THE CHARACTERISATION OF HIGH PRESSURE INJECTION

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ABSTRACT

High pressure ("common rail") fuel injection systems require accurate characterisation to ensure that the delivered system matches the oxidation and chamber turbulence requirements of the engine designer and in particular to demonstrate that the acoustic cavitation essential to lowered combustion temperatures and reduced pre-combustion chemistry times can be achieved. These characteristics are crucial in meeting emission requirements and the study of sono-chemistry and its pressure/volume effects is of growing importance to engine design, for all direct injection systems whether diesel or gasoline.

There are a number of methods by which the timing and rate of separate injection events can be represented and measured.

One common method is to determine pressure changes within a chamber of known volume and from this data extrapolate an approximation of the timing and volumes.

The preferable method, and that employed within the AKRIBIS systems, is to directly measure actual fluid volumes and durations. This is achieved by measuring the displacement of a piston operating a highly accurate lvdt (linear variable displacement transformer) device and the data so obtained allows for the accurate extrapolation of the actual parameters of the injection system.

Changing the back-pressure applied to the piston can vary the pressure within the chamber: that back pressure is applied using nitrogen. Some users of the system specify high back pressure: we have operated at pressures as high as 180 atmospheres but the more normal back pressure for a diesel injector test and characterisation is much lower and in some cases simulates the geometric compression ratio of a diesel at around 20 atmospheres.

The introduction of common rail (and of electronic unit injectors) posed interesting challenges, notably the proper interpretation of results. Time intervals and as a result absolute amounts reduced with pilot injection amounts in the single figure micro-litre range and with time intervals measured in microseconds. The ability of the AKRIBIS system to resolve volumes down to 0.025 cubic millimetres and to operate at micro-second rates is essential for the proper characterisation of injection events.

The initial rate traces produced at rail pressures in excess of 1200 bar appeared to have excessive noise (figure 1). Since these fluctuations had not been apparent at lower injection pressures of around 1000 bar (figure 2), there was an initial assumption that the more rigorous flow rate and time demands of high pressure injection were causing a mixture of mechanical variation and of electronic random noise. However, a more considered examination proved that neither event was correct. If the mechanical route, which ascribed oscillation or "ringing" to the piston, had been correct, the rate trace would have shown negative points (figure 3). This clearly was not occurring. What was occurring was that the velocity of the piston was varying.

In order to eliminate either mechanical noise or electronic noise, the rate traces of a significant number of injections were averaged. (figure 4). What remains shows a consistent and repeatable pattern, with only minor variations that should be expected at the volumes and time bases being used. Some of this fluctuation and perhaps all of it is a result of the vibration of the injector itself, operating at high flow rates.

It is the explanation and interpretation of this data that is the subject of this brief presentation.

TIMING

Since the timing intervals are extremely short, actual start and finish timing measurements for each injection event are significantly affected by lags or leads in the system.

Measurement systems that rely on pressure effects have a significant start lead. This is due to the fact that the chamber pressure rises in advance of the actual fluid delivery, representing the time taken for the fuel to travel from the opening valve through the injector orifices. This lead relates to a number of quite complex factors including start pressure, chamber shape, and chamber turbulence.

The AKRIBIS system has a known start lag represented by delays within the electronics and measuring system, related to the speed at which the electrical impulses can be moved through the systems and to the initial stiction of the measuring device. (figure 5) This lag is known accurately to be some 60 microseconds, and recent software changes have increased the accuracy of timings of multiple events. The anticipation of fluid delivery is of most importance to the engine designer since the actual times available to complete pre-combustion chemistry are in fact shorter than that indicated. The consequences can include unexpected over-fuelling especially at high delivery/high demand settings. The observation of these phenomena, without an appreciation that the measurement system has misled the engine manufacturer, can be frustrating in attempting to meet increasingly rigorous emission strictures.

A signal lag on closing exists in the AKRIBIS system, and is known: it results from the inertia of the piston. Again, recent work has shown that the AKRIBIS is relatively insensitive to piston mass, and as a result any closing inertia can be corrected in the interpretation software. Since the actual fuel delivery is known extremely accurately through mass over-checking where the actual fuel injected over a large number of events is collected and measured and then compared with the sum of the piston displacement, the displacement of the event by a known time can be incorporated in any conclusions drawn from the results.

POSITIVE DISPLACEMENT MEASUREMENT

The positive displacement measurement systems rely on a piston constrained by a known back pressure, moving to allow extremely accurate measurement of delivered volumes. Although any such system is inherently accurate and gives direct readings of delivered volumes, the raw data contains a number of factors apart from simple increase in volume.

Where low pressure, high flow injection events are being studied or characterised, the anomalous effects are reduced since the response rate of the system is lower. However, high-pressure injection using modern orificed injectors behaves and has to behave in a fundamentally different way.

As we have seen, there are a number of relatively high frequency fluctuations in the delivery flow rate. These fluctuations are markedly different from those observed at lower injection pressures and are too regular and too consistent to be accounted for by droplet conglomeration. Modern high-pressure diesel injection systems already operate with super-sonic flow rates through the delivery orifices and this super-sonic flow rate induces ultra-sound effects. Direct injection gasoline systems inevitably will follow suit. In both cases, the demand for higher engine speeds places further demands on the technology of compressing pre-combustion changes into shorter and shorter times. Our work has indicated that as a direct result of this intermittent super-sonic flow, acoustic cavitation voids are formed within the actual fuel droplets and its the collapse of these voids that reduces the apparent volume and results in the observed fluctuations in flow rates. The fluctuation provides some measure of the degree to which cavitation voids are formed and collapse (figure 6).

FUEL CAVITATION

Examination of the injection results is instructive and is of particular importance in characterising pilot injection. As the injector valve opens, gas within the injector is ejected causing an immediate and rapid rise in chamber pressure. Because the volumes are small, the actual pressure rise that is achieved is small, but if the opening time is determined by pressure change the actual start of injection flow will be some 100 micro-seconds after that initial pressure increase, depending on rail pressure, injector design etc.

