# The Sootless Diesel: Use of In-Plume Fuel Transformation to Enable High-Load, High-Efficiency, Clean Combustion


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**Abstract**

The mitigation of carbonaceous particulate matter formed within heavy-load direct-injection combustion engines is explored under this research project, both experimentally and numerically. A free-piston, single-shot experimental device is used to create high-temperature-air environments, upwards of 1800 K. A single Diesel injector delivers the fuel, and a high frame-rate camera images the process. Two simple alcohols, methanol and ethanol, are focused on at this stage of research and resultant color images indicate that soot forms within the jet shortly after autoignition. The amount of soot formed is then perturbed in two ways: by the addition of water, and by varying injection timing. The water is observed to suppress soot formation, and this is most likely attributed to its participation as a thermal diluent. Water as a chemical moderator, aiding in the fuel-fragment oxidation process, remains a desirable goal. The advancement of injection timing shows that mixing can be enhanced to a point where no soot is observable.

In addition to the experimental results, a model is being developed to help understand the chemical kinetics responsible for producing soot precursor species in significant amounts. The model solves for an axisymmetric, steady-state, gaseous jet in the axial and radial dimensions. A chemical reaction sub-model is then added to predict fuel-specific reactions. Further analysis is required to make conclusions regarding spatial or temporal soot formation tendencies within the jet.

In order to connect with production vehicle engines, a single-cylinder, direct-injection engine is operated with both methanol and ethanol fuels as well. The emissions are analyzed by a smoke meter, and results indicate that methanol is capable of staying below the 2010 emissions limit up to full-load, stoichiometric operation. Ethanol is equally promising as its soot emissions are not far above this limit. The use of a modern piezo-actuated injector capable of multi-injection fuel scheduling will likely prove to reduce soot formation even further by enhancing mixing with early fuel delivery pulses. In order to aid in the autoignition of alcohol fuels within conventional engine geometry, some amount of intake air pre-heating is required. This can alternatively be addressed with the use of in-cylinder ceramic coatings as a low-heat-rejection (LHR) strategy. The

benefits of engine efficiency are explored in depth with an LHR engine simulation. The efficiency gains are fully realized when the exhaust enthalpy is intelligently utilized. The engine model suggests that upwards of 60% indicated efficiency is achievable through thermal regeneration of the exhaust exergy. The overarching result is that high-temperature combustion, achieved through means of high boost and low-heat-rejection, has the potential to make for a clean, highly efficient sootless Diesel engine that operates on neat alcohol fuels.

**Introduction**

The emission of solid particulate matter from combustion-generated sources is a serious issue for both the environment as well as public health. The consequence of particulate aerosols has been clearly exemplified in recent news regarding the air quality in China [1]. A number of cities within that country are highly populated and traffic congested, making China a first-in-line customer for soot-reduction technologies. Besides the economic opportunity for developing such advanced engine strategies, the increase in average global temperatures and resultant environmental and ecological effects demand the attention of engine manufacturers are researchers alike.

In this research project, the goal is to understand all possible avenues for reducing, if not eliminating, cylinder-out soot emissions while at the same time preserving the high-load work capability of direct-injection engines. Diesel engines are known for their relatively high efficiency, as compared to conventional spark-ignition engines, for two primary reasons: the effective compression ratio may be increased significantly without an unintended fuel autoignition limit (i.e. engine knock), and the lack of throttle for load control reduces pumping losses. The major disadvantage, however, is that fuel-rich regions within the combustion jet produces particulate matter, and thus expensive after-treatment equipment is required. Within the broader research community, soot avoidance strategies are mainly focused on staying below the soot formation threshold by means of high levels of dilution and operating in a low-temperature regime. Although this is promising for reducing emissions, load capability suffers significantly.

Previously, GCEP-funded research has identified what is referred to as the *Extreme States Principle* [2]. This states that by performing combustion reactions at high internal energy states (i.e. within high-temperature air) the entropy generation can be reduced, and the change is manifested as available work for extraction. An experimental device was built to prove this concept; an apparatus which can achieve up to 100:1 geometric compression ratios. It has the added benefit of optical access through a sapphire end-wall. In the context of soot formation, the device lends itself towards addressing several possible strategies and allows validation of the effect via optical diagnostics.

One such strategy is the use of a fuel with moderator that is injected as a blend. Water is an attractive additive, and alcohol fuels are nice in this regard due to their complete miscibility. There are two primary roles that the water can play as a moderator: either as a thermal diluent or as a chemical participant. In the former case, peak combustion temperatures are reduced, nearing the low-temperature soot formation threshold. The latter case refers to a situation where the water dissociates and adds oxidizing radicals that can react with fuel fragments before they form soot precursor species, namely aromatic hydrocarbons. Both effects are being investigated in this project.

Another strategy is the use of enhanced mixing of fuel and air prior to autoignition. Very early injections start to approach the limit of homogeneous charge compression ignition (HCCI), and this leads to challenges with combustion phasing and large rates of pressure rise. This combustion style is beyond the scope of this work, although the soot formation issue is sufficiently avoided. Here, it is a multi-injection strategy that is considered whereby some of the fuel is delivered early and later injection pulses control combustion phasing and shape the pressure profile. Experimental evidence from optical access shows how a soot formation threshold is identified, and this is reported for an ethanol injection.

