INVESTIGATION OF THE FUEL SPRAY ATOMIZATION SPECTRUM IN COMMON-RAIL SYSTEM FOR DIESEL ENGINES

Antoni Jankowski
Barbara Sieminska-Jankowska
Institute of Aeronautics, BK
Al. Krakowska 110/114, 02-256 Warszawa, Poland, ajank@ilot.edu.pl
Alexander Sandel
The National Automotive Center, Warren, MI 48397-5000, USA, sandela@tacom.army.mil
Cezary Bocheński
Department of Production Management and Engineering, Warsaw Agricultural University,
ul. Nowoursynowska 166, 02-787 Warszawa, Poland, wip_koip@sggw.waw.pl

Abstract

Experimental results of the influence of the fuel viscosity and injection pressure on the fuel droplet diameter and velocity distribution in a fuel spray are presented in this paper. The experiments were carried out on the special test stand with the constant volume chamber. The measurements were performed using the LDV, PDPA, and PIV laser systems. Two experimental Diesel fuels for compression ignition engines with different viscosity values were used in the experiments. The injection pressures varied from 50 MPa to 130 MPa. The tests results show that the common rail injection systems, when it was fuelled with the fuel of smaller viscosity produce the droplets of smaller diameters than fuel with a bigger viscosity value. As the injection pressure was increased the droplets with finer diameter as well as for fuel with smaller and with bigger viscosity has been produced by this system. In this paper samples of the experimental results of the velocity fields in the fuel sprays are also presented.

1. Introduction

The reasons for conducting at present a wide range of research in the field of reducing the CO$_2$ emission are greater stress put on limiting the CO$_2$ emission and the perspective of introducing limits on CO$_2$ emission regarding the combustion engines producers. These are also reasons for greater interest in application of Diesel engines with direct injection to motor vehicles.

Diesel engines, among internal combustion engines, are characterized by the lowest fuel consumption and therefore the minimal CO$_2$ emission. Alongside with introducing Diesel engines the problems with high emission of NO$_x$ and particulates may occur. There is a necessity of simultaneous reducing the CO$_2$ emission and NO$_x$ and particulates emission. The solution of these problems may include a better preparation of the mixture, which is lately obtained by increasing the injection pressure even to 200 MPa and using appropriate fuel with strictly determined physical and chemical characteristics, such as viscosity, surface tension, density and precisely specified content of different hydrocarbons in fuel. The aim of such activity is to obtain a stream of small, homogeneous droplets.

In order to generate high-pressure injection the common-rail type fueling system has to be applied. In such system, defined for certain conditions of motor operation, constant injection pressure is maintained. It means that constant circumstances of fuel injection exist, which result in high repeatability of injection course in particular cylinders as well as in time function of engine operation. Common-rail systems require the use of precise control system, while it is necessary to accurately measure fuel dose. This is realized by the timing of opening injection valve and by the change of injection angle. Such control assures electronic control
systems but it cannot be realized with use of mechanical control systems. Investigation of the fuel spray atomization in injection engine systems allow adequate configuration of the streams of injected fuel. The configuration of the stream should guarantee low fuel consumption and low exhaust emission of toxic components. Examinations of fuel injection can be nowadays carried out at very high, professional level due to development of optical investigation methods, such as high-speed photography, holography and laser anemometry. Reaching the low level of exhaust gas emission is relevant, while Diesel engine runs at high excess of air and hitherto efficient catalytic exhaust aftertreatment systems for Diesel engines have not been designed.

Experimental results of the influence of the injection pressure and fuel viscosity on the fuel droplet diameter and velocity in the fuel spray are presented in this paper. The measurements of the droplets velocity were performed with use of dynamic laser analyzer LDV (Laser Doppler Velocimeter). The measurements of the droplets diameters were performed using the PDPA (Phase Doppler Particle Analyzer). The distribution of droplets in fuel spray were determined by two methods, using laser analyzer PIV (Particle Imaging Velocimetry) and based on the measurement results performed using PDPA system, which also, in some sense, determined values for scaling with PIV system.

The experiments were carried out on the laboratory test stand in the constant volume chamber, at ambient constant temperature and pressure, using two types of fuel with different viscosity. The injection pressure amounted to 50 MPa, 70 MPa, 100 MPa and 130 MPa. The tests results show that injection system fuelled with the fuel of smaller viscosity has produced droplets of smaller diameters, than system fuelled with fuel with bigger viscosity. As for influence of the injection pressure, alongside with the growth of pressure the diameters of droplets decrease, however using the fuel of smaller viscosity resulted in bigger diminution of droplets diameters than with the use of fuel with bigger viscosity.

2. Mechanism of fuel spray preparation

Many theoretical and research works have been devoted to the problem of generating fuel spray, however they did not lead to establishing synonymous views on this matter. Disintegration of the fuel spray is connected with disturbance on its surface due to performance of the internal and external forces on surface tension forces. Disintegration of the fuel spray occurs while the value of the tensile force exceeds the value of the consolidation force, which is the surface tension.

