Article citation info:
KNEFEL T. Technical assessment of Common Rail injectors on the ground of overflow bench tests. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2012; 14 (1): 42–53.

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TECHNICAL ASSESSMENT OF COMMON RAIL INJECTORS ON THE GROUND OF OVERFLOW BENCH TESTS

OCENA TECHNICZNA WTRYSKIWACZY COMMON RAIL NA PODSTAWIE DOŚWIADCZALNYCH BADAŃ PRZELEWÓW*

The majority of actually produced Diesel engines operated as power units in passenger cars are equipped with injection systems of Common Rail type. Injectors with solenoid valve are implemented to a large extent of these engines. In the paper is discussed an assessment of differences in fuel dosing accomplished by injectors of various generations and are estimated quantities of fuel needed to actuate operation of the injectors. It has been specified a share of overflow volume in dose of injected fuel. One introduced also an index of efficiency, as a quantity to evaluate amount of decompressed fuel. Elementary overflows and differences in the elementary overflows are presented, both in case of efficient and inefficient injectors. There are evaluated leaks for elements from the 1st generation. It has been proposed a methodology of proceeding to assess technical conditions of the injectors after some time of operation.

Keywords: *Diesel engine, Common Rail injection system, solenoid-valve injector, diagnostics and technical assessment of injectors.*

Większość aktualnie produkowanych silników o zapłonie samoczynnym do napędu samochodów osobowych jest wyposażona w układy zasilania typu Common Rail. W dużej liczbie stosowane są wtryskiwacze z elektromagnetycznym zaworem. W artykule przedstawiono ocenę różnic w dawkowaniu realizowanym przez wtryskiwacze różnych generacji oraz oszacowano ilości paliwa niezbędne do uruchomienia wtryskiwaczy. Określono udział przelewu w dawce wtryskiwanego paliwa. Wprowadzono pojęcie wskaźnika sprawności, jako wielkości umożliwiającej ocenę ilości rozprężanego paliwa. Przedstawiono jednostkowe przelewy i różnice w jednostkowych przelewach zarówno dla sprawnych wtryskiwaczy, jak i niesprawnego. Wyznaczono przecieki dla elementów I generacji. Zaproponowano metodykę postępowania przy ocenie stanu technicznego wtryskiwaczy po pewnym okresie eksploatacji.

Słowa kluczowe: *silnik o zapłonie samoczynnym, układ wtryskowy Common Rail, elektromagnetyczny wtryskiwacz, diagnostyka ocena techniczna wtryskiwaczy.*

1. Introduction

Modern Diesel engines used in passenger cars, in majority of cases are equipped with hydraulic accumulator type injection systems. Such situation is caused by unquestionable advantages, from which the best seems to be a possibility of shaping of injection rate, and the same, pressure in combustion chamber of the engine. This process can be accomplished in relatively easy way with use of injectors operating in Common Rail system, through change of fuel discharge intensity from the injectors. Also, in the injectors used in hydraulic accumulator type injection systems occurs a process of batching of fuel dose supplied to the cylinder, which in the next step is reduced in size by atomizer and when mixed with air becomes air-fuel mixture initially prepared to ignition. Thus, the injectors as working elements of injection systems play very important role in obtainment of pre-assumed parameters of combustion engine operation [1]. However, due to operational conditions, the injectors remain the most sensitive for damage components of the system [3]. To detect a malfunctions in the accumulator type injection systems are used various methods of diagnostics, inclusive of methods based on model of the system [2]. It is worth, however, to consider a development of relatively simple, standardized rules of assessment of already used injectors, and in such way, after introduction of such rules, assure operation of correctly functioning elements.

Nowadays, in passenger car's engines are used two types of the injectors: the first ones, introduced to production earlier, are actuated by solenoid valve; and the second ones, which operate owing to stack of quartz plates and implementation of piezoelectric effect [7, 10]. Anyhow, in prevailing number of Common Rail systems are actually still implemented injectors actuated by solenoid valve. From beginning of their implementation to vehicles in 1997, such injectors were perfected and still developed mainly in order to enable high pressure fuel injection, to assure possibly short time of reaction on preset electric excitation and change of fuel discharge intensity from the atomizer [5, 6, 8, 11].

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

2. Objective of the tests

Process of needle lift control in the injectors with solenoid valve occurs with use of quick-shift valve, incorporated into upper part of the injector (Fig. 1). Fuel flowing in under high pressure is divided into two streams, the first stream flowing in through opening „D", to control chamber „K" located under valve stem, causes opening of the needle. It means that this portion of fuel becomes decompressed and through opening „W", together with leaks arisen on mating surfaces of precision pairs, is directed, via overflow tubes, back to fuel tank. For needs of the present paper, this portion is called shortly as: „overflow".

Fuel quantity, injected by the injector to engine's combustion chamber is the second stream of the fuel.

To the analyzes which are described below were also introduced a notions of „injectors of the 1st and the 2nd generation". As the 1st generation injectors are called such injectors, which were used in the first, after launch of accumulator type injection systems, series of mass production engines. Together with development of feeding systems, one commenced assembly of more new injectors, which enable accomplishment of smaller dwell times between partial doses. Such injectors are called as the 2nd generation. Issue of possibility of division into parts does not belong to subject-matter of the present considerations, for which two objectives are assumed. The first objective, cognitive one, is assessment of differences in dosing of Common Rail injection system, operating at beginning with the 1st generation, and next with the 2nd generation injectors, as well as estimation of fuel quantity necessary to activate the injectors.

It have been evaluated differences in overflow value between correctly functioning injectors in various areas of injection system operation. There were also taken into consideration consequences of control signal generated by inefficient injector. Simultaneously, attempt was taken to evaluate volume of fuel leaks with respect to injected fuel quantity. The second objective, utilitarian one, is development of a proposal of diagnostic criterion for injectors actuated with use of solenoid valve.

3. Objects of the tests and test bed

Injectors, both of the 1st and the 2nd generation were the objects of the tests. The first type injectors are used in turbocharged engine of 1700ccm class and are equipped with 6 holes with diameter of 0,15 mm. In turn, injectors of the 2nd generation serve to feeding of turbocharged engine of 1300ccm class, and are equipped with 5 holes having diameter of 0,13 mm [4].

All the injectors were controlled with use of the same, KSSiP-2 type laboratory controller of Common Rail system, developed and produced by the Technical University of Bielsko-Biała. Operating parameters were input from level of PC class computer. Moreover, the test bed has comprised:

- Star-8 test bed, totally modernized for needs of testing of Common Rail injection systems, equipped with wavy motion electric motor and fuel tank with heating, cooling and temperature control systems, among others,
- high pressure pump with three pistons, and throttling type of pressure control,
- hydraulic rail having 20ccm capacity, used in the engine having 1700ccm swept capacity,
- AVL pressure measuring line (SDL-31 extensometric transducer, A09 amplifier) connected to computer and oscilloscope, enabling measurements of pressure in the rail.

