PRELIMINARY RESEARCHES OF INFLUENCE OF DIFFERENT LOADS ON WORKING CONDITIONS AND PERFORMANCES OF THE PISTON COMBUSTION ENGINE WITH DIRECT FUEL INJECTION

Barbara Jankowska-Sieminska

Institute of Aeronautics
Al. Krakowska 110/114 02-256 Warsaw, Poland
tel.+48 22 846 0011, fax: +48 22 846 4432
e-mail: kones@ilot.edu.pl

Antoni Jankowski

Institute of Aeronautics
Al. Krakowska 110/114 02-256 Warsaw, Poland
tel.+48 22 846 0011, fax: +48 22 846 4432
e-mail: kones@ilot.edu.pl

Marcin Slezak

Motor Transport Institute
ul. Jagiellonska 80, 03-301 Warsaw, Poland
tel.: +48 22 6753058, fax: +48 22 811 0906
e-mail: marcin.slezak@its.waw.pl

Abstract

The most of research works with reference to piston engines with the direct fuel injection concentrate on two basic systems . One system is a homogeneous system and refers to high engine loads both from the point of view of torque and rotational engine speed. The second system refers to small loads and rotational engine speeds which usually do not exceed 50 % of the maximum allowable loads and the rotational speed.
These systems were an object of the analysis and research with use of the laser-equipment , mostly the PDPA and LDV. For the comparison only the PIV research were brought over. In brought over analysis one returned the special attention on stratified combustion, homogeneous combustion, water injection and water fuel emulsions, heat exchange.

In particular research injectors, the combustion space of the constant of the volume with 3D laser equipment (PDPA, LDV), results of researches of fuel spray concerning droplet diameters, results of researches of fuel spray concerning droplet distribution of lineal and volume, and dependences Rosin-Rammler, results of researches of fuel spray concerning distribution of 3D droplet velocity, results of the analysis of combustion rate and impulse for fuel spray are presented in the paper. The obtainment of small droplet dimensions is possible in the way increasing of the injection pressure. However high increasing of the pressure unfavourably bears on life of fuel equipment. From other methods one can mention methods mechanical improvements of spraying of the fuel. One of mechanical methods stayed put-upon in research of the ignition process.

Keywords: *combustion engines, direct fuel injection , mixture preparation* processes *, homogeneous strategy , heterogeneous strategy, laser-methods*

1. Introduction

The most of research works with reference to piston engines with the direct fuel injection concentrate on two basic systems . One system is a homogeneous system and refers to high engine loads both from the point of view of torque and rotational engine speed. The second system refers to small loads and rotational engine speeds which usually do not exceed 50 % of the maximum allowable loads and the rotational speed (Fig. 1). This system is a heterogeneous system. Ideas relating to two names are speculative ideas and Ideas relating to two names are speculative ideas and essential conditions occurring in an engine significant differ from homogeneous conditions and heterogeneous ones, where also homogeneous areas are visible.

The first system, the homogeneous system, is also characterized that it can be applied both with reference to Diesel and a spark-ignition engines. This system is characterized with the early fuel injection, usually during the intake stroke. So there is a lot of time for proper (homogeneous) preparation combustion mixture which should be homogeneous. However even uniform distribution of the fuel in combustion chamber does not give the full view of qualitative and quantitative preparation of the mixture. The quality of injected fuel spray has a very big meaning for obtainment of correct work parameters of the engine referring to torque, fuel consumption and emission level of exhaust gases. Preliminary researches showed that the quality of injected fuel spray having very essential importance for the obtainment of suitable parameters engine work was name only homogeneous spray, and practically her homogeneity refers to the macro scale. Such approach for the problem is a strong simplification. Such approach for the problem is a large reduction, if the accepted name of the homogeneous charge has to be applied. Uniform fuel distribution in combustion chamber differs only this system from second one, where fuel can be not uniform distributed in combustion chamber and can also appear areas where there is not fuel at all.

In the second work system, the heterogeneous system, fuel is heterogeneously distributed in combustion chamber. In this system of engine work, fuel injection occurs close to end-point phase of compression stroke. So, there is a little time for combustion mixture preparation . However in the zone of the mixture ignition should be homogeneous, and fuel spray should be characterized with small dimensions of fuel droplets. This refers especially for so called "the cold" ignition which at the heterogeneous mixture can not appear or miss fire will appear, what negatively affects on engine economic parameters and emission level of exhaust gases. In this second system the exchange and thermal conditions have essential influence on the correct process run of the combustion and emission level of exhaust gases.

