2008-01-1028

The Challenge of Precise Characterizing the Specific Large-Span Flows in Urea Dosing Systems for NO_x Reduction

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ABSTRACT

The reduction of nitrous oxides in the exhaust gases of internal combustion engines using a urea water solution is gaining more and more importance. While maintaining the future exhaust gas emission regulations, like the Euro 6 for passenger cars and the Euro 5 for commercial vehicles, urea dosing allows the engine management to be modified to improve fuel economy as well.

The system manufacturer Robert Bosch has started early to develop the necessary dosing systems for the urea water solution. More than 300.000 Units have been delivered in 2007 for heavy duty applications. Typical dosing quantities for those systems are in the range of 0.01 l/h for passenger car systems and up to 10 l/h for commercial vehicles.

During the first years of development and application of urea dosing systems, instantaneous flow measuring devices were used, which were not operating fully satisfactory. When checking the different measuring principles on the market, the controlled gear pump measuring system of AVL-Pierburg Instruments, which was up to then only in use for fuels, seemed to have the best chances for achieving the very specific demands of the urea dosing systems. The development of a specific device was found to be necessary. The development of this specific device and its first results are described in this paper.

INTRODUCTION

Both the small flows of 0.01 l/h, as well as the extremely large flow span of 1:1000, are challenges with which conventional measurement principles are not able to comply. In addition to this, the flow to be measured is pulsating according to the dosing mechanism using Injectors similar to those used in conventional fuel injection systems.

At the request of Robert Bosch AVL has adopted their well known Pierburg Flow Measurement Principle for use with urea water solution. By using this technology not only the extremely small flows can be covered, but also the large flow span and the pulsating nature of the urea flow in the urea dosing systems.

In this paper the main flow specifications of the dosing systems are summarized. From the dosing system specifications the measurement system requirements have been derived. Optimized and standardized measurement setups had been developed for maintaining optimum dosing system performance together with maintaining optimum conditions for the flow measurement setup. Measurement examples give an impression on what is possible in the dosing and characterization of the dosed urea water solutions today. The application examples cover the development laboratory, the production audit and the application on the engine test beds and in vehicles.

SCR - SELECTIVE CATALYTIC REDUCTION

OVERVIEW **–** In addition to the advantages of efficiency and sportiness, the modern diesel engine must also satisfy the requirements of emission regulations.

Ways of reducing NO_X emissions include the NO_X storage catalytic converter (NSC) and the selective catalytic converter (SCR) system.

Unlike the NSC, SCR uses a noble-metal-free catalytic converter and even works when there is excess oxygen. The selective catalytic reduction (SCR) is a continuous process which operates independently of the engine

management control. It enables the reduction of NO_X emissions while simultaneously maintaining low fuel consumption.
The SCR process uses the highly selective substance ammonia (NH_3) as a reduction agent. It is added to the vehicle as another fluid in non-hazardous precursor substances, e.g. in the form of a 32,5% urea-water solution (AdBlue®), and is metered into the exhaust gas. (1)

CHEMICAL REACTION – The ammonia to enable the SCR reaction results in 2 steps from the urea-water solution through a thermal decomposition (Eq.1) and the following hydrolysis (Eq. 2).

(Eq. 1) $$(NH_2)_2CO -> NH_3 + HNCO$$

(Eq. 2) $$HNCO + H_2O -> NH_3 + CO_2$$

Subsequently the ammonia reacts within the SCR catalyst according to the following equations

(Eq. 3) $$4NO + 4NH_3 + O_2 -> 4N_2 + 6H_2O$$

(Eq. 4) $$NO + NO_2 + 2NH_3 -> 2N_2 + 3H_2O$$

(Eq. 5) $$6NO_2 + 8NH_3 -> 7N_2 + 12H_2O$$

At low temperatures (<300 °C) the conversion occurs according to Eq. 4. For an adequate low temperature conversion a NO2 : NO ratio of 1:1 needs to be realized. Under these conditions an adequate conversion at a temperature of 170 .. 200 °C can be achieved.

To enhance the conversion rate at low temperatures the oxidation of NO to NO_X is usually realized by a diesel oxidation catalyst (DOC), which is essential for the efficiency of the system. (2)

SCR SYSTEM

For the exact metering of reduction agent AdBlue® into the exhaust gas a SCR system, marketed by Bosch as “DENOXTRONIC”, has been developed (Figure 1).

