EXPERIMENTAL INVESTIGATIONS IN DIRECT INJECTED SI TWO-STROKE ENGINE

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Abstract

The paper presents the latest experimental results of small power two-stroke engine with electronic controlled high pressure direct fuel injection. The work is one of the first solutions in such engines in Poland and was provided on industrial engine with capacity 115 cm^3. A special experimental equipment and electronic control of fuel dose and injection phases enables to obtain a big decrease of specific fuel consumption and exhaust gas emission, particularly hydrocarbons with the same level of torque. Applying of direct injection in small power two-stroke engine gives possibility to fulfil exhaust emission requirements. The paper presents the experimental stand and fuel injection system with results of main engine parameters and emission of chosen chemical components. The configuration of injection system was designed on the basis of previous simulation test in GT-Power and KIVA3V. Earlier fuel injection influences on better evaporation and mixture formation with small stratification, which enables full mixture combustion. Direct fuel injection in two-stroke engine decreases hydrocarbon emission 10 times and specific fuel consumption about 30% in comparison to carburetted engine. Exhaust gas emission is on level of four stroke engines with low emission of NOx. The engine was equipped with conventional automotive injector, which was not suited to small cylinder capacity. .On the basis of the simulations and experimental tests a main conclusion can be drawn, that the spray guided direct fuel injection is a way to obtain cleaner and more effective two-stroke engine for small power units.

***Keywords**: transport, combustion engines, direct fuel injection*

1. Introduction

Two-stroke engines still are used in small applications where the different operation position are needed especially in wood working, motorbikes, small motorcycles, watercraft units, garden movers and other. Because of simple design a low price two-stroke engine are very attractive for possible users. However for natural environment they emit much more hydrocarbons and carbon monoxide to atmosphere than four stroke engines. This is caused by specific symmetric timing of exhaust and transfer port, which influences on escaping of air-fuel mixture to the exhaust system during scavenge process. Unburned fuel causes higher emission of hydrocarbons with lower emission NOx, which is caused by higher internal exhaust gas recirculation. Direct fuel injection reduces hydrocarbon emission with proper design of the injection timing and the positioning of the injector. For many years there are carried out investigations of direct fuel injection in SI two-stroke engines in order to reduce hydrocarbons emission. The company Piaggio in Italy [7] much effort put for finding the best solution in scooter engines. Location of the conventional automotive injectors depends on their thermal resistance during combustion process and different structure of mixture formation. The overall gas flow in the two-stroke engine has a significant effect on the motion and evaporation of the fuel spray. It was found that the most important parameters strongly influenced on droplet vaporization process in the cylinder and spatial vapour distribution is: fluid flow pattern, injector location, injection timing and injection pressure. In previous paper authors [6] presented simulation models and results of numerical calculation both for zero-dimensional model and 3-dimensional model using mostly Kiva program [1] as CFD tool for industrial two-stroke engine Robin EC12 with capacity 115 cm^3 with loop scavenge system (two transfer ports).

The provided simulations enabled determination of the best location of the fuel injector in the combustion chamber. Now on the market there are any direct fuel injectors for small power two-stroke engine and therefore the authors applied the conventional automotive injector from 4-cylinder four stroke engines. Every design requires much efforts and experimental tests for proper realization such fuelling. Direct fuel injection reduces significantly hydrocarbons emission, however does not increase engine power for the same engine geometry and ports timing. Reduction of hydrocarbons emission is connected with lower fuel consumption for mixtures, close to stoichiometric value of air fuel ratio. Injection of fuel in two-stroke engine should take place after closing of the exhaust port (about 90 deg BTC of piston position). For this reason there is no time for full fuel evaporation. Modern high pressure fuel injectors enable faster nozzle opening and minimum opening time is reduced from 2 ms for multipoint injectors to 300 μs for automotive direct fuel injectors. Therefore injection time can be significantly reduced, which enables longer time for fuel droplet evaporation before ignition.

