

Geometric and Topological Considerations to Maximize Remotely Mounted Cylinder Pressure Transducer Data Quality

Gary J. Patterson*

General Motors Corporation, GM Racing

Richard S. Davis

General Motors Corporation, GM Powertrain

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ABSTRACT

The piezoelectric cylinder pressure transducer is ubiquitous for developing and optimizing the combustion process in modern internal combustion engines. Over the past three decades, significant advances in cylinder pressure transducer technology and enormous advances in digital computing sophistication have made the acquisition and analysis of engine cylinder pressure the cornerstone diagnostic tool for today's engine combustion community. Such improvements in the ease of acquiring cylinder pressure based metrics have, in many instances, fostered the assertion that the transducer is faithfully indicating the actual in-cylinder pressure. Careful analysis, however, can uncover anomalies in the cylinder pressure data quality resulting from thermal shock [1].

Randolph [2] laid the foundation for General Motor's pursuit of remotely mounted piezoelectric cylinder pressure transducers, with fresh approaches to connecting passage design and the thermal protection of the transducer diaphragm. This paper builds on that foundation by introducing additional parameters affecting thermal shock. The effect of cylinder pressure increasing after flame arrival at the transducer passage is a primary factor assessed. These new techniques have been applied to combustion system development programs in the pursuit of research quality data for general spark-ignition engine development, and have

improved our cylinder pressure data quality as an organization.

The concept of radius fraction burned as a technique for the topological accounting of the propagating flame front, and its interaction with the connecting passage and transducer cavity volume is introduced. Simplified analysis techniques to allow the combustion engineer to select appropriate mounting locations and thermal protection treatments are presented. Comparison of the simplified estimation to VisioTomo and Ion Probe Head Gasket data are also shown.

The critical volume ratio between the flame shield passages and transducer tip cavity as a function of in-cylinder pressure at flame arrival divided by peak cylinder pressure is also developed as a technique to prevent hot burned gas products from contacting the transducer face. Characteristic contour plots are presented to guide the combustion engineer to an optimized measurement installation based on combustion phasing and sensor location.

Transducer selection and evaluation is limited to mounting packages that can be readily applied to modern, automotive SI engines. But, in our corporate experience, it is still possible to produce reference quality data with proper transducer mounting. The concepts herein should be applicable to any in-cylinder pressure measurement situation with a propagating flame.

* Current affiliation for Gary J. Patterson: AVL North America, Inc., Plymouth, MI

INTRODUCTION

Inaccuracies in measured cylinder pressure from thermal shock induced intercycle drift have been well documented throughout the history of engine indication and, despite decades of continuous improvement, still represent a challenge for today's combustion engineer. Comparison of different operating conditions and technologies become clouded by thermal shock-induced trends which may not reflect the true change in engine performance. The desire to further improve engine efficiency and reduce exhaust emissions has focused further attention on in-cylinder pressure based combustion metrics for real time operation optimization with technologies such as spark ignition direct injection (SIDI) and variable camshaft phasing. The de rigueur standard for pressure sensing elements utilizes the piezoelectric effect of crystals which have the advantages of small size, high frequency response, and relative insensitivity to temperature, barometric pressure and relative humidity. However, currently available cylinder pressure transducers do suffer from intracycle sensitivity shifts as the temperature of the transducer diaphragm changes due to the combustion event.

Most recent work [8, 9 and 10] has focused on modeling the thermal strain of the pressure transducer diaphragm, and applying correction algorithms to correct for thermal shock after digitization. However, this paper will focus instead on mounting techniques that will improve data quality to the point that reference grade cylinder pressure data is measured up front, with a minimum of inconvenience.

The ideal cylinder pressure measurement system is accurate throughout individual cycles and from cycle-to-cycle and day-to-day. It does not interact with the combustion event in the cylinder, is easy to maintain, insensitive to vibration and dirt, and does not consist of small, intricate parts. It should also be relatively inexpensive and durable. This is not, of course, the current state of the art, where the accurate measurement of cylinder pressure is laborious, tedious, and often involves accessories with very small passages that require frequent cleaning. This paper will not change all of these realities, but it will provide a roadmap to follow if the reader is willing to invest due diligence to reap the rewards of accurate cylinder pressure data.

