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Shaping combustion process in SI engine by air injection

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A number of methods was proposed during last decades for shaping the combustion process in SI piston engines [1, 2, 4, 10, 12]. All of them were developed aiming at the decrease of fuel consumption and the search for reduction of pollutant emissions. None of those methods however was effective enough to be widely applied and to stop the need for farther research in that direction.

One of the methods recently proposed was the attempt to influence the combustion process initiated by the conventional spark ignition with the air jet introduced in the combustion chamber from outside [11]. The method, known as the Jet Dispersed Combustion (JDC), was intensively investigated during recent years with the use of the model experimental set-ups (combustion bombs, single compression machines and single cylinder research engines) as well as the actual production car engine [3, 5–9]. The results of the studies have shown that the air injection to the combustion chamber after the combustion process was initiated has a potential to stimulate combustion and to utilize the heat released in a more efficient way. The JDC method allows for the intensification of the heat release process and to increase by that the peak cycle pressure and the work of the cycle. The air injection can be used for shaping of the pressure profile increasing significantly magnitude of the cycle mean effective pressure, improving engine cycle-per-cycle variability and positively influencing the pollutant emissions.

I. Introduction

The general idea of the presented method is to use combustion gases from the burning zone, initiated by the conventional spark ignition, as a source of hot, chemically active gas particles and to disperse them throughout the remaining volume of the chamber (Fig. 1). The kinetic energy of the air jet introduced into the chamber from outside is used as a driving force to disperse the combustion products from the primary combustion zone. The air jet penetrates through the primary zone and its action removes the hot gases ouf of that zone helping them to mix up with unburned mixture and also serving as the turbulizer. This creates the effect similar to well known Toyota TGP combustion system but here the action of the prechamber is substituted by the operation of the air jet. This gives the unique opportunity to influence the combustion process after it was initiated.

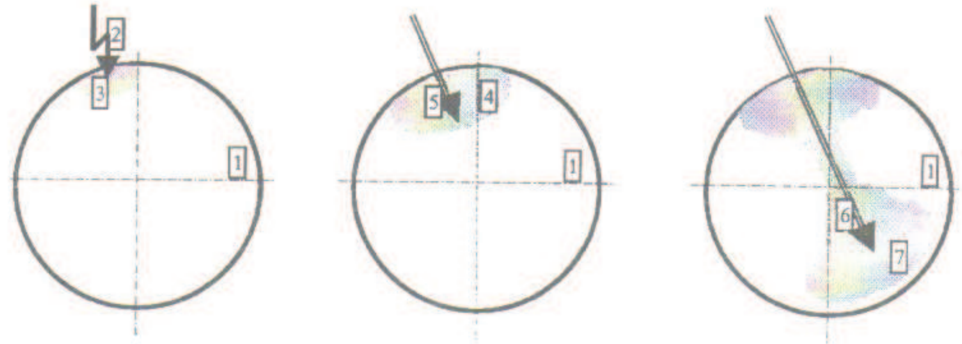

Fig. 1. Three stages of the combustion process shaped by the air jet; 1 — combustion chamber, 2 — ignition spark, 3 — primary combustion zone, 4 — primary combustion zone (big enough after a certain time), 5 — air jet (start of the injection), 6 — air jet (end of the injection), 7 — secondary combustion zone (effect of the jet action)

2. Combustion bomb study

Combustion bomb study revealed that two different combustion mechanisms can be observed [11]. One of them, described as the "thermal" one, occurs when the primary combustion zone is large enough. The air jet is passing through that zone and is convecting the combustion gases toward the unburned mixture. This creates the phenomenon similar to that known as the torch ignition. During the injection period the highly turbulized combustion zone is created with the high rate of heat release. Right after termination of the injection the turbulence tends to decrease and whole combustion process slows down due to its laminarization. The pressure-time profile of the process is shown in Fig. 2a. The change of the pressure rise rate (inclination of the pressure trace) after about 30 ms from ignition corresponds to the time when highly turbulent combustion, stimulated by air jet becomes slower and slower after the jet action was terminated. The word "thermal" was used for this

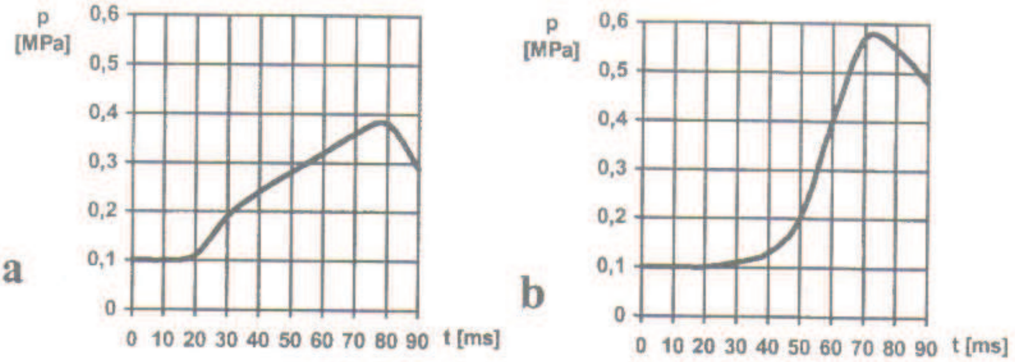

Fig. 2. The pressure-time profiles in the constant volume bomb; a — "thermal" mechanism, b — "chemical" mechanism