An additional research device is used to address practical engine considerations. A single-cylinder, reciprocating engine is operated with a single overhead injector using a seven-hole nozzle in order to deliver sufficient fuel up to full-load conditions. Both methanol and ethanol have been tested, and soot measurements obtained. The data shown in this report are promising as both alcohol fuels perform very well compared to the 2010 emissions limit. The interest in operating at stoichiometric conditions is to allow for the use of a three-way catalyst. This would then offer a means to provide very low $NO_x$, CO and unburned hydrocarbon emissions.

## Background

*Alcohols as Engine Fuels*

Methanol has a history of being used as a fuel for racing vehicles. Its large enthalpy of vaporization allows for evaporative cooling of the intake air, thereby increasing the charge density per stroke. It also has a high octane number that allows high compression ratios to be used. Its toxicity to humans, however, makes it challenging to deploy and use on a large scale.

The use of neat ethanol, as well as blends, continues to have research attention. Applied to spark-ignited engine operation, ethanol is resistant to autoignition and thus has a relatively high octane rating, which can allow for higher compression ratios. For ethanol as a compression ignition engine fuel the focus has been put on diluted conditions, where trapped residual exhaust gases help to reduce peak combustion temperatures and thus avoid soot formation [3]. Maximal engine work output, however, is sacrificed. As a fuel additive, the inherent oxygen content of ethanol has been shown to reduce particulate matter, although it may not be enough to avoid after-treatment [4].

*Simulating Direct-Injection Combustion*

Simulating the process of liquid fuel injection, atomization, vaporization, mixing with air, and ultimately combustion is a challenging task. Models have been developed at a number of research institutions with a variety of capabilities and goals. One class of model uses empirical correlations to estimate fuel-air mixture preparation and divides the jet into a number of discrete zones (or packets) for computational simplicity [5]. This type of phenomenological model is capable of estimating heat release rates and even emissions. The disadvantage is that many empirical correlations are often engine- or fuel-specific, and applying these models to a broader range of applications (i.e. high pressure and temperature, off-nominal environments) is difficult to do with confidence. A more complicated approach resolves the three-dimensional turbulent flow throughout the cylinder with computational fluid dynamics. Sub-models are then applied that account for fuel droplet formation and evaporation, air entrainment, etc [6]. This type of modeling is computationally demanding, and otherwise requires a great deal of care in setting up specific conditions.

Under this research project, a model is desired that can compute temporal and spatial species formation within a reacting jet by making a number of reasonable assumptions and simplifications. Thus it may be exercised over a variety of parameters in order to help understand soot formation trends and to guide experimental investigations.

## Results

*Experimental Images*

Injections of methanol and ethanol are made into similar high temperature and pressure air environments, and images are taken in order to observe soot formation behavior. The following figure shows each fuel jet after ignition during the nominal "steady-state" period of the jet.

