ANALYSIS OF FUEL SPRAY PREPARATION FOR INTERNAL COMBUSTION ENGINES

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Abstract

In this paper the results of the drop size and its distribution in fuel spray produced by common rail and air assist systems of injection have been presented. Measuring equipment and testing have been described. The laser systems: LDV, PDPA and RSA have been applied to perform of the measurements. The results show that by applying the common rail system and air assist system can be obtain similar size dimension of droplet in injected fuel spray. Introduction of very high pressure direct injection in CI engines, GDI and air - assist systems in SI engines were beneficial from the view point of emission and fuel consumption.

1. INTRODUCTION

The most important challenge concerning future cars is today: excellent fuel efficiency, clean emissions and driving comfort. Growing awareness of global warning is a big problem for engine and car designers and manufacturers because the engines with a small efficiency are not accepted already. In order to prevent global warming the reduction of carbon dioxide, one of the greenhouse gases, is required. Reduction of CO_2 by cars requires to develop and promote the use of an automotive power plants that emits significantly less CO_2 and another pollutant composite of emissions than conventional engines with conventional fueling systems.

Effective combustion of liquid fuels in engines (compression ignition and spark ignition) is dependent on effective mixture preparation. Injection process is one of the most important in effective mixture preparation. The aim of effective atomization is increase the specific surface area of the fuel and thereby achieve high rates of mixing and evaporation in combustion chamber or in intake manifold. In the most combustion systems reduction in fuel drop size leads to higher volumetric heat release rates, easier light up, a wider burning range and lower exhaust concentrations of pollutant emissions. The most critical conditions are in direct injection process into combustion chamber because of very short time for evaporation and mixing of injected fuel. Drop size must be closely controlled to achieve the desired rates of heat and mass transfer. If the drop size in combustion chamber are very small they must fill all volume because their energy is small and mixing process is difficult. Very small droplet can contribute to nitric oxides emissions. Fueling systems have dominantly influence on mixture preparation process in spark ignition and compression ignition engines.

Introduction of very high pressure direct injection in CI engines, GDI and air - assist systems in SI engines were beneficial from the viewpoint of emissions and fuel consumption. The common rail systems is the answer on the need of low fuel consumption and low exhaust emissions Common rail refers to the single fuel injection line on the engine, whereas conventional direct injection Diesel engines must repeatedly generate fuel pressure for each injection. In common rail engines the pressure is buildup independently of the injection sequence and remains permanently available in the fuel line. Common rail injection systems are the biggest recent technical advance. The future of compression ignition direct injections engines is the common rail approach. This rail system permit to obtain higher specific output, lower fuel consumption, much reduced noise and generally improved characteristics. Specific power and torque are increased by approximately 40 percent compared with indirect injection Diesel engines, while specific fuel consumption is 30 percent better (and therefore carbon dioxide emissions). The main advantage of a common rail systems is that there is no relationship between engine speed and injection pressure. In conventional fuel injection systems only limited pressure can be generated at low engine speed. In addition high speed engines offer reduced time for fuel and air mixture preparation. But common rail system can generated high pressure already at a low engine speeds which is limited by power of the fuel pump only. It seems that common rail injection systems will be instrumental in engineering Diesel engines that will comply with future emission regulations. Those systems use multiple injections per combustion stroke to control emissions. The interval between the end of the pilot injection and the start of the main injection is today so short as 0.7 milliseconds. Today efforts are directed to increase number of injections per combustion stroke to five, from present two, and raising the maximum pressure to 200 MPa, from the present 150 MPa.

GDI system appears to be less beneficial from the viewpoint of emissions and fuel consumptions than suppose earlier, while the cost of injection systems and associated, complex catalytic systems is high. The high fuel economy of the GDI engines is achieved by elimination of the pumping losses associates with throttling the intake system. Completely elimination of a throttling would imply that the air fuel ratio could exceed 50:1 under light loads. The GDI system, in real conditions operates with a small throttling, under low speed and light loads parameters, and the air fuel ratio is between 30:1 and 24:1 because this makes engine control easier and speed variability smaller. The problem is that many current GDI systems suffer from increased row engine emissions levels, which leads to a high dependence on the exhaust aftertreatment system. Not only are row emissions higher, but exhaust gas temperatures are typically lower when running lean which is not conductive to high catalyst conversion efficiency. Added to this is the fact that when running lean, NO_x reduction becomes difficult in comparison to conventional port injected engine after treatment systems. Hence some doubts, recently accompanying the opinions - coined several years ago [6] - about future general use of such systems. It appear that equally beneficial from the point of view of fuel consumption and exhaust emission is the system of injection into intake manifold, which is much less complex and expensive, both in terms of its manufacture and operation. Thus, the prospects of expansion of uses of such systems are growing.

