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# II.4 Advanced Light-Duty SI Engine Fuels Research: Multiple Optical Diagnostics of Well-Mixed and Stratified Operation

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## Project Introduction

Ever tighter fuel economy standards and concerns about energy security motivate efforts to improve engine efficiency and to develop alternative fuels. This project contributes to the science base needed by industry to develop highly efficient direct injection spark ignition (DISI) engines that also beneficially exploit the different properties of alternative fuels. Here, the emphasis is on lean operation, which can provide higher efficiencies than traditional non-dilute stoichiometric operation. Since lean operation can lead to issues with ignition stability, slow flame propagation and low combustion efficiency, the focus is on techniques that can overcome these challenges. Specifically, fuel stratification is used to ensure ignition and completeness of combustion but this technique has soot and $NO_x$ emissions challenges. For ultra-lean well-mixed operation, turbulent deflagration can be combined with controlled end-gas autoignition to render mixed-mode combustion for sufficiently fast heat release. However, such mixed-mode combustion requires very stable inflammation, motivating studies on the effects of near-spark flow and turbulence, and the use of small amounts of fuel stratification near the spark plug.

## Objectives

- Provide the science base needed by industry to understand how emerging alternative fuels impact highly efficient DISI light-duty engines being developed by industry
- Elucidate how engine design and operation can be optimized for most efficient use of future fuels
- Develop and apply advanced optical diagnostics for probing in-cylinder processes

## Approach

The Alternative Fuels DISI Engine Lab at Sandia houses an engine that is capable of both performance testing and in-cylinder optical diagnostics. First, performance testing with an all-metal engine configuration is conducted over wide ranges of operating conditions and alternative fuel blends. This allows quantifying fuel efficiency and exhaust emissions behavior. Second, in-cylinder processes are examined with high-speed optical diagnostics, including advanced laser-based techniques. This reveals the mechanisms that govern the combustion process. Computer modeling provides additional insight of the governing combustion fundamentals. The combination of performance testing, exhaust emissions measurements, optical diagnostics, and modeling allows building a comprehensive science base.

## Results

Key accomplishments for Fiscal Year 2017:

- Demonstrated when Particulate Matter Index (PMI) predicts smoke emissions for DISI operation, and when it does not
- Identified how soot production pathways change with fuel type and operating conditions for stratified charge spark ignition (SI) operation
- Developed semi-quantitative wall-wetting diagnostics based on refractive index matching (RIM)
- Examined how the high heat of vaporization of E30 (30% ethanol, 70% gasoline) leads to increased wall wetting and pool fires
- Established stratification technique to stabilize ultra-lean SI combustion for effective parametric fuel studies of lean autoignition

In the following sections, selected detailed examples of Fiscal Year 2017 accomplishments are presented.

### *Fully Stratified Operation*

Spray-guided stratified charge SI operation is one promising approach to lean operation that can provide high thermal efficiency, but fuel stratification can cause high engine-out smoke levels. The Co-Optima effort requires an understanding of soot formation pathways and how they are affected by fuel composition and fuel specifications. In this research task, the applicability of PMI is assessed for both stratified lean and well-mixed stoichiometric operation. However, only results for stratified operation are presented in this report. PMI is a fuel property metric that is intended to be predictive of particulate emissions from SI engines (Aikawa et al. 2010). For stratified operation with moderate boost at 2,000 rpm, the plotted brown circles in Figure II.4.1 show that the engine-out soot increases monotonically with increased PMI, consistent with literature results. However, for naturally aspirated operation at 1,000 rpm, the light blue squares show that the measured engine-out soot is highest for the E30 fuel. Hence, PMI is not predictive of engine out-soot for these naturally aspirated conditions. In-cylinder optical diagnostics have revealed that under these conditions, the enhanced vaporization cooling associated with the ethanol fraction in E30 causes wall wetting and pool fires, as illustrated in the top right portion of Figure II.4.1. These findings highlight the need to further develop fuel property metrics that can predict the effect of fuel on engine particulate matter (PM) emissions, and also to closely monitor the formation of fuel wall films for advanced combustion systems that utilize direct fuel injection.

