STUDY OF COMBUSTION AND PNEUMATIC SPARK IGNITION ENGINE

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Abstract

The paper describes the work of high speed spark ignition engine with additional high pressure air injection during combustion process. The analyzed conception of combustion and pneumatic engine is based on the European patent EPO - EP2 103777 A2 and polish announcement UP RP P-3 87992. The paper presents the results of theoretical and numerical investigations for different analyzed control parameters of the injection dose of air with comparison of work parameters for standard and modified engine. Additional post air injection enables achieving higher expansion pressure and additional oxygen for better fuel combustion. At proper air dose the charge temperature slightly decreases, which enables applying of a cheaper turbocharger in such engine in regard of thermal resistance of materials. The engine is equipped with electronic control system of air injection and direct fuel injection. The paper shows an increase of dynamic engine performance for constant timings and pressure of air injection and variations of engine work in comparison to standard engine. Additionally the paper shows possible energy recovery system of such engine in the car. The conception is a certain input for "downsizing" of engines and reduction of exhaust emission. The results presented in the paper were obtained from computer programs based on prepared mathematical model.

Keywords: *Transport, engine development, fuelling, emission*

1. Idea of combustion and pneumatic engine

The main task in development of internal combustion engines is achieving a high power or high torque at low rotational speed however for small size power units. Increasing of higher requirements of exhaust gas emission every year forces to find non-conventional solutions in combustion processes, fuelling and controlling system, new technologies. The main problem of increasing of total efficiency is increasing of efficiency of combustion process or using energy which is lost (heat exchange, energy of exhaust gases, friction forces and others). Natural way is increasing of mean effective pressure by using turbocharger or using additional energy stored in tanks or battery. This leads to non-conventional power sources or hybrid systems. Despite the high progress of the new types of combustion processes such HCCI, CAI, ATAC and other or applying of different complicated fuel injection systems the emission of the combustion products of the hydrocarbon fuel is still high, particularly in lower engine loads. Only small energy of fuel (about 25-45%) depending on the engine type is transformed into mechanical power. The application of alternative energy sources and alternative driving system is need instead of those based on fossil fuels. However the main environmental problem is in big cities with transportation where only the fossil fuels are used. Recently there are considered the hybrid systems and fuel cells system for future transportation means. Till now the electric power is produced mostly in many countries on the fossil fuels. It is connected with production of CO_2 and emission of the toxic components of exhaust gases. The electric vehicles have small possibility to drive a long distance. Till now the highest distance for such vehicles reaches maximum 150 km at medium speed and load. For that reason an additional source power for generating an electric energy or driving source is required.

Using electrical energy recovered in cars during deceleration or braking, also in low loads on the road is known way and is applied in hybrid vehicles. Such vehicles have one internal combustion engine and one or two electric machines and also a heavy battery pack. Recovering of lost energy causes an increase of total efficiency and thus causes lower fuel consumption. Recently there is big interest of applying pneumatic engines as additional power source in small vehicles.

The proposal concerns to certain hybrid combustion system in internal combustion engines both compression and spark ignition in order to achieve higher indicated mean effective pressure and lower fuel consumption. The solution is combination of two fuelling systems: the first direct fuel injection and the second high pressure air injection. Dosing of both fluids is shifted in CA one relative to second. Additional air helps in the charge mixing, increasing of charge turbulence and causes quicker combustion process by additional oxygen in the regions, where local excess air coefficient is small (below ignition boundary). Besides fuel dose the mass of charge increases in the cylinder causing a significant increment of pressure. This paper concerns only to applying of air injection in spark ignition engines. The influence of an additional air dose in compression ignition engines can help to break the fuel jet with possibility to burn the droplets in the kernel of fuel jet. In this way CI engine can reduce amount of emitted soot and nanoparticles. The presented solution of combustion and pneumatic engine is based on the European patent EPO - EP2 103777 A2 obtained by Wiatrak and polish announcement UP RP P-387992. The simple diagram of the solution is presented in Fig.1 for SI engine. High pressure bottle contains the air under pressure below 500 bar and is supplied to the pneumatic injector through the safe valve, pressure controller, which reduces high pressure according to demand of engine. The electrical signal from ECU controls both air pressure and time of opening and closing of the pneumatic valve. It was assumed, that SI engine posses a high pressure direct fuel injection system also controlled by ECU. The electronic control of fuel injector and air injector enables to obtain optimal engine parameters by small amount of fuel and air.