This paper discuses the results of examination of fuel injection systems with the use of a laser systems: laser Doppler velocimeter (LDV), a phase Doppler particle analyzer (PDPA) real time signal analyzer (RSA). The injection systems examined were: air assisted, pressure type, used primarily for injection into intake manifolds of SI engines and another one used for common rail type direct HP injection into CI engines. The results of the experiments show that high pressure common rail system as well as air assist system produce of fuel droplet with similarly small dimension. In the last years air assist system was applied to the mixed operation:

in port injection and in direct injection to combustion chamber system simultaneously for better controlling of exhaust emission and fuel efficiency.

2. APPARATUS

The instrumentation used for the present work is basically a dynamic laser Doppler analyzer of particle dimensions and velocities. It is composed of three systems: LDV - the 3D velocity measurement, PDPA - a particle size measurement system and RSA - a real- time signal analyzer. The systems allow to measure the sizes of particles ranging from 0.5 mm to 2mm and the velocities within 0 - 630 m/s. Computer software is used for controlling the course of measurement and for real - time data acquisition. In the Fig.1 and the Fig.2 the system are presented.

Fig. 1. *Laser source of monochromatic light beams*

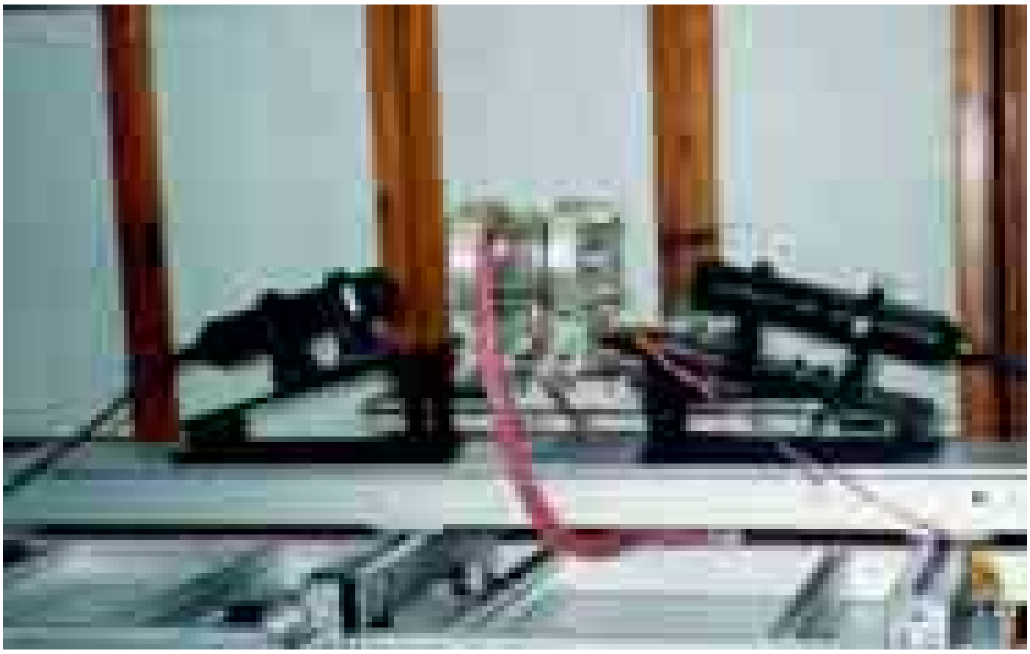

Fig. 2. *Power measurements of laser beams*

Measuring system include: a 10W argon-ion Spectra Physics laser as the source of monochromatic light beams (green – 514.5 nm, blue 488 nm and violet – 476.5 nm.), a Bragg's cell drive, transmitter, receiver, detectors and real time signal analyzer. Detailed data concerning of the equipment can found in references [22]. Fuel spray from an injection system under examination is injected into the measuring chamber located between the transmitter and the receiver. Both the transmitter and receiver are mounted on an x-y coordinate bench, capable of moving relative to the measuring chamber in x-y plane. The bench movements are controlled automatically by a computer program, or manually from keyboard. Thus, the spray examination may be performed to a programmed sequence. The data acquisition system comprises a PC, monitor and printer, allowing a visual presentation of results or a printout. The real dimension of each droplet is proportional to the phase shift of two laser beams, whereas the velocity of droplets is proportional to the Doppler's frequency.