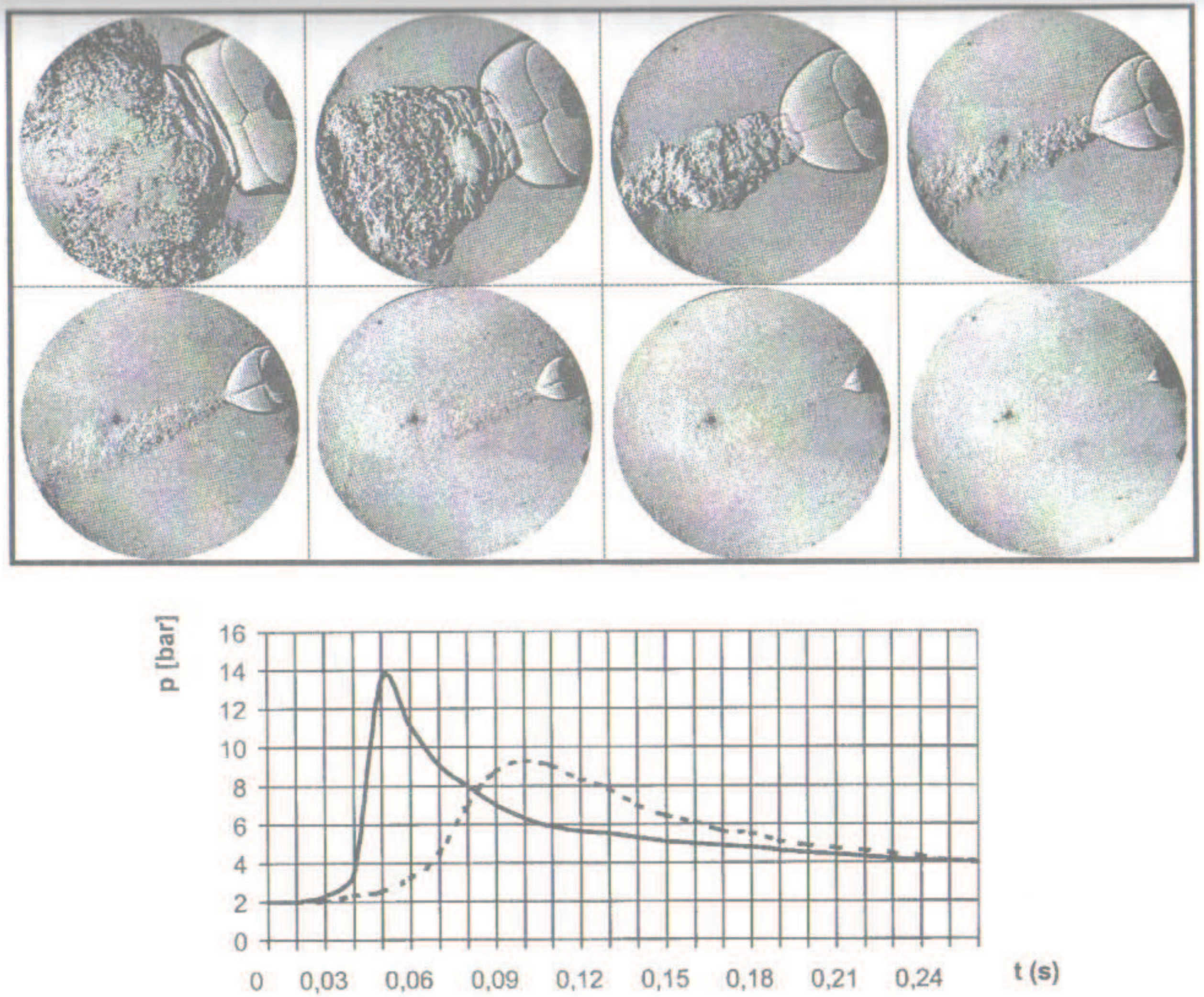

Fig. 3. Succeeding stages of the combustion in the constant volume bomb (injection through central electrode of the spark plug). Continuous line — corresponding pressure-time profile. Dashed line — pressure-time profile for no-injection case (for comparison)

case because the thermal energy carried out by gas particles is supposed to be an important factor which is enhancing combustion. This mechanism was observed almost within the whole range of the experimental conditions studied.

Another mechanism, called "chemical", was observed when the injection took place earlier. At that time the primary combustion zone was much smaller. The jet removes the combustion gases from that zone spreading them out as it was before. The primary zone shrinks and eventually can entirely vanish as it was demonstrated in [11]. In this case however the concentration of the hot and chemically active gas particles dispersed in the unburned mixture is too small to sustain visible combustion although the chemical reactions are still in progress. After several milliseconds the reignition of the charge takes place in the volumetric-like mode. The burning rate in this case is much higher (Fig. 2b) but the pressure starts to increase much later than in the "thermal" case. The word "chemical" for this mechanism was used because it looks that here the combustion chemistry, and especially chemical reaction intermediate products play an essential role.

The extensive experimental studies performed with the use of the constant volume combustion chamber proved that the system is insensitive on the type of the injected gas: it was no difference in the results when the air, the same mixture as in the chamber and the inert gas (argon) were used as injection gases. This indicates that the dominant driving force in such system is the kinetic energy of the jet rather than its internal energy. Moreover, it has been proved that the amount of the injected gas can be very small, negligible in comparison with the volume of the combustion chamber. Also injection duration is unimportant. The parameter of the primary importance is the injection timing with respect to the spark ignition.

Very important from the practical point of view is the observation that the air jet can serve as a tool to direct the spreading of the combustion zone in the required direction. This is illustrated in Fig. 3. The conventionally initiated primary combustion zone is disturbed by the jet introduced in this case via the orifice in the central spark plug electrode. Evidently the combustion zone spreads in the direction "marked" by the jet. The registered simultaneously pressure traces demonsrate significantly increased burning rate for the case with injection when compared with the non-injection case (laminar burning).

3. Combustion observation in a research engine

The special single cylinder research engine was used for this part of the study. The combustion process was observed and registered by means of the high speed camera (1000 frames/sec) and the schlieren system. Optical access to the combustion chamber was assured in the direction of the cylinder axis through transparent cylinder head and piston crown. Methane-air mixture, premixed in the induction tube, was used in the stoichiometric proportions.

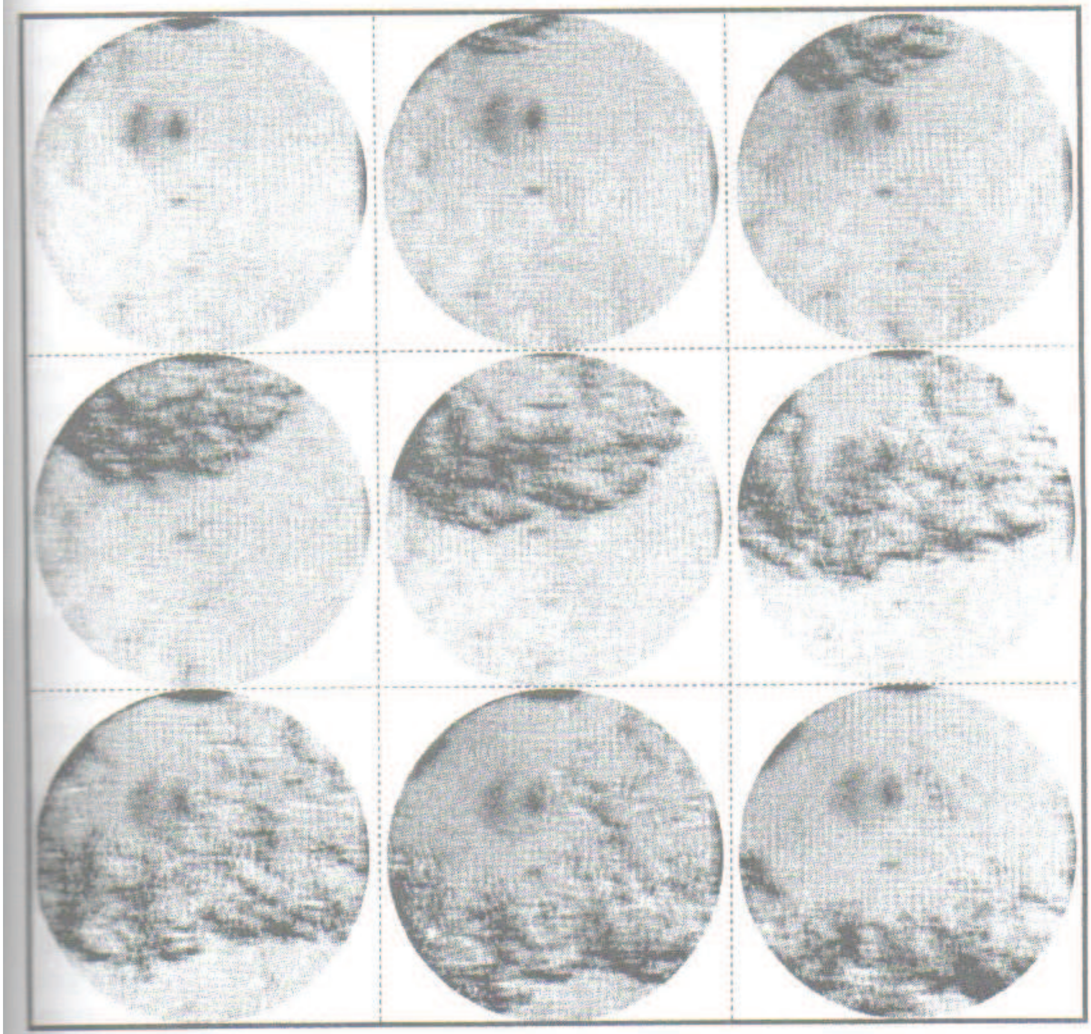

Fig. 4. Succeeding stages of the combustion in the single cylinder research engine without the action of the air injection

