CONSEIL INTERNATIONAL DES MACHINES A COMBUSTION

INTERNATIONAL COUNCIL ON COMBUSTION ENGINES

HIGH TEMPERATURE PRESSURE SENSOR BASED ON THIN FILM STRAIN GAUGES ON STAINLESS STEEL FOR CONTINUOUS CYLINDER PRESSURE CONTROL

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ABSTRACT:

This paper describes the design and performance of imes long-life high-temperature thin film strain gauge pressure sensors that have been specifically developed for monitoring of reciprocating compressors, natural gas or diesel engines, and high-pressure fuel systems.

In a robust, durable, and low-cost design imes pressure sensors utilize the principle of thin film layers. Basis is a thin film cell which forms a metal substrate. This is overlaid by insulation layers which form an electrical barrier to the metal. TION (Titanium oxi-nitride, patented) and nickel for the functional layers of the measuring cell , with the result that the substrate can be designed thicker, which in turn has a significant effect on the longevity of the sensor.

Finally, the measuring cells are thermally aged at high temperature. Altogether the sensor is no bigger than a spark-plug.

The most important measured value describing the operation of a diesel or gas engine is cylinder pressure. By constant monitoring of this pressure, as enabled by the imes system, malfunctions and wear can be recognized immediately. Permanent monitoring and control of cylinder pressure is of growing importance.

The test results reported here are obtained from marine diesel engines and natural gas engines . In the longest application to date, many combustion pressure sensors have demonstrated more than 10,000 hours or 500 million pressure-cycles continuous operation. Dynamic pressure sensors for compressor monitoring have already prooven lifetime of more than 1 billion cycles. In compressor applications the sensor typically demonstrates +/-0.5% accuracy while combustion pressure sensor accuracy is +/-1% at calibration temperature. For almost two years a number of indicator valve mounted cylinder pressure sensors have been evaluated for calibration stability showing excellent performance over a 6-month test run period.

INTRODUCTION:

Cylinder pressure is the fundamental variable that determines a combustion engine’s opera-ting state. In particular, combustion pressure information can be used in advanced engine control and monitoring systems, if available continuously and in real-time. Based on cylinder-specific pressure information, closed-loop control applications have been proposed for power balancing in large-bore natural gas engines, lean burn combustion in passenger cars. The most advanced controls each cylinder and each combustion cycle are controlled in what has been termed the Controlled Combustion Engine.

Most of the diesel engine use of cylinder pressure sensors has been, however, in the area of engine balancing and monitoring. Larger diesel engines, typically with 6 or more cylinders, are frequently prone to cylinder to cylinder variability requiring periodic re-balancing and frequent adjustments. In some older marine engines, periodic balancing as frequent as every single month is required to maintain nominal engine operating and emission characteristics.

Recently cylinder pressure monitoring has also become more and more popular in the field of Condition Based Maintenance (CBM) . For the future marine ship owners attempt to eliminate the traditional scheduled maintenance and will go for CBM. Based on cylinder pressure evolution over time various diagnostic and prognostic techniques have been reported leading to early detection of such problems as piston scuffing, overheating, cracking of cylinder heads, fuel injection system failures, or bearing failure.

For new and demanding applications in measuring and control technology more and more sensors employing the thin film technologie are being used. Their major advantage: maximum information content in minimum dimensions, extreme flexibility, high precision and economic production.

In cooperation with STW in Kaufbeuren , Germany, we developed to production readiness a high temperature measuring cell capable of withstanding the extreme conditions prevailing on diesel and gas engines. Our successful cooperation enables us to offer high quality, innovative products for cylinder pressure measurement, incl. hardware and software which open the way to new possibilities in engine control. Among the most important charecteristics of imes sensors are their resistance to wide variations in the temperature of the medium, since temperture on the pressure side of the membrane during the ignition process can reach up to 1700 °C for a few milliseconds. Our aim of developing a high temperature sensor, capable of withstanding to 100 million to a (US) billion full load cycles has been achieved

Until today the widespread use of cylinder pressure based monitoring and control systems has been limited by one important factor: the lack of a cost-effective, reliable, and long lasting combustion pressure sensor. Piezoelectric quartz pressure sensors that have been used for many years in engine development and for calibration, but have not been acceptable for routine implementation in production engines. They are also subject to electromagnetic interference effects, have a limited lifetime, and are unacceptably expensive.

Lower cost piezoceramic devices, such as spark plug washers and boss-type sensors, do not offer high accuracy under all engine conditions, are subject to electrical interference problems, and are prone to large temperature errors. In addition, their durability is not sufficient for use in production engines as a consequence of degrading effects of alloy egregation, selective oxidation, and diffusion.