This system consists of several components such as the AdBlue® tank, supply module, dosing module and dosing control unit, as well as NO_X and temperature sensors to regulate the flow of the reduction agent.

The challenges of developing SCR systems are in dealing with extreme climatic conditions as AdBlue® freezes at approx. -11 °C. The AdBlue® tank, a heating pot as a separate unit within the tank, lines and metering unit must be able to withstand freezing and hot conditions.

Essential components are heated to ensure permanent dosing capability after given thawing time. The tank

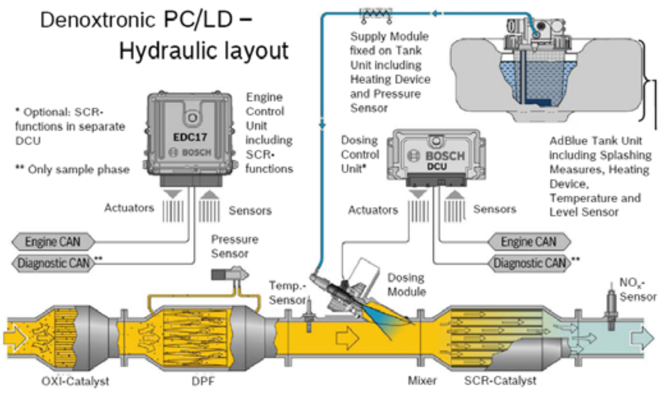


Figure 1: DENOXTRONIC PC/LD Hydraulic >Layout

volume enables a mileage that corresponds to the oil change interval in order to refill during regular service, being independent of the infrastructure status regarding AdBlue®

The system pressure is generated by a supply unit that contains a membrane pump, a filter, pressure sensor and a 4/2 way valve to enable the system to evacuate the reduction agent out of the pressure lines and dosing module when the vehicle will be stalled.

The dosing module consists out of a solenoid valve within a passively cooled housing. The whole system is controlled by the dosing control unit which gives a demand in mg/s which is converted into actuation signals (frequency and time period) for the dosing valve.

A parameter essential for the application is the Feed-level α, defined as the molar ratio of metered NH3 to the level of NO_X within the exhaust gas. Under ideal conditions (no NH3 break through, no secondary reactions, no NH3-oxidation) α is direct proportional to the NO_X-reduction: for α = 1 a theoretical 100% NO_X reduction is achieved. In practice a NO_X-reduction for a NH3 break through of < 20 ppm of 90% can be reached for stationary as well as dynamic conditions. The required amount of AdBlue® corresponds to round about 5% of needed diesel fuel.

The SCR system runs continuously and, unlike NSC, requires only minimal intervention in the combustion engine. Therefore the required dosing level of AdBlue® needs to be thoroughly applied in order to prevent NH3 to break through which results in an environmental contamination.

To validate the application as well as to characterize the flow curve of the dosing module a measurement technique had to be developed that could measure these very small flow rates with a very high reproducibility.

For the testing of the SCR system and its components, test stands with completely new technology had to be developed. The test stand e.g. for the dosing modules consists of:

- the tank for the AdBlue® fluid with filter equipment and temperature control
- the fluid pump with the pressure control unit
- the dosing control unit with the power supply to energize the dosing module
- the flow measuring system, situated between the pressure control unit and the dosing module
- the mounting device for the dosing modules

The challenges for the design of the SCR test stands are:

- to use components, e.g. for the pressure control, which withstand the AdBlue® fluid
- to find an appropriate flow measuring device, fulfilling all the specific requirements

Regarding the measuring device, the first test stand was equipped with a Coriolis type system, a device type, which is well proven for other measurement purposes in the fuel injection systems. But the repeatability of the results, determined in comprehensive measurement capability procedures and represented by the so called cg – value, was not satisfactory over the complete range of the dosing amount (Table 1). For the lower flows, the cg – values are weak, since these flows are at the bottom end of the application, smaller than the low end of the application of this device. But, if a device with a lower flow capacity would have been used, suitable for these low flows, the pressure drop at the high end of the application would be too large for the correct function of the dosing modules.