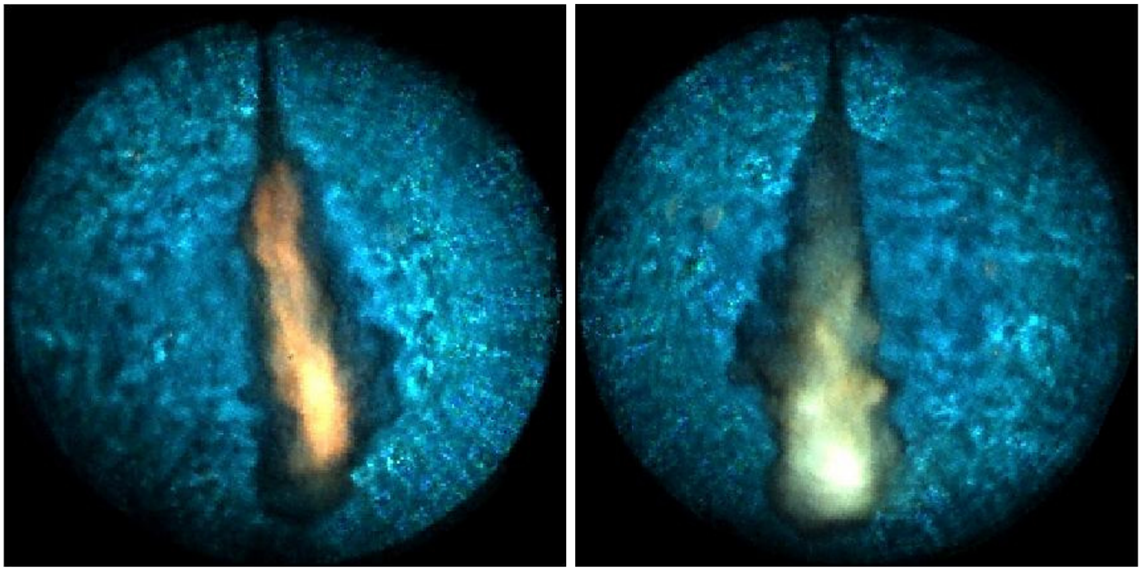

**Figure 1:** Comparison between methanol (left) and ethanol (right) injections

In the above figure, the images are taken at top dead center (TDC) for a compression ratio of ~ 43:1. The ambient air temperature and pressure are approximately 1180 K and 175 bar, respectively. This comparison shows a number of features. First, the color of the soot radiation is noticeably different. Soot particles radiate similar to a blackbody, and their temperature is directly related to the wavelength of emitted light. The images indicate that the flame temperature is lower for the orange color within the methanol jet, compared to the yellow radiation from the ethanol jet. This is explained, in part, by the fact that methanol has an enthalpy of vaporization that is roughly 30% greater than ethanol by mass, and this results in lower vaporized fuel temperatures, and hence lower peak combustion temperatures. Secondly, the location where the soot is observed to first form within the jet, relative to the injector nozzle, is further upstream and more discrete for the methanol fuel. The jets do, however, show some common features. For instance, the width of each jet is roughly the same, indicating that the air entrainment rates are comparable.

Figure 1 is helpful in making a qualitative assessment of relative soot formation characteristics as a function of the fuel under consideration. The next step is to observe how injection timing and fuel preparation (i.e. mixing with a moderator species, such as water) strategies can be used to reduce particulate formation. One such initial investigation has been made by mixing water with methanol prior to injection. The following figure shows a comparison of this strategy with that of injecting neat methanol

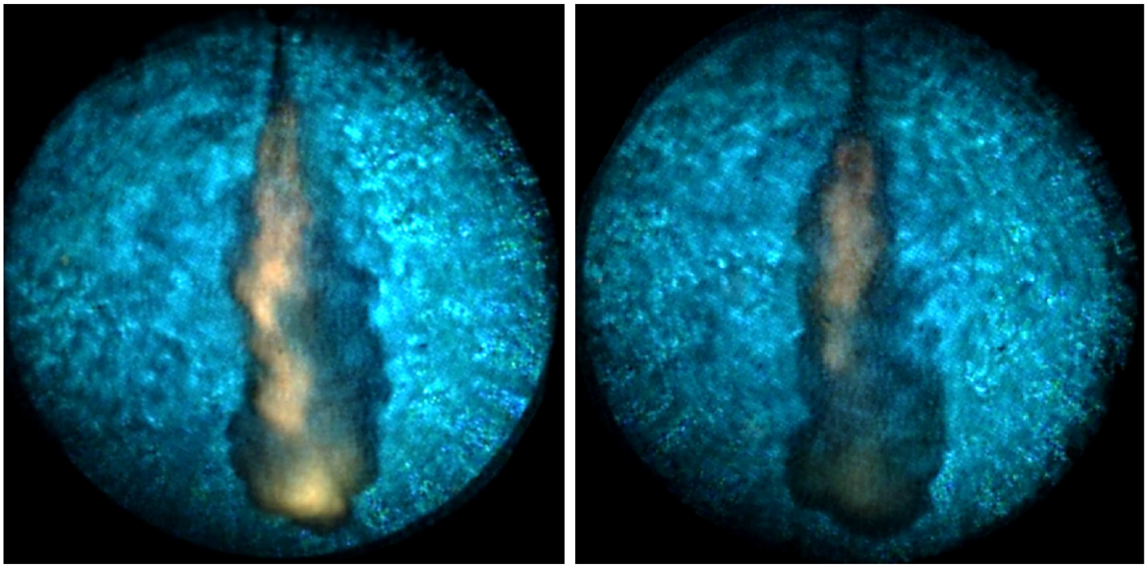

**Figure 2:** Comparison between neat methanol (left) and a 4:1 molar mixture of methanol and water (right)

The images above are taken at TDC for a compression ratio of ~ 46:1 with an associated ambient air temperature and pressure of approximately 1200 K and 185 bar. The neat methanol injection image on the left shows soot radiation similar to that shown in Figure 1. The image on the right shows an injection of methanol-water mixture in a 4:1 ratio by mole. This jet does show some soot particles radiating in the visible wavelengths, although considerably less than with no water. There are two possible causes. First, there could be a chemical effect whereby the water dissociates, contributing OH radicals and allowing the cracked fuel species to oxidize rather that form aromatic ring soot precursors. Second, there may be a thermal effect where the water's relatively large enthalpy of vaporization (approximately twice that of methanol) cools the gas and keeps peak combustion temperatures below the threshold of forming significant amounts of soot. It is believed that the latter affect is responsible in this case, since the dissociation of water is very energy intensive. Further experiments are planned to investigate the chemical effect of moderator addition, perhaps with the use of more aggressive components, such as a water-hydrogen peroxide solution.

Next, an investigation is made into the effect of injection timing on the influence of soot formation. The fuel used here is neat ethanol. The following figure shows two images that are captured at the same time during the free-piston travel. The image on the left reflects an injection start time of 2.7 ms before top dead center (BTDC), and on the right 2.2 ms BTDC.

