used however three fuels were used in experiments with LDV and PDPA equipment.

Fig.5 illustrates distribution of the vectors and velocity field for the No.1 fuel at pressure 100 MPa, time t=0.39 ms.

Fig.5. Velocity field in the spray for No. 1 fuel

Fig.6 shows distribution of the vectors and velocity field for fuel No.2 at pressure 100 MPa, time t=0.44 ms.

For both tested fuels, growth of pressure caused larger uniform of velocity and disturbances in velocity field, which fostered homogenizing of the fuel-air mixture. The area of self-ignition appearance in volumetric model can be found on the fuel spray front, where favorable thermodynamic conditions occur leading to intensification of diffusion.

If viscosity grows the volume of atomized fuel is diminishing. Larger range of droplet diameters in the fuel spray and increased velocity at its front can be observed. Despite lack of full repeatability of tests results, the tendencies mentioned above also occur in another conditions of experiment.
3. Application of LDV and PDPA equipment for research of fuel droplets atomization and velocity

The most relevant knowledge concerning diameter of droplets and their distribution in fuel spray is required by engine designers. In general industrial flows and flows in injection process are turbulent. Turbulent motion is 3D, vertical, and diffusive, governing general Navier - Stokes equations which are very hard (or impossible) to solve:

$$\rho \frac{DU_i}{Dt} = \frac{\partial \tau_{ij}}{\partial X_j} + \rho f_i - \frac{\partial p}{\partial X_j},$$

Measurements enable obtaining the results of experiments in the easier way and with higher accuracy. When we have to measure velocities in transparent environment we must apply the seeding.

The experiments in test stand concerning injection pressures and temperatures of injected fuels were performed in conditions similar to those in Diesel engine. In engine environment the droplets diameters differ, depending on conditions of outflow and fuel characteristics. To analyze the injection process of generating fuel spray it is better to use one droplet of constant diameter representative for given outflow conditions, rather than a group of different diameters.

There are few representative characteristics of mean droplet diameter used in the experiment descriptions. They include, among others, such means as arithmetic diameter ($D_{10}$), surface diameter ($D_{20}$), volume diameter ($D_{30}$), Sauter diameter ($D_{32}$), and Herdan diameter ($D_{34}$).
With reference to PDPA system, five mean diameters were distinguished in order to determine spray parameters: $D_{10}$, $D_{20}$, $D_{30}$, $D_{32}$ and $D_{43}$.

$D_{10}$ diameter is known as arithmetic mean and its meaning is to make comparisons.

$D_{20}$ diameter is described as droplet surface function, which enables to compare the average surface of measured droplets.

$D_{30}$ diameter is droplet volume function which enables to compare the volumes of measured droplets.

$D_{32}$ diameter (Sauter mean diameter) is derived from ratio of all droplet volumes sum to all droplet surface sum, and is used to analyze the processes of heat and mass exchange.

$D_{43}$ diameter (Herdan diameter) is derived from ratio of the sum of the fourth power of droplet diameters to the sum of the third power of droplet diameters, and is used to analyze combustion processes, and gives a possibility of a closer examination of activities, which embrace combustion processes.

Difference in mean droplets diameters is the measure of droplets diameters uniformity in fuel spray. In order to determine change of these mean droplet diameters, at high injection pressures and varied fuel viscosity, investigation of fuel spray atomization spectrum has been carried out with use of dynamic laser analyzer LDV (Laser Doppler Velocimeter) and PDPA (Phase Doppler Particle Analyzer) made by Aerometrics. The Spectra Physics argon ion laser has been used in the experiment. Measurement system enables realization of velocity measurements in 3 directions (3D).

![Fig. 7. Focal region of LDV and PDPA transmitter](image)

The laser Doppler principle is best described by using an interference model. An interference pattern composed of light and dark fringes is formed at the point of intersection of the two beams. The distance between the fringes is known and is dependent only upon the angle of intersection $\phi$ and the frequency of the laser light $f_0$. Even the smallest droplets passing through the optically striped focal region cause the light is scattered in all directions. The front lens of the LDV collects the scattered light and directs it to the photo detectors (APD), which produces an electrical signal, proportional to the scattered light intensity. The intensity modulation $f_D$ of the scattered light, caused by the droplet passing vertically through the stripped measurement volume, is directly proportional to the droplet’s velocity. The measurement principle of velocity component consists in registration of change in laser beam frequency, which is proportional to fuel droplet velocity. Droplet dimension measurements consist in registration of laser beam deviation while passing by the droplet, which is proportional to its diameter.