To minimize the exhaust aftertreatment burden, low engine-out $NO_x$ is required for lean stratified charge SI operation, which in turn mandates the use of exhaust gas recirculation (EGR) to limit peak combustion temperatures. However, Figure II.4.2 shows that the response of engine-out soot to EGR varies greatly with fuel and operating conditions. For moderately boosted operation at 2,000 rpm using the High-Aromatic Co-Optima Core fuel, the application of EGR increases engine-out soot while $NO_x$ is suppressed. Simplistically, engine-out soot = (soot formed) - (soot oxidized). Soot oxidation is impeded by EGR, explaining this $NO_x$–PM trade-off, which is analogous to that of diesel combustion. For this type of stratified charge SI engine operation at 2,000 rpm, previous work has indicated that soot formation is a bulk-gas phenomenon (Zeng et al. 2017). For such conditions with bulk-gas soot as the dominating path to exhaust soot, Figure II.4.1 shows that PMI is predictive. In stark contrast, for non-boosted operation at 1,000 rpm using E30 fuel, Figure II.4.2 shows that engine-out soot goes down with $NO_x$ as EGR is applied, suggesting a different soot production pathway. Since soot oxidation is hampered by EGR, the reduction of engine-out soot with increasing EGR must be caused by a strong reduction of the soot formation. The fouling of the piston bowl window can be used as an indicator of the amount of soot formed in pool fires. The upper part of Figure II.4.2 shows that the soot deposit rate is much greater for the case with 18% $O_2$ in the intake, indicating more sooting near-wall flames. Hence, it can be surmised that the soot formation is controlled by the intensity of pool fires. For these conditions, Figure II.4.1 shows that PMI is not predictive of engine-out soot.

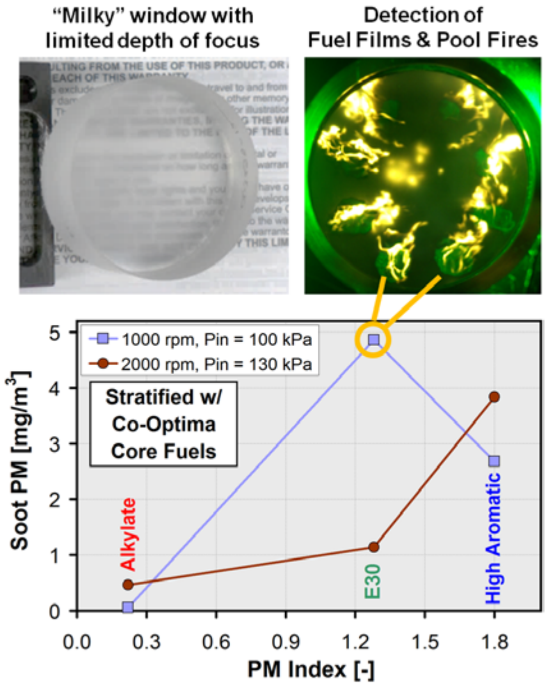
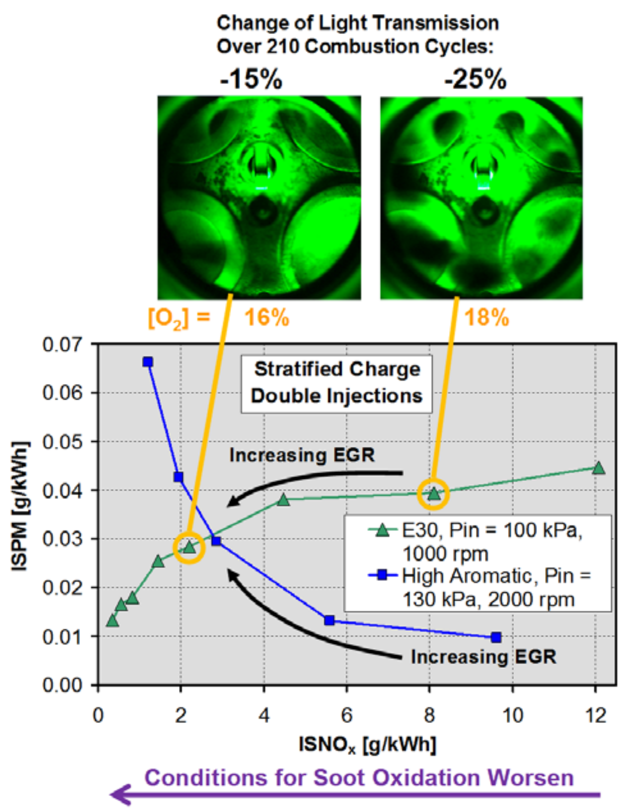



Figure II.4.1 - For boosted, stratified charge, direct injection SI operation at 2,000 rpm, engine-out soot increases monotonically with the fuels' PMI, as the soot formation is primarily occurring in the bulk gases. But for naturally aspirated operation at 1,000 rpm, soot emissions for E30 are higher than predicted from PMI due to the formation of pool fires. PMI values were provided by Fioroni et al. (2017). Figure by Magnus Sjöberg and Carl-Philipp Ding, SNL.




