GLOW PLUG INTEGRATED CYLINDER PRESSURE SENSOR FOR CLOSED LOOP ENGINE CONTROL

Marek T. Wlodarczyk

Optrand, Inc.
46155 Five Mile Rd.
Plymouth, MI 48170, USA
tel.: (734) 451-3480 fax: (734) 451-2945
e-mail: president@optrand.com

Abstract

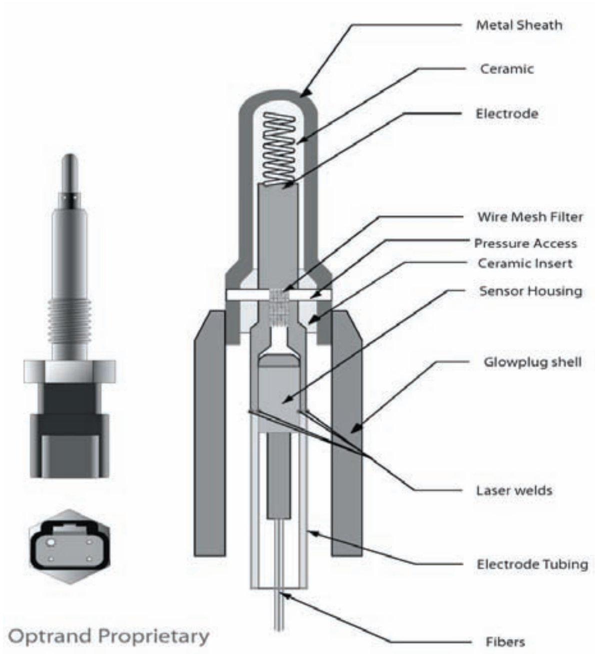
The PressureSense Glow Plug^{TM} combines a miniature fiber optic-based cylinder pressure sensor with the automotive glow plug. The 1.7mm diameter sensor is sealed inside a glow plug heater and the sensor signal conditioner is encapsulated into a "smart connector". The sensor operates on the proven principle of light intensity changes, transmitted by two optical fibers, upon reflection from a deflecting metal diaphragm. The sensor materials, dimensions, and the assembly technique are optimized to compensate for diaphragm deflection dependence on temperature associated with engine load changes. The device is compensated for all major environmental factors encountered under the hood of an automobile including LED and photodiode temperature dependence and aging, fiber-to-opto-electronics coupling fluctuations, and vibration and humidity effects. Under combustion conditions the sensor offers the total accuracy of +/-1.5% over the projected sensor life of 10 thousand hours. Such high sensor accuracy allows advanced closed loop control strategies for diesel and HCCI engines based on real time computations of Indicated Mean Effective Pressure (IMEP) and mass fraction burned. These control strategies have been shown to result in as much as 12% reduction in NOx emissions and 15% of particulate emissions in a closed loop controlled diesel engine versus its conventional counterpart.

1. Background

Cylinder pressure is the fundamental engine parameter that provides the most direct and valuable information for advanced control and monitoring systems of internal combustion engines [1]. Such systems are presently developed by numerous engine manufacturers in order to meet the emission regulations that currently affect with a varying degree of severity all types of engines including those used in passenger cars, trucks, off-road vehicles, watercrafts, ships, and locomotives as well as stationary engines used in gas and oil pipelines or electricity generation. Diesel engines in particular can significantly benefit from cylinder pressure-based controls resulting in reduced harmful emissions, lover engine noise levels, better fuel economy, and drivability. Recently, 15% and 12% reduction in soot and NOx emissions, respectively, were demonstrated due to closed loop control of fuel injection based on information provided by pressure sensors located in all cylinders [2]. In diesel passenger cars and light duty trucks a preferred way of introducing a pressure sensor into a combustion chamber is through a glow plug so no engine head modifications are required.