Measurements are realized in the local region, which is determined by two crossing laser beams, the zero one and the Doppler one. The focal optical region of laser transmitter has the rhomboidal shape (Fig.7), which maximum dimensions in the optical system amounted to
17.6 mm × 1.4 mm × 1.4 mm. The diameter of laser beam is 1.4 mm, distance between zero and Doppler beams amounted to 39.74 mm.

Fig. 8 presents the view of probe volume and test chamber.

Fig. 8. View of test chamber and probe volume

Measurement laser, together with Bragg Cell, which enables to obtain two beams (zero and Doppler ones) from one laser beam, alongside with six light pipe system, which allows performing tests in natural conditions are presented in Fig. 9.

Fig. 9. View of Spectra Physics measurement laser and fiber drive (Bragg cell)

Fig. 10. View of signal analyzing system and results acquisition system

The test results presented in this paper were obtained in the distance of 100 mm from injection nozzles output, in axis of the spray. When the distances from nozzle were longer droplet distribution was more uniform. As the distance was shorter, greater scatter of tests results occurred.

In Fig. 11 and Fig. 12 the results of measurement of droplet diameters and velocity droplets are presented. The results of diameter and volume of droplets distribution are matched by Rosin-Rammler function. This function for droplets size distribution may be expressed in the form:

\[ 1 - Q = \exp\left(-\frac{D}{X}\right)^2, \]

but for the volume distribution is given by:
\[
\frac{dQ}{dD} = q \left( \frac{\ln D}{\ln X} \right)^{q-1} \exp\left( \frac{\ln D}{\ln X} \right)^q.
\]

The Q is the fraction of the total volume contained in droplets of diameter less than D, and X and q are constants. By applying the Rosin-Rammler equations to spray it is possible to describe the drop size distribution in terms of two parameters X and q. The exponent q is a measure of the spread of droplet sizes. If the q value is higher the spray is more uniform. Because the value of q in Rosin-Rammler function for the spray in this test is high (for most sprays this value is from 1.5 to 4.0) and amounts to 3.41507, which means that the spray is uniform.

In Fig. 11 test results of fuel spray droplet diameter for test fuel No.1 and test fuel No.2 with use of LDV and PDPA laser equipment are presented.
In Fig.14 test results of fuel spray droplet diameter for test fuel No.1 and RME are shown.

Research results of droplets velocity using LDV laser apparatus are presented in Fig.15. Tests results of droplet turbulence with use of laser equipment PDPA and LDV are presented in Fig.16.

As it may be observed from the presented results of droplets diameter spray spectrum, using Diesel fuel with higher viscosity caused increase of SMD ($D_{32}$) at pressure 130 MPa about 16%, at pressure 100 MPa about 31%, and at pressure 70 MPa about 17%.

$V$ [m/s]
Simultaneously, the difference between mean diameters of $D_{10}$ and $D_{32}$, at the same pressure growths, is a convincing evidence of increased fuel diameters non-homogeneity in the spray of fuel with higher viscosity. The biggest differences between Sauter mean diameters of test fuel No.1 and RME, which is characterized by four times higher viscosity, were observed. In this case the $D_{32}$ for RME fuel was bigger 2.4 times at pressure 130 MPa, 1.7 times at pressure 100 MPa and 1.5 times at pressure 70 MPa. The research confirmed that increase of injection pressures causes growth of homogeneity of fuel sprays.
Such big differences in atomization process have to influence on mixture preparation and combustion processes in internal combustion engines, and they can follow changes in engine design or fueling system design.

Concerning velocity and turbulence distributions of atomized fuel droplets, the velocity in axis direction of fuel spray was dominant almost in all cases.

4. Conclusions

- The research has shown that properties of fuels as a density, viscosity and surface tension influence structure of the spray, droplet spectrum and velocities of the droplets and therefore impact on mixture preparation process and combustion process.
- The increase of injection pressure caused droplet diameters growth independent from test fuel used.
- The injector of fuel injection system fueled with fuel of higher viscosity produced the droplets with bigger diameters than fuel of lower viscosity.
- The biggest droplets were produced for RME fuel, which viscosity was from two to four times higher than Diesel oil.
- The research carried out on a common-rail injection system using PIV laser equipment reveals lack of homogeneity and symmetry of velocities field in fuel spray. Inside the spray the velocities of droplets were much bigger than outside the spray. Big differences between neighbor droplets occurred.

References


