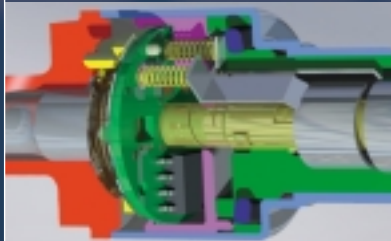


Perfection built in


www.beru.com

Reprint
MTZ



Pressure Sensor Glow Plug (PSG) for Diesel Engines

Special reprint from
Motortechnischen Zeitschrift (MTZ)

Perfection built in

Perfection built in

Perfection built in





Pressure Sensor Glow Plug (PSG) for Diesel Engines

Future emission limits for diesel vehicles are demanding a further drastic reduction in exhaust gas components particles and nitric oxide. Since these values cannot be represented with combustion tuning measures alone at the moment, the active exhaust gas post-treatment will become a permanent technological component in the diesel engine. In addition, the combustion will have to be optimised by a closed-loop control to also reduce the basic emissions considerably. Beru AG has developed a combustion chamber sensor (Pressure Sensor Glow Plug - PSG) for this which is integrated in the glow plug.

**By Hans Houben,
Arno Marto, Frank
Pechhold, Michael
Haußner and
Marc Borgers**

1 Introduction

The future exhaust gas limits for diesel engines in the USA and Europe are about 10 – 20 percent in relation to the current values, **Figure 1**. The particle reduction being aimed at would appear attainable – even over the required life span – with exhaust gas filter systems. However, the presently known post-treatment measures alone are not enough to also achieve the demanded NO_x aims. Therefore the basic emissions of the engines must also be greatly improved. Therefore intensive worldwide research is being done on various combustion processes such as HCCI (Homogeneous Charge Compression Ignition), HCLI (Homogeneous Charge Late Injection), HPLI (Highly Premixed Late Injection), DCCS (Dilution Controlled Combustion System) because all these processes are distinguished by very low NO_x emissions. In the combination of optimised combustion and exhaust gas post treatment, the emission limits of the next stage seem achievable. It may even be possible to dispense with a NO_x post-treatment altogether.

All of the combustion processes mentioned has one thing in common: the ignition takes place depending on the condition of the mixture and can therefore no longer be built any more as an "open loop" which was fitted in the diesel engines in the past. However, in order to set up a "closed loop" combustion control, information from the combustion chamber is required. This can be obtained for example from a sensor which supplies the data necessary for control [2]. From a constructional point of view, however, additional holes in the cylinder head are to be avoided. This applies particularly for modern four-valve heads with their restricted space.

The basic conditions outlined here are a particular challenge to the Beru company as a specialist for diesel cold start technology and the world's biggest manufacturer of glow plugs to take on the project under the aspect of "glow plug with combustion chamber sensor function". The glow plug occupies a mixture optimised position in the combustion chamber due to its main function for a diesel engine cold start. It is therefore ideally suitable as a carrier for such a combustion chamber sensor. The results of various concept analysis in the development of a glow plug with a combustion chamber sensor are described below.

2 Development Goals

Development goals have been formulated with regard to customer needs in which the following requirements must be met:

- no impairment of the heating function
- miniaturisation of the whole sensor due to the restricted installation space in the cylinder head
- a robust and accurate, static measuring method
- no cross sensitivity of the sensor, especially to structure-borne noise signals
- the development of a modular system to be able to use the sensor for different glow plugs
- guarantee of easy assembly for the customer (ideally as for a modern glow plug).

3 Examined Sensor Concepts

Four measuring methods basically suitable for the aim in the opinion of the Beru development team were included in the closer pre-examinations: ionic current measurement, optical pressure measurement, piezo-electric pressure measurement and piezo-resistive pressure measurement.

3.1 Ionic Current Measurement

Ions are produced thermally and chemically during the combustion process so that an ionic current dependent on the combustion process is measurable by applying a voltage at a sensor [3]. In order to measure this ionic current with a glow plug, the heating rod reaching into the combustion chamber must be electrically isolated from the body and from the cylinder head. This is achieved on the inside by a pressed plastic sleeve and on the outside by a glass-ceramic coating of the heating rod. In order to retain the classic, single-pole electrical connection of the glow plug, a diode is integrated in the top part which connects the heating function on applying a positive voltage and measures the ionic current at negative voltage, **Figure 2**.

The Authors



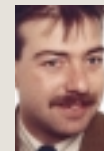
Dipl.-Ing. Hans Houben, Manager of the Development Department at Beru AG in Ludwigsburg.