		1st Test Stand
		Coriolis Type
AdBlue® Flow	T	cg
6000 g/h	± 3,0 %	1,49
900 g/h	± 4,6 %	0,48
300 g/h	± 9,0 %	0,41

$cg = 0,2 \cdot T / 6\sigma$
T = tolerance
σ = standard deviation of the repeatability

Table 1: cg-values of dosing module test stands, requested: cg ≥ 1,33

MEASUREMENT SYSTEM REQUIREMENTS

After the first approach using Coriolis type flow meters a more detailed analysis of requirements given by the properties was performed to identify the appropriate measuring device available on the market to meet the specific requirement. The following requirements, given by the properties of the urea dosing system, have to be fulfilled by the measuring system:

- no effect on the dosing system, especially no pressure drop
- wetted surfaces not subject to corrosion by the urea fluid
- through flow range 0.01 … 10 l/h (for passenger car engines up to heavy duty truck engines)
- able to cope with dosing frequencies from 1 to 4 Hz and with constant flows
- able to measure shot-to-shot (development)
- system pressure up to 10 bar, pressure peeks up to 20 bar
- not effected by external vibrations (in the case of car applications)

The combination of these requirements presents a great challenge to the measurement system and test bench set up. Especially the demand for the high flow span (relation low flow to high flow 1 : 1000) together with the demand for no pressure drop for the complete flow range will mean a problem for most of the various flow measuring systems. All the well known and well proven measuring systems for the diesel fuel injection will fail in at least one feature to fulfill such specific requirements.

	EMI Injection Indicator	IA Injection Analyzer	Coriolis Type Flow Meter	Gear Type Flow Meter	Balance	Controlled Gear Type Flow Meter
No pressure drop	-	-	-	-	+	+
Flow span 1 : 1000	+	+	-	-	+	+
1…4 Hz	+	+	+	+	+	+
Constant flow	-	-	+	+	+	+
Shot-to-shot	+	+	-	-	-	+
Insensitive to vibrations	+	+	-	+	-	+

+ … Requirement is fulfilled
- … Requirement is not fulfilled

Table 2 – List of requirements and system principles

Only the controlled gear type flow meter is able to fulfill all the requirements. For this reason the development of the well proven PLU 131 HP STS for the specific application at AdBlue® dosing systems was started.

The required measuring system is to be used for the following purposes:

• component development laboratory (e.g. for the dosing modules)	for component development
• system development laboratory (for complete SCR-system)	for system development
• engine test stand (engine with SCR-system)	for the application of the SCR-system to the individual engine type
• in-car-measurement	for in-car-checking of the appropriate application
• series production shop floor	for testing of each manufactured component (e.g. each dosing module)
• production quality control	for the over checking of the production quality

In principle, it is possible to apply different measurement devices for the different purposes. But in practice, for the handling of the processes in development, application and production, it is a large advantage, if the same type of device could be used for all these purposes. So measurement results can be transferred from the development stage to the car application or to the production shop floor directly, and the validation process of the measurement device must be done only once.

MEASUREMENT PRINCIPLE

The Urea flow measurement system is based on the well established PLU flow sensor (Figure 2)

Figure 2; PLU 131 HP STS flow sensor

The PLU flow sensor is a volumetric measurement principle. It combines in parallel a gyratory and a translational flow sensor principle (Figure 3) in one single system.

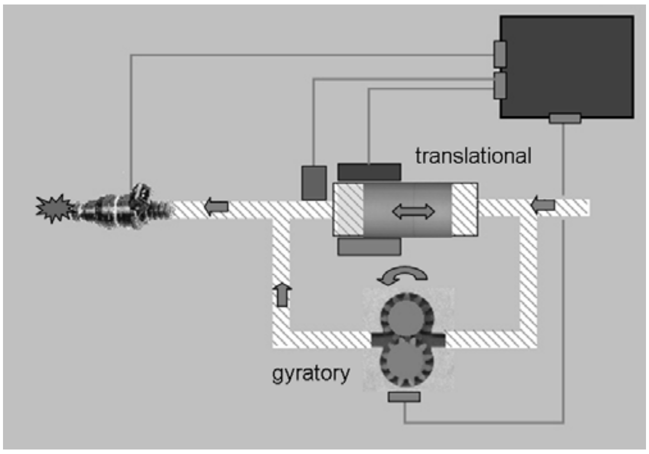


Figure 3: PLU flow measurement principle

The gyratory principle is a servo driven high precision gear head counter incorporating the high precision base calibration of the flow sensor. The translational principle works as a high speed physical flow integrator and is also responsible for the zero pressure-difference over the instrument. The zero pressure-difference principle allows the instrument to avoid any interaction with the system analyzed while being able to sense time resolved flow. Other features originating from the zero pressure difference principle are the wear free operation of the gyratory flow sensor, its life time calibration and its invariability against viscosity effects.