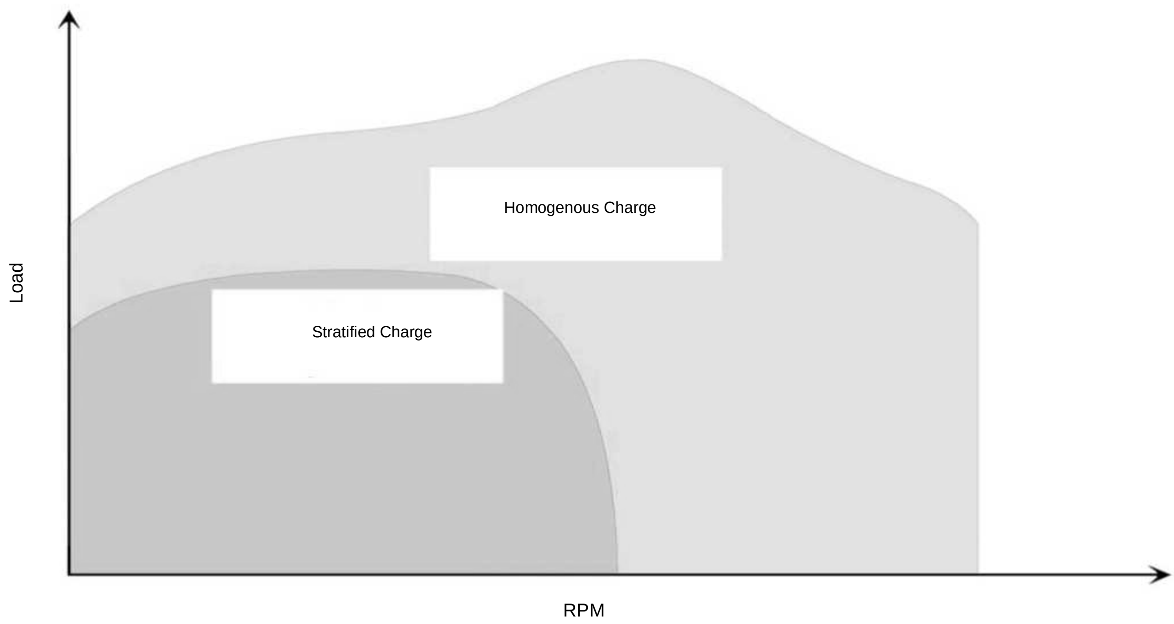


Fig. 1. Two strategies of the power supply of with the spark-ignition engines with the direct-injection: the stratified charge at small loads and rotational speeds and the homogeneous charge at big loads and rotational speeds of the engine

The heat flux passes from charge across a boundary layer of thermal resistance on the wall of combustion chambers (cylinder liner, cylinder head and piston crown), itself wall, the boundary layer of thermal resistance on the outer side of combustion chamber to cooling fluid cylinder wall and head, and on a other piston side, an oil-layer from a oil sump. Heat lost in cooling system of the walls is the row of 15 - 20 % heat supplied in fuel, and with reference to the rated power of the engine it takes out of 40 - 50 % and even more. The temperature on boundary surfaces of the layers spreads according to thermal resistances of these layers. From the point of view of the cycle of the highest efficiency, the charge temperature should be the maximal (but on the walls not higher than acceptable one of the wall material; novel materials, eg. ceramic, let on application of high temperatures). On the other side the temperature cooling fluid is settled automatically on several degrees below boiling heats cooling fluid. The barrier layer of cool charge on internal walls of combustion chambers is so advantageous from point of view of engine efficiency. Charge is swirled, what provides charge exchange and restore of the barrier layer. Too intensive swirl influences however unfavorably on combustion processes and besides the high temperature bears on the NO_x emission level. On conditions of heat exchange in combustion chamber of the piston-engine, and what to these is going run of combustion processes, engine performance and level emission of combustion gases influences the water injection and exhaust gases recirculation (EGR), what one ought to take into account in analysis of present-day combustion engines.

Explored experimental included derivation of homogeneous fuel spray for the homogeneous system , estimation of the fuel spray homogeneity by means of special analytical methods, the mathematical description of experimental data by means of different dependences, and determination of the best description of the fuel spray quality. In reference to different fuel sprays, the best qualitative description according to brought over research has been obtained by means of the Herdan diameter (D_{43}).

2. Stratified combustion

In ideal case the engine is operated without throttle and with lean overall mixture. The direct injection for SI engines with stratified operation combines the improvement of charge cycle and thermal efficiency (Fig. 2.). Therewith the direct injection is the most promising engine-related measure regarding fuel efficiency. However stratified operation in early stages was limited on a small area in the engine map. The stratified engine map is limited to small engine speeds and low loads because of the dependency of the mixture process on the piston position and because of unreliable inflammation under some conditions. Consequently the benefit in fuel consumption is limited on this small engine map which is hardly used in the real drive cycle. Further the fuel consumption benefits are reduced by extended wall wetting on the piston surface leading to considerable energy loss. Another difficulty of all lean burn engines is the exhaust gas aftertreatment with regard to the reduction of NOx emissions. Therefore the NOx storage catalysts are used mostly in combination with an intermittent lean-rich engine operation. While the engine is running lean the NOx is stored in the catalyst until the storage capacity is reached. Then the engine is switched to rich operation to enable a regeneration of the catalyst. Especially at higher loads high NOx raw emissions occur at stratified operation so that switching from stratified to homogeneous mode achieves a higher overall efficiency. To allow a reduction of the regeneration frequency of the catalyst and to enable stratified operation at higher loads, the engine development should be focused on the reduction of the NOx emissions. These engines achieve a benefit in fuel efficiency mainly by downsizing effects while using the very efficient 3-way catalyst technology. A lot of investigations shown that the stratified operation map may be larger for the next generation of direct injection engines. These engines are realized with a spray guided idea. Due to a narrow arrangement between spark plug and injector the mixture process is not supported by the piston surface. The mixture process is nearly independent of the piston motion. This leads to a significant reduction of piston wall wetting. Further the ignition and combustion timing can be adjusted regarding thermal efficiency concerns instead of mixture process requirements.