2. Device description

The PressureSense Glow Plug^{TM} (PSGP) combines a miniature, high temperature cylinder pressure sensor and a glow plug used in passenger car diesel engines. Figs. 1 and 2 show the PSGP designs targeted for production engines based on a conventional glow plug with a metal sheath heater and a ceramic glow plug, respectively. The 1.7mm diameter fiber optic-based sensor is welded into the heater electrode having a pressure passage to guide combustion gasses to the sensor diaphragm. Due to the location of the pressure access orifice in the mid section of the glow plug heater the device “self-cleans” during glow plug activation; when the pressure passage temperature reaches the temperature of ~650^{o}C deposits burn off. The sensor signal conditioner is encapsulated in an automotive-like connector directly attached to the glow plug body with 3 smaller sensor pins and the fourth (largest) pin dedicated to the glow plug heater.



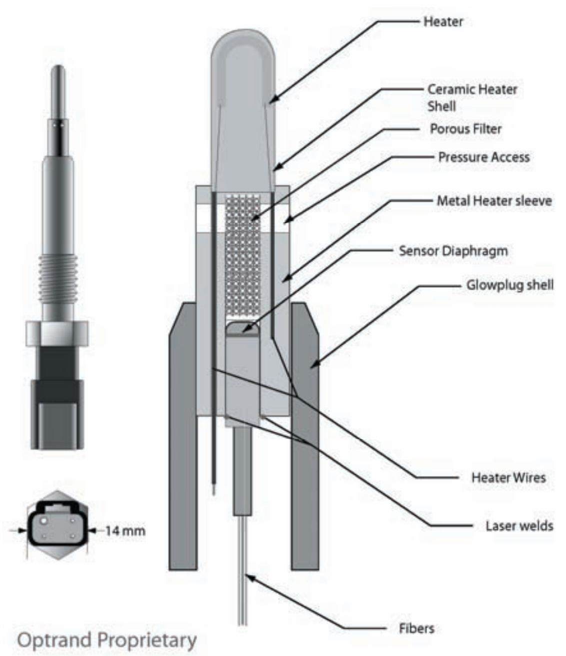


Fig. 1. PSGP based on metal sheath heater

Fig. 2. PSGP based on ceramic heater

Since the designs shown in Figs. 1 and 2 are not yet in mass production, prototype devices have been used in engine tests and development of closed loop engine control strategies. Fig. 3 shows a “dummy” PSGP, which has the glow plug dimensions but does not have a heater while Fig. 4 shows a picture of a fully functional PSGP.

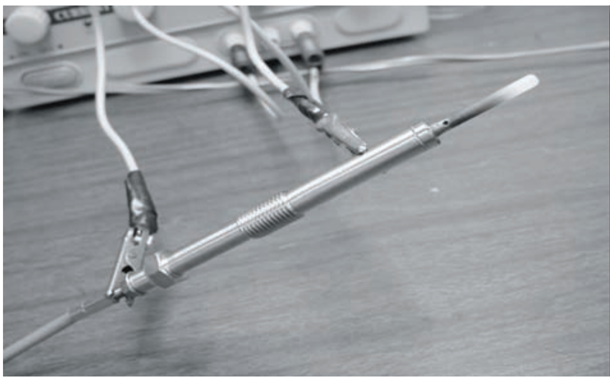
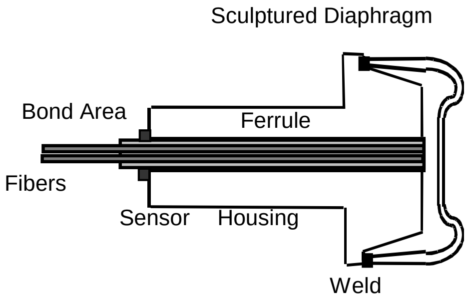


Fig. 3. Prototype “Dummy” PSGP

Fig. 4. Prototype fully functional PSGP

The pressure sensor used in the PSGP consists of three basic components: a sensing head, a fiber optic cable, and a signal conditioner, as shown in Fig. 5 and Fig. 6.



