

Pilot Injection Ignition Properties Under Low-Temperature, Dilute In-Cylinder Conditions

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ABSTRACT

Measurements of ignition behavior, homogeneous reactor simulations employing detailed kinetics, and quantitative in-cylinder imaging of fuel-air distributions are used to delineate the impact of temperature, dilution, pilot injection mass, and injection pressure on the pilot ignition process. For dilute, low-temperature conditions characterized by a lengthy ignition delay, pilot ignition is impeded by the formation of excessively lean mixture. Under these conditions, smaller pilot mass or higher injection pressures further lengthen the pilot ignition delay. Similarly, excessively rich mixtures formed under relatively short ignition delay conditions typical of conventional diesel combustion will also prolong the ignition delay. In this latter case, smaller pilot mass or higher injection pressures will shorten the ignition delay. The minimum charge temperature required to effect a robust pilot ignition event is strongly dependent on charge O₂ concentration. Measured fuel-air ratio distributions, coupled with the homogeneous reactor simulations, show this temperature dependency to be due to both kinetics and over-mixing caused by the long ignition delay associated with dilute mixtures.

The simulations also show that the impact of dilution on the ignition process is dominated by the added heat capacity of the diluent rather than by changes in the kinetic pathways. For practical dilution levels (14-20% charge O₂ concentration) and moderate near-TDC temperatures (850-900 K), the simulations indicate that the optimal equivalence ratio to promote pilot ignition is between approximately 1.0 and 1.6, with the richer mixtures being appropriate to more dilute conditions. Lastly, pilot injection strategies are applied to a low-load, highly premixed operating condition. Robust pilot ignition events improve HC, CO and the COV of IMEP, but may deteriorate noise and soot emissions.

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INTRODUCTION

Pilot injection (also called pre-injection) strategies are commonly used in conventional automotive diesel combustion systems for the control of combustion noise and emissions. A pilot injection is usually intended to reduce the ignition delay of the main injection, thereby reducing the amount of fuel-air premixing. Consequently, combustion noise, cold-start behavior, and HC and CO emissions are all improved, though NO_x emissions may be compromised [1, 2] and soot emissions nearly always deteriorate. Modern engine design and operating trends, however, favor lower compression ratios and more dilute mixtures (higher EGR rates), resulting in highly pre-mixed, low-temperature

combustion (LTC) at light loads. LTC provides very low light-load NO_x and soot emissions, but combustion noise, HC, and CO emissions can be excessive. There is thus potential for considerable synergy in merging pilot injections with LTC operation - conceivably resulting in low levels of all criteria emissions as well as improved combustion noise characteristics.

Exploiting this potential synergy can be difficult. To achieve substantially premixed LTC, it is usually considered necessary that the ignition delay exceed the injection duration (e.g. [3]). Because pilot injections shorten the ignition delay of the main injection, they have been considered unsuitable for LTC operating modes and consequently 'post' or 'split' injection strategies have been applied [4, 5]. Moreover, under

extreme conditions of low in-cylinder temperature and density, and/or low pilot mass, a pilot injection can fail to ignite [4, 6, 7, 8, 9, 10]. Pilot injection strategies have nevertheless been successfully applied to LTC strategies, though a larger pilot injection mass is reportedly needed to control noise and ensure stable combustion [11, 12]. Even with a significant amount of heat release from the pilot injection, a positive dwell between the end of the main injection and the main ignition event can be achieved. Recent work has also shown that even when ignition occurs well before the end of injection, low noise and NO_x with acceptable soot emissions can be obtained. Kitamura and Ito [13] achieved low engine-out soot and NO levels at loads approaching 14 bar IMEP while injecting the main portion of the fuel directly into the burning pilot.

Despite these successes, and despite numerous publications documenting the effects of pilot injection on combustion and emissions (e.g. [1, 2, 6, 9, 10, 14, 15, 16, 17, 18]), the thermodynamic conditions under which a pilot injection ignites and the impact of operating parameters such as injection pressure or pilot mass on pilot ignition, on the ignition of the subsequent main injection, and on the ensuing noise and emissions levels have either not been examined or are not well understood.