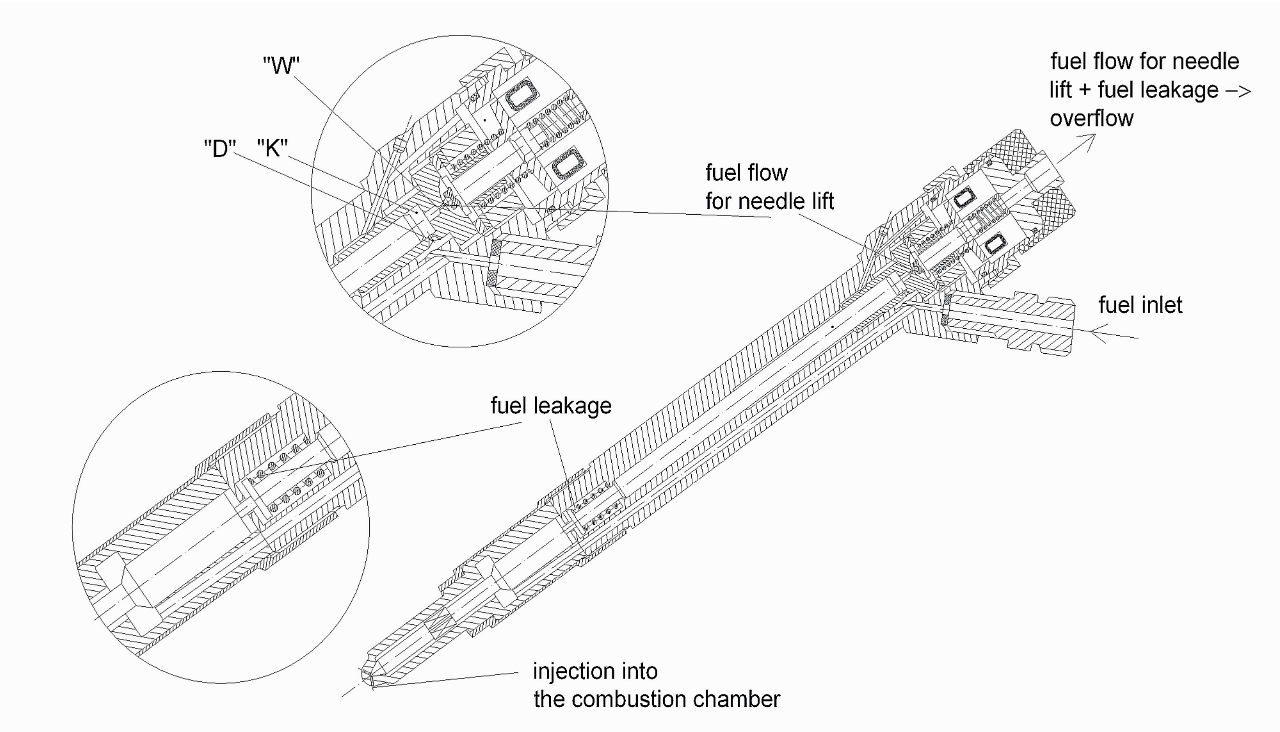

Fig. 1. Solenoid-valve injector scheme

In course of the stand tests, the injection system had operated without pressure stabilization and dosage correction systems.

During the measurements one measured both mass of fuel supplied by individual injectors, as well as masses flowing out through overflow pipes. Graduated cylinders were weighted on electronic scales of the WPE type, produced by Zakład Mechaniki Precyzyjnej RAD-WAG in Radom. Both elementary dose of injected fuel and elementary mass of the overflow were calculated as average value from 250 working cycles of the injectors. Temperature of the fuel was maintained on constant level within range of 40±2°C.

4. Characteristics of dosage and overflow of the injectors

In the first succession, for each one from the injectors of the 1st generation, one measured injected fuel quantities of fuels and (to a separate graduated cylinders) overflows flowing out from overflow pipes. Each time, commencing and termination of the measurement occurred automatically after calculation of preset number of working cycles. There were supplied single injected fuel quantity injections. Results of measurements of the injected fuel quantities, as well as overflows, depending on a preset time of injection and with respect to a single cycle, are presented in the Fig. 2. Making analysis of the presented runs, it can be noticed that elementary dose of the fuel is practically in linear dependence from opening time of control valve of the injector, and grows together with its increase. Such shapes of the characteristics cause, that tested injectors perfectly suit to operation in electronically controlled power units, where control of injected fuel quantity is accomplished through change of opening time of control valve of the injectors and change of injection pressure. Applied values of opening times for the 1st generation injectors effected in fact, that presented fragments of the characteristics result from operation of the needle in non ballistic range of travel, and hence, after reaching maximal lift [1].

Different runs were obtained for the inefficient injector marked as No. 4. Linear characteristics are obtained at the pressure of 990 bar, but after slight growth of the pressure in the rail (up to 1000 bar) one obtains nonlinear characteristics, with significantly changed values.

Values of elementary overflows are growing as well; both together with growth of the opening time and pressure inside the rail, but attained increments of the values are smaller than in case of the injected fuel quantities. In majority of cases, the changes occur in nonlinear way.

Measured values of the overflows in the injector No. 4 (for considered levels of the pressure) are distinctly higher than in case of other injectors. Significant changes are seen even at small changes of the pressure. It is visible especially for the highest pressure, where the differences reach nearly 100 %.

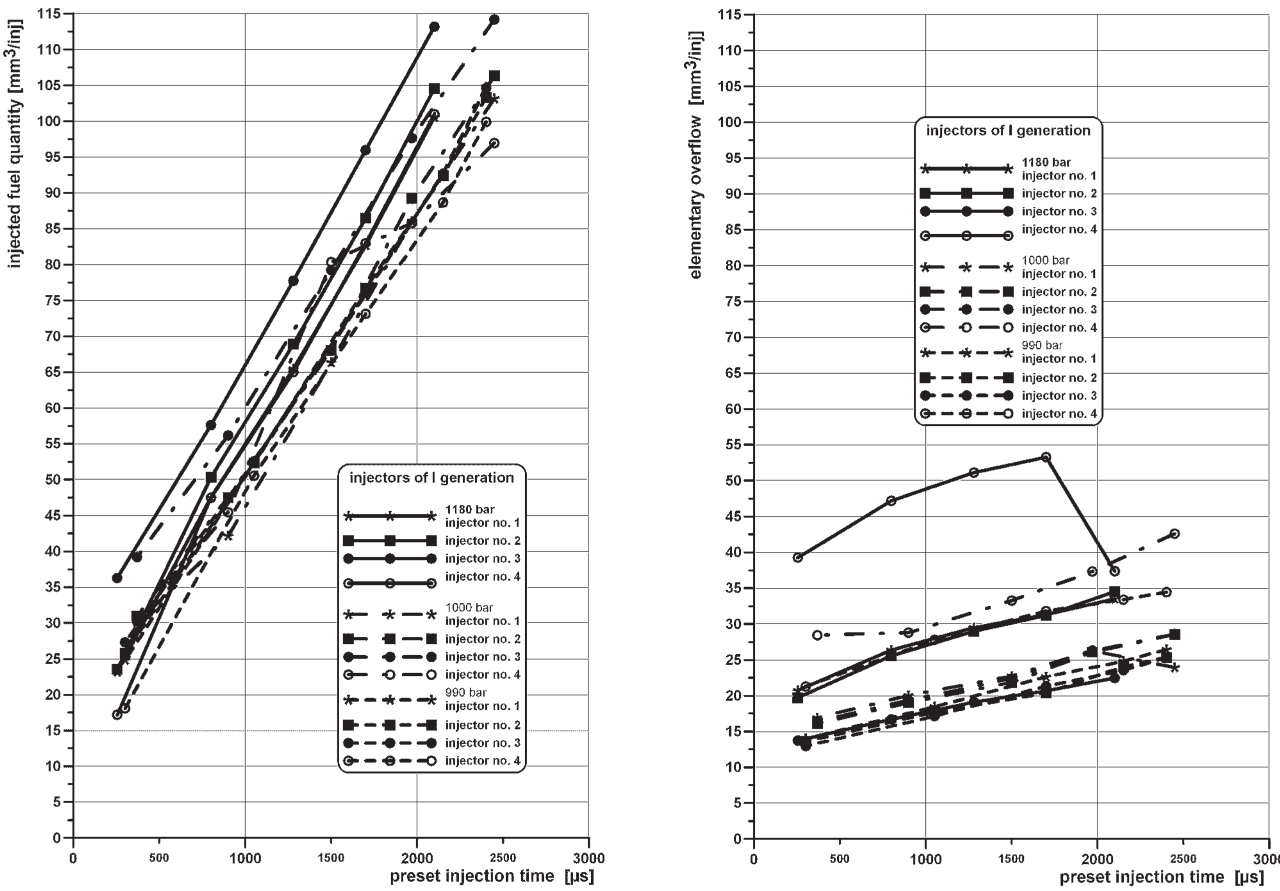

Fig. 2. Injected fuel quantities and overflows of the 1st generation injectors at different injection pressures