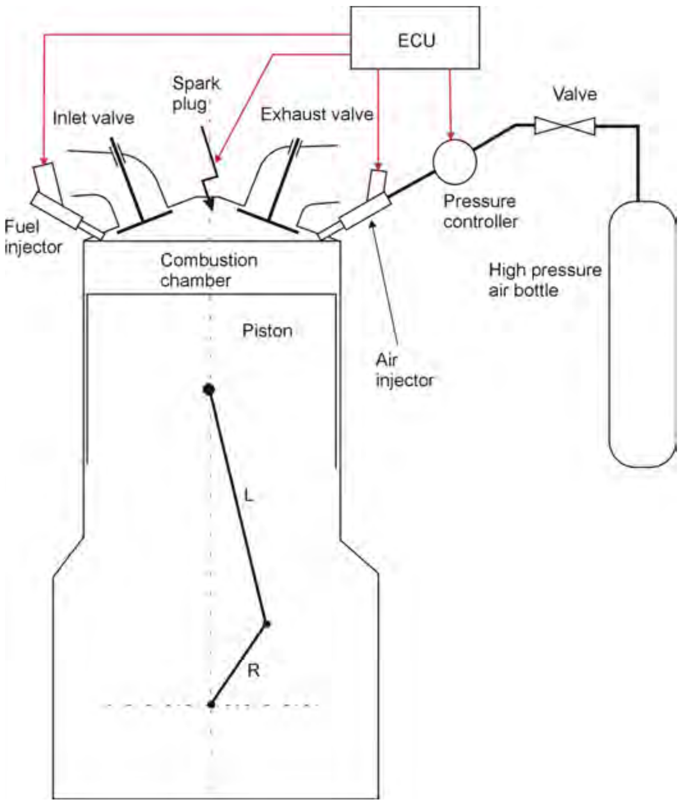

Fig. 1. Diagram of combustion and pneumatic SI engine

Additional value of torque depends on the air mass delivered from the tank trough the air injector to the cylinder. One of the most important factors influencing on work of such engine is valve timing and value of the air pressure and temperature. The combustion and pneumatic engine enables the driving of the vehicle with real zero emission as a result of lower temperature (decreasing of NOx emission) and full fuel combustion (CO absence). These advantages induced on the authors to wide theoretical and calculation analysis of the problem.

2. Engine object

The paper presents theoretical considerations and calculation of work parameters of combustion and pneumatic SI engine. In order to recognize some control and geometrical parameters on engine performance one cylinder SI engine was taken into account. For analysis only one cylinder of the engine 2SZ-FE YARIS with capacity 1.3 l was chosen. Theoretically the engine was equipped with the high pressure air injection system at pressure 300 bar.

Technical data of 2SZ-FE taken for analysis:

- four stroke engine,
- 4 valves (2 inlet and 2 outlet valves),
- pentroof combustion chamber,
- constant ignition time 15 deg BTDC,
- bore D=72 mm,
- stroke S=79.7 mm,
- compression ratio ε=10,
- length of connecting rod L=129.5 mm.

In standard version the engine is equipped with multipoint injection system. Cracow University of Technology modified the original engine with possible direct fuel injection and such engine was taken in theoretical investigations. Calculation model took into account the real geometry 2SZ-FE engine.

3. Calculation model

The bottle of certain volume contains the air at high pressure. The pressure of stored air in the bottle or tank (about 500 bar) is reduced by pressure regulator to smaller injection pressure about 100-150 bar. The pressure is controlled by the sensor and the air is delivered by the pipe of small diameter (about 5-8 mm) to the valve. The air flow control should enable the high pressure in the cylinder ATDC and on the other hand the opening of the pneumatic valve lasts very short (about 40-60 deg CA) and for this reason the natural frequency of the moving elements in the valve should be high. The calculation was carried out by using educational version of GT-Power software from Gamma Technologies, Inc., however also own software was written for this purpose. Presented results were obtained from GT-Power, program widely used in automotive industry. The diagram of calculation model in that software is presented in Fig. 2. The model consists many visual objects representing real engine objects. Each object is described by physical and mathematical representation of phenomena taking place in real object such pipes, volumes, pipe’s junction, valves. Full mathematical description of physical phenomena is out of scope of the paper.