Dipl.-Phys. Ing. Arno Marto, is responsible for Sensor Development at Beru AG in Ludwigsburg



Dipl.-Ing. (FH) Frank Pechhold, is head of the Construction in the Sensor Development at Beru AG in Ludwigsburg



Michael Haußner, work's in the Diesel Cold Start Technology department on the development of rod glow plugs.



Marc Borgers, has headed the Texas Instruments team for integration of the sensor function in glow plugs with the Beru AG.

1 Introduction

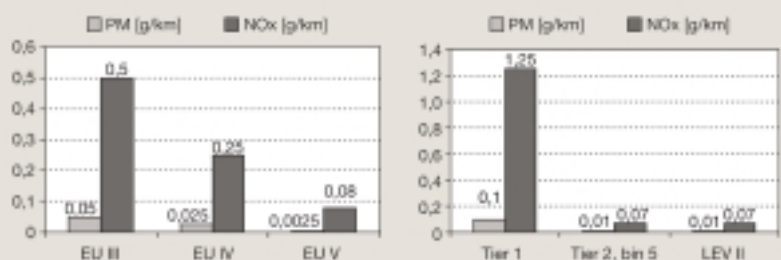


Figure 1: Present and future emission limits for car diesel engines in Europe left and the USA

This System [3] was tested up to the B-sample stage with several thousand operating hours. The signal evaluation shows that there is a correlation with the heat release curve in the first approach. The time-based variables such as beginning of combustion of pre- and main injection can be measured here reliably. The pre-injection can also be kept constantly low over the life span of the engine by calibrating the injector flow and combustion misfires or nozzle needle problems can be detected. However, other thermodynamic variables can only be measured indirectly and conditionally.

3.2 Optical Pressure Sensor

An optical pressure sensor which allows integration in a glow plug due to its external diameter of only 1.7 mm has been used. The sensor's measuring principle is based on a classic pressure diaphragm. Two optical fibres are arranged opposite the mirrored inside whereby light is fed in through one fibre and a reflected, pressure proportional signal can be received over the other fibre.

The accuracy of the sensor signal is positive, the constructional effort for glow plug integration, the danger of coking of the inlet ducts and the opto-electrical conversion can be seen as critical.

3.3 Piezo-electric Sensor

In the knocking sensor on the engine crankcase a piezo-ceramic measuring element on a lead zirconate-titanate basis (PZT) which is integrated in a spring-mass system, takes up the accelerations and converts them into an electrical charge [1, 4].

In **Figure 3** the constructional integration of a circular, piezo-ceramic element is shown in a glow plug.

The measuring element is contacted and pre-tensioned with appropriate insulation between the inner pole and the glow plug body. Installed in the cylinder head, the combustion chamber pressure generates a contraction of glow plug body and cylinder head base and thus a relative movement between the glow plug inner pole and body [1]. The resulting change in the charge at the piezo-element can be measured at the contacts.

Basically positive in this construction is the solution of not exposing the sensor directly to the combustion chamber but using the glow plug as a transmission element. This avoids the familiar problems of temperature resistance and thermal shock.

The tests made by Beru at different operating points of the engine show, however, that although this concept provides good accuracy in the high pressure part,

deviations occur in the low pressure part. In addition high frequency faults are determined at increasing speed.

This is due to the construction because the glow plug and the cylinder head ultimately serve as a transmitter to the measuring element and therefore also pick up structure-borne noise from nearby engine components. Beru still considers the measurement of slight changes in charge and the long-term stability of polycrystalline piezo-ceramics to be critical.

3.4 Piezo-resistive Sensor

In the automotive sector, pressure sensors which operate on a piezo-resistive basis are very widely used. The technology is widely introduced and proven. It is distinguished by high accuracy, long-term stability and calibration capacity. This measuring principle is described in more detail below.

3.5 Evaluation of the Different Sensor Systems

The Table compares the advantages and disadvantages of the four concepts under examination. After evaluating the methods described here with respect to the development goals, pursuance of the piezo-resistive option promises the most success.