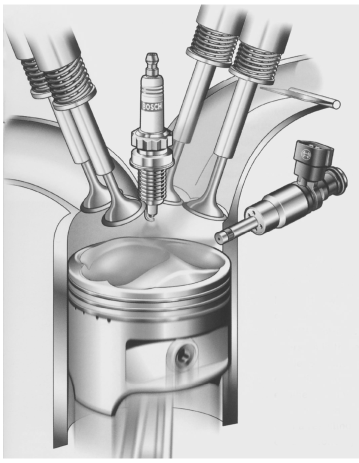


Fig. 2. The strategy of the power supply of engines with the spark-ignition direct-injection: the stratified charge at small loads and rotational speeds of the engine

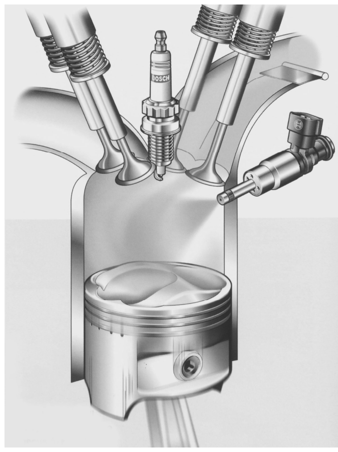


Fig. 3. The strategy of the power supply of engines with the spark-ignition and direct-injection: the homogeneous charge at big loads and rotational speeds of the engine

The advantage is that no defined charge motion is required to enable the mixture transport as necessary for air-guided concepts. Consequently charge motion strategies can be involved to support the combustion and fuel evaporation specifically. The advantages of the spray guided combustion concept can be enhanced further with the combination of turbo charging and increased injection pressure. Further the direct injection allows a comparatively high compression ratio even for turbocharged engines because the knock tendency is reduced. Compared to natural aspirated engines the increased air-mass in case of the turbocharged engines allows an extension of the stratified engine map leading to a benefit in fuel economy. Another advantage of turbo charging is the increase in power at full load operation.

3. Homogeneous combustion

The homogenous combustion strategy has potential to reduce NOx, PM emissions and improve part load engine efficiency. It is suitable for a variety of fuel types (Fig. 3.). However, to achieve a successful application, problems such as control of ignition timing and heat release rate over the entire engine operation range, have to be solved. Homogenous combustion needs an essential ignition temperature. The methods used to achieve such a temperature have to be able to manage the rate of heat release followed by ignition and avoid extreme sharp pressure increases.

The results obtained from experimental investigations and theoretical simulation studies have indicated that the control over homogenous combustion can be achieved with lean mixtures in a limited range (λ >2) by using various engine control strategies and air/fuel mixture modifications. Variable Compression Ratio and valve timing technologies are potential control technologies for homogenous combustion. Late fuel in cylinder direct injection can be an ideal strategy for homogenous combustion with heavy fuels, such as diesel at low loads. Since the main ignition of homogenous combustion occurs at a certain temperature, which is independent of fuel types, modification of the air/fuel mixture by fuel blending or using various additives can only control homogenous combustion via their effects on the heat release rate during first stage ignition. The selection of additives should be in agreement with the fuel type and its octane number.

Future experimental investigations should focus on variable valve timing, late in-cylinder injection for heavy fuel in particular, and supercharging. These potential technologies can be

applied individually or combined in various forms. Most calculations have so far been done using closed cycles. The impact between intake and exhaust flows has serious effects upon the temperature time history of the charge inside the combustion chamber. Therefore, it is anticipated that such an impact may have a serious effect on homogenous combustion as well, since homogenous combustion is very sensitive to charge temperature time history. Using a lean air/fuel mixture or diluting a richer mixture largely with EGR can control the heat release rate of homogenous combustion, but it will result in poor power output. SI offers a high power output density. A hybrid homogenous-SI strategy can therefore operate the engine with homogenous at low loads to improve emission and efficiency, without sacrificing the high load performance where SI strategy can be used. For engines utilising heavy fuels, homogenous has the potential to significantly reduce PM and NOx emissions without sacrificing fuel efficiency. However, this benefit can only be considered when the engine load is low. At high load, fuel enrichment would largely increase the heat release rate of homogenous combustion and result in an extremely high cylinder pressure increase, due to the nature of simultaneous combustion throughout the entire combustion chamber. At high load, conventional Diesel engine may still have to be employed.
Compared to SI, high compression ratios are preferred by CAI combustion due to its self-ignition nature. Therefore a higher thermal efficiency can be obtained. Values of CR may reach 21:1 for Diesel engine and 12:1 for SI engine. Fuel rich zones are the main source of PM emissions in conventional Diesel engine. However, with CAI strategy, air and fuel mixture are premixed before combustion starts, and thus very low PM emissions can be achieved.

Homogenous combustion is a combustion process which utilises homogeneous air/fuel mixture, but combustion is initiated by fuel self-ignition. It therefore combines features of both SI and Diesel engine combustion. During the compression process, different parts of the charge mixture have different heat capacities due to local in-homogeneities which results in non-unified temperature distribution throughout the combustion chamber. When the hotter parts overcome their threshold energies, ignition of these zones is initiated. The energy exothermal warms and compresses the remainder of the charge, increasing the temperature, until full-scale ignition is established after a short time delay. Therefore, homogenous combustion is a thermal environment related auto-ignition process, but ignition itself is controlled by the chemical kinetics of the mixture with relatively little influence of turbulence and mixing.

