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INVESTIGATION OF SHORT INJECTIONS USING STANDARD AND MODIFIED COMMON RAIL INJECTORS

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ABSTRACT–The control of the fuel to be introduced into the combustion chamber under idling and low-load conditions is known to be a problem in Diesel engines, owing to the relatively small fraction of the full-load fuel needed under light loads. Thus, particular attention should be paid to the behavior of the injector with reference to short injection events. This work presents the results of an experimental campaign carried out with two different types of common rail injectors, a standard injector and a modified one. The latter, coming from a simple modification realized in a standard injector, exhibits linear behavior between injected fuel and solenoid energizing time in the field of short injections. A direct comparison of the two injection behaviors suggests a possible way to better control short or pilot injections.

KEY WORDS : Common rail, Short injection, Injection rate, Hydro-grinding, Linear behavior

1. INTRODUCTION

Diesel engines equipped with direct fuel injection systems are widely used thanks to their high efficiency and their adoption in passenger cars has been increasing recently. The necessity of keeping the pollutant emissions of Diesel passenger cars within the stringent limits imposed by regulations, coupled with the higher request for performance, which should be comparable to gasoline automotive trade, has pushed research to new technology solutions. Common rail (CR) fuel injection equipments (FIEs) seem to be very effective in meeting this target, thanks to their flexibility in injection management.

The search for better combustion in direct injection (DI) Diesel engines, regardless of the engine size and use, has a strong link with the capability of the FIE to finely control the amount of fuel introduced into the combustion chamber. As a matter of fact, injections characterized by very small amount of fuel, such as pilot injections, are a special feature of CR FIEs and recently the pilot injection control has been widely adopted in DI Diesel engines.

Research addressing the influence of pilot injection parameters on pilot-main combustion has been carried out by several researchers (Tanaka *et al.*, 2002; Carlucci *et al.*, 2003a; Badami *et al.*, 2003; Carlucci *et al.*, 2005). The possibility of injecting small amounts of fuel, even split, just before the main injection has very important impacts on the capability to design advanced Diesel engines that can meet the standards for gaseous emissions.

However, a short injection necessary to feed the engine with a small amount of fuel may be considered as a pilot injection. Actually, the control of the fuel that should be introduced into the combustion chamber under idling and low-load conditions is known to be a problem in Diesel engines FIEs, owing to the relatively small fraction of the full-load fuel needed under light loads. Moreover, in multi-cylinder DI Diesel engines, cylinder-to-cylinder deviations in combustion and exhaust gas emissions are common, even if they have been minimized by CR type injection systems. Fuel mass and spray formation are thought to cause such deviations, which influence exhaust gas emissions and even engine stability, as reported by Kitayama *et al.* (2003). Usually, unburned hydrocarbons and odorous gases increase if combustion in each cylinder is not identical at low loads and low engine speeds, like at idling. Especially when pilot injection is applied to reduce engine noise at idling, the deviations in injected fuel mass and the spray shape increase, leading to cylinder-to-cylinder deviations in combustion and HC emissions (Kitayama *et al.*, 2003). Moreover, if the injector is equipped with a VCO nozzle with single-guided needle, it is known that initial sprays are not uniform, especially at low-load conditions. Experimental studies revealed that smoke increase is mainly caused by spray formation irregularities, that

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are induced by needle tip deviation from the seat center under a condition of low needle lift, leading to high local fuel concentration (Iiyama *et al.*, 1992; Bae and Kang, 2000). On the other hand, research on the spray patterns of VCO nozzles under low needle lift conditions was carried out by Soteriou *et al.* (1995) with large-scale transparent nozzles. These authors concluded that eccentricity of the needle tip and partial hydraulic flip are responsible for different spray patterns.

Regarding the working principle of the CR injector, reference may be done, among the several technical papers, to Stumpp and Ricco (1996), Boehner and Hummel (1997) and Ficarella *et al.* (2005). In the last work, the authors studied in detail, by means of computer modeling and simulation, the possibility of achieving injection rate modulations. In particular, the injection behavior of CR injectors equipped with geometrically modified control valves was investigated and the parallel experimental campaign validated the theoretical results.

