New Measurement Technology for Direct-Injection Systems of Diesel and Gasoline Engines

Modern fuel injection systems are exhausting the limits of injector technologies. Therefore the testing quality of the injectors in product development, serial production and field determines the efficiency of modern injection systems and its total cost. Reliability, reproducibility and standardized interpretation of injector measurement data therefore have become key success factors for injector and system suppliers as well as for OEMs. To assure these key success factors the AVL wants to contribute substantially by a new measurement system, called AVL Shot To Shot PLU 131, for direct injection systems of diesel and gasoline engines.

1 Foreward-looking Combustion Concepts Demand for Efficient Fuel Injection Systems

The driving forces in internal combustion engine development are the striving for fuel economy, minimized exhaust gas emissions and high individual drivability. Fuel injection systems are considered to be the key for trend-setting combustion strategies to meet these development targets: spray pattern, distribution of droplet size and injected quantity have to be optimized for all operating conditions.

Basically the injected fuel quantity has to fulfill two requirements: On one hand modern concepts demand for increasing degrees of freedom to control the rate of injection for both, multiple injection as well as for injection rate shaping of the main injection(s). On the other hand for constance and reproducability of optimized conditions a maximum of correlation between actual rate and ideal target rate is required, according to time as well as to quantity. The pre-injection of common-rail injection diesel systems is to be mentioned for example: here a small reduction of injection rate already causes increasing noise, a small increase causes increasing emissions.

2 Efficient Fuel Injection Systems Require Efficient Measurement Systems

The increasing dominance of piezo-electric actuators in injector technology for direct injection of diesel and gasoline engines can be traced back to its potential to fulfill both described requirements: of all outstanding performance criteria only the high dynamics of this actuator technology shall be mentioned.

The injector development and the high-precision injector manufacturing have to learn to control properties as aging, clamping and memory phenomena. Securing of injector quality requires highly dynamic and precise measurement systems for the reproducible determination of quantities and rates in development, validation and in the quality assurance of manufacturing.

3 Requirements for Efficient Measurement Systems

The requirements for measurement systems for quantity and rate determination of injectors can be split in two classes. The first class is about minimum combined measurement uncertainty. For the serious determination of the combined measurement uncertainty the ISO guide GUM (Guide to the Expression of Uncertainty in Measurement) has become a worldwide-accepted rule-base [1, 2]. Due to its mutual interaction the performance testing of injectors under testing conditions can only be done considering the assessment of the fuel injection system, the test bed and the measurement system. Therefore the same data characteristics in development, manufacturing and in the field are a necessary decision base for the development of injector design and manufacturing concept.

The second class is about the measurement capability under real operating conditions. It comprises the following points:
- Possibility of using a downstream adaptation of the fuel injector on multi-cylinder fuel injection system test rig
- possible adaptation upstream of the fuel injector for the application on a fired engine also together with a simultaneous spray pattern analysis
- first shot capability to investigate hot and cold start conditions
- high number of applicable multiple injections
- transient speed and temperature conditions
- minimum time gap between discrete injections
- wide operating range concerning temperature and pressure.

3.1 Common Measurement Methods for Injection Quantity and Rate Measurement

Typical test setups are multi and single clamping test-rig setups on one hand and setups for the measurement on the fired engine and in combination with spray pattern analysis on the other hand. The available measurement systems therefore basically use one of three different measurement principles that sustain on the direct and highly time resolved measurement of different base parameters:
- pressure and temperature
- volume (piston stroke measurement)
- flow.

Partly a correction of the injection quantity and rate signal with additional measurement quantities is applied in these measurement systems.

3.2 New Flow Measurement System

The company AVL developed the new measurement system AVL Shot To Shot PLU 131, **Figure 1**, to series production that relies on the direct flow measurement. For this reason the strengths of both alternative measurement principles – either quantity or rate determination – are combined in one device. The patented dual measurement principle of the measurement system continuously is tracing back the highly time resolved flow rate of the measurement to the 2000-times practical-proven installations of the PLU measurement element, those values again are traceable to national standards, **Figure 2**.