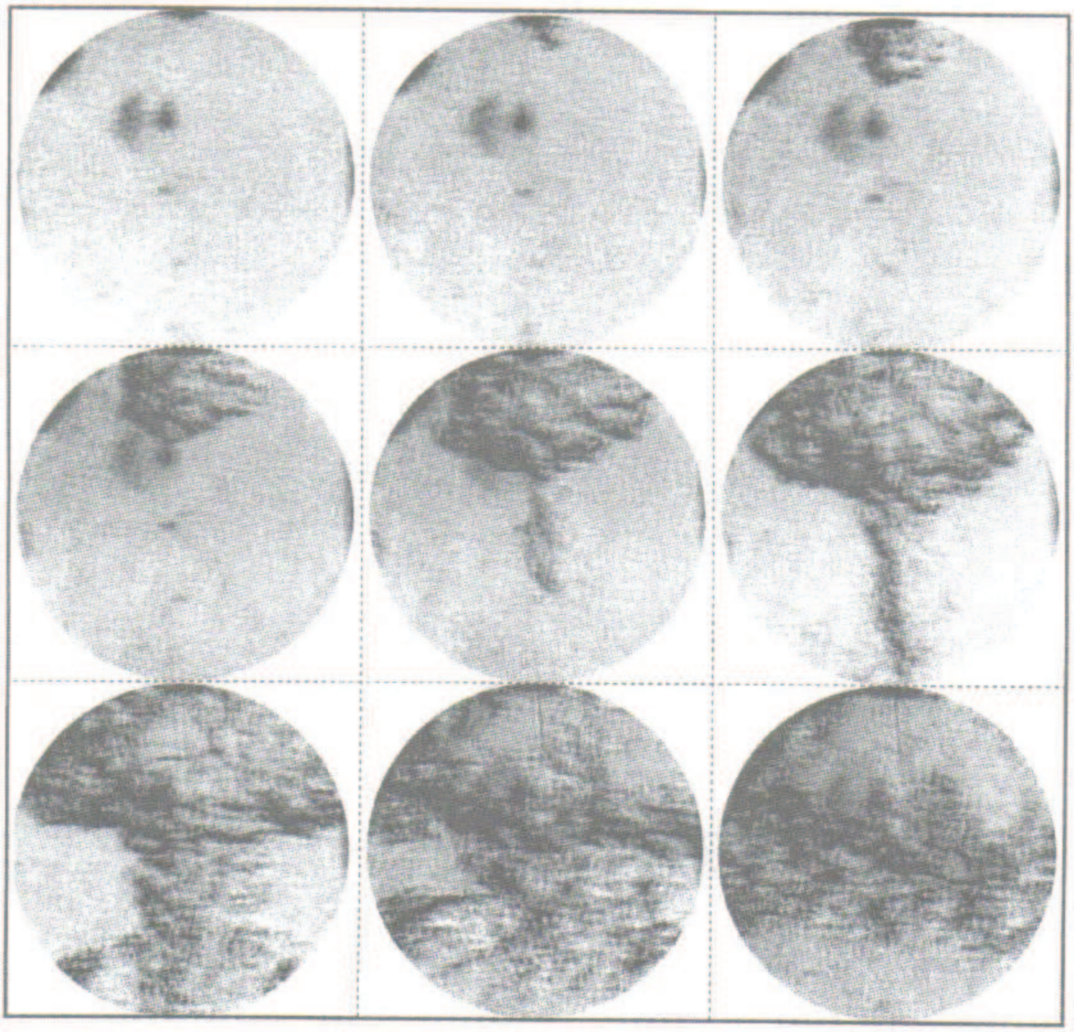

Fig. 5. Succeeding stages of the combustion in the single cylinder research engine with the action of the air (injection through central electrode of the spark plug)

Series of the framed pictures of the combustion processes without and with the action of the air jet are presented in Fig. 4 and Fig. 5 respectively. The qualitative comparison of these two series of pictures evidently shows the presented method of combustion stimulation (JDC) can be applied also to the engine combustion system and it can be quite effective. Practically all the positive effects observed during the combustion bomb experiments appear also in the engine. The action of the air jet is able to enhance significantly combustion process and also has the potential to be used to direct the flame propagation in the required region of the combustion chamber.

4. Investigation of an actual engine

It is evident that the results obtained with the use of the model experimental setups can not be directly related to a real production engine. Firstly, time to complete combustion in the engine at each cycle is an order of magnitude shorter than in the combustion bomb and even in the slow running research engine. Secondly, the turbulence intensity level is much greater in the engine than it was during the constant volume bomb studies. So, the preliminary tests were primarily devoted to check the technical arrangement of the injection system and to answer for fundamental question: will the engine combustion system react on the injection at all?

4.1. Engine

The production FSM 126A1 (650) engine was used. The injection system was applied to only one of two engine cylinders. The second cylinder was operating in the conventional way. All the engine operational parameters remained unchanged. During the course of investigations following parametes were adjusted: spark advance angle, idling speed, mixture strength at idle and discharge rate of the main carburetor nozzle.

The air was injected either through the central electrode of the spark plug or with the use of the separate injection nozzle located in the cylinder head below the spark plug (Fig. 6). The nozzle orifice diameter was always 0.7 mm except the version *f*, where the diameter of each single orifice was 0.22 mm which gave the total discharge area the same as it was for the single orifice.

The air was used as an injection gas. The series of experiments were also performed where the argon was injected. These tests confirmed the previous conclusion that the type of the injected gas is practically unimportant.

Beginning and end of the injection, or being more precise — the generation of the electric impulses for opening and closing of the fast acting solenoid valve was controlled with the precision of the one degree of the crankshaft revolution. The injection and the spark were activated by the electronic control unit coupled with the indicator of the crankshaft angular position.

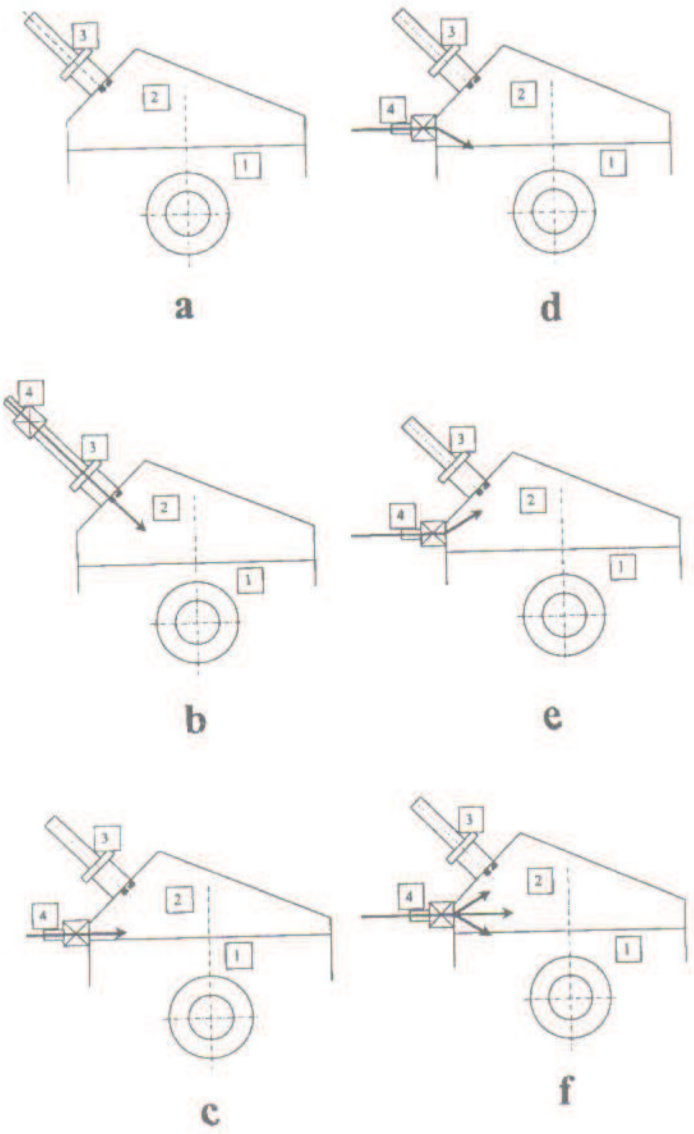

Fig. 6. The schematic of the injection arrangements investigated in the actual engine; a — combustion chamber without air injection, b — combustion chamber with air injection through central electrode of the spark plug, c — combustion chamber with air injection parallel to the piston crown, d — combustion chamber with air injection toward piston crown, e— combustion chamber with air injection toward spark plug, f — combustion chamber with air injection through multi-orifice nozzle, 1 — piston crown, 2 — combustion chamber, 3 — spark plug, 4 — electromagnetic valve to control the injection timing

4.2. Experimental setup

The experimental test rig was equipped with the Indiscop to register the pressure profiles which were subsequently the subject of the on-line analysis of the heat release.