The software calculates various kinds of droplet diameters, namely: D_{10}, $D_{20,}$ $D_{30,}$ $D_{32,}$ D_{43}. Differences in droplet mean diameter values indicate homogeneity of a fuel spray. If the differences between D_{10} and D_{32} values are small – the dimensions of individual droplets in the fuel spray are close to each other. Large differences between D_{10} and D_{32} values signify a wide spread of droplet dimensions in the spray.

The Sauter and Herdan mean diameters are most important from the viewpoint of engine combustion processes. The Sauter D_{32} mean diameter is a valuable indicator in heat and mass transfer analysis, while the Herdan D_{43} mean diameter is mostly used in the analysis of combustion processes. The phenomena occurring in the combustion space of a cylinder: mixture formation and combustion are sufficiently complex to make every additional tool of their evaluation helpful. This is certainly true with reference to the laser Doppler instrumentation.

3. MEASURING SET-UP

The set-up used in the measurements of fuel atomization by a common rail system injector ranged within 30-130 MPa is shown in Fig.3. It comprises the measuring instruments (LDV, PDPA and RSA systems), an electro-mechanical part (injection pump drive), hydraulic system generating the spray of injected fuel and measuring chamber [10].

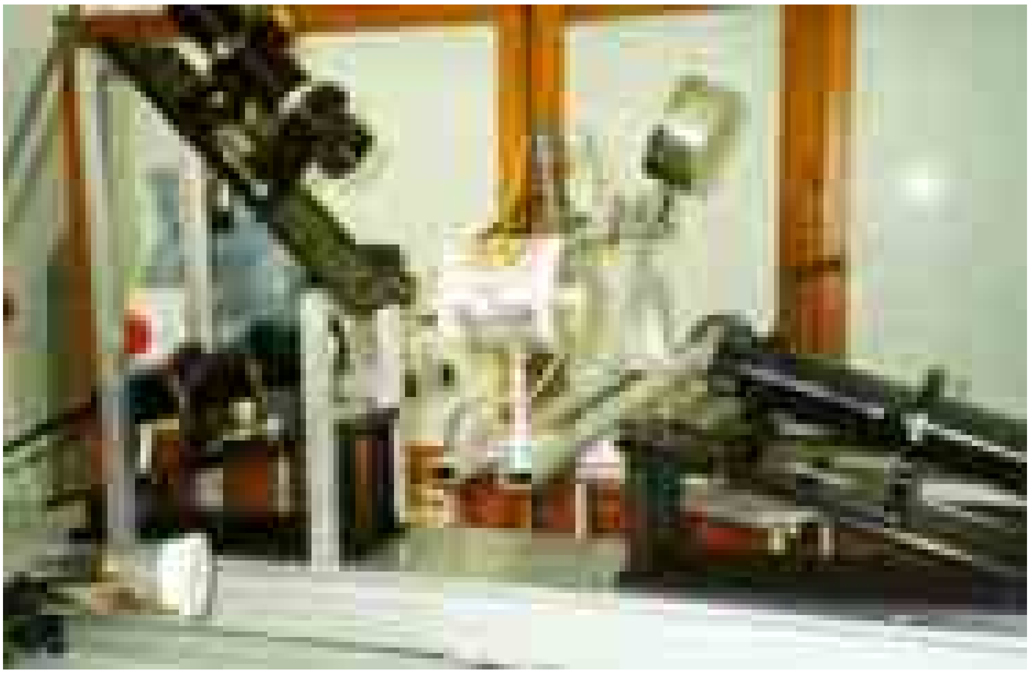

Fig. 3. *Set up used for measurements of common rail fuel sprays*

Test chamber is located in the dedicated space between laser beam transmitter and laser beam receiver. The measuring chamber is furnished with two quartz windows, providing optical access to its inside. Injector mounted in a holder may vary of the injector position, which produces fuel spray. Fuel is fed from tank by low-pressure pump to high-pressure pump. Then it passes through a system of high-pressure lines to the common-rail high-pressure accumulator, from which it is transferred to the injector. Solenoid valve to control the pressure in high-pressure accumulator, indicated by pressure gauge. Valve is operated from power supply. Power supply and electronic control system are used to put in operation the injector solenoid valve. High-pressure pump is driven by electric motor, a variable speed drive. The pump with its drive, the high-pressure accumulator, injector and measuring chamber remain fixed to a rigid foundation. The measuring system including the laser beam transmitter and receiver can be moved relative to that foundation, allowing to vary the point where a fuel spray is penetrated by the laser beam. By moving the optical system manually or automatically it is possible to perform measurements at specified points of a fuel spray. Although it remains a tedious task to analyze the spatial distribution and time variation of spray parameters, the outcome possible with the use of the laser droplet size and velocity analyzer are a large step forward in comparison with the less sophisticated tools used not long ago.