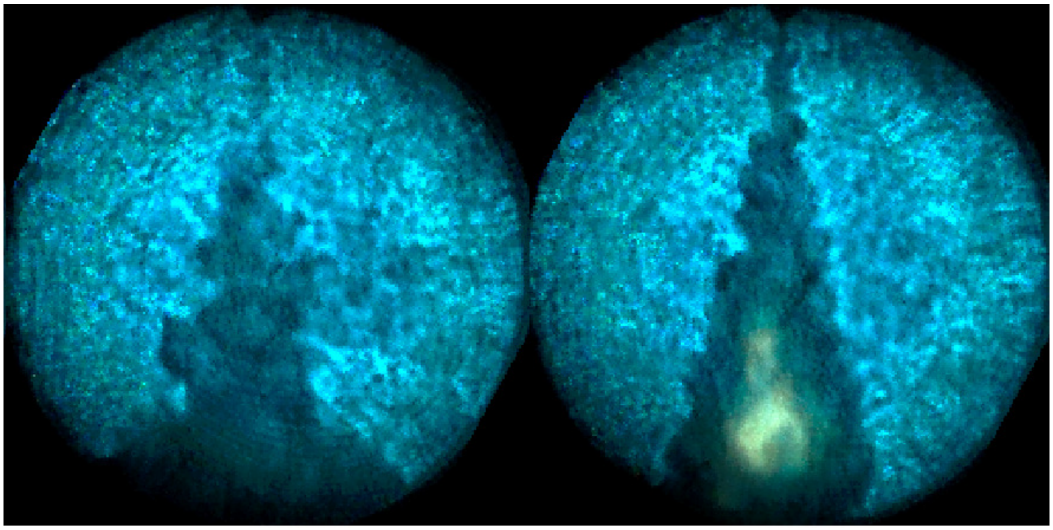

**Figure 3:** Neat ethanol injection, comparing injection timing and resultant soot formation

The above figure clearly shows that for the situation on the right, a soot-formation threshold has been crossed. The image on the left indicates that the air entrainment and mixing rates are sufficient to suppress any significant soot build-up. This comparison demonstrates the importance of the competition between air entrainment and mixing time scales versus the ignition delay time for the mixture.

*Numerical Modeling Results*

In order to understand jet mixing and combustion behavior, a model is being developed that is based on conservation principles of mass, momentum and energy [7]. The jet is assumed to be in steady-state and axisymmetric, thus axial and radial dimensions are resolved. Also, the atomization of fuel and vaporization of the droplets are assumed to happen sufficiently fast such that flow field has two distinct phases: a penetrating liquid core and a surrounding gas phase mixture of fuel and air. Profiles of mean axial velocity, mean mixture fraction, and mean enthalpy for the gas mixture are computed. Turbulence parameters are implicitly included through an assumed profile shape function for both axial velocity and mixture fraction. The assumed function for the velocity profile is Gaussian-like and of the form:

$$\overline{U}(x,r) = C_1 \cdot \left(\frac{1}{x}\right) \cdot \left(1 + C_2(x) \cdot \left(\frac{r}{x}\right)^2\right)^{-2} \tag{1}$$

At any particular plane that is normal to the jet axis, the conservation of momentum flux at axial location *x* is described as:

$$J(x) = \int_0^{r_\infty} \bar{\rho}(x,r) \cdot \overline{U}(x,r)^2 \cdot 2\pi r \cdot dr \tag{2}$$

It is noted that the gas density under the integral also varies, thus an iterative solution procedure is required. The momentum flux must be conserved at each downstream location, and its value is equal that which is injected at the nozzle tip:

$$J(x) = J_o = \rho_{liq} \cdot {U_{jet}}^2 \cdot \pi \cdot \left(\frac{d_{nozzle}}{2}\right)^2 \qquad (3)$$

In this equation, $\rho_{liq}$ is the liquid density of the fuel, $d_{nozzle}$ is the injector nozzle diameter, and $U_{jet}$ is the velocity of the liquid issuing into the combustion chamber. This allows for the computation of a mean velocity profile, at each particular axial location, and is defined for all radial values.

The mixture fraction varies from a value of unity within the liquid fuel at the nozzle tip to a value of zero in the surrounded air, and is defined at any location as:

$$Z = \frac{\dot{m}_{fuel}}{\dot{m}_{total}} = \frac{\dot{m}_{fuel}}{\dot{m}_{air} + \dot{m}_{fuel}} \qquad (4)$$

The assumed profile shape is of the same form as that for the axial velocity function, and the determination of its constants are based on fuel mass flow conservation at each axial location, as described by:

$$\dot{m}_{fuel}(x) = \int_0^{r_\infty} \bar{Z}(x,r) \cdot \bar{\rho}(x,r) \cdot \bar{U}(x,r) \cdot 2\pi r \cdot dr \qquad (5)$$

The total fuel flow rate is imposed by the condition at the nozzle tip:

$$\dot{m}_{fuel} = \rho_{liq} \cdot U_{jet} \cdot \pi \cdot \left(\frac{d_{nozzle}}{2}\right)^2 \qquad (6)$$

The following graph shows the resultant mixture fraction of the flow field. The parameters used apply to the injection of neat ethanol into air that has been isentropically compressed from ambient conditions to a compression ratio of 60, such that the surrounding air is at a temperature and pressure of 1300 K and 270 bar, respectively. The fuel pressure is 1200 bar, typical for a common-rail Diesel fuel delivery system, and the resultant liquid velocity is 318 m/s. The line that corresponds to a stoichiometric mixture has been highlighted.