Although CR FIEs are relatively new, the technical literature is rich in works dealing with the injection behavior of the injector, which represents the most important component of the system. Among the several theoretical studies, one can refer to the more recent, i.e. Mulemane *et al.* (2004), Nam *et al.* (2004), Payri *et al.* (2004) and Ficarella *et al.* (2005). The great number of such technical papers reflects the importance of fuel injection in engine improvement and design. Nevertheless, almost all of the research present in literature considers simulations of injection events characteristic of medium-load and full-load conditions, so that the experimental campaign necessary to validate the proposed model is strictly oriented to tests concerning long injection events with large amounts of injected fuel. With reference to experimental investigations oriented to the study of the dynamic behavior of the injector, often coupled with a spray characterization analysis, the researches carried out by Han *et al.* (2000), Henein *et al.* (2002), Wang *et al.* (2003) and Bermudez *et al.* (2005) are probably among the most outstanding, together with the research of Lyu and Shin (2002), investigating the VCO and minisac nozzle characteristics on engine performance. However, an important issue remains, i.e. investigations of short injection events realized at high injection pressures, according to the current trend of FIEs requiring higher and higher injection pressures (Mahr, 2002).

This work aims to study the injection behavior of two CR injectors with reference to short energizing times, i.e. small amounts of injected fuel. Thus, the scope of the current work is to investigate the short injections field of a standard CR injector and to present a simple modification of the same injector capable of possible improvements.

2. EXPERIMENTAL ACTIVITY

Figure 1 shows a schematic layout of the fuel injection test rig used in the experimental campaign.

The injection rate meter is similar to the one suggested by Bosch (1966). The method for measuring the injection rate is based on the calculation of the flow velocity by the pressure-velocity equation, which is valid for a single pressure wave in a non stationary flow:

$$p=a\cdot\rho\cdot u \tag{1}$$

In the previous equation, p is the pressure, a is the velocity of sound in the fluid, ρ is the density of the fuel and u is the flow velocity. The injector nozzle discharges into a calibrated hydraulic tubing with predetermined length. The fuel quantity per time unit (Q) injected by the nozzle into the metering tubing produces an equivalent liquid velocity whose magnitude depends on the internal diameter of the tubing itself. Such a fuel flow gives rise to a pressure wave proportional to Q, which is measured by a proper transducer located within the nozzle adapter and conditioned using a charge amplifier. The pressure signal is then recorded at a suitable sampling rate (here fixed equal to 33 kHz) and used for the calculation of the injection rate. Considering that changes in pressure of the fluid propagate at the velocity of sound and produce a

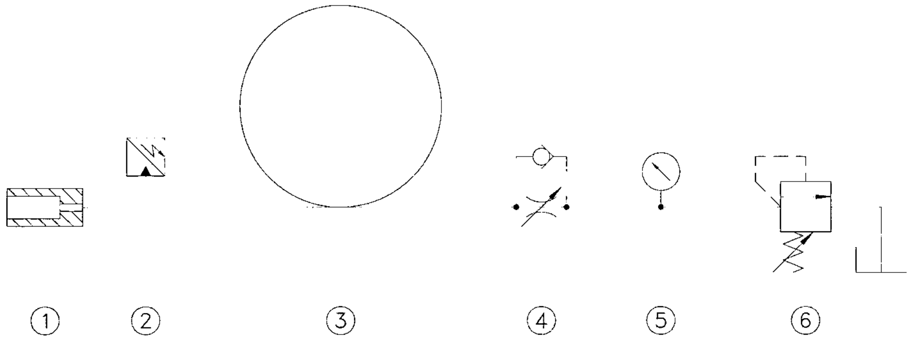

Figure 1. Fuel injection test rig (1, adapter for injector fixing; 2, pressure transducer; 3, metering tubing; 4, variable orifice with check valve; 5, manometer; 6, pressure relief valve).

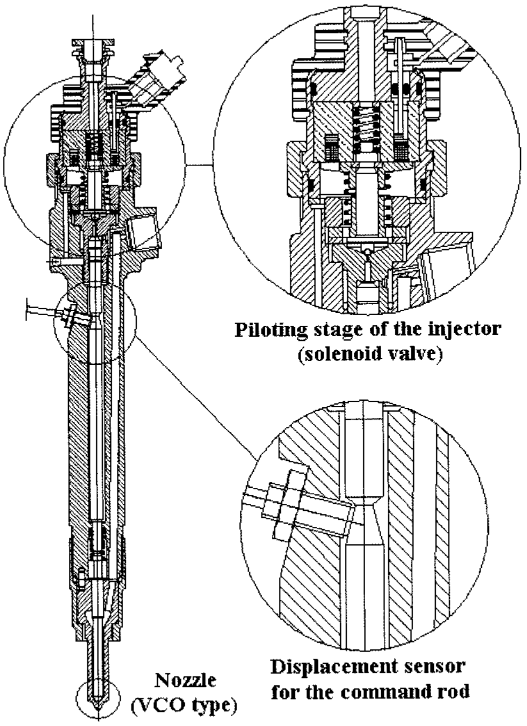

Figure 2. CR injector with details of its piloting stage and of the position of the displacement sensor for the command rod.