As liquid flows to and then through the injector nozzle orifices, flow is very fast through the nozzles, giving rise to extreme thin plate vortex venturi effects and creating very significant cavitation within the flow pattern. The separation of flow from the orifice wall, as turbulent adherent drag builds up and the vena contracta diminishes, is important in the creation of the desired cloud of small droplets, typically of nano particle size, as opposed to the theoretical “hydraulic flip” jet. The flow is typically pulsating at very high frequencies, with through orifice velocities well in excess of the speed of sound. The speed of sound within a gas-liquid phase typical of diesel fuel can be as low as 20 metres/sec.: through orifice velocities are typically ranging from 500 metres/sec at 1000 bar to well over 800 metres/sec at rail pressures of 1800 bar.

Consequently, within each droplet a series of cavitation bubbles will form. As a result, the apparent injection volume will be higher than the actual liquid volume. Each cavitation bubble will collapse: the lifetime of the bubble is typically around 1 to 2.50 micro-seconds in a liquid and somewhat less than that in a gaseous environment.

Considerable levels of energy are involved in the cavitation creation. In fact, the cavitation effect is probably more pronounced in tests injecting into liquid than into an actual combustion chamber, but the difference is unlikely to be significant except in terms of bubble collapse rates. In fuel (as opposed to test fluid) there will be extensive nucleation sites, both from dissolved gases and from very small particles that pass through the line filters.

There is a reduction in pressure from the rail pressure of 1500 to 1800 bar to the chamber pressure of 20 bar and the preponderance of this energy is absorbed in the creation of cavitation bubbles. The formation, growth and implosive collapse of acoustically induced cavities in liquids irradiated by high frequency vibration results in complex sonochemistry. As each bubble collapses, very high molecular excitation frequencies are achieved that can be observed experimentally as either very high temperatures or as sonoluminescence. It is this collapse energy release that is observed as temperature rises in the AKRIBIS system. In non-volatile fuels, cavitation collapse temperatures as high as 5000K have been observed, but cavitation voids in gaseous hydrocarbons produce far lower temperatures because of the absorption of energy in long chain breakdown.

An important measurement for engine development teams is to estimate the degree of sonochemical activity that occurs. Although sonochemical changes (for example, breakdown into gaseous hydrocarbons, low molecular weight fractions and heavier remnants can occur in time scales as short as 10-^{10} seconds, measuring changes in temperature can be indicative: classically, expanding the compressed liquid in the rail system into the lower pressure environment of the measurement chamber (or of the combustion chamber) should reduce the temperature of the charge. However, a significant temperature rise is observed that depends again on rail pressure and this rise in observed temperature provides a measure of the prevalence and decay rates of the cavitation voids. The decay rates and energy transfers of the cavitation voids can also be observed by monitoring electro-magnetic emissions generated by the void collapse: at very high energy rates, this emission can occur within the visible light spectrum and is often described as sonoluminescence. At lower energy levels, the emissions are below the infrared spectrum and may be observed using high frequency radio and microwave probes.

The sonoluminescence can be sufficiently pronounced as to trigger emissions at wavelengths shorter than infrared with durations measured in femto seconds.

The result of the energy transfer inherent in the cavitation bubble collapse is to break the long chain hydrocarbon molecules in the fuel down to shorter chain constituents, including methane and hydrogen. This compresses the pre-combustion oxidation period to the point where diesel fuel can be combusted within short time periods, but critically it also introduces lower temperature mixture constituents (notably hydrogen) that lower combustion temperatures and which reduce the formation of oxides of nitrogen.

The importance of these measurements is that the very high frequency vibrational mode induced with the cavitation void collapse has an important effect on the long chain fuel molecules, releasing hydrogen and some short chain hydrocarbons. Because of the lower combustion temperatures of hydrogen (typically 400C or so) this sonochemical effect reduces combustion temperatures and inhibits the production of nitrous oxides.

It is known that cavitation void collapse releases hydroxyl radicals that break down double-carbon bonds. It is worth noting that the active constituent of exhaust gas used in auto-ignition is a hydroxyl radical and it is informative that the underlying chemistry remains the same.

What is also observed is a marked apparent temperature rise resulting from raised injection pressures. At high line pressures the apparent temperature observed close to the injector orifice can reach as much as 160^{o}C (figure 7). This temperature rise is explicable in terms of flow dynamics and is a rise of as much as 120^{o}C or more over the temperature of fuel exiting the high pressure pump. It is known that the collapse of cavitation voids results in very high transient temperatures resulting from the high frequency molecular vibration levels, but the overall energy balance remains. However, in a non-volatile test liquid, all of the transferred energy will be seen in a temperature rise of the injected liquid. Where a volatile hydrocarbon is in effect acoustically cracked into simpler constituents, a significant proportion of the energy transferred from the pressure pump will be absorbed in the cracking process.

The results of acoustic-cavitation will be to accelerate pre-combustion chemistry and to break up the long chain hydro-carbon molecules into more volatile fractions including hydrogen. The practical result is that inducing cavitation voids inside the fuel droplets by promoting super-sonic flow rates reduces combustion temperatures, limiting Nox formation and reducing the time required for pre-combustion chemistry allowing diesel engines to operate at higher speeds.

The injector design induces sono-cavitation into the flow stream and the individual flow streams themselves have induced pulsation resulting from the fluctuating turbulent drag in the orifice itself. However, the wave form in the pump and rail assembly perturbs the through-orifice flows and, since at various flow stages the chamber pressure can rise towards line pressure, these fluctuations can also affect measurement.

The overall result is what might be termed a noisy signal, where a representation of the rate of flow will contain within it some inherent system noise, some noise generated by the delivery system and the highly fluctuating results of the actual delivery.

