SENSOR QUALITY FOR LOW PRESSURE INDICATION – RESEARCH AND SOLUTIONS

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Abstract

In order to analyze the processes during the gas exchange in the engine, knowledge of pressure states in both inlet and outlet is required. This pressure measuring is known as "low pressure indication". In the presented work, three examples of controlling the quality of low pressure measurement are presented.

The projects performed during the collaboration with Kistler showed the high demands regarding accuracy, dimensions and lifetime of measuring chains and piezoresistive sensors for low pressure measurement. To gain reliable results for use in simulation tools for calculating and modeling gas exchange phase the sensor and measuring chain must be designed in order to consider all possible influences on the signal such as thermal and mechanical stress, electrical parasitic induction and gas dynamic effects. The increasing demand regarding accuracy and low thermal drift for highly dynamic measurements and the restricted space available in most applications are further challenges.

It was shown that: a small inaccuracy of measurement, lower than 10 mbar can be attained, the asymmetric course of the exhaust pulse can clearly be verified, and a protection screen for a sensor exposed to the exhaust blow-off pressure wave can be a tool to optimize between longlife and accuracy.

1. Introduction

Low pressure measurement as a basis for analysis of the gas exchange process [1-3], has gained importance over the past years, not least because of the increasingly demanding emission regulations [9]. In order to reduce emissions, engine manufacturers are focusing on the optimization of gas exchange. The inlet and exhaust pressure curves are used for experimental analysis (e.g. residual gas calculation) and for validation of simulation results (ex. CFD). Slight pressure differences in the intake and exhaust section influence the inflow and exhaust of the cylinder (e.g. filling, residual gas fraction). Analysis of gas exchange thus demands a precise knowledge of the pressure (absolute pressure level and phase). The absolute pressure level and the dynamic of pressure curves in the intake and outlet section are influenced by several issues: radial position and distance to cylinder head of the sensor, mounting (fitting, flush mounted, directly or in cooling adapter), quality of zero point setting (in warm condition), type and performance of sensor, measuring devices and data acquisition. A higher inaccuracy would not allow a proper calculation of the gas exchange phase as there is a correlation between the pressure values and the gas mass flows. The requirement is to reach a measuring inaccuracy of lower than 10 mbar at all engine conditions, see Fig. 1 [4]. A higher inaccuracy would not allow a proper calculation of the gas exchange phase as there is a correlation between the pressure values and the gas mass flows.

In cooperation with Kistler Instruments AG, the Laboratory for IC-engines & Exhaust Emission Control (AFHB) at the Bern University of Applied Sciences has been analyzing the methods and influences of low pressure measurement with different Kistler sensors and also several aspects of the influences on the pressure curves measured by sensors in low pressure measurement. In this work some of the results and findings gained over the past years will be shown, including different measuring methods, sensor positioning and specific measures when measuring in the exhaust gas.

General technical information regarding the low pressure measurement is also provided to give an overview of the situation and highlight the high precision reached by the Kistler pressure sensors and quality requirements when measuring with such in the inlet and outlet.

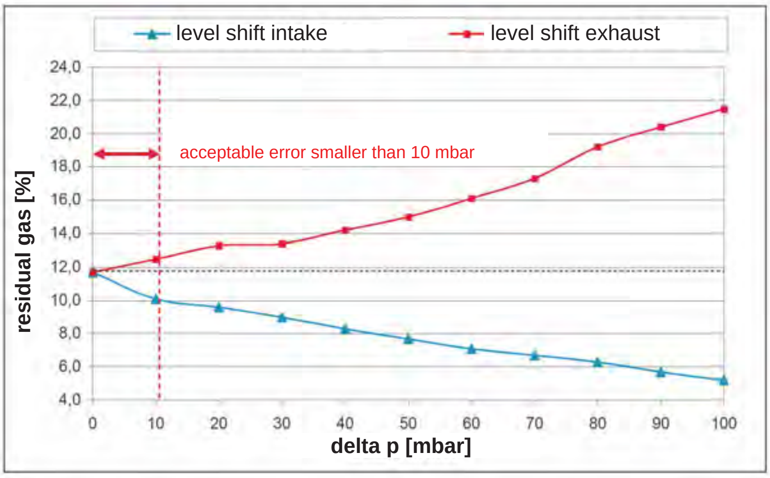

Fig. 1. Influence of the shift of pressure level in the inlet and outlet on the calculated residual gas content at 3000 rpm / part load [4]

2. General technical information

In this chapter, general information regarding the pressure indication will be given in order to summarise the issues encountered when measuring with high precision sensors. Due to their highly sensitive measuring cells care must be taken to avoid any electrical (ex. grounding, ignition) and physical (ex. temperature, tension, gas dynamics) influence on the pressure signal in order to ensure best possible reliability of the measured values.

Measuring principles

In order to measure and record the pressure curves in the combustion chamber as well as in the corresponding gas exchange equipment during a whole working cycle, very accurate measuring chains are needed.

In cylinder pressure measurement, the piezoelectric sensors are the most commonly used, although they can only measure the dynamic part of the pressure curves. This results in the task of referencing the measured signal in each cycle. This can be realized by using a reference pressure sensor in the intake or by calculation (of known gas properties) during pressure rise in compression stroke [1].

On piezoelectric pressure sensors, Fig. 2, the pressure from the adjacent medium acts on the surface of the membrane, which is deformed proportionally. The resulting force acts directly on the crystal, inducing a shift of charge. The charge carriers are absorbed by electrodes.

Some specifics of the piezoelectric effect are:

- extremely high measuring range (up to 10^5 bar),
- generated charge usually very small,
- high demands regarding isolating resistance (10^{12} Ohm),

- because of parasitic resistance no possibility of static measurements,
- very high stiffness,
- suited for mounting positions with high thermal stress,
- good linearity,
- good dynamic behaviour,
- high thermal stability.