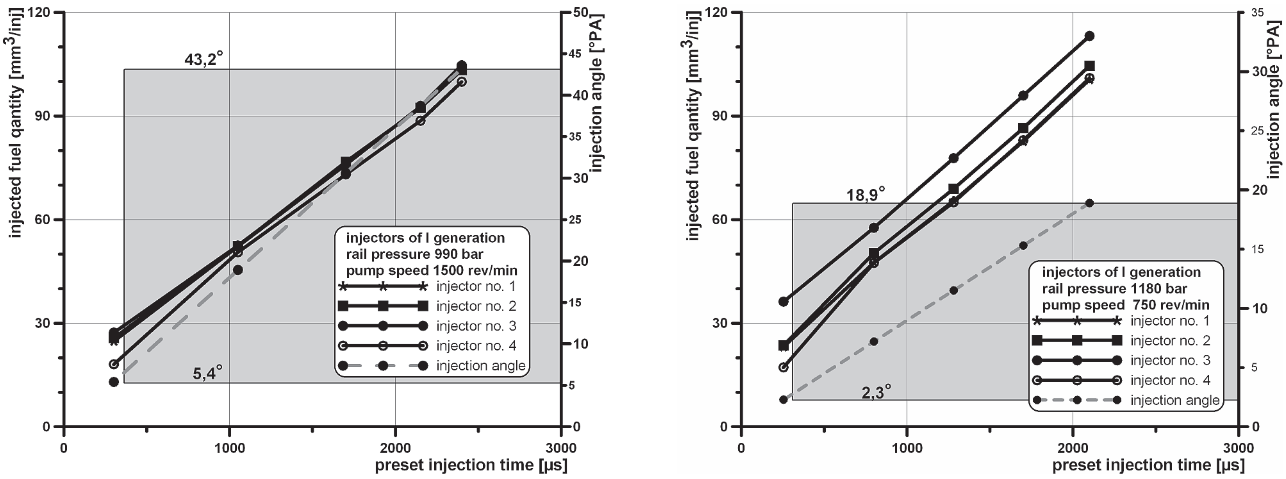

Fig. 3. Injected fuel quantities and injection angles versus preset injection time for a different injectors of the 1st generation

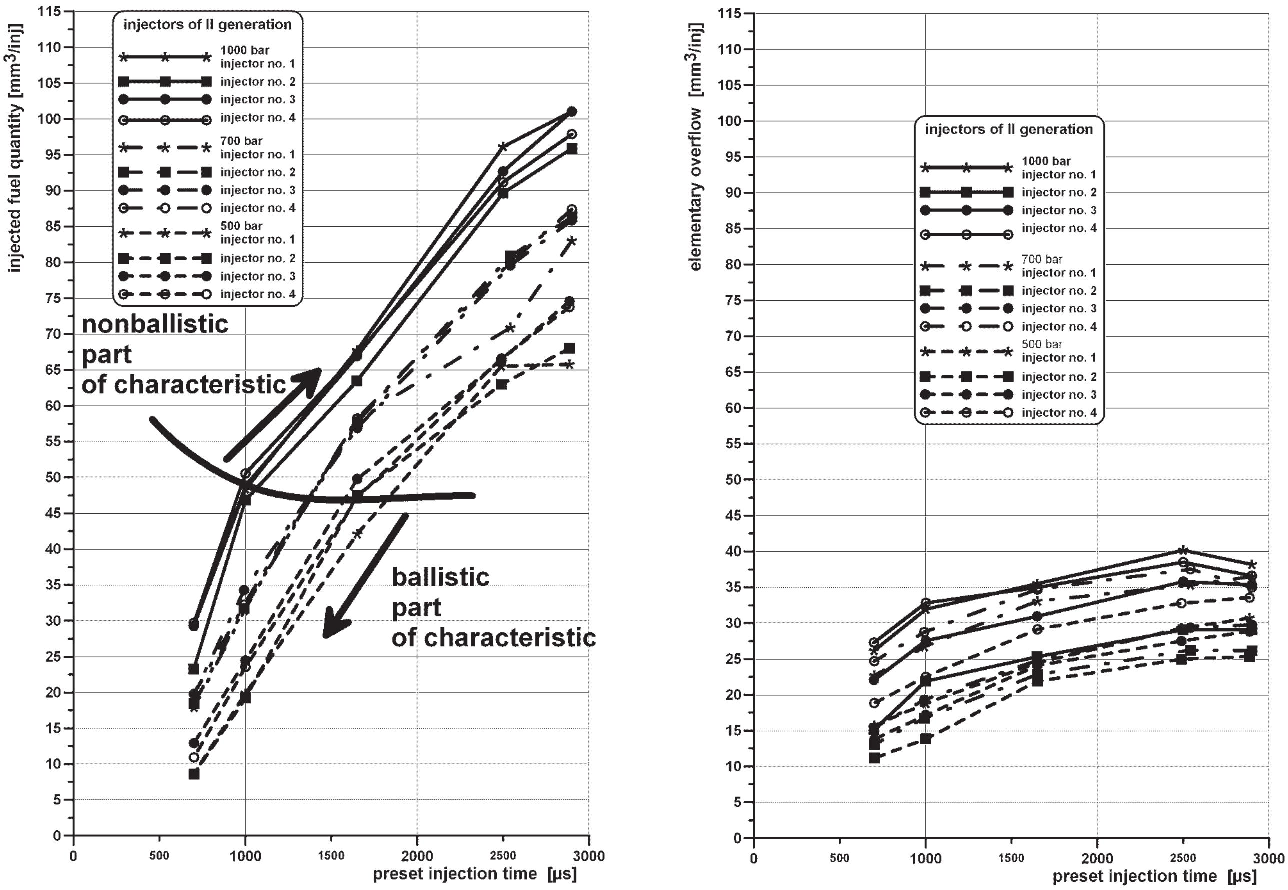

Fig. 4. Injected fuel quantities and overflows versus total preset injection time for different injectors of the 2nd generation

As mentioned earlier, one from advantages of accumulator type injection system is possibility of shaping of engine operation parameters through change of injection parameters. Exemplary characteristics of the 1st generation injectors, drawn for various fuel pressure in the rail (990 and 1180 bar) and for two rotating speeds of high pressure pump (1500 and 750 rpm) are presented in the Fig. 3. In the diagrams are additionally plotted, with dotted lines and grey color rectangles, the ranges of variability of injection angle. The angles were recalculated into crankshaft rotation degrees of a hypothetical engine. The measurements were performed in such way to have similar sizes of fuel dose at different operational parameters of the system. It is seen that is possible to supply the same size of the dose at different parameters of injection. It is possible, at relatively small injection angle (2,3 ÷ 18,9°; Fig. 3, RH side part), to set a higher pressure of the injection to obtain a better atomization, i.e. supply to cylinder in short time a bigger quantity of energy. Hence, it is possible to use also a lower pressures of the injection, but the angles attained shall be bigger (5,4 ÷ 43,2°; Fig. 3, LH side part), however, in such case fuel supply shall be distributed for more degree of crankshaft rotations angle. Fact if high values of the injection angle shall be utilized by engine designers remains the open issue.

There were also performed measurements of dosing for the 2nd generation injectors. Similarly like earlier, the measurements were made for not split injection dose, and results are presented in the Fig. 4. It can be seen, that change of supplied fuel dose in function of time occurs with various intensity. Total area of the characteristics can be divided into three areas. The first area denotes the most often used at partial engine loads area of ballistic range of injectors operation, up to maximal lift of the needle. This area includes interval from 1000 up to about 1700 μs. The second area, non-ballistic area, when the needle supports on bumper, is characteristic of the times up to 2500 μs and can be used to feeding of engines at high loads or during start-up. The third part characterizes area with opening times longer than 2500 μs. In spite of high values of preset time, there wasn't observed any excessive growth of injector's temperature, the injectors functioned correctly, but as seen from analyses of technical data from service stations, the times from this area are not used in practice.

Boundaries of the areas of the characteristics depend substantially on pressure of the fuel. Transition from ballistic to non-ballistic area of engine operation occurs earlier in case of pressure growth. In the presented example, at the pressure of 1000 bar the needle reaches the bumper as early as for 1000 μs, at lower pressure (500 bar) - for 1650 μs. To have more precise determination of the boundaries, one should perform measurements of dosing for more points.

Group of injectors discussed here is characteristic of lower rate of dose's value growth in function of the opening time than in case of the 1st generation injectors. For the same pressures a smaller values are obtained. It results from fact of smaller cross-section areas of outflow active surfaces in used atomizers.

Similarly like in case of the first group of the injectors, values of elementary overflows are growing together with growth of the opening times, and with growth of pressure within rail. Rates of the growth values are smaller than in case of doses, and are comparable to the overflows of the first generation injectors. Division of the characteristics into parts, with similar values of the boundaries like in case of the doses, can be seen. Measured values of the overflows are bigger than values obtained for the first generation injectors.

5. Comparison of doses and overflows

To make direct comparison and quantitative assessment of fuel doses and overflows (expressed in mm^3/injection) for the both groups of the injectors, in the Figs. 5 and 6 are shown the both quantities. There were selected only such operating points, in which the injectors operated with rail pressure of 1000 bar. There were set various values of injection duration.

