Possibilities of improvement fuel atomization process in CI – engines

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Abstract. Modern combustion engines development is targeted on respect of environment protection. Engine constructor main task is lowering toxic substances emission in exhaust. This trend is the same for CI and spark ignition engines. Toxic substances content in exhaust depend on many factors like combustion chamber construction, the sort of fuel and inlet system, fuel – air mixture organize process, the sort of fuel and engine work environment. It was very important period in motorization development implementing electronic engine work steering systems. The factors influence on emission in exhaust analysis shows that there is possibility reduce toxic substances in fumes through correct organizing fuel – air combustion mixture in CI – engine. The injecting fuel streams parameters influence on combustion mixture forming process. The article presents fuel injector modification concept. The aim of modern fuel injector modification is improvement of fuel stream parameters like range, width, atomization and obtuse angle. The performing researches show that making changes on non – working needle part influence especially on particles and carbon monoxide emission.

1. Introduction

Research problems of common CI – engines concern environmental protection issues. The most important researcher consideration aspect is toxic substances emission in exhaust. The experiments are conducted on lowering fumes pollution in many directions: using electronic systems steering engine work, using exhaust riding systems, vary engine systems modification and using biodiesel. Common Rail system has been implemented to perform strict environmental norms. The benefit of this system is possibility to adapt fuel injection timing, time and pressure to engine work condition thanks separation high pressure pump and fuel injectors by uses pressure rail. There are known various Common Rail system solutions but its principle of operation is the same. The essence of work relies on sharing injection dosages in one engine work cycle and adjusting injection timing, time and pressure. The aim of this solution is appropriate organizing fuel – air mixture in engine combustion chamber way in order to reduction toxic substances in exhaust like nitrogen oxides, carbon monoxide and particles. Common Rail CI – engine is composed with air intake, fuel injection and exhaust system. Whole engine work is managed by steering device, which takes dates from sensors and adequate steers execute engine elements. This solution makes possible to make multi-phase fuel injection process, engine noise, toxic substances in fumes and fuel consumption reduction, as well improve performance through increasing power and engine torque. Multi-phase fuel injection process consists in split on few fuel dosages: initial, main and after injection dosages. The number of dosages during one engine cycle work depend on electrohydraulic fuel injector construction. The most important is initial dosage calling pilot or pre injection. The main task of initial dosages is preparing the combustion chamber so that main dosage underwent of combustion by gentle pressure increasing. It is characterized by soft engine work, decreases noise during its work eliminate knocking combustion phenomena. Initial dosage task is shorten ignition delay. The shorter time from appearing fuel drop in engine combustion chamber to the first self-ignition indications the whole combustion process in engine is softer, what influence on toxic substances emission and engine performance. The range of fuel injection rate is control by engine computer additionally through lengthen and shorten the time of fuel injectors work. Engine computer converts the signals from crankshaft position sensor and when one fuel injector starts to change works parameters or there is changing the pressure inside one of cylinders so that engine work driver corrects fuel injectors work time in order to compensate engine work. The next advantage of Common Rail system is high pressure from 25 MPa during engine idle speed up to 180 MPa during maximum fuel injector load. It is very good fuel spraying and distribution in combustion chamber thanks very high pressures, what improves better mixing with air. There is possibility to improve more spraying and distribution fuel in combustion chamber in modern CI – engines through fuel injector nozzle modification.

2. The influence fuel injection parameters on combustion process in CI – engines

Fuel injection process is electronic controlled in modern CI – engines and depends on engine load and work conditions. The entry factors depend on engine work procedures are pressure in injection system and time of injectors controlling what influences on fuel injection dosages. There is possibility to improve fuel injection spraying process independent from engine load through injector nozzle modification. Fuel injection spraying procedure is a brake up of fuel stream flow with high speed making a lot of drops next door injection nozzle holes [6]. The main factors causes fuel streams spraying process are initial forces overflowing during fuel injector nozzle flow. The forces value depends on injector nozzle construction, injector fuel speed through inner channels and its section, geometric shapes and sections fuel injector nozzle holes, the sort of injector nozzle holes edges and physical fuel properties. The dynamics resistance forces influence on overflowing fuel from injector nozzle holes, which amuse stream on drops with vary diameter. This process calls fuel overflowing streams crumble. The drops deformation and break up in fuel streams depend on aerodynamic resistance, fuel surface tension and viscosity. The fuel crumble duration last so long as stabilization drops forces allow higher values than drops breaking up phenomena. The fuel particles which are in flowing streams in combustion chamber moving with turbulent variable speed during injection process. Graphic relationships between drops diameter and relative count calling spraying characteristics are used to quality crumble and homogeneous spraying process estimate [1].