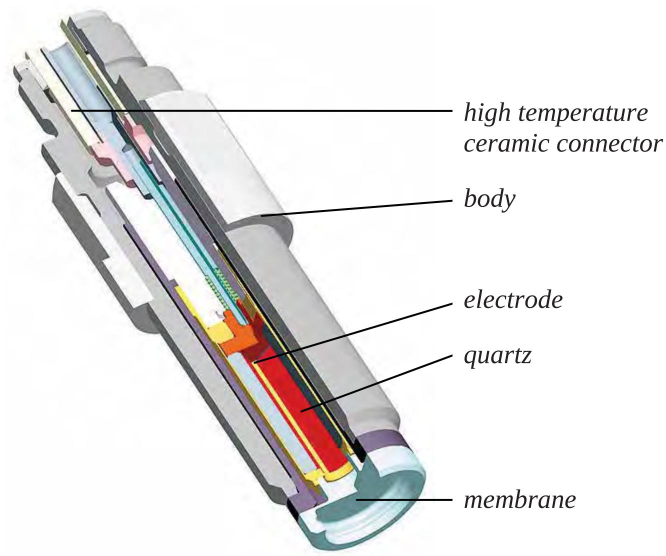

Fig. 2. Principle of the piezoelectric sensor [5]

For low pressure measurement, piezoresistive sensors are used, which measure absolute and dynamic pressure. In a piezoresistive sensor, the pressure is measured using semiconductor resistors, which are arranged to a Wheatstone bridge allowing part of the resistors to be under tension and the others under pressure. This results in a change in resistance, which can be measured. The resistors are located in the sensor chip integrated into the measuring cell, Fig. 3. Depending on a range of application criterias, such as
- available space,
- required accuracy,
- thermal load,
- vibration,
- media (e.g. soot admission),

a suitable sensor and equipment need to be chosen [10]. State-of-the –art solutions can be seen in Fig. 4.

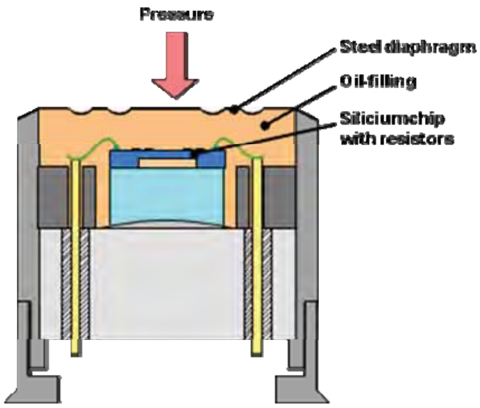

Fig. 3. Principle of the piezoresistive sensor [4]

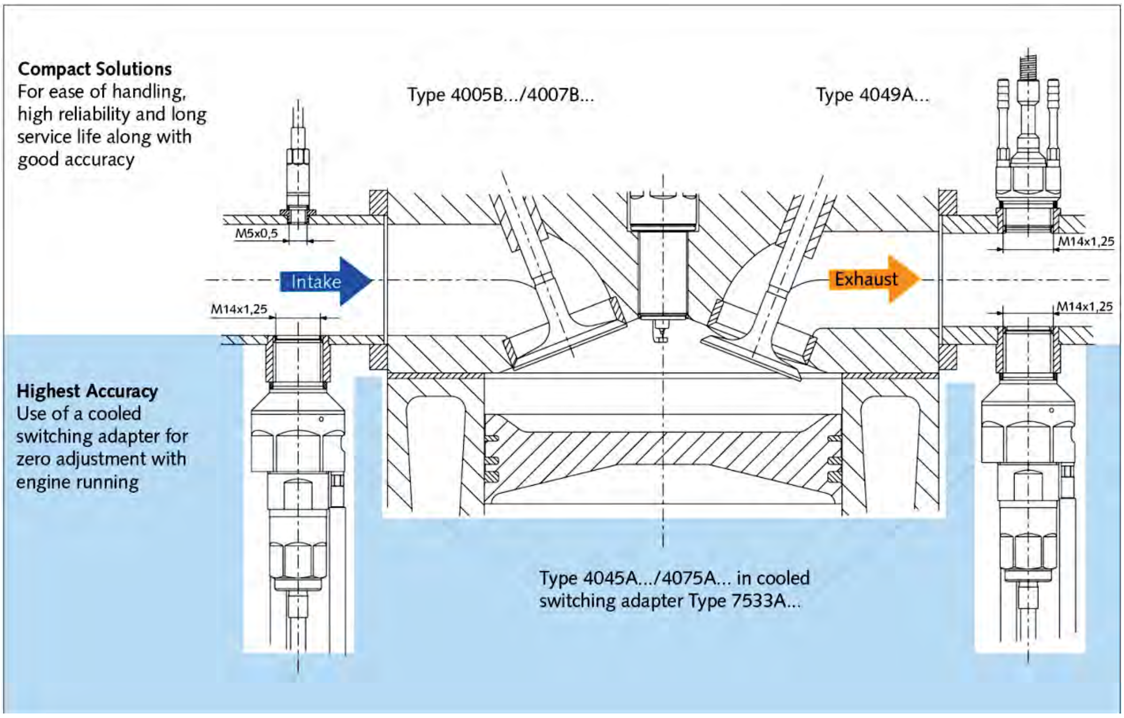

Fig. 4. State-of-the-art solutions of Kistler for low pressure measurement [10]

For intake pressure measurement, miniature pressure sensors (Type 4005/4007) are mostly suitable. Due to Kistlers DCE-principle (direct chip exposure) the sensor can be built very compact, and can be installed directly in the manifold.