$ISNO_x$ – indicated specific $NO_x$; ISPM – indicated specific PM

Figure II.4.2 - A change of $NO_x$–PM trade-off indicates a change of the dominating soot production pathway with fuel type and operating conditions. Figure by Magnus Sjöberg.

*Optical Diagnostics Development*

The interaction of fuel sprays and piston surfaces can be problematic for specific combinations of fuels and operating points, causing soot formation. To identify sources of exhaust smoke, efforts were devoted to the development of optical diagnostic techniques to quantify both wall wetting and pool fires in a direct injection SI engine. The technique that was selected to measure wall wetting is RIM, as first published by Drake et al. (2002). Several aspects of the RIM application were not clear from published papers, prompting further development work at Sandia. During Fiscal Year 2017, the quest for quantitative fuel film measurements involved the use of various light sources and light application approaches. In addition, substantial effort was spent on calibration methodologies and quantifying the influence of the surface roughness of the RIM windows being used. Figure II.4.3 highlights one successful implementation. Here, a continuous-wave (CW) laser beam is split into two beams, which are used to illuminate the upper rough surface of the piston-bowl window from two directions. As demonstrated in Figure II.4.3, the contrast between the wall films seen for the E30 and the alkylate fuels provides a good example of the strong effect of fuel properties on the tendency to form fuel films.

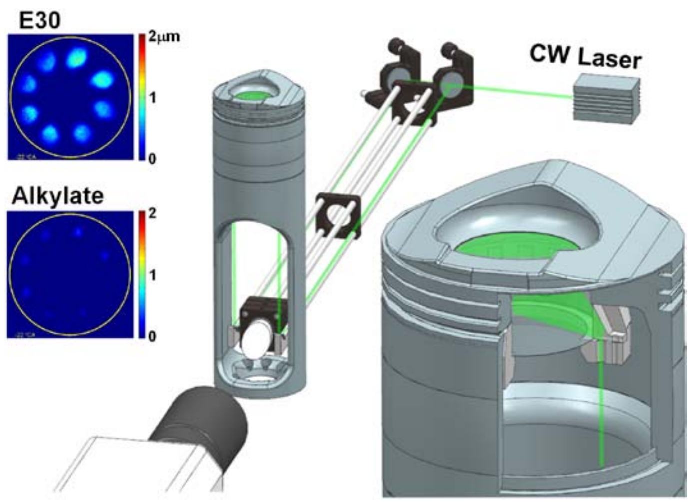


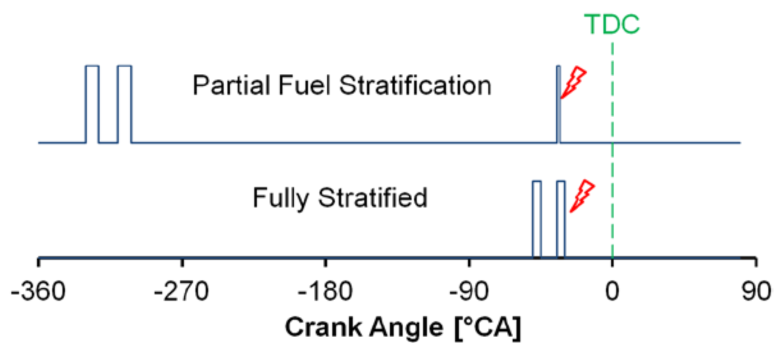

Figure II.4.3 - Laser-based measurements allow the detection of fuel wall films for various combinations of fuels and operating conditions that are prone to pool fires. Figure by Carl-Philipp Ding, Xu He, and Magnus Sjöberg, SNL

In addition to the measurement of fuel film thickness, the use of a piston bowl window with a rough surface and a "milky" appearance allows separation of flames from pool fires from sooting flames in the bulk gases. Effectively, the surface roughness limits the depth of focus as demonstrated in the upper left portion of Figure II.4.1. Therefore, flames that originate in pool fires appear sharp because they are located very close to the piston surface.