The composition of the combustion gases from the investigated cylinder was measured and registered for the following species: CO, HC and NO_x. The exhaust gas temperature was also measured by means of thermocouple located in the middle of the exhaust pipe about 0.3 m behind the exhaust valve.

The injection pressure at idle was 8 bar. It was set on the level which allowed for the slightly undercritical flow through the injection orifice. The injection pressure at the partial and full loads was 20 bar. Its magnitude was limited by the practical limitation of the high speed solenoid valve. The injection time was as short as it was possible because of the inertia of the solenoid valve. During preliminary test it was observed that the time when the valve is opened does not have any influence on the combustion process. This statement is supported by the observation that the fast pressure rise in the combustion chamber after combustion initiation automatically terminates injection (due to diminished pressure difference at both sides of the valve) and shortens by that injection period. During engine idling conditions the valve controlling injection was opened during 8 deg CA and at partial and full loads it depended on the engine speed: from 15 deg CA at 2000 rpm to 30 deg CA at 4000 rpm.

It was estimated that the mass of the injected air is negligibly small in relation to the mass of the whole charge. In the extreme case (i.e. during idling) when the mass of the charge is small the fraction of the injection air in the whole charge did not exceed 3%. At the increased load of the engine the mass of the charge increases and therefore the fraction of the injected air gets smaller and smaller.

4.3. Pressure profiles

Pressure profiles in the engine cylinder at the different injection timing are presented in Fig. 7. The typical pressure trace for the idling engine with no injection is shown in Fig. 7a (thick line) and the trace for the motored conditions (thin line) is introduced as a reference. It can be seen that very slow combustion in idling engine does not cause any increase of the peak cycle pressure. The combustion itself was not very stable at this case (relatively high cycle-per-cycle variation) and the time of the combustion was long.

Injection of the air activated long before the spark ignition resulted in the higher peak pressure value. It is so because the greater mass burning speed was caused by turbulizing action of the jet. Registered pressure traces for every investigated injection direction were of the character shown in Fig. 7b. The magnitude and the peak pressure angle depended significantly on the injection direction because at each case the region of the combustion chamber turbulized by the jet was different. The greatest pressure rise was with the injection directed toward the piston crown (Fig. 6d) i.e. up to 8 bar. For any other injection direction lower peak pressure values were observed.

Similar pressure rise was observed at the case when the injection was activated along with the spark ignition (Fig. 7c) or when injection was delayed with respect to the ignition. The significant pressure rise rate appeared always immediately after injection. For the injection directions shown in Fig. 6bcd the peak pressure values

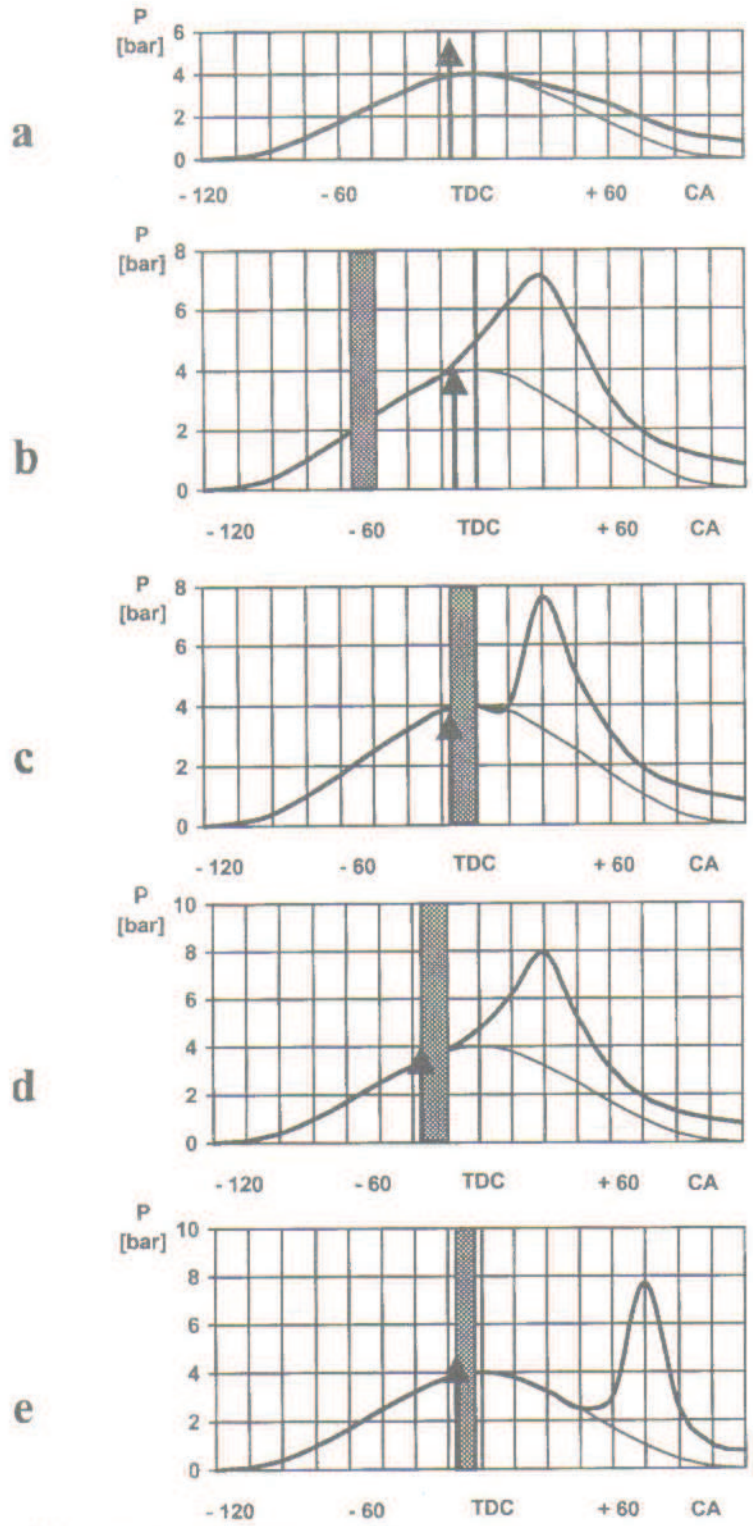

Fig. 7. Series of the pressure profiles registered at various injection timing — engine idling (the arrow symbolises ignition spark, the rectangle symbolises air injection, the thin line corresponding to engine motored); a — without injection, b — injection before the ignition, c — injection and ignition in the same time, d — injection and ignition in the same time — spark advance increased, e — combustion reinitialisation case (after blowing away the flame by the jet)

were relatively high at the level of the 8 bar. The injection in remaining directions also resulted in higher pressure values (from 4.5 to 6 bar) but no as significant as before. In these cases it is very probable that the JDC combustion mechanism is responsible for the pressure rise. The phenomenon of the combustion stimulation in the air jet direction is also very probable. This statement is supported by the fact that the greatest effects are observed for the cases with injection via central spark plug electrode and toward the spark plug (Fig. 6be); in the cases the possibility of the direct interaction of the jet with the burning zone is the greatest. The multi-jet injection was not effective probably because of the low penetration ability.