Combustion process was analyzed at assumption of two-zone model with turbulent speed and simple model of formation of toxic components such as CO, NO, HC, CO_2 and H_2O. For this reason comparison of work parameters and emission of exhaust gases for standard engine and combustion and pneumatic version can be possible. The engine-object in Fig.2 control the engine work, the air injection pressure was changed by data included in table of the object of the air injector. Thermodynamic parameters of gases and fuel were depended on temperature and pressure. Friction and heat exchange with wall was taken into account during that analysis.

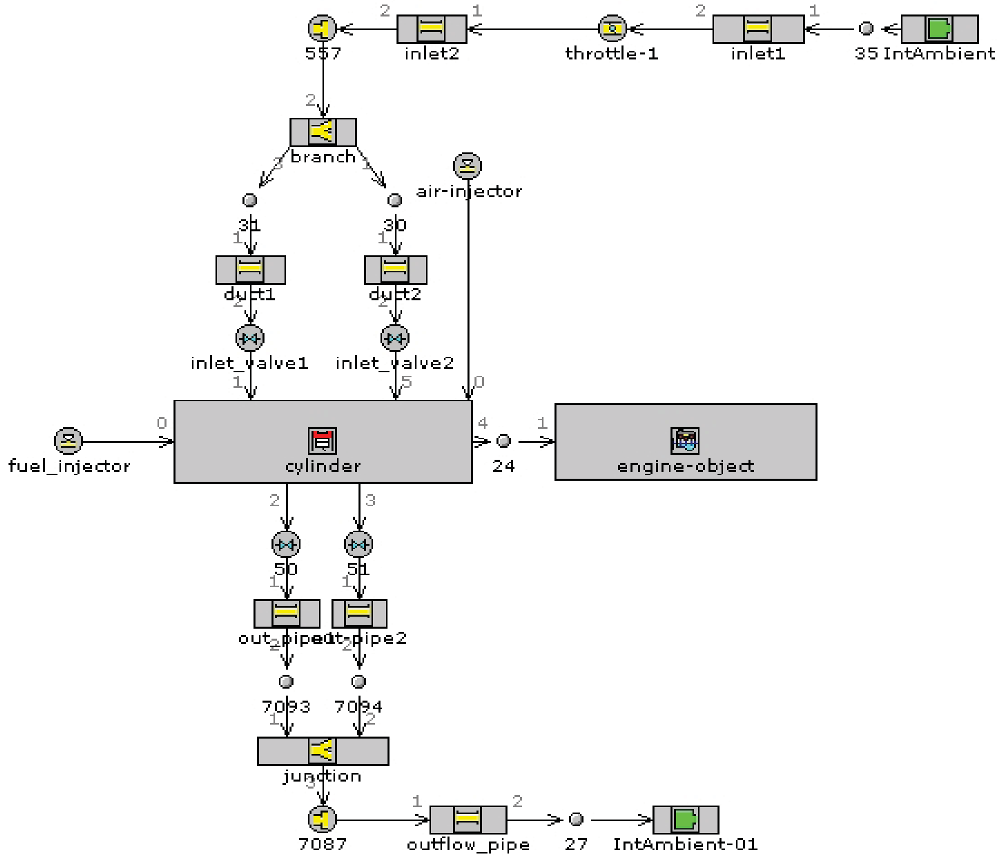

Fig. 2. Diagram of calculating model in GT-Power program

4. Results of calculation

The calculations were carried out for different rotational speeds, filling air pressure and valve control parameters. The results shown here were obtained for constant fuel flow rate 3.8 g/s at beginning of fuel injection 120 deg BTDC, which was not enough for higher rotational speeds. It was assumed constant air injection pressure 150 bar with initial temperature 300 K. Fig. 3 and 2 show pressure traces in the cylinder for standard and hybrid engine at 2500 and 3500 rpm, respectively.