Values of the overflow of the 1st generation injectors (injectors No.1, 2, 3) grow together with growth of injected dose and all are included within range of 16,1 mm^3/injection in case of the shortest time, to 28,6 mm^3/injection in case of the longest time. In the analyzed range of injectors operation, the overflows

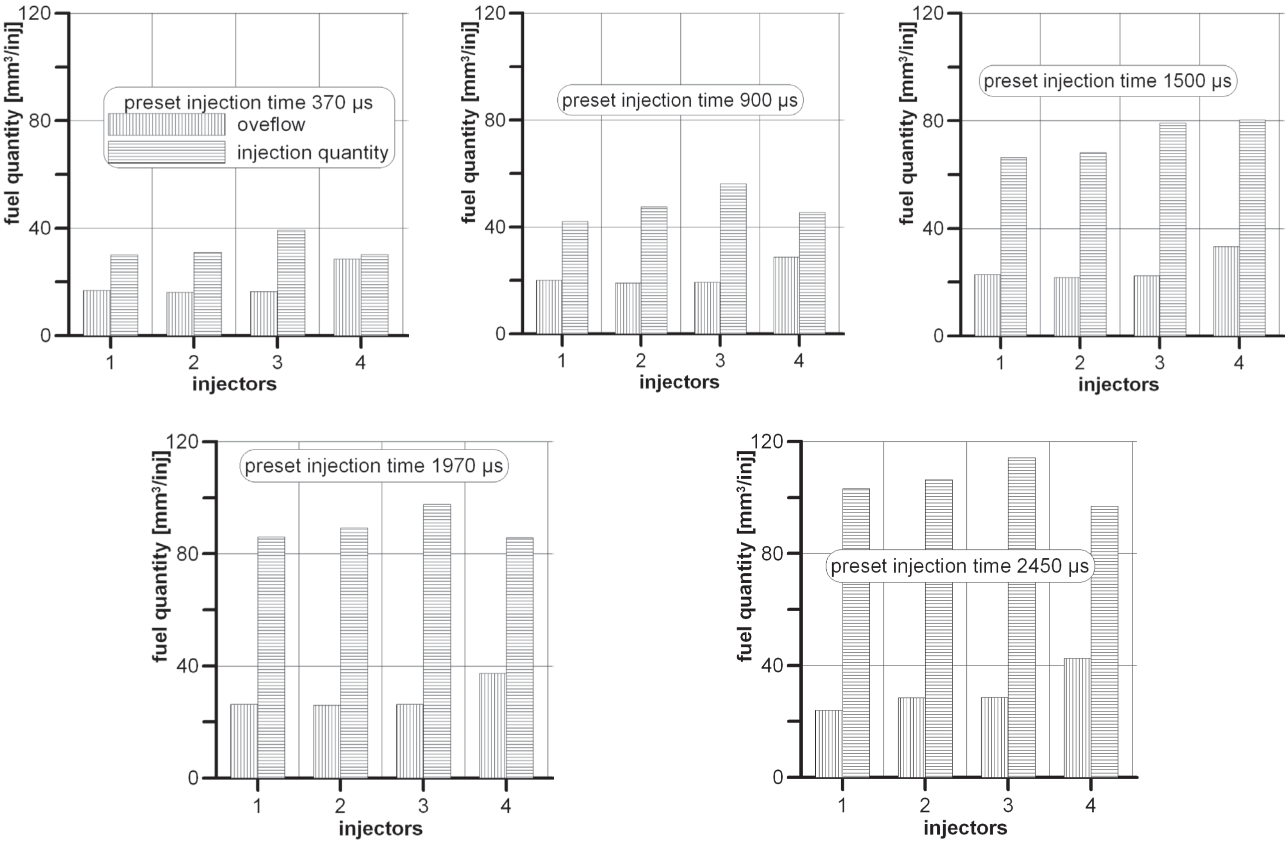

Fig. 5. Comparison of injected fuel quantities and overflows for injectors of the 1st generation

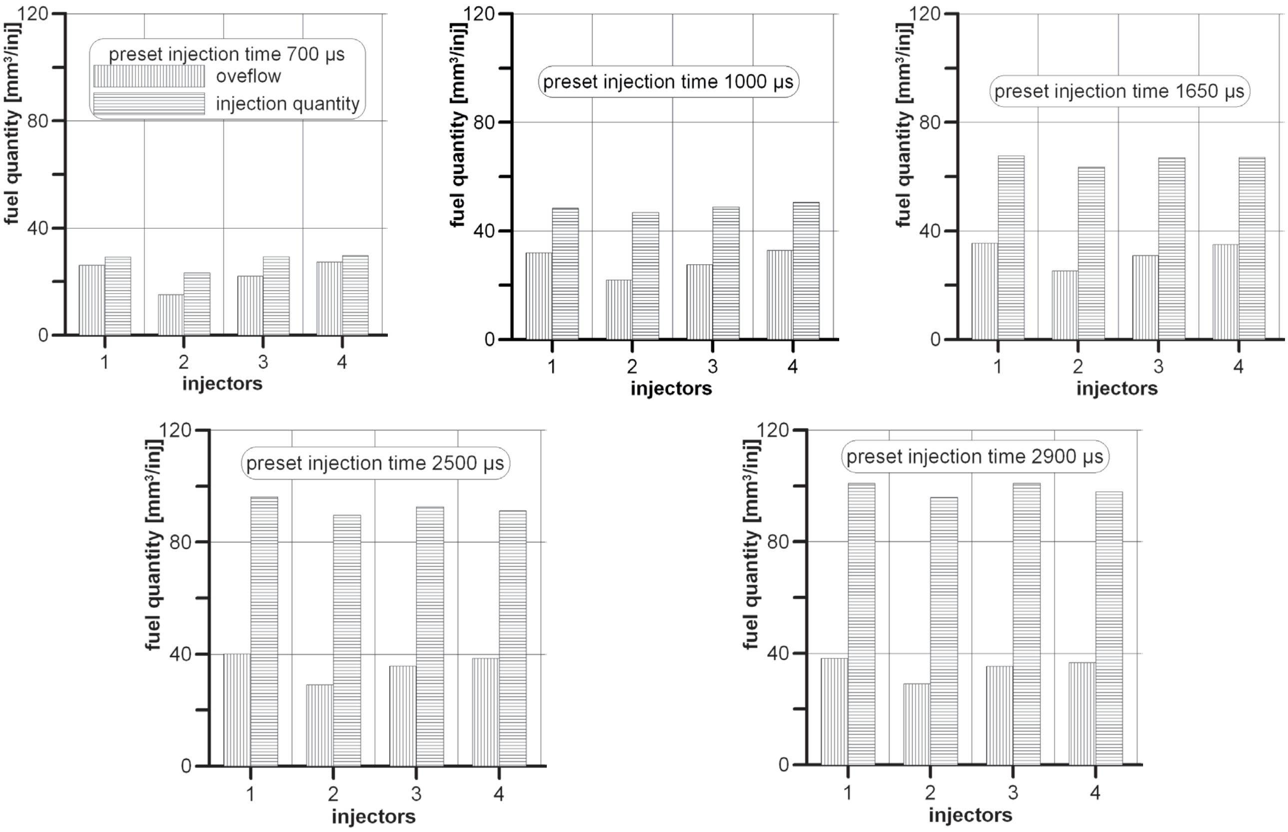

Fig. 6. Comparison of injected fuel quantities and overflows versus for injectors of the 2nd generation

increase with about 77 %. Very good compatibility of values for these three injectors attracts our attention here – their runs practically coincide. Anyhow, for inefficient injector No. 4 they are maintained on a higher level (28,4÷42,6 mm^3/injection, growth with 50 %).

The overflows in the 2nd generation injectors reach values from 11,1÷40,4 mm^3/injection (growth with 260%). Big divergences in the values are present, reaching even up to 30 %. At similar level of dosing, injectors of the 2nd generation are characteristic of bigger values of the overflow.

This short analysis enables to ascertain, that for short opening times, especially for injectors of the 2nd generation, volumes of the overflow are comparable with volumes of supplied doses. It proves about relatively big amount of energy which needs to be used in such case to accomplish injection of the fuel. Increase of the overflow values occurs more slowly than increase of the doses, and therefore share of energy needed to injectors' operation decreases together with growth of injection time.