Likewise, the ability of computational models to accurately capture pilot ignition behavior has not been established. A predictive simulation capability is important not only for numerical optimization of diesel combustion, but also for natural gas engines employing a diesel pilot for ignition (e.g. [19]). A major focus of this paper is to provide a sound physical understanding of pilot injection mixture formation and ignition, as well as data which can be employed to develop and validate computational tools that are able to capture this behavior.

Additionally, we anticipate that the information presented will be useful for the development and refinement of real-time, model-based control strategies for fuel injection timing. For example, in the Mazda SkyActiv-D [20] light-duty engine, ignition timing is controlled during transients or changes in environmental conditions by calculating the expected ignition delay from estimates of the charge O_2 content and in-cylinder temperature, and adjusting the injection timing to maintain optimal combustion phasing. The Toyota i-ART system [21], which adjusts injection timing based on detected fuel ignition quality, is another example where model-based analysis and control is used to reduce engine noise while maintaining strict emissions compliance. Very few data are available on which to base reliable control models.

In this paper we systematically investigate the pilot ignition process as fuel mass, intake charge O_2 content, in-cylinder temperature, and fuel injection pressure are varied. The measured ignition behavior is compared to the results of homogeneous reactor simulations to evaluate how closely the pilot ignition process can be captured with current models for

the chemical kinetics. We also correlate previously reported pilot injection fuel-air distributions measured using planar laser-induced fluorescence (PLIF) with the ignition behavior, to enable a clearer understanding of how the in-cylinder fuel-air distribution impacts the pilot ignition process. Finally, we examine how the pilot injection impacts the ignition and subsequent combustion of the main injection for various combinations of pilot mass and injection pressure.

EXPERIMENT

Engine and Fuel Injection Equipment

The engine used in this study was a modified 1.9 L GM light-duty diesel engine that provides optical access to the combustion chamber. The main geometric specifications are provided in Table 1 and a schematic of the engine is shown in Fig. 1. The engine features a Bowditch-style piston which can be fitted with either a fused-silica piston top for optical measurements or with a titanium piston top if extensive emission and cylinder pressure based data are to be acquired. Both piston tops have the identical geometry, featuring a reentrant bowl and valve cut-outs in the piston top.

Table 1. Engine and injection system and fuel specifications

Engine Geometry	
Bore [mm]	82.0
Stroke [mm]	90.4
Displacement Vol. [L]	0.477
Geometric CR	16.7
Squish Height [mm]	0.88
Injection Parameters	
Injector	Bosch CRI2.2
Sac Type	Mini Sac
Sac Volume	0.23 mm ³
Holes	7
Nozzle Diameter	0.14 mm
Hole Geometry	KS1.5/86
Included Angle	149°
Fuel	
US CN47 diesel fuel <i>or</i>	
42% <i>n</i> -C ₁₆ H ₃₄ ; 58% <i>iso</i> -C ₁₆ H ₃₄ blend with 0.5 vol% 1-methylnaphthalene tracer	

Optical access through the sides of the combustion chamber was achieved through fused silica windows (50 mm wide by 25 mm tall) located at the top of the cylinder liner. These windows are positioned to allow unobstructed optical access into the clearance volume, even when the piston is located at TDC. The engine is also equipped with a Kistler 6125b pressure transducer mounted in the location of the production engine glow plug, and the in-cylinder pressure is acquired every 0.25° crank angle (CA). Results are reported in this work in °CA after top-dead-center (aTDC).

