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MEASUREMENT METHODS FOR DETERMINING THE PARAMETERS OF INJECTORS IN INTERNAL COMBUSTION ENGINES

Norbert Grzesik, Ryszard Zaremba

Polish Air Force Academy
Dywizjonu 303 Street 12, 08-521 Dęblin, Poland
tel.:+48 81 5517785, fax: +48 81 5517784
e-mail: norbertgrzesik@02.pl, zarys20@wp.pl

Abstract

The general principle of internal combustion engine operation has not changed since the engine structure was first developed. However, the system of blending the air and fuel into a mixture with the parameters ensuring effective fuel combustion processes has been evolving over the years. In the simplest engines, the fuel-air mixture was produced in the inlet manifold i.e. in the carburettor systems while the more advanced motors were equipped with the system of Single Point Injection (SPI), and further on with the Multi-Point Injection (MPI) where each of the cylinders has its own individual injector. The Multi-Point Injection (MPI) system has evolved into a Gasoline Direct Injection (GDI) system where the injector sprays fuel directly into the combustion chambers.

Presently, due to the restrictive regulations governing the issues of exhaust gases' composition and emissions, manufacturers of the engines used mainly in the automotive industry apply the system of multi-point indirect injection to the intake manifold or the system of direct fuel injection to the combustion chambers. In both systems, these are the injectors dosing precise amounts of fuel, which are the most important, and the most accurate elements of the system.

The article presents the injectors' macro- and microscopic parameters used for the purpose of the fuel dispersants' technical condition and performance assessment. Additionally, it refers to direct and optical methods of microscopic parameters measurement enabling fuel spray diagnostics.

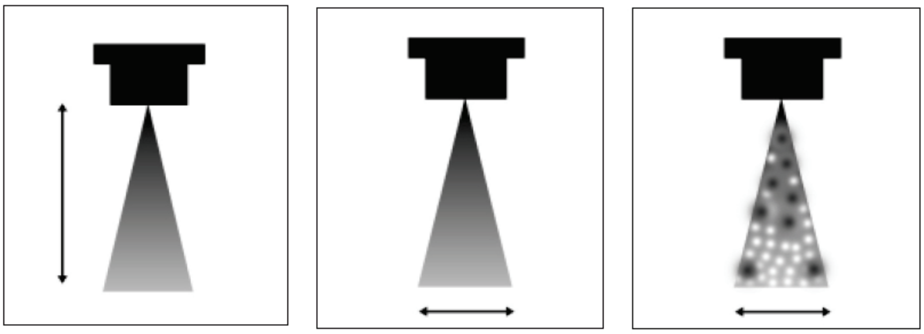
Keywords: *engines, fuel injectors, fuel spray diagnostics*

1. Parameters of injectors in internal combustion engines

The currently used fuel injectors should be characterised by the following parameters:

- injector nozzle opening time (measured in ms; determining the minimum injection time),
- injector nozzle closing time (measured in ms determining the minimum injection time),
- working pressure (the range of pressure determining the linear characteristics of an injector output),
- injector output (in cm^3),
- fuel spray front penetration – the fuel spray front penetration rate must be exactly the same for all injectors in a given engine. In the injectors in which a change of spray front length occurred the fuel-air mixture is formed in the point other than that originally designed which may result in increased fuel consumption, improper engine operation and faster engine components' wear. The fuel spray front penetration has also significant impact on the hazardous substances generation in the course of combustion process,
- fuel spray cone angle and spray area - engine manufacturers make use of injectors with various fuel injection characteristics which results from different structures of engine intake systems, different types of engine heads (8 V, 16 V, 20 V) and different fuel-air mixture formation parameters. Adequate injection characteristics ensures appropriate combustion parameters and consequently proper engine operation,
- fuel droplet size – proper fuel atomisation has a significant impact on the fuel combustion parameters. The most effective use of fuel, i.e. its most effective combustion, requires preparation of adequate fuel-air mixture. Manufacturers apply the higher and higher injection pressure in order to obtain the finest possible fuel droplets, which while evaporating at the

time, measured in milliseconds form a combustible fuel-air mixture. Improper atomisation leads to an increased fuel consumption and an increased hydrocarbons, nitrogen oxides and carbon monoxide emission, which may often result in the exhaust system defects.



A B C

Fig. 1. Graphical representation of the basic parameters of injectors: A– fuel spray penetration; B – fuel spray cone angle; C – fuel droplets diameters

2. Measurements of the microscopic parameters of atomised liquid

Measurements of atomised liquid microstructure are rather difficult mainly due to large quantities of produced droplets, wide range of droplets' diameters, variable droplets' velocity, changes in the droplets' shape and size occurring during the measurement procedure, etc.