It appears that in all the presented cases combustion stimulation occurred too late from the practical point of view. It was so because during series of tests the spark advance angle was kept constant. A correction of the shape of the pressure profile however can be made by increasing the spark advance. This is demonstrated in Fig. 7d, prepared for the injection in version shown in Fig. 6a. The increase in spark advance angle results in conventional-like shape of the pressure trace and the peak pressure is even higher than before.

Sometimes another interesting case could be observed. The jet action seemed to terminate combustion because the pressure profile for the time being was the same as for the motored conditions (Fig. 7e). The combustion peak pressure appeared after the significant delay period and the pressure rise rate was very high. It might be the case corresponding to the combustion mechanism denoted before as the "chemical" one.

For all tests run at idling engine conditions it was measured that the air injection was causing remarkable, up to almost two-fold increase of the mean effective pressure (Fig. 9a). The magnitude of that increase was dependent on the injection direction and in most efficient cases (i.e. — injection via central spark plug electrode and in the direction parallel to the piston crown) reached even 70%. The increase of the mean effective pressure usually brought along the rise of the engine speed of about 100 – 200 rpm.

The influence of the injection was observed in the whole range of the engine operational conditions. The character of the changes of the pressure trace for loaded engine is introduced in Fig. 8. The injection results — as it was at the idling case — in increase of the peak cycle pressure, higher pressure rise rate and greater mean effective pressure (Fig. 9b). All the injection directions were effective but the best results were obtained at the directions presented in Fig. 6bcd.

The phenomena observed are coupled with the acceleration of the burning process and this, in turn, results in shortening the time for heat exchange between the combustion gases and cylinder walls (lower heat flux to the walls). The better mixing of the fuel and air caused by the turbulizing action of the jet also influences the in-cylinder processes.

The influence of the injection on the combustion process is diminished along with the increase if the engine load. It can be speculated however that it is the result of the weaker penetration of the jet along with the increase of the load (lower pressure difference upstream and downstream of the injector) than the feature of the system

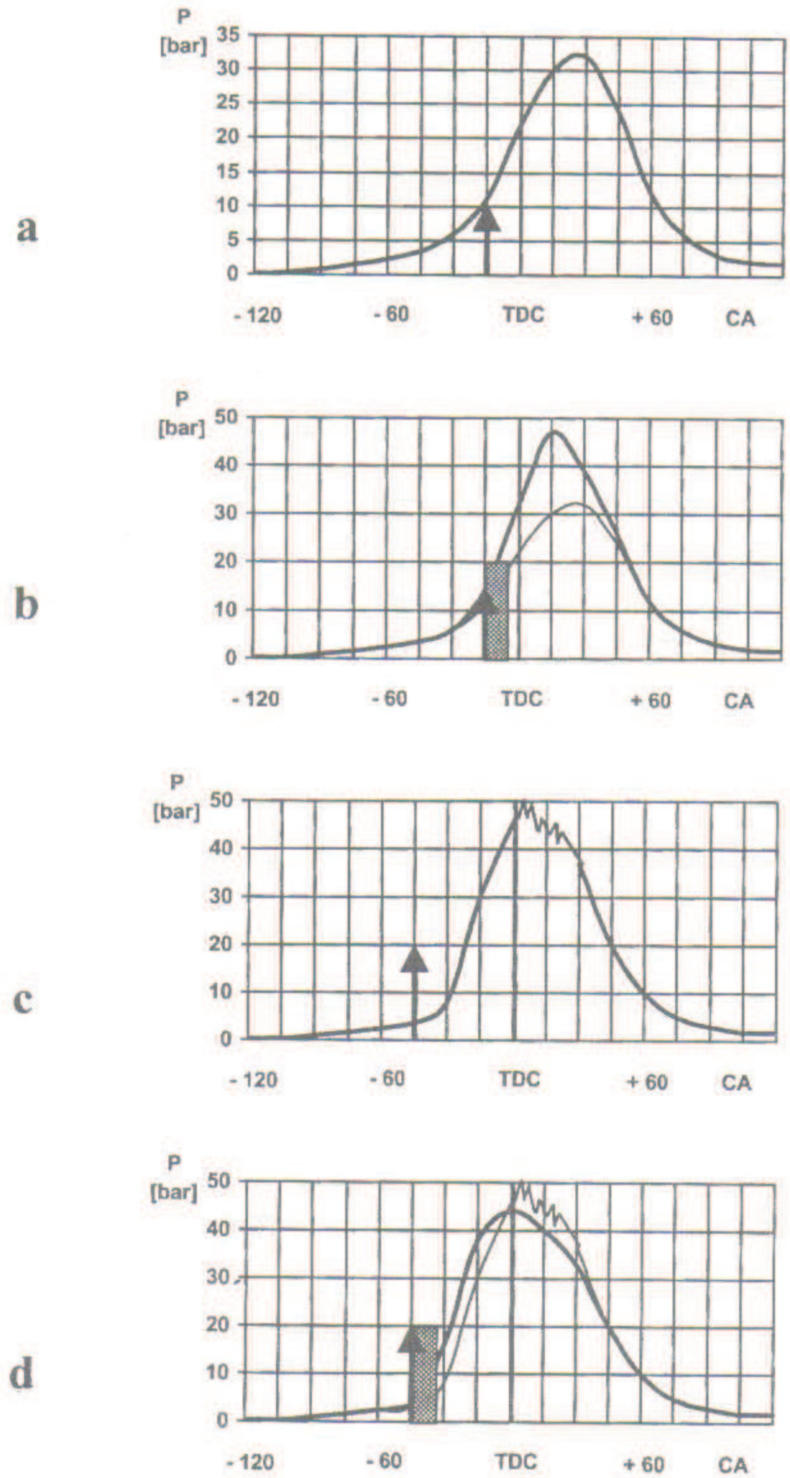

Fig. 8. Influence of the injection on pressure profiles — 50% load (the arrow symbolises ignition spark, the rectangle symbolises air injection, the thin line corresponding to no-injection case); a — without injection, b — with injection, c — spark advance increased without injection (knocking), d — spark advance increased with injection (knocking eliminated)

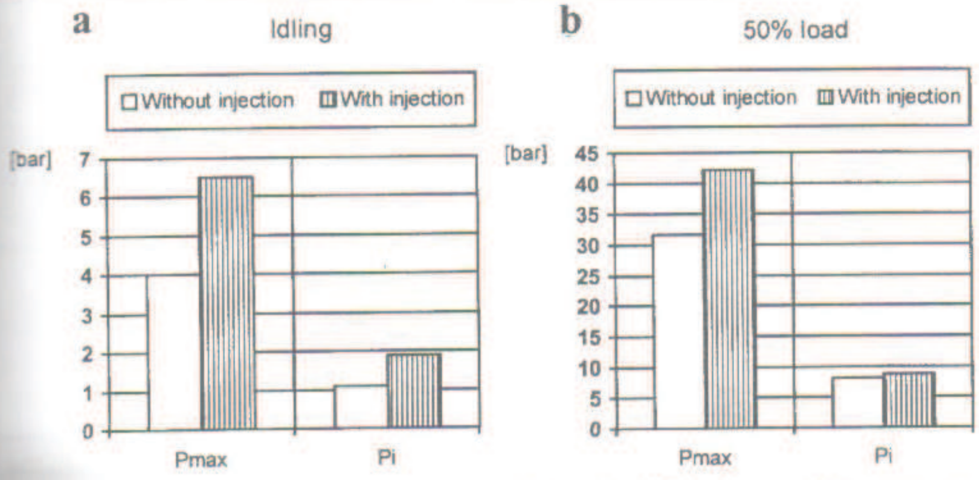

Fig. 9. Influence of the air jet on cycle peak pressure P_{max} and on indicated mean effective pressure P_i (injection through spark plug central elecrode); a — idling, b — partial load

itself. The sudden pressure rise after ignition at full load already in several degrees CA exceeded the injection pressure shortening by that actual period of the injection valve opening. It is quite probable that the JDC method of combustion stimulation will be also very effective at full load when the technical difficulties to increase injection pressure would be obviated.

