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Alternative Fuels DISI Engine Research

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Overall 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.
- How engine design and operation can be optimized for most efficient use of future fuels.

Fiscal Year (FY) 2014 Objectives

- Continue work towards a conceptual model of stratified SI combustion that incorporates the effects of fuel on combustion rate, ignition stability and exhaust-emissions formation.
- Identify and explain combinations of fuel characteristics and operating strategies that enable stable and efficient well-mixed lean SI operation.
- Conduct initial tests with advanced ignition systems.

FY 2014 Accomplishments

- Demonstrated combined effects of gasoline-ethanol blend ratio and spark-timing strategy on exhaust soot.
- Quantified and examined in detail factors that govern heat-release rate and its variability when the stratification level is tailored to the fuel composition. This included optical measurements of spray variability, flow field and flame development.
- Quantified lean stability limits and fuel-efficiency gains for E85 and gasoline fuels.
- Examined combined effects of intake heat and fuel type on the ability to achieve controlled end-gas autoignition for higher combustion efficiency for lean SI operation.
- Conducted a combined optical/performance study of advanced multi-pulse transient plasma ignition for E85, explaining fundamental ignition requirements for stable ultra-lean combustion.
- These accomplishments address one of the barriers identified by DOE VT: Inadequate data for fuel property effects on combustion and engine efficiency optimization.

Future Directions

- Examine the use of intake boost for load-range extension of stratified-charge operation.
- Continue development of a conceptual model of stratified combustion that includes both highly-stratified operation using "head ignition" for high-ethanol fuels, and less stratified operation using "tail ignition" for acceptable soot with lower-ethanol fuels.
- Continue examination of well-mixed lean/dilute operation, using both regular spark and advanced multi-pulse ignition systems in combination with E0-E30 gasoline blends.
- Examine the effect of fuel type on combustion and fuel-economy gain for SI operation with partial fuel stratification.

Introduction

Due to concerns about future petroleum supply and accelerating climate change, increased engine efficiency and alternative fuels are of interest. This project contributes to the science-base needed by industry to develop highly efficient DISI engines that also beneficially exploit the different properties of alternative fuels. Lean operation is studied since it 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, focus is on techniques that can overcome these challenges. Specifically, fuel stratification can be used to ensure ignition and completeness of combustion, but may lead to soot and NO_x emissions challenges. Advanced ignition system and intake air preheating both promote ignition stability. Controlled end-gas autoignition can be used maintain high combustion efficiency for ultra-lean well-mixed conditions. However, the response of both combustion and exhaust emission to these techniques depends on the fuel properties. Therefore, to achieve optimal fuel-economy gains, the combustion-control strategies of the engine must adopt to the fuel being utilized.

Approach

The Alternative Fuels DISI Engine Lab at Sandia houses an engine that is set up for 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. Second, in-cylinder processes are examined with high-speed optical diagnostics, including advanced laser-based techniques. Computer modeling provides knowledge of governing combustion fundamentals. The combination of performance testing, exhaust-emissions measurements, optical diagnostics, and modeling allows building a comprehensive science-base.

Results

In the following, examples of accomplishments during FY2014 are presented.

Stratified Charge Operation - Previous work on stratified-charge combustion using E85 and gasoline showed that the spark timing relative to the fuel injection has to be adjusted with the fuel type to maintain misfire-free operation [1]. Exhaust emissions can also dictate what spark-timing strategy needs to be employed. This is exemplified for an engine load corresponding to $IMEP_n$ = 320 kPa in Fig. 1.

Here, smoke emissions are compared for operation across a range of gasoline-ethanol blends using two different spark-timing strategies. "Head ignition" was accomplished by timing the spark ignition so that it coincides with the beginning of the fuel-injection event, thereby igniting the leading edge of the two fuel sprays near the spark-plug gap. This minimizes the time available for premixing of fuel and air prior to combustion. In contrast, for "tail ignition" the spark timing coincides with the last liquid passing by the spark-plug gap, thereby igniting the end of the fuel sprays near the spark-plug gap. This allows more time for fuel-air mixing, thereby reducing both the degree of stratification and the fuel/air-equivalence ratios in flame regions. An engine speed of 1000 rpm was used and SOI was fixed at -23°CA for all data points. Figure 1 shows that the engine-out smoke level is acceptably low (<0.1 FSN) for E85 and E100 regardless of the spark-timing strategy. However, if the head-ignition strategy is used for gasoline or E35 very high smoke levels result. Hence, the smoke emissions mandate the use of tail ignition for gasoline and E35 fuel. (Further reduction of smoke to below 0.1 FSN can be achieved for gasoline by advancing the injection timing, but these data are not shown in Fig. 1.)