corresponding change in the flow velocity, it is possible to apply the above-mentioned theory to a single pressure wave moving within the constant flow area tubing at the speed of sound. Thus, the instantaneous injection rate may be calculated as

$$Q=A_t\cdot u \tag{2}$$

where A_t represents the inner cross sectional area of the tubing. Now, combining the two previous equations,

$$Q=\frac{A_t}{a\cdot\rho}\cdot p \tag{3}$$

it is possible to realize that the injected fuel quantity per time unit is a linear function of pressure, which allows quantitative characterization of individual injections.

As for the fuel quantity per stroke (IF_{st}), equation (3) has to be integrated over the injection period, from the start of injection (SOI) to the end of injection (EOI) i.e.

$$IF_{st}=\int_{SOI}^{EOI}Q\cdot dt=\frac{A_t}{a\cdot\rho}\cdot\int_{SOI}^{EOI}p\cdot dt \tag{4}$$

Equation (4) returns the quantity of fuel injected per stroke as a function of pressure and time.

Pressure at station 2 in Figure 1 was measured by means of a Kistler 6052 piezoelectric pressure transducer. A Kistler 5011 charge amplifier was used to convert the electrical charge yielded by the sensor into a proportional DC voltage.

Regarding the needle lift, which was measured together with the injected fuel rate, here it is worth noting that the real measurement refers to the command rod movement and not strictly to the needle lift, since the elastic release of the command rod - needle assembly cannot be neglected (Henein *et al.*, 2002). Figure 2 shows the injector equipped with the transducer for the detection of such a movement: a non-contact eddy current displacement transducer ($\mu\varepsilon$ S05) was employed with a signal conditioning unit ($\mu\varepsilon$ multiNCDT 300).

The first movement of the command rod does not cause the needle to leave its seat instantaneously, so that it does not indicate the actual start of the injection process. Regarding the closing stage, the above-mentioned elastic release of the assembly influences the needle motion also when the needle itself is closing the nozzle. Moreover, the pressure transducer in the metering device, as shown in Figure 1, was located distant from the nozzle position, so that a fixed delay may be expected between the signals referring to the injection rate and to the command rod movement.

In order to better realize the last considerations, Figure 3 shows two signals acquired with reference to command rod movement and injection rate when the solenoid is energized for 200 μs and rail pressure is fixed equal to 135 MPa. From Figure 3, one can easily determine the above-mentioned delay, when referring to the falling part of the two signals.

Figure 4 shows how to determine the start of injection (SOI), the end of injection (EOI) and the injection duration, necessary for next considerations.

Four voltages with reference to the rising and falling parts of the fuel rate, respectively, are to be set (Figure 4). The SOI is determined as the intersection between the horizontal time axis and the straight line passing through the intersections between the rising part of the fuel rate

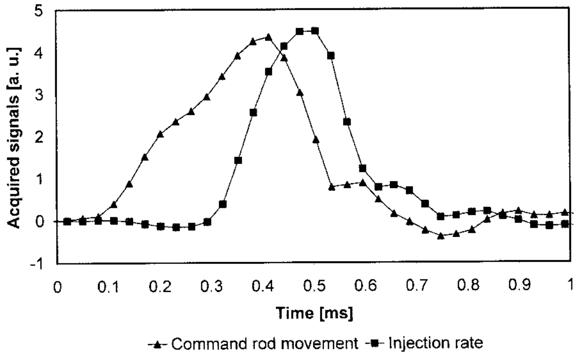

Figure 3. Command rod movement and injection rate for rail pressure and ET equal to 135 MPa and 200 μs, respectively (a.u. - arbitrary units).

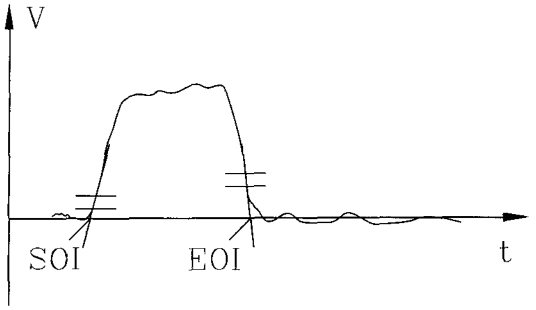

Figure 4. Method to determine the duration of injection with reference to its start and end.

and the first two voltage levels. The EOI is determined in a similar way, i.e. it is the intersection point between the horizontal time axis and the straight line passing through the intersections between the other two voltage levels and the falling part of the fuel rate. The fuel injection period consists of the difference between the above mentioned EOI and SOI.