UREA SPECIFIC ADAPTATION – Standard PLU flow meters are optimized for a wide variety of fuel specifications. In comparison to fuels, a 32,5% urea-water solution differs significantly in density and pH-value. To cope with the alkaline nature of the urea-water solution, the aluminum components of the flow meter are replaced by a synthetic material. All metallic components, like the gyratory flow sensor are made from corrosion resistant, stainless steel grades.

To cope with the density of the Urea Water Solution (Figure 4), the translational flow sensor is adjusted to the density of the fluid of 1,09 g/cm³. The density adjustment is responsible for the ultra low flow capability of the instrument. Only the material of some few components needed to be changed in the urea-version of the PLU flow sensor compared to the well established and proven fuel type sensors. The performance and the reliability of the instruments remain unchanged and allow a straight forward implementation of the new instrument versions in the various kinds of urea dosing applications.

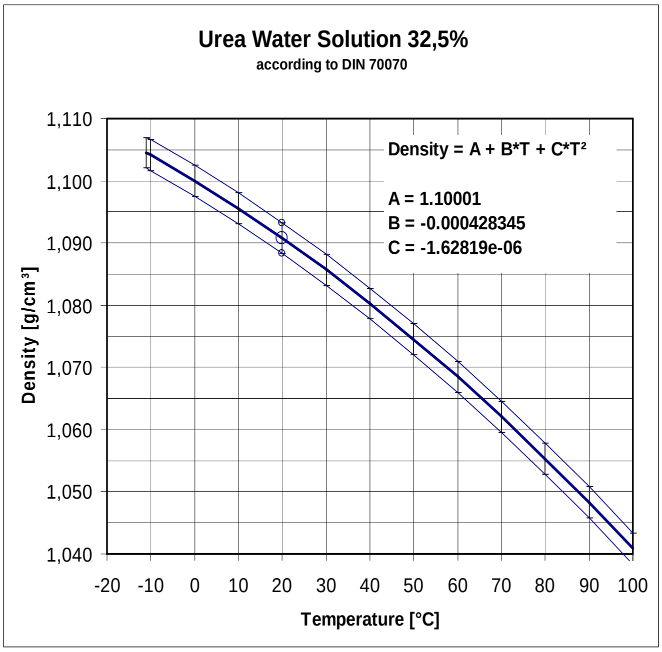


Figure 4: Density of 32,5% Urea Water Solution (5)

Application	PLU 131 Urea flow Sensor	Indi Shot STS Module	Indicating System STS Extension	PLU 4000 Frequency Module
component development laboratory	X	X		
system development laboratory	X	X		
engine test stand	X		Software Extension	
in car measurement	X			X
production shop floor	X			X
production quality control	X	(x)		X

Table 3: PLU Shot to Shot System data acquisition modules

APPLICATIONS – The modular concept of the PLU Shot to Shot system is the base for the different applications in development, production, application and field service of urea dosing systems and components. The main modules are the PLU flow sensor and the data acquisition system. While the flow sensor is identical for all applications, the data acquisition modules can be chosen to get the best value for the investment (Table 3).

Indi Shot STS Acquisition Module – is a high performance 8-channel data acquisition system with a time resolution of up to 400 kHz. Extensions of up to 32 channels are possible by simply cascading up to 4 STS Modules.

Indicating System STS Extension – together with a simple adaptor, the PLU flow sensor can be directly connected to the AVL Indimaster family of indicating systems. Using this option allows to use up to 24 PLU flow sensors in parallel with one central data acquisition system.

PLU 4000 Frequency Acquisition Module – This module is a solution for all applications not needing the single shot data acquisition. However, the PLU-flow sensor still works internally on a shot to shot basis, but only the data of the gyratory flow sensor is evaluated and transferred to the frequency output.