Any inherent system noise would be created by fluctuations in the mechanical system, where vibration in the measurement probe and in the movement of the piston can be observed. Mechanical noise will be random in relation to the injection event and by averaging a significant number of flow rate signals, the random noise is effectively removed (figure 8). The apparently noisy but consistent signal that remains gives an indication of the decay rates of the droplets and also of the decay rates of the cavitation voids. Comparing the performance and delivery signals of an injector at different rail pressures gives a very clear indication of the ultrasonic activity induced at higher rail pressures.

By applying both of these corrections, a more accurate representation of the actual injection flows can be achieved. The size and form of the injector orifices can also be monitored. Where emission standards are strict and where pre-combustion chemistry is a critical and controlled aspect of emission controls, any departure from the desired acoustic cavitation regime requires to be identified.

Since the sampling rate of the chamber volume changes is extremely high, limited only by the electronics system response rates, the actual data is entirely representative of the delivery methodology of the injector on test. This compares with other measurement systems where the sampling rate is constrained by the recovery of the pressure measurement system, giving a more averaged rate indication.

The disadvantage of this averaged rate indication lies in the necessity for the injector to induce high levels of cavitation, resulting in the sono-chemical changes critical in achieving structured combustion, within the short periods available for pre-combustion molecular breakdown and the reduced combustion temperatures that result from the long chain disintegration. Without this, engine speeds become flame front limited and the benefits of a common rail, high injection pressure system can be lost.

The AKRIBIS system, especially at back pressures that broadly simulate combustion chamber conditions, allows a better representation of the volume changes and the frequency of those volume changes associated with vacuum bubble growth and collapse.

This critical characteristic of injection is observed in the real time response of the AKRIBIS system. As the rate signal is modified by filtering, the actual cavitation effects can be seen more clearly and further filtering will provide a rate trace that averages the cavitation effect, giving two or three gross peak/trough points within each event.

Changes in rail pressure, in orifice diameter and in the taper of each orifice will significantly influence the degree of cavitation, the duration of the cavitation bubble and the energy release on collapse. All of these factors will be critical in the shortest combustion period (that is, the maximum engine speed that can be attained without over-fuelling) and in the maintenance of reduced combustion temperatures, especially in pilot and final injection events.

USE OF DATA

The accurate characterisation of delivery rates and timings, of droplet coagulation, of cavitation bubble formation and collapse and of the excitation frequency and amplitude allows an extrapolation of molecular disintegration in the pre-combustion phase. The work we are now undertaking is to relate the collected data from the new AKRIBIS units to pre-combustion chemical changes and in particular to estimate the hydrogen and volatile fractions produced by the cavitation void breakdowns. From this, an estimate of the revised proportions of the fuel can be made and an indication of combustion temperature and timing made. By calculating the pre-combustion breakdown, the stoichometric levels of the resultant mixture can be calculated allowing revisions of flow rates and timings. This is an iterative process, since flow rate reductions in turn are likely to increase the volatile fraction.

Although the work currently being done, and the new generation equipment and software that is being developed, are primarily aimed at the high injection pressure diesel market, successful direct injection of gasoline will require increasing injection pressures to allow high engine speeds allied with lowered combustion temperatures, which in turn rely on effective pre-combustion chemistry releasing volatile fractions.

The ability to determine acoustic cavitation in the charge and, as a result, characterise the expected actual mixture at the time of ignition is, we believe, an important tool for the engine designer. The observation of the decay of acoustic induced perturbation in the charge is an equally important tool for the fuel system manufacturer since it provides a direct, rapid and simple measure of the repeatability of orifice size and geometry in a production environment.