4 Focuses of Development

The Beru project team has defined the following special points of focus for the development of such a Pressure Sensor Glow Plug (PSG):

- high integration of the sensor element and the electronics in the glow plug by suitable installation and connection technology
- development of an automatable production process

3.1 Ionic Current Measurement

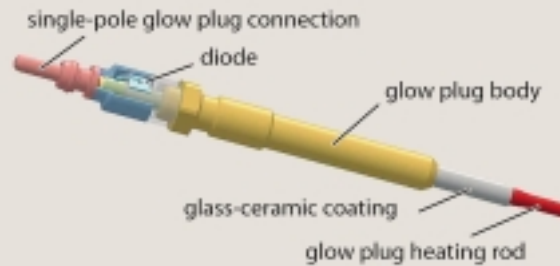


Figure 2: Structure of a glow plug with ionic current measuring function

3.3 Piezo-electric Sensor

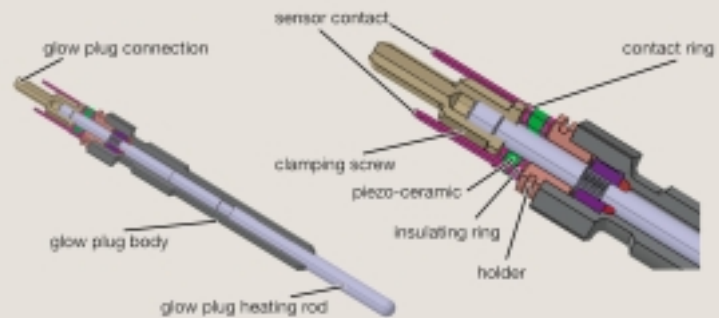


Figure 3: Structure of a piezo-electric combustion pressure sensor

3.5 Evaluation of the Different Sensor Systems

Table: Evaluation matrix of the four examined systems

technology	ionic current	optical	piezo-electric	piezo-resistive
accuracy	-	++	+	++
stability of the signal	+	++	-	++
costs	-	--	+	+
robustness	+	-	+	++
output signal	-	++	+	++
static pressure measurement	--	++	--	++

5.1 Mechanical Structure

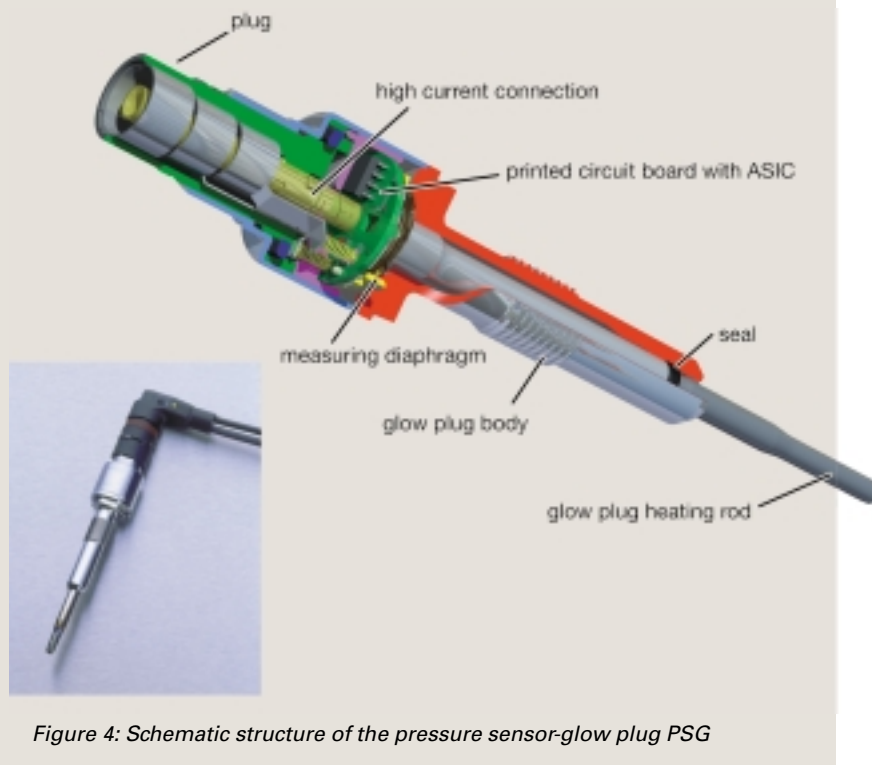


Figure 4: Schematic structure of the pressure sensor-glow plug PSG

- temperature decoupling of the combustion chamber from the sensor element by a movable heating rod as a pressure transmitter
- development of a coaxial, miniature plug system with integrated high current connection
- mechanical decoupling of the high current connection from the heating rod as a pressure transmitter.

5 Pressure Sensor Glow Plug

The development of the PSG pursued by Beru takes place in close co-operation with Texas Instruments Holland B.V., which are responsible for the conception and implementation of the sensor component to be installed in the glow plug.