Flow Sensor Integration – Because of the unique hydraulic construction of the PLU flow sensor, the integration into urea dosing systems is quite simple. The PLU sensor is mounted upstream the injector in the supply line, as close as possible to the dosing valve. Even though the PLU does not cause any pressure loss in the system, it adds some volume to the system on the one hand, and on the other hand precautions should be taken not to expose the flow meter to air-fluid mixtures as such mixtures would influence the accuracy of the flow measurement. The flow meter could be exposed to air or air-liquid mixtures while draining the supply line before the system is switched off. The draining function is implemented in all systems to avoid freezing of the urea water solution during the cold season. Two 2/3-way valves allow switching the PLU into a bypass and allow the system to drain or fill without compromising the PLU.

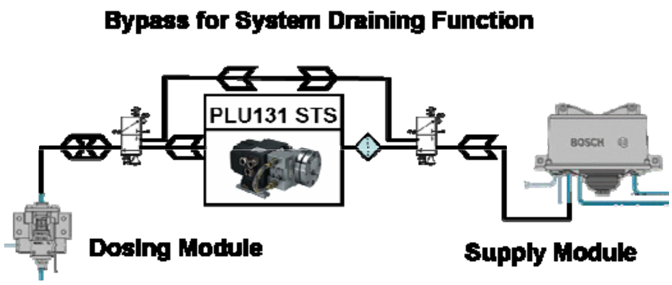


Figure 5: PLU 131 STS Flow Sensor Integration in Urea Dosing System

MEASUREMENT UNCERTAINTY BUDGET

Beside the functional requirements for the measurement system listed before, the measurement process was characterized in detail, in order to achieve *precise and correct* measurement results as defined below.

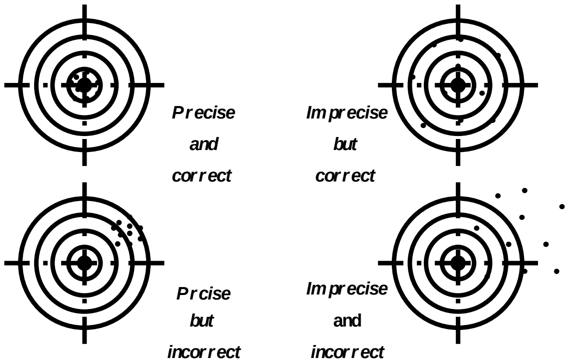


Figure 6: Target – Analogy according to ISO 3534-1

In order to achieve best precise and correct measurement results it has to be taken under consideration that for the verification of complete AdBlue- systems and especially their dosing units in test set ups for

- Research & Development
- Serial Production
- Quality Assurance
- Engine Test Bed
- Mobile Testing on the road

not only the measurement device respectively its calibration uncertainty has to come to the fore but rather the measurement **uncertainty of the acquired measurement results under the specific operational conditions**.

Therefore the definitions of boundary conditions for measurements which comply with actual working conditions are essential.

Real operational condition means for instance:

- Measuring time = cycle time of the injector in the dosing module
- Cycle time = 0.5Hz to 4Hz
- Medium- and Environment Temperature conform to respective application
- Pressure condition conform to respective application
- Different Test Fluids

Measurement processes and test set ups must be optimized for best reproducibility to guarantee comparability over a long period under real operational conditions.

As the corpus of legislation for the evaluation of process orientated combined measurement uncertainties since 1995 the Guide to the expression of Uncertainty in Measurements (GUM) became internationally accepted. (4) The basis for the determination of combined measurement uncertainties according to GUM a clear definition of influencing variables, so called measurement uncertainty-budget, for the measurement result are required, helping to define the performance of the complete test set up.

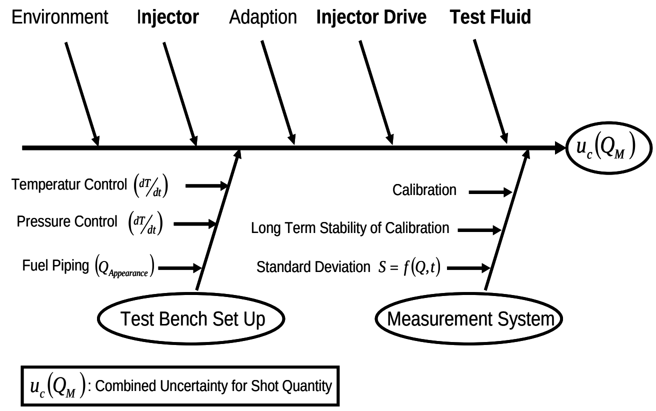


Figure 7: Fish Bone Diagram "Causes for Measurement Uncertainty"

Figure 7 shows that a perfect measurement device can not guarantee perfect measurement results by itself. Minimized combined measurement uncertainty can be achieved by optimal combinations between all the components involved in the measurement process.