*Lean Autoignition Studies*

Lean or dilute well-mixed SI engine operation can improve thermal efficiency, but one key challenge is to maintain stable combustion without misfires. Another challenge is to maintain a 10–90% burn duration below 30° crank angle (°CA). The latter can be achieved via the use of mixed-mode combustion, which features a combination of turbulent deflagration and end-gas autoignition (Sjöberg and Zeng 2016). Although dubbed mixed-mode combustion here, it is conceptually the same as spark-assisted compression ignition combustion studied by others (Manofsky Olesky 2014). The main differences are that a larger fraction of the combustion is flame-based and that the level of internal residuals (or external EGR) is much lower. For both spark-assisted compression ignition and the current mixed-mode approach, practical implementation requires that suitable fuels are available in the marketplace, and that appropriate autoignition metrics are available to specify the fuels being used. Consequently, the applicability of Research Octane Number and Motor Octane Number for autoignition under lean conditions is currently being assessed for a range of fuels. To enable effective parametric studies of lean autoignition, it is important to overcome challenges associated with unstable flame development. To this effect, recent work has been devoted to establishing an operating methodology that is applicable over wide ranges of fuels and operating conditions.

The stratified charge capable DISI engine used here can be operated with most of the fuel injected during the intake stroke and with an additional short injection at the time of spark, as illustrated in the top portion of Figure II.4.4. The late injection enriches the regions surrounding the spark plug, as illustrated with infrared (IR) fuel–vapor imaging (Zeng et al. 2017) in the lower row of Figure II.4.5. Thanks to the enriched region, the early flame development is very fast and repeatable from cycle to cycle. An example of this is shown in Figure II.4.6, which plots the apparent heat release rate (AHRR) against the mass fraction burned for 250 individual cycles. The fuel used here is a high cycloalkane fuel, which is one out of five Co-Optima Core fuels. In this case, only 1.6 mg of fuel is injected late, which is substantially less than the image examples in Figure II.4.5. Even so, the deflagration-based AHRR is relatively repeatable, especially considering that $\varphi$ is only 0.50 outside the enriched regions near the spark plug. The transition to an autoignition-dominated AHRR occurs for mass fraction burned ≈53%, as marked by a rapid rise of the AHRR. The magnitude of this second AHRR peak varies from cycle to cycle, but the peak has a distinct shape for almost all 250 cycles. Only five cycles display no, or only weak, end-gas autoignition. Indicated mean effective pressure variability is also very low, only 0.9%, suggesting that this technique can enable parametric fuel studies of lean autoignition limits. Such studies are currently being conducted for a range of Co-Optima fuels.




TDC – top dead center

Figure II.4.4 - Conceptual comparison of fuel injection and spark timing strategies for operation with partial fuel stratification and full stratification. Figure by Magnus Sjöberg and Zongjie Hu, SNL.

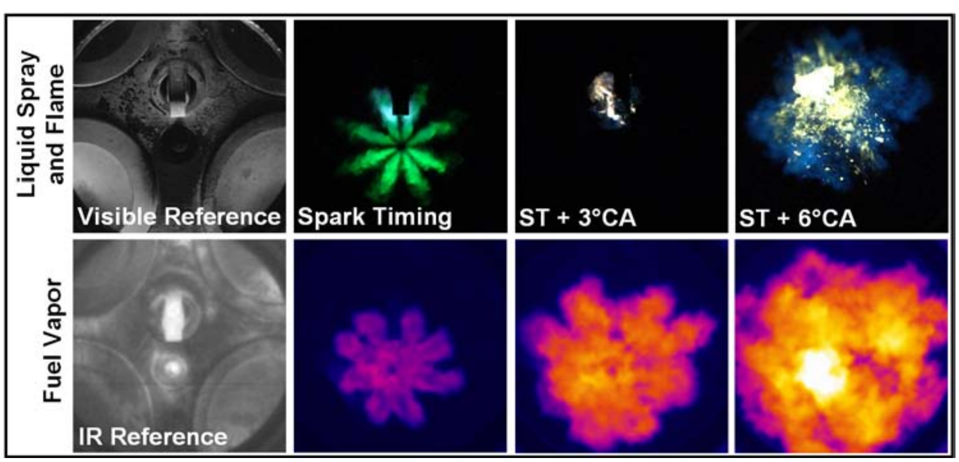
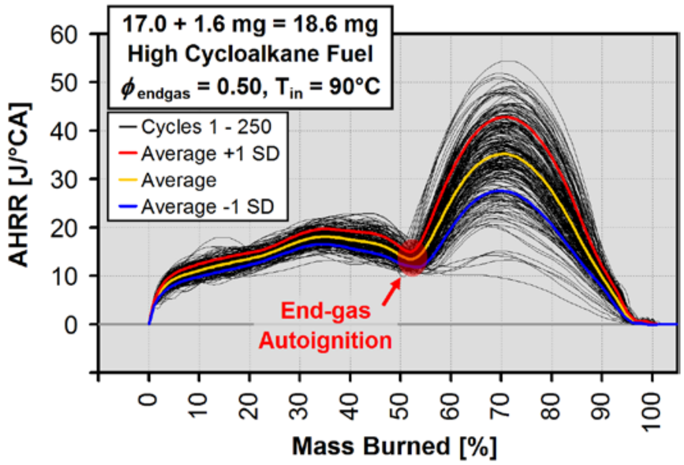