Since the sooting propensity of the fuel dictates what spark-timing strategy can be used, the fuel type indirectly affects the heat-release rate and how it scales with changes to the engine speed. This basic, but very important aspect is illustrated in Fig. 2. The time-based AHRR (in kW) of well-mixed stoichiometric combustion scales nearly 1:1 with the engine speed, as is well-known from the engine-combustion literature on turbulent premixed deflagration [2]. In contrast, the AHRR for highly stratified operation with head ignition only increases slightly with engine speed. As discussed in Ref. [3], for highly stratified spray-guided combustion, the heat-release rate of the main combustion phase is primarily controlled by mixing rates and turbulence level associated with fuel-jet penetration. Figure 2 shows that the trend for operation with tail ignition falls in between those of well-mixed and head-ignition. This indicates that the AHRR is controlled by fuel-air mixing and turbulence associated with both the fuel spray and the intake-generated flow.

The intake-generated flow is not only important for the heat-release rate. Performance testing reveals that operation with intake-generated swirl reduces cycle-to-cycle variations of stratified combustion, especially for higher engine speeds. Extensive PIV measurements have been conducted to clarify the stabilizing mechanism of swirl, as reported in Ref. [4]. These included operation with and without swirl, and operation with and without injection. In addition, these flow measurements were combined with engine performance testing using gasoline fuel. Figure 3 demonstrates some of the key findings. At this engine speed of 2000 rpm, operation with intake-generated tumble flow results in a COV of IMEP = 3.5%, which is higher than desirable. By applying a combination of swirl and tumble, the IMEP variability can be strongly reduced. Figure 3 shows that this stabilization of combustion is correlated with an increase of the 'flow similarity'. 'Flow similarity' quantifies how similar an individual cycle is to the ensemble-averaged flow field [4]. Figure 3 demonstrates that after the end of injection, a representative single cycle exhibits a flow field with high resemblance to the ensemble-averaged flow. Flame imaging (not presented here) reveals that the early flame development is more stable when the flow near the spark plug is repeatable from cycle to cycle. This is consistent with the reduced variability of IMEP.

<u>Lean well-mixed operation</u> – Figure 4 demonstrates some of the observations from well-mixed lean operation, comparing the performance of gasoline and E85. The engine speed was maintained at 1000 rpm, and the injected amount of fuel was held constant for each data set while the intake pressure was increased to lean out the charge, reducing ϕ. Figure 4b shows that a substantial increase of the efficiency can be obtained. Without intake air preheating, the relative fuel-economy gain is roughly 12% for both gasoline and E85 at ϕ = 0.67 - 0.70. When intake air preheating is applied, Fig. 4c shows that the lean stability limit shifts to lower ϕ for both fuels. Associated with this is a greater relative fuel-economy improvement for both fuels. However, gasoline benefits more from the intake air preheating, showing a 20% fuel-economy improvement relative to stoichiometric (ϕ = 1) operation for ϕ = 0.53. The difference between the fuels arises due to the appearance of repeatable end-gas autoignition for the lower-octane gasoline fuel, as

Fig. 5 illustrates. This end-gas autoignition consumes fuel ahead of the slow turbulent flame, thereby increasing both combustion efficiency (Fig. 4a) and thermal efficiency. This example demonstrates that end-gas autoignition can be used beneficially to enable ultra-lean SI operation, but that a change of fuel type or increased octane number needs to be factored in by the control algorithms of the engine. For more details of these experiments and for a demonstration of the use of advanced ignition for lean operation, please refer to Ref. [5].

Conclusions

- The alternative fuels DISI engine lab at Sandia contributes to the science-base needed by industry to take full advantage of future fuels in advanced internal combustion engines.
- Continued and substantial progress has been made towards a conceptual model of stratified SI combustion that accounts for fuel type, degree of stratification, and the intake-generated flow field.
- Gasoline/ethanol blend proportions influence optimal spark-timing strategies for stratified operation since more mixing time is required for gasoline-dominated fuel blends to avoid excessive soot formation.
- Factors that govern the heat-release rate for stratified-charge operation change with fuel type due to different spark-timing strategies.
- Increasing engine speed can challenge the combustion stability of stratified-charge operation. Highly stratified operation with high-ethanol blends is affected differently than less stratified operation with gasoline. Interaction between intake-generated swirl and fuel sprays creates a strong and stable vortex that contributes to stable combustion.
- For DISI operation with well-mixed charge and no intake heat, lean stability limits and fuel-economy gains are identical for E85 and gasoline. However, for operation with intake-air preheating, the lower-octane gasoline fuel exhibits a fuel-economy advantage due to repeatable endgas autoignition that helps maintaining high combustion efficiency.
- Multi-pulse transient plasma ignition demonstrates strong benefits to stabilize lean operation by offering a faster transition to fully turbulent combustion compared to regular spark ignition.

References

1. M. Sjöberg and D.L. Reuss, "NO_x-Reduction by Injection-Timing Retard in a Stratified-Charge DISI Engine using Gasoline and E85," SAE Int. J. Fuels Lubr. 5(3):1096-1113, 2012.
2. J.B. Heywood, Internal Combustion Engine Fundamentals, McGraw-Hill, New York, 1988.
3. M. Sjöberg, W. Zeng, and D.L. Reuss, ”Role of Engine Speed and In-cylinder Flow Field for Stratified and Well-mixed DISI Engine Combustion using E70”, SAE Int. J. Engines 7(2):642-655, 2014.
4. W. Zeng, M. Sjöberg, and D.L. Reuss, “PIV Examination of Spray-Enhanced Swirl Flow for Combustion Stabilization in a Spray-Guided Stratified-Charge DISI Engine”, in press for Int. J. of Engine Research, 2014.
5. M. Sjöberg, W. Zeng, D. Singleton, J.M. Sanders, and M.A. Gundersen, “Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-mixed E85 DISI Engine Operation”, SAE Int. J. Engines 7(4):1781-1801, 2014.