The parameters injected fuel stream influence fundamentally on combustion mixture formation in CI – engine. Combustion mixture formation process assemble with spraying and distribution fuel streams, fuel heat up and evaporate as well with mixing air and fuel. Preparing combustion mixture goes from the moment of fuel injection beginning till finish combustion process. Combustion process course has been in detail described in monograph [1]. It depends on quantitative and quality injection characteristics, combustion chamber construction, fuel properties, speed and direction of distributing charge, the place of mounting fuel injectors and interrelation of fuel streams. The self-ignition spraying fuel is chain, multiphase reaction. The first ignition centre are made according to volumetric combustion process. It is beginning than flame spreading and air – fuel mixture combustion process preparing during ignition delay period. Combustion mixture overcomes in diffusion burning phase and it is beginning afterburning process. The combustion process in CI – engines overcomes in a few phases [1, 12].

Delay ignition period (τ_s) is the first stage of combustion process. It is the time between the beginning of fuel injection till appearing the first centre self-ignition (this is the point, when pressure in cylinder in order to heat emitting has bigger value than pressure in cylinder by air compressing without injection process). Delay ignition period is a time, when fuel stream breaking up on the drops, partially evaporating and mix fuel steams with air and chemical reactions speeding up. It is pursued to shorten ignition delay period, because shorter ignition delay causes less fuel inflow to engine chamber what reduce increasing pressure during combustion process. When the pressure increase is intense during combustion process, it will grow combustion temperature , what is favour to increase nitrogen oxide in exhaust, engine heat – stroke and noise during combustion process. The analysis of literature shows that middle pressure increase speed shouldn't exceed 0,3 – 0,8 MPa on one degree turn of crankshaft. Following factors influences on ignition period delay [1, 5, 12].

1. fuel cetane number determines the fuel ability to self-ignition. The higher fuel cetane number the better fuel combustion abilities. It is possibility to increase cetane number through vary fuel additive.
2. the sort of combustion chamber influences on ignition delay value because there are differences of fuel decomposition in chamber partitions areas and temperature decay of partitions combustion chamber.
3. fuel pressure and temperature on the beginning fuel injection process influence on the first stage of combustion. The pressure grows with temperature and by lower injection timing shorten ignition delay. When engine is used in order to exploitation mileage, the pressures and temperatures decrease during cylinder compression through leakiness what make longer ignition delay.
4. quantity and quality fuel injection characteristics. Fuel injection dosage and shape of stream influence on ignition delay. Proper injection dosages (initial and main) and fuel streams atomization shorten ignition delay.
5. engine speed growing improves spraying and increases pressure and temperature in combustion chamber, what makes shorter ignition delay.
6. focused intensity of charge move in combustion chamber shorten ignition delay.

Ignition delay can be calculated according to J. B. Heywood from the following relationship [4]:

$$\tau_s = (0{,}36 + 0{,}22 \cdot c_m) \cdot \exp[E_a(\frac{1}{RT_2} - \frac{1}{17{,}19}) \cdot (\frac{21{,}2}{P_2 - 12{,}4})^{0{,}63}] \tag{1}$$

c_m – piston speed $[\frac{m}{s}]$,
E_a – activation energy [J],
R – universal gas constant $[\frac{J}{mol \cdot K}]$,
T_2–temperature in combustion chamber [K]
P_2 – pressure in combustion chamber [MPa]
Activation energy can be calculated from following relationship [4]:

$$E_A = \frac{618{,}840}{LC + 25} \text{ [J/mol]} \tag{2}$$

LC – cetane number

The analysis of relationship (1) shows that cetane number in fuel content increases ignition delay period. Theoretically considerations [1, 2] present that spraying quality in combustion chamber don't influence on ignition delay. However considerations concern old construction engines, which work on low pressures in injection system and with old generations fuel injectors. Common Rail system works on pressures 25 – 200 MPa. There are inside system vary phenomena. Turbulent fuel flow in injector nozzle makes that atomization, width, range and angle of flowing out stream have other values than in classic systems. Modification made on injector nozzle can improve additional fuel swirl what influence on combustion mixture creation.