The above considerations caused, that for the both groups of the injectors, based on the same measurement points, one performed analysis of percentage share of the overflow in the

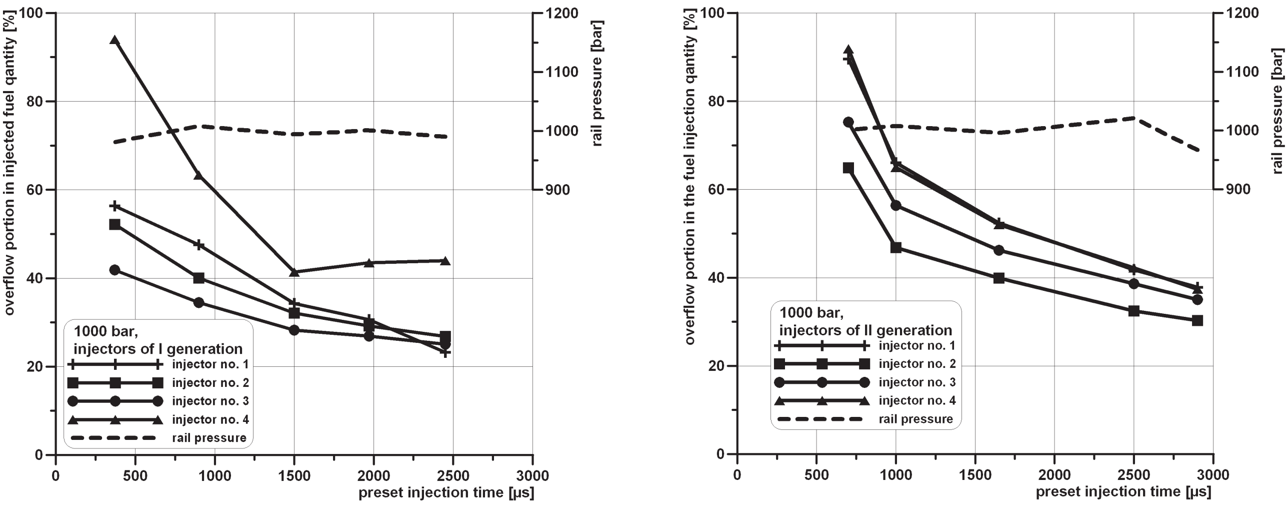

Fig. 7. Comparison of overflow portion in injected fuel quantity versus preset injection time for the 1st and the 2nd generation injectors

dose. The share was evaluated in each point as a quotient of the overflow and supplied dose of fuel. Results, in function of the opening time, are presented in the Fig. 7. Additionally, in the diagrams are shown values of fuel pressure in the rail, prevailing during the injection.

For the first three injectors of the 1st generation, share of the overflow in the dose decreases together with growth of their opening time, while for the forth injector the share initially decreases from 94% at 370 μs to 42% at 1500 μs, and next grows to 44% at 2450 μs. Among three other injectors, the biggest decrease occurs successively: for the first one (with 33%) from 56% to 23%, for the second one (with 25%) from 52% at 370 μs to 27% at 2450 μs and the smallest decrease for the third injector which amounted to 16% (from 41% at 370 μs to 25% at 2450 μs). It has been acknowledged, that pressure change in the rail didn't have any important effect on results of the analysis.

In turn, for injectors of the 2nd generation, two curves showing values of share of the overflow for the injectors No. 1 and No. 4 slightly differ from each other. At the beginning (for 700 μs) their values amount to: 90% for the injector No. 1 and 92% for the injector No. 4, while for the longest opening times (2900 μs) value of the share for the both injectors amounts to 37%. For these injectors, change of overflow's share in the dose for complete analyzed range of changes of opening time amounts to 51% and 53% respectively. Other two curves differ from each other with values in each point of the opening time, from 10% at 700 μs to 6% at 2900 μs, whereas changes of overflow's share in the dose occurs from 75% to 36% for the third injector, and from 65% to 30% for the injector No. 2. Effect of pressure changes seems to be not significant.

In complete range of analyzed opening times, share of the overflow in the dose of the 2nd generation injectors is bigger than for the 1st generation injectors, obviously except inefficient injector No.4. For small dosages, it reaches even 90 %. Intensity of the changes for the 2nd generation is meaningful, especially in case of injectors No, 1 and 4 (from 90 % to 36 %). Values presented here can prove about striving of design engineers after obtainment of short actuation times in the 2nd generation injectors, through induction of a bigger fuel stream (comparing with the 1st generation), resulting in lifting of the needle. At the same pressure, quantity of fuel needed to lift the needle is approximately constant, and hence, strongly reducing share of the overflow when the dose is growing.

It is interesting to compare runs of overflow shares for the 2nd generation injectors with run plotted for inefficient, forth injector of the 1st generation. Values and intensity of changes are similar. Hence reservation, that it should be taken a special care during possible usage of the above mentioned runs to assessment of technical conditions of the injectors. To make the assessment, it is necessary to know reference runs, performed for a given type of correctly functioning injectors.

6. The efficiency index of injectors and differences in elementary overflows

Considerable share of the overflows in the dose was the reason for which the author has introduced conventional concept of injector's efficiency index. The matter here is to assess what is a share of fuel injected to the cylinder in total amount of the fuel supplied to the injector, and what is a share of decompressed fuel which is directed back to fuel tank. The index was defined as quotient of elementary dose of fuel and sum of elementary overflow and dose. Results are summarized in the Fig. 8. For the both groups of the injectors, values of the index are growing together with growth of the opening time, i.e. – for the sake of constant pressure – together with growth of the dose. Three efficient injectors of the 1st generation, in relation to the 2nd generation injectors, in complete analyzed range of their operation reach higher values of the index. The highest ones were recorded for the injector No. 3, for which the index changed from 70 to 80 %. The fourth injector, i.e. inefficient one, reaches values from 52 % for a shorter, to 72 % for a longer opening time. These are values comparable to or even little bit higher than in the injectors of the 2nd generation, for which, especially at short opening times, one obtains values from 52 to 60 % only.

The runs presented here confirm previous observations about bigger fuel streams used to actuate the 2nd generation injectors. It is seen, that in situation of short opening times, in some cases even half of fuel supplied to injectors under high

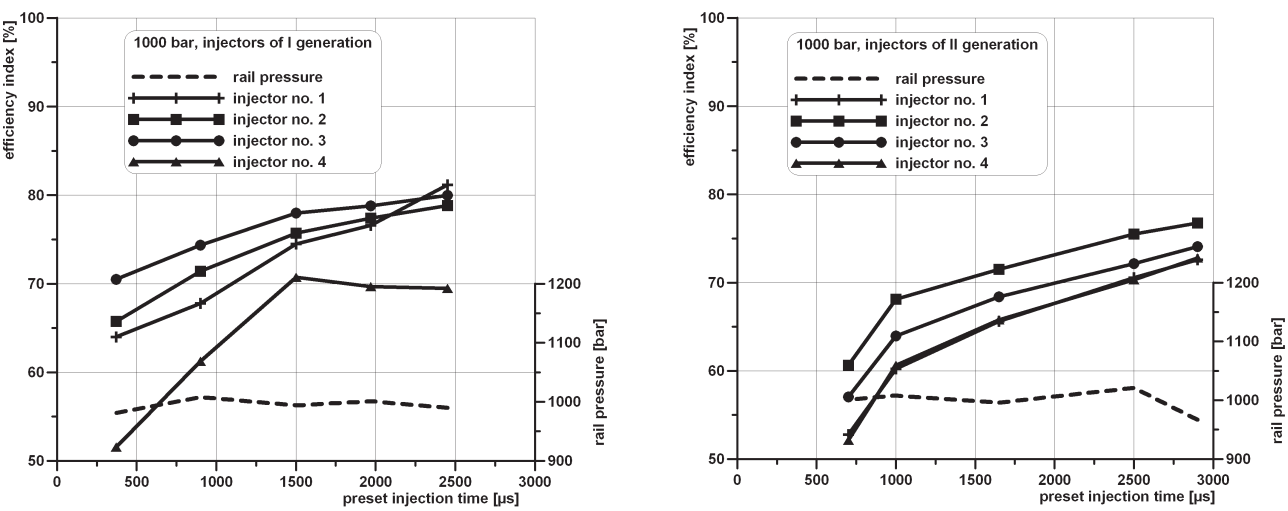

Fig. 8. Comparison of efficiency index versus preset injection time for the 1st and the 2nd generation injectors