On exhaust side the sensors need always to be actively cooled due to high exhaust temperatures of 1000°C and beyond. Because exposition to harsh media (soot, combustion gases) a sensor with media separation is suitable, see Fig. 4. These sensors (Type 4049/4075/4045) have steel diaphragm and oil filling for force transfer to the measuring cell.

If highest accuracy needs to be achieved, it is necessary to use cooled switching adapters, see Fig. 4. By using of such adapters, the sensors “zero-line” can be referenced to known ambient pressure with engine running. This enables to make an adjustment at the same boundary conditions (e.g. thermal load) as the consecutive measurement is done.

To summarize, every low pressure indication measurement can only be realized with certain tradeoffs. To gain the desired accuracy, the procedures and the measuring technology must be chosen in order to allow for the numerous influencing factors to be considered.

Signal quality / conditioning

Usually the electric signal from a sensor is not directly exploitable but has to be amplified. This signal amplification has a particular importance when measuring with piezoelectric (PE) sensors as they only generate charges of a few picocoulombs (cylinder pressure measurement). The charge amplifier converts the charge into a proportional voltage. The fact that piezoelectric sensors don’t have a reference to ambient pressure, means that this measuring chains need to be added with a signal conditioner in order to correct the signal courses.

When operating piezoresistive sensors (PR), signal amplifiers are needed to amplify the outlet voltage of the measuring bridges and are additionally capable of digitally enhance thermal behaviour and linearity. At the same time the integrated constant voltage source supplies the sensors. The outlet voltage of an amplifier is usually maximum 10 volt.

Connections between the sensors and the amplifiers must be highly isolating to prevent electrical drift. Because of the very small currents passing through this connection cables, they are very susceptible to electrical interferences.

To ensure best possible accuracy of these measuring chains, special attention must be given to:
- ground isolation of piezoelectric sensor (to prevent ignition influences etc.) (PE),
- acceleration compensation of piezoelectric sensors (PE),
- zero point setting (usually in warm condition, meaning all sensors and amplifiers at operation temperature) (PR),
- calibration of measuring chains: sensor / amplifier / eventually signal conditioner / data acquisition device; usually for piezoresistive sensors for example, the sensor and amplifier are calibrated together before delivery and cannot be interchanged (PR),
- appropriate setting of low- and high pass filters,
- resolution of A/D converter,
- drift compensation and prevention.

Influence of sensor temperature and mounting position on signal dynamic in low pressure measurement

The temperature of the sensors should ideally be held constant to prevent thermal zero point shift during the measurement. Also, the zero-point setting of the sensors should take place simultaneously to ensure that no differences in zero point value occur. Especially when measuring in the exhaust, cooling adapters are mandatory to protect the measuring element from overheating.

Due to the gas dynamic oscillation in the exhaust, sensor signals can be influenced by flow effects in the exhaust piping (chapter 2). Therefore the radial positioning of the sensor should be chosen with regard to the geometry of the exhaust system. There are also measures to be taken in order to minimize signal noise such as pipe oscillations caused by gas dynamic effects in the sensor cavity (e.g. chapter 3).

3. Measuring set-up

Measuring Equipment

Data acquisition:
- Kistler DATAC data acquisition device Type DATAC-1, 8-channel, sample rate 500 kHz per 4 channel, input 0…10V,
- COM Electronic crank-angle-sensor, Type 2611, linked to DATAC, CA resolution 1°CA, RPM-range 20…12000 rpm.

Pressure sensor cooling:
- Kistler sensor cooling device, Type 2621C, flow per sensor 0.25–0.5 l/min, thermostat control range 50± 5°C,
- cooling water measuring device supplied by Kistler to check and regulate flow through sensor, (only used in work of chapter 3).

Test engine

Engine
- Manufacturer: Mercedes-Benz
- Type: M111
- Displacement: 2199 cm^3
- Rated RPM: 5500 rpm
- Rated power: 110 kW
- Torque: 210Nm at 4000 rpm
- Model: 4 cylinders R
- Compression ratio: 9.8:1
- Bore-stroke ratio: 86 mm/89.9 mm
- Emission control: three way catalyst
- Fuel: Standard 95 ROZ unleaded fuel used for all tests