The experiments have shown that the air injection can also stimulate knocking combustion because of the increased pressure rise rate and the higher peak pressure value. Also excessive spark advance is disadvantageous from that point of view (Fig. 8c). On the contrary, the air injection, especially in directions shown in Fig. 6bdc removes the traces of knocking combustion, burning process proceeds longer and the peak pressure is lower (Fig. 8d).

During the course of investigations it was discovered that the degree of the influence of the air injection was independent of the mixture stoichiometry. A the lean side of the stoichiometry the application of the injection resulted in the tendency for combustion termination.

The measurements of the cycle-per-cycle variability were also performed. The standard deviations of the cycle peak pressure, its angle of appearance and the mean effective pressure were taken as criteria. The air injection was increasing the variability of the peak pressure and the angle of its appearance for idle run of the engine. The cyclic variability of the mean effective pressure was improved for enriched mixtures and it was increased for the lean and "normal" mixtures, when "normal" means the mixture prepared by the production carburetor. The negative influence of the jet under this respect comes out from the tendency to distinguish combustion by the jet action under conditions where the mass of the charge in the cylinder is small. This tendency was not observed at increased load of the engine when the influence of the jet action on cyclic variability was always positive (Fig. 10).

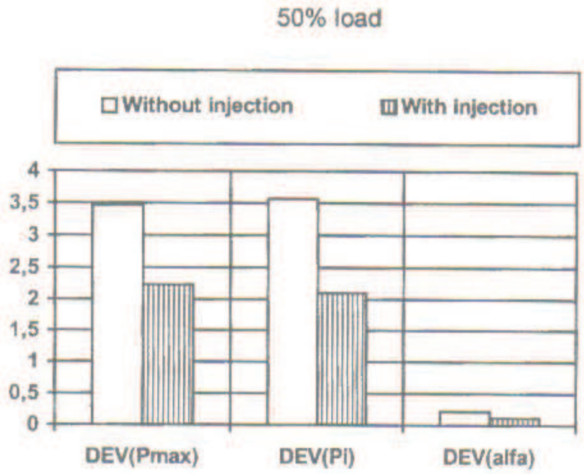

Fig. 10. Influence of the air jet on the cyclic variability at partial load (injection through spark plug central electrode). DEV (P_{max}), DEV (alfa), DEV(P_i) — cycle-to-cycle variations in cycle peak pressure, corresponding crank angle and indicated mean effective pressure

4.4. Analysis of the exhaust gases

The results of the investigations indicated the significant influence of the air injection on the pollutant emissions. For idling conditions, at the production carburetor settings, great decrease of the carbon monoxide concentration (up to ten-fold) was observed when the injection was activated. At the same time the concentration of the unburned hydrocarbons increased remarkably. The reason for that is — as it was before in the cyclic variation analysis — the tendency to distinguish the flame by the jet action. Also the two-fold decrease of the exhaust gas temperature and, by that, remarkably lower nitric oxide concentration was observed. Mixture enrichment caused still lower concentration of the pollutants. Finally, significant reduction of the carbon monoxide and moderate reduction of the nitric oxide was measured in the case with injection in comparison to the non-injection version, when the HC concentration remained practically on the unchanged level (Fig. 11a). The point has to be stressed that the same degree of the purity of the exhaust gases was impossible to obtain only in the way of the optimal carburetor adjustment (with no injection). The exhaust gas temperature remained always lower for the system with injection than without it (Fig. 12a).

For the half and full load of the engine the injection activation always resulted in remarkable reduction of the pollutant emissions (Fig. 11b).

The air injection, independently of its direction, always lowered carbon monoxide concentration (sometimes many-fold) and remarkable reduction of the unburned hydrocarbons content (about 40%). The air injection practically has not influence on the nitric oxide concentration. At the full and partial load of the engine the air injection also stimulates exhaust gas temperature decrease (Fig. 12b). It was not

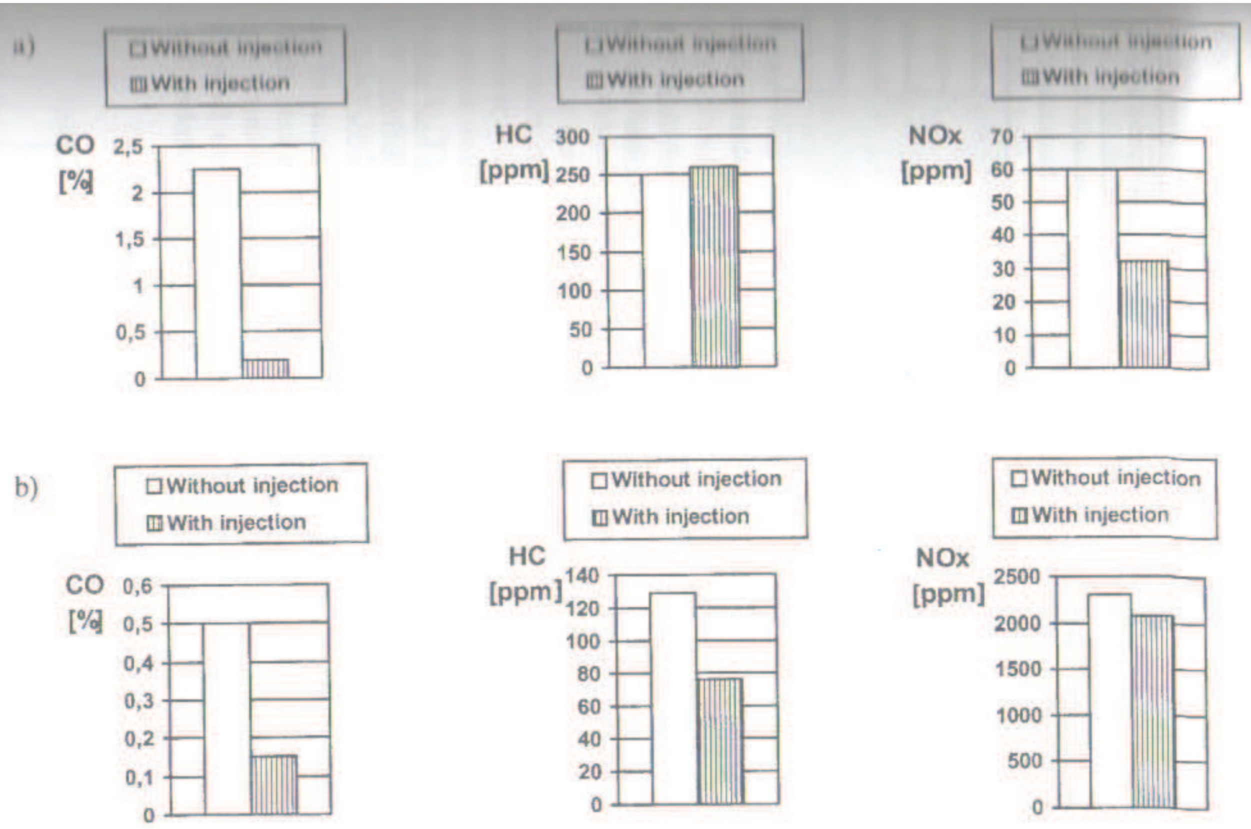

Fig. 11. Decreasing of the CO, HC and NO_x concentration in the exhaust gas after injection application (injection through spark plug central electrode); a — idling, b — 50% load