SENSOR

SENSOR ON THIN FILM TECHNIC

High temperature pressure sensors are required for monitoring the cylider pressure of engines. Commonly used (i.e. quartz pressure sensors) are able to measure the dynamic cylinder pressure with small thermodynamic errors, but these systems are not suited for the high load cycling which accumulates when online measurement is performed.

In addition to the common quality requirements for pressure sensors, such small hysteries, good linearity, and small temperature dependence, the following requirements must also be met:

- The long temperature stability
- The sensor has to withstand temperature peaks in the pressure medium up to 1700 °C (see fig. 1)
- Load frequencies > 10^8 are typical during sensor life.
- The thermal shock error due to extremly fast variations in the pressure medium temperature has to be small(< 0,5 %)

The performance of our developed sensor (product name HTT-01) displays all these characteristics. In addition the sensor is suited for static pressure measurements in other applications such as synthetic material production or applications where extremly high temperatures occurs.

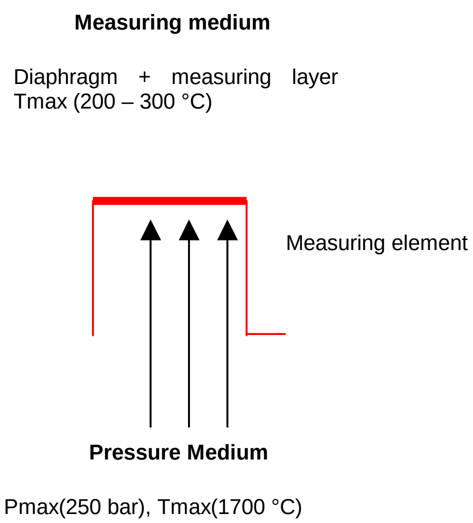

Fig.1: Pressure and measuring side of the measuring cell

CALCULATION OF MECHANICAL PERFORMANCE

FEM (Finite element calculations) had been used for the detailed construction (see fig.2). The bright parts shows high mechanical load, the darker parts shows lower mechanical load.

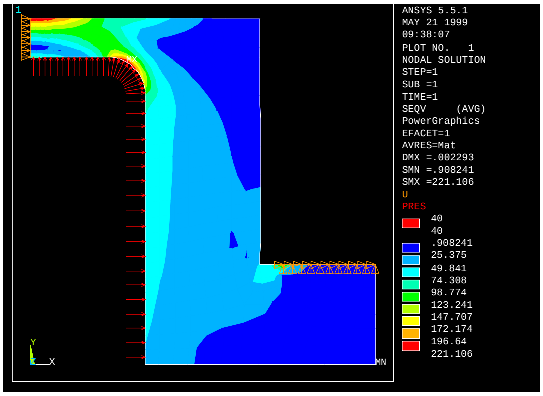

Fig.2: FEM (Finite element calculation)

THIN FILM LAYERS

The sensor consists of a high temperature thin film strain gauge deposited onto a stainless steel diafragm. Prior to deposition the diaphragm is coated with an insulating layer. An additional thin film temperature sensor integrated onto the surface allows the electronic compensation of the temperature of the pressure signal. Figure 4 shows the layout the pattern used, with red areas representing nickel structures and black areas TION (Titan oxy nitrid) structures. The conductor lines of the meander have a width of 40 µm, the diameter of the sensor is 6 millmeters.

a) Insulating layers

First polished surface of the stainless steel diaphragm is coated with a SiO_2 thinfilm deposited by a PECVD process. Such films show very good surface conformity and high thermal stability up to 800 °C (see fig. 3).

b) Thin film strain gauge

As strain gauge material TION was chosen. This material is deposited using a reactive sputtering process. By variation of the nitrogen/oxygen ratio in the sputter gas the temperature coefficient of the resistance (TCR) is adjustable. With an optimized deposition process a variation of TCR of TION resistors of better than +- 20ppm/°C was reached. The specific resistance of such a layer is about 150 µΩcm.

The films are long term stable in air up to 350° C. TION films are patterned using a reactive plasma etching process.

c) Thin film temperature sensor and contact pad material. Nickel is used as temperature sensor and pad material. After a suitable stabilization process nickel has a sufficient long term stability and it can be soldered or bonded easily. Contacting the sensor is thus possible without a third deposition of a contact material (see fig.4)

DIAPHRAGM AND HOUSING

The diaphragm is first welded to the pressure connector part by e-beam welding. Afer bonding the electrical connections, the first housing part is welded to the connector (see fig.5). Then the cables are soldered (max. 600 °C) to the electrical socket. And the second part of the housing, with the socket already in place, is welded to the others. The housing is ware and air tight and can be readily modified for other applications.