5.1 Mechanical Structure

The mechanical structure of the glow plug is one of the essential points in the concept. For this, the heating rod, which is usually pressed tightly into the glow body, is designed to be movable which makes new demands as far as sealing off against hot combustion gases is concerned. The glow tube and the inner pole are extended and protrude from the glow plug body at the top. There the measuring diaphragm is welded to the body and glow tube.

To reliably control the thermal load, a heating rod of the Beru Instant Start System ISS [5] is used which only glows at the tip due to the arrangement of heating and control coil. This solution also seems suitable for future series applications because all German car manufacturers now offer diesel engines with ISS [5] at least as an option.

The heating rod is flexibly mounted in the PSG glow plug body and transfers the pressure as a force to a diaphragm. The actual pressure sensor is therefore remote from the combustion chamber in an area where much more favourable ambient conditions prevail, **Figure 4**.

In the sense of a complete system solution which enables the PSG also to be used like a conventional glow plug in the series and later workshop assembly, an appropriate plug system which meets the special requirements has been developed.

Here the three necessary sensor contacts are arranged concentrically around the high current contact with different diameters on three levels. The decoupling of the plug from the movable heating rod takes place for the sensor contacts by means of spring contacts and by the special design of the high current contact at the inner pole of the glow plug. With an external diameter of just 16 mm in the plugged state they have succeeded in keeping the installation space requirements to a minimum. The version shown here allows independent glow and pressure measurement functions.

5.2 Measuring Principle

The pressure measurement is based on the Texas Instruments "Micro-fused Strain Gage" technique (MSG). It enables hermetically sealed, accurate and failsafe sensors to be made at low cost. Micro-mechanical, mono-crystalline silicon wire strain gauges are used which are bonded to a high grade steel diaphragm as a Wheatstone bridge with a low melting point glass, **Figure 5**. This technique allows use under the harsh conditions of