DISCUSSION OF ACHIEVED MEASUREMENT RESULTS

It would go beyond the scope of this paper to provide from a complete and detailed measurement uncertainty budget the combined measurement uncertainty for achievable results according to GUM.

However it is possible to determine combined uncertainties for achieved measurements under the assumption, that non- systematical influence of all relevant standard uncertainties are within the standard deviations for the average values indicated by the measurement unit.

For combined measurement uncertainty of indicated average values does apply:

$$u_c(Q_M)=\sqrt{u_Z^2(Q_M)+u_L^2(Q_M)+u_T^2(Q_M)+u_K^2(Q_M)}$$

Q_M	Shot Volume
$u_c(Q_M)$	Combined Uncertainty of Q_M
$u_Z(Q_M)$	Standard Uncertainty for measuring time (cycle time) under operational conditions
$u_L(Q_M)$	Standard Uncertainty for long term calibration stability
$u_T(Q_M)$	Standard Uncertainty for temperature influence
$u_K(Q_M)$	Standard Uncertainty for calibration under laboratory condition

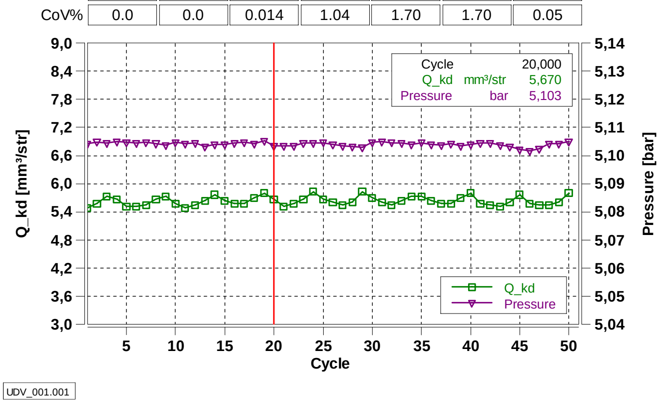
The dominating element in this is the Standard Uncertainty for the cycle time under real operational conditions. This uncertainty includes the non systematical influences of the measuring system, the test set up respectively its temperature and pressure control, the injector itself, its driver and the test fluid.

All other influences are additionally relevant for the measuring system.

As an example the Combined Measurement Uncertainty for a measurement at 1 Hz and 0.6% Duty Cycle with extremely low flow rate is determined as follow:

Standard Uncertainty for cycle time
Q_kd = 5, 63 mm³/stroke (5, 61 mg/s)

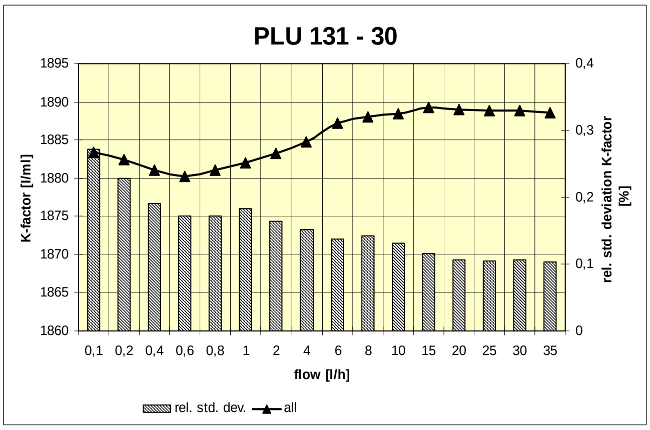
	Freq Hz	Duty_Cyc %	Pressure bar	TI1 ms	Q_kd mm³/str	Q_kd mg/s	T_M C
Mean	1.0	0.6	5.10	6.41	5.63	5.61	24.33
CoV%	0.0	0.0	0.014	1.04	1.70	1.70	0.05