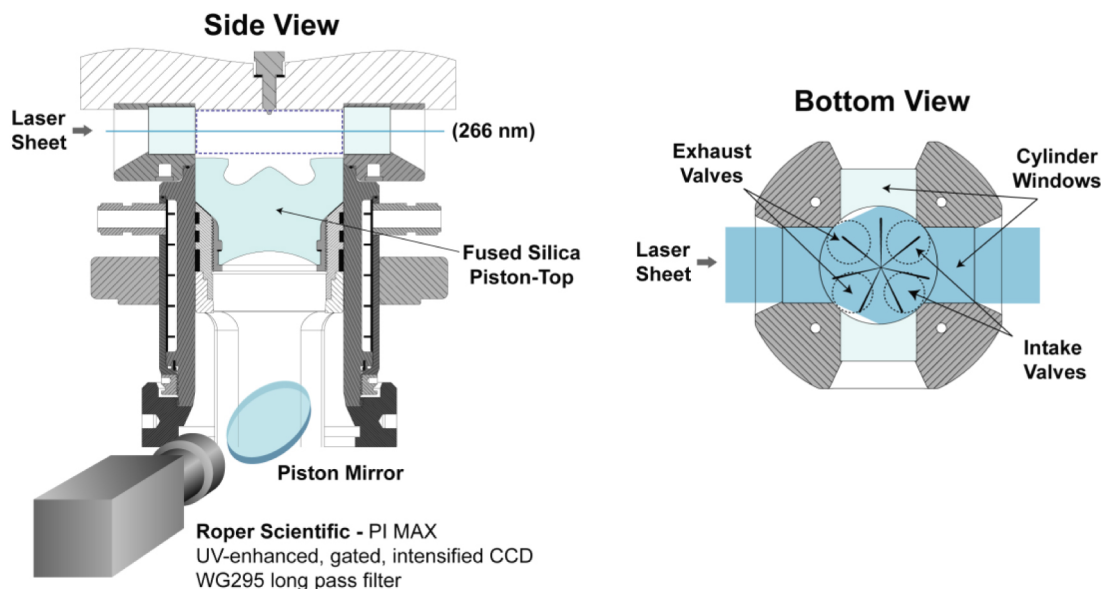


Figure 1. Schematic of the optically accessible diesel engine depicting the location of the laser sheet and camera viewing

Table 2. Fuel Properties @ 360 K

	Density [g/L]	Kinematic Viscosity [mm ² /s]	Boiling Temp [K]	Vapor Pressure [kPa]	Surface Tension [N/m]
42% <i>n</i> -C ₁₆ H ₃₄ 58% <i>iso</i> -C ₁₆ H ₃₄	736	1.51	520 – 560	0.3	0.020
75% <i>n</i> -C ₇ H ₁₆ 25% <i>iso</i> -C ₈ H ₁₈	609	0.39	372	71.0	0.013
#2 diesel fuel	840 – 865	~2.2	~440 – 630	~0.4	~0.03

The fuel injector used in the initial portion of this study, when only a single injection was employed, was a Bosch CRI2.2 high-pressure, electronically controlled, common-rail injector. For the latter portion of the study, in which the impact of pilot mass and injection pressure on the main combustion event was investigated, a pre-production, solenoid-actuated Bosch CRI2.16 injector was used. The latter injector was designed to allow short injection dwell times between the pilot and main injections. In both cases, the injector was equipped with a 7-hole, mini-sac injector tip with an included angle of 149°. The 7 fuel orifices are equally spaced and have a nominal diameter of 0.14 mm. Additional specifications of the fuel injector nozzle are listed in [Table 1](#).

To ensure that the pilot injection quantities were accurate, the injector calibration was performed with the injector mounted in the engine, subject to approximately the same clamping forces and local thermal environment as when the engine is operating (the coolant flow through the head and its temperature were unchanged, such that the only difference the injector experienced during the calibration process was lower heat transfer to the injector tip). To perform this calibration, the optical cylinder liner was lowered, and a small pressurized vessel mounted against the head to collect injected fuel. The back pressure in the vessel was set to match

the approximate cylinder pressure during the injection event. The injected mass was determined by weighing the fuel collected in the vessel after a large number of injection events (typically 100).

Data obtained for cylinder pressure and emissions based analysis of pilot ignition were acquired while the engine was operated with a conventional US #2 diesel fuel with a cetane number *CN* of 47. To enable quantitative, laser-induced fluorescence based measurements of the in-cylinder equivalence ratio distribution, a low fluorescence base fuel, comprised of the diesel reference fuels *n*- and *iso*-C₁₆H₃₄ (2,2,4,4,6,8,8-heptamethylnonane) was used. The fuel blend proportions, 42% *n*-C₁₆H₃₄ and 58% *iso*-C₁₆H₃₄ by volume, were selected to match the ignition delay of the conventional diesel fuel. Although the ignition delay was matched, the *CN* for this blend calculated from the relationship provided by Heywood [22] is 50.7 - slightly higher than the conventional diesel fuel. This “DPRF58” fuel much more closely approximates the physical properties of #2 diesel fuel impacting injection, atomization, and vaporization than our previously used [23] low-fluorescence base fuel based on a blend of the gasoline primary reference fuels *n*-C₇H₁₆ and *iso*-C₈H₁₈, as shown in [Table 2](#).