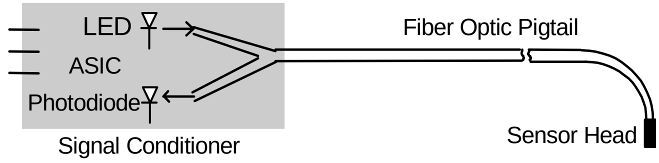


Fig. 5. Schematic sensor construction

Fig. 6. Sensor head construction

The sensor head contains stainless steel housing with a welded Inconel diaphragm, a metal ferrule welded into the housing, and two fibers bonded inside the ferrule, as schematically shown in Fig. 6. The mass production PSGP version has a miniature signal conditioner that contains just two parts: a custom LED-photodiode transceiver and an Application Specific Integrated Circuit (ASIC). In order to meet the automotive reliability, performance, and cost targets the optical fibers are permanently bonded to the LED and photodiode chips.

The sensor's response results from diaphragm displacement due to pressure that changes the intensity of an optical signal transmitted from the sending to the receiving fiber [3]. The diaphragm shape and material have been selected to meet the requirement of maximum sensitivity at acceptable non-linearity, low creep, and fatigue life of hundreds of millions of pressure cycles. The sensor is compensated for all major temperature effects encountered in combustion engines: (1) long time-constant effects, of the order of minutes, are associated with varying under-hood engine temperatures ranging from –40^{o}C to 150^{o}C. Such changes result in changing the LED output, which if not compensated for will lead to errors as large as tens of percent. In addition, the LED output degrades at elevated temperatures. (2) Medium time-constant effects, of the order of a few seconds, are associated with increased diaphragm deflection during increased engine load (due to increase in diaphragm temperature). (3) Short time-constant effects, of the order of several milliseconds, are associated with diaphragm distortion due to exposure to combustion gasses.

The long-term errors, both in the signal conditioner and the sensor tip areas, are compensated by the Auto-Reference circuitry [3]. This circuitry continuously regulates the LED light intensity in such a way that the minimum sensor output (offset) is maintained at a constant level over the sensor life resulting in constant sensor sensitivity. The mid-term error compensation relies on the auto-referencing technique and an optimum selection of sensors components' thermal expansion coefficients and dimensions. Through an intentional increase in the distance between the diaphragm and the fibers with increasing sensor temperature, the resulting reduction in sensor electronic gain compensates for the diaphragm's deflection increase with temperature. Finally, the short time constant error is minimized by the small heat flux that the diaphragm is exposed to due to the small diameter of the pressure passage, a wire mesh filter, and the low average sensor temperature resulting from the sensor location close to the glow plug sealing surface.

3. Specifications and performance

The PressureSense Glow Plug targets engine control and monitoring applications that require high absolute accuracy. Basic specifications of the device intended for production engine applications are summarized in Table 1.

Table 1. PressureSense Glow Plug sensor specifications

Pressure range:	0 - 200 bar
Over-pressure range:	Minimum 1.5x pressure range
Accuracy (under all operating conditions)	+/-1.5% of reading above 5bar
Accuracy (under all operating conditions)	+/-0.2 bar below 5bar
Frequency response:	0.1-1Hz to 10-20 kHz
Temperature Coefficient of Sensitivity	< 0.01%/ºC
Sensor diameter:	1.7 mm
Signal to Noise Ratio (@ 20 kHz)	1000:1
Sensor housing continuous temperature:	-40ºC to 380ºC
Connector continuous temperature range:	-40ºC to 150ºC
Sensor Output:	0.5(0.3)V - 4.5 (3.5)V
Power supply	5v, 20mA max current
Life time:	10k hours or 500 Million cycles
Glow plug type/thread	Metal sheath or ceramic/M8 to M14

Figs. 7a and 7b demonstrate typical performance of the device as tested on a single cylinder genset engine. Kistler 6061water-cooled piezoelectric transducer was used as references. As seen in Figs. 7a and 7b the sensor demonstrates excellent linearity and minimum thermal shock error. It is to be noted that the pressure response show some small “ringing” effect due to the PSGP pressure passages. However, this ringing can be easily filtered as the characteristics frequencies of interest in diesel engines are below the ringing frequency.