Measurements carried out on petrol low pressure affair assist injection systems involved the same arrangement of the dynamic, laser Doppler particle size and velocity analyzer as in the measurements on the HP common-rail injection system for CI engines. The design of measuring chamber and the fuel supply system were different. Instead of a complex mechanically driven pump, the fuel was fed from a pressure vessel (pressurized fuel accumulator) with an air cushion controlled by a system of pressure reducing valves. A diagrammatic arrangement of the fuel supply system is shown in Fig.4. Fig.5 is a photograph of the measuring set-up with a part of measuring system and the measuring chamber.

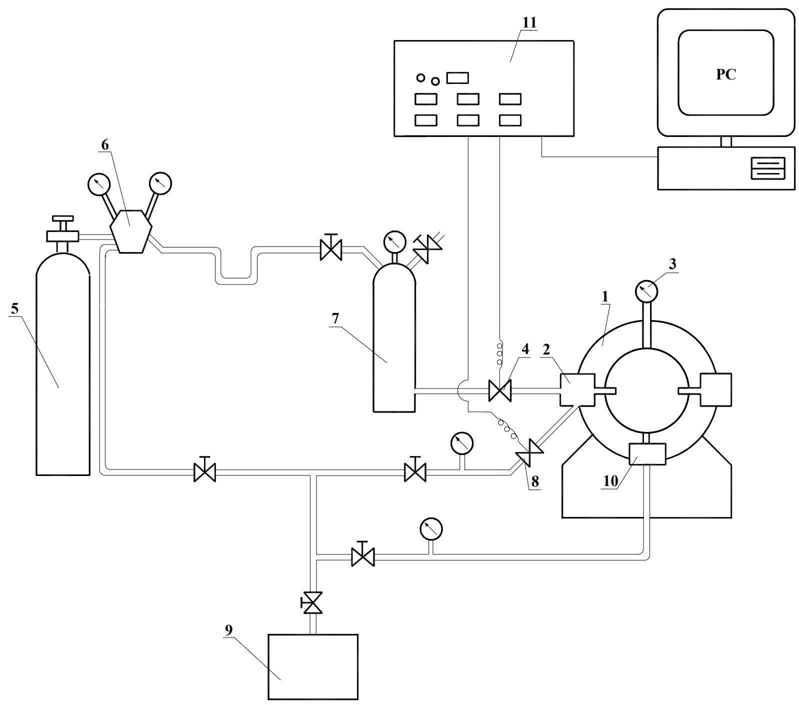

Fig. 4. *Arrangement of fuelling system for air-assist atomizer testing*
1 - test chamber, 2 - atomizer, 3 - manometer, 4 - fuelling solenoid valve, 5 - compressed air cylinder, 6 - reducing valve, 7 - pressurized fuel accumulator, 8 - solenoid valve of air-assist system, 9 - vacuum pump, 10 - connector, electronic control module

Fig. 5. *View of set up with test combustion chamber*

Cylindrical measuring chamber 1, shown in Fig.4, is furnished with quartz windows allowing optical access to its inside. There are holes in the chamber walls, to accommodate the injector tested, spark plugs and manometer 3 allowing measuring pressure inside the chamber. Additional connection 10 is used to fill the chamber with compressed air or empty it with the use of a vacuum pump 9. Fuel is fed to the injection system under examination, from pressure vessel 7, through solenoid valve 4. Air cushion in vessel 7 is maintained by supplying compressed air from cylinder 5 via pressure reducing valve 6. The air assist in fuel atomization is fed to the injector through solenoid valve 8 and a reducing valve 6 for pressure control. Control unit 11 enables selecting injection time. It may also control ignition in the chamber, if combustion is included in a measuring run, or operate a camera recording the injection process. For measurements in dynamic conditions, a pressure gage indicating the measuring chamber pressure is mounted instead of manometer 3. The course of pressure variation and other control variables may be pre-set and recorded using a PC.