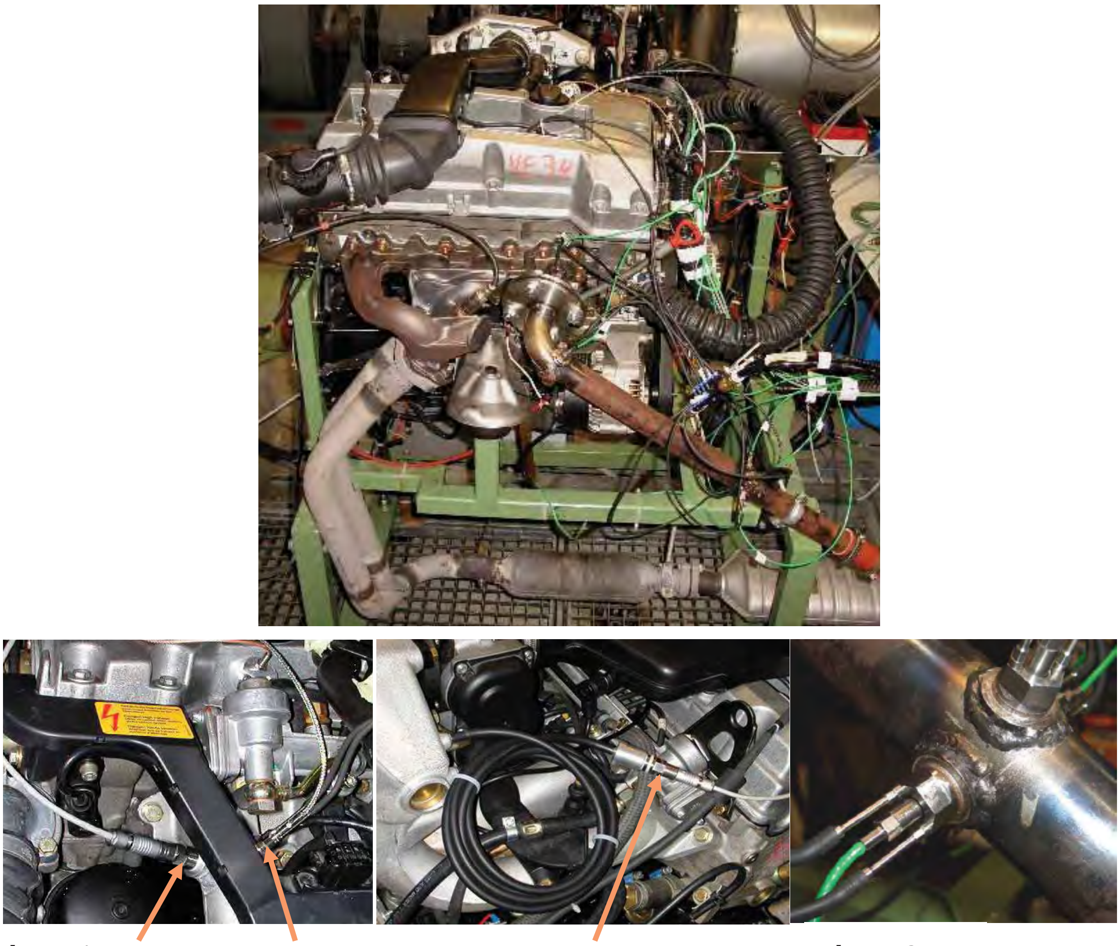

Fig. 5. Mercedes engine on the test stand and zoom on a measuring plane (chapter 2) and the intake arrangement (chapter 1)

Used sensors/adapters

Cylinder pressure:
- Kistler high pressure piezoelectric sensor, water cooled Type 6061B, sensitivity ≈ 25 pC/bar, Range 0…250 bar,
- Kistler charge amplifier, Type 5011B,
- Kistler signal conditioner, Type 5219A, conditioning of measuring signal.

Low pressure measurement (intake), chapter 1:
- Kistler low pressure piezoresistive sensor, Type 4043A1 with amplifier Type 4603, Range 1 bar (abs.),
- Kistler low pressure piezoelectric sensor, Type 6052B, sensitivity 20.5 pC/bar, Range 0…250 bar,
- Kistler charge amplifier, Type 5011,
- Kistler signal conditioner, Type 5219A, conditioning of measuring signal.

Low pressure measurement (exhaust), (chapter 2):
- Kistler low pressure piezoresistive sensor, water cooled mounting adapter, Type 7525,
- Kistler piezoresistive pressure sensor Type 4005BA with amplifier Type 4618A2, Range 0…5bar.

Low pressure measurement (exhaust), (chapter 3):
- Kistler water cooled piezoresistive pressure sensor Type 4049A with amplifier Type 4665, Range 0…5bar.

4. Results

4.1. Comparison of direct and indirect method of low pressure measurement at intake [6]

In this chapter, two different methods for low pressure measurement will be discussed. Basically there are two methods for low pressure measurements:

- direct method: static and dynamic signal part are measured with one piezoresistive sensor, Fig. 6,
- indirect method: In addition to a piezoresisitive sensor measuring the static part a piezoelectric sensor is used for the dynamic part, Fig. 6.

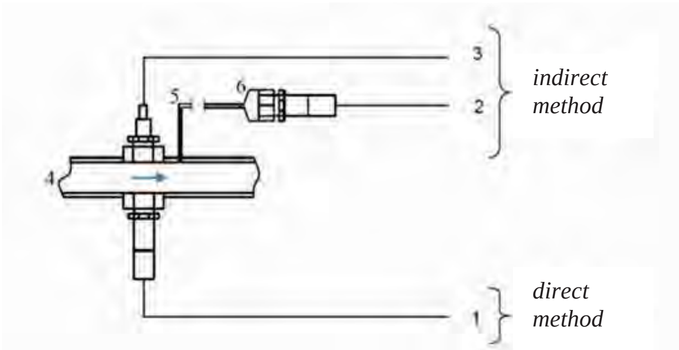

Fig. 6. Pressure measurement methods: 1 – piezoresistive sensor (channel 1; reference) – p1, 2 – piezoresistive sensor (channel 2; static part; tube connection) – p2, 3 — piezoelectric sensor (channel 3; dynamic part) – p3, 4 – intake manifold, 5 – tube (l=2000mm), 6 – adapter

The measurements were conducted in the intake manifold of the described test engine. Table 1 shows the operation points defined to compare the two measuring methods.

Tab. 1. Selected operation points for measurements

operation point	Engine speed [rpm]	Engine torque [Nm]	load index [%]
1	775	0	0
2	2000	0	0
3	2000	78	50
4	2000	156	100
5	3000	0	0
6	3000	81	50
7	3000	162	100

The goal of this comparison was to gain knowledge about which measurement method delivered the more accurate results as both methods were being used.

The direct method uses a fast piezoresistive sensor to measure the pressure. It measures both the static and dynamic signal part (p1).

The indirect method combines the advantages of both sensor types. The dynamic part is measured by a piezoelectric sensor (p3). To measure the static mean absolute pressure, an additional, piezoresistive sensor is used (p2). It is connected with a tube to a connecting point in the intake manifold. The difference of the mean values of p2 and p3 is used to mathematically correct the signal course of p3. In Fig. 7 and 8, the difference of this corrected signal to the signal from the direct method (p1) is stated as delta p and used to compare the two measuring methods.