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Figure 1: The new measurement system AVL Shot To Shot PLU 131

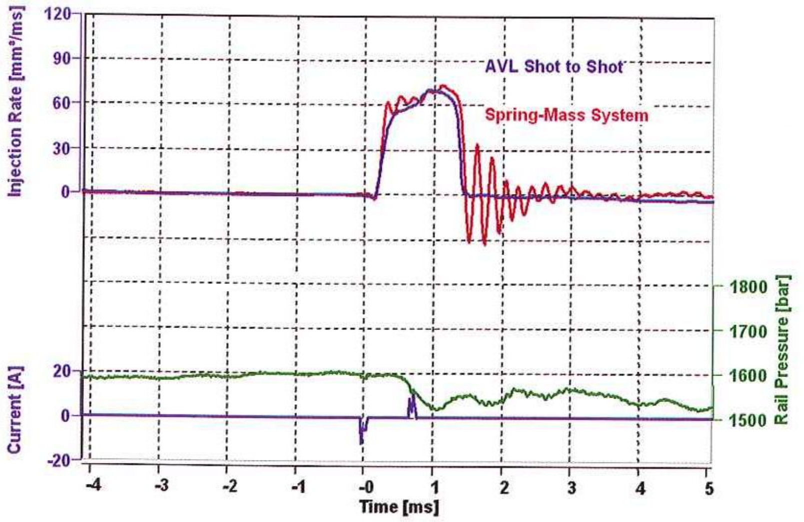

Figure 2: Comparison of the measured flow rates curves with the AVL measurement system compared to a conventional piston-stroke measurement system versus injector current and rail pressure at a diesel engine

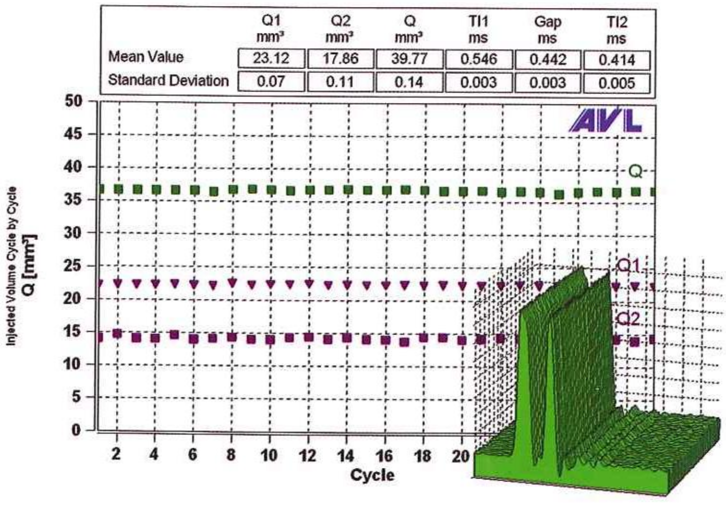

Figure 3: Cycle based fractions of a split injection with indication of mean values and standard deviations, measured with the AVL system at a gasoline engine

The word PLU stands for the former company "Pierburg Luftfahrtgeräte Union". With this new measurement system a unique accuracy is achieved, **Figure 3**: the standard uncertainties of calibration and long-term stability in the whole measurement range starting at 0.01 l/h are 0.1 % each. In comparison to absolute errors – typical for systems that are based on pressure and temperature – the advantage of relative errors is found especially at small injection quantities, where emission and noise require high precision of the fuel metered. For example the measurement system shows at 1 mm^3 injection a combined measurement uncertainty for the calibration and long-term stability of less than 0.003 mm^3 ($k = 2$, according to [1]). The advantages of the high accuracy of the measurement system are apparent:

- efficient development of injectors due to the possibility of the separation of influencing variables
- during injector manufacturing on one hand maximum production yield due to optimal utilization of manufacturing and clamping tolerances, on the other hand superior comparability of measurement data of production lots due to the low standard uncertainty of long term stability
- securing the comparability of measurement data and their consistent interpretation between development, validation, manufacturing and field observation.

The appreciated high dynamics of the injector requires a measurement system with virtually no mass for its objective assessment. The high dynamics of the AVL measurement system shown in **Figure 4** is caused by the direct flow measurement because the fuel in the measurement system does not have to accelerate any additional mass during the injection event. Spring-mass systems – typical for piston stroke measurement – are characterized by oscillation. The damping of these oscillations is forbidden because the requirement for measuring post injections is the dynamics.