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figure 1

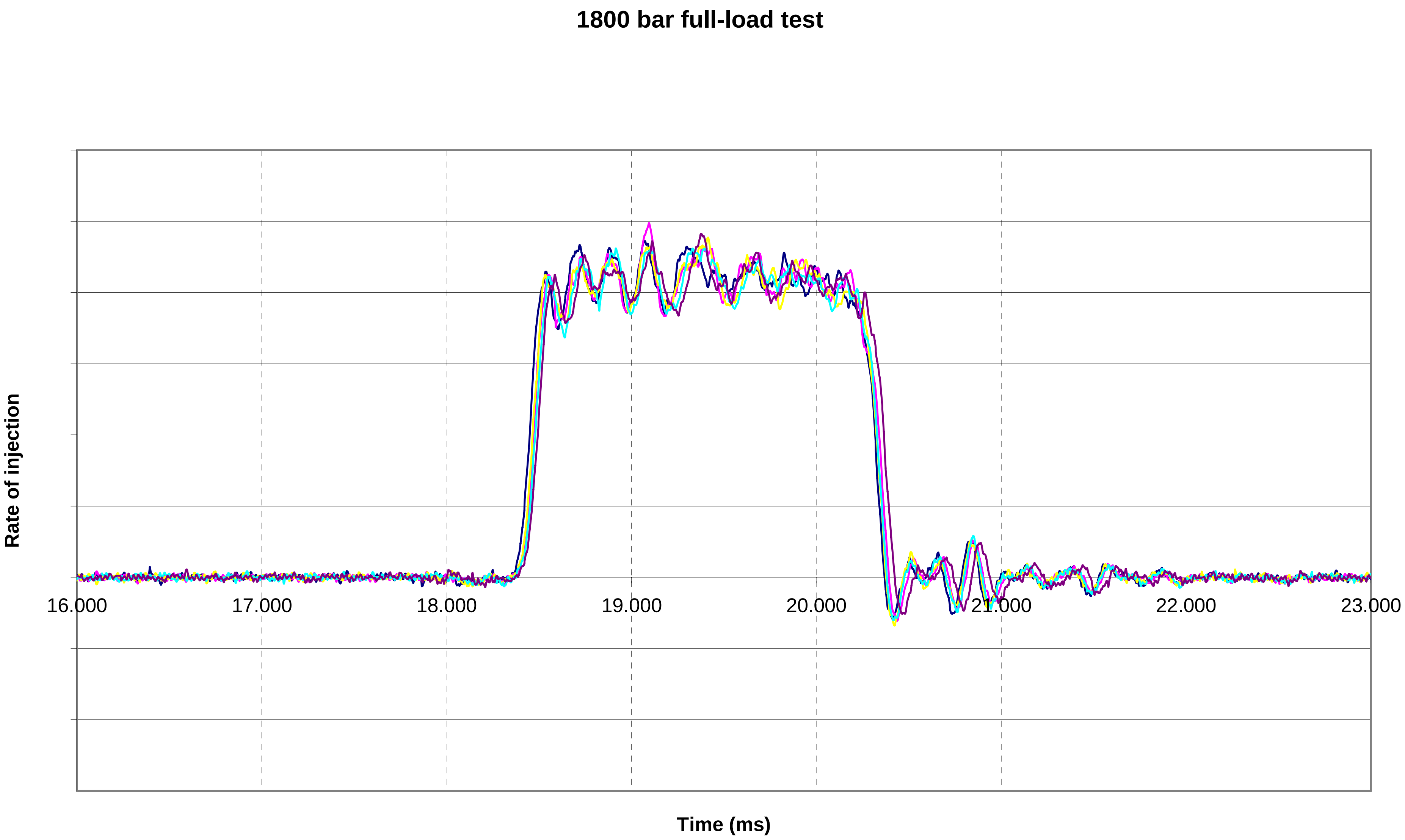
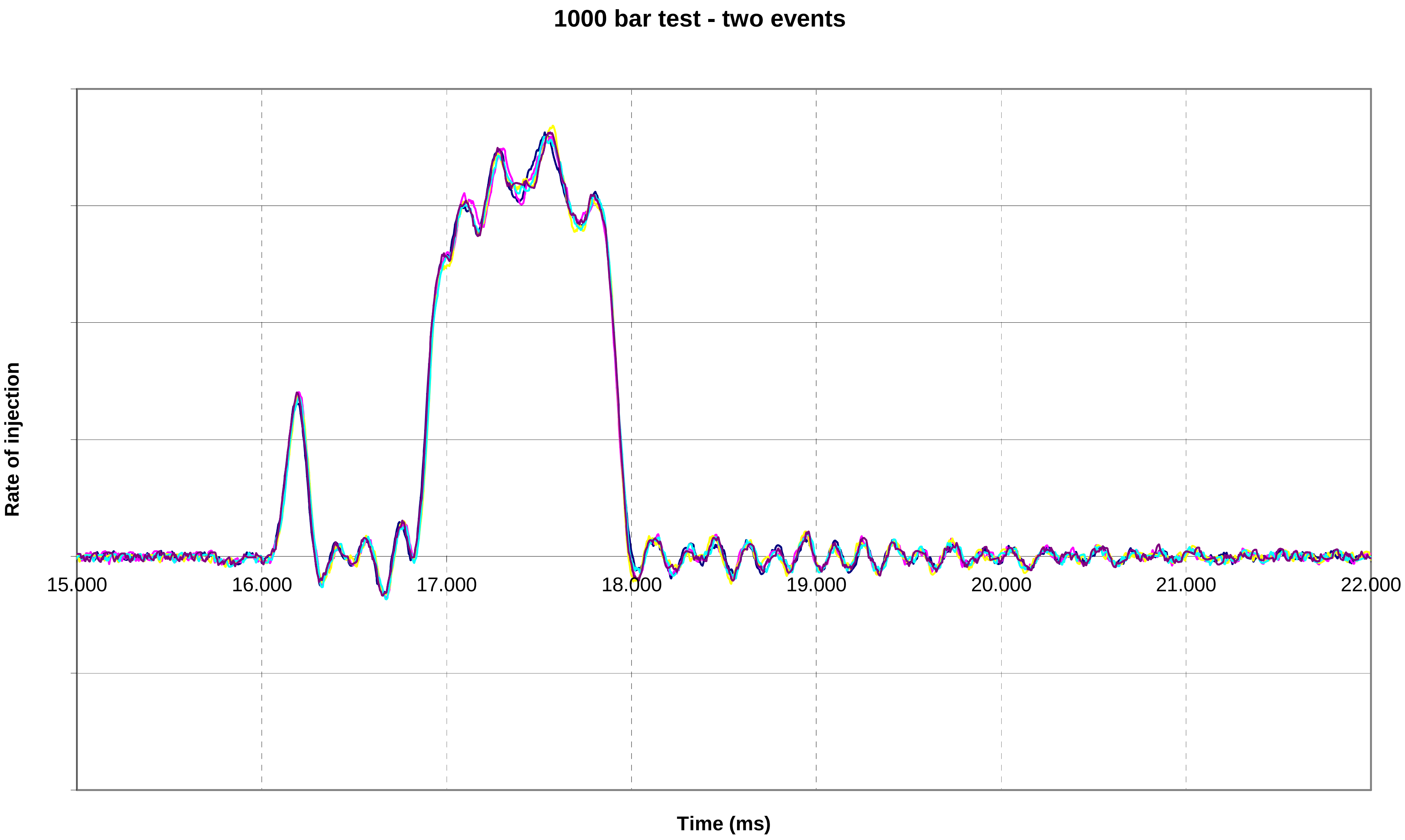

