

Effects of EGR Dilution and Fuels on Spark Plug Temperatures in Gasoline Engines

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ABSTRACT

The addition of exhaust gas recirculation (EGR) has demonstrated the potential to significantly improve engine efficiency by allowing high CR operation due to a reduction in knock tendency, heat transfer, and pumping losses. In addition, EGR also reduces the engine-out emission of nitrogen oxides, particulates, and carbon monoxide while further improving efficiency at stoichiometric air/fuel ratios. However, improvements in efficiency through enhanced combustion phasing at high compression ratios can result in a significant increase in cylinder pressure. As cylinder pressure and temperature are both important parameters for estimating the durability requirements of the engine - in effect specifying the material and engineering required for the head and block - the impact of EGR on surface temperatures, when combined with the cylinder pressure data, will provide an important understanding of the design requirements for future cylinder heads. This paper examines the combustion chamber temperatures for several dilution and combustion regimes by using spark plug temperatures as a proxy. The investigation involved a 2.4 L MPI engine with a CR of 11.4 and high levels of cooled EGR. The engine was equipped with a modified ignition system which extended the EGR limit to more than 25% and used instrumented spark plugs for temperature measurements. EGR sweeps were conducted at knock limited and non-knock limited conditions. In addition, potential fuel factors were explored using an E85 ethanol blend. Finally, spark plugs with two different heat ranges were tested at selected load points. The results show combustion phasing is the primary factor effecting spark plug temperatures and, at knock limited conditions, the temperature change was not monotonic with the EGR rate. At constant combustion phasing, i.e. when the engine was not knock limited without EGR, the use of cooled EGR significantly reduced spark plug temperatures. At higher loads, however, spark plug temperatures slightly increased from better combustion phasing and the elimination of fuel enrichment.

CITATION: Gukelberger, R., Alger, T., Mangold, B., Boehler, J. et al., "Effects of EGR Dilution and Fuels on Spark Plug Temperatures in Gasoline Engines," *SAE Int. J. Engines* 6(1):2013, doi:10.4271/2013-01-1632.

INTRODUCTION

Increases in fuel prices along with stringent government regulations have created a demand for cleaner and more fuel efficient engine concepts. While compression ignition engines have been known for decades to have superior efficiency over spark ignited engines, they are significantly challenged from an emissions compliance perspective. Since a primary source of the benefit of CI engines is their lean operation, they require lean NO_x aftertreatment, which are both complex and expensive. Therefore, the focus of

development has shifted to the relatively inexpensive gasoline-fueled engines - improve the efficiency to compete with diesel engines while maintaining ultra-low emissions by using a three-way catalyst. One promising approach is downsizing in combination with boosting of gasoline direct injected engines. These engines increase fuel economy primarily by reducing pumping and friction losses and by increasing the specific heats of the working fluid and the compression ratio [1, 2]. Fuel economy improvements of a downsized GDI engine over a conventional naturally aspirated SI engine can range in the order of 12 - 15% over

the NEDC [3, 4]. As a result, the highly boosted, downsized gasoline direct injection engine has achieved significant market penetration in recent years. Another promising approach to further improve efficiency and emissions is the addition of recirculated, cooled exhaust gas to either GDI or MPI gasoline engines. The use of EGR has been shown to reduce pumping losses, knock tendency, heat transfer losses and the emissions of the oxides of nitrogen and carbon monoxide. In addition, with approximately 10% cooled EGR the enrichment region can be completely eliminated [5, 6, 7, 8, 9].