HYPOTHESIS DEVELOPMENT

The average temperature of a thermally protected cylinder pressure transducer will vary from ~100°C at light load to ~200°C at WOT for an engine with 90°C coolant temperature, and may exceed 500°C for non protected flush mounted transducers. Figure 1 shows average transducer temperature recorded with a thermocouple installed in a commercially available, non-water cooled piezoelectric transducer over a range of part- and full-load operating conditions. The data was generated using different mounting schemes with the same transducer mounting location. This shows that

thermal protection reduces the heat load on the transducer face, with a subsequent reduction of the peak instantaneous heat flux into the transducer assembly.

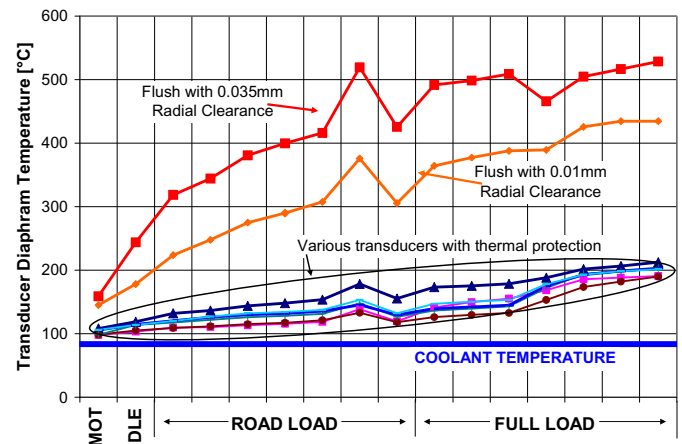


Figure 1: Transducer operating temperature as a function of operating condition and mounting scheme

If burned and unburned gasses within the combustion chamber are considered separately, it follows that there is some temperature rise in the unburned gasses due to the pressure rise that closely obeys the ideal gas law, with the burned gas temperature being much higher (and also changing with pressure). Typical values for burned and unburned gas temperatures versus crankshaft position for road-load with MBT timing, WOT with MBT timing, and WOT with typical knock limited (borderline) timing are shown in Figures 2 and 3.

It is well documented [19] that the peak temperatures of the first gasses to burn are up to 300°C hotter than the gasses that burn in the middle and towards the end of the combustion event. This results from the fact that as the early gasses combust, they expand considerably which effectively removes energy from these burned gasses. As additional heat is released from combustion of the remaining charge, energy is added to these initial combustion products, raising their temperature significantly higher than they would have otherwise obtained. The net effect is that the gasses that are burned prior to peak cylinder pressure being reached will achieve a higher peak temperature than the mixture that burns as cylinder pressure is falling. The authors point this out only to introduce the idea that it is beneficial to mount the transducer away from the ignition source in the end gas region.

It is apparent from Figures 1, 2 and 3 that the peak burned gas temperature is over 2000°K hotter than the transducer, while the unburned gasses are only 200°K to 350°K hotter. Considering this temperature difference and its effect on transient temperature of the transducer tip, it is clear that if the transducer tip can be isolated from the burning and burned gasses that thermal shock can be significantly reduced.

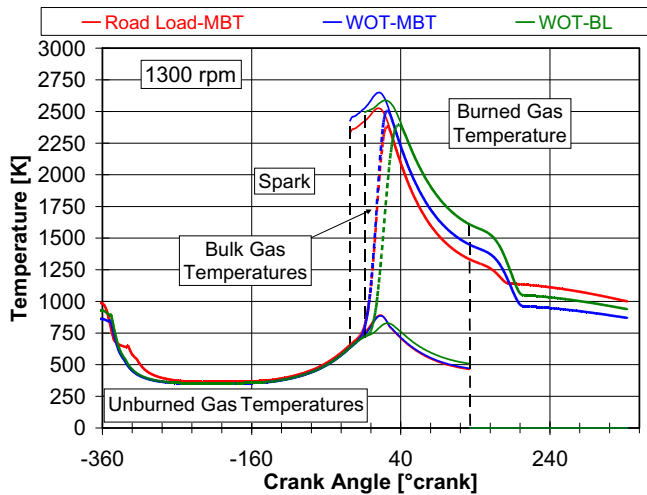


Figure 2: Typical Burned and Unburned Gas Temperatures versus Crank Angle; various operating conditions

