

Prospects for High-Temperature Combustion, Neat Alcohol-Fueled Diesel Engines

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ABSTRACT

The use of neat alcohols, namely methanol and ethanol, in direct-injection, compression-ignited engines is difficult, most notably due to their poor ignitability. By employing a high-temperature combustion strategy, this challenge may be overcome, thus creating the opportunity for using these oxygenated and inherently low-sooting fuels for heavy-load applications.

Experimental data are provided from a single-cylinder research engine that shows particulate matter (PM) emissions for Diesel-style combustion of both methanol and ethanol that are below the current US Government regulation limit. The level of particulates remained low up to stoichiometric ratios of fuel and air. A complete emissions analysis indicates a high combustion efficiency of ~ 96% at stoichiometric conditions.

In order to achieve reliable combustion, some form of intake-air preheating was required. The issue of ignitability is addressed with modeling which indicates that highly turbocharged, non-intercooled air into a cylinder with low heat rejection (LHR) surfaces can achieve conditions that satisfy acceptable ignition delay requirements. With increased exhaust enthalpy, opportunities exist to use thermal or mechanical exhaust regeneration strategies. All of these features contribute to a clean, high-efficiency Diesel engine with heavy-load capability.

To explore the nature of soot formation within alcohol spray jets, images are provided from another single-cylinder device with optical access. The images show single-plume combustion for both methanol and ethanol into an air environment similar to that of an engine. Broadband luminosity is observable for both fuels within the interior of each jet. This indicates that a balance exists between soot formation and oxidation, the difference of which is responsible for engine-out emissions.

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INTRODUCTION

Neat alcohols as alternative fuels for Diesel engines have been under investigation for several decades. Commercial engine development was addressed by the Detroit Diesel Corporation in the early 1980's with the production of a methanol-fueled, compression-ignited (CI) engine [1]. The combination of low cetane number and large enthalpy of vaporization was addressed by retaining hot combustion products within the cylinder to create sufficient ignition conditions near top dead center (TDC) with a relatively high compression ratio, up to 23:1 [2]. The engine operated in a direct-injection, two-stroke fashion, and the amount of exhaust gas removed during the scavenging process was controlled for stable combustion. Glow plugs were used for cold-start operation only. Particulate measurements from the engine were non-negligible, and this was attributed in large part to burned engine oil since the PM emissions did not increase with fuel-air ratio.

Southwest Research Institute has also conducted testing with a single-cylinder, four-stroke engine operating on neat methanol, as well as wet methanol and methanol blended with higher alcohols [3]. In order to achieve consistent autoignition, a compression ratio of 18.9:1 with intake air preheating to 138 °C was required, which was interpreted as the simulation of turbocharging without intercooling. The reported smoke data is very low across the load range tested, which remained below stoichiometric conditions.

A low heat rejection engine has been used by Dhinagar *et al.* to investigate emissions and performance for direct-injection, spark-assisted combustion of methanol and ethanol as compared to Diesel fuel [4]. In this study, a single-cylinder engine with a compression ratio of 16.5:1 was outfit with an insulated piston face and head. The measurements of PM and smoke number were reported being essentially zero for both

alcohols, as compared to the Diesel-fuel baseline. The apparent heat release rate data indicated that the increase in compressed air temperature due to LHR surfaces allowed combustion to occur in two phases: that initiated by the spark plug, and that attributed to autoignition. This implies that the operating conditions were almost sufficient for unassisted autoignition of the alcohol sprays.

Ethanol has been researched by Shen *et al.* in a partially premixed combustion (PPC) approach [5]. Here, a significant amount of fuel-air mixing is desired before combustion, although a separate late injection is used for phasing control. The tested equivalence ratios approached, but did not meet, stoichiometric conditions. Peak temperatures were limited by the overall lean combustion and the use of EGR for NO_x avoidance. Measurements from the PPC split injection strategy show low soot emissions, as expected from the large amount of pre-mixing. In their experimental setup, intake boosting and intake air preheating were required for ignition.

The inherent nature of low soot emissions from oxygenated fuels was analyzed in detail by Miyamoto *et al.* They showed experimentally that if the oxygen mass fraction of a fuel is greater than 30%, the measured smoke number is nearly zero [6]. This may be achieved through the use of either neat or blended fuels. From this perspective, it is clear that both methanol (50% oxygen mass fraction) and ethanol (35% oxygen mass fraction) are attractive choices, and are expected to emit low levels of soot. Similarly, dimethyl ether (DME) has the same atomic composition as ethanol and is also expected to form little soot.