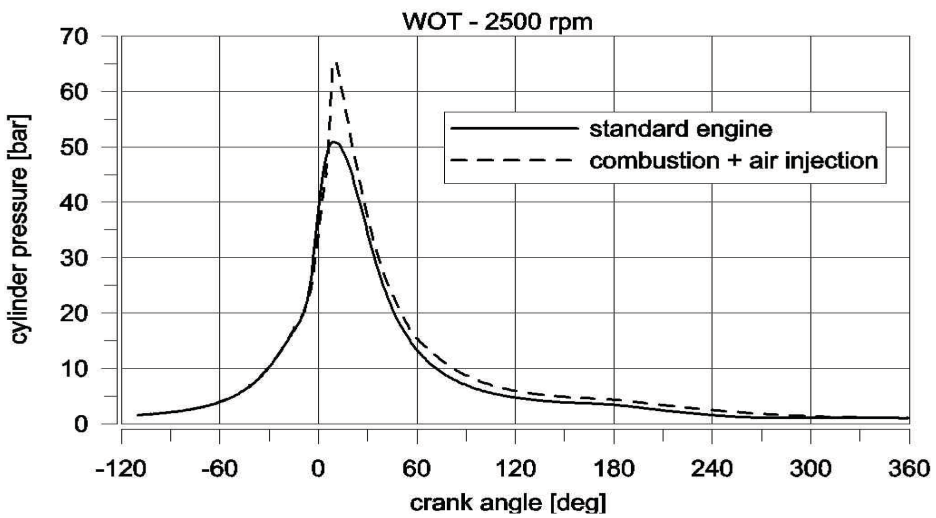

Fig. 3. Cylinder pressure traces in standard engine and with additional air post-injection at 2500 rpm

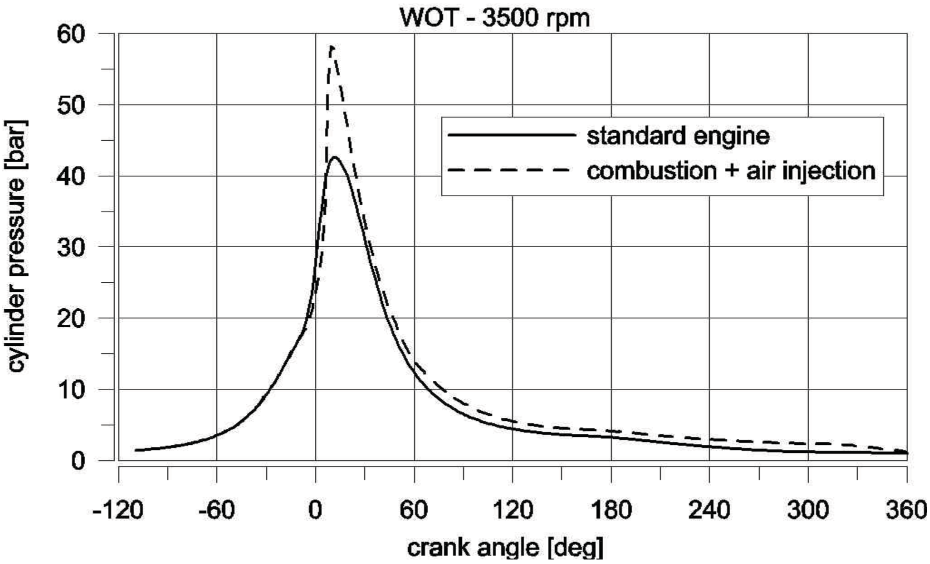

Fig. 4. Cylinder pressure traces in standard engine and with additional air post-injection at 3500 rpm

The air injection took place 5 deg ATDC of piston position and lasted 40 deg CA. On both graphs it is seen an increase of pressure in the cylinder in the hybrid engine. Earlier supplying of air causes lower air consumption and higher internal pressure because of lower volume of combustion chamber.

The cold air causes decreasing of temperature, which is not good for combustion and decreasing of specific internal energy, however decreases thermal loads of walls of cylinder, cylinder head and piston. Variations of temperatures in the cylinder are shown for both engines in Fig. 5 and 6 for 2500 and 3500 rpm, respectively. Both graphs show a big decrease of temperature inside the cylinder after air injection. By increasing of injected air temperature this change is not so big. Low exhaust gas temperature does not enable using turbocharger which is a certain disadvantage. Also low exhaust temperature eliminates using of a catalytic reactor; however results of calculation show a decreasing of CO and NO emission. Highest temperature for both engines is on the same level at constant angle of air injection.

Very interested is variation of indicated mean effective pressure (imep) in function of rotational speeds for the same fuel mass flow rate and valve timings for both engines. Fig. 7 shows about 25% increasing of imep for hybrid engine in relation to standard engine.