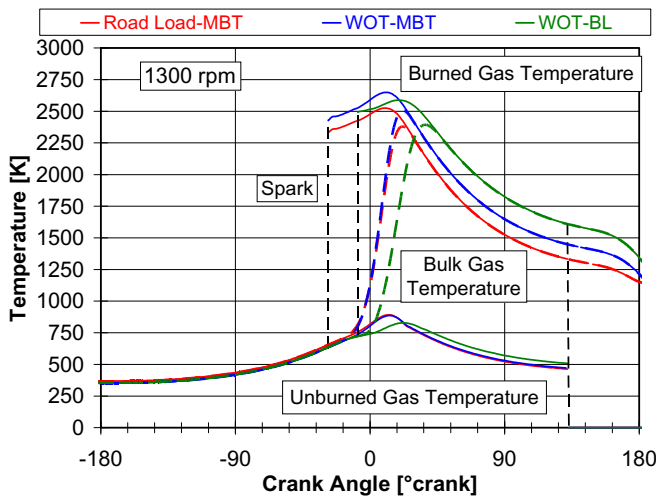


Figure 3: Typical Burned and Unburned Gas Temperatures versus Crank Angle during combustion; various operating conditions

What is not as immediately apparent is that the ability of the connecting passage to quench a propagating flame is not enough to preclude very hot gasses from reaching the transducer. It is possible for burned gasses to be fluid-mechanically transported through the passage onto the transducer's face due to the increase of in-cylinder pressure after the flame front has passed the transducer location. For a connecting passage(s) to preclude the impingement of hot gasses on the transducer face, it must have a volume sufficiently large relative to the transducer cavity volume to contain all burned (and burning) gasses that are compressed into it after the flame traverses the passage entrance. This critical volume ratio is approximately defined according to the relationship:

$$\left(\frac{V_p}{V_{cr}} \right)_{crit} = \left(\frac{P_{max}}{P_{FA}} \right)^{1/1.32}$$

Where V_p is the passage volume, V_{cr} is the transducer cavity or crevice volume (as shown in Figure 4), P_{max} is the peak cylinder pressure, and P_{FA} is the in-cylinder

pressure at the time the flame front arrives at the passage entrance. The relationship is developed on the premise that the volume of gas in the passage at the time of flame arrival must first be completely displaced into the transducer cavity before burned gasses can reach the transducer cavity. This analysis assumes that the thermal protection design is effective in quenching the flame propagation into the passage. It should be noted that this relationship only applies if the cylinder pressure is rising when the flame front arrives at the passage entrance. The optimal, highly desirable situation is to have the flame arrival at the transducer passage occur after peak pressure. See section labeled SPECIAL CASE: CYLINDER PRESSURE DROPPING AT TIME OF FLAME ARRIVAL for details.

While this paper does not attempt to cover the specifics of transducer mounting passage design, it is important to note that there are other consideration and requirements that need to be met in addition to the critical volume ratio and the effective quenching of the flame propagation. Principal among these is the frequency response characteristics of the passage which must be high enough to not significantly phase shift or attenuate the pressure seen by the transducer. For example, while the critical volume ratio and flame quenching requirements could be met by using a very long passage, this would impair the frequency response of the system.

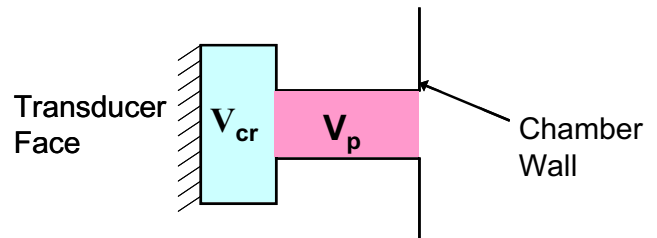


Figure 4: Schematic of remotely mounted transducer passage volumes

To apply the above critical volume relationship, it is required to determine at what point in the cycle the flame front reaches the passage entrance. This could be done empirically by installing an ionization sensor in the transducer mounting port or by using an Ion Probe Head Gasket (IPHG) and a Fiber Optic Spark Plug (FOSP) with appropriate analysis software to visualize the advancing flame front [20, 21] or by measuring light intensity such as with VisioTomo [22] as shown in Figure 5. This is a substantial undertaking if good cylinder pressure data is all that is desired. Alternately, a Computational Fluid Dynamics model with representative combustion visualization could be utilized to yield similar information. But this level of analysis is not always available for the specific combustion system being instrumented.

Fortunately, some simplifications are possible that allow the combustion engineer to reasonably approximate when the flame arrives at the passage. These simplifications are in the form of equations for Radius Fraction Burned (R_{FB}) from Mass Fraction