Operating Conditions and Procedure

For all measurements presented in this study, the engine was operated with a fixed pilot start-of-injection (SOI) of -15°CA at 1500 RPM (Table 3). To examine the impact of the pilot on the main combustion event, a limited number of measurements were also obtained with a pilot-main injection strategy, with the main injection SOI fixed at 2°CA .

Table 3. Operating Conditions

Engine Speed [RPM]	1500
Swirl ratio (Ricardo)	2.2
Coolant Temperature	87°C
Pilot injection mass [mg]	1,2,3,4,5,6
Injection pressure [bar]	500, 860, 1220
Start-of-Injection [$^{\circ}\text{CA}$]	-15
Peak near-TDC bulk density [kg/m^3]	21.1
CA Avg. bulk density (SOI – TDC) [kg/m^3]	19.6

Cylinder pressure measurements characterizing the combustion of a pilot injection were performed at a variety of charge O_2 concentrations, obtained by diluting the intake charge with N_2 and CO_2 . The proportions of CO_2 and N_2 were selected to match the mixture specific heat of complete combustion products at a temperature of 600 K. For all O_2 concentrations, the engine was operated with a constant intake mass flow rate, leading to a peak in-cylinder bulk-average density of $21.1 \text{ kg}/\text{m}^3$. The crank-angle-averaged near-TDC density, averaged between SOI and TDC, was $19.6 \text{ kg}/\text{m}^3$. The near-TDC temperatures averaged over the same period were varied to cover a range encompassing both conventional and low-temperature combustion regimes, and varied from approximately 810-960 K, depending on the O_2 concentration and intake temperatures, as shown in Table 4. In-cylinder temperatures were estimated from 1-D simulations of the induction and compression stroke using a commercial code (GT-Power), which was calibrated to match the cylinder pressure trace under the 10% O_2 , 90°C operating condition listed in Table 4. Because the cylinder pressure is impacted by both charge composition and intake temperature, the near-TDC, crank-angle-averaged pressure varied as well.

As explained below, the apparent heat release derived from the cylinder pressure/volume history is employed as a primary metric for ignition. The apparent heat release rate was computed using an iterative, two-zone model, in which gas properties are dependent on both mixture composition and temperature. The effects of heat transfer and crevice flows are accounted for by subtracting the apparent heat release rate calculated from a corresponding motored pressure trace. Because the optical engine is skip-fired, and changes to the motored heat transfer associated with the pilot injection and combustion are anticipated to be small, this procedure is expected to provide sufficient accuracy.

Table 4. Motored temperatures and pressures [K, bar], averaged SOI to TDC

O_2 Concentration – Fired Operation					
Intake Temp.	10% O_2	12% O_2	14% O_2	16% O_2	18% O_2
303 K 30°C	813 K 43.8 bar	820 K 44.5 bar	828 K 44.9 bar	833 K 46.1 bar	841 K 46.4 bar
323 K 50°C	838 K 45.0 bar	845 K 45.4 bar	851 K 46.9 bar	858 K 47.6 bar	866 K 48.6 bar
363 K 90°C	883 K 46.6 bar	890 K 47.2 bar	899 K 47.8 bar	906 K 48.6 bar	915 K 49.3 bar
403 K 130°C	928 K 49.4 bar	936 K 51.0 bar	944 K 50.9 bar	952 K 51.6 bar	961 K 51.7 bar

N_2 Environment for PLIF

Intake Temp.	0% O_2
300 K 27°C	852 K 50.4 bar
381 K 108°C	930 K 53.9 bar

Optical Measurements of Equivalence Ratio Distributions

To examine the mixture preparation process and thereby the impact of the in-cylinder equivalence ratio distribution on the ignition of pilot injections, 0.5% by volume of 1-methylnaphthalene was added to the DPRF58 base fuel to serve as a fluorescent tracer for the PLIF measurements. Fluorescence was excited with a horizontal laser sheet ($\lambda = 266 \text{ nm}$) at the three locations shown in Figure 2, and collected through the Bowditch piston assembly as shown in Figure 1. The lower two measurement planes are at a location that is fixed with respect to the piston position, while the upper plane bisects the clearance height.