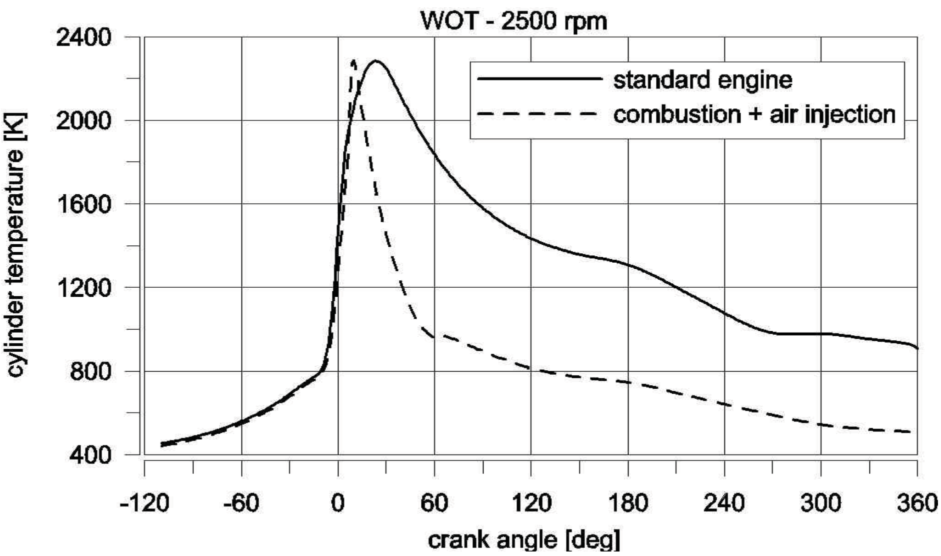

Fig. 5. Cylinder temperature traces in standard engine and with additional air post-injection at 2500 rpm

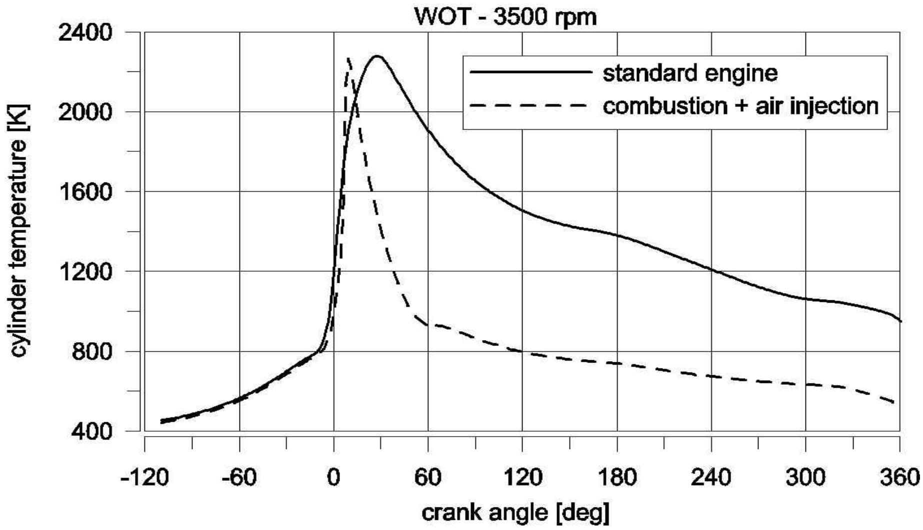

Fig. 6. Cylinder temperature traces in standard engine and with additional air post-injection at 3500 rpm

Increase of imep is attractive for lower rotational speeds and the engine performance is close to compression ignition engines. Applying of hybrid engine is not effective at higher rotational speeds, where imep is the same for both engines and air injection should be given up. The results would be different for change of fuel dose at every rotational speed.