The second phase is called kinetic combustion (fast combustion) and it lasts from air – fuel mixture ignition till maximum pressure in combustion chamber. During this stage occurs partly oxidation of combustion mixture prepared during ignition delay. The result of it is very fast heat liberated and pressure increases. The velocity of air and fuel mixing limits end phase of kinetic combustion. The following factors influence on kinetic combustion:

1. magnitude, quality and spraying characteristics of fuel injection dosage supplied during ignition delay period and kinetic combustion. Fuel supplies less quantity during ignition delay and better atomization and spraying causes better air – fuel mixture mixing and less pressure increases in combustion chamber,
2. combustion chamber construction,
3. spread velocity of charge value in combustion chamber influence on heat give off during kinetic combustion,
4. engine speed,
5. engine load.

The third phase of combustion process begins when reaction is faster than air – fuel mixing velocity. This stage is called diffusion combustion. It starts during the highest pressure in combustion chamber and lasted till the highest temperature [5, 12]. The third phase of combustion depends on:

1. using engine load increase value of heat give off,
2. fuel injection dosage and spraying quality,
3. spread velocity of charge value in combustion chamber influence on heat give off during kinetic combustion,
4. engine speed.

Fourth combustion stage in CI – engine is called burn out. It begins when the temperature in combustion chamber is the highest and it lasts till finish heat give off. It happens soot burning reaction during this phase. It depends on:

1. spraying and atomization process in last phase of combustion. Big drops diameter cause long lasting injection, what makes that burn out combustion mixture is longer. It makes worst using heat energy and influences on engine work and reliability what carbonize engine elements and fuel injection,
2. turbulent moving of combustion mixture,
3. engine load.

Analysis of the literature and conducted researches show that fuel stream parameters influence on combustion process and toxic emission in CI – engine. Author's researches [8, 11] shows that using catalytic layer on not working part of fuel injector could influence on work and ecological CI – engine parameters. Analysis has been performed on old engine with mechanically fuel injection system. Cavitation is very essential phenomenon during fuel flow inside fuel injector nozzle. There are destroying and non – destroying materials pulses when cavitation appears. The researches describe [3] that there is possibility to improve spraying and distributing fuel in CI – engine using cavitation pulses through increasing turbulence in injector nozzle. Paper [9] describes the relationship between cavitation inside injector nozzle and spray characteristic. Visual researches has been made 1,5 mm behind injector holes and show that air bubbles in fuel outlet increasing turbulence improving fuel atomization and fuel stream angle. There are two types of holes in injector nozzle: conical and cylindrical. Researches [9] show that fuel injectors with conical holes have smaller abilities to induce cavitation phenomena by higher outlet speed than cylindrical but fuel – air formation properties are similar for both solutions. The analysis demonstrates that by cavitation fuel flow in cylindrical holes fuel outlet speed and angle stream are higher [10].The scientific considerations [1, 6, 12] demonstrate that injected fuel streams parameters could shorten ignition delay what improve combustion process in CI – engine.

3. The concept of fuel injector modification

Main aim of fuel injector nozzle modification is injection process improvement in modern CI – engine with Common Rail system. Fuel injection process can be consider under quantity and quality aspect. The value describing quantity aspect is fuel injection dosage and quality the shape, range, width, angle, velocity and atomization flowing fuel stream from injector nozzle.

The devices of injection system CI – engine responsible for spraying and distributing fuel in combustion chamber is injector. There are known two types of modern fuel injectors: electromagnetic and piezoelectric. The principle of work both types is similar there are only differences by construction.

There is analysis and modified electromagnetic Bosch generation 1.0 fuel injector with catalogue number 0445 110 083.
There has been made fuel injector nozzle needle modification in order to improve injection process fig. 1 [7]. There has been installed special channels on not working part of needle. The main task of modification is triggering turbulent fuel flow through injector nozzle.