The formed large droplets may experience further disintegration if they are found in the area of variable dynamic pressures growing together with the growth of relative velocity, which can be noticed especially at high injection pressures. The biggest impact on droplets diameter has aerodynamic forces as well as forces generated by surface tension. When aerodynamic force raises the deformation and further disintegration of droplets occurs [2].

The most common criterion of droplet disintegration is Weber Number (equality of aerodynamic forces and surface tension). Disintegration occurs if \( \text{We} \geq \text{We}_{kr} \).

Weber Number (We) is defined as:

\[
\text{We} = \frac{\rho w^2 d}{\sigma},
\]

where:

- \( w \) – droplet relative velocity,
- \( \rho \) - gas density,
Weber Number shows high accordance with tests results in conditions of determined liquid flow, when the injection sets in the medium, which lacks of factor influence.

– If droplets are influenced by acceleration or injection sets in the stream of flowing liquid, the conditions of droplets disintegration change. There are many formulas, which take into account differences in conditions in which Weber Number was derived and the actual stream disintegration conditions.

For instance, Hinze, taking into consideration influence of viscosity on stream disintegration introduced correction factor:

$$Z = \frac{\sqrt{We}}{Re},$$

where:  
Re - Reynolds Number,  
Z – correction factor.

Dimensionless number shows the ratio of internal viscosity forces and surface tension forces.

Calculations, which need to be made in order to establish fuel spray atomization spectrum are very complicated and require taking into account different similarity numbers, which makes it impossible to present them in this paper due to its limited volume and experimental character.

At high injection pressures, as it occurs in common-rail systems, the droplet relative velocity increases, which influences secondary disintegration.

As it was mentioned earlier in this paper, huge impact on droplets diameter and distribution is influenced by fuel viscosity and surface tension.

The growth of dynamic viscosity causes larger range of fuel spray and decrease in its volume.

Viscosity and surface tension influence on the size of the droplet diameter, according to empirical dependence:

$$r = \frac{\sqrt{3\sigma}}{Ep - A \mu w}$$

where:

Ep – pulsation energy,

$\mu$, $\sigma$ - dynamic viscosity and surface tension respectively.

The number and variety of factors that have impact on generating droplets, cause that theoretical dependences are not able to illustrate the phenomenon complexity. In the conditions of Diesel engine operation course of fuel injection is variable, which results from change in forcing, of fuel injection pump velocity, lasting effects, which accompany the outflow and disturbances caused by fuel compressibility and vibration of the system. These complicated motor operation conditions cause experimental methods of investigations of fuel spray atomization assure better tests results, which in addition can be applied in scientific and practical activities.
3. Measurement of velocity distribution in spray with PIV

The experiments were carried out at special test stand, which enabled realization of single injection (also multiphase) at variable pressures using the visualization of the process [1]. The properties of two different fuels, which were used in the experiment, are shown in Fig. 1.

![Fig. 1. Characteristics of tested fuels: 1 and 2](image)

- **a** - viscosity
- **b** - density
- **c** – surface tension

The Common-Rail system, with the possibility of changing the injection pressure from 50 MPa to 170 MPa, was used in the experiment. In order to determine the velocity structure and distribution the PIV (Particle Image Velocimetry) research system was applied. Fig. 2 shows the schematic of PIV apparatus, and Fig. 3 - the view of the system. 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, enables visualization of flows, which includes the structure of turbulent flows. The important advantage of the system is the possibility of defining turbulences and Reynolds stress. Moreover, it assures quick operation in automatic cycle. Fig. 4 illustrates distribution of vectors and velocity field for fuel No. 1 at pressure 50 MPa, time $t = 0.64$ sec.

Fig. 5 shows distribution of the vectors and velocity field for fuel No.2 at pressure 50 MPa, time $t = 0.52$ sec. For both tested fuels, growth of pressure caused larger velocity homogenization and disturbances in velocity field, which foster 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. When viscosity growths the volume of atomized fuel is diminishing, larger range of 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 different conditions of experiment.
Fig. 4. Velocity vectors distribution and flow field for 1 tested fuel, $p = 50$ MPa

Fig. 5. Velocity vectors distribution and flow field for 2 tested fuel, $p = 50$ MPa
4. Research of fuel sprays with LDV and PDPA methods

The knowledge of droplets diameter and distribution in fuel spray is relevant in performing experiments of atomized fuel stream in conditions similar to those in Diesel engine. In engine environment droplets diameters are different, depending on conditions of outflow and fuel characteristics. To analyze the process of generating the stream it is more favorable to use one droplet of constant diameter characteristic for given outflow conditions, rather than a group of different diameters. There are several representative mean droplet diameters used in the literature. They include, among others, Sauter Mean Diameter ($D_{32}$ or SMD), arithmetic diameter ($D_{10}$), surface diameter ($D_{20}$), volumetric diameter ($D_{30}$) or Herdan diameter ($D_{43}$).