The primary purpose of this study was to investigate the effect of EGR dilution and fuels on combustion chamber temperatures. In general, the response of the engine to the addition of cooled EGR (lower NO_x and CO and reduced knock) indicates that the flame temperatures decrease with an increase in the EGR rates. This result can be explained by both thermal and chemical effects. By introducing exhaust gas with a higher heat capacity than air, the peak cylinder temperatures are lowered while the heat energy released during combustion remains constant. This is called the thermal effect. The chemical effect is a highly endothermic process and results in the dissociation of H_2O vapor and CO_2 . Peak temperatures are hereby reduced by adsorbing the thermal combustion energy [10, 11]. The decreased combustion temperatures in combination with increased thermal mass significantly decrease the engine's tendency to knock [12]. As a result, the compression ratio can be increased and / or a more advanced combustion phasing can be applied. Increasing the compression ratio, particularly when combined with advanced combustion phasing, elevates combustion pressures. These increased pressures, at more advanced combustion phasing, bring with them concerns over increased bulk gas temperatures in the engine. Since modern engines are rapidly increasing their requirements for durability and peak cylinder pressures, information on the impact of EGR on both surface temperatures (which are difficult to measure) and cylinder pressure (which is relatively simple to measure) will provide important information on the design requirements for modern, high efficiency engines. Finally, pre-ignition is emerging as a problem of highly boosted SI applications. In some cases, pre-ignition combined with knock can lead to catastrophic engine failures or at least intolerable loud engine noise [13, 14, 15]. Spark plugs have been known to be a significant source of pre-ignition. As a result, some concern has arisen for the surface temperatures in the combustion chamber with EGR dilution.

There are several methodologies to measure in-cylinder temperatures. One non-intrusive approach is to use optical diagnostics such as Coherent Anti-Stokes Raman Spectroscopy (CARS) [16], laser-induced fluorescence (LIF) [17], and holographic interferometry [18]. These techniques have the advantage of fine temporal and spatial resolution. In more recent work, laser induced phosphorescence (LIP) was

mainly used to measure surface temperatures of pistons [19, 20] more accurately as well as valve and cylinder heads [21] and flame temperatures [22]. The LIP technique requires a thin thermographic phosphor coating on the desired surface area. UV laser radiation is then used to excite the phosphor. The resulting phosphorescence emissions will decay as a function of time and can be detected by a photomultiplier. Since the phosphorescence time decay is dependent on temperature, the surface temperature can be calculated [23, 21]. An additional non-intrusive method is infrared pyrometry as used by [24]. This surface temperature measurement can be employed on fast moving parts, i.e. valves, pistons and turbines. A photodiode measures the intensity of thermal radiation emitted by the hot surface. By artificially heating a surface and measuring the intensity of radiation prior to the actual engine test, temperature as a function of intensity can be determined. However, the surface emissivity can change severely due to surface roughness, condition, observation angle and wavelength. For example, carbon deposits or liquid fuel can induce significant measuring errors [25].

All optical diagnostic techniques require that the combustion chamber is equipped with an optical access point such as a quartz cylinder liner, a quartz or sapphire window in the piston, or access via one of the two intake or exhaust ports. Most researchers, therefore, use a single cylinder research engine or a constant volume combustion vessel. However, neither of these can perfectly replicate multi-cylinder engine operation, and high engine speed and load conditions are not achievable. Moreover, quartz has completely different thermal conductivities than a metallic combustion chamber and hence may bias the actual heat transfer [26]. Another, yet more exotic combustion chamber temperature measurement is the hardness method. Mizuno et al. [27] used it to determine the temperature distribution across a piston crown. The principle is to measure the Vickers hardness of the material after it is exposed to elevated and constant temperatures over an extended period of time. As temperature exposure increases, each metal begins to soften. Since the Vickers hardness of a given material is a function of temperature, temperature profiles can be obtained. The hardness method, however, cannot be used for transient temperature measurements and the measured parts cannot be re-used.

Combustion wall temperatures and heat transfer are usually measured using thin-film surface thermocouples or heat flux probes. This intrusive approach often requires heavy modification to cylinder head, liner, or pistons but can be utilized on production engines. Drawbacks include sealing issues, the signal transfer from thermocouple to the conditioning unit, especially when used on a reciprocating piston, and the potential to affect combustion characteristics and / or flow fields. Also, the temporal resolution is usually low. However, since the combustion chamber temperatures of an actual production engine with added EGR were of interest and averaged temperatures were sufficient, the common

thermocouple measurement was selected. To maintain the stock engine hardware, instrumented spark plugs were determined to offer the best compromise between robustness, data rate and the ability to capture real-world conditions.

EXPERIMENTAL SETUP

A four stroke, four cylinder turbocharged 2.4 L MPI engine was used in the course of this study (Figure 1, top). This engine has been utilized in previous studies of EGR [9, 28, 29] at Southwest Research Institute as part of the HEDGE I consortium. The 2.4 L engine has a peak torque of 400 N-m @ 2400 rpm and a peak power of 240 kW @ 5600 rpm (Figure 1, bottom). The engine was port fuel injected and also employs variable camshaft phasing on both the intake and exhaust cams. In stock form, the engine operates at 8.6:1 compression ratio, which was increased for these tests to 11.4:1 for high EGR operation.