A perfect measurement method should meet the following requirements:

- high accuracy,
- no disturbance to the spray of droplets during measurement,
- low costs of measurement equipment,
- short time of measurement duration,
- low labour-intensity in compilation of the test results,
- usefulness of the method for laboratory and technical measurements,
- possibility to measure small-size droplets,
- possibility to measure the spatial structure of the spray of droplets.

None of the currently applied methods meets all of the above-specified requirements. A specific method is selected depending on the purpose of a measurement.

2.1. Contact methods

This type of measurement methods requires a direct contact of the measurement equipment with the tested droplets.

a) Slide sampling method – is based on droplets deposition on a flat surface with a suitable structure. In experiments, the best results were obtained with the use of a layer of soot and a thin layer of magnesium oxide at the top. A droplet deposited on such a surface, similarly to a solid dropping into a soft layer of snow, creates a crater. The crater diameter is usually larger than the droplet diameter *D*. The relationship between these diameters is represented by the following empirical equation:

$$d/D=0.77\ We^{0.2},$$

where the We is Weber number.

b) Immersion liquid sampling method – many features of this method are similar to the above presented method but the properties of the sampling layer are different. The immersion liquid should be chemically neutral, transparent, should have the density lower than the density of the liquid being atomized, it should be immiscible with the atomized liquid and should be characterized by low surface tension. Droplets embedded in the immersion liquid are clearly visible and for that reason, the photographic method can be used for the purpose of their analysis. However, this method is affected by errors related to the droplets coalescence, the secondary droplets disintegration caused by collision with the liquid surface and droplets evaporation.

c) Droplets freezing method – liquid is atomizer in a cooling chamber and the droplets fall down on the chamber floor covered with liquid nitrogen. Also, probes cooled with liquid nitrogen can be used. Frozen droplets are then sieved (sorted) or photographed.
d) Needle probe method – two needles (electrode) are placed opposite each other in a spray of atomized liquid. A source of power and an impulse counter are connected to the needles and every moment that the needle tips get in contact through a droplet of fluid is recorded by the counter. Only the droplets with a parameter wider than the distance between the needles can make the tips of two needles meet. The distance between the needles can be changed throughout the measurement procedure. The disadvantage of this method is the closing of the whole circuit for the time 10 times longer than the time of a droplet passing which is the result of the needles bridging by the droplets owing to adhesion forces.
e) Gravitational classification method – the principle of this method is based on the analysis of differential penetration of droplets during their fall in a stationary environment. When a pressure atomizer is placed horizontally, a natural classification of droplets takes place, since large droplets will fall at a larger distance from the atomizer than the small ones. The droplets are „captured" on blotting paper (tissue paper), plates or flat vessels and weighed. This method can be applied in the case of not too large volume jets.

Contact methods are applied mainly in laboratory tests, and they are not used for industrial measurements due to the fact that they are too labour-intensive and time consuming. Additionally, there is no possibility to measure small-size droplets with the use of such methods.

2.2. Optical methods – Studies on the flow characteristics and average diameter of fuel droplets in a spray cone atomised by swirl injector

The currently preferred methods of measurement of microscopic parameters of an atomizer liquid spray are the optical methods. Despite the costs of measurement equipment are rather high the optical methods are less labour consuming and provide a high accuracy of measurement. Additionally, they shorten the time of the measurement duration.

The main function of an injector is to spray a suitable quantity of fuel to the combustion chamber to be atomised in such way that will enable its evaporation and formation of a homogenous fuel-air mixture to achieve the highest possible combustion efficiency. Adequate atomisation of the fuel should assure stability and continuity of the combustion process and should prevent the flame "blow-out" or extinguishing in all engine-operating areas. Additionally, it should guarantee proper distribution of exhaust emissions in a cross-section of the combustion chamber outlet.

However, during an internal combustion engine operation some deviations from the work parameters of particular injectors may be observed. The said changes of the parameter values refer mainly to:

- the change in the spectrum of the atomised fuel spray,
- the increase of the deviations from axisymmetrical distribution of the function characterising spatial distribution of droplets within a spay cone and the change in the flow characteristics.

In turbojet engines the changes of parameters may result in a deformation of the temperature field distribution in all cross-sections of the flow channel leading to the combustion chambers, as far as to the exhaust system, and in overheating of the turbine inner walls, drives and vanes. As a consequence of the malfunctions, a thrust loss and an increase in unitary fuel consumption are observed. Due to the above, it is a proper diagnostics enabling the selection of the most appropriate injectors that plays the key role here.