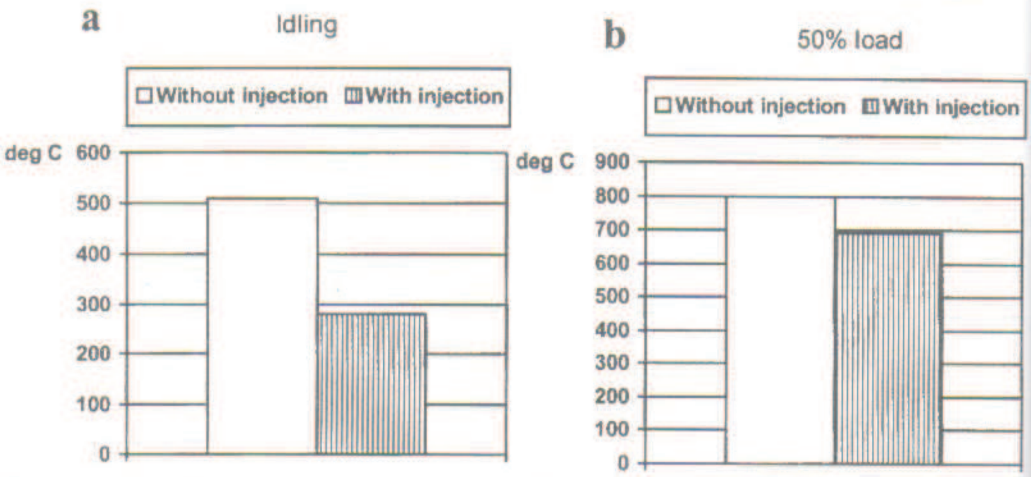

Fig. 12. Influence of the air jet on the exhaust gas temperature (injection through spark plug central electrode); a — idling, b — partial load

observed any dependence of the injection delay time on the pollutant emissions. The exhaust gas composition was also insensitive on the injection direction. All the injection directions show up similar effectiveness under this respect.

4.5. Heat release analysis

Idling

One of the most effective injection directions was taken as a base for the heat release analysis, and namely the injection via the orifice in the central spark plug electrode. The single pressure profile registered during the course of the investigations was considered.

The first of the analysis is that the air injection during the initial phase of the combustion process causes the process deceleration. In the no-injection case about 10% of the heat was released up to 0.8 deg CA but when injection was activated — up to 8.1 deg CA. It results from the dispersion of the combustion products from the primary combustion zone in the remaining volume of the combustion chamber. This

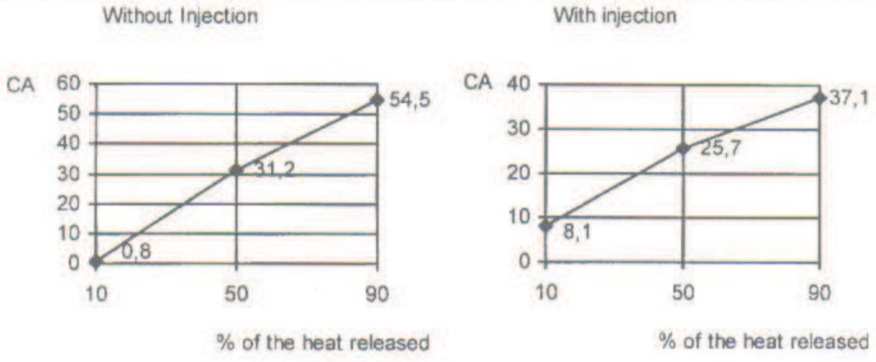

Fig. 13. Illustration of the combustion acceleration being the effect of the air jet (idling — injection through spark plug central electrode)

leads to the significant combustion process acceleration however during later phase of the burning which is in accordance with the JDC combustion mechanism introduced before. Eventually the combustion process ends earlier in the system with injection than in the no-injection case. This is illustrated in Fig. 13. For the case with injection 50% of the heat is released at 25.7 deg CA but 90% — at 37.1 deg CA. The corresponding values for the no-injection case are: 31.2 and 54.5 deg CA.

The heat release rate measured in kJ/kg·deg CA for the injection case reaches much higher values: its maximum appears at 29.0 deg CA and the value is 33.7 kJ/kg·deg CA. The corresponding numbers for the no-injection case are: 34.0 deg CA and 10.8 kJ/kg·deg CA. This comparison indicates that the heat release rate is about tripled for the injection case in relation to the case without injection. The significant combustion acceleration and, by that, shortening of the time for the heat exchange with the combustion chamber walls is very important and it is advantageous from the point of view of the energy balance and the engine thermal efficiency. The introduced analysis has shown that the air injection stimulated release of the twice as much energy than for the no-injection case (increase from 358 kJ/kg to 696 kJ/kg) and this resulted in the increase of the cycle work.

The heat release analysis gave interesting results regarding the combustion gas temperature. The maximum in-cylinder temperature without injection is at 61 deg CA. For the injection case, because of the combustion acceleration the maximum in-cylinder temperature is reached already at 42 deg CA and it is about twice as high as before. The time available for the heat exchange between the burned gases and the chamber walls is remarkably longer and by that the exhaust gas temperature is lower (Fig. 14). This explains the controversy among the three observed effects of the injection application: the combustion acceleration, the increase of the mean effective pressure and the lowering of the exhaust gas temperature.

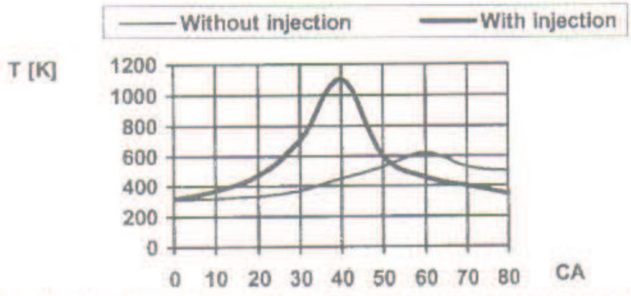

Fig. 14. Combustion chamber charge temperature (idling, injection through spark plug central electrode) — temperature profiles explain the reason of the exhaust gas temperature decrease after injection application

Load

For this case the heat release analysis was based (as before) on the single registered pressure profile for the half- and full load of the engine for the injection via the central spark plug electrode.

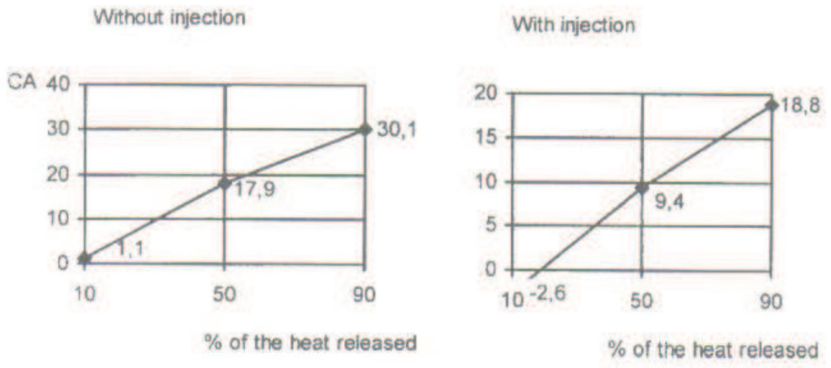

Fig. 15. Illustration of the combustion acceleration being the effect of the air jet (25% load — injection through spark plug central electrode)

The combustion process acceleration was observed for the partial load (25%) of the engine (Fig. 15). It was not however registered the combustion deceleration during the initial phase of the combustion process as it was at idle. In this case the ability of the jet to influence the initial combustion phase is weaker because of greater mass of the fresh charge and smaller fraction of the combustion gases from the previous cycle in the cylinder. The action of the injection is however efficient because about 90% of the heat was released already at 18.8 deg CA ATDC. For the case of the conventional combustion such amount of heat was released later at 30.1 deg CA. The heat release rate determined in kJ/kg·deg CA for the injection case reaches greater values than for no-injection case: its maximum appears at 13.0 deg CA and it is 129.6 kJ/kg·deg CA. Corresponding numberes for the no-injection case are: 21.0 deg CA and 77.7 kJ/kg·deg CA. The action of the injection under these conditions increased the total amount of the heat released about 24%.