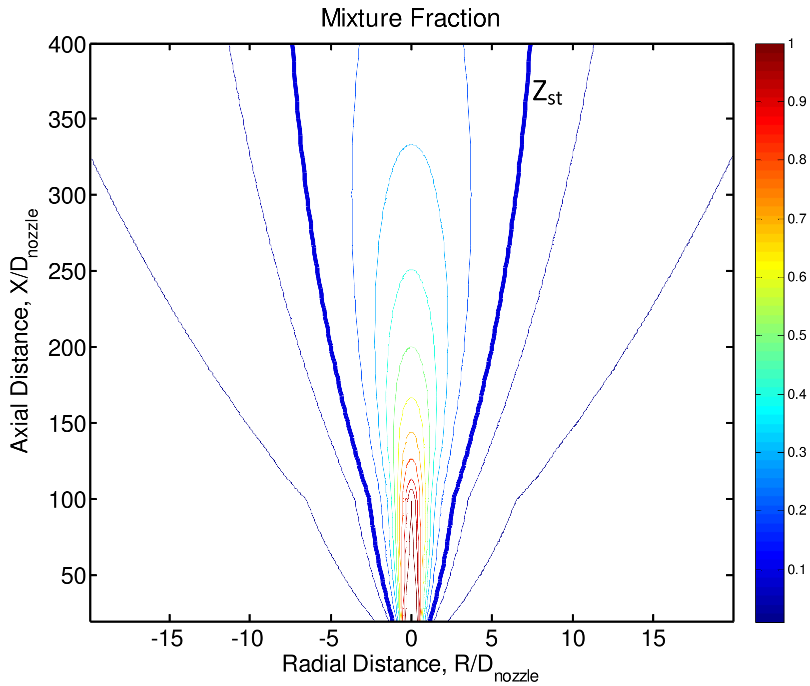


**Figure 4:** Model results showing mean mixture fraction within an ethanol injection

The model uses liquid penetration depth as an input parameter. This could easily be determined experimentally for ethanol, as was done by Matt Svrcek using Diesel no.2 under previous GCEP work [8].

With the mixture fraction solved, the enthalpy of the flow may be determined by making the assumption that the turbulent Lewis number is unity. This implies that turbulent mixing of mass and energy are equivalent. Turbulent gas jet theory pioneered by Abramovich indicates that this is a reasonable assumption [9]. The mean enthalpy throughout the axially symmetric jet is then computed from the known Z($x,r$) function:

$$\bar{Z}(x,r) = \frac{\bar{h}(x,r) - h_{air}^{\infty}}{(h_{jet}+h_{fg}) - h_{air}^{\infty}} \qquad (7)$$

In equation 7, $h_{\text{jet}}$ is the enthalpy of the liquid fuel at the nozzle tip conditions, and $h_{fg}$ is the enthalpy of vaporization of the fuel. In order to accurately determine these two values, a fundamental equation for the thermodynamic properties of ethanol as a real fluid is employed [10]. Properties of the gas phase are assumed to follow ideal gas laws.

Once mean values of composition and enthalpy are determined throughout the jet, the unreacted gas temperatures can be computed. This provides a starting point for how to incorporate chemical kinetics and to observe resultant combustion temperatures and species formation. The following graph shows a comparison of two cases: On the left is the resultant gas temperature if at all locations within the jet chemical equilibrium is reached; on the right is a plot of gas temperatures if time-dependent chemical reactions are taken into account. The latter relies on the use of a chemical kinetics model, and the results shown here incorporate a mechanism developed by the Lawrence Livermore National Lab for ethanol combustion [11].