4. RESULTS OF MEASUREMENTS

The results presented below refer to tests conducted on a common rail injection system and a low pressure, air-assisted petrol injector.

4.1. Common rail system testing

The measuring runs carried out on the monorail system consisted in determination of mean diameter values as function of injection pressure in different cross-sections of the fuel spray. An injector was especially modified for that purpose, so that only a single jet of fuel entered the measuring chamber. Fuel issuing from two remaining orifices was conducted to a separate collecting vessel. The results shown represent averages from three measuring runs at least.

Values of the measured droplet mean diameters as function of injection pressure have been plotted in the Fig.6.

As may be seen from the presented results, pressure increase from 30 MPa to 130 MPa caused a reduction of fuel drop diameter, namely a twofold reduction of the value of D_{10} diameter and a fivefold reduction of D_{32}. A convincing evidence of increased spray homogeneity followed from the fact of D_{32} values approaching those of D_{10} as the pressure increased. The effect of pressure was most pronounced in the range of variation 30 MPa to 90 MPa, where a step reduction of D_{32} diameter value is observed, together with its fourfold reduction.

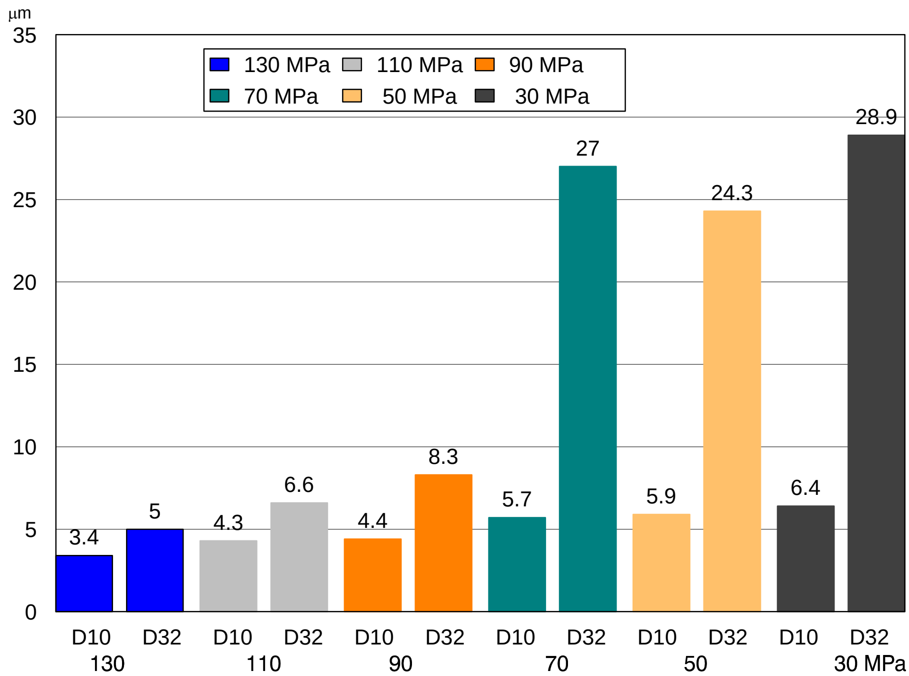

Fig. 6. *Average values of measured mean diameters D_{10} and D_{32} for common rail injector*

The same variation became a monotonous one at pressures beyond 90 MPa, and the reduction of D_{32} and that of D_{10} were close to each other. In terms of the ratio of diameter values at 130 MPa and 90 MPa the reduction was limited to about 0.8 for D_{10} and to about 0.7 for D_{32}. The character of mean diameters versus pressure variation as plotted in the graphs allows to conclude that although the noted increase of the spray homogeneity with injection pressure will continue beyond the pressure limit tested, it will be much slower and may not justify the technical effort and difficulties faced when applying pressures still higher. One should, however, remain cautious in drawing general conclusions from the examination of a single injection system. Certain difficulties experienced when testing the HP injection system were caused by a short duration of injector action and the necessity of removing the tiny droplets remaining in the measuring chamber after each action. With imperfect emptying of the measuring chamber, the remaining droplets of the same size as the ones produced by the injector could affect the results of measurements.