The intermolecular bonding of DME is different than ethanol, with the oxygen atom located between two methyl groups. As a result, its properties are different. Most notably, it has a Diesel-fuel-like cetane rating, in the range of 55-60. Its early use in Diesel engines was investigated as an ignition improver for DI methanol in a compression ignition engine [7, 8]. The DME was admitted into the intake air, and the direct injection of methanol was sufficiently ignited. It was believed that the lean DME-air mixture combusted during the compression stroke, thus raising the ambient gas temperature to a level that was acceptable for methanol ignition delay. As a neat DI fuel, DME has been tested and shown to enable clean and efficient operation of a Diesel engine [9, 10]. It is noteworthy that DME requires storage at several bar above atmospheric pressure in order to remain a liquid.

ALCOHOL SPRAY IGNITION REQUIREMENTS

A major difficulty in using either neat methanol or ethanol in a Diesel engine is their low cetane numbers (~ 1-10) [11] compared to traditional Diesel fuel (~ 45). For typical conditions at TDC, the compressed air temperature is insufficient to achieve ignitability requirements for either alcohol.

Measurements of ignition delay for sprays of ethanol and methanol into Diesel-like conditions in a constant-volume combustion vessel have been made by Siebers and Edwards [12]. Their data for methanol and ethanol is reproduced in Figs. 1 and 2, respectively, showing ignition delay times as a function of temperature. This temperature pertains to the core gas, which is a bulk gas value that has been corrected for the thermal boundary layer volume. The pressure delay is defined as the time required for an increase of 0.25 atm above the pressure that would have been measured had no injection occurred.

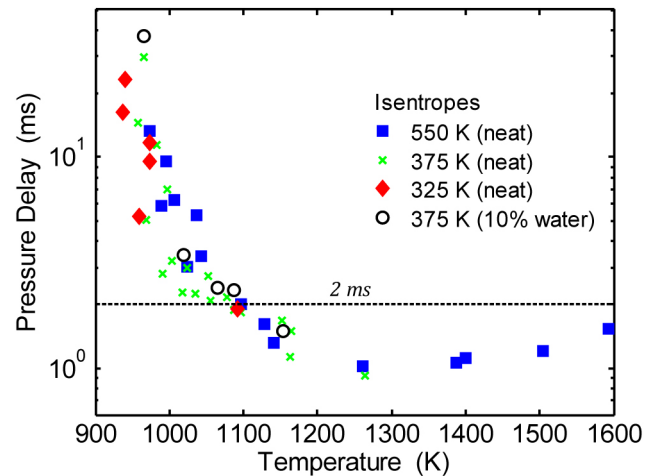


Figure 1. Methanol spray ignition delay as a function of temperature. Data reproduced from reference [12].

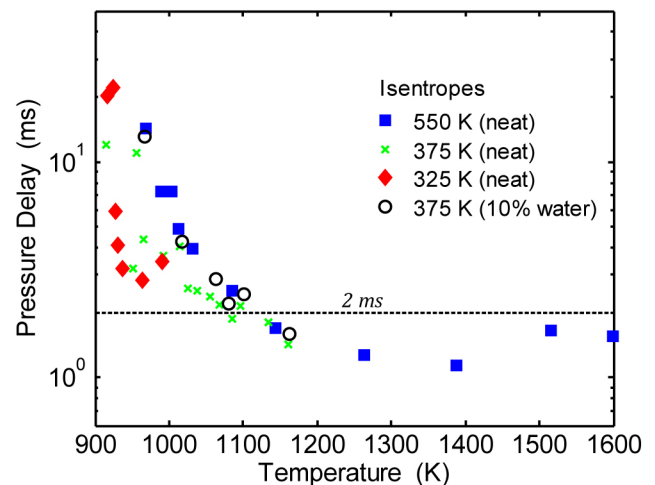


Figure 2. Ethanol spray ignition delay as a function of temperature. Data reproduced from reference [12].

Both figures show a number of data point collections which correspond to isentropic compression of ambient pressure air at a given initial temperature. If a delay of 2 ms is defined as the minimum threshold for what is acceptable within a Diesel engine, a start-of-injection (SOI) in-cylinder temperature of about 1100 K is required for both alcohols. The data also indicate that if the volume of fuel injected contains 10% water, this ignition behavior is not affected.