Due to the low measurement times requirement the usage of the measurement system in injector production enables manufacturing concepts with substantial cost savings. Because of the continuous measurement process the system is permanently in active state and works without any cyclical draining activity. The possible adaptation upstream the injector up to 250 bar – that is looking in flow direction in front of the injector in the high pressure area – has several advantages: manufacturing benefits by the lack of contamination risk from the injector; in development it enables the measurement without unwanted back pressure influence of the test rig; and the use on fired engine test rigs with up to more than 25,000 rpm or even a simultaneous spray pattern analysis can be managed. That means for gasoline injection systems all requirements listed in Chapter 3 are fulfilled with one universal measurement system, **Figure 5**.

4 Conclusion

AVL introduced the measurement system AVL Shot To Shot PLU 131 for the determination of injection quantities and injection rates curves of direct-injection systems in combustion engines. It is characterized in both metrological questions by a minimum combined measurement uncertainty and highest dynamics simultaneously. Due to the proven PLU measurement principle it assures minimum overall cost of operation by high availability, long-term stability, data reliability and short measurement time.

The measurement system provides the possibility of reproducible and interpretable determination of injector specific characteristics over all areas that are involved in the product life cycle of the injector up into the field. Consequently AVL contributes substantially to the optimization of the processes and concerning cost in development of injectors and fuel injection systems as well as in their manufacturing. Optional consultancy products secure short commissioning time and process stability.

References

[1] International Organization for Standardization (ISO): Guide to the Expression of Uncertainty in Measurement. Genf, 1995, ISBN 92-67-10188-9

[2] Schrift DKD-3: Angabe der Messunsicherheit bei Kalibrierungen. Akkreditierungsstelle des Deutschen Kalibrierdienstes (DKD) bei der Physikalisch-Technischen Bundesanstalt (PTB), Braunschweig, Januar 1998

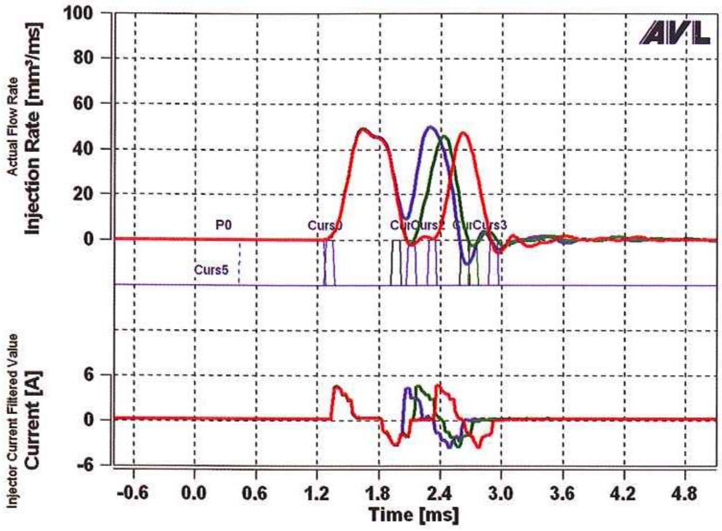

Figure 4: Flow rate curves of multiple injections with different separation periods to hydraulic overlapping versus injector current, measured with the AVL system at a gasoline engine

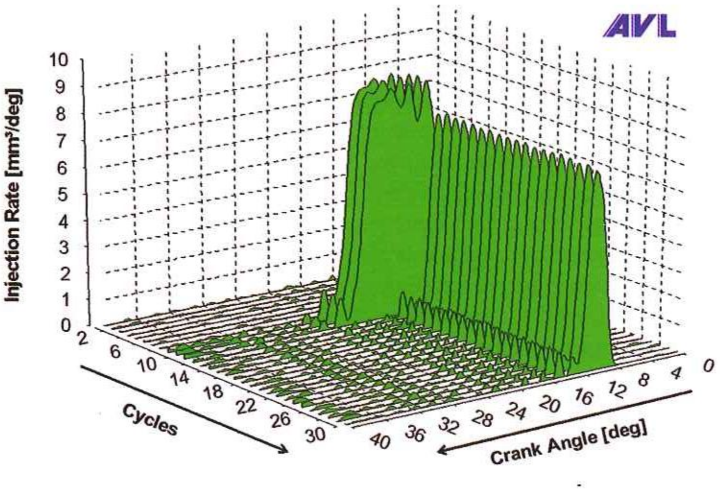

Figure 5: Flow rate curves of a typical engine start-sequence beginning with the very first shot, measured with the AVL system at a gasoline engine