4.2 Measurements on LP petrol injector of air-assist type

The sizes of droplets obtained from air-assist type injectors may be as small as those produced by the HP injectors in common rail system. The air-assist injectors are designed to inject petrol into intake manifold of an engine. They can operate as continuous or cyclic injection devices, the duration of injection period being longer than for the common rail system even in the cyclic mode of operation. This causes the number of droplets counted in every single measuring run to be very large. The measurement results of droplet diameters as a function of injection pressure refer to a conventional petrol injector are presented in Fig.7, whereas the results of Fig.8 – to the air examined air-assist injector.

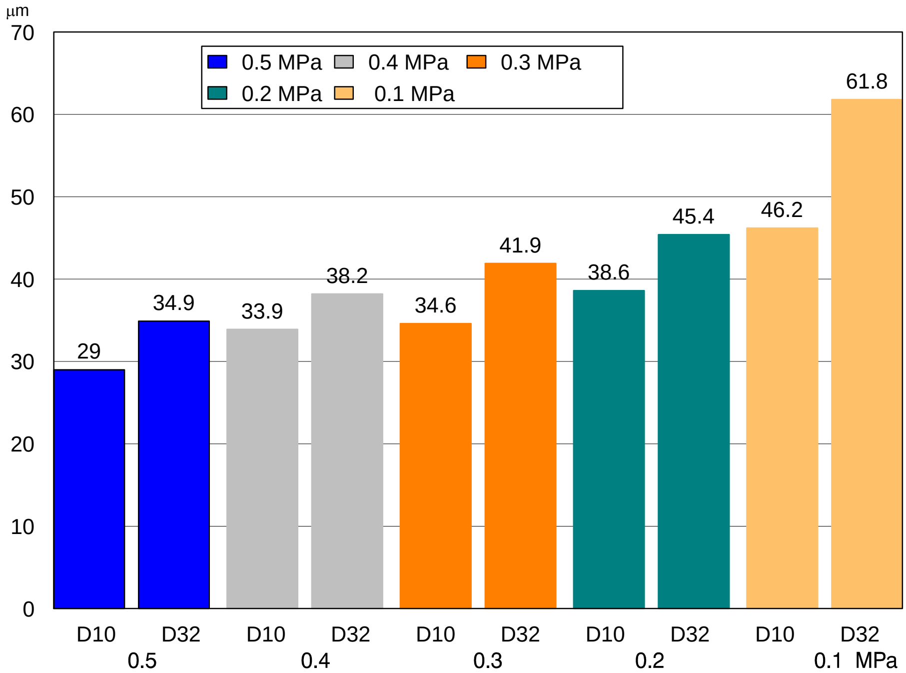

Fig. 7. *Average values of measured mean diameters for conventional atomizer*

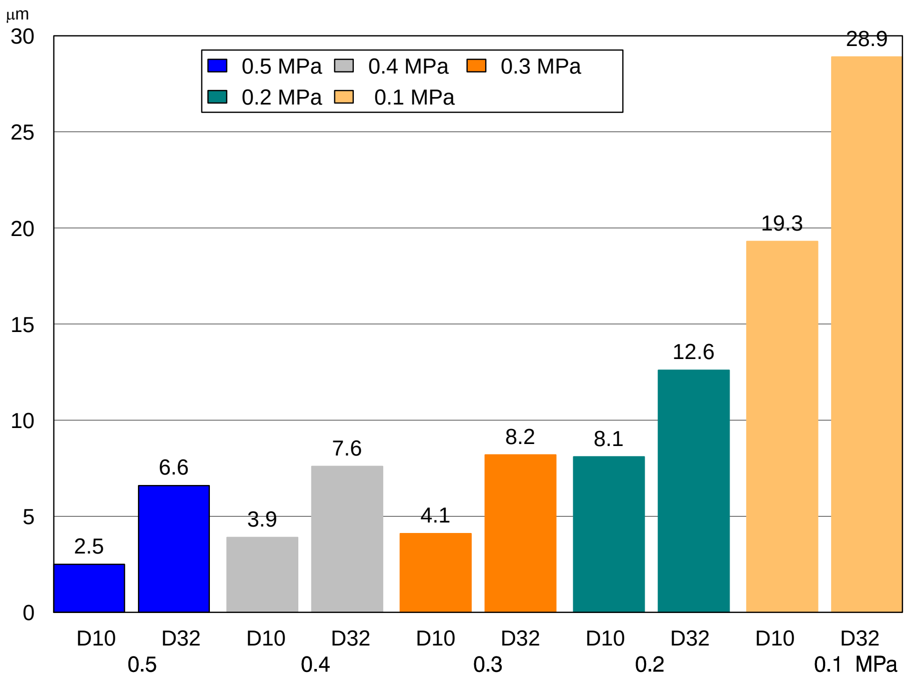

Fig. 8. *Average values of measured mean diameters for air-assist atomizer*

From a comparison it is evident that spray generated by the conventional injector is relatively homogeneous but with drop diameters much larger than those produced by the air-assist injector. The effect of pressure on the drop size is much more pronounced for the air-assist than for the conventional injector. Taking the pressure variation range 0.1 MPa to 0.5 MPa one can note that for the conventional injector D_{10} is reduced 1.6 times and D_{32} 1.8 times. With the same pressure increase the figures for the air-assist injector are D_{10} reduced 7.8 times and D_{32} reduced 4.4 times. One should conclude that the higher injection pressure yields a non-homogeneous spray, although it is composed of very small droplets. Another observation is that injection pressure increase is not the only means of producing fine atomization. It may be necessary to combine high injection pressure with small droplet sizes in CI engines, because the duration of injection has to be very short and there may be no sufficient time for the jet of fuel to develop if the pressure was lower.

It was also noticed during the testing of air-assist petrol injectors of cyclic operation that a large drop of fuel may be seen forming frequently when the injector nozzle is closing. The presence of such large drop may affect the injector properties, with possible adverse influence on engine performance.