The requirement for 1100 K air at SOI is not an unrealistic challenge. This issue is addressed with a thermodynamic, crank-angle resolved engine simulation. The model includes ideal gas properties with heat capacity as a function of temperature, a heat transfer model to account for energy transfer between the working fluid and the engine surfaces, as well as a two-zone combustion model. Five different configurations were analyzed in detail for an engine with a geometric compression ratio of 17:1: (1) a naturally aspirated conventional CI configuration, (2) a LHR engine with thermal barrier coated surfaces on the head, piston face, valves and ports, (3) a turbocharged metal-surfaced engine with intercooling, (4) a turbocharged LHR engine with intercooling, and (5) a non-intercooled turbocharged engine with LHR surfaces. The peak air temperatures achieved by each model are shown in the following table. These values are computed by allowing the simulated surface temperatures to reach steady-state, which are influenced by combustion. Then an additional cycle is simulated with the combustion sub-model inactivated. The corresponding peak temperatures of this last cycle are listed in [Table 1](#).

[Table 1. Peak TDC air temperatures achievable for engine configurations with a geometric CR of 17:1.](#)

Engine Model Configuration	Peak Air Temperature (K)
Naturally aspirated, metal surfaces	1077
Naturally aspirated, LHR surfaces	1131
Intercooled turbocharger (2.5 bar intake manifold pressure), metal surfaces	1146
Intercooled turbocharger (2.5 bar), LHR surfaces	1215
Non-intercooled turbocharger (2.5 bar), LHR surfaces	1295

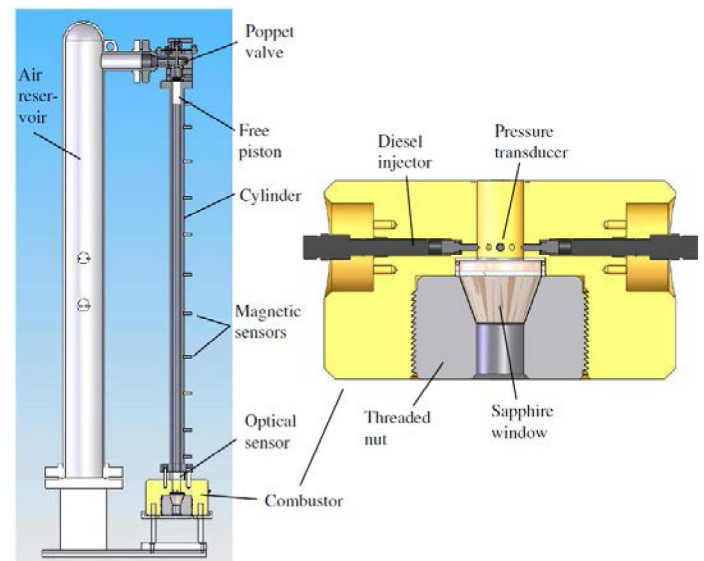
The conventional engine configuration never reaches the 1100 K temperature necessary for alcohol ignition, while the addition of LHR surfaces only reaches the temperature threshold for such a small period of time that phasing combustion would be difficult. This demonstrates that turbocharging, in addition to LHR surfaces, will be necessary to achieve acceptable pre-injection temperatures over a wide range of injection timings. Note that although intercooling makes a small improvement to the load and efficiency of an engine, it lowers peak temperatures and thus limits the possible injection timings.

EXPERIMENTAL SETUPS

Two separate single-cylinder devices are employed for taking images and making emissions measurements. One device has optical access and uses a free-piston architecture, making its operation single-shot with only one fuel injection event occurring near TDC. The other is a continuously reciprocating engine with simulated boost capability.

Free-Piston Device with Optical Access

[Figure 3](#) shows the apparatus used to image fuel injections. A 3 m tall, 2.3 inch diameter cylinder has a 3 inch thick sapphire wall on one end, and a fast-acting poppet valve on the other. A 7 inch long mirror-faced piston is loaded into the end adjacent to the valve. Upon actuation, the valve allows delivery of compressed air from the reservoir on the order of a few hundred psi. The piston then compresses the trapped air towards the sapphire end-wall, achieving any compression ratio up to 100:1. Due to the free-piston architecture, the peak air density is maintained for a very short period, on the order of a couple milliseconds. The device was operated with a single injection event beginning approximately 1 ms before TDC. A Bosch, solenoid-actuated, common-rail Diesel injector is mounted perpendicular to the stroke axis. It has a nozzle with a single 150 micron diameter orifice aligned with the injector body. A Haskel air-driven liquid pump is used to provide the fuel rail pressure, typically 1400 bar.



[Figure 3. Experimental device used for optical access. Graphic provided by M. Svrcek \[13\].](#)

Images were obtained with a Phantom high-speed digital camera fitted with a Nikon 50 mm lens. The frame interval was set to 27 μ s, and the exposure time was varied. An argon-ion laser was used for illumination of the cylinder bore via the sapphire end-wall. A Schlieren imaging technique was employed in order to clearly visualize the internal air motion, fuel injection, and plume dilatation upon ignition. Broadband radiation was captured by the color sensitive camera indicating