Results showed that the indirect method was nearly comparable in terms of accuracy with the direct method measurement. The maximal difference of 10 mbar explained in Fig. 1 was undercut in all operation points until 3000 rpm, Fig. 8. According to these measures, the indirect method can be an alternative to the direct method.

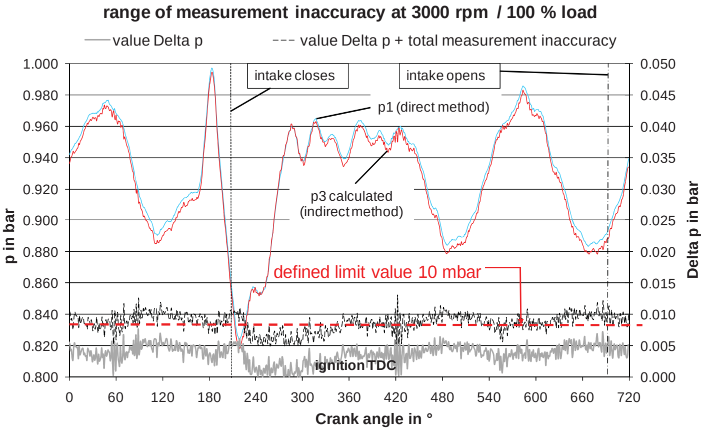

Fig. 7. Pressure curves with different measuring methods and resulting pressure differences

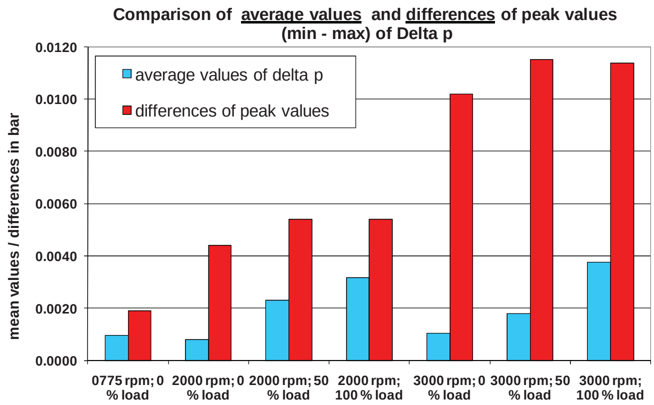

Fig. 8. Comparison of mean values and peak value differences of delta p

But it must be indicated that the indirect method cannot be used in transient operation unless the piezoresistive sensor is mounted directly to the manifold and its signal used as a continuous reference signal for the piezoelectric signal conditioner. This is because the tube connection generates phase shifting in transient operation. Moreover, there are some additional issues to bear in mind when using the indirect measuring method:

- The use of two measuring chains increases the sources of error and thus measurement uncertainty,
- The use of piezoelectric sensors demands ground isolated and acceleration compensated sensors and increases the measurement complexity in general,
- Depending on the application, the fact that a second sensor mounting position has to be created can be critical in terms of space requirements.

Further statements about the indirect method, especially for the use in exhaust system are given in [10]:

- The advantage of the indirect method is the use of conventional piezoresistive sensors without cooling for example due to the tube connection which gives low temperatures and no contamination if used in exhaust.
- However it must be bared in mind that the accuracy of the indirect method depends from various boundary conditions like tube length (phase shift), pressure tap geometry, operation point and location (difference of dynamic pressure).
- There are varying errors of the remote sensing system regarding the determination of the mean pressure level between 15…20 mbar in exhaust systems.

Finally the indirect method is not recommended for dynamic measurements and measurements in exhaust port.

4.2. Low pressure measurement in the exhaust: impact of the sensor position [7]

The absolute pressure level and the dynamic of pressure curves in the intake and outlet section are influenced by several issues: position of the sensor, adjustment (fitting, directly or in cooling adapter), quality of zero point setting (in warm condition), type and performance of sensor, measuring devices and data acquisition. In this chapter, the focus was set on the aspect of sensor positioning. To evaluate the differences of the sensor positions, attention to the other aspects was essential.

The goal of this work was to gain experience in how to reach a sensor position which delivers representative pressure curves. Therefore a custom made exhaust manifold was created allowing the isolation of a cylinder to avoid the influence on gas dynamic effects from other cylinders, see Fig. 5. Pressure measurements where carried out in different planes of the exhaust pipe. The schematic of measuring set-up is shown in Fig. 9.