The methods of measurement of injector parameters can be divided into two types of tests, namely the tests of the macro- and micro-structure of atomised fluid. Control measurements of the fuel consumption $Q(\Delta p)$, spray cone angle $\alpha(\Delta p)$, peripheral spray cone irregularity $I(\Phi,\Delta p)$ and radial spray cone irregularity $I(r,\Delta p)$ are not considered to be a sufficient criterion for a satisfactory assessment of an injector as they do not take into account the information concerning the degree of the fuel spray atomisation.

Therefore, the information concerning the spray cone microstructure, i.e. the spectrum of the droplets diameters $p(D)$, their spatial distribution $D(x,y,z)$ and velocity $v(x,y,z)$ become extremely significant. The measurements of the sprayed fluid microstructure constitute a complicated experimental task due to extremely small dimensions of the tested objects and their time and space variability. Difficulties stem mainly from a large quantity of the droplets formed, a wide range of their diameters, significant diversification of the droplets velocity and the changes in their shape and size while in motion.

Tests on fuel aerosols characterised by relatively high measurement accuracy, short time of measurement duration, low labour-intensity in compilation of the test results and low costs of the measuring equipment are of major importance for the diagnostics of possible problems. The process should not significantly disturb the fuel spray itself. What seems essential here is a possibility to record the droplets with the diameter below 50 μm and to understand the spatial structure of an atomised fuel spray.

A great majority of the applied measurement methods only selectively comply with the above-specified criteria. An advantage of the photographic methods is the low cost of equipment while their significant disadvantage is a rather complicated data processing procedure. Similar difficulties in the data analysis occur when it comes to the holographic method enabling to obtain images of sprays with large droplets. Trace methods, despite not too complicated measurement techniques and relatively low testing costs, are affected by material errors.

Most of the above enumerated requirements are met by the diffraction method making use of the Fraunhofer's diffraction of a plane-parallel coherent light wave propagating through a spay cone. A light beam dispersed in a droplet produces characteristic diffraction rings the sizes of which are inversely proportional to the droplet diameter. A distinguishing feature of this method is the fact that the image generated by the droplets does not depend on their location within a spray, which enables measurements to be carried out while the droplets move at any speed. An advantage of the diffraction method is a short time of the diffraction images recording and a possibility to determine an average droplet diameter $D_{śr}(\Delta p)$ in a relatively large spray cone. However, the above-mentioned advantage eliminates a possibility for fully understand the spatial structure of the tested liquid spray. The diffraction method meets the following requirements:

- the environment of dispersion and the atomize liquid are optically homogenous and isotropic,
- the length of the incident light wave is equal to the length of the dispersed light wave,
- the droplets are circular in shape and their diameter is longer than the length of the light wave,
- an average distance between the droplets is a few times longer than the length of light wave,
- the mutual interaction between the waves diffracted on the neighbouring droplets is ignored,
- droplets are randomly distributed in space,
- a light wave undergoes diffraction only once.

The image of diffraction is influenced by all droplets present in the measurement space as the distribution of the light intensity recorded in the focal plane of the lens realizing the Fourier's diffraction image transformation is a superposition of the images created by each droplet. This forms the basis for the major characteristics of this version of the diffraction method based on summing up – and finally on averaging, which is done at the stage of physical phenomena. A simplification of the information concerning the spectrum of atomised spray $p(D)$ to the mean value $D_{śr}$ (arithmetic mean), sometimes referred to as substitute diameter D_z, constitutes some kind of limitation to this method, which, however, may prove to be its merit in the case of serial comparative testing. This particular feature of the above described diffraction method, together with the representativeness of the area of measurement, determines its usefulness in the diagnostics of the equipment producing fuel sprays.