2. Experimental instrumentation

Experimental works were carried out after many theoretical considerations and simulation processes, which were basis for proper determination of geometric and hydraulic parameters of the direct fuel injection system. The authors applied high pressure system of fuel injection cooperating with charge flow in combustion chamber. The influence of gas motion during compression process was presented in papers [5, 6]. The laboratory equipment was very simple for the first experimental investigations, because the general task was to found any interaction between control parameters (start and duration of injection, fuel pressure, location of injector, checking of the chosen injectors and other parameters). The most important were to modify the air cooled engine Robin EC12, which was also used for other tests in previous works. The engine geometrical parameters are shown in Tab. 1

Tab. 1. Engine specification with direct fuel injection

Number of cylinder	1
Swept volume, cm^3	115
Bore, mm	54
Stroke, mm	50
Connecting rod length, mm	110
Compression ratio	8
Transfer ports close, ° ABDC	57
Exhaust port close, ° ABDC	77

The engine was equipped with one nozzle high pressure injector from VW FSI engine No. 0261 500 005, which is obviously designed for higher cylinder volume of engine. Application of direct fuel injection system has required additional supplying of lubricating oil. Two-stroke was equipped with rolling bearings, which enables dosing of small amount of lubricating oil to the inlet air. The oil was supplied directly to the throat of the original carburettor, which fulfilled only the role of a controller of air flow to the crankcase. The amount of oil was governed by a special valve in proportion 1:50 (oil to air). In order to achieve smaller fuel droplet the high injection pressure was applied. For that reason on the laboratory stand a special high pressure pump was used driven separately by electrical motor. The engine was fully controlled by specially written software.

3. Engine test stand

Full electronic control of engine work by programmer of eddy current dynamometer was fulfilled by special software working in Labview environment. The simplified diagram of engine stand is presented in Fig. 1 showing the main units of whole injection and flow system. Mass flow of fuel was determined by a special measurement unit for small dose of fuel, because industrial system was not so precise.

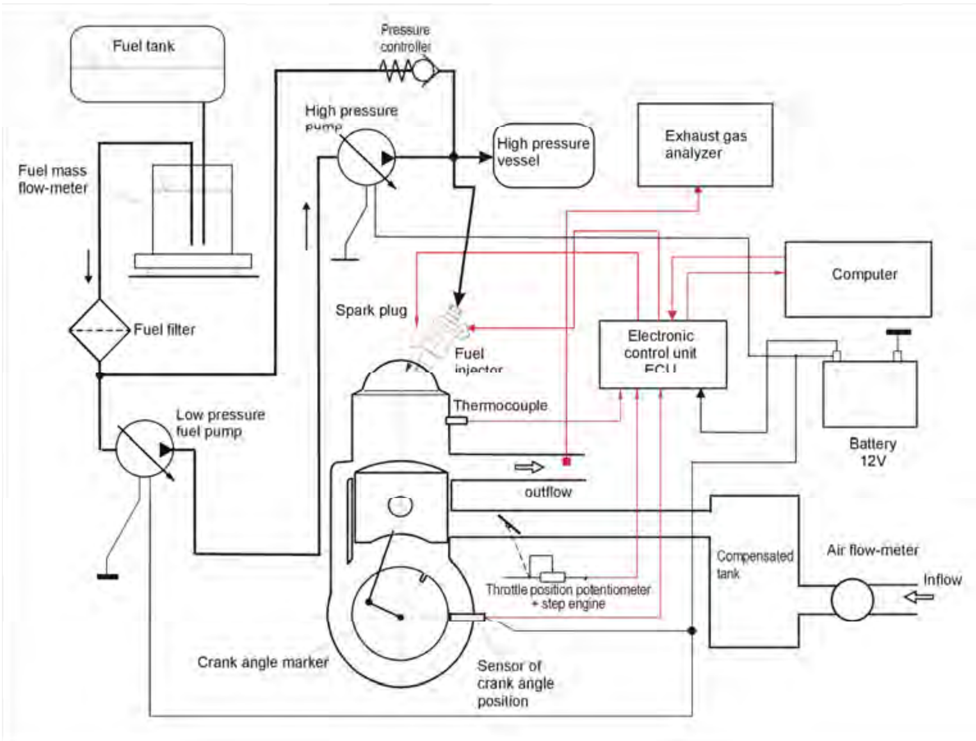

Fig. 1. Diagram of direct fuel injection two-stroke engine on experimental stand

Air mass flow rate was determined by the flow meter (heated wire). Low pressure pump delivered the fuel to the high pressure pump and pressure was regulated by an industrial multi-range pressure controller. Value of pressure was set from 35 to 65 bar. Oscillation of pressure was reduced by applying of high pressure vessel with volume about 0.5 l. Excess of fuel was returned to low pressure system between the fuel filter and the low pressure pump. The software in the computer enabled change of the fuel dose by change of the injection time. In dependence of engine speeds the beginning of fuel injection changed from 100 to 60 deg BTC of piston position.