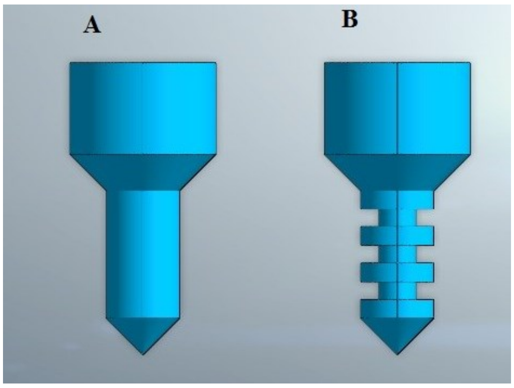

Figure 1. Fuel injector needle A) standard, B) modified

Fuel injector nozzle is the part of injector responsible for correct fuel injection process. It is composed with nozzle and needle. The fuel overflows to needle chamber through inlet channel than surrounds not working part of needle. The channels have ring shape. When injector work the needle moves in reciprocating motion and makes additional fuel swirls. When the needle open holes in the nozzle, fuel injection begins to combustion chamber. The main task of modification is improve spraying process through turbulence trigger in the nozzle and accompany phenomena**.**

4. Objective study

The aim of work is possibilities of improvement fuel atomization process in CI – engines. The researches has conducted according to following program: the analysis of combustion process in CI – engine, the conception of fuel injector modification presenting, laboratory and engine researches describing.

5. Laboratory researches

Laboratory researches has been made by using test bench STPiW3. The aim was check if the fuel injector with a modified spray nozzle works properly. Fuel injection and return doses were researchnext to different adjustment of fuel injector. Two fuel injectors were subjected to testing – the first one with a factory-made spray nozzle, and the second one with a spray modified (Table 1, Table 2). Modified channels have to change quality of fuel stream but the quantity fig. 2 (dosage).

Table 1. Results of injection and return dose testing for standard fuel injector

Fuel injector, serial number 0445110083, with standard spray nozzle					
Test number	Test parameters	Fuel injection dose		Fuel return dose	
		Set value	Actual value	Set value	Actual value
1	145 MPa, 60 s	0	0	0.00–72.00	21.32
2	135 MPa, 780 μs	34.71–49.69	44.1	16.00–58.00	27.53
3	30 MPa, 420 μs	0.31–3.89	2.65	0.00–72.00	6.45
4	80 MPa, 26μs	0.31–4.09	1.34	0.00–72.00	7.14

Table 2. Results of injection and return dose testing for modified fuel injector

Fuel injector, serial number 0445110083, with modified spray nozzle					
Test number	Test parameters	Fuel injection dose		Fuel return dose	
		Set value	Actual value	Set value	Actual value
1	145 MPa, 60 s	0	0	0.00–72.00	34.1
2	135 MPa, 780 µs	34.71–49.69	46.6	16.00–58.00	32.3
3	30 MPa, 420 µs	0.31–3.89	1.9	0.00–72.00	7.1
4	80 MPa, 26µs	0.31–4.09	2.4	0.00–72.00	9.0

Quantity analysis has been conducted on follow parameters. Test no 1 is a fuel injector leak test by 145 MPa pressure. There is research return dosage. Test no 2 is full load research. There are researched injection and return dosages by maximum fuel injector working pressure. Test no 3 is idle speed research and no 4 initial dosage.
Figure 2 presents the results of injected fuel stream visualization. Researches has been conducted by pressure 20 MPa and fuel injector steering time 300 µs. This is area response for initial dosages. Experiment shows that fuel stream in modified injector the is more atomized and dispersed.