The acquired data consisted of the energizing current, the fuel injection rate and the needle lift. In order to reduce the random error effects, about twenty consecutive cycles were acquired after stationary working conditions of the system were reached. Pressure and displacement signals were digitized, simultaneously with the signal of the energizing current to the injector, by means of an analog/ digital acquisition board (National Instruments type 4472) on a PC. The system was monitored with homemade software for data capture in the LabVIEW™ programming environment.

The energizing time (ET) was varied during the experiments according to a constant time step, equal to 25 μs. Such a time step was supposed to be sufficient, as concerns the current investigations, with reference to previous experimental tests carried out by Carlucci *et al.* (2003a, 2005) on a 1930 cm^3 four cylinders DI Diesel engine (FIAT 154 D1.000) equipped with a Garrett TD2502 turbocharger, where pilot injections were varied according to three ET values, equal to 150, 200 and 250 μs.

The results presented in the following section come from investigations carried out with injectors equipped with the same nozzle but different control valves. The nozzle is a single-guided VCO one, characterized by a stationary flow rate equal to 13.33±0.27 mm^3/ms at a constant injection pressure of 10 MPa and with the needle lift fixed to 250 μm (Kampmann *et al.*, 1996).

The control valves equipping the investigated injectors differ in terms of discharge properties through the Z hole (4 in Figure 5). They are a standard valve and a modified one whose Z hole was hydro-ground in order to achieve a 20% increase in the discharge properties of the hole itself. Both valves were tested on a hydraulic test bench and the steady state discharge properties were measured for a fixed pressure drop equal to 10 MPa and a back pressure fixed to 6 MPa (Arvizzigno, 2002). In fact, when the solenoid injector is energized, the control volume (5 in Figure 5) does not fully deplete, presenting always a back pressure to the fuel flow entering the Z hole.

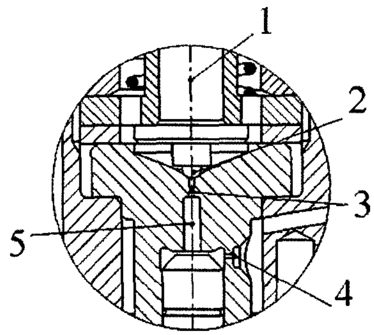

Figure 5. Details of the control valve, piloting stage of the CR injector (1, pin; 2, ball valve; 3 A hole; 4, Z hole; 5, control volume).

3. SHORT INJECTIONS ANALYSIS

Published technical papers dealing with the hydraulic characterization of CR injectors were mainly oriented to injection events characteristic of partial-load and full-load conditions, as previously mentioned, so that amounts of injected fuel are considerably large. In this work, the injection behavior is analyzed with particular reference to short ETs.

Considering the actual trend for FIEs requiring higher injection pressure, investigations were carried out with reference to rail pressures equal to 120 MPa and 135 MPa, respectively. Such pressure levels were chosen because the tests were carried out with Bosch first generation type CR injectors, and maximum operating pressure for these injectors is fixed to 135 MPa.

Figure 6 shows the injected fuel map of a standard

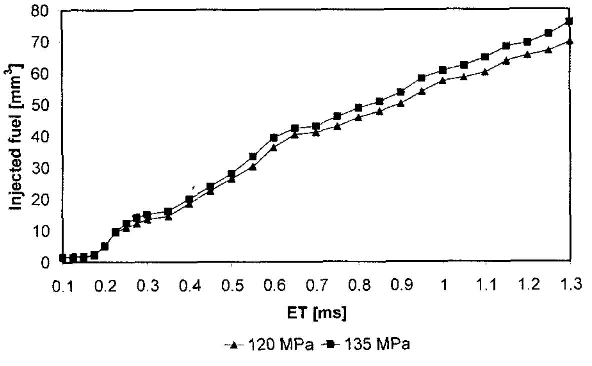

Figure 6. Cumulative fuel injected by the standard injector for rail pressures equal to 120 MPa and 135 MPa.