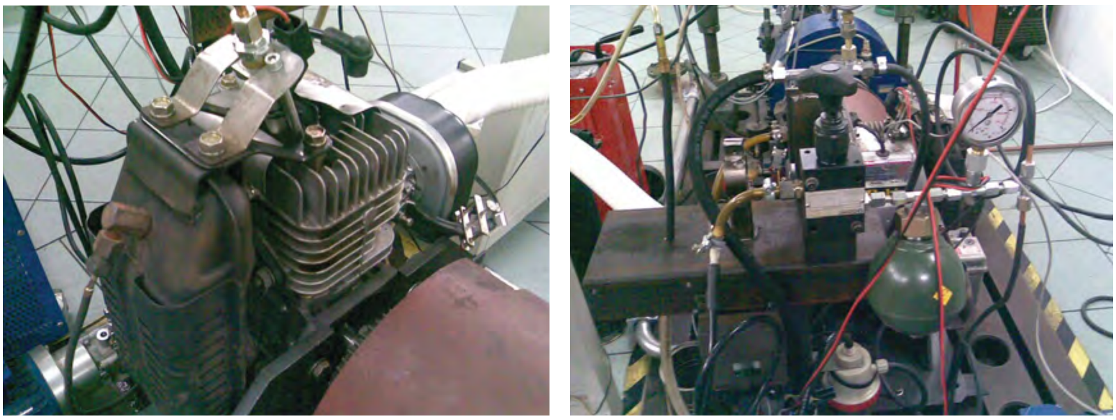

Fig. 2. Photos of experimental stand with direct fuel injection two-stroke engine

Views of the experimental stand are presented in Fig. 2, where left photo shows the cylinder with fuel injector and right photo shows laboratory fuel system. Fuel pressure was observed from the manometer. All control signals were determined in relation to the crank position in BDC by using the encoder directly mounted on the end of the crankshaft. For determination of volumetric concentration of main exhaust gas components a typical exhaust analyzer Arcon with NDIR system was used, but it measured also concentration of NO. In standard engine start of ignition was set 20 deg BTDC, but in the modified engine the ignition can be changed.

4. Experimental investigations

The limit of the paper does not allow presenting all results achieved during long-lasting testing. Only main results are shown both for standard carburetted engine and for direct fuel injection engine. During experimental investigations influence of injection timing and fuel pressure level for different loads and engine rotational speeds was observed. Preliminary results of the tests showed advantages and disadvantages of applied feeding system. Engine parameters were determined for standard (carburetted) engine and modified engine with direct fuel injection (DFI) system. For carburetted version the measured brake power is slightly higher than for DFI system. Engine power variation is shown in Fig. 3 for both versions. For the sake of applied commercial injector tests of DFI engine were carried out in smaller engine range of rotational speed (2200–4200 rpm). For the carburetted engine maximum power takes place at higher rotational speed than for the DFI engine. At the same scavenge timing the volumetric efficiency is the same for both version. In the DFI engine power depends on amount of injected fuel, which controls the air-fuel ratio.

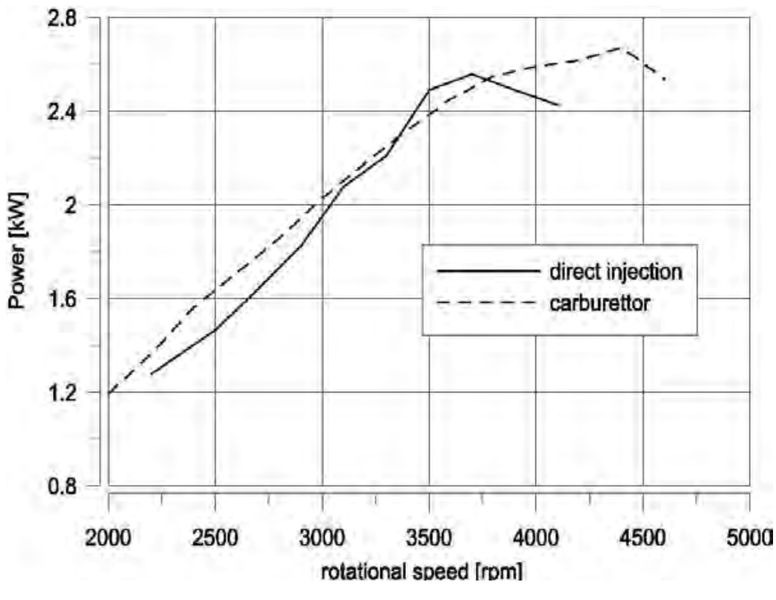

Fig. 3 Comparison of engine power in carburetted version and direct fuel injection version