For the engine higher loads (between 50% and 100%) the air injection also causes the combustion acceleration and the increase of the magnitude of the mean effective pressure (Fig. 16 and 17) although the improvement is not so remarkable as it was at lower loads. It is in accordance with the results of the previous investigations [5–9]

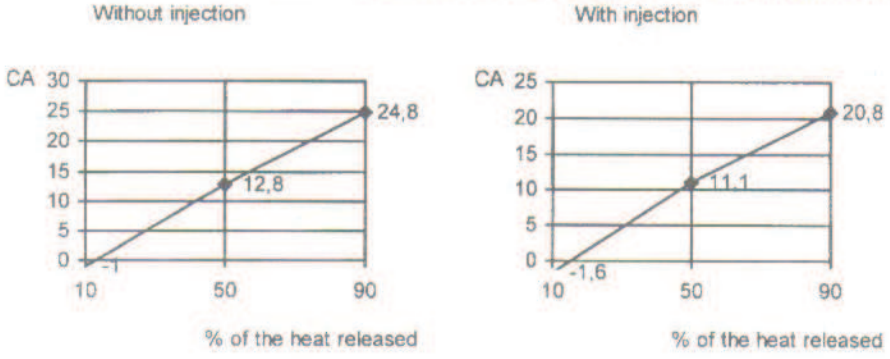

Fig. 16. Illustration of the combustion acceleration being the effect of the air jet (50% load — injection through spark plug central electrode)

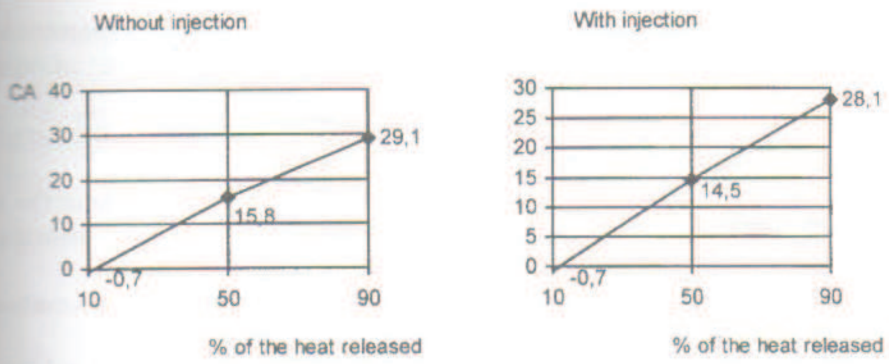

Fig. 17. Illustration of the combustion acceleration being the effect of the air jet (full load — injection through spark plug central electrode)

where it was concluded that the influence of the air jet is diminishing along with the increase of the engine load. This comes out from the fact that at greater engine loads the ability of the jet to penetrate the combustion chamber becomes weaker as it was discussed before. The tendency to lower the exhaust gas temperature was also observed at the high loads of the engine despite the fact that at these conditions the in-cylinder temperature was higher with injection than without it. The explanation of that phenomenon is presented in Fig. 18 (analogously to the explanation discussed for the idling conditions).

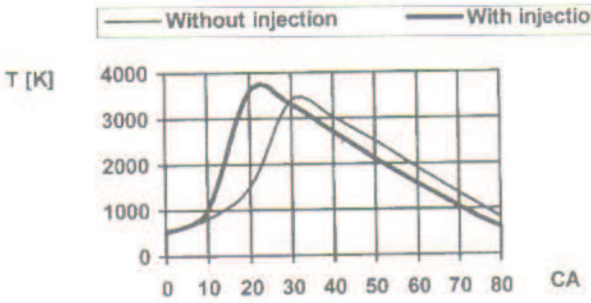

Fig. 18. Combustion chamber charge temperature (50% load — injection through spark plug central electrode)

5. Summary

The introduced investigations clearly indicated that the air jet can be the effective tool to shape the combustion process in SI piston engines. The following conclusions can be drawn:

1. The air jet can be effective practically at any region of the engine operational conditions. The decrease of the effectiveness of the jet action along with the increase of the engine load results rather from technical limitations than the general feature if the JDC method.

2. The amount of the air injected can be very small. The most important is the kinetic energy of the jet which should be able to assure the deep penetration of the combustion chamber volume.
3. It is possible to direct the combustion propagation toward the required region of the combustion chamber by suitable direction of the air injection.
4. The use of the air injection can significantly increase the magnitude of the mean effective pressure, pressure rise rate, peak cycle pressure and shorten the combustion time.
5. The air injection can be used to stimulate or to prevent the knocking combustion phenomenon.
6. The air injection can significantly accelerate the combustion process and increase by that the heat release rate.
7. The action of the air jet decreases the exhaust gas temperature (despite that the in-cylinder temperature increases).
8. The air injection is influencing the cycle-per-cycle variability and for higher engine loads the influence is favorable.
9. The application of the air injection can remarkably lower pollutant emissions especially at higher engine loads (especially carbon monoxide and unburned hydrocarbons).
10. The character of the in-cylinder phenomena caused by the injection mostly depends on the injection direction, the time of its activation and on the composition of the charge.
11. The charge turbulization and the dispersion of the combustion products in the primary combustion phase by the air jet are the phenomena responsible for all the specified above effects.

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Kształtowanie procesu spalania w silniku ZI za pomocą strugi powietrza

Streszczenie

W okresie ostatnich kilkunastu lat zaproponowano wiele metod kształtowania procesu spalania w silnikach tłokowych o zapłonie iskrowym [1, 2, 4, 10, 12]. Podstawowe cele tych działań to zmniejszenie zużycia paliwa (wzrost sprawności cieplnej, w której tkwią stosunkowo duże rezerwy) oraz zmniejszenie emisji podstawowych składników toksycznych. Żadna z dotychczas przedstawionych metod nie okazała się jednak na tyle skuteczna, aby można było zastosować ją powszechnie i aby zniknęła potrzeba dalszych poszukiwań w tym kierunku.

Jednym ze sposobów oddziaływania na zainicjowany wyładowaniem iskrowym proces spalania jest zastosowanie wtrysku wprowadzonej z zewnątrz do komory spalania strugi niepalnego gazu [11]. Metoda ta, opisana w niektórych źródłach pod nazwą Jet Dispersed Combustion (JDC), została w ciągu ostatnich kilku lat przebadana zarówno na urządzeniach modelowych, takich jak komora o stałej objętości, maszyna pojedynczego sprężu czy jednocylindrowy silnik badawczy, jak i na obiektach rzeczywistych, takich jak produkcyjny silnik samochodowy [3, 5, 6, 7, 8, 9]. Badania wykazały, że wtrysk strugi niepalnego gazu, na przykład powietrza, jest skutecznym narzędziem kształtowania spalania i może przynieść rezultaty w postaci efektywniejszego wykorzystania ciepła potencjalnie zawartego w paliwie. W szczególności może przyspieszać cały proces wywiązywania ciepła, co zazwyczaj owocuje większą prędkością narastania ciśnienia oraz większą szczytową wartością ciśnienia spalania. W tłokowym silniku spalinowym o zapłonie iskrowym, za pomocą tej metody można wpływać na kształt wykresu indykatorowego, istotnie zwiększyć wartość średniego ciśnienia indykowanego, wpływać na twardość i równomierność biegu silnika, a także istotnie zmniejszyć koncentrację w spalinach podstawowych składników toksycznych.