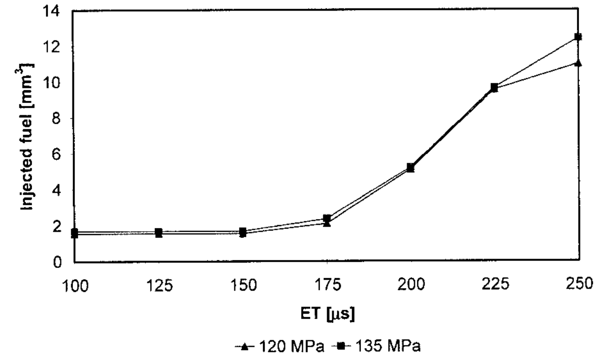

Figure 7. Cumulative fuel injected by the standard injector for short ETs.

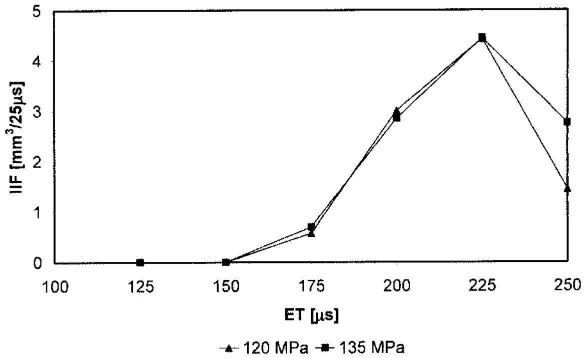

Figure 8. Increase in injected fuel (IIF) for the standard injector.

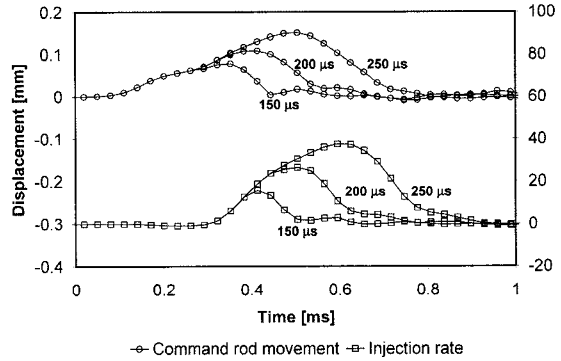

Figure 9. Command rod movements and injection rates when energizing the injector for 150, 200 and 250 μs (rail pressure equal to 120 MPa).

injector for the two considered rail pressures. Actually, the response of the injector in terms of injected fuel, when rail pressure is fixed and ET varies, is not strictly linear over the entire ET range: when the ET is shorter than 300 μs, it is difficult to achieve a linear behavior.

Figure 7 shows an enlarged view of Figure 6 with reference to short ETs. The behavior of the injector seems to be particularly singular. One possible explanation would be a transient phenomenon that may be considered sufficiently extinguished after a certain time interval. In fact, it is possible to appreciate that, when ET is very short, no sensible variations in fuel delivery seem to be achieved when increasing ET up to 150 µs. Later, a sudden increase in injected fuel occurs.

Such an injection behavior, characteristic of the highest injection pressures and evident for ET increasing up to 150 μs, was already highlighted by Ficarella *et al.* (1999) whose theoretical model predicted and justified such a behavior.

Now, in order to more closely examine short injection events, a special parameter, here called IIF, is introduced. IIF is defined as the increase in injected fuel for a fixed increment of ET, so that it represents a sort of instantaneous slope in the injected fuel map. Here such an increment of ET is fixed at 25 μs and justified by previous tests carried out by Carlucci *et al.* (2003a, 2005) when short pilot injections were performed before a main injection. The ETs for those pilot injections were fixed equal to 150, 200 and 250 μs then, on the basis of those experiments, the injector behavior is here analyzed with reference to these ETs and to the mid points of the time intervals [150÷200] and [200÷250]. However, it should be noted that, even if the injectors of the CR FIE feeding the engine tested by Carlucci *et al.* (2003a, 2005) were Bosch first generation type CR injectors, they were equipped with a nozzle different from the one adopted for the current study.

Of course, a good linearity between injected fuel and ET will be better represented by an almost constant value of IIF, in the range of ETs under study.

Thus, looking at Figures 7 and 8, a standard injector does not seem to guarantee increases in the injected fuel proportional to ET when energized for short times. In fact, it is possible to appreciate that, when ET is equal to 200 μs, a serious increase in IIF is achieved if compared with the injected fuel for ET equal to 175 μs. Analogous considerations may be made when the injector is energized for 225 μs.

These sudden increases in the amount of injected fuel, as shown in Figure 8, highlight an injection behaviour in the working field characteristic of short ETs which is anything but linear, if compared with the almost linear behavior of the electro-injector when energized for a longer time.