s = 1, 7 %
n = 50 shots
Distribution: Normal

$$u_Z(Q_M)=\frac{1{,}7\%}{\sqrt{50}}=0{,}24\%$$

Additional component for **long term calibration stability**, determined by proved experienced values of AVL (3)



n = 12 over 6 years
Distribution: Normal
s = 0,15%

$$u_L(Q_M)=\frac{0{,}15\%}{\sqrt{12}}=0{,}043\%$$

The Standard Uncertainty for long term calibration stability determined under laboratory condition states the long term change of the calibration of the measuring system based on the fact, that the initially determined calibration factors are not modified at any time.

Standard Uncertainty for temperature influence

$$Q_{Temp}=\frac{dT}{dt}\times\beta\times V_{Cirquit}$$

$$B_{Temp}=\frac{Q_{Temp}}{(Q,m)_{Measure}}=\frac{dT}{dt}\times\beta\times\frac{V_{Cirquit}}{(Q,m)_{Measure}}$$

Distribution: Triangle
s = 0, 2%
(Estimated quality of temperature control for inlet temperature and a gradient of ±0,1°K and a volume in the measuring circuit of approx.100 mm³)

$$u_T(Q_M)=\frac{0{,}2\%}{\sqrt{24}}=0{,}041\%$$

Standard Uncertainty for calibration under laboratory condition

Distribution: Normal

$$u_K(Q_M) = \sqrt{u_r^2 + u_s^2}$$

(Values for u_r and u_s, discern from calibration certificate of AVL calibration benches, traceable to National Standards:

$$u_K(Q_M) = 0{,}047\%$$

Including these rates the combined uncertainty can be calculated as follow:

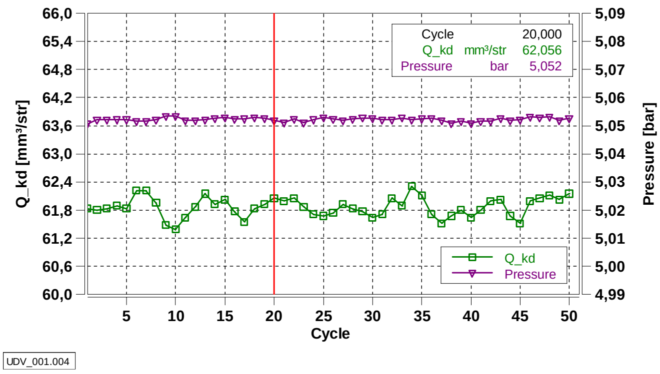
$$u_c(Q_M) = \sqrt{0{,}24^2 + 0{,}043^2 + 0{,}041^2 + 0{,}047^2} = 0{,}25\%$$

In order to obtain the uncertainty for 95%, according to GUM this value has to be multiplied by the expansion factor 2, whereby the extended combined measurement uncertainty can be obtained to:

$$\boxed{\pm u_c(Q_M) = 0{,}5\%}$$

For a Duty cycle of 20% at 4HZ and 246.71mg/s

	Freq Hz	Duty_Cyc %	Pressure bar	TI1 ms	Q_kd mm³/str	Q_kd mg/s	T_M C
Mean	4.0	20.0	5.05	50.05	61.86	246.71	24.32
CoV%	0.0	0.0	0.013	0.01	0.34	0.34	0.06



can be obtained:

$$\boxed{\pm u_c(Q_M) = 0{,}18\%}$$

These samples of obtained combined measurement uncertainties for average values of 50 shots suits excellent for the later described measurement capabilities (Cg-values) for production test benches and ensures that in serial production all produced dosing systems are within the production tolerance over long terms.

PROGRESS IN PRECISE CHARACTERIZING

The PLU131 HP STS was chosen as the basic measuring system and especially designed to be used for the urea fluid and the SCR dosing systems. Table 4

This measuring device, applied to the same test stand, gave a significant improvement to the repeatability in the lower flow range (Table 4) without having a disadvantage at the high end of the application.

Using the experiences of the first test stand, a second test stand was planned. It was equipped with an improved pressure control system and with the AVL shot to shot PLU 131 UREA from the beginning. A further significant improvement for the repeatability of the measured values for the complete range of the flow was reached.