SENSOR HTT-01

Sensor (Fig.6 ,7,8) and amplifier electronic are connected via cable and will be calibrated for the temperature and pressure range in our workshop. Any additional calibration during sensor life time is not necessary !

SENSOR INSTALLATION

The sensor can be installed head mounted (see fig. 9) or at the indicator flange (see fig.10).

BENEFIT BASED ON SPECIFIC CYLINDER PRESSURE INFORMATION

- Optimisation of air-fuel ratio
- Optimisation of air-gas ratio
- Balancing of power
- Balancing of Pmax
- Knock detection
- Missfiring detection
- Reduction of NOx
- Reduction of smoke
- Reduction of soot emissions

SENSOR PERFORMANCE

The basic specifications of the pressure sensors currently offered by imes for control and monitoring applications of industrial engines and machinery are summarized below:

Fig. 11 demonstrates the comparison data obtained with a imes sensor on a twelve cylinder MTU 4000 gasengine at the indicator channel. A water-cooled, indicator channel mounted research-grade piezoelectric transducer (Kistler 6061) was used as a reference.

The data presented in Fig. 11 were obtained with a sensor designed for nominal (300 bar) pressure range. The measurement and reference traces are normalized so their peak-to-peak values are equalized. Compared to the full-scale output of approximately 100 bar, +/-0.25% accuracy was recorded, including linearity, hysteresis, repeatability, and thermal shock.

The data obtained on a large-bore two stroke diesel engine is shown in Fig.12 ,13 comparing the performance of imes sensor against a watercooled Kistler 7061. Both sensors were mounted in a indicator flange. Note excellent linearity, hysteresis, and thermal shock performance of +/- 0,5% of imes uncooled sensor.

Over the last year several hundred of our sensors have been subject to durability and calibration stability tests in natural gas and diesel engines as well as on gas compressors and fuel injection pumps. Many of these sensors have demonstrated up to date durability exceeding 500 Million pressure cycles or 10,000 hours.

In addition to the endurance tests, during the last year tens of sensors have been subjected to long-term calibration stability tests. Periodically, every few to several months, imes sensors were recalibrated using air or water-cooled reference transducers. During a 6 to 12 month period the sensors demonstrated excellent calibration stability (compared to the initial values), ranging from a non-detectable to +/-0.1% change in the sensor sensitivity value.

SUMMARY AND CONCLUSIONS:

In a robust, durable, and low-cost design imes pressure sensors operate on the principle of thin film layers. When optimized for high linearity, signal level, and modulation, the sensor demonstrates accuracy comparable to that of a laboratory-grade piezoelectric sensor.

For combustion engine applications the sensor can be either directly inserted into an engine head, Kiene valve or indicator flange. At constant temperature the sensor accuracy is typically +/-0.25%; under combustion conditions the combined sensor's hysteresis, non-linearity, and thermal shock effects result in pressure reading accuracy of +/-1% to +/-2% full-scale output.

For head-mounted or indicator channel combustion applications the warranty is extended to unprecedented 500 Million pressure cycles.To date, hundreds of Kiene valve or at the indicator flange mounted sensors have demonstrated the lifetime of at least 10,000 hours and over 500 Million pressure cycles. The sensors have also demonstrated an excellent calibration stability, better that 0.1%.