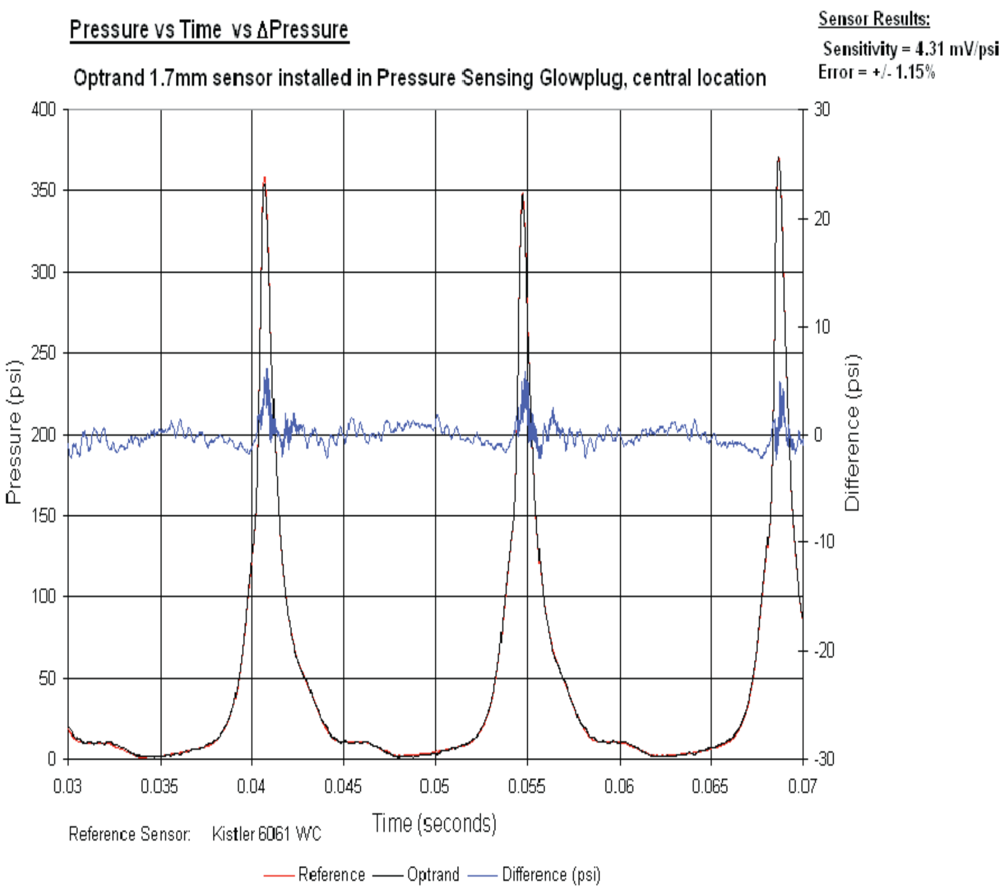


Fig. 7a. Pressure vs. time performance comparison

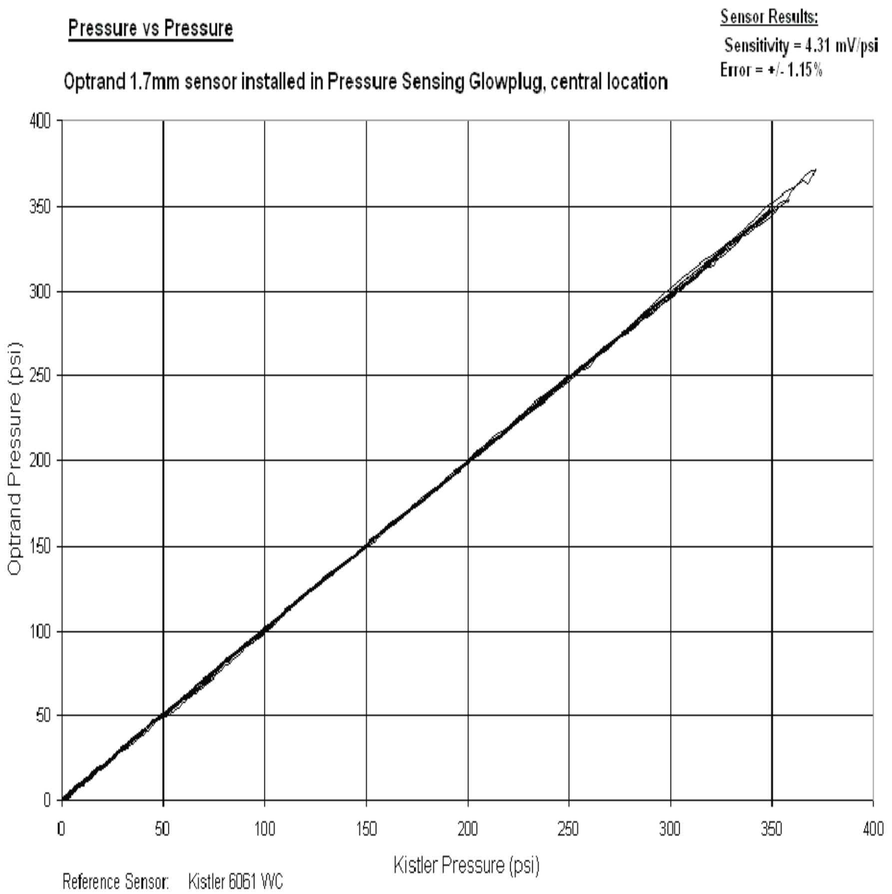


Fig. 7b. Pressure vs. pressure comparison

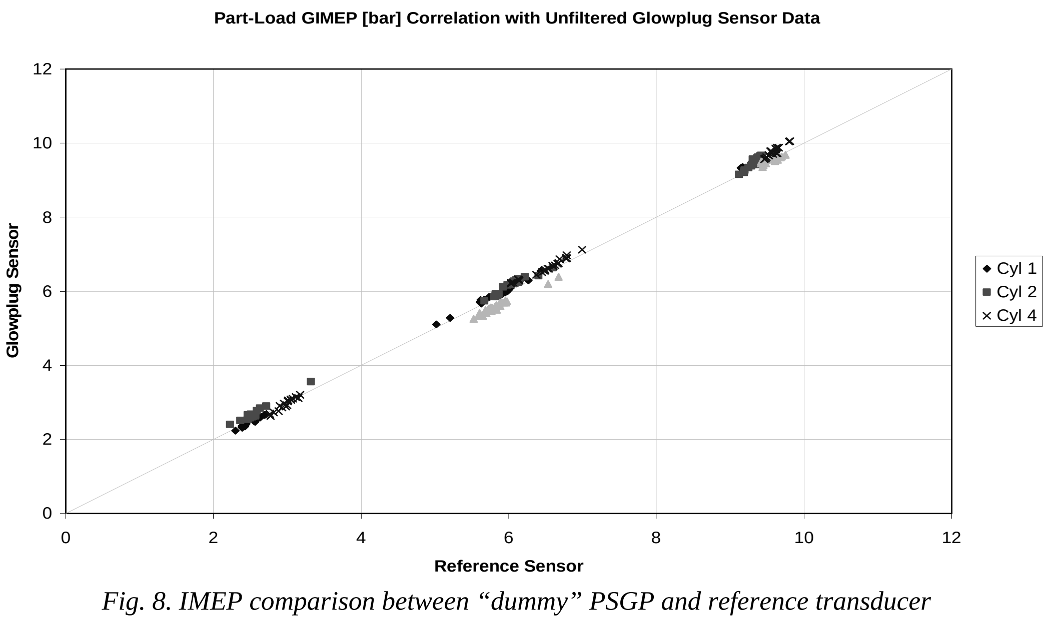


Fig. 8. IMEP comparison between "dummy" PSGP and reference transducer

Figs. 8 and 9 show the comparisons between the Indicated Mean Effective Pressure and 50% burn rate values calculated based on the dummy PSGP output versus the values obtained with the Kistler 6053 reference transducer. The data was collected in all four cylinders of a 1.9l common rail passenger car diesel engine. Notice that in spite of some small ringing of the PSGP traces the accuracy of the calculated values is exceptionally good, within 1% of the values obtained with the reference transducer.