5.2 Measuring Principle

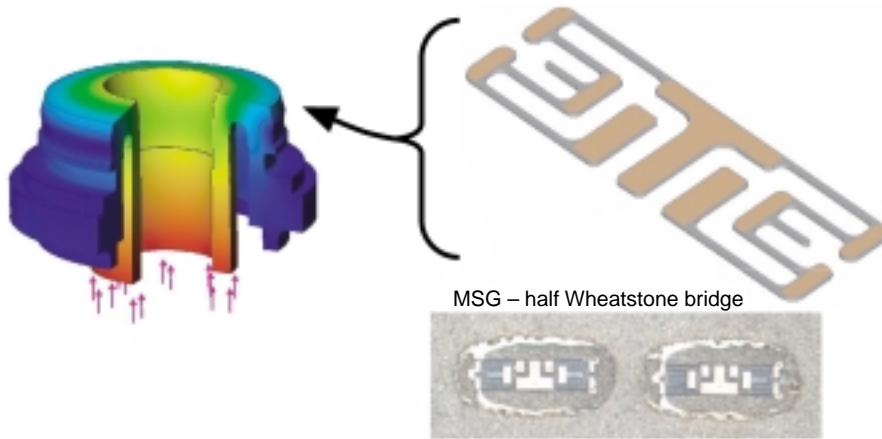


Figure 5: The metal diaphragm as an FEM model with the Wheatstone bridge

5.3 Evaluation Electronics

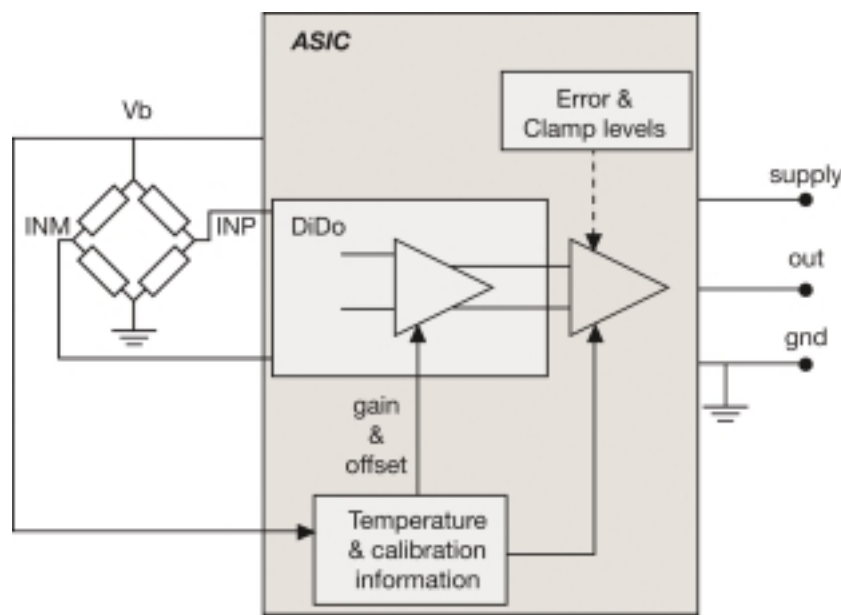


Figure 6: The ASIC with its functions

the engine mounting. This proven method is used today for brake pressure measurement (ESP), rail pressure measurement (CR), fuel pressure (GDI) and pressure measurement in the gearbox. In this application the pressure is converted by the heating rod surface into a force and transferred to the sensor element which is decoupled from the hot area of the combustion chamber as a result. The

stainless steel diaphragm is deformed by the force.

Using the Finite Element Method (FEM) the diaphragm has been optimised in terms of static behaviour (sensitivity and excess pressure strength) but also in its dynamic properties. For example the natural frequency could be shifted to 17 kHz and thus to an uncritical range for engine mounting. The FEM method was also used

for thermal calculations. The great advantages of the piezo-resistive over the piezo-electric method are the possibility of measuring static pressures (i.e. also the “zero line”) and the low drift – especially the gain – over the life span.

5.3 Evaluation Electronics

For the further processing of the signals of the Wheatstone bridge Texas Instruments is developing an appropriate ASIC the block circuit of which is illustrated in Figure 6.

The ASIC design is special adapted to this application: high bandwidth (up to 10 kHz), low noise, temperature compensation and plug programmable. The temperature compensation eliminates offset and gain errors over the whole temperature range. The temperature signal is supplied by the measuring diaphragm not the ASIC so that no additional errors can occur in compensation due to picking up the temperature close to the engine. In case of further restriction in installation space, the ASIC can be installed in flip-chip technique on a flexboard.

Standard diagnostic functions are integrated in the ASIC for internal (wire bonds) and external errors (cable). The signal level then goes into an error band so that the control unit can detect the sensor defect or contacting defect.

5.4 Specification

The development goals led to the sensor parameters listed below.

■ supply voltage	5V
■ supply current	<15 mA
■ signal voltage	0.5 .. 4.5 V
■ temperature range	-40 .. 125 °C
■ measuring range	0 .. 200 bar
■ excess pressure	220 bar
■ error (linearity, hysteresis)	+/- 2 % FSO
■ temperature error	+/- 2 % FSO
■ bandwidth	10 kHz

6 Measuring Results

Initial measuring results with A-samples on a common rail car diesel engine still exhibited strong deviations from the indexing sensor made by Kistler which was used as a reference sensor. The reason for this was on the one hand a 2-kHz noise and a phase shift of the evaluation electronics used. On the other hand the natural frequencies of the sensor came into effect. Figure 7 shows the signal trajectories of the samples at different speeds and load states in comparison with the reference sensor.

The sensor which is a mass-spring-damper system consisting of heating rod,

6 Measuring Results

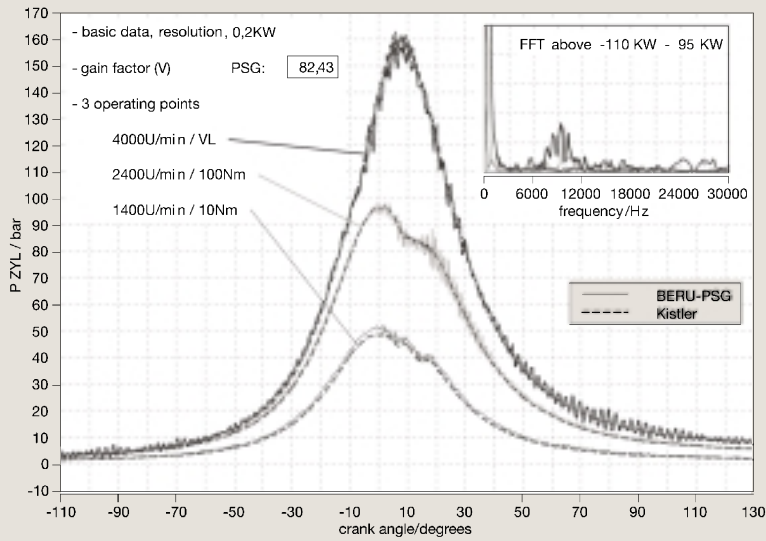


Figure 7: Combustion chamber pressure signals (various operating points, Fourier analysis)