By applying of high pressure direct fuel injection, atomizing of fuel is enough for quick evaporation of droplets, despite of shorter time than in four stroke engine. This phenomenon enables full combustion of fuel and at almost the same power engine consumes lower amount of fuel. Fig. 4 presents comparison of specific fuel consumption for both engine versions. It is observed a considerable decrease of bsfc for engine with direct fuel injection at whole range of rotational speed. Reduction of fuel consumption reaches almost 35% in comparison to carburetted version and is close to values of four stroke engines. Injected fuel to the cylinder is fully consumed during combustion process and in comparison to carburetted engine the mixture does not flow into exhaust port during scavenge process. This influences also on lower emission of hydrocarbons, which is the main reason of decreasing of participation of two-stroke engine in the market.

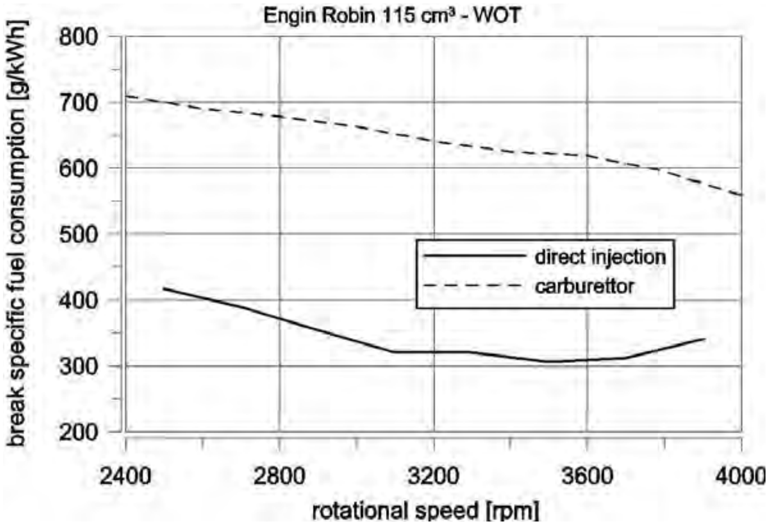

Fig. 4. Comparison of break specific fuel consumption of engine in carburetted version and direct fuel injection version

Comparison of volumetric concentration of hydrocarbons for both versions is shown in Fig. 5 (logarithmic scale). For carburetted engine HC emission reaches 4500 ppm and is ten times higher than for DFI engine, where highest value of HC emission amounts 450 ppm at lower rotational speed. Lowest value of HC concentration amounted about 100 ppm at 3700 rpm (without catalytic converter) and is near homologation requirements for car engine.

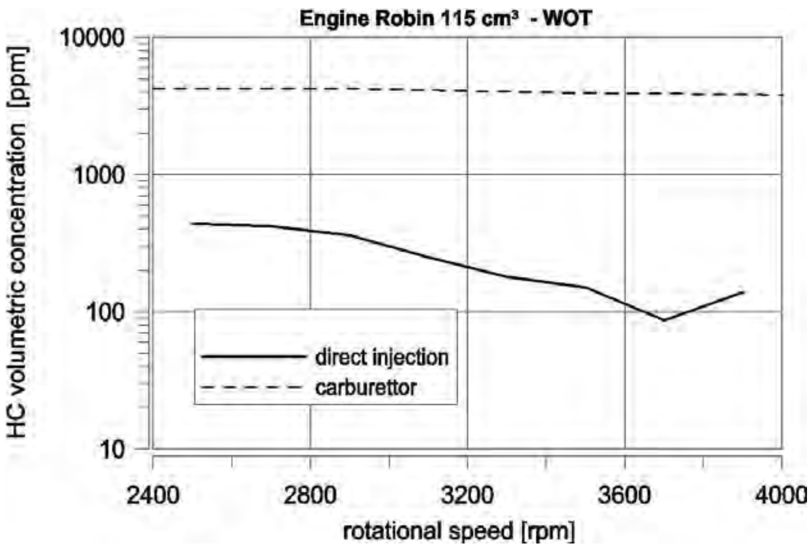

Fig. 5. Comparison of hydrocarbon volumetric concentration in exhaust gases in two-stroke engine for carburetted version and direct fuel injection version

Like the hydrocarbon emission DFI engine emits also lower amounts of carbon monoxide, which is caused by better combustion process. Dose of injected fuel enables achieving of different range of air-fuel ratios. For both cases the air excess coefficient was the same and amounted 1.05. In carburetted engine there are an increase of CO emission with increasing of engine rotational speed in comparison to DFI engine, where at higher rotational speed the concentration of CO amounted 2% (Fig. 6).