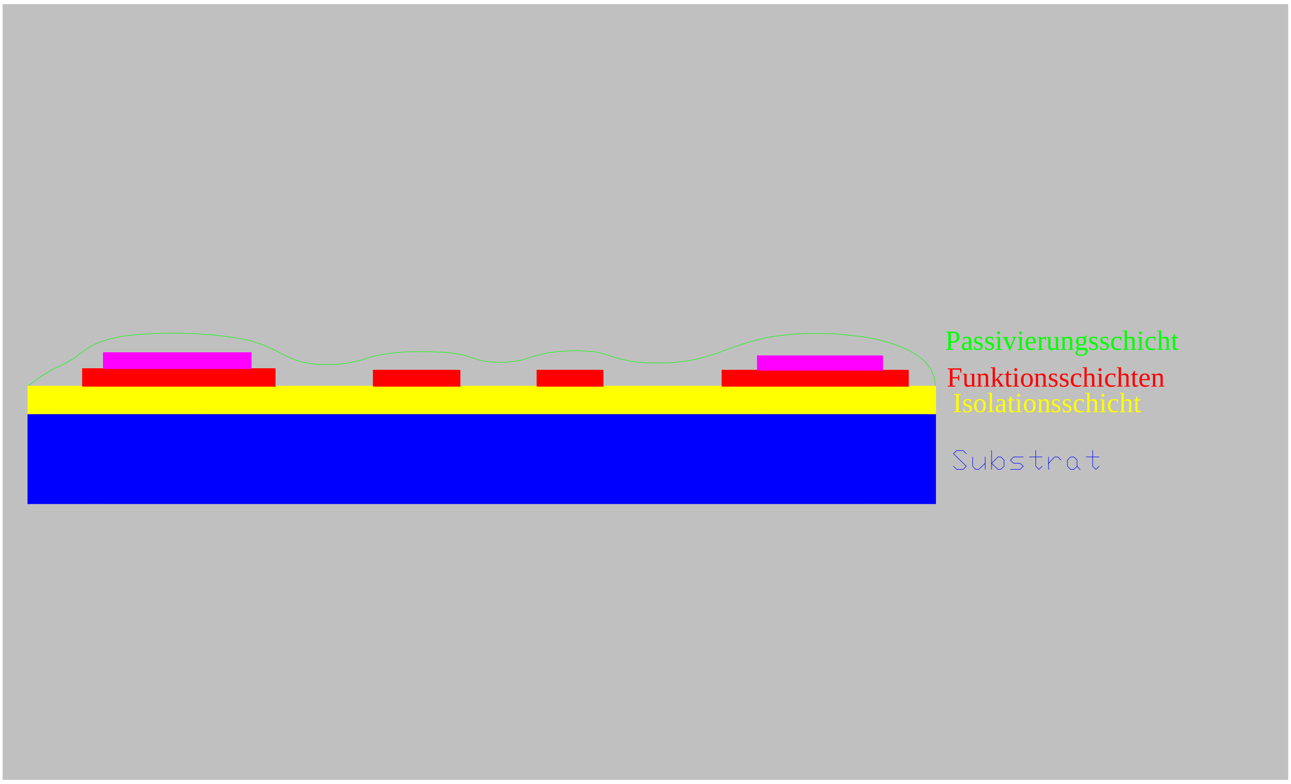

Fig. 3: Thin film layers (Diaphragm with isolation and function layers)

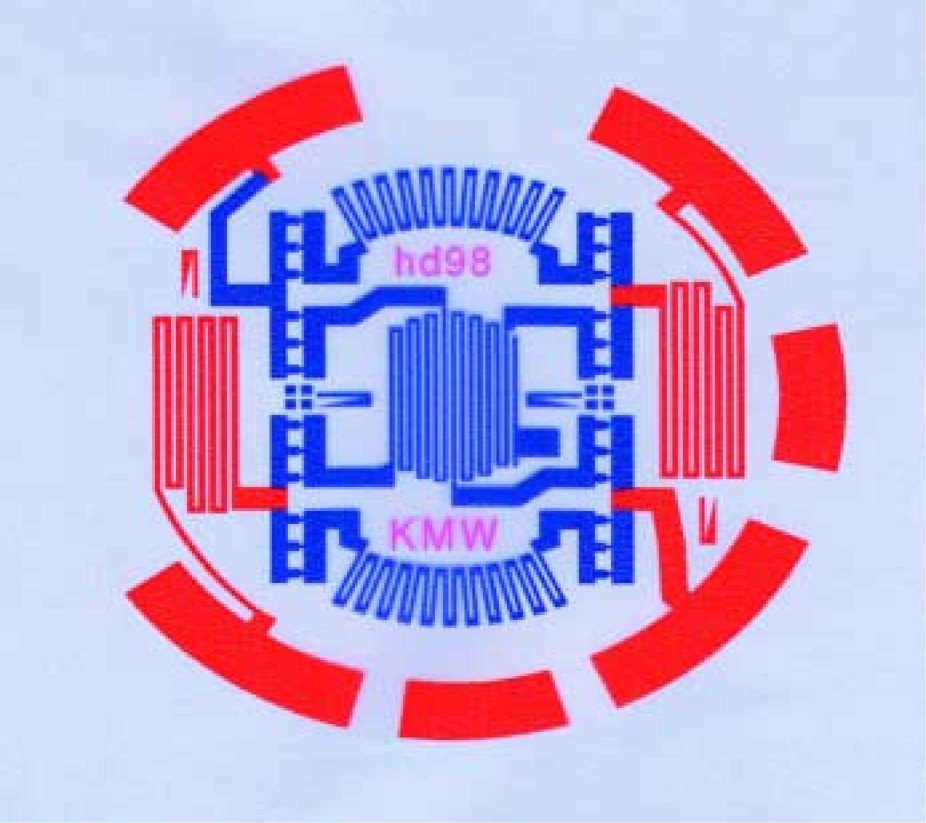

Fig.4: Layout of the pattern

Fig.5: Thin film structures of a bonded measuring cell.