In order to better realize the dynamic behavior of the injector, Figures 9 and 10 show three experimental command rod movements together with the correspondent injection rates, with reference to the two considered rail pressure levels and to ETs equal to 150, 200 and 250 μs, respectively.

From Figures 9 and 10, it is possible to appreciate the considerable increase in injected fuel when energizing

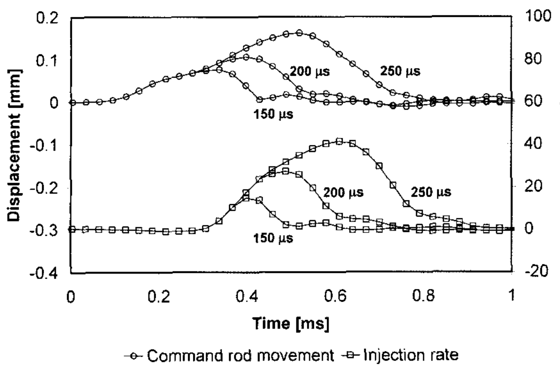

Figure 10. Command rod movements and injection rates when energizing the injector for 150, 200 and 250 µs (rail pressure equal to 135 MPa).

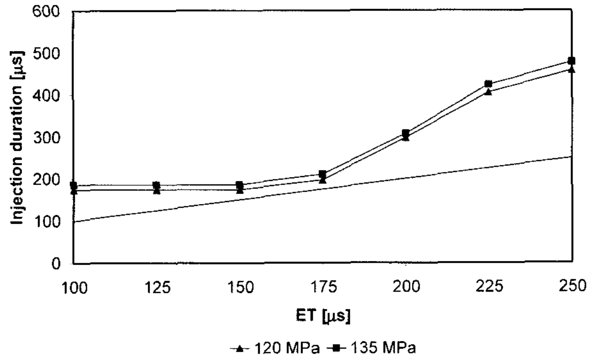

Figure 11. Actual injection duration vs. ET when performing short injections (rail pressure equal to 120 MPa and 135 MPa, respectively).

the injector solenoid for a longer time.

Another relevant result achieved during the experimental campaign is shown in Figure 11. It regards the correspondence between the solenoid energizing time and the actual duration of the injection events. It is possible to detect again the trend already shown in Figure 7: namely, the duration of the injection event (time difference from EOI to SOI) is always longer than the energizing time.

In order to perform short injections and better meter the amount of fuel injected during such events, a more evident linearity is desirable between ET and injected fuel. Thus, the range where IIF presents larger values should be limited or even eliminated.

Attempts at designing injectors with fuel delivery as much as possible proportional to ET were previously made by Ganser (2000): considering a wide range of injection pressures, right after the SOI, injected fuel was quite linear with respect to ET. This is an important condition if short injections with small fuel quantities have to be produced.

As previously mentioned, the problem of performing short injections should not be underestimated, especially when feeding the engine under idling and low-load conditions.

Actually, a more linear relation between energizing time and injected fuel may be a precious tool for a better metering of the fuel itself. Nevertheless, with reference to Figure 6, it is possible to realize an appreciable linearity between injected fuel and ET only after a specific ET value, when transient and instability phenomena no longer affect the injector response, as reported by Ficarella *et al.* (1999). Thus, modifications in the injector are necessary in order to achieve a different injection behavior, with particular reference to injection events characteristic of small amounts of injected fuel.

Recent research by Carlucci *et al.* (2003b) and Ficarella *et al.* (2005) was aimed at studying how to achieve a modulation of the injection rate, leading to modified injectors whose control valve Z hole was hydro-ground. This process clearly causes an increase in the discharge flow rate through the Z hole, so that the needle displacement is retarded and its velocity is slower when leaving its seat. Suggestions concerning the realization of particular modifications in order to achieve modulations of the initial stage of the injection rate were reported by Ficarella *et al.* (2005). Trends in the reductions of the fuel injected during the first stage of the injection event were reported as well. Such reductions were achieved with a progressively increasing delay of the hydraulic SOI with respect to the starting current. A series of particular control valves was just realized to equip the injectors on the occasion of experimental tests oriented to characterize the engine behavior in terms of noise and block vibrations (Carlucci *et al.*, 2004).