A B

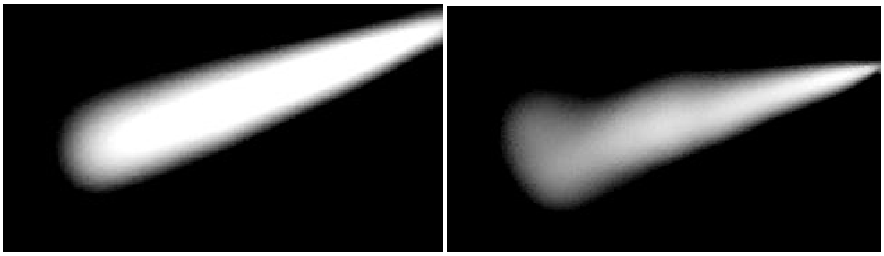

Figure 2. Comparison of fuel streams A) standard fuel injector, B) modified fuel injector

6. Engine researches

Engine research has been made on Fiat 1,3 JTD with dynamometer EMX 100/100 presented on fi. 3B.

A B

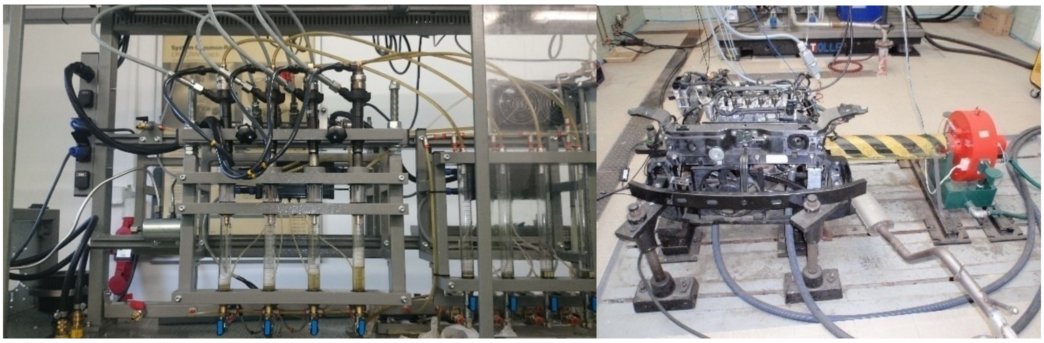

Figure 3. Test bench A) Test benchSTPiW3, B) Engine test bench Fiat 1,3 JTD MULTIJET 16V with dynamometer EMX 100/100

Engine researches has been conducted in order to follow schema: external and ecological characteristic make. There have been researched the engine and ecological parameters during research fig. 4.

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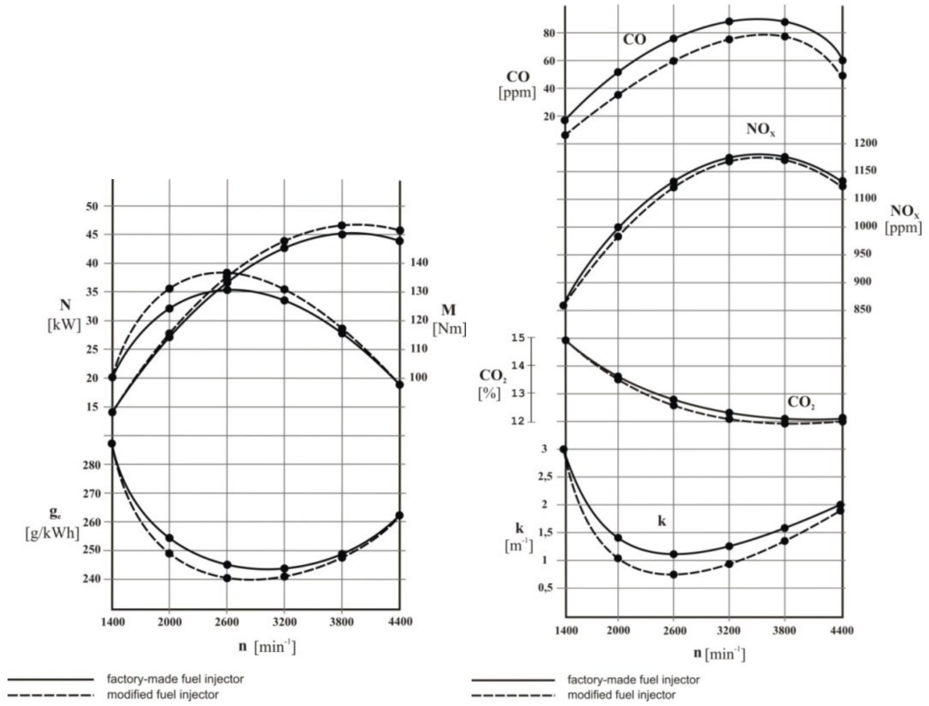

Figure 4. Engine test results A) external characteristic Fiat 1,3 JTD, B) engine ecological characteristic Fiat 1,3 JTD

There have been tested: engine power (N), engine torque (M), specific fuel consumption (g_e), carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO_2) and particles emission.