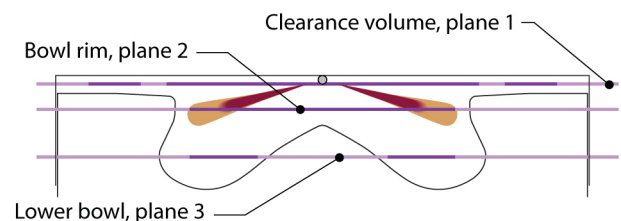


Figure 2. Location of the PLIF measurement planes. Darkened portions of the laser sheets correspond to imaged areas

Because the tracer fluorescence is strongly quenched by O_2 , for the imaging studies the engine was operated with a pure nitrogen intake stream and combustion did not occur. Two different intake temperatures were employed, 27°C and 108°C, which resulted in average temperatures between SOI and TDC of 852 and 930 K, near the upper and lower bounds of the temperatures shown in Table 4. The near-TDC average density was equal to that used for the fired operating conditions - 19.6 kg/m³. Images of fluorescence from each plane were collected over 50 engine cycles, and referenced to calibration images obtained in a homogeneous mixture with a known fuel mole fraction to obtain quantitative images for the fuel mole fraction distributions. The fuel distributions are reported as equivalence ratio distributions, assuming a specified O_2 content in the ambient charge. The relationship between fuel mole fraction χ_{fuel} and equivalence ratio ϕ is

$$\phi = \frac{\chi_{fuel,d}}{(1 - \chi_{fuel,d})} \cdot \frac{24.5}{\chi_{O_2}} \quad (1)$$

Additional diagnostic details describing these measurements are provided in [24].

RESULTS

Experiments

In-cylinder pressure, temperature, and heat release

To aid the reader in understanding the progress of the pilot ignition event and the typical thermodynamic conditions under which it occurs, Figure 3 presents the cycle-averaged pressure, bulk temperature, and heat release traces corresponding to the 14% O_2 , 30°C intake temperature condition. The temperature traces are derived by scaling the simulated motored temperature trace by the ratio of fired to motored pressure. To ensure that the area under the heat release traces is representative of the completeness of combustion, not the relative fuel delivery, the heat release has been normalized by the lower heating value of the injected fuel.

The pressure, temperature, and heat release traces in Figure 3 clearly show the two-stage ignition behavior typical of diesel fuels. Initial low-temperature heat release (LTHR) reaches a local maximum near -8°CA. The bulk of the energy release, however, occurs in the high-temperature portion of the heat release (HTHR), which commences approximately 5°CA later. For each of the pilot injection quantities shown, the normalized LTHR seen in Figure 3 is equally robust for all pilot quantities. It is the HTHR that fails to launch with small pilot mass. With a pilot injection mass greater than 2 mg, the peak heat release per unit fuel injected seen near 2-3°CA is at least double that seen with the lower mass injections, and a distinct, rapid rise in pressure and temperature occurs at this time that is not seen with a lower pilot mass.