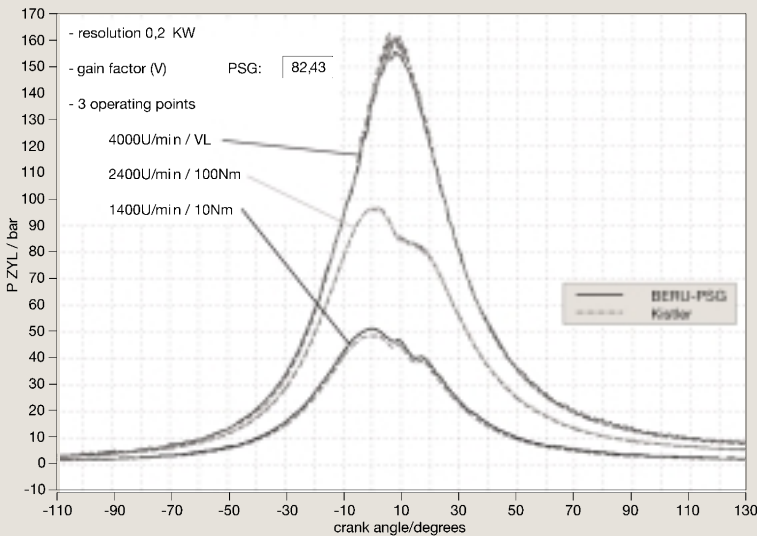


Figure 8: Combustion chamber pressure signals (optimised natural frequency)

measuring diaphragm and seal has a natural resonance between 7 and 11 kHz. By reducing the weight of the heating rod and increasing the rigidity of the diaphragm, a natural frequency above 17 kHz has been achieved.

Figure 8 shows a typical signal trajectory of the Beru PSG optimised in terms of natural frequency in comparison with the reference sensor.

7 Production and Calibration

The flex-board is soldered to the plug and is delivered to the production line after folding to a complete pre-assembled sensor-plug module. After finishing the Pressure Sensor Glow Plug the component is tested and calibrated at three temperatures. The typical data determined are then written in the ASIC.

8 Summary and Forecast

To show the future emission limits, research is being done on new combustion processes for the diesel engine such as HC-Cl, HCLI, HPLI, and DCCS, also requirement based on the distinct limit for the toleranz of the emission-relevant components, which demand a closed loop control. Beru AG has tested different methods which supply signals to the engine control from the combustion chamber. The cylinder pressure measurement has proven most advantageous. Together with Texas Instruments Holland B.V. a combustion chamber pressure sensor on piezo-resistive basis is being developed which is integrated in a glow plug. A plug system which allows independent glow and measuring functions has been adapted. Initial measurements with A- and B-samples of the Pressure Sensor Glow Plug (PSG) show a high accuracy and quality of the concept.

Beru AG therefore presents an innovative glow plug with combustion chamber pressure sensor which possibly represents a key function for exploring further potential for emission reduction in the diesel engine and therefore holds great promise for the future.

The technique described here can furthermore be implemented not only with the ISS steel glow plugs but can also be combined with a Beru ceramic glow plug concept.

References

- [1] Moriwaki, J.; Murai, H.; Kameshima, A.: Glow Plug with Combustion Pressure Sensor. In: SAE Technical Paper Series 2003-01-0707
- [2] Sellnau, M. C. et al.: Cylinder-Pressure-Based Engine Control using Pressure-Ratio-Management and Low-Cost Non-Intrusive Cylinder Pressure Sensors. In: SAE Technical Paper Series 2000-01-0932
- [3] Glavmo, M.; Spadafora, P.; Bosch, R.: Closed Loop Start of Combustion Control Utilizing Ionization Sensing in a Diesel Engine
- [4] Mobley, C.: Non-Intrusive In-Cylinder Pressure Measurement of Internal Combustion Engines. In: SAE Technical Paper Series 1999-01-0544
- [5] Houben, H.; Uhl, G.; Schmitz, H.-G.; Endler, M.: The New Electronically Controlled Glow System ISS for Diesel Engines. In: MTZ (61) 2000, Nr. 10, S. 668-676



BERU Aktiengesellschaft
Mörkestrasse 155,
D-71636 Ludwigsburg
P. O. Box 229,
D-71602 Ludwigsburg
Phone: ++49/7141/132-693
Fax: ++49/7141/132-220
info@beru.de
www.beru.com