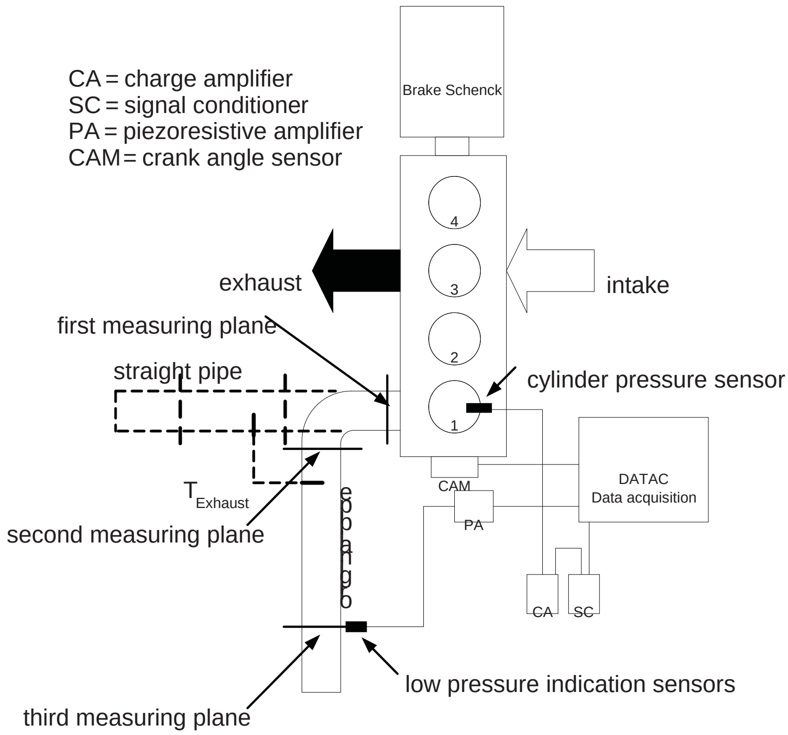

Fig. 9. Measuring set up for investigation of the exhaust blow off on Mercedes M111

All measurements where carried out at steady state warm operation condition of the engine, at 2 operating points: 2000 rpm full load and 2500 rpm full load. As shown in Fig. 9 and 10 measurements where made in three different planes of the measuring pipe. Each plane could be equipped with 4 pressure sensors except for the first measuring plane with 3 sensors possible. A single pressure sensor was mounted in the outside radius of the bend measuring pipe to get an impression of flow effects due to redirection. These positions also apply to the straight pipe used in third measuring phase except for position 7 (not mounted).

During the first stage of measurement, sensors where additionally interchanged to demonstrate that the pressure differences where due to gas dynamic effects in the exhaust pipe and not to differences between the sensors. The first stage of measurements included measuring in all planes of the original pipe (see Fig. 10) at both standard operating points. Finally in the last stage the straight pipe was mounted to get a reference especially in order to compare the pressure differences in the second plane of the original pipe with those in the same plane of the straight pipe. Measurements where also carried out in the first and third measuring planes.

Before each measurement, a zero point setting was applied for each sensor at warm operating condition of the engine. The repeatability of measurements was also investigated throughout all measurement stages and proved to be very good, this providing a reliable basis for later comparison of the results.

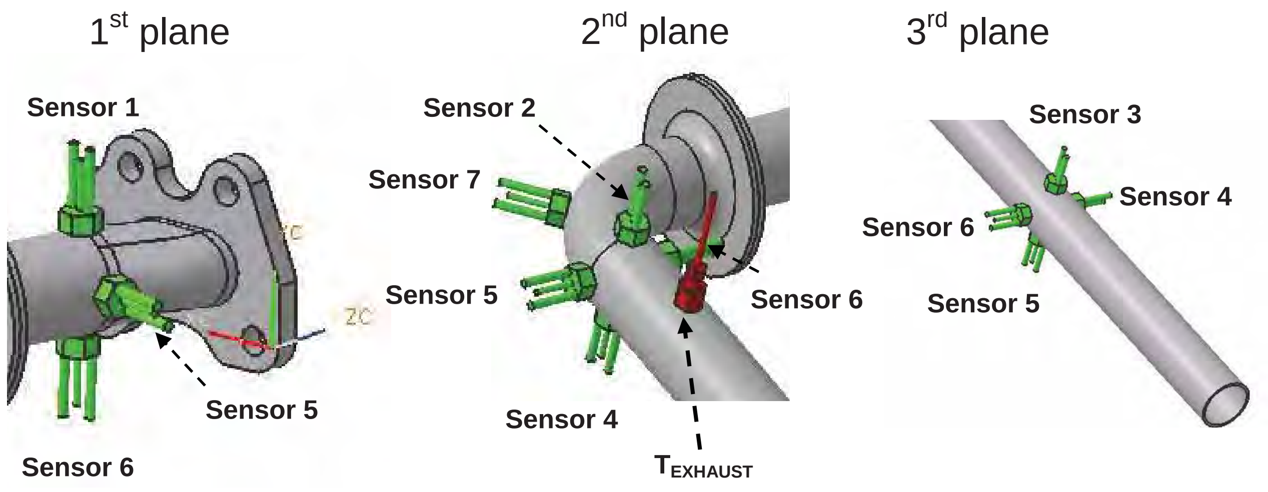

Fig. 10. Sensor positions in first, second and third measuring plane in the research exhaust pipe

Results of pressure indication showed obvious pressure differences between sensors within the same measuring plane, especially in the plane after the bend which represented the interesting area regarding the influences of gas dynamic effects. These differences only appeared significantly during the first blow off wave. Figure 11 shows the low pressure indication results for the second measuring plane at 2500 rpm full load.

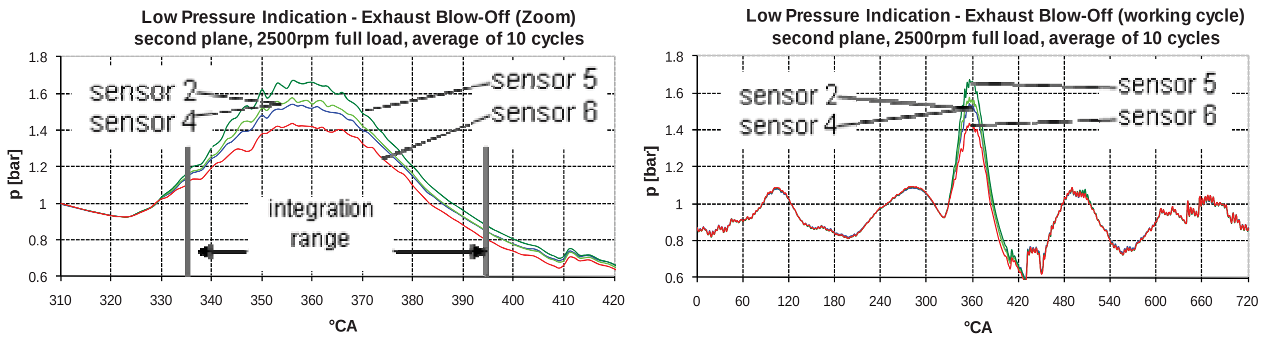

Fig. 11: Exhaust blow off in working cycle and zoom showing sensor differences (second plane)