FY 2014 Publications/Presentations

1. M. Sjöberg, W. Zeng, D.L. Reuss, R. Zhao, F. Egolfopoulos, M. Mehl, and W. Pitz., “Characterization of Spray-guided DISI Engine Combustion with near-TDC Injection of E85 using High-Speed Imaging, Spectroscopy, Flame Measurements and Modeling”, presented at SAE/KSAE 2013 Powertrains, Fuels & Lubricants meeting in Seoul, South Korea, Oct 2013.

2. M. Sjöberg, W. Zeng, and D.L. Reuss, "Soot and NO_x Considerations for a Stratified-Charge DISI Engine using Gasoline/Ethanol Blends", presented at 2013 Hyundai-Kia International Powertrain Conference, Hwaseong, South Korea, Oct 2013.
3. M. Sjöberg, W. Zeng, D. Singleton, J.M. Sanders, and M.A. Gundersen, "Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-mixed E85 SI Engine Operation", presented at AEC Program Review Meeting, Sandia, Livermore, CA, Feb 2014.
4. W. Zeng, M. Sjöberg, and D.L. Reuss, "Combined Effects of Flow/Spray Interactions and EGR on Combustion Variability for a Stratified DISI Engine", presented at AEC Program Review Meeting, Sandia, Livermore, CA, Feb 2014.
5. M. Sjöberg, "DISI with Gasoline/Ethanol Blends", presented at CRC Advanced Fuel and Engine Efficiency Workshop, Baltimore, MD, Feb 2014.
6. M. Sjöberg, W. Zeng, and D.L. Reuss, "Role of Engine Speed and In-cylinder Flow Field for Stratified and Well-mixed DISI Engine Combustion using E70", presented at SAE 2014 World Congress & Exhibition, and published in SAE Int. J. Engines 7(2):642-655, 2014.
7. W. Zeng, M. Sjöberg, and D.L. Reuss, "Using PIV Measurements to Determine the Role of the In-Cylinder Flow Field for Stratified DISI Engine Combustion", presented at SAE 2014 World Congress & Exhibition, and published in SAE Int. J. Engines 7(2):615-632, 2014.
8. M. Sjöberg, "Advanced Lean-Burn DI Spark Ignition Fuels Research", presented at the 2014 Annual Merit Review and Peer Evaluation Meeting, Washington, DC, June 2014.
9. W. Zeng, M. Sjöberg, and D.L. Reuss, "Combined Effects of Flow/Spray Interactions and EGR on Combustion Variability for a Stratified DISI Engine", presented at 35th International Symposium on Combustion, and published in Proc. Combust. Inst., 2014.
10. W. Zeng, M. Sjöberg, and D.L. Reuss, "The Role of Spray-Enhanced Swirl Flow for Combustion Stabilization in a Stratified-Charge DISI Engine", presented at AEC Program Review Meeting, USCAR, Southfield, MI, Aug 2014.
11. M. Sjöberg, W. Zeng, D. Singleton, J.M. Sanders, and M.A. Gundersen, "Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-mixed E85 DISI Engine Operation", presented at SAE 2014 International Powertrain, Fuels & Lubricants Meeting, and published in SAE Int. J. Engines 7(4):1781-1801, 2014.
12. W. Zeng, M. Sjöberg, and D.L. Reuss, "PIV Examination of Spray-Enhanced Swirl Flow for Combustion Stabilization in a Spray-Guided Stratified-Charge DISI Engine", in press for Int. J. of Engine Research, 2014.

Special Recognitions & Awards

Magnus Sjöberg received an SAE Excellence in Oral Presentation Award for a presentation of stratified DISI operation using E85 fuel at the SAE/KSAE 2013 Powertrains, Fuels & Lubricants meeting in Seoul, South Korea.

Acronyms

ϕ	Fuel/Air Equivalence Ratio
$[O_2]$	mole fraction of oxygen (in intake)
°CA	Crank Angle Degrees
AEC	Advanced Engine Combustion
AHRR	Apparent Heat-Release Rate
COV	Coefficient of Variation
DI	Direct Injection
DISI	Direct-Injection Spark Ignition
DOE	Department of Energy
E35	Fuel blend with 35% ethanol and 65% gasoline by volume.

E70 Fuel blend with 70% ethanol and 30% gasoline by volume.
E85 Fuel blend with 85% ethanol and 15% gasoline by volume.
E100 Neat ethanol fuel.
FSN Filter Smoke Number
FY Fiscal Year
IMEP Indicated Mean Effective Pressure
kW Kilowatt
NO_x Nitrogen Oxides
PIV Particle Image Velocimetry
rpm Revolutions per minute
SI Spark Ignition
SOI Start of Injection
VT Vehicle Technologies

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Figures