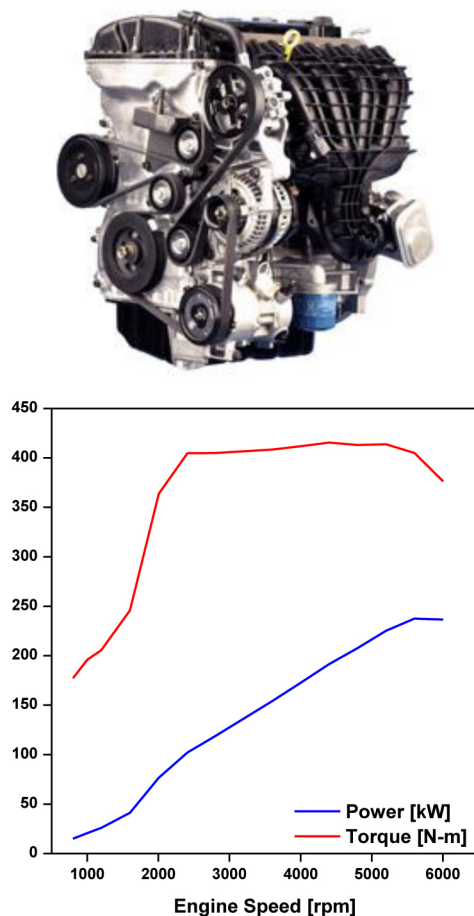


Figure 1. 2.4 L engine (top: image; bottom stock torque and power curves)

One of the most important parameters in improving the dilution tolerance of the engine is the ignition system. An advanced ignition system, described in detail in a previous publication [30], was employed to improve the EGR tolerance of the engine. In addition to the upgraded ignition coils, the spark plugs were upgraded from the stock plugs, which had relatively large, nickel-coated copper center electrodes, small gaps, and traditional ground straps. The instrumented spark plugs were installed in cylinder #1 of the engine, while the rest of the engine used single fine electrode spark plugs, with a small diameter (~ 0.6 mm) fine wire center electrode and a similar pad of precious metal on the ground strap. In addition, to further improve the engine's EGR tolerance, the spark plugs were operated with a large (> 1 mm) gap. Autolite[®] provided instrumented spark plugs for two heat ranges. The colder spark plug featured a 10.1 mm insulator tip-length whereas the hotter plug's insulator tip was extended to 14 mm. A schematic of the spark plugs equipped with thermocouples is depicted in Figure 2.

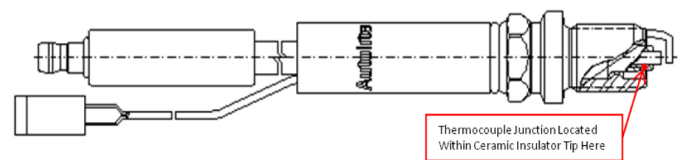


Figure 2. Instrumented spark plug from Autolite[®]

Finally, a prototype EGR system was installed on the engine. Figure 3 shows the EGR system layout utilized on the 2.4 L engine. The system consisted of an EGR cooler and valve, installed in a low pressure loop (LPL) configuration, with the EGR drawn after the turbocharger and connected to the intake prior to the compressor. A cooler was installed in the EGR loop, upstream of the EGR valve, to reduce the EGR temperature to ~ 100 - 120 °C. The LPL EGR design was chosen to limit backpressure on the engine at high loads, with the intent to reduce the amount of hot internal residual and knock at low speeds and high loads. At low loads, the engine has limited tolerance for cooled EGR and the dilution required to operate the engine was provided by increasing the overlap using the dual cam phaser system.

Since the engine was boosted, a water-to-air aftercooler was employed. The aftercooler was controlled to maintain the intake manifold temperature at 42 °C at high load conditions. In cases where the compressor-out temperature was less than 42 °C, the aftercooler had little or no effect. In addition, all test conditions presented in this document, unless otherwise noted, are performed at a stoichiometric air-fuel ratio, which was 14.6:1 for the Haltermann EEE gasoline and 9.8:1 for the E85 ethanol-gasoline blend. A brief description of the operating variables is shown in Table 1.