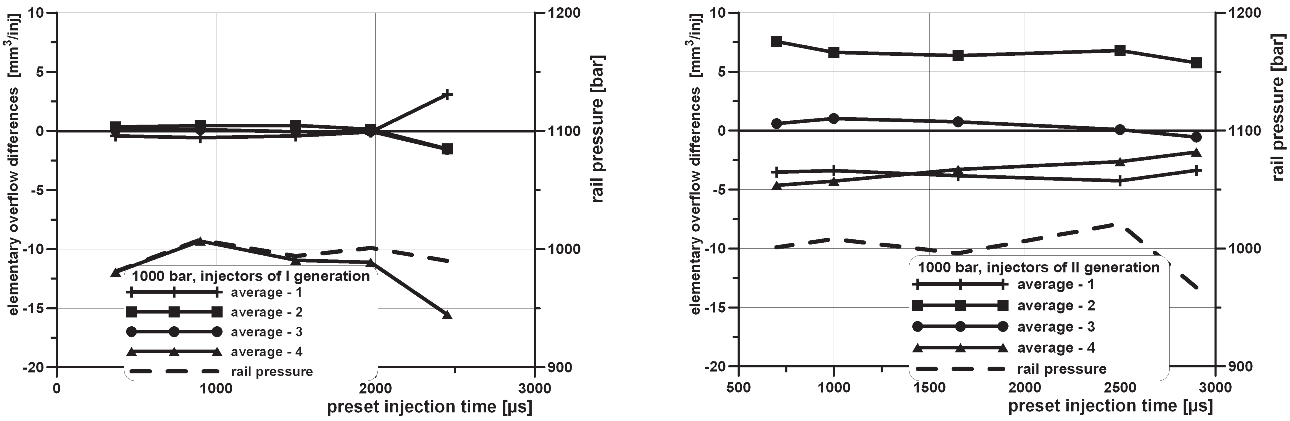

Fig. 9. Comparison of elementary overflow differences versus preset injection time for the 1st and the 2nd generation injectors

pressure is returned to fuel tank. In consequence, part of energy supplied to the fuel in order to increase pressure becomes lost, what obviously reduces efficiency of the injection system.

In course of further analysis, for the both generations, and depending on the opening time of the injectors, one evaluated absolute differences (Fig. 9) and percentage differences (Fig. 10) of elementary overflows. As a benchmark values, separately for each group of the injectors, one assumed average values of the overflows calculated for each from opening times of the injector. Only correctly functioning injectors were taken into consideration. Hence, individual solid lines illustrate (for a given time) differences between average value of the overflow of a given injector (Fig. 9) and (in percent) quotients of the differences mentioned above and the average value (Fig.10). In the Figures these values are denominated as „average – 1", average – 2", etc. With dotted lines are drawn pressure runs in the hydraulic rail.

zero value, and simply overlap each other. It proves about very similar parameters of their control streams. Absolute differences do not exceed 1 mm^3/injection, with exception of measurement points with the highest value of preset opening times of the injectors, where they reach value of 3 mm^3/injection. Percentage differences (Fig. 10) do not exceed 3 %, only for the longest time they take values from interval of 5,6 ÷ 11,4 %.

Results for the 2nd generation injectors are slightly different. Immediately is noticeable a bigger scatter of the results, although all are practically linear. For two injectors the differences are bigger; for two others are smaller than the average. Injector No. 2 differs most from the others. Its overflows are the smallest, and therefore the biggest departures from the average occur, amounting to about 6 mm^3/injection. Relative percentage differences take higher values: injectors No. 2 and 3, with smaller values of the overflows, differing from the average from 1,5 to 33 %, while the two others, with higher overflows from 2 to 15 %.

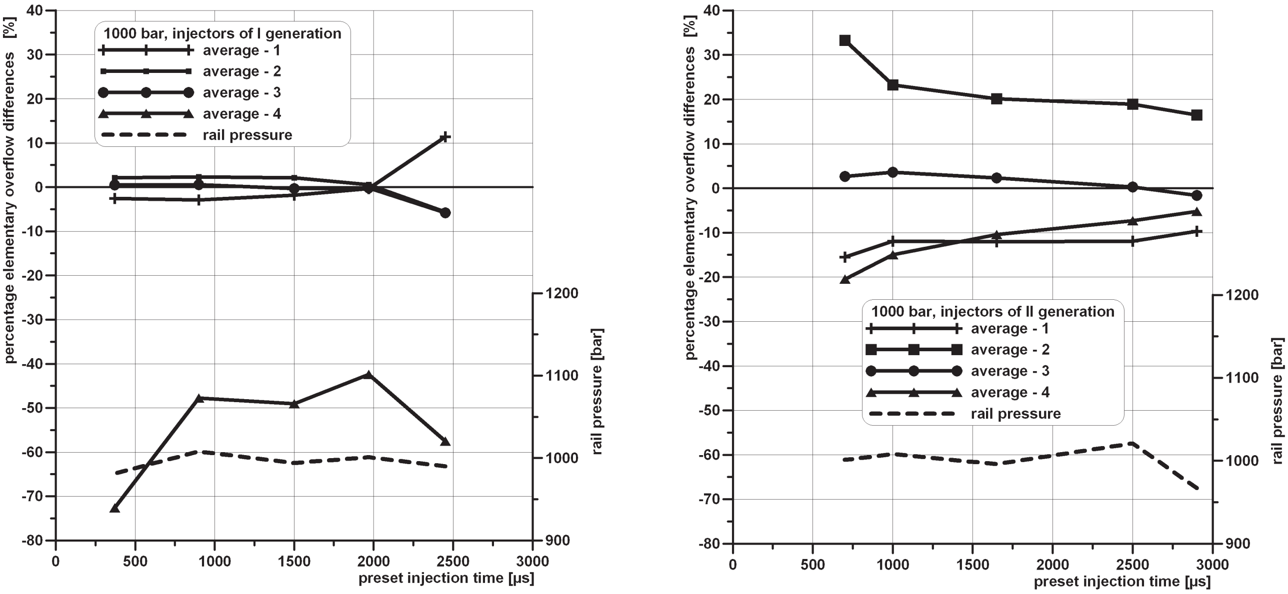

Fig. 10. Comparison of percentage elementary overflow differences versus preset injection time for the 1st and the 2nd generation injectors

Making analysis of results obtained for the 1st generation injectors is possible to be noticed (Fig. 9) that runs of three correctly functioning injectors are similar, and oscillate around

On base of the presented analyses it is possible to ascertain, that the most suitable is assessment and comparison of the overflows based on relative percentage differences. Quantitative ap-

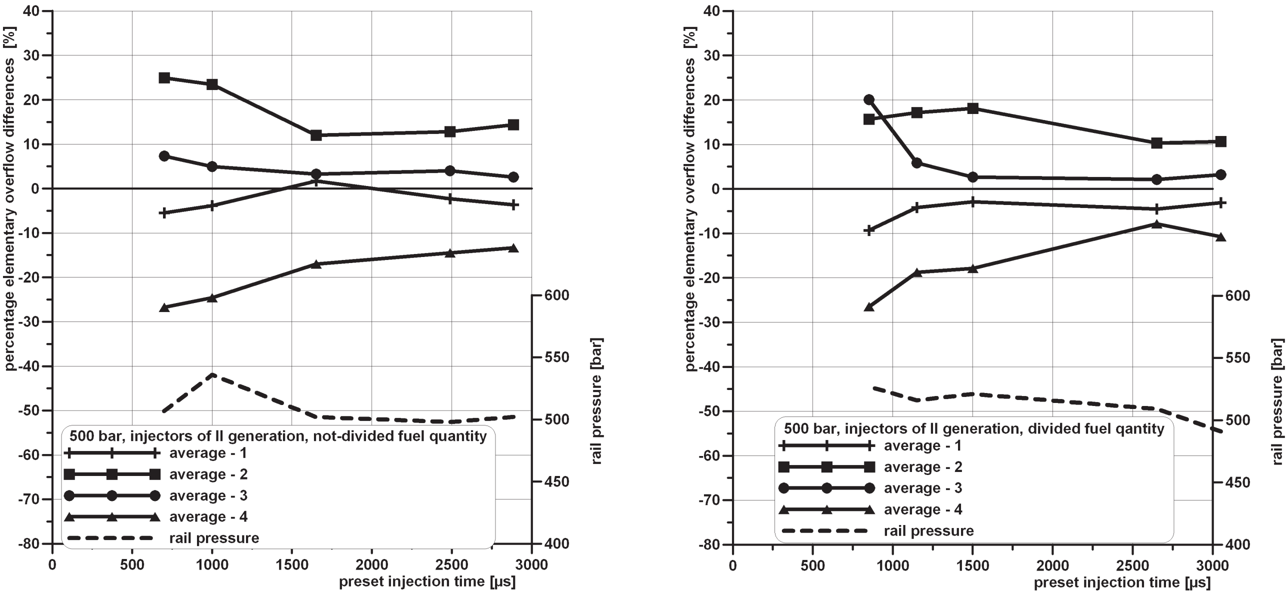

Fig. 11. Comparison of percentage elementary overflow differences versus total preset injection time for not-divided and divided injected fuel quantity (2nd generation injectors)

proach only, as well as approach based on simple differences is not sufficient. It is the best seen on example of the 2nd generation injectors, where evaluation of relative differences revealed comparatively big discrepancies of the analyzed values.