Fig.6: Sensor housing with thread M14x1,25

Measuring range pressure	bar	0...300, others on request
Overload pressure	bar	800
Load cycles		>10^8 Full load cycles
Frequency range	kHz	20
Accuracy at balancing temperature	%	+/- 1
Sensor housing temperature	°C	max. 300
Supply voltage	VDC	18...30
Output signal pressure	mA	4...20
Output signal temperatur	mA	4...20
Electrical connector		Plug connection M12
Thread		M14 x 1,25 ; others on request
Type of protection		IP 65
Dimension sensor	mm	65 x ∅ 18 ; SW 19
Dimension electronic	mm	100 x ∅ 17
Tightening torque	Nm	25
Weight incl. electronic	g	250

Fig. 7: Technical data cylinder pressure sensor HTT-01

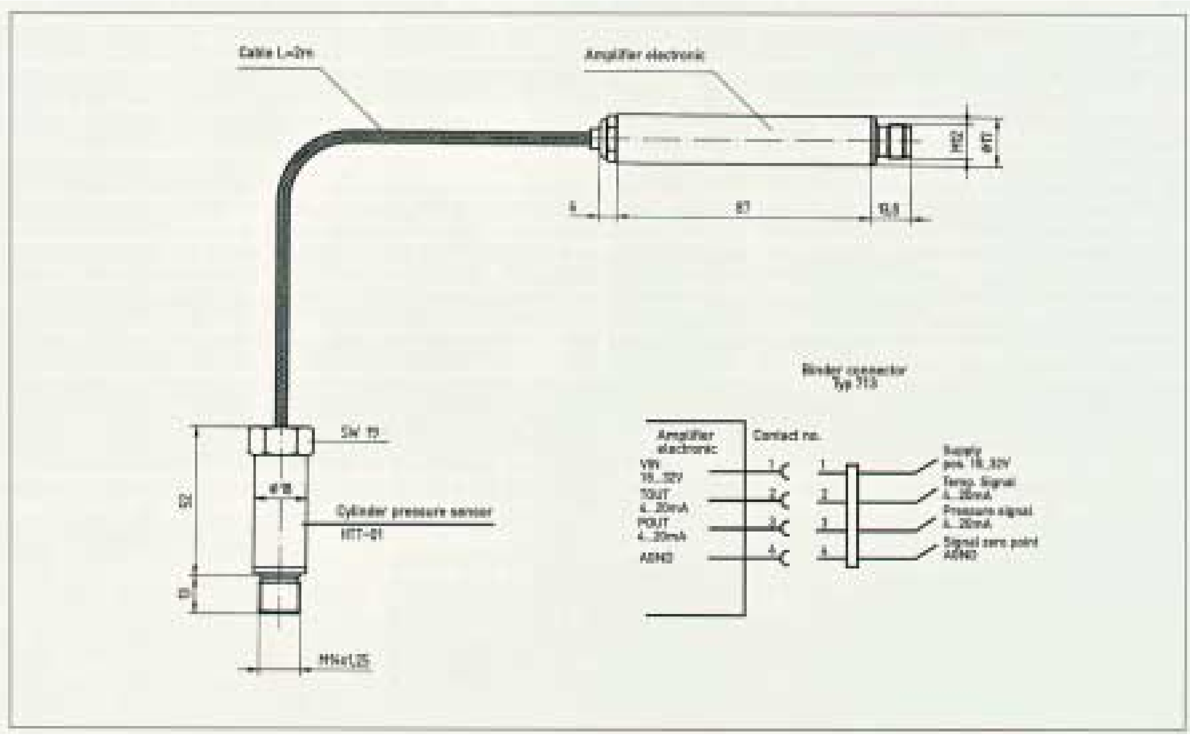

Fig.8: Drawing cylinder pressure sensor HTT-01 incl. amplifier unit

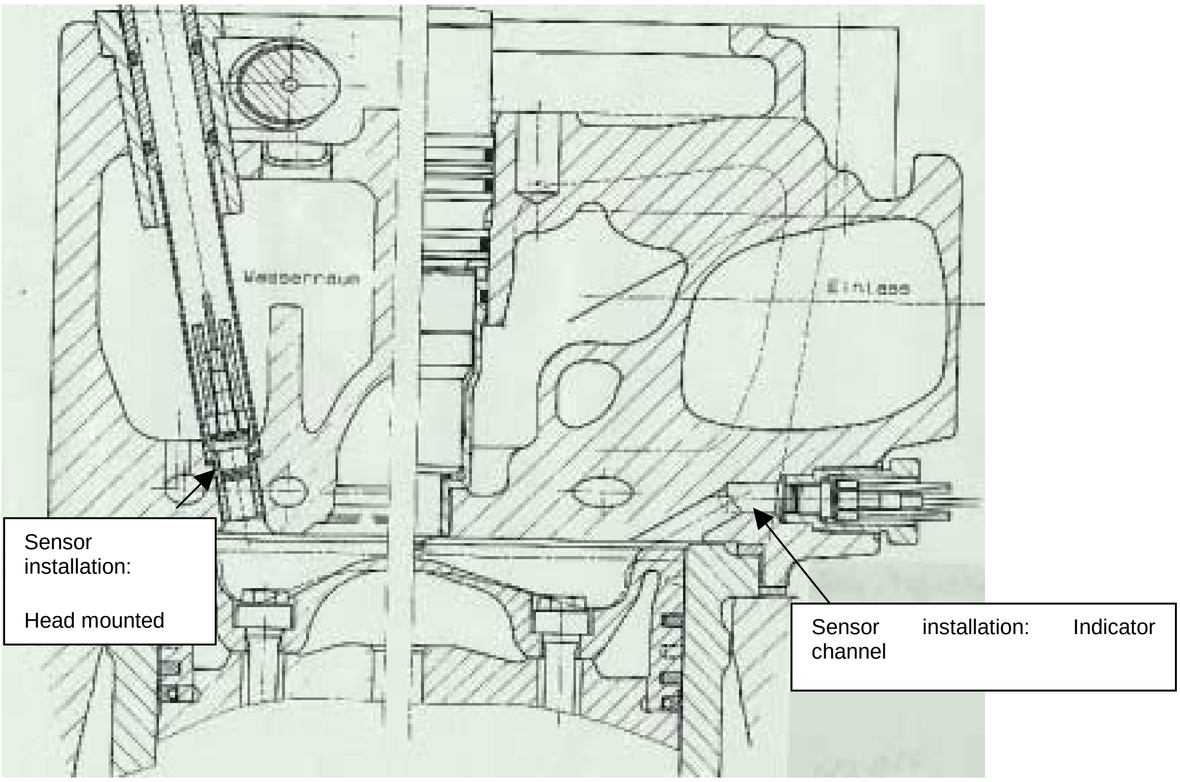

Fig.9: Sensor installation on a 4-stroke Diesel engine

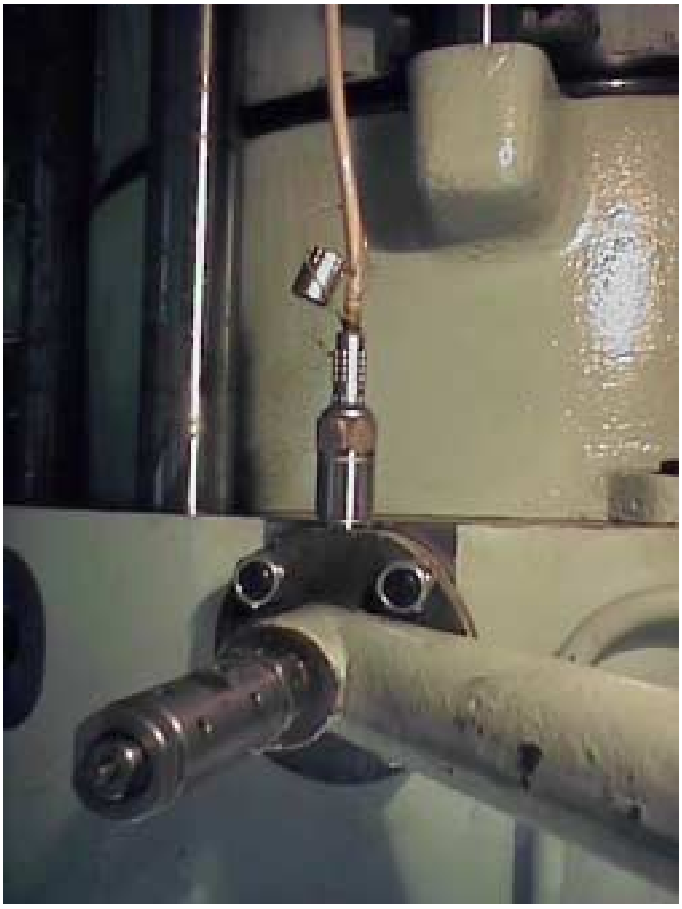

Fig.10: Sensor installation on a 2-stroke engine (Indicator flange)