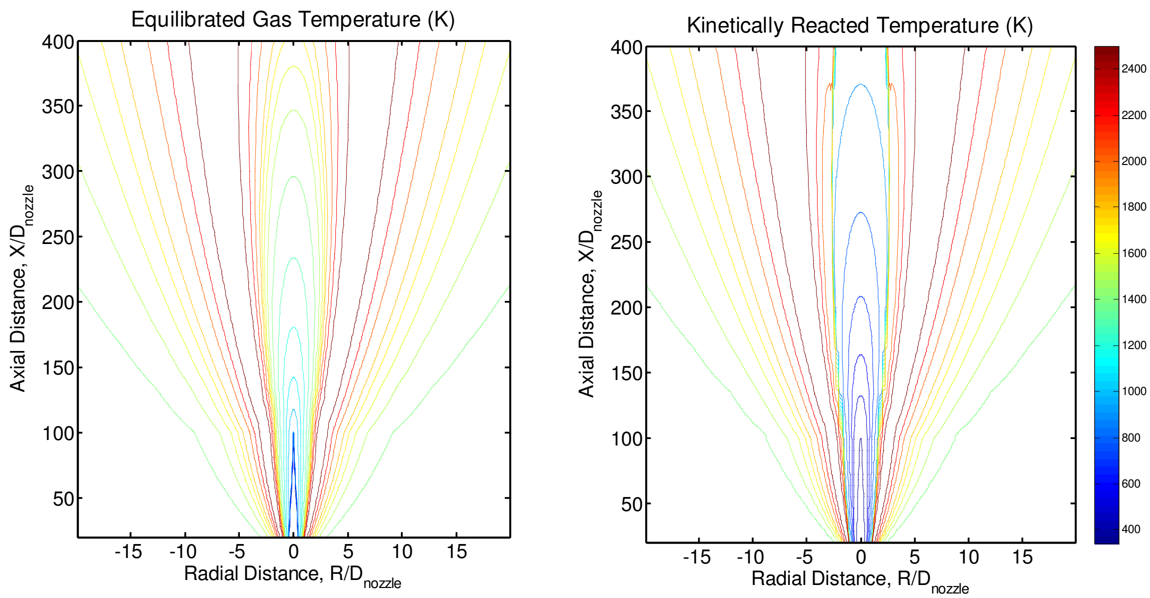


**Figure 5:** Model result comparing equilibrium temperature of the jet and the temperature obtained by applying a chemical reaction model

For both plots in the figure above, the highest temperatures are reached right around the contour that corresponds to a stoichiometric mixture, as can be seen in comparison with Figure 4. The major difference between the two is the rich core region in the center of the jet. For the case that includes time-dependent chemistry, the model indicates that the rich inner mixture remains relatively cool until a point where enough air has been entrained, and then the reaction progresses to equilibrium rapidly within the region that is just slightly rich of stoichiometric.

*Engine Experiments*

While the free-piston, extreme compression device is helpful in observing single-jet soot formation behavior, a connection to real world engines needs to be made. To address this issue, a single-cylinder, direct-injection research engine is used to measure engine-out soot emissions for a variety of fuels and injection strategies. An AVL soot meter is employed to measure the smoke number at the exhaust output. This number predicts a soot concentration, which is then normalized by the work output of the engine (indicated work) to compare against the current emissions limit.

This research engine uses a 17:1 geometric compression ratio – a representative value for Diesel engines. Boosting may be simulated using a synthetic turbocharging system, but for initial measurements the back pressure is held at ambient conditions while enough air is supplied to provide 100% volumetric efficiency (i.e. perfect breathing, no boost). Fuel is injected directly overhead into a bowl-in-piston geometry.

Two different injectors are used: a Bosch solenoid-actuated injector used in Volvo turbo-Diesels, and a Bosch piezo-actuated injector used in the Volkswagen Jetta. While the solenoid injector allows for the study of conventional, single-shot fuel injections, the piezo injector is capable of multiple fuel injections per cycle. Early injections can be used to promote increased fuel-air mixing before ignition, while late injections can be used to provide load extension and to limit the rate-of-rise and peak pressures.

Initial soot emission experiments compare three fuels: standard Diesel no.2, which sets a baseline and provides a comparison point to established Diesel emission data, neat ethanol, and neat methanol. The use of alcohols presents a number of challenges with the reciprocating engine. For one, and perhaps most importantly, the low viscosity of the alcohols is problematic for pumps and injectors designed for gasoline or Diesel. While the fuel pump has shown no deterioration thus far, it is limited to a lower operating pressure when using alcohols, which may be due to fluid losses past sealing elements. The solenoid injector is especially difficult to use with alcohols, and a significant decrease in injection quality occurs rather quickly while testing. The piezo injector performs much better, with no indication of injection quality loss. Alcohol fuels may also have corrosive effects that damage components, although flushing all components with Diesel after alcohol injection operation helps minimize this issue. A lubricity improver could be added to the alcohol fuel, although it may have an unknown effect on soot formation and has been avoided thus far.

Alcohol fuels also present the challenge of being much more resistant to autoignition than Diesel. When operating with ambient-temperature intake air, a 17:1 compression ratio is insufficient to ignite directly-injected ethanol or methanol. As a result, an intake heater is used to vary the intake air temperature between 100 – 200 degrees Celsius, as needed to provide for well-behaved autoignition. In a production engine, it is possible that uncooled turbocharger compression would increase intake charge temperature enough for stable alcohol operation. Additionally, exhaust gases could be trapped as residuals within the cylinder to increase BDC charge temperatures.

Figure 6 below shows the effect of equivalence ratio on soot emissions. For each fuel, the timing for a single pulse injection and intake air temperature are held constant while the injection duration is varied to change equivalence ratio (i.e. load). It is noted that the Diesel fuel injection is performed at a lower rail pressure to enable lower loads. While this further increases Diesel soot formation due to worse atomization and fuel air mixing, it does not change the general trend observed in the data.