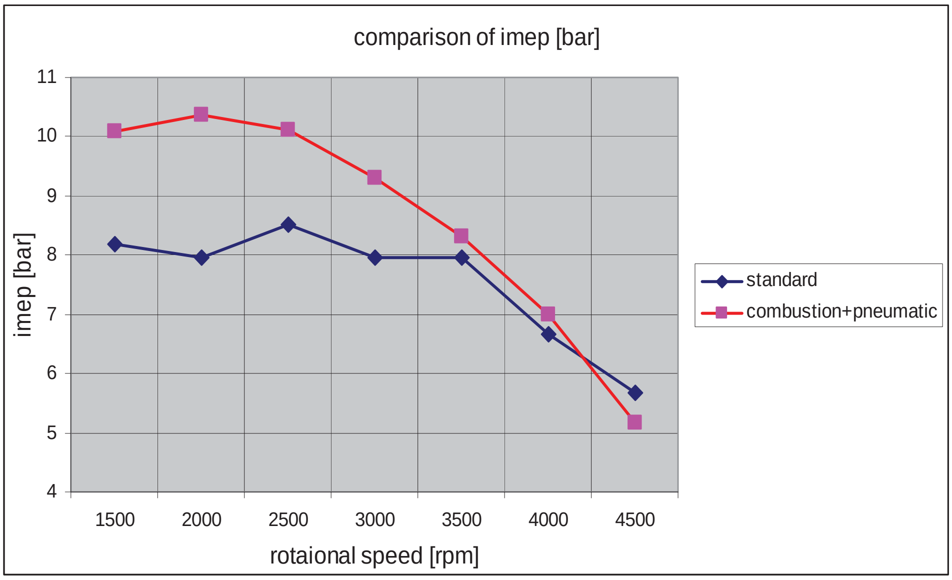

Fig. 7. Comparison of indicated mean effective pressure in standard and hybrid engine

Effectiveness of engine work is assessed by determination of total efficiency which for SI four stroke engine engines is below 33%. The energy delivered to the engine is derived from compression of the air to the bottle and the filling of the bottle can be carried out during deceleration and braking of the vehicle as in classical hybrid vehicles applied on the market, where recovered energy is delivered to the compressor. Numerical calculations show a significant increase of total engine efficiency from 32% to 40% at 1500 rpm for hybrid engine as shown in Fig. 8 and this efficiency is higher in whole range of rotational speed in comparison to the standard engine. For both engines this efficiency decreases with increasing of rotational speed. Total efficiency is calculated from specific fuel consumption. For hybrid engine delivered fuel mass was the same and therefore specific bsfc has lower values for the same rotational speeds (Fig. 9) and is close to values in automotive CI engines about 200 g/kWh.

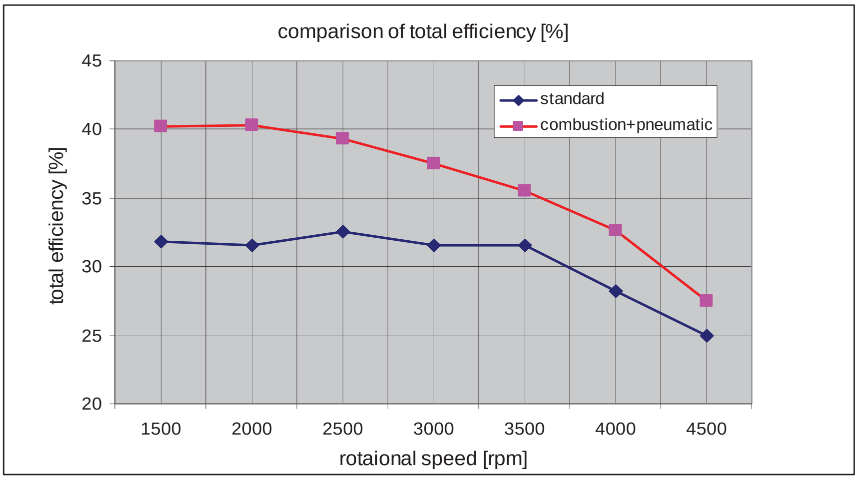

Fig. 8. Comparison of total efficiency in engine with direct fuel injection (standard) and in hybrid engine

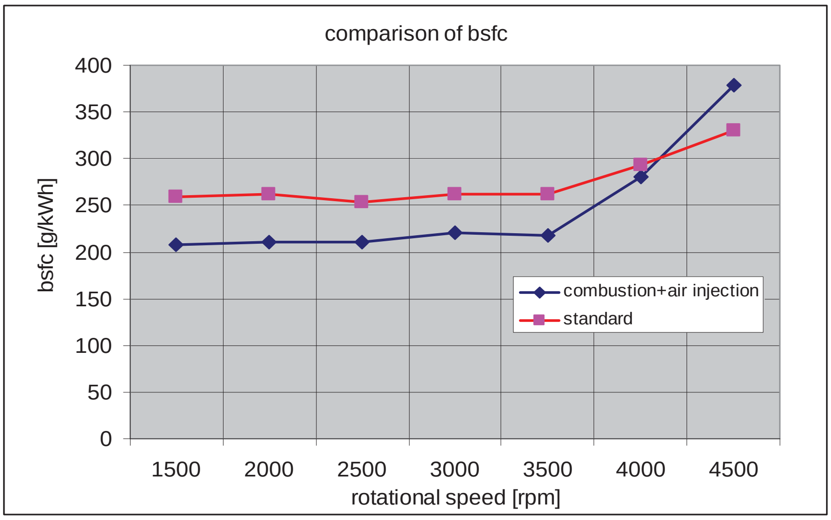

Fig. 9. Comparison of specific fuel consumption in engine with direct fuel injection (standard) and in hybrid engine