4. Water injection

Water can be incorporated into diesel fuels in two forms: micro emulsions (10^{-10} m) and macro emulsions (10^{-6} m). Micro emulsions are especially suitable for if the fuel stability and acceptability by the distribution system. However, they require higher surfactant concentrations and consequently they have a cost/effectiveness challenge, especially at high water concentrations. On the other hand, macro emulsions are specially suited for applications where fuel cost acceptance is a major consideration, since they require lower surfactant concentrations for preparation. Macro emulsions, however, have a white distinctive color because water is distributed in micron range droplets. This characteristic also poses a stability challenge, because water tends to settle over time, when the fuel is kept quiescent.

Water introduction causes NO_x reduction, PM reduction, variability of the addition of water, effects on cold start, lubricating oil dilution, and expenditure. As the main portion of NO_x is formed by highly temperature-dependent reactions, it has been tried for a long time to utilize the heat of vaporization of water for reducing the combustion chamber temperatures. For that reason but not only there is a good idea to apply of exhaust gases recalculations (EGR). Other methods are: water injection into the inlet manifold, water injection directly into the combustion chamber by means of a separate nozzle, injection of a pre-mixed diesel fuel-water emulsion, injection of a diesel fuel-water-diesel fuel sequence by means of a particularly modified nozzle. For obtaining a maximum NO_x reduction from a minimum of water, it has to be brought to the right spot at the right time, namely to those spaces in the combustion chamber where the highest temperatures prevail for considerable periods of time, i.e. the post flame areas. For this reason it is essential to introduce the water by help of the nozzle used for injecting the diesel fuel, as is the case when diesel fuel-water emulsions are injected as well as with the stratified diesel fuel-water. In this regard, the other methods, namely inlet manifold water injection and direct water injection with a separate nozzle, are unfavourable as they supply water also to areas where it is ineffective or even harmful in other respects. Thus, the amount of water required for a certain NOx reduction is twice as great as with water injection by means of the diesel fuel injection nozzle. This excessive quantity of water reduces the temperature level all over the combustion chamber to the extent that soot oxidation is impeded and HC emission increased, resulting in an increased PM emission. In addition, lubricating oil dilution corrosion, and increased wear are observed with these methods. Inlet manifold water injection yielded NO_x reduction rates of 30 percent, in combination with EGR up to 50 percent. Next method, diesel fuel-water emulsion, which lowers the combustion temperatures, which is undesirable at the beginning and end of combustion and results in increased ignition delay, engine noise, and retarded combustion. Thus, at the beginning and end of injection only diesel fuel is introduced into the combustion chamber, to the effect that the aforementioned disadvantages are prevented. In this way, 15 percent lower NOx emissions are measured when the same amount of fuel as with diesel fuel-water emulsion is introduced. Compared to the use of diesel fuel water emulsions, the most import property of the DWD system is that the amount of water injected can be quickly varied dependent on engine load and speed, which is of highest importance in view of transient operating conditions and cold start. The exhaust gas opacity is considerably reduced with diesel fuel-water emulsions too, reportedly by 80 percent. Improved mixture formation due to the increased injection quantity and, therefore, higher injection pressure as well as micro explosions may play a part, and the same might apply to improved soot oxidation by H. and OH. Radicals resulting from partial dissociation of the water. When using diesel fuel-water emulsions, the opacity reduction does not correspond to a comparably large PM reduction, as this is affected by a marked increase in HC emission.

5. Laser researches

Experimental laser researches (PDPA, LDV, PIV) allowed to determine basic spray parameters of atomized fuel including droplet dimensions and velocity field. The view of research injectors for SI engines for research of atomization process, from left worked out injector research with air assist is presented in Fig. 4 and view of combustion chamber of the constant volume with laser equipment 3D (2 transducers and 1 receiver) - in Fig. 5.

Fig. 4. Research injectors, on the left experimental injector with air assist

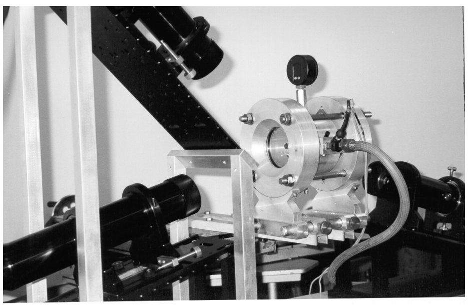


Fig. 5. The combustion space of the constant of the volume with 3D laser equipment (PDPA, LDV)

Researches were concentrated on measurement of droplet dimensions, their dispersion in spray by determination their substitutive diameters and velocity fields in combustion chamber of constant volume. The substitutive diameter is definite by the general dependence expressed by equation:

$$(D_{ab})^{a-b} = \frac{\int_{D_o}^{D_{max}} D^a (di/dD) dD}{\int_{D_o}^{D_{max}} D^b (di/dD) dD}, \qquad (1)$$

where:

D_{ab} – substitutive diameter of droplets in spray order a+b,

D – diameter of droplet in spray,

D_o – minimum-diameter of droplet in spray,

D_{max} – maximum-diameter of droplet in spray,

i – droplet number.

If the spray is homogeneous with reference to droplet dimensions , then all kinds of diameters are equal. Thus a measure of the homogeneity of fuel spray are differences among each diameters. Self-evident is that clear homogeneous spray are possible only theoretically.