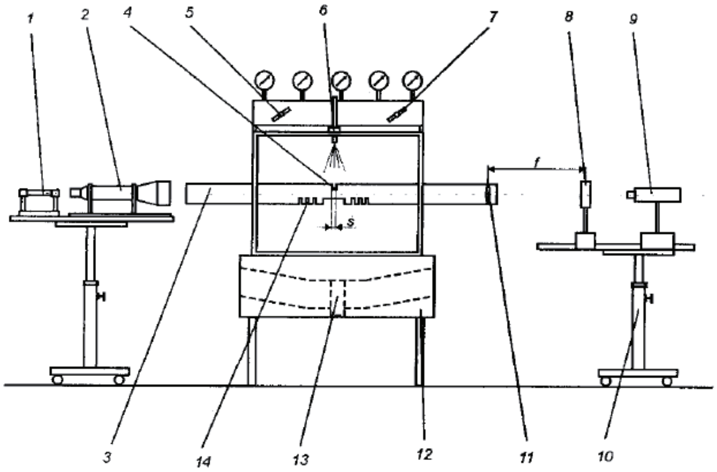


Fig. 2. Test scheme for the measurements of flow characteristics and of the average droplet diameter in a array cone of atomised by swirl injector; 1 – laser module; 2 – collimator; 3 – protective tube; 4 – inlet aperture; 5 – sprayed liquid regulation valve; 6 – injector (tested); 7 – air inlet valve; 8 – focusing screen in the imaging plane; 9 – camera; 10 – adjustment table 11 – lens for the Fourier's transformation; 12 – measurement chamber; 13 – liquid run-off from the measurement chamber; 14 – holes in the pipe

Three basic systems can be distinguished in the above presented test stand:

- the system generating a plane monochromatic wave,
- the measurement chamber,
- the system of diffraction images recording and processing.

3. Measurements of the fuel spray atomised by the CommonRail injection system

The Common Rail injection system equipped with the instruments for measuring the parameters of an atomised fuel spray:

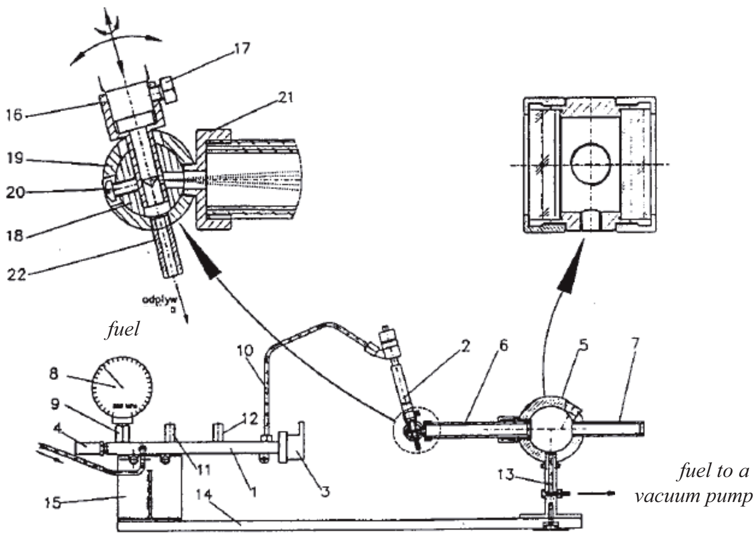


Fig. 3. CommonRail injection system equipped with the instruments for measuring the parameters of an atomised fuel spray; 1 – high-pressure fuel manifold; 2 – injector; 3 – pressure control valve; 4 – pressure sensor; 5 – visualisation chamber; 6,7 – transparent cylinder; 8 – manometer; 9 – manometer connector; 10 – high-pressure injection line; 11,12 – plug; 13 – visualisation chamber console; 14 – base; 15 – support of the high-pressure fuel manifold; 16 – injector socket; 17 – tightening screw; 18 – adjustable head, 19 – adjustable cylinder; 20 – tightening screw; 21 – fitting; 22 – fuel drain

The figure presents a test bench used for the measurements of atomised fuel spray parameters. The stand consists of a mechanical-electrical-hydraulic section and measurement equipment. The mechanical-electrical-hydraulic section includes the instrumented CR system consisting of an electric motor-driven high-pressure pump where the motor is equipped with an inverter enabling stepless adjustment of the motor rotation speed and consequently of the high-pressure pumps rotation speed . The high-pressure pump is fed with the fuel from the fuel tank by an electric fuel pump. The high-pressure pump forces the fuel to the manifold (1) in which the pressure is regulated with the use of a pressure control valve (3). The injector (2) is connected to the manifold (1) and is controlled electronically with the use of the system enabling the realization of single injections into the visualisation chamber (13). The fuel spray injected to the chamber is scanned with laser beams from the optical transmitter being part of the stand measurement equipment.

Measurements of the fuel atomisation parameters are carried out with the use of Phase Doppler Particle Analyser (PDPA) and the fuel droplets' velocity is measured with the use of Laser Doppler Velocimeter (LDV) which enables the measurements of droplet dimensions within the range from 0.5 μm to 1 mm, and of droplet velocity within the range from 0 m/s to 630 m/s, as well as the detection of turbulences. The measurement system is equipped with an argon laser, with the output power of 10 W, which makes it possible to carry out measurements in the areas of high droplets density, count the number of droplets in particular dimension groups, assess the distribution of droplets in a fuel spray, measure the droplets velocity, detect turbulences and calculate an average droplet diameter.