Prototype PSGPs have been used by several engine manufacturers in their development of closed loop control strategies for diesel engines demonstrating significant soot and NOx reduction and other significant benefits [2]. The durability and reliability of the device has been validated over a 4-year period of in-vehicle on-road use. In the longest durability tests so far close to twenty non-glowing devices have been used over 500 hours without any performance degradation or soot fouling. Durability testing of the glowing PSGP prototypes is underway. In addition, a prototype PSGP based on a ceramic heater is currently under development.

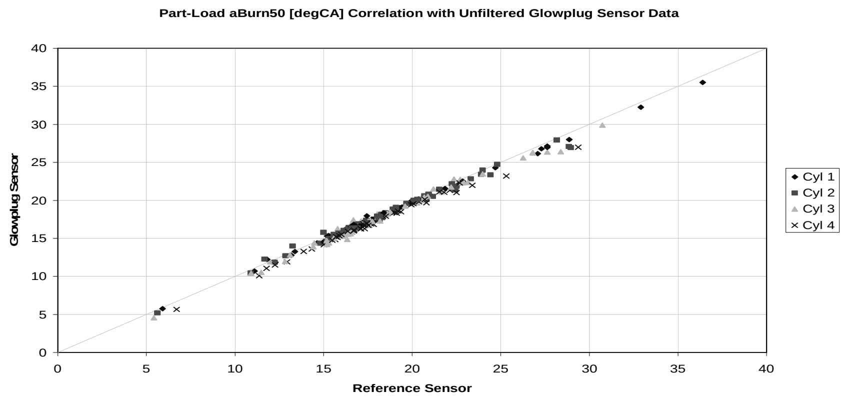


Fig. 9. 50% mass fraction burned comparison

4. Summary and conclusions

The PressureSense glow plug combines a 1.7mm diameter cylinder pressure sensor and a glow plug in one, higher functionality device. A dual fiber based dynamic sensor utilizes the proven principle of reflected light intensity changes due to flexing metal diaphragm. The sensor's miniature signal conditioner contains a photodiode, an LED, and associated electronic circuitry combined in an ASIC encapsulated in a 4-pin automotive-like connector. The auto-referencing technique maintains sensor calibration by compensating for the signal conditioner temperature and aging effects over the range of –40° to +150°C. The sensor head materials and dimensions are optimized to compensate for engine load related errors resulting in the thermal coefficient of sensitivity of +/-0.01%/°C. The glow plug integrated sensor offers unprecedented total accuracy of +/-1.5% against a water cooled reference transducer at pressures above 5 bars and less than 0.2 bar error for pressure below 5 bars. In the longest durability tests so far some non-glowing devices have been used over 500 hours without any performance degradation or soot fouling. The work remaining is to demonstrate long term durability of the device with a functioning glow plug heater and based on a ceramic heater. The first use of the PressureSense Glow Plug in production engines is expected in 2008.

References

[1] Sellnau M., Matekunas F. A., Battiston P. A., Chang C. F. and Lancaster D. R., "Cylinder-Pressure-Based Engine Control Using Pressure-Ratio-Management and Low-Cost Non-Intrusive Cylinder Pressure Sensors," SAE Paper No. 2000-01-0932, 2000.

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[3] Wlodarczyk M. T., "Fiber-Optic Pressure Sensor for Automotive Engine Controls," Proceedings of SPIE 3000, pp. 51-59, 1997.

[4] Ulrich R., Wlodarczyk and Wlodarczyk M. T., "High-Accuracy Low-Cost Cylinder Pressure Sensor for Advanced Engine Controls," SAE paper No. 2001-01-0991.