Conclusions

The article describes the influence of fuel injector modification on atomization and spraying parameters in combustion chamber CI engine. The modification has been made on not working part of fuel injector needle. The researches has been conducted in two stages. The first part has been made in laboratory on the test bench. It has been carried out the visualization of fuel injection stream (fig. 2) and it was tested the influence of modification on injection and return dosages (tab. 1 and 2). Researches shows (fig. 2) that changes in fuel injector nozzle influences on shape of fuel stream. There is noticeable by analysis engine ecological characteristic that carbon monoxide (CO) and particles emission (k) are lower by uses modified fuel injector. It has been changed stream angle and fuel atomization (fig. 2)what could influence on ecological parameters according to the authors. Fuel injector modification changed physically fuel stream parameters like range, angle, atomization and width. This treatment could fasten air – fuel mixture creation through better spray and atomization, what decrease toxic substances in exhaust fig. 4. Modification decreases nitrogen oxide not much. There is possibility to lower nitrogen oxide in fumes through changing fuel chemical properties [8]. The channels made on not working part of nozzle needle changed engine power, torque and specific fuel consumption not much fig. 4A. It should be notice that modification not influence on quantity fuel injection parameters tab. 1 and 2. The analysis of conducted researches performs that fuel injector nozzle modification influences only on physically fuel injection parameters. The next directions of researches are: the measurement of pressures and temperatures in engine combustion chamber by using modified fuel injectors and compare with standard and the analysis of use modified fuel injectors with biofuel in modern CI engine with Common Rail system.

References

[1] Ambrozik A 2010 Analiza cykli pracy czterosuwowych silników spalinowych. Wydawnictwo Politechniki Świętokrzyskiej Kielce.
[2] Ambrozik A Ambrozik T Łagowski P 2015 Fuel impact of emissions of harmful components of the exhaust gas from the CI engines during cold start up. Eksploatacja i Niezawodnosc – Maintenance and Reliability 17 (1) 95–99.
[3] Desantes J. M., Payri R., Salvadore F. J., De la Morena J 2010 Influence of cavitation phenomenon on primary break up and spray behavior at stationary conditions. Fuel. 89, 3033 – 3041.
[4] Heywood J.B. 1998 Internal Combustion Engine Fundamentals McGraw – Hill Inc. New York United States of America.
[5] Lotko W. 1997 Zasilanie silników wysokoprężnych paliwami węglowodorowymi i roślinnymi. Wydawnictwo Naukowo – Techniczne Warszawa.
[6] Orliński P 2013 Wybrane zagadnienia procesu spalania paliw pochodzenia roślinnego w silnikach o zapłonie samoczynnym Instytut Naukowo – Wydawniczy „SPATIUM" Radom.
[7] Osipowicz T. Fuel injector nozzle Patent no. 222791.
[8] Osipowicz T, Abramek K. F. 2014 Catalytic treatment in Diesel engine injectors. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 16(1) 22–28.
[9] Payri F., Bermudez V, Payri R., Salvadore F. J. The influence of cavitation on the internal flow and the spray characteristics in diesel injections nozzles. Fuel. 2004. 83, 419 – 431.
[10] Payri R., Garcia A., Domenech V., Durrett R., Plazas A. H. An experimental study of gasoline effects on injection rate, momentum flux and spray characteristics using a common rail injection system. Fuel. 2012. 97, 390 – 399.
[11] Stoeck T, Osipowicz T. Abramek K. F. 2014 Methodology for the repair of Denso Common Rail solenoid injectors. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 16(2) 270–275.
[12] Wajand J. A. Wajand J. T. 2005 Tłokowe silniki spalinowe średnio – i szybkoobrotowe. Wydawnictwa Naukowo – Techniczne Warszawa.