In two-stroke engines emission of NOx is lower than in four stroke engine as a result of internal exhaust gas recirculation (IEGR). However in two-stroke engines with direct fuel injection there is seen insignificant increase of volumetric concentration of NO. Comparison of volumetric concentration of NO for both engines is presented in Fig. 7. Maximum value of NO emission does not exceed 300 ppm, which is several times lower than in four stroke engine.

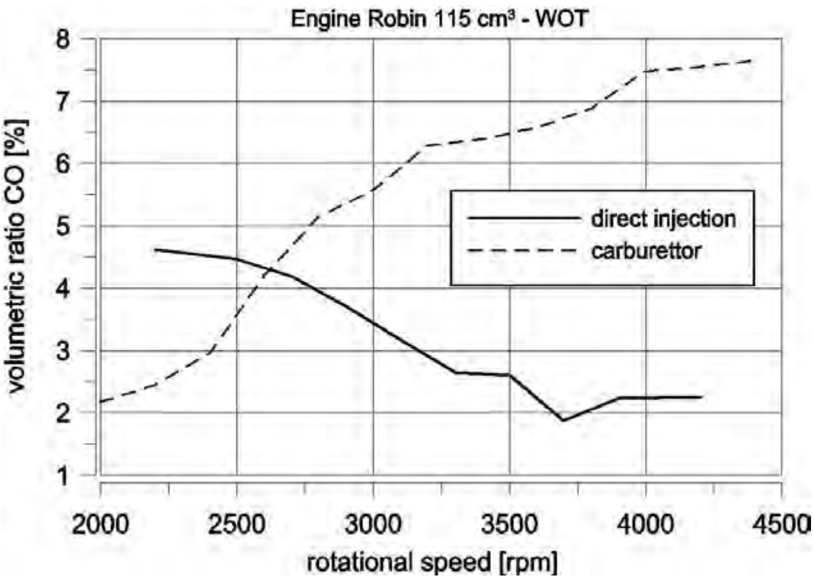

Fig. 6. Comparison of carbon monoxide volumetric concentration in exhaust gases in two-stroke engine for carburetted version and direct fuel injection version

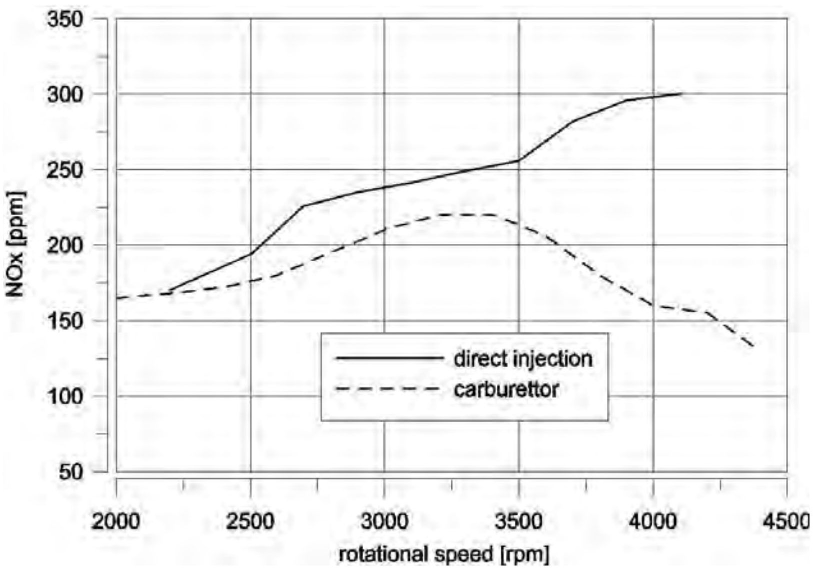

Fig. 7. Comparison of NOx volumetric concentration in exhaust gases in two-stroke engine for carburetted version and direct fuel injection version

Volumetric concentration of CO_2 for both versions was the same and oscillated in the range 9-11%. It can be seen that reaching 14% of CO_2 as in four stroke engines is not possible on this stage of investigations, because of higher emission level of CO. The current target is increasing of thermal efficiency by achieving of complete combustion process.