The modelling spray fuel dispersion o is possible with many dependences. A most widespread method is the method Rosin-Rammler d described by dependence:

$$1 – Q = \exp \{- (D / X)^q\}, \qquad (2)$$

where:

Q –volume droplet part of smaller diameter than D,

D – droplet diameter,

X – parameter describing stipulated droplet diameter,

q – parameter describing degree of droplet dispersion.

Results of laser researches are presented in Fig. 6, 7 and 8.
In Fig. 9 data for determining of the relative velocity of combustion in constant chamber volume and impulse charge are presented

6. Conclusions

The obtainment of small droplet dimensions is possible in the way increasing of the injection pressure. However high increasing of the pressure unfavourably bears on life of fuel equipment. From other methods one can mention methods mechanical improvements of spraying of the fuel. One of mechanical methods stayed put-upon in research of the ignition process.
Similar connected results with increasing of the pressure one can obtain by means of other methods from which most known is air assist for the process of fuel atomization. This method has however certain due limitations with the necessity of usage of the air-compressor. Other methods concerning improvements of the process of spraying are an object of numerous research works, in this also carried by authors of the paper.

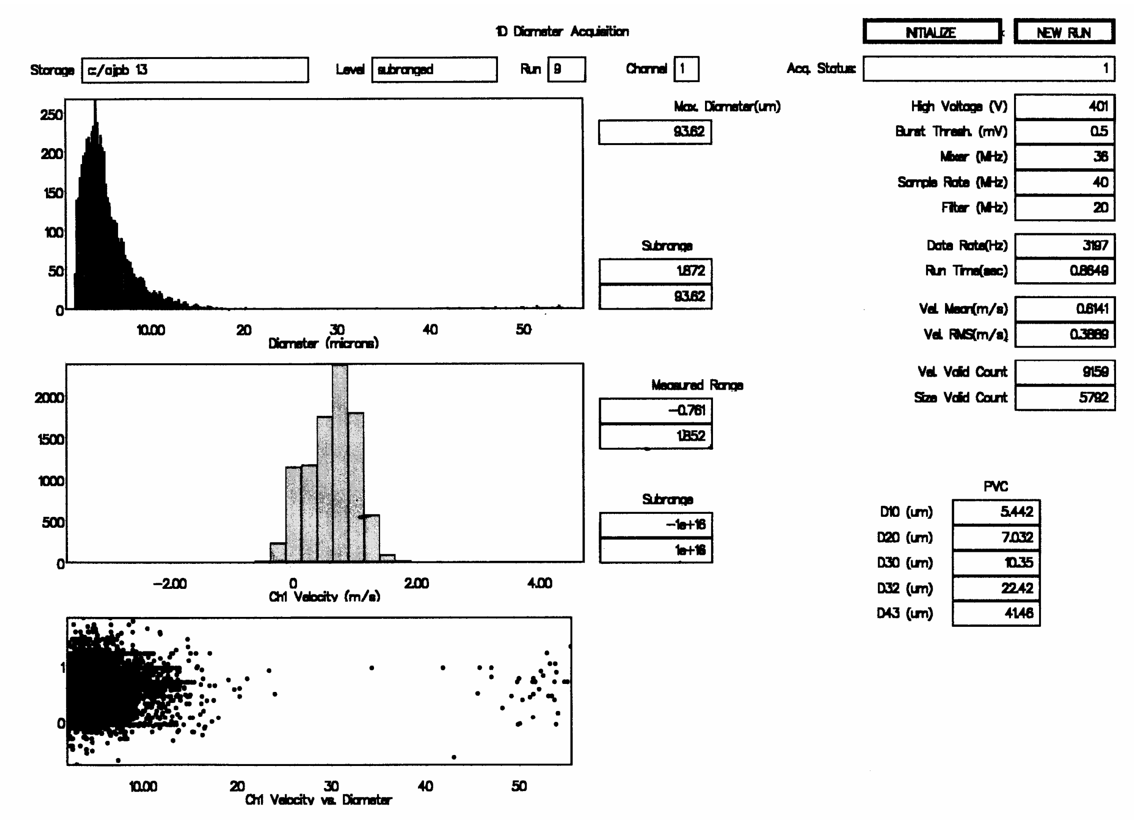


Fig. 6. Results of researches of fuel spray concerning droplet diameters for two kinds of principle dimensions small within the range about 10 μm and greater - within the range about 50 μm