The pressure differences between sensors in the same measuring plane due to the asymmetric course of the exhaust wave proved to be low in the first and third measuring plane. In the second measuring plane after the crook of the exhaust pipe big differences where noticed between sensor/position 5 and 6, showed in Fig. 11. The flow through the bend caused pressure at position 5 to rise while the pressure at position 6 was lowered significantly. On the other hand the vertical positions 2 and 4 showed very little differences and thus no important influence due to the flow around the bend, see Fig. 11. To gain an overview of the pressure situation inside the second measuring plane results were finally visualized as shown in Fig. 12, in which the blow off window of approx. 60°CA was averaged. Finally, based on this representation all measured planes and position could be evaluated and recommendations regarding less or more favourable positioning of the sensors could be established.

The measurements with the straight pipe were compared in all planes with those of the original pipe and delivered as expected much more uniform pressure curves except for the first plane. The first plane delivered almost constant sensor differences over all measurement phases and thus wasn't influenced by the following pipe geometry.

The investigations concerning the characterisation of different sensor positions for low pressure indication led to the evaluation of three different positions:

- A near cylinder head position (Fig. 10) proved to deliver the best results with low differences between radially positioned sensors to the average pressure measured in the corresponding measuring plane and very low influence on signal differences due to the following pipe geometry. On the other hand, a near cylinder head positioning could be critical regarding space requirements.
- A position after the crook of the exhaust manifold usually to be found on most of the engines should be placed like sensors 2 and 4 in Fig. 10 to avoid strong gas dynamic flow effects to be measured due to (see position 5 and 6, second plane) the bend in the exhaust pipe. This position can deliver good results as the emplacement is near to the exhaust valve and a good accuracy of phase and amplitude can be assumed.
- A position in further distance of the exhaust valve showed very uniform pressure signals in the whole measuring plane as the exhaust stream becomes uniform in the flow section but this position was to far away to get reliable pressure levels representing the situation at the exhaust valve.

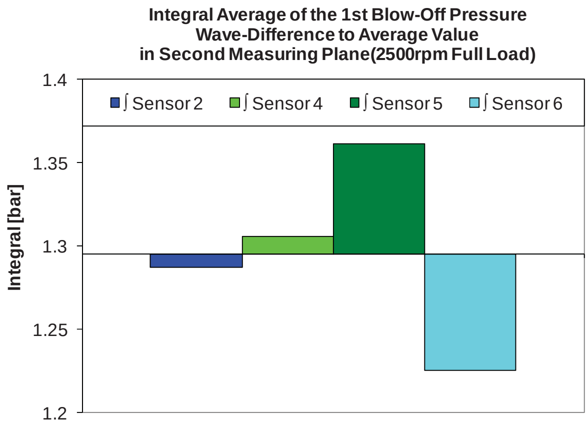

Fig. 12. Overview of pressure situation in second measuring plane (approx. 60°CA blow off window averaged)

The reference with the straight pipe could be established and showed the influence of the bend in the original measuring pipe and the resulting gas dynamic effects on the pressure signal differences of the sensors. Changing the pipe angle had little influence on the measured pressure curves as the geometry of the pipe is of greater influence on the gas dynamic effects.

Changes of parameters like load and engine speed showed the expected influence on pressure level, although load had a more significant influence on pressure level of the sensor differences compared to a slight rise of pressure due to the higher engine speed.

4.3. Screen design for sensors used for exhaust pressure measurement [8]

In this chapter, the focus is on protection measures for sensors used for exhaust pressure me-asurement in internal combustion engines. Due to exhaust temperatures of 1000°C or higher, sensors installed in the exhaust need to be actively water cooled to prevent overheating.

As detailed knowledge of the kind of heat transfer is important for a sensor design, extensive investigations have been made to estimate the fractions of conduc-tive, convective and irradiation heat transfer. It could be shown that most heat energy is brought into the sensor by its mounting thread by conduction. An irradiative heat transfer is on one hand accomplished from outside into the housing of the sensor (irradiation of manifold). On the other hand some irradiative and convective heat transfer is brought directly into the sensor by its front. As the sensitive measuring module is directly exposed to the hot exhaust gas, it is important to manage the heat load from the front side.

To reduce the heat load from the front, screens are applied for heat protection, Fig. 13. As part

of this work different screen designs have been studied to determine lowest heat impact and best sensor performance. Functions of a screen are:
- Heat protection,
- Mechanical protection of steel diaphragm,
- Reduction of soot deposition in the sensor cavity,
- Dissipation of pipe oscillation.

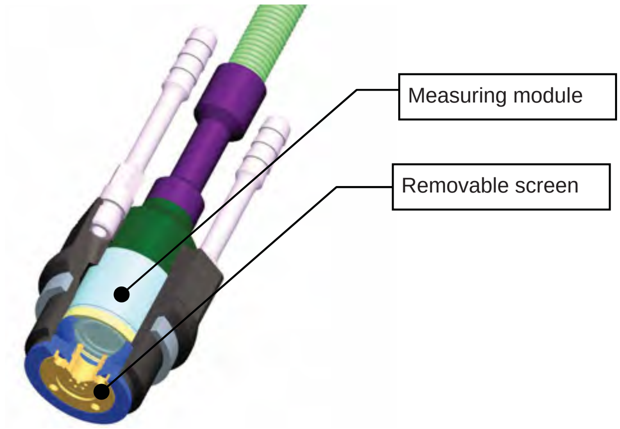

Fig. 13. Kistler sensor type 4049A with screen

The challenge in developing the ideal screen is to find a design which provides good thermal protection (keeps the temperature of the measuring module low), has not the tendency for clogging and has good properties regarding gas dynamics.