		1st Test Stand		2nd Test Stand
		Coriolis Type	PLU 131	PLU 131
AdBlue® Flow	T	cg	cg	cg
6000 g/h	± 3,0 %	1,49	1,39	9,48
900 g/h	± 4,6 %	0,48	2,80	5,69
300 g/h	± 9,0 %	0,41	2,41	4,53

cg = 0,2 · T/ 6σ
T = tolerance
σ = standard deviation of the repeatability

Table 4: cg-values of dosing module test stands, requested: cg ≥ 1,33

So the joint development in combination with the final development of the test stand together with the new measuring system AVL shot to shot PLU 131 UREA gave excellent results in terms of the repeatability of the measurement results.

CONCLUSION

In close cooperation between AVL Pierburg Instruments and Robert Bosch the challenge for a precise characterizing of Urea Dosing Systems was obtained most successfully.

The flow measurement system of AVL in combination with test benches of Robert Bosch for R&D and serial production guaranties precise and correct measurements and therefore proven and excellent quality of AdBlue® dosing systems manufactured by Robert Bosch.

The ongoing effective cooperation of both, together with prospective OEM's will provide further solutions for measurements in engine test benches and mobile tests on the road in order to guarantee continuity and comparability of measurement results in the entire developing process of AdBlue® Dosing systems.

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APPENDIX

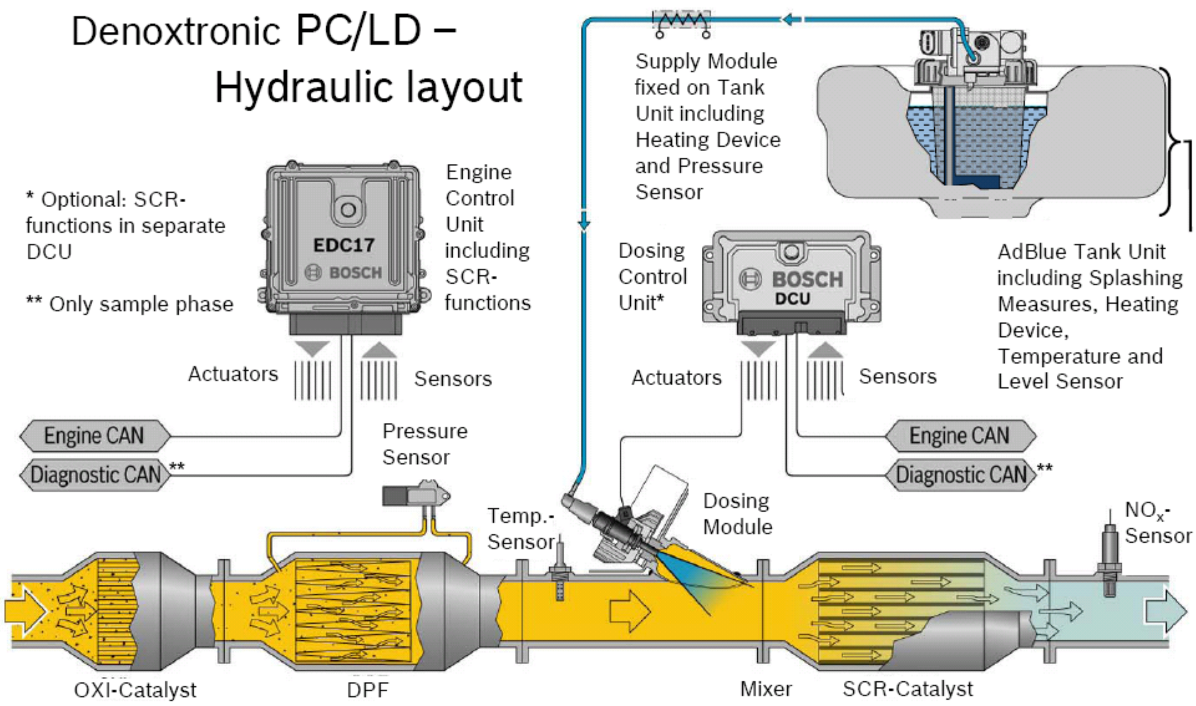

Figure 1: DENOXTRONIC PC/LD Hydraulic >Layout