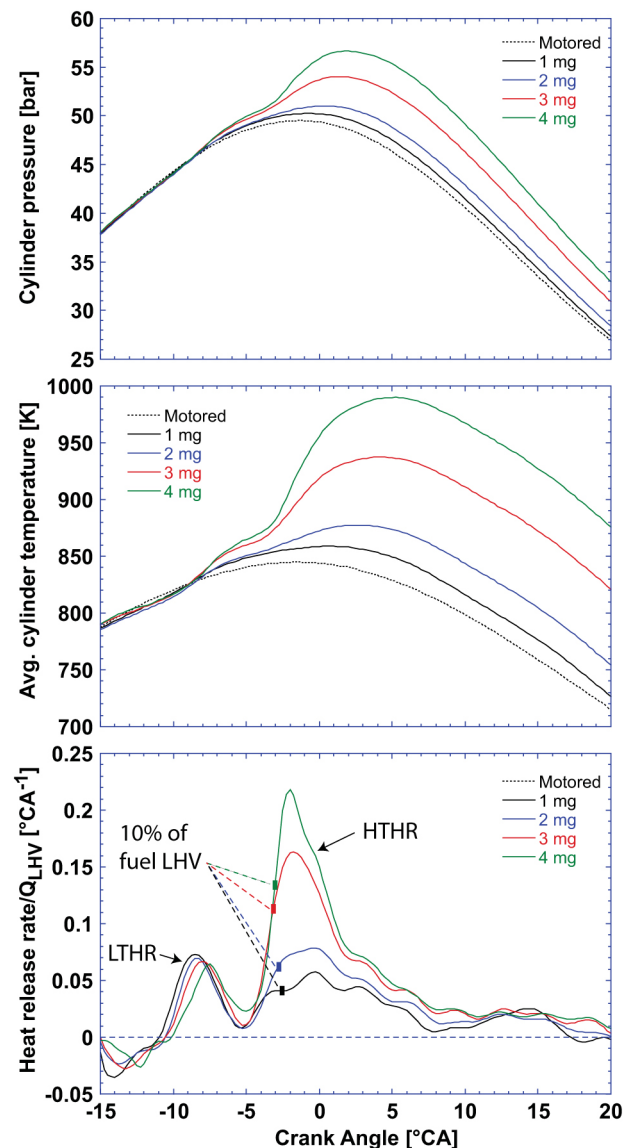


Figure 3. In-cylinder pressure, temperature, and heat release traces characterizing the thermodynamic conditions and the progress of the combustion event. The single pilot injection shows distinct periods of initial low temperature heat release (LTHR) and high-temperature heat release (HTHR).

The heat release trace was used to define both the timing of the auto-ignition of the pilot injection as well as the robustness of the ignition event. We defined a “robust” ignition event as one in which energy corresponding to 40% of the lower heating value (LHV) of the fuel was released between SOI and 10°CA. Heat release occurring later than 10°CA would be of little utility in promoting timely ignition of the main injection. For our #2 diesel fuel, the heat release thresholds corresponding to ignition were 17.1, 34.3, and 51.4 J for pilot injection quantities of 1, 2, and 3 mg, respectively. Within the literature [7], ignition has also been determined by the observation of positive heat release from

the pilot injection, although no quantitative details are provided.

To determine the minimum ignition temperature needed for robust ignition at each O_2 concentration, the measured heat release between SOI and 10° aTDC for each operating condition was plotted against the average near-TDC temperatures in Table 4, and a smooth curve was fit to the data using a well-behaved interpolation algorithm [25]. From this curve, the temperature corresponding to the 40% LHV threshold was determined. If the ignition threshold was within a few joules of the measured cumulative heat release at the lowest temperature, a small amount of extrapolation was performed to identify a minimum ignition temperature.

Ignition timing can be defined using several different metrics [26]. Many of these metrics, such as the time at which the cylinder pressure with fuel injection recovers to the motored pressure level, give ignition delays that are representative of the timing of the initial, low temperature heat release (LTHR). We prefer a metric that is representative of the timing of the high temperature heat release (HTHR) period. It is the mixture state at this time of rapid temperature rise that will determine the peak pilot combustion temperatures achieved - which are expected to greatly affect the subsequent ignition of the main injection, as well as the formation and oxidation of emissions formed from the pilot fuel itself. Accordingly, we define the pilot ignition delay τ as the time from the start of injection until 10% of the lower heating value (LHV) of the fuel has been released. As seen in Figure 3, this definition corresponds to the rising flank of the HTHR portion of the heat release curve, behavior which was consistently observed under all conditions that resulted in a robust ignition event. Under conditions providing poor ignition characteristics, the computed ignition times move closer to the onset of the rising flank, and thus slightly underestimate the observed increase in ignition delay. We also examined other metrics, such as those based on the maximum rate of change in heat release, but found that these measures could be misleading and error-prone when ignition was poor and both the heat release and its rate of change were small.