Using the runs presented in the Fig. 11, one endeavored to assess an effect of fuel supply method on size of differences in the elementary overflows. To do it, in the first succession one made measurements of not divided dose, result of such measurements are presented in the LH side of the Fig. 11. Next, previously preset injection times were divided into two equal parts, separated with dwell of 150 µs. Results of these measurements are shown on the RH side of the Fig. 11. During this stage injectors of the 2nd generation were used. Values observed in the both diagrams slightly change with respect to each other. Such small differences can result from adoption of relatively small value of the dwell, what resulted in situation in which the needle was permanently lifted. Due to it, significant change of the overflow value was not possible. It seems that changes of the pressure do not have any effect on runs of the differences.

In both groups of the measurements is possible to notice a bigger values of differences for smaller values of the times, and smaller for bigger time. Probably, it results from more stable, at long opening times of the injector, behavior of the needle during injection.

In the face of confirmed significant differences in overflow values of the injector No. 4, comparing with the injectors of the 1st generation, it has been decided to take attempt to evaluate a reasons of their presence. The overflows, except fuel used to actuation of the injectors, consist also of leaks, and therefore, such leaks needed to be evaluated for the analyzed group of the injectors. For the conventional injectors, evaluation of the leaks between pressure faces is the most commonly performed with use of pressure drop in time method. In case of the injectors from Common Rail system, more accurate and more convenient seems to be the method of direct measurement, implemented in the present work and performed with use of complete injection system incorporated in the test stand. Prior start of measurement of the leaks, one disconnected electric cables supplying control signal to solenoid valve of the injectors. Owing to it, control valve remained closed and fuel flow across control chamber was not possible; and the fuel flowing out through overflow pipes came from leaks only. The leaks were collected into graduated cylinder. Simultaneously, one measured number of potential cycles of injection system operation. Size of measured leaks is presented in the same way as in case of the doses and the overflows, in reference to a single operational cycle.

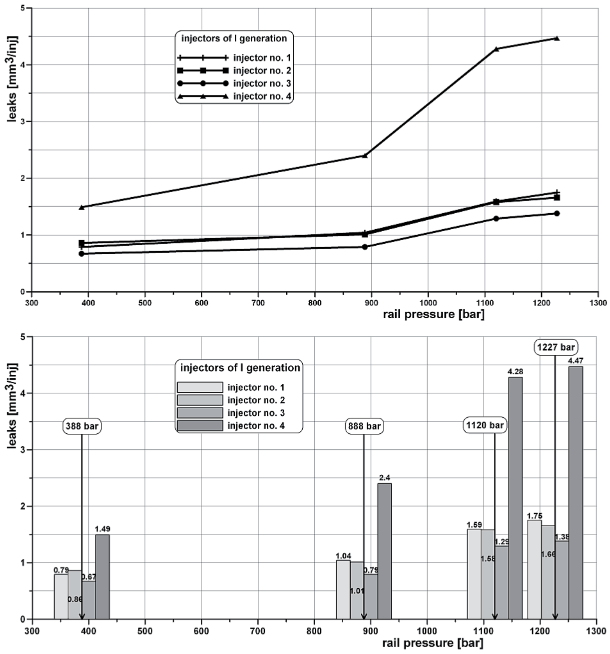

Fig. 12. The 1st generation injectors leakages versus rail pressure

In rail were maintained pressures possibly the most similar to the pressures used in the measuring points selected earlier. It had created some problems, because pressure in the rail after disconnection of the injectors was very unstable, and its stabilization and maintenance during measurements on the assumed level had required many attempts. Various values of the pressure were obtained via change of rotational speed and output capacity of high pressure pump.

In the Fig. 12, in function of pressure inside the rail, are presented leaks in tested injectors of the 1st generation. In the linear diagram is distinctly seen, that the values for injectors No. 1 and 2 are very similar, and are changing from 0,8 mm^3/injection to1,8 mm^3/injection. Injector No. 3, in complete range of pressure change, is typical of smaller leaks, which amount from 0,7 mm^3/injection at 388 bar to 1,4 mm^3/injection for 1227 bar. Whereas, for the injector No. 4, values of the overflow are changing from 1,5 mm^3 to less than 4,5 mm^3, and thus the increments and generated values are much more bigger than for the other injectors. To visualize differences in the leaks, the same values are presented in form of bar diagram. It can be seen that as the pressure is growing, size of the leak from injector No. 1, with respect to the injector No.2, is also growing, anyhow the difference between them remains relatively small. Values of the leaks from the fourth injector are three times higher than leaks from the third injector.

It could be seen, that increased leaks from the fourth injector can explain reasons of significant discrepancies in presented earlier runs concerning injectors of the 1st generation. For sure, growth of the leaks resulted in reduction of supplied dose, although it is difficult to ascertain to which extent. However, differences between efficient and inefficient injectors are too big to be explained by the leaks only. A source of the discrepancies could be also not proper operation of control valve of the fourth injector, caused, for instance, by wrong assembly or smaller active flow area of the atomizer.

As already mentioned earlier, development of a proposed diagnostic criterion for the injectors used in hydraulic accumulator systems became one from the main objectives of the present work. Although overflows of the injectors were evaluated earlier, there was also a need to assess what would be an effect of high pressure pump's rotational speed on this quantity. The problem is to find answer to question if tests of the injectors can be performed for any rotational speed of high pressure pump, or not. Obviously, leaks from the injectors, but not from the high pressure pump, are significant in course of these considerations.

Suitable measurements of elementary overflows were performed for injectors of the 1st generation. In the Fig. 13 are shown results of the measurements, being difference between average value for three correctly functioning injectors, and value of the overflow for a given injector. Because it was suspected that rotational speed can have an effect on leaks of the injectors, a special attention was paid on results obtained for the injector No. 4. It was demonstrated earlier, that just in this case the biggest volume of fuel flowed though clearances between flow areas.

In the first succession one performed measurements in conditions conducive to high values of the leaks, i.e. high pressure of fuel and low rotational speed of the pump. Speed of 750 rpm was taken, and for such speed one applied pressure higher than for other speeds, which amounted to 1180 bar (dotted line). There were obtained in such way results, being some kind of re-