![Fig. 6. Measurement point layout](image)

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displacement of laser beam by minimum 3°. PDPA system, which measures droplets diameters, is calibrated, LDV system, used also for droplets diameters measurements, does not require calibration. Measurement system enables realization of velocity measurements in 3 directions (3D). The measurement principle of velocity component consists in registration of change in laser beam frequency, which is proportional to fuel droplet velocity. Velocity component can be determined by using the following formula:

\[ v_i = \frac{f_D}{f_0 \sin \Phi} \]

where:

- \( v_i \) - droplet component velocity,
- \( f_D \) - modulated frequency of Doppler laser beam,
- \( f_0 \) - laser light frequency,
- \( \Phi \) - angle of intersection laser and Doppler beams.

Fig. 7. View of probe volume and test chamber

Measurement system allows utilization of 3 different laser beams: green one of 514.5 nm wavelength, blue one of 488 nm wavelength, and violet one of 476.5 nm wavelength. Droplet diameter measurement consists in registration of laser beam deviation while passing by the droplet, which is proportional to its diameter. Fuel droplet is observed from two detectors of two different distances: \( AB = 10.79 \) mm and \( AC = 32.15 \) mm. Each droplet is measured repeatedly and measurements results are compared. If the differences in measurements exceed 10%, the measurements results are rejected.

Measurements results of each single droplet moving through rhomboidal test section are recorded by the computer.

With reference to PDPA system, five 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 the meaning of using it, is to make comparisons. \( D_{20} \) diameter is described as droplet surface function, which enables the comparison of measured droplets average surface. \( D_{30} \) 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 volumes sum to 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 sum of fourth power of droplet diameters to 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. Differences in average droplets diameters are the measure of droplets diameters homogeneity in fuel spray. Layout of test points, at which experiments were performed, is presented in Fig. 6. Fig. 7 presents the view of probe volume and test chamber.

![Fig. 8. View of Spectra Physics Laser and Bragg Cell](image)

![Fig. 9. Real Signal Time Analyzer and Acquisition System](image)
In order to determine test points, research was conducted, which aim was to examine distances from injection nozzle, ranging from 50 mm to 350 mm. Droplet distribution was more uniform while the distances from nozzle were bigger. As the distance was shorter, greater scatter of tests results occurred. Since the environment, in which injection system was working was similar to engine one, the test points distances were as follows: 65 mm, 75 mm and 100 mm in axis of fuel spray. However at distance of 100 mm measurements were also done in symmetric points with reference to fuel spray axis at 10 mm distance.

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. 8.

Fig. 9 presents signals analysis system, tests results acquisition system with reference to each measured direction (of laser beam – 3 RSA processors), and experiments results presentation system.

Droplets velocity investigations results using LDV laser apparatus are presented in Fig. 10. Droplets diameters tests results with use of laser equipment PDPA and LDV are presented in Fig. 11.

Fig. 10. Measured velocity values histogram at the 1 measurement point for different injection pressures for two tested fuels with different viscosities
5. Conclusions

Physical process of generating the fuel spray is strongly influenced by fuel viscosity, density and surface tension, which depend on fractional constitution and the process of crude oil refining and additives. Diesel fuels, used in vehicles can differ considerably by viscosity value, which leads to significant differences in the injection processes.

Using the PIV investigation method, the velocity structure and distribution in fuel spray was determined. Velocity discontinuity and change in direction in particular regions of the spray were identified. The image of fuel spray differs, depending on viscosity of fuels.

Using the LDV and PDPA research methods the mean droplet diameters (Sauter), their velocity and distribution were determined. Pressure growth resulted in decrease of droplet diameter. Viscosity growth influenced increase of droplet diameter.

Injection system supplied with fuel No. 1 of smaller viscosity, generated droplets of smaller diameters, than fuel No. 2 of bigger viscosity. Sauter mean diameter (SMD), with reference to fuel of bigger viscosity, at pressure of 70 MPa was larger by 28%, at 100 MPa more by 8%, and at 130 MPa more by 15%. It has been stated, that alongside with the injection pressure growth diminishing of droplets diameters occurred. Sauter droplet diameter (SMD) at pressure growth ranging from 70 MPa to 130 MPa diminished by 47% with reference to fuel No. 1, and by 41 % with reference to fuel No. 2.

In connection with small fuel droplets diameters, droplet velocity was quickly decreasing, as the distance from injection nozzle was greater. Some significant turbulence heterogeneity (RMS) occurred, which may be influenced by discontinuity of velocity field as observed in PIV investigation.
Bibliography