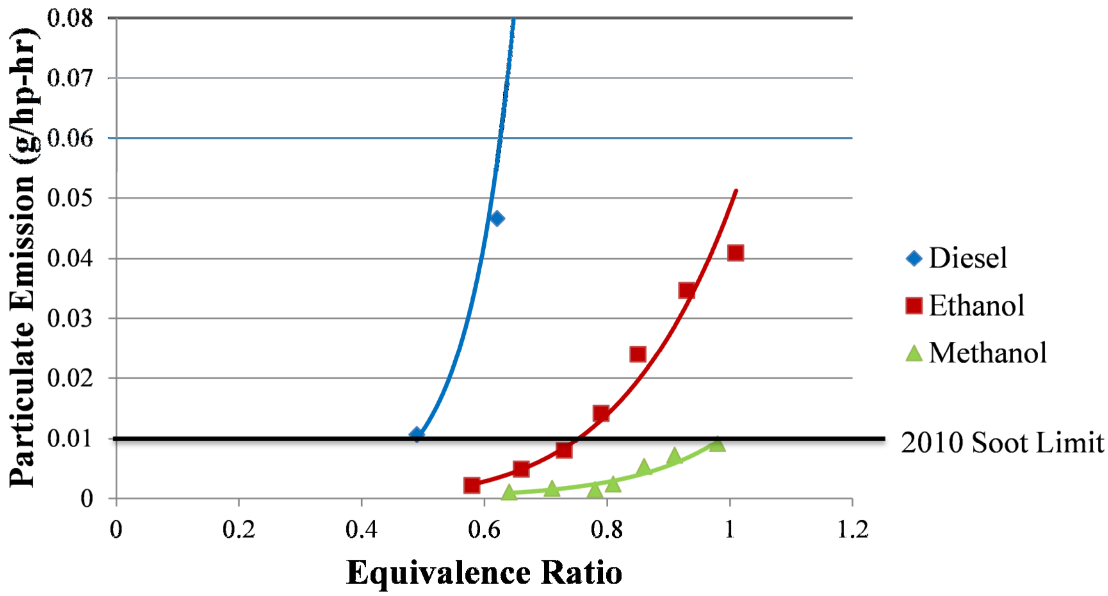


**Figure 6:** Smoke meter emission measurements from a single-cylinder reciprocating engine, comparing alcohol fuels and Diesel

Figure 6 shows that Diesel soot emissions increase dramatically past an equivalence ratio of 0.6, and are beyond the scale of the plot for richer mixtures. All Diesel fuel data points indicate that a particulate filter is required to meet emission standards. The ethanol particulate measurements, although considerably less than that of Diesel, still exceed the emissions limit as the equivalence ratio approaches stoichiometric. Methanol injections do form some soot, as previously shown in the single-shot experimental images. In this apparatus, the cylinder-out smoke measurements show that it remains below the emissions limit out to stoichiometric operation.

For the data shown in Figure 6 the injector used is the more common solenoid-actuated type. Preliminary tests using the piezo-actuated injector, however, indicate that soot measurements are compliant with the 2010 limit out to stoichiometric operation with ethanol for just a single-pulse injection. In addition, a multi-injection strategy has the potential to reduce cylinder-out particulates even further. Soot emissions can be reduced by another factor of three by implementing a small (25% of the total delivery) pre-injection to promote early fuel-air mixing. This indicates that utilizing the latest injection hardware technology and more sophisticated scheduling strategies may allow directly-injected ethanol operation without any soot after-treatment equipment.

*Engine Efficiency Consequences*

There is an interesting consequence of desiring high air-temperatures for both autoignition requirements of alcohol fuels as well as a potential means for driving in-plume fuel reformation reactions with moderator species. This is that high in-cylinder gas temperatures may be achieved by eliminating the loss as heat transfer to the coolant, and allowing in-cylinder surface temperatures to remain high. This naturally leads to a broader discussion of overall engine efficiency.

Heat transfer from combustion gases can significantly reduce engine efficiency, especially at high-load conditions, and accounts for roughly 25% of the fuel's exergy. The high combustion temperatures and large surface-to-volume ratios at TDC demand some insulation of the combustion chamber to avoid loss of work potential as heat transfer through the surfaces. This can be accomplished by using ceramic coatings on engine parts, namely the non-lubricated surfaces like the piston face, head, valves and ports. Coating technology is ubiquitous in the gas turbine industry, and has been an active area of engine research for thirty years. While more work may be necessary to improve coating effectiveness and durability, it does hold promise for reducing heat transfer losses in high temperature combustion processes.

Heat loss reduction is essential for raising efficiency in a high-temperature combustion strategy. It is also useful as a means to further utilize the *Extreme States Principle*. The phenomenon of reducing entropy generation and increasing work output efficiency was experimentally proven with the free-piston, extreme compression device, which enables high-energy-state combustion through high geometric compression ratios. Elevated surface temperatures achieved in low-heat-rejection (LHR) engines serve a similar purpose by heating the intake charge to a higher energy state. However, this comes at the cost of reduced charge density. Modeling indicates that pre-ignition charge temperatures can be increased by at least 40 K in an LHR engine. This means that combustion chamber insulation would not only minimize heat transfer losses, but also reduce the irreversibility of the combustion reaction.

High compression ratios and reduced heat transfer are only part of the pathway to higher engine efficiency. The complete discussion must include exhaust utilization. The effect of reducing heat transfer alone is small. The primary opportunity is the increased exhaust enthalpy, a resource from which further work extraction must be considered.