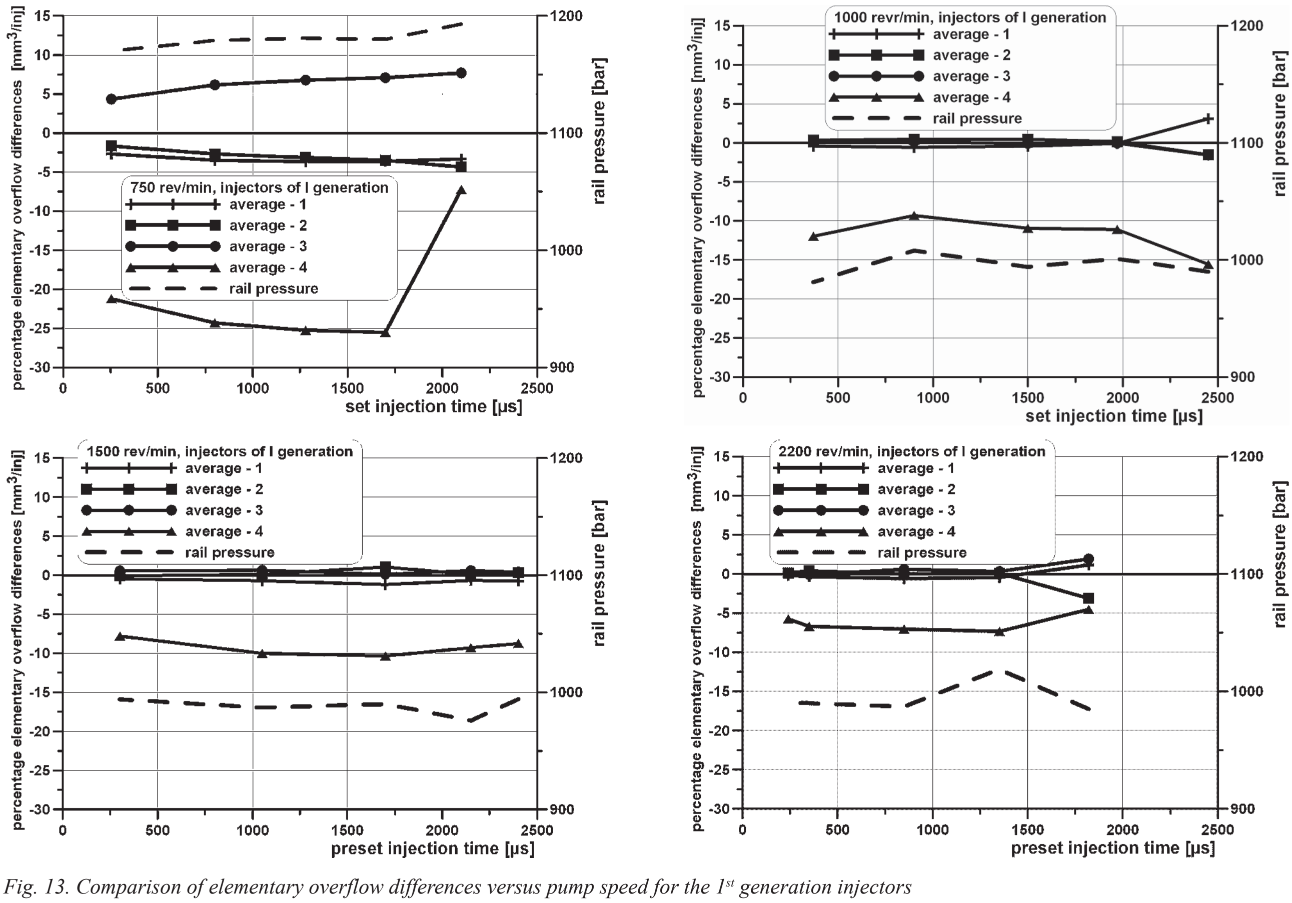

Fig. 13. Comparison of elementary overflow differences versus pump speed for the 1st generation injectors

ference values for the leaks, which can be obtained in the tested injection system. They did not constitute, however, a subject-matter of detailed considerations. Further measurements were carried out for the same values of 1000 bar in the rail (dotted lines), and for more and more high rotational speeds equal to 1000, 1500 and 2200 rpm.

Growth of the rotational speed resulted in reduction in differences of the elementary overflows. When the changes in case of correctly functioning injectors are small, and it can be assumed that they lay within limits of measurement error, while for the injector No. 4 are significant. For this injector, the leaks between pressure faces of precise pairs decrease together with growth of the rotational speed, even with 50 %. Because measurements of the analyzed cases were performed at practically constant and equal pressures of fuel, reasons of this phenomenon should be seen in increased, together with increase of the rotational speed, frequency of injectors operation. The frequency causes that share of time, when movement of the needle occurs and when dynamic caulking of the precise pair is possible, is bigger. From the above is evident, that is not without a meaning, at which rotational speed verification tests should be carried out. Assumption of too high speeds could result in wrong image of injectors condition.

7. Summary

Performed comparative analysis of the injectors of two generations enables their assessment from possibility of usage in Diesel engine point of view. In the Table 1, for the both groups of the injectors, are listed maximal and minimal values of analyzed quantities. Limit values in parentheses, written in grey color fields, concern damaged injector of the 1st generation.

Based on the performed comparative analysis and list of values of individual quantities one has formulated the final remarks. Boundaries of injectors' characteristics area depend on fuel pressure. Transition from ballistic to non ballistic area of the operation occurs earlier when a higher pressure prevails in the rail.

Taking into consideration analyzed range of the 1st generation injectors operation, it is seen, that for this group of the injectors dependence of injection dose for preset time of the opening becomes linear, practically in whole analyzed range. It enables precise batching of fuel doses, what is important when multipoint injection is used. Also it is possible to use compensation algorithms for small doses, necessary due to wear of the system during its operation [5].

Run of the analyzed characteristics of the 2nd generation injectors are partially linear, what can prove about not-complete opening of the needle on initial fragments of the characteristics. Values of elementary overflows increase both with growth of the opening time and growth of pressure in the rail. Intensity of overflow's growth is smaller in case of the doses. Measured values of the overflows are different for the both generations. The bigger ones were measured for injectors of the 2nd generation. For this group of the injectors, they grow more rapidly together with increase of opening time of the injector.

Together with growth of the dose, share of the overflow in the dose decreases. Share of the overflow in doses of the 2nd generation injectors is bigger than for injectors of the 1st generation. For small doses it reaches even 90 %. Rate of change of the shares for the 2nd generation is also considerable. Higher values of the overflow can prove about pursuit after shorter times of the needle lifting for the injectors of the 2nd generation.

At the same constant pressure, quantity of fuel necessary to lift the needle is approximately constant, and hence, strongly decreasing share of the overflow when the dose increases. Based on the mentioned above runs, one can make assessment of technical conditions of the injectors, while it is very important to know the reference runs, made at least for a few dozens of correctly functioning injectors of the same type. It can happen however, that measurement results for efficient and inefficient components are similar, like already happened in case of injectors of the 2nd generation and injector No. 4 from the 1st generation.

For the both groups, when pressure values are constant, the efficiency index increases together with growth of the opening time. In complete analyzed range, injectors of the 1st generation feature higher values of the efficiency index than injectors from the second group. It results from smaller volumes of fuel used to activation of the injectors.

When the opening times are shorter, nearly half of fuel supplied to the injectors at high pressure is used to activation of the injectors. Maximal value of the efficiency index reached level of 80 %.

Table 1. Summary of compared parameters for both groups of the injectors

quantitative confrontation compared parameters	**1st generation injectors**		**2nd generation injectors**	
	minimal value	**maximal value**	**minimal value**	**maximal value**
overflow [mm³/inj]	**16,1**	**28,6 (42,6)**	**11,1**	**40,4**
overflow portion in injected fuel quantity [%]	**23,2**	**56,3 (94)**	**30,3**	**91,9**
injectors efficiency index [%]	**64**	**81.2 (70,7)**	**52,1**	**76,8**
elementary overflow differences [mm³/inj]	**-1,6**	**3,1 (-9,3)**	**-4,6**	**7,5**
percentage elementary overflow differences [%]	**-5,6 (-72,6)**	**11,4**	**-20,5**	**33,3**

Differences between elementary overflows referred to average value can result from manufacturing tolerances of solenoid valves which control operation of the injectors, and hence, different reaction times of the solenoid valves on control pulse.

For injectors of the 1st generation, together with growth of rotational speed of high pressure pump, differences in volumes of the overflows decrease, especially for inefficient injector. It was caused by reducing share of leak in the overflow, which size was similar for all injectors.

None significant effect of division of injection dose on differences in the elementary overflows, referenced to the average value, has been confirmed. It could be result of implemented short time of the dwell.

Fuel leaks, measured for correctly functioning injectors of the 1st generation are changing from 0,67 mm^3/injection at pressure 388 bar to 1,75 mm^3/injection at 1227 bar. In case of inefficient fourth injector, the leaks amounted to: from 1,49 to 4,47 mm^3/injection respectively, and hence they are from 120 to 150 % bigger. Their values depend on pressure of fuel in the rail and rotational speed of high pressure pump. Increase of the rotational speed effects in growth of frequency of injectors operation, what increases share of time when dynamic caulking of this precise pair is possible.

Low values of the leaks (like e.g. in the injector No. 3) result in reduction of the overflows, and the same, improve the efficiency index.

Therefore, in case of any doubts concerning technical conditions of the injectors from Common Rail system, one should perform measurements both of the overflows and the leaks.

On base of the test results and performed analyses, one proposes to adopt the following methodology of proceeding during evaluation of criteria values and assessment of new injectors from Common Rail systems, which are actuated by solenoid valve:

1. Accomplishment of measurements for not divided dose of the injection.
2. Determination of two points for measurement of overflow and leaks – the first point corresponding to engine parameters on idle speed [3], and the second point corresponding to the lowest rotational speed of maximal torque.
3. Evaluation of criteria values of leaks and overflows for a given type of injectors, based on measurement results of representative group of at least 20 injectors.

In practice, based on evaluated criteria values, to perform assessment of injectors already being in use, one proposes the following order of the activities:

1. Accomplishment of measurements for not divided dose of injection.
2. Measurements of the overflow in measuring points; obtained values referred to criteria values should not differ more than 10%.
3. In case of ambiguous measurement results, measurement of the leaks in evaluated operational points.

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