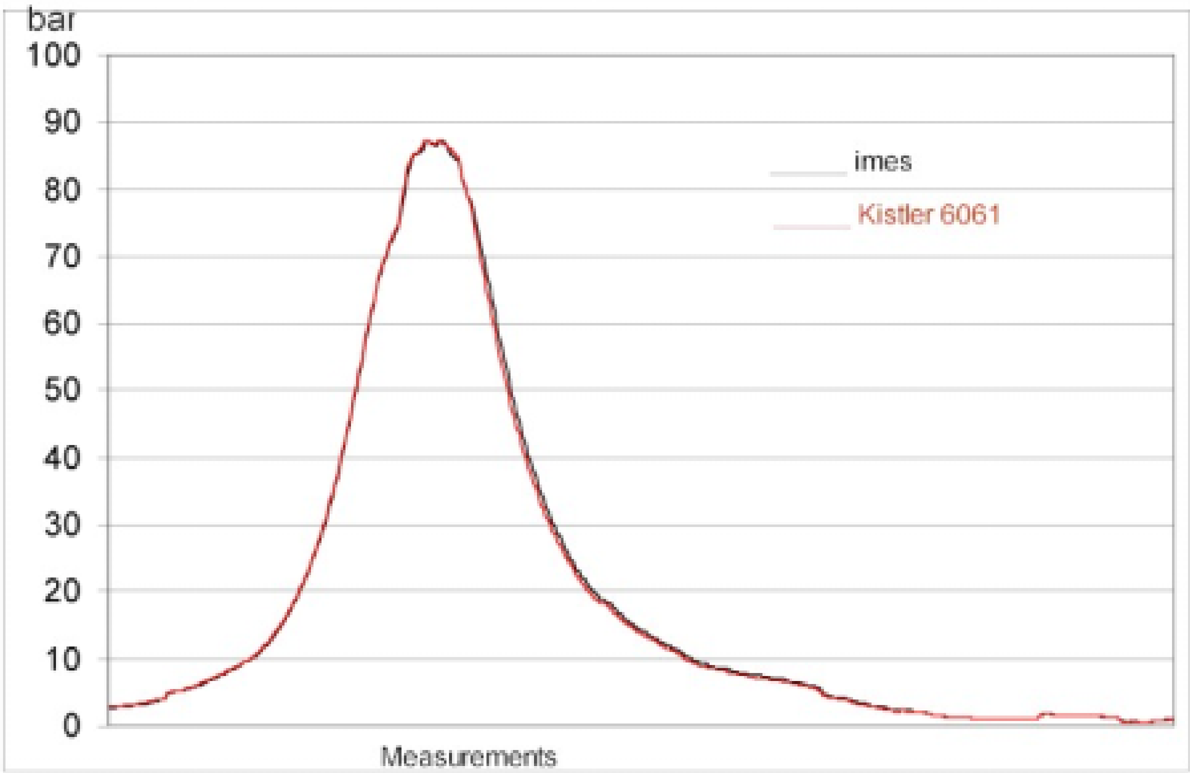

Fig.11: Comparison imes/Kistler at MTU Gasengine 4000 (1500 RPM)