The most common form of exhaust enthalpy utilization is a turbocharger, which uses the energy to compress the intake charge. This compression creates a higher effective compression ratio and helps to further increase pre-combustion temperature, upwards of 100 K, resulting in a greater reduction of combustion irreversibility. Further expansion, beyond what is necessary for pre-compression, can be accomplished either in-cylinder with an asymmetric expansion stroke, or external to the cylinder in a separate turbine compounded to the crankshaft. Additional exhaust energy extraction could be accomplished by thermal regeneration, for instance heating compressed water and creating steam for reinjection into the cylinder. There is also a possibility of adding a bottoming cycle, such as a Rankine cycle, albeit in a compact form for transportation purposes.

An engine model is created to quantify the benefit from combinations of these options. The possible efficiency gains for some of these configurations are shown below.

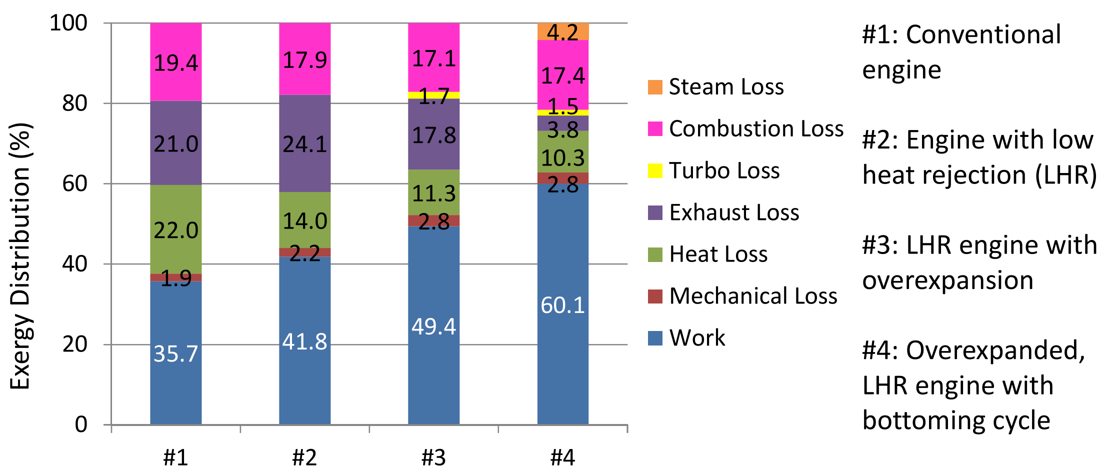


**Figure 7:** Fuel exergy distribution plots showing the increase in work output for low-heat-rejection strategies with exhaust enthalpy utilization

The engine model results show an increase in efficiency as heat transfer is reduced and exhaust enthalpy is utilized more completely. As expected from the *Extreme States Principle,* the combustion irreversibility (i.e. exergy destruction) is also reduced from the conventional engine case. The geometric compression ratio used in the model is 17:1, similar to the single-cylinder research engine. The model also uses a 2.5 bar boost pressure on the intake raising the effective compression ratio to about 30:1, which accounts for intake charge heating.

**Progress**

The work accomplished thus far under the Sootless Diesel GCEP project has illuminated a number of avenues that may well prove to be practically viable methods for significantly reducing engine-out soot emissions. The simple inclusion of water either injected with the fuel or separately has the potential to both reduce particulate formation and offer increased engine efficiency via thermal regeneration. Once more details regarding each strategy are further understood, this may provide a short path to Diesel engine modification and cleaner, more fuel-efficient operation.

The soot emission measurements from the alcohol fuels are very promising. These initial results indicate that with the use of modern injectors and the capability afforded with multi-pulse injection scheduling, cylinder-out particulates may not require any after-treatment, even up to full load conditions. Especially in light of growing commercial ethanol production trends, heavy-load Diesel engines operating on such a fuel could find its way to market relatively soon.

**Future Plans**

*Experimental Research*

The results from the low-heat-rejection engine simulation provide some additional direction for experimental investigation with both the reciprocating and free-piston devices. While the upper end of compression ratios for the free-piston device is 100:1, it is important to investigate soot reduction strategies down to ~ 30:1 compression ratios, which could be implemented within conventional engines.

Regarding the free-piston device, future experimentation will include a further exploration of chemically participating moderator addition. With water, a high pre-heat of ambient air and use of a high compression ratio may be enough to dissociate the water. If not, there is the possibility of using a water-hydrogen peroxide solution in order to demonstrate its effects. This would not necessarily be a practical solution for commercial engines. Also, there is interest in using higher-carbon alcohol fuels, such as propanol and butanol, in order to observe their soot-forming tendencies.

With the single-cylinder reciprocating engine, a ceramic coating will be applied to the piston face, valves, and exhaust port surfaces. Testing will then be conducted with the fuels to observe autoignition behavior as well as soot emission measurements, in addition to evaluating the increase in energy content of the exhaust gas.

*Simulation Development*

The results shown for the turbulent gas jet model require further validation from experimental data. Additionally, the incorporation of a chemical mechanism that includes relevant soot precursor species, namely aromatic compounds such as benzene and naphthalene, will be added in order to understand soot formation propensity. Ultimately, this model will be used to explore different fuels, the effect of moderator addition, and combustion characteristics through a variety of injection conditions.

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