1800 bar full-load test
Rate of injection
16.000
17.000
18.000
19.000
20.000
21.000
22.000
23.000
Time (ms)

figure 2


1000 bar test - two events
Rate of injection
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16.000
17.000
18.000
19.000
20.000
21.000
22.000
Time (ms)

figure 3

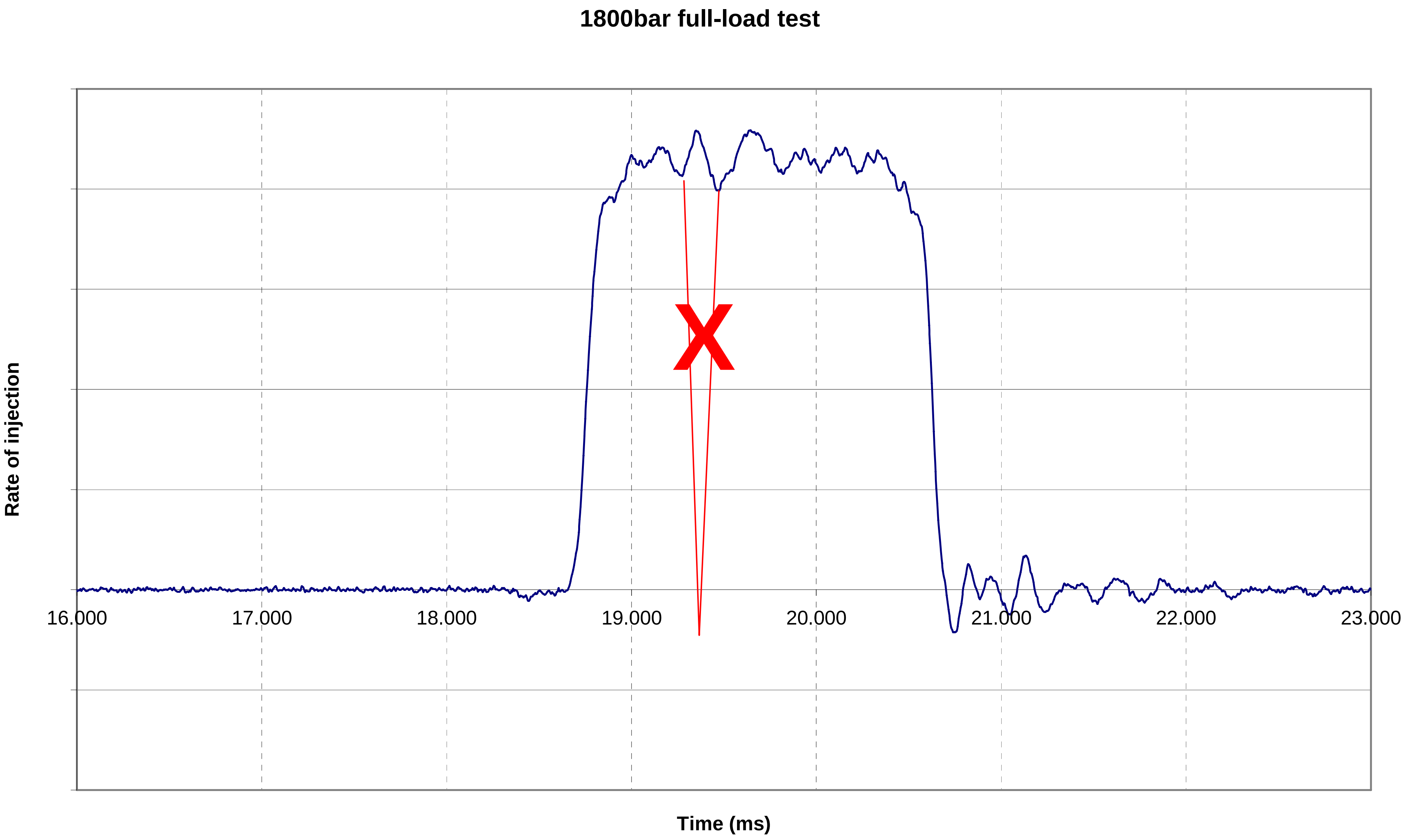

1800bar full-load test
Rate of injection
X
16.000
17.000
18.000
19.000
20.000
21.000
22.000
23.000
Time (ms)