A range of screens which have been studied is represented in Fig. 14.

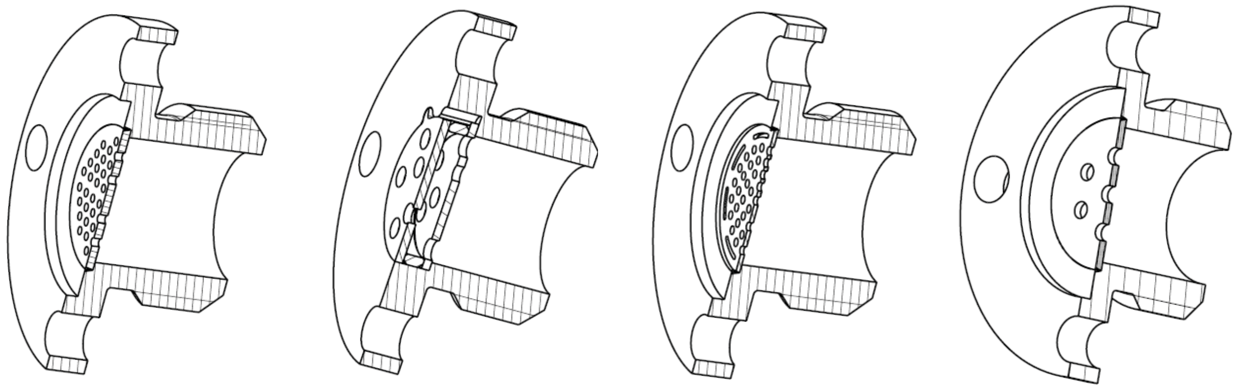

Fig. 14. Different types of screens which have been studied for best sensor performance

The screens have been tested in exhaust application in order to find the best trade off between thermal protection an gas dynamics. The different designs distinguish between thickness, bore diameter and number of bores. Both, the diameter of the bore and the overall surface area of the screen allow a heat transfer from the hot gas to the sensor housing and finally to the cooling water.

Because of thermal reasons the measuring module can not be flush with the front. The back set of the module leads to a cavity which would cause a slight pipe oscillation. The presence of a screen disturbs the development of this oscillation without sacrificing the bandwidth of the pressure measurement.

Figure 15 shows different pressure cycles of different screen application with corresponding temperature of the sensing element. The water cooling temperature is 50°C.

This study resulted in better knowledge of heat transfer of sensors installed in exhaust manifold.

Extensive measurements with different screens could confirm a best screen design regarding sensor performance.

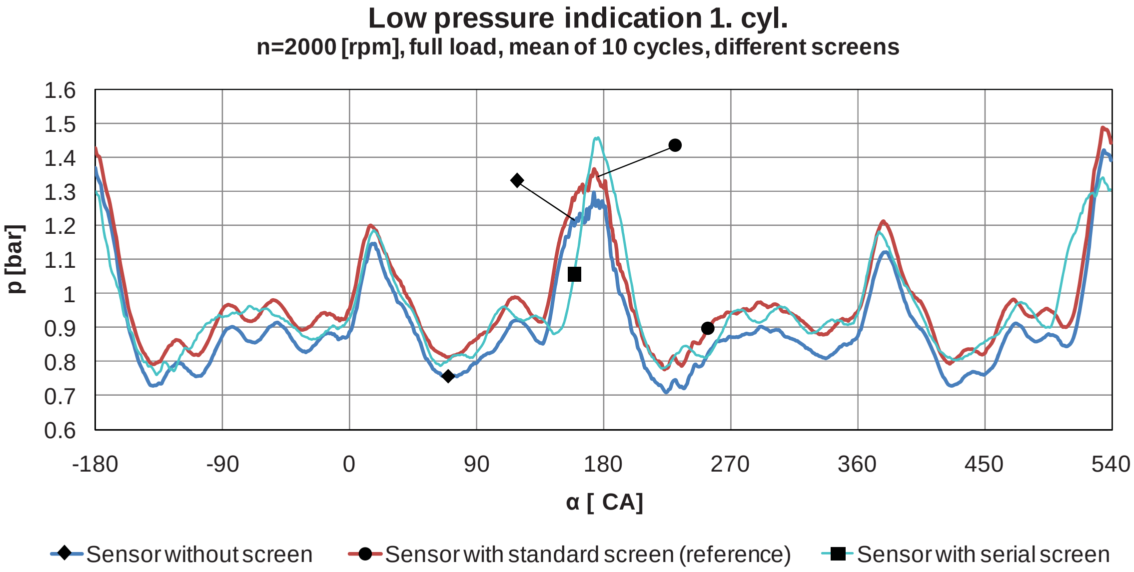

Fig. 15. Pressure curves with different screens, 2000 rpm / full load

5. Conclusions

The presented projects performed during the collaboration with Kistler showed the high demands regarding accuracy, dimensions and lifetime of measuring chains and piezoresistive sensors for low pressure measurement. To gain reliable results for use in simulation tools for calculating and modeling gas exchange phase the sensor and measuring chain must be designed in order to consider all possible influences on the signal such as thermal and mechanical stress, electrical parasitic induction and gas dynamic effects. The increasing demand regarding accuracy and low thermal drift for highly dynamic measurements and the restricted space available in most applications are further challenges.

The performed measurements showed a high degree of precision and quality of Kistler indicating techniques and the constant improvement and quality control of their products.

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