5. CONCLUSIONS

The measurements carried out on a common rail injection system and an air-assist type injector allow to draw the following conclusions:

1. Producing very small droplet sizes, of the order of 2-4 μm is possible with the both examined types of injection system.
1. For the common rail CI engine injection system, the injection pressure increase from 30 MPa to 130 MPa produced a reduction of mean droplet diameters D_{10} and D_{32}. Relative value reduction was more pronounced for D_{32} than for D_{10}, indicating increased spray homogeneity.
2. Pressure increase from 30 MPa to 130 MPa for the common rail injection system resulted in D_{10} reduction 1.9 times and D_{32} reduction 5.1 times. The ratio of D_{32} to D_{10} value was 4.5 at 30 MPa and only 1.6 at 130 MPa, providing a strong evidence of spray homogeneity in the latter conditions.
3. Taking the ratio of D_{32} to D_{10} mean diameter as a measure of non-homogeneity of drop sizes in a spray, for the air assist type of injector the ratio amounted to 1.50 at the lower from the test pressure values (0.1 MPa) and to 2.7 at the higher one (0.5 MPa). This indicates a wider range of droplet sizes for higher pressure, no matter how small the size. The trend was opposite for the conventional injector. Although with droplets several times bigger than those produced by the air-assist injector, growing pressure resulted in increasing spray homogeneity.By confronting the results of spray measurements with engine performance data, it is possible arrive at answers to some basic questions of the type of how to organize the process of mixture formation in order to optimize engine parameters, especially its economy and environmental impact.

References

[1] Arndt P., Putz W.: Der neue Vierzylinder - Dieselmotor OM 611 mit Common Rail - Einspritzung. MTZ, 12/1997.

[2] Bachalo W. D.: Injection, Dispersion and Combustion of Liquid Fuels. 25th Symposium (International) on Combustion / The Combustion Institute, 1994.

[3] Będziński R., Jankowski A., et al.: Application of Modern Optical Methods in Experimental Investigation of Phenomena Occurring in Internal Combustion Engines. Journal of Polish CIMAC. Vol.1, No.1, Warsaw, 1994.

[4] Cooperative Emissions Programs Grow. Technology Today. March 1994.