figure 4

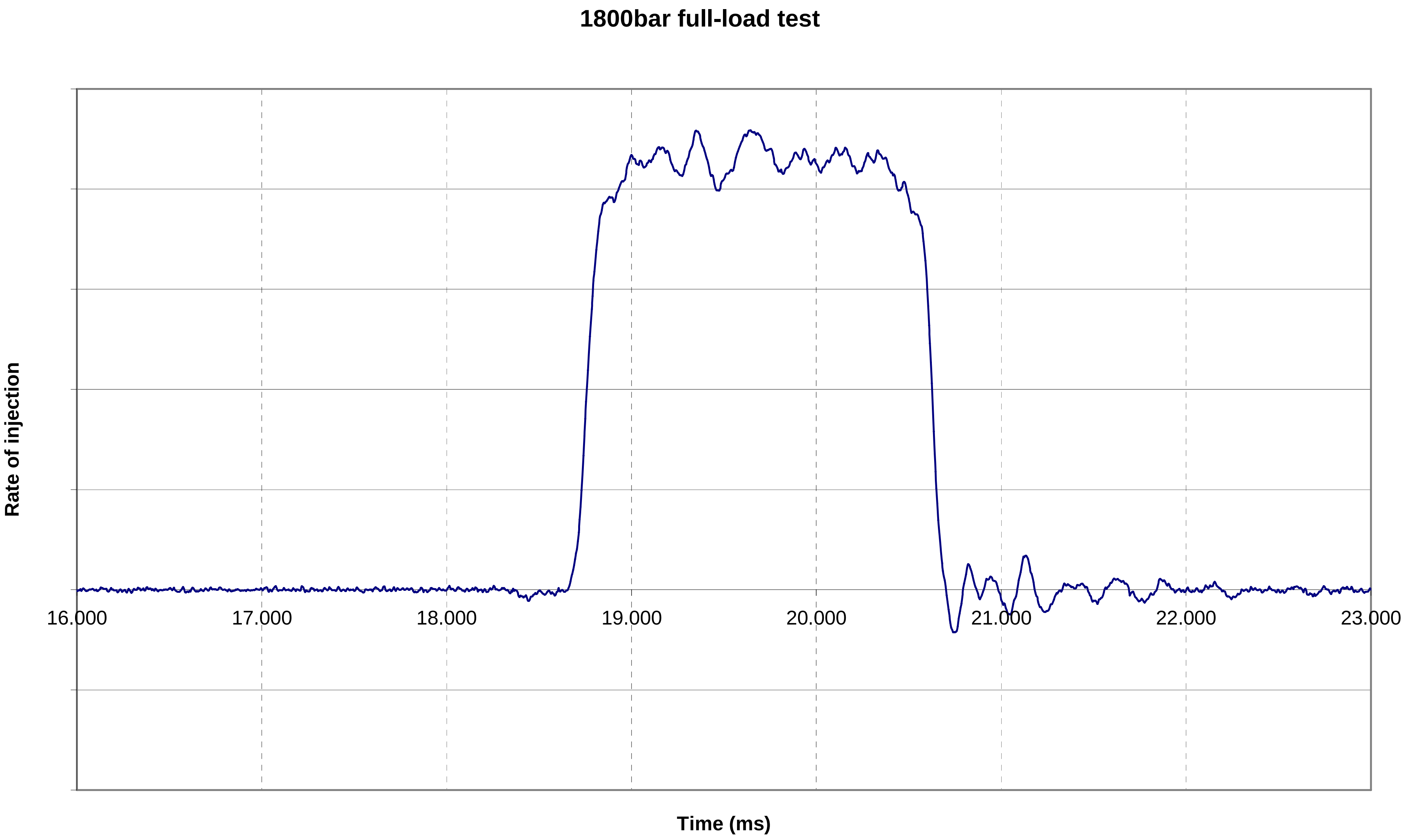

1800bar full-load test
Rate of injection
16.000
17.000
18.000
19.000
20.000
21.000
22.000
23.000
Time (ms)

figure 5

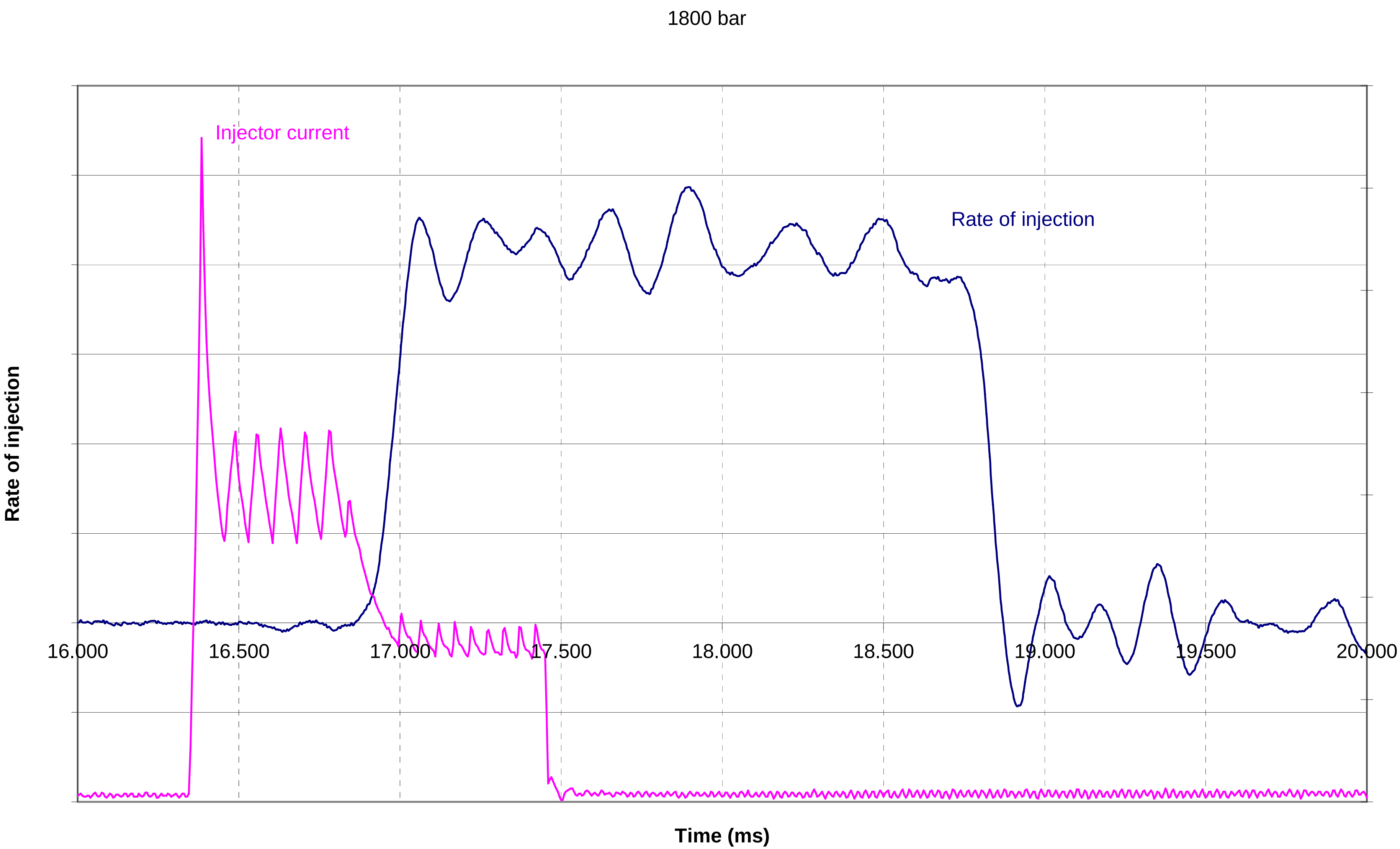

1800 bar
Injector current
Rate of injection
Rate of injection
16.000
16.500
17.000
17.500
18.000
18.500
19.000
19.500
20.000
Time (ms)