Figure 12 shows the fuel delivery of a modified injector equipped with a control valve whose Z hole discharge properties are increased up to 20% with respect to the two investigated injection pressures (120 MPa and 135 MPa, respectively) and short injection events. If these results

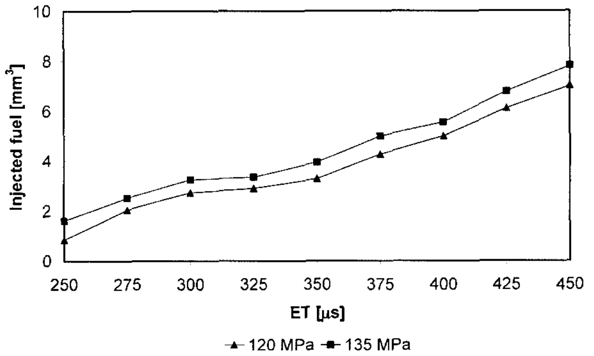

Figure 12. Cumulative fuel injected by the modified injector for short ETs.

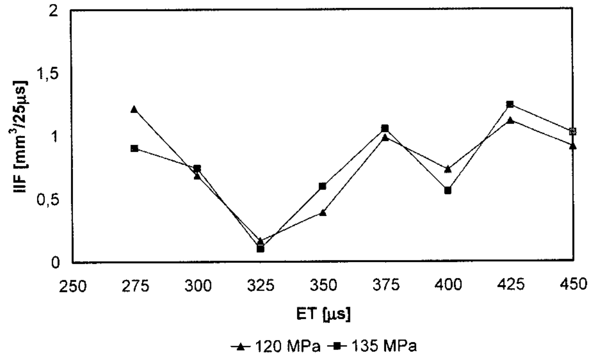

Figure 13. Increase in injected fuel (IIF) for the modified injector.

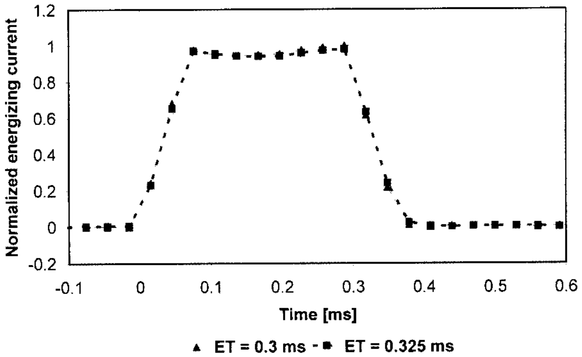

Figure 14. Normalized energizing currents.

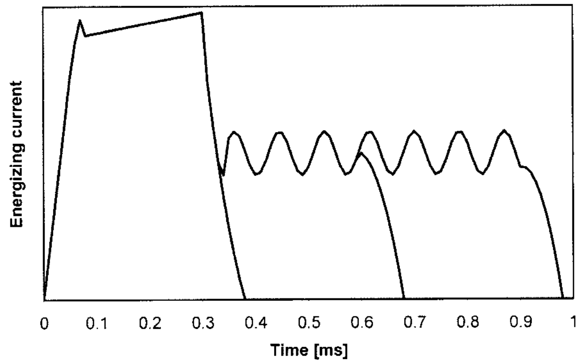

Figure 15. Schematic time evolution of three energizing currents (ETs equal to 0.3, 0.6 and 0.9 ms, respectively).

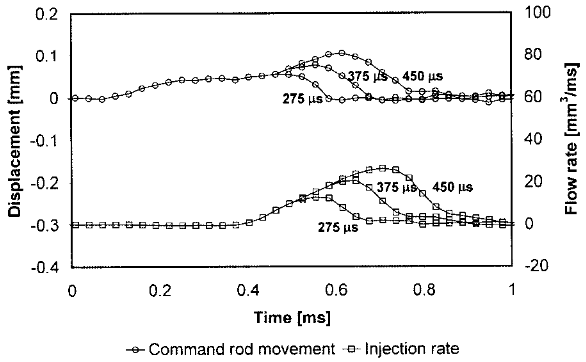

Figure 16. Command rod movements and injection rates when energizing the modified injector for 275, 375 and 450 μs (rail pressure equal to 120 MPa).

are compared with the ones presented in Figure 6, it is possible to appreciate that ETs must be longer than 250 μs, otherwise injection cannot occur or is not steady and repetitive. Such a result is simply justified with reference to the working principle of the injector. Increasing the discharge properties of the Z hole (4 in Figure 5), when the solenoid is energized, the control volume (5 in Figure 5) depletes no more quickly, so that the consequent upward velocity of the command rod - needle assembly is considerably reduced. Thus, ETs for the modified injector are necessarily longer than ETs for a standard injector.