Figure II.4.5 - IR fuel–vapor imaging reveals extent of fuel stratification relative to the flame spread for operation with a late injection of 3.6 mg gasoline at the time of spark. Figure by Magnus Sjöberg, SNL.




SD – standard deviation

Figure II.4.6 - Injection of 1.6 mg of fuel at the time of spark stabilizes combustion, enabling studying autoignition of lean end-gas with $\varphi$ = 0.50, 1,400 rpm, $P_{in}$ = 100 kPa. Figure by Magnus Sjöberg, SNL.

## Conclusions

These research tasks are contributing strongly to both the Co-Optima project and to the science of fuel–combustion interactions for advanced SI engine combustion.

For the DISI engine used here, PMI is a good predictor of exhaust soot for fully warmed-up steady-state operation, both for stoichiometric well-mixed operation and for boosted stratified charge operation. However, PMI is not predictive of soot for an E30 fuel under colder transient stoichiometric operation, nor for stratified charge non-boosted operation. Specifically, for non-boosted stratified charge operation, wall wetting and pool fires become a dominating soot production pathway when E30 fuel is used.

The RIM technique works well as a diagnostics for fuel wall wetting, both with light-emitting diode- and laser-based illumination. The milky window RIM technique also allows distinguishing near-wall flames from soot flames in the bulk gases.

Lastly, it was demonstrated that partial fuel stratification is very effective for stabilizing flame development in an overall ultra-lean charge, enabling parametric fuel studies of lean autoignition limits.

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Zeng, W., M. Sjöberg, D.L. Reuss, and Z. Hu. “High-Speed PIV, Spray, Combustion Luminosity, and Infrared Fuel-Vapor Imaging for Probing Tumble-Flow-Induced Asymmetry of Gasoline Distribution in a

Spray-Guided Stratified-Charge DISI Engine." *Proc. Comb. Inst*. 36:3, pp. 3459–3466, 2017, doi: 10.1016/j.proci.2016.08.047.

## Key Fiscal Year 2017 Publications

1. Zeng, W., M. Sjöberg, D.L. Reuss, and Z. Hu. "High-Speed PIV, Spray, Combustion Luminosity, and Infrared Fuel-Vapor Imaging for Probing Tumble-Flow-Induced Asymmetry of Gasoline Distribution in a Spray-Guided Stratified-Charge DISI Engine." *Proc. Comb. Inst.* 36:3, pp. 3459–3466, 2017, doi: 10.1016/j.proci.2016.08.047.

2. Zeng W. and M. Sjöberg. "Utilizing boost and double injections for enhanced stratified-charge direct-injection spark-ignition engine operation with gasoline and E30 fuels." IJER 18:1-2, pp. 131–142, 2017, doi: 10.1177/1468087416685512.

3. Singleton, D., J.M. Sanders, M.A. Thomas Jr., M. Sjöberg, J. Sevik, M. Pamminger, and T. Wallner. "Improved dilution tolerance using a production-intent compact nanosecond pulse ignition system." 3rd Int. Conf. on Ignition Systems for Gasoline Engines, Berlin, Germany, November 2016.

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