figure 6

1800 bar full-load test

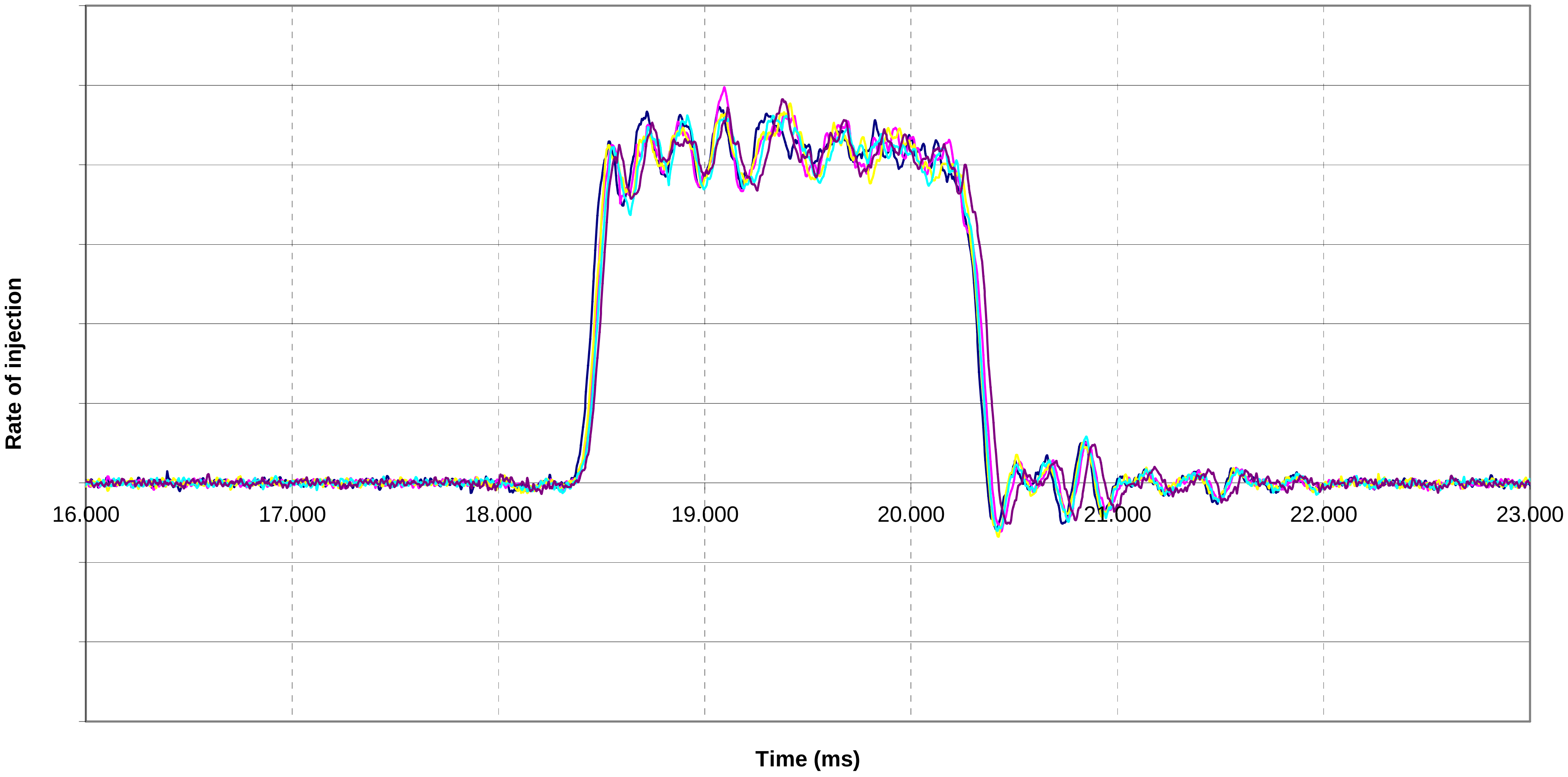


figure 7

Discharge temperature for various injection pressures
Fluid supply temperature 40 °C