Minimum ignition temperature

Figure 4 illustrates how the minimum ignition temperature needed for robust ignition varies with $[O_2]$ for various pilot injection quantities and injection pressures. Notice that at the highest $[O_2]$, the ignition temperature typically approaches an asymptote between 800 and 830 K, while at the lowest $[O_2]$ the highest measured ignition temperature is approximately 930 K, a spread of a little over 100 K. This change in ignition temperature is considerably smaller than what has been previously reported in the literature. Overlaid on the results obtained at an injection pressure of 860 bar are the results reported by Mendez and Thirouard [7]. An ignition temperature of approximately 950 K was observed at an $[O_2]$ of only 16%, even though the

ignition temperatures at the highest O_2 concentrations are similar.

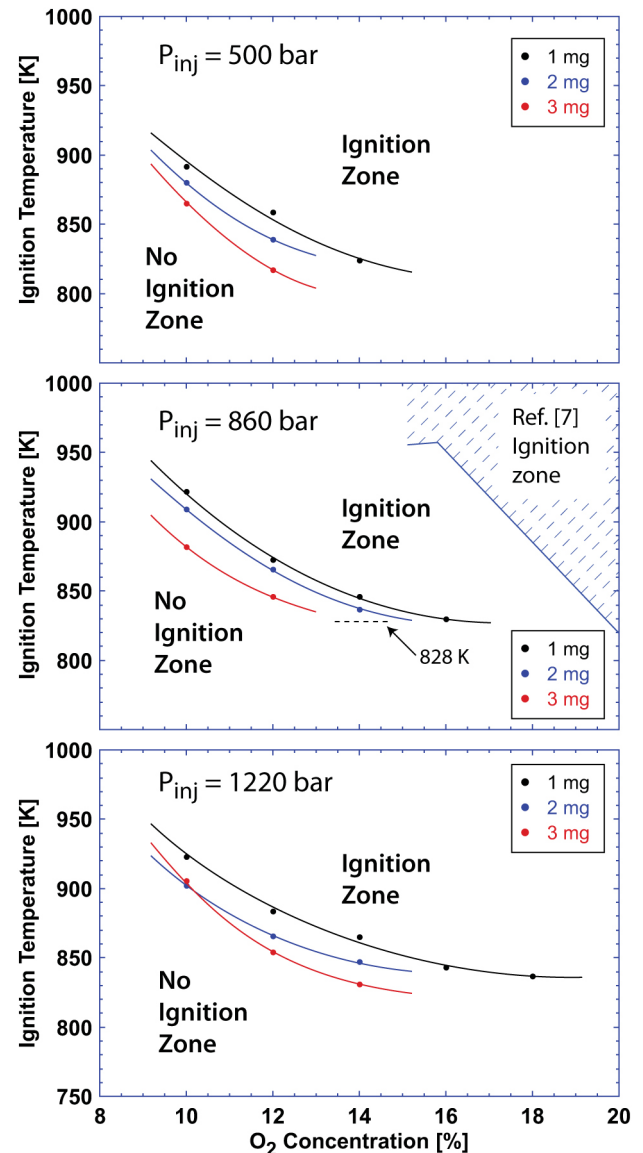


Figure 4. Measured variation of pilot ignition temperature with $[O_2]$ for various pilot injection quantities. At the highest O_2 concentrations, the mixture ignited even at the minimum intake temperature of $30^\circ C$ and the ignition temperature could not be resolved

This discrepancy seems unlikely to be due to differences in the way ignition is defined, as the 'positive heat release' criterion described in [7] seems less restrictive than our definition, and should result in lower ignition temperatures. Similarly, a difference in the manner in which temperature is calculated is unlikely to be responsible. The GT-Power temperature estimate is within 3 K in the near-TDC averaging window of the temperature that is computed from the ideal gas law (the method used in [7]), and the choice to report the temperature at -20° CA in [7] rather than our average