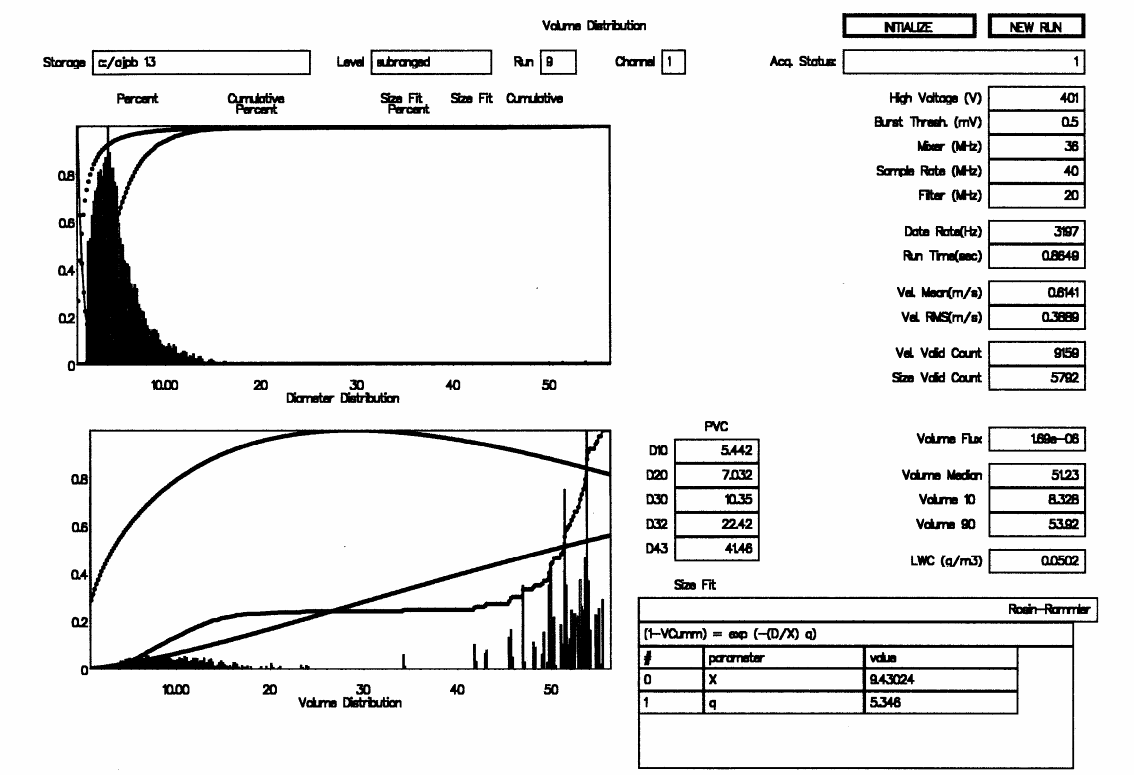


Fig. 7. Results of researches of fuel spray concerning droplet distribution of lineal and volume, and dependences Rosin-Rammler for two kinds