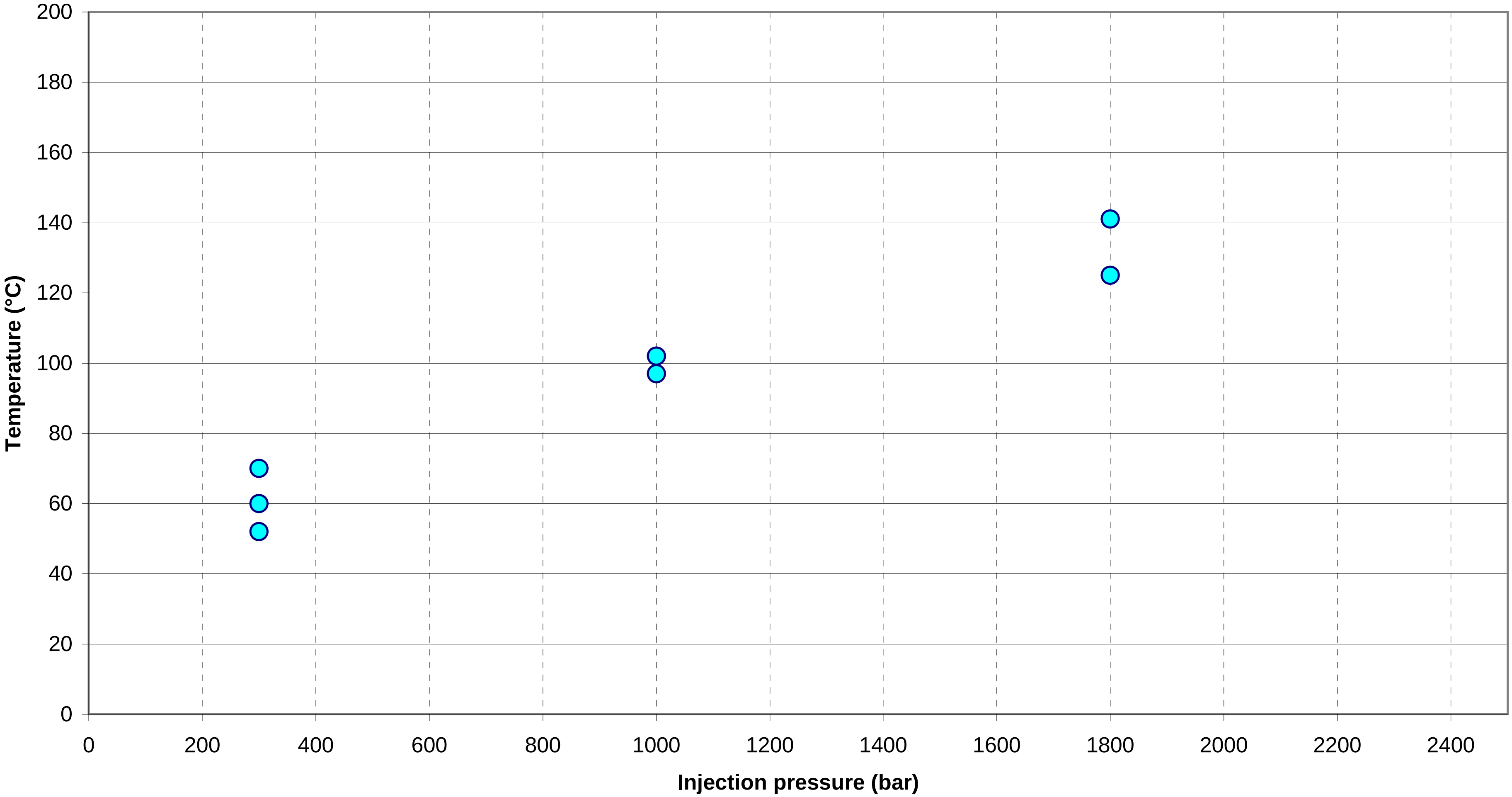
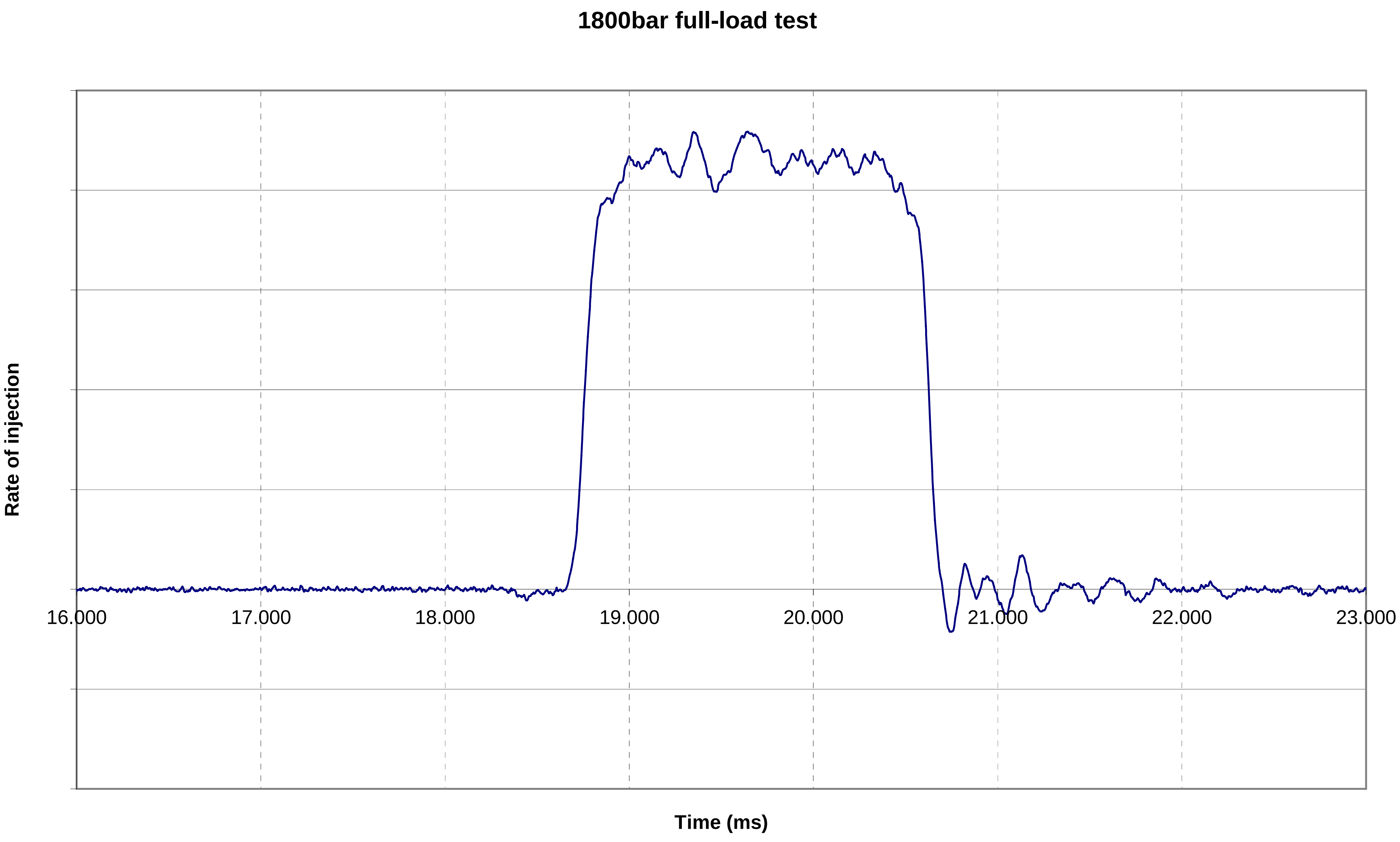


figure 8


1800bar full-load test
Rate of injection
16.000
17.000
18.000
19.000
20.000
21.000
22.000
23.000
Time (ms)