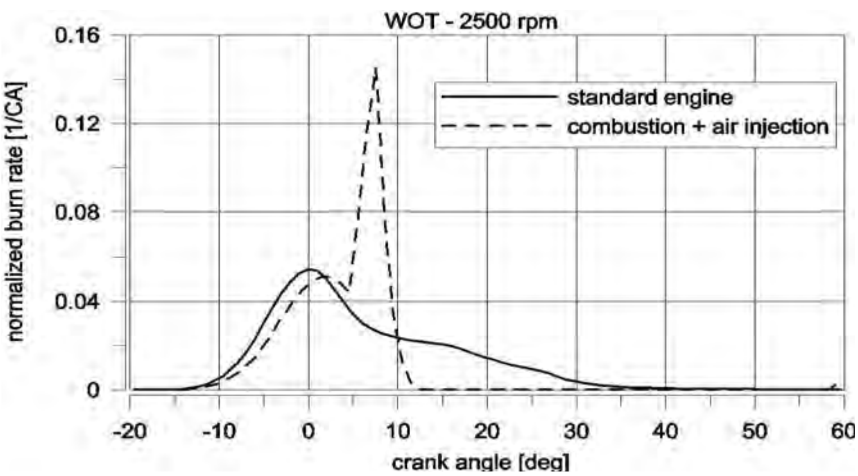

Fig. 10. Comparison of normalized burn rate for standard and hybrid engines at 2500 rpm

Additional air injection causes a shift of highest combustion velocity later. However, the next stage of combustion is very quick with high velocity which is seen in Fig. 10 at 3500 rpm. Full combustion process is finished at CA 13 deg ATDC. Such quick combustion process influences on lower value of CO in cylinder in hybrid engine in comparison to standard engine (Fig. 11). Despite the fact, that on CO concentration influences charge mass, amount of CO in cylinder is several times lower. Investigations show also a big decrease of NO concentration in cylinder.

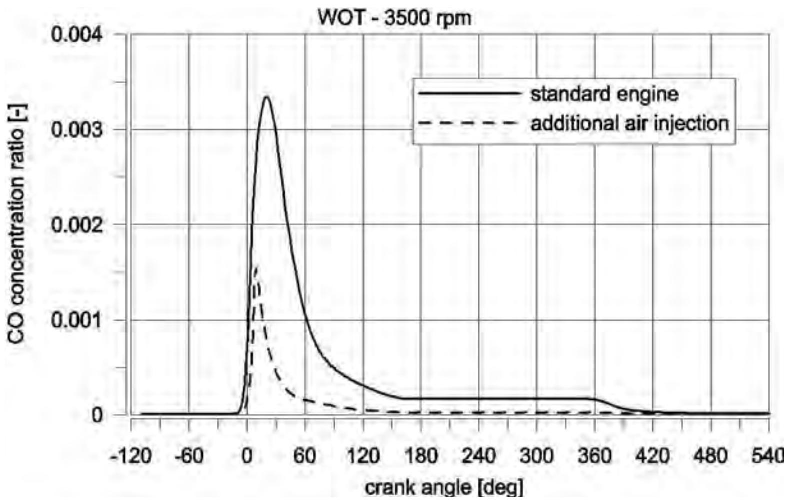

Fig. 11. Comparison of cylinder CO concentration at 3500 rpm for standard and hybrid engines

5. Preliminary conclusions

1. Presented hybrid engine enables achieving higher mean effective pressure in comparison to standard SI engine.
2. Lower temperature of exhaust gases does not allow applying a turbocharger.
3. Applying of additional high pressure air injection above 150 bar increases total efficiency of engine to 40% at lower rotational speeds and decreases specific fuel consumption to values close CI engines about 200 g/kWh.
4. In hybrid engine total time of combustion process is very short and maximum of burn velocity is shifted later in comparison to standard engine. Shifted combustion process takes place with high burning rate.
5. Additional air causes lower CO and NO emission, which is caused by additional oxygen and lowering of temperature in the cylinder.

6. References

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