of principle dimensions small within the range about 10 μm and greater - within the range about 50 μm

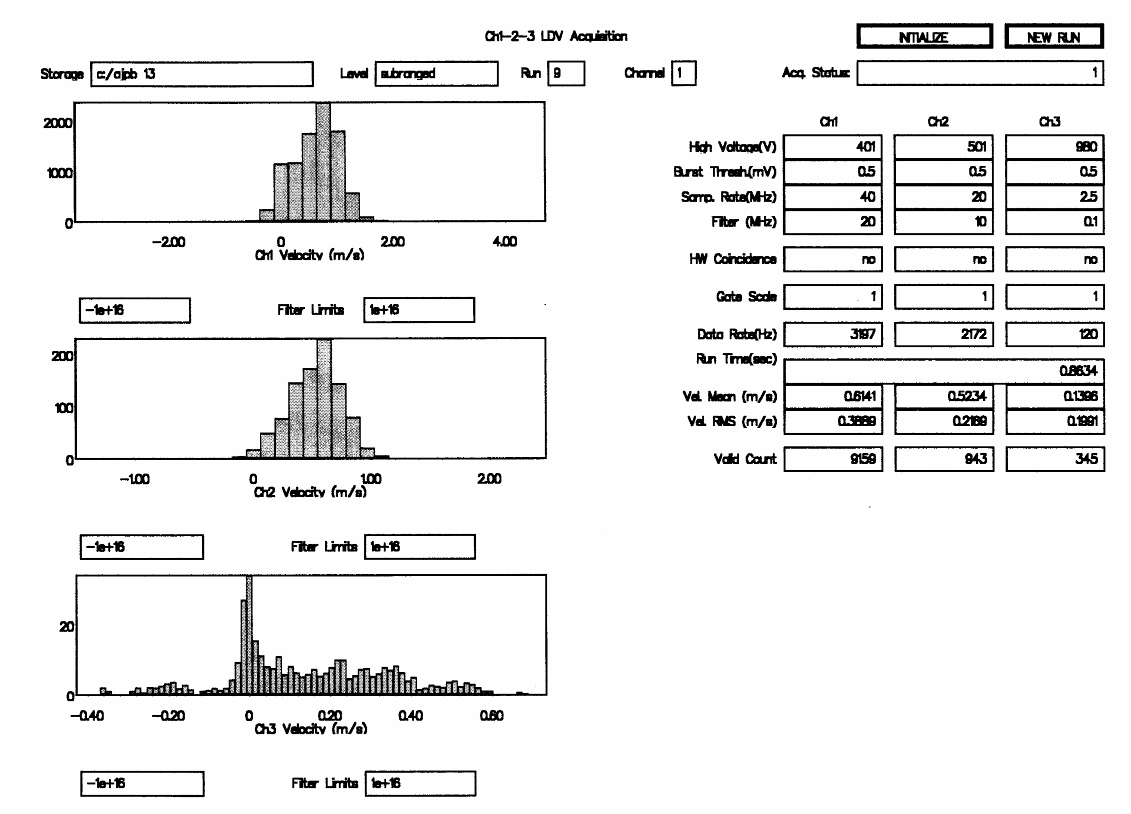
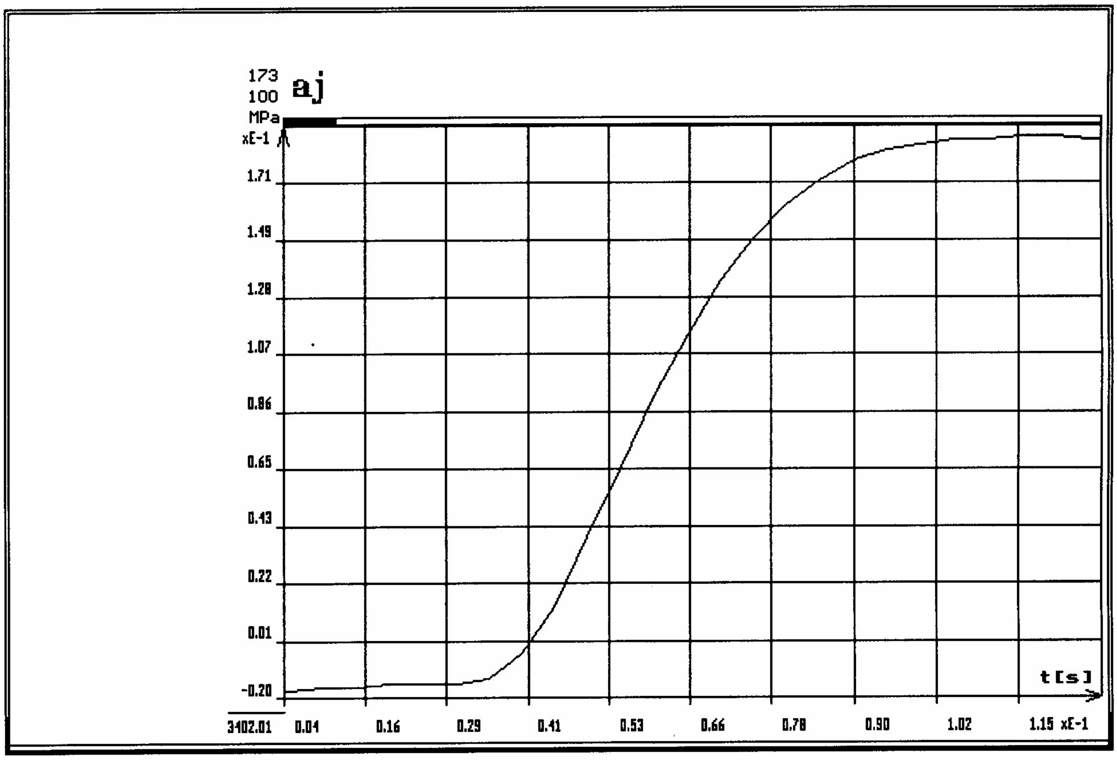