4. Visualisation of diesel engine fuel injection

The conditions in which measurements and visualisation of the fuel injection and combustion processes in a diesel engine cylinder are carried out require application of a slightly different measurement equipment from that used for the purpose of high-speed video recording systems applied in other branches of science. Specific requirements governing safe engine performance measurements comprise a necessity to protect the optical components against high temperature and to minimise the dimension of the endoscopic probe providing optical access to the combustion chamber. The fact that measurements can be carried out on any mass-produced engine seems to be the greatest advantage of endoscopy used in video recording of the injection process.

Application of the digital measurement systems, enabling storage and archiving of the images in the function of crankshaft rotation angle taken not during only one but during numerous engine operation cycles, is very useful for a reliable visualisation of the engine fuel injection process.

Optical access to the combustion chamber (or to any other location of images recording) is provided by the above-mentioned endoscope attached directly to the lens of the digital camera. Due to the fact that successive images are taken during various engine operation cycles the frequency of recording does not directly limit the angular distance of the successive exposures recorded. Consequently, the measurement system stores and files the images of the in-cylinder phenomena shifted only by a minimum crankshaft angle.

The values most commonly measured in the course of visualisation of the in-cylinder fuel injection process are the value of the in-cylinder pressure, the value of the injection system fuel pressure and the changes in the injector needle lift in the function of the rotation angle of the engine crankshaft.

Application of endoscopy in the video-recording of a diesel engine in-cylinder injection and combustion processes and the analysis of the recorded images make it possible to determine the whole range of parameters to be used for the purpose of cause-and-effect analysis of the observed phenomena, among others, of the actual start of fuel injection and the start of auto-injection, the fuel spray cone angle, the spray front penetration or the fuel spray area.

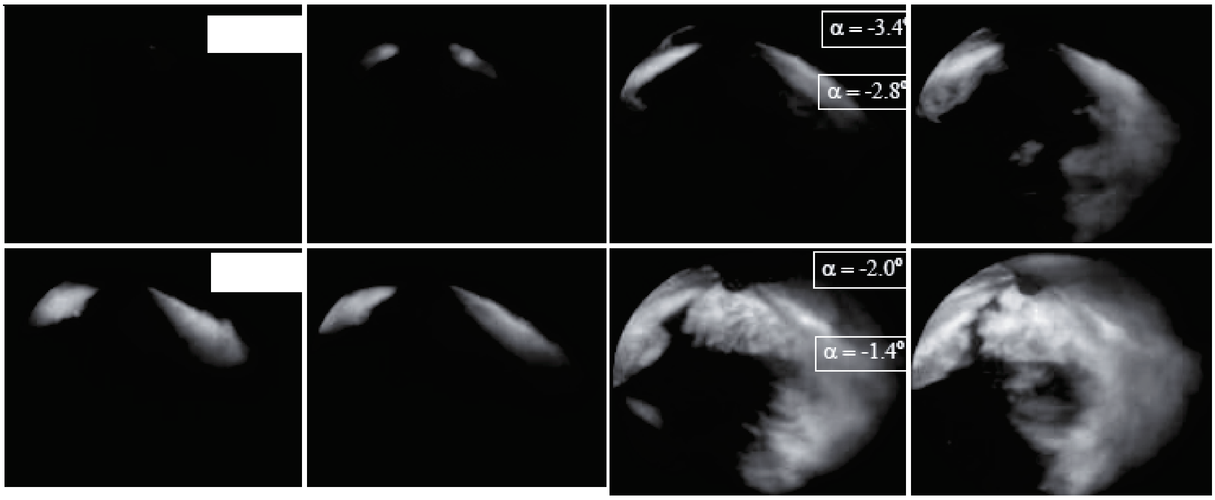


Fig. 4. A sample of the recorded injection and combustion process in a diesel engine cylinder for the selected rotation angles of the engine crankshaft

5.Summary

Application of the cutting edge technologies in the injector's production significantly increased the accuracy of their manufacturing accuracy and increased the repeatability of their parameters. Development of the modern measurement methods, measurement techniques and measurement equipment create new possibilities for measuring the parameters of injectors in the internal combustion engines. The present-day measurement technology enables to replace the measuring cylinders with extremely precise flow sensors making it possible to read off the test results at a randomly selected short time interval. Application of the contemporary digital technology together with the use of computers and the possibilities of image recognition would eliminate the subjectivity of the measurements. The degree of engine structure complexity and the tendencies to reduce its mass have resulted in an increase of their susceptibility to damage. Therefore, it seems that the mode of diagnosing the injectors based on the measurement of basic macroscopic.

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