Looking at Figures 12 and 13, one sees that the field of short injection events presents a sufficiently linear relation between injected fuel and ET. In fact, the IIF parameter oscillates around a fuel volume of 1 mm^3, with the only exception of the time interval [300÷350]. In order to justify such a behavior, it is necessary to consider the functioning of the electro-injector. The current energizing the solenoid, initially fixed by the ECU to its maximum value, is decreased to a holding level just after a period of solenoid energizing equal to 300 μs. That is why the injector does not seem to be sensible to any increase in energizing time just in the above-mentioned time interval.

In order to better understand the previous considerations, Figure 14 shows the recorded signals of two synchronized energizing currents for the periods of 300 and 325 μs, respectively. Of course, the signals concern the energizing currents commanded by the ECU of the FIE, so that they are not dependent on the nature of the modification in the control valve of the injector itself. It is possible to appreciate that the acquired currents are nearly superimposed and justify the results presented in Figures 12 and 13 referring to the time interval [300÷325].

When ET is longer than 335÷340 μs, a holding current level, almost equal to one half of the maximum current value, is sufficient to keep on energizing the solenoid, so that the injected fuel increases with longer ETs.

Figure 15 schematically shows the time evolution of three energizing currents with reference to three different ETs equal to 0.3, 0.6 and 0.9 ms, respectively.

As previously proposed in Figures 9 and 10, Figures 16 and 17 now show the dynamic behavior of the modified injector in terms of command rod movements and injection rates, by way of example. Injection pressures are always equal to 120 and 135 MPa, whereas ETs are equal to 275, 375 and 450 μs, respectively. Looking at

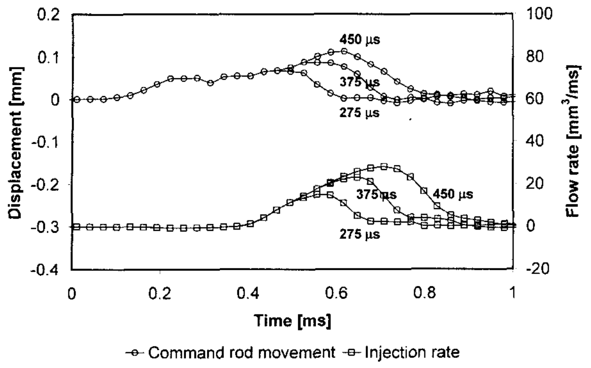

Figure 17. Command rod movements and injection rates when energizing the modified injector for 275, 375 and 450 μs (rail pressure equal to 135 MPa).

these last two figures, the following results are noteworthy:

(1) the elastic release of the command rod - needle assembly lasts a longer time if compared with the behavior characteristic of the standard injector;

(2) the SOI is retarded almost 100 μs with respect to the standard injection, but the simplest solution for such a problem may consist of simply advancing the injection timing (Carlucci *et al.*, 2004);

(3) the initial stages of the injection process appear smoother if compared with the ones presented in Figures 9 and 10. Such a result was already anticipated by Ficarella *et al.* (2005).

Finally, according to the results achieved with the two injectors, it should be considered that the energizing time (ET) of the injector solenoid is not an engine parameter that is as significant as the injected fuel. The latter is the real reference parameter (Tanaka *et al.*, 2002), so that the comparison between results in Figure 6 (or 7) and results in Figure 12 should be proposed only with reference to the same amount of fuel. Thus, when using the modified injectors, once the injection pressure and the amount of pilot fuel are fixed, the time necessary to hold the solenoid injector energized may be determined just entering the y-axis in Figure 12 and determining the energizing time in the x-axis (Carlucci *et al.*, 2004).

Of course, fixing the same ET, the modified injector will never reach the fuel rate of the standard one.

4. CONCLUSIONS

The injection behavior of a standard CR injector was investigated with reference to short energizing times and high injection pressures. The results showed that a desired linearity between the injected fuel and the electric command is somewhat difficult to achieve. A possible explanation may be found in transient phenomena occurring in the first period of energizing, so that they are no more relevant when energizing the solenoid for a longer time.

Later, in agreement with such a hypothesis, an injector modified according to the suggestions of previous studies by the authors was tested.

With reference to the field of short injection events, the new injection behaviour appeared to be improved, if compared with the response of the standard injector. In the modified injector the stage characteristic of the shortest energizing times, with constant injected fuel, was eliminated and a more linear response of the new injector was observed with respect to the standard one.

Another difference between the two injectors consists of the hydraulic behavior of the modified one, retarded in its initial stage if compared with the one of the standard injector. However, in order to respect the same start of injection, once this delay is quantified for a fixed injection pressure, the drawback may be solved by anticipating the timing of the modified injector with respect to the standard one.

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