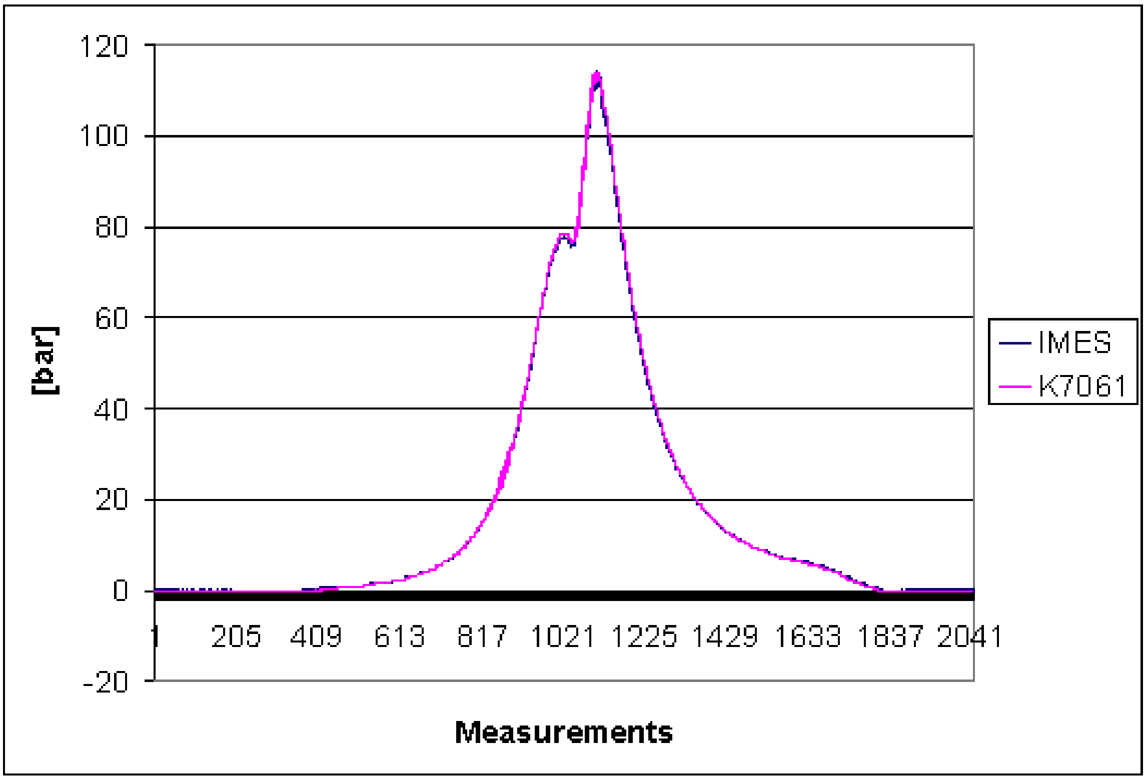

Fig.12: Comparison imes/Kistler at MAN B&W 6 L70 MC

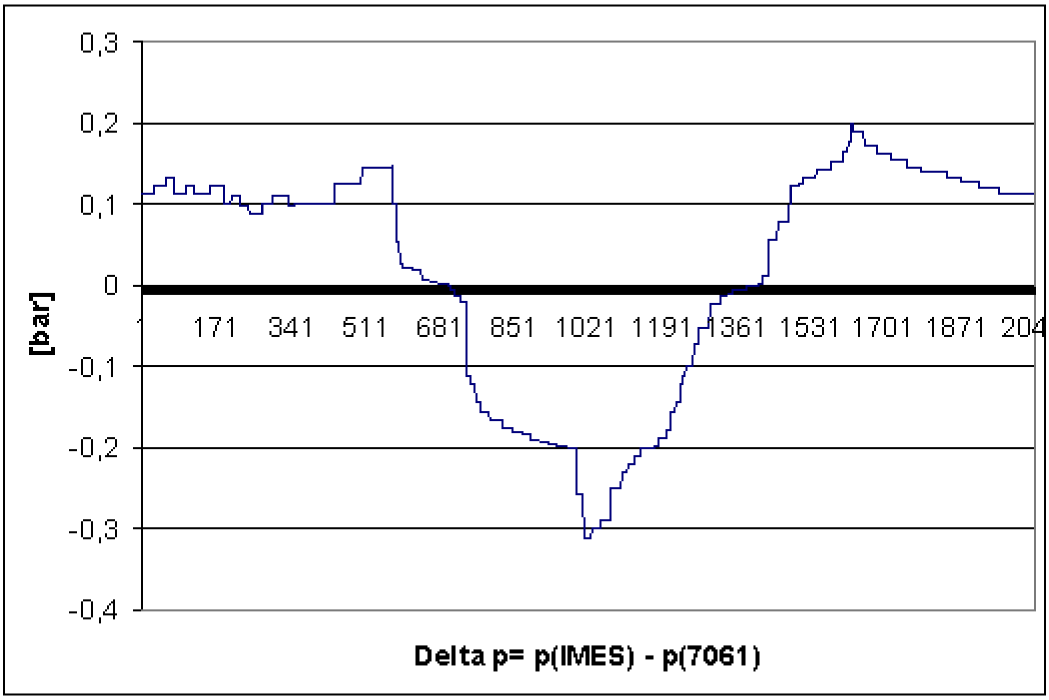

Fig.13: Comparison imes/Kistler