The tests concerned also measurement of cylinder pressure for different loads and rotational speeds. For that reason the piezo-optical sensor from Optrand company was used, which was directly mounted in the wall of cylinder head. Another Kistler piezo-resistive sensor measured pressure inside engine crankcase. All electric signals from sensors were transformed by amplifiers to the computer in the function of crank angle (encoder) and from data variations of pressure are achieved. Fig. 8 presents pressure traces in the cylinder of two-stroke engine with direct fuel injection at WOT for two rotational speeds 2500 and 3500 rpm. It can be noticed that maximum of pressure takes place at 15 deg ATDC of piston position for both speeds, however the start of combustion takes place at constant value of ignition advance. Maximum pressure does not exceed 30 bar and is a typical value for industrial two-stroke engines and combustion process takes place without knocking.

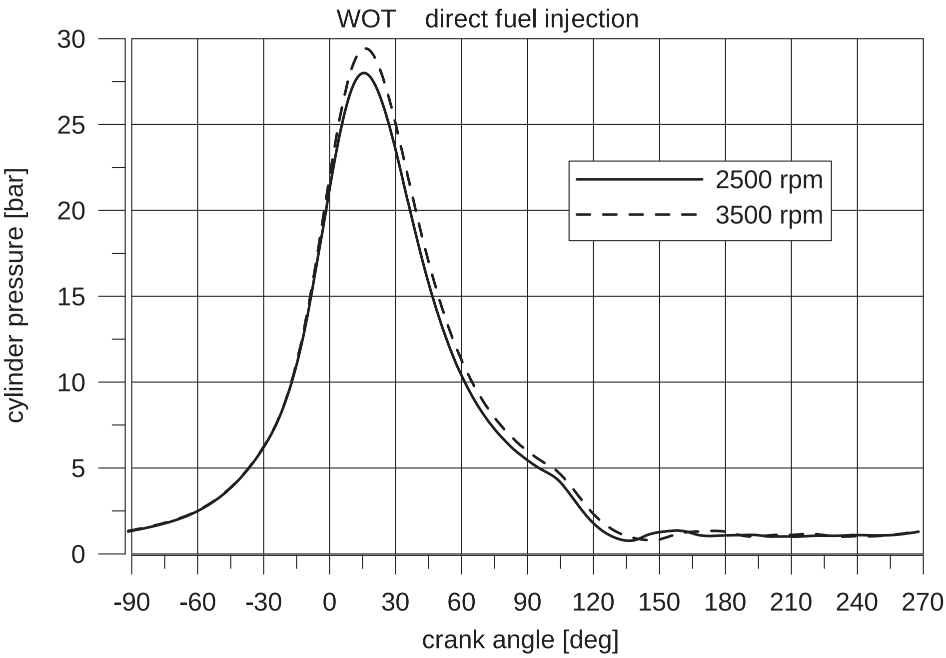

Fig. 8. Measured pressure traces in cylinder of direct fuel injection two-stroke engine at 2000 and 3000 rpm

5. Conclusions and remarks

On the basis of carried out preliminary experimental investigations of two-stroke engine with direct fuel injection the following conclusions can be drawn:

1. Direct fuel injection does not assure higher engine power because for the constant transfer and exhaust ports timing the same air is delivered to the crankcase and cylinder.
2. The modified engine almost ten times reduces hydrocarbons emission and is close to HC concentration in exhaust gases in four stroke engines.
3. High pressure direct fuel injection decreases significantly specific fuel consumption above 30% in comparison to carburetted engine, as a result of lower fuel escape to the exhaust port during scavenge process.
4. Atomizing of fuel and high pressure injection increase gas turbulence and for this reason the combustion process is improved. Concentration of CO in exhaust gases is lower, however amount of NOx slightly increases.
5. Applying of direct fuel injection in two-stroke SI engines increases competition of them on the market as a result of lower impact on natural environment by reduction of hydrocarbon emission and lower fuel consumption.
6. Lower specific fuel consumption enables achieving of total efficiency near 30%.

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