[5] Fraidl G. K., Piock W. F., Wirth M.: Gasoline Direct Injection: Actual Trends and Future Strategies for Injection and Combustion Systems. SAE Paper 960465, 1996.

[6] Hochstad H., Arnall D.: To DI for „Homogenous Charge is the Best Way to Provide the Highest Engine Power”. Engine Technology International. January 2001, Issue 4/00.

[7] Hoffman K., Hummel K., Maderstein T., Peters A.: Das Common - Rail Einspritzsystem ein neues Kapitel der Dieseleinspritztechnik. MTZ, 10/1997.

[8] Jankowski A., Sęczyk J., Siwiec S.: LDV Measurement of the Flow Field in the Swirl Chamber with Combustion. Proceedings of 3rd Japan - Central Europe Joint Workshop. Bratislava, Slovakia, 1998.

[9] Jankowski A., Sęczyk J., Wolański P: The Preliminary Investigations of Fuel Injection with Air Assisted Injector in Constant Volume Bomb (in Polish). Proceedings of International Scientific Conference on Internal Combustion Engines ”KONES’93”. Gdańsk - Jurata, 1993. ISBN 83-900666-1-0.

[10] Jankowski A., Sęczyk J., Zbierski K.: Measurement of the structure Fuel Spray Produced with the Common Rail System (in Polish). Journal of KONES. Vol.7, No.1-2, Warsaw - Lublin, 2000. ISBN 83-900666-6-3, ISSN 1231-4005.

[11] Jankowski A.: An Investigation of the Mixture Preparation by Laser Doppler Method (in Polish). Journal of KONES. Vol.2, No.1, Warsaw, 1995. ISBN 83-900666-4-5, ISSN 1231-4005.

[12] Jankowski A.: Investigation of the Fuel Injection Process in the Constant Volume Chamber (in Polish). Journal of KONES. Vol.2, No.1, Warsaw - Lublin, 1994. ISBN 83-900666-3-7, ISSN 1231-4005.

[13] Jankowski A.: Laser Doppler Measurements of the Spectrum of the Atomized Fuel Spray Generated by a Low-Pressure Injector (in Polish). Journal of KONES. Vol.5, No.1, Warsaw - Gdańsk, 1998. ISSN 1231-4005.

[14] Krenkiel D.: Diesel Injection Systems to meet Future Emission Levels. XXIII International Scientific Conference on Combustion Engines ”KONES’97”. Bielsko - Biała, 1997.

[15] Lefebvre A. H.: Atomization and Sprays. Hemisphere Publishing Corporation. New York, 1989.

[16] Lefebvre A. H.: The Role of Fuel Preparation in Low - Emission Combustion. Transactions of the ASME. Journal of Engineering for Gas Turbines and Power. Vol.117, October 1995.

[17] Maly R. R.: State of the Art and Future Needs in S.I. Engine Combustion (Invited Topical Review). 25th Symposium (International) on Combustion / The Combustion Institute, 1994.

[18] Su T. F., Chang C. T., Warrick C. B., Farrel P. V.: Recent Measurements of Fuel Injection System. Journal of KONES. Vol.2, No.1, Zakopane, 1996. ISBN 83-900666-5-3, ISSN 1231-4005.

[19] Su T. F., Coil M. A., Farrel P. V.: Two-Dimensional Optical Methods for Spray Diagnostics. Journal of KONES. Vol.2, No.1, Warsaw - Lublin, 1994. ISBN 83-900666-3-7, ISSN 1231-4005.

[20] Zbierski K.: Study of Time Histories of fuel Pressures and Movements of Nozzle Needle in Injection Systems of Compression Ignition Engines (in Polish). Scientific Bulletin of Łódź Technical University. Nr.850, Łódź, 2000. ISSN 0137-4834.

[21] Zhao H., Ladommatos N.: Optical Diagnostics for In-Cylinder Mixture Formation Measurement in IC Engines. Progress in Energy and Combustion Science. Vol.24, No.4, 1998. Elsevier Science Ltd. ISSN 0360-1285.

[22] Jankowski A., Sandel A., Siemińska - Jankowska B., Sęczyk J.: Measurement of Drop Size Distribution in Fuel Sprays by Laser Methods. Journal of KONES. Vol.8, No.3-4, 2001.