Fig. 8. Results of researches of fuel spray concerning distribution of 3D droplet velocity for two kinds of principle dimensions small within the range about 10 μm and greater - within the range about 50 μm



$t_{min} (t_1)$ [s]	p_{min} (p_1) [MPa]
0,0356	0,002
$t_{max\,r}$ (t_r) [s]	p_{max} (p_r) [MPa]
0,085	0,19
Δ t [s]	Δ p [MPa]
0,0494	0,188
$\frac{\Delta p}{\Delta t} \left[\frac{MPa}{s} \right]$	3,806
$\int_{t_{min}}^{t_{max}} p\, dt$ [kPa s]	4,644

Fig. 9. Results of the analysis of combustion rate and impulse for fuel spray of D_{43} 28,8 μm, λ=2,8

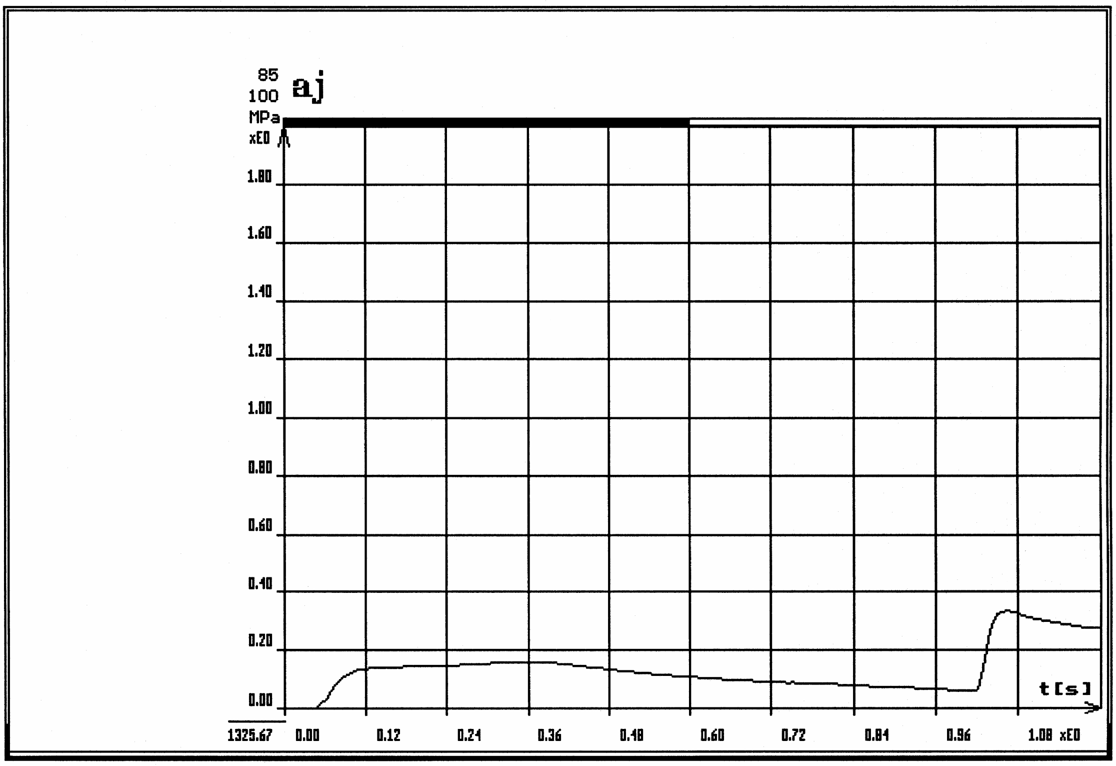


Fig. 10. Run of the combustion process in constant volume chamber for the heterogeneous fuel spray (λ=2,5)

Applied fuels can differ with the value viscosity and the surface tension what can have the essential influence at additives for fuels having different proprieties than gasoline (ethanol). It leads for considerable differences in process of the fuel/air mixture preparation.

The PIV research method lets on definition of the structure and distribution of velocity in stream. It lets on quality rather evaluation than quantity one. Laser-methods PDPA and LDV let on the qualification of diameters of droplets, their velocities and dispersion.
From brought over research the combustion process in the constant volume chamber about the constant of the volume results that the ignition and the correct combustion are possible, when the fuel spray is characterized with small measurements of the diameter D43 which does not exceed the value of 30 μm.

If in the fuel spray she appears droplets of dimensions exceeding 30 μm, but also the sufficient number small droplets of the D_{43} diameter of 30 μm, is the ignition and the combustion are also possible, though the combustion be characterized with different rate during durations of the all process.

During research of the ignition process of the and the combustion at higher pressure in the constant chamber volume (for the value of 1 MPa) appointed that, at large dimensions of droplets, when D_{43} is greater than 30 μm the ignition is not possible, even at the essential growth of the pressure in combustion chamber. Critical influence on the ignition in conditions of the cold combustion chamber has a fuel atomization.

The essential atomization of the fuel influences favourably on the emission level of toxic components of exhaust fumes gases, in this especially on the level the emission of hydrocarbons because of eliminating of misfires and on the level the emission of nitrous oxides on account the short time staying droplet of the fuel in burning zone.

The PDPA laser method can be prosperously applied for the diagnostics of the injection's apparatus of engines with the spark-ignition, diesel, as well as of turbine-engines.

Most injurious are drops in the stream of the fuel about large dimensions. Even several such droplets firmly change the process of the combustion and the emission of components of toxic combustion gases, mostly (NO_x). The process of spraying from the point of view processes of combustion and ignition, as well as of the level the emission characterizes the best supplementary diameter D_{43} which the value is nearing for the volume median.

References

[1] Ambrozik, A., Jankowski, A., Kruczynski, S., Slezak, M., *Researches of CI engine fed with the vegetable fuel RME oriented on heat release*, FIFSITA Paper F2006P256, 2006.

[2] Ambrozik, A., Jankowski, A., Slezak, M., *Some problems using of vegetable fuels in diesel engines*, Journal of KONES Powertrain and Transport, Vol. 13, No. 4, Warsaw, 2006.

[3] Jankowski, A., Sieminska, B.*, Slawinski, Z., *The resistance on thermal shocks of combustion engine pistons*, FIFSITA Paper F2006M232, 2006.

[4] Kim, H., Lai, M.-C., Yoon, S., Quelhas, S., Kumar, N., Yoo, J. S., *Correlating Port Fuel injection to Wetted Fuel Footprints on Combustion Chamber Walls and UBHC in Engine Start Processes,* SAE Paper 2003-01-3240 2003.

[5] Klein, D., and Cheng, *W. K., Spark Ignition Engine Hydrocarbon Emissions Behaviors in Stopping and Restarting,* SAE Paper 2002-01-2804, 2002.

[6] Kruczynski, S. W., Danilczyk, W., Ambrozik, A., Jankowski, A.*, Slezak, M., *Performance of three way catalytic converter containing magnesium oxide for SI engines with lean mixtures,* FISITA Paper F2006P237, 2006.

[7] Landsberg, G. B., Heywood, J. B., and Cheng, W. K., *Contribution of Liquid Fuel to Hydrocarbon Emissions in Spark Ignition Engines*, SAE Paper 2001-01-3587, 2001.

[8] Lee, S, Tong, K., Quay, B. Q., Zello, J. V., and Santavicca, D., *Effects of Swirl and Tumble on Mixture Preparation During Cold Start of a Gasoline Direct-Injection Engine*, SAE Paper 2000-01-1900 2000.

[9] Santoso, H., and Cheng, W. K., *Mixture Preparation and Hydrocarbon Emissions Behaviors in the First Cycle of SI Engine Cranking,* SAE Paper 2002-01-2805, 2002.

[10] Schock, H., Shen, Y., Timm, E., Stuecken, T., and Fedewa, A., *The Measurement and Control of Cyclic Variations of Flow in a Piston Cylinder Assembly*, SAE Paper 2003-01-1357, 2003.
[11] Shin, Y., Cheng, W., and Heywood, J. B., *Liquid Gasoline Behavior in the Engine Cylinder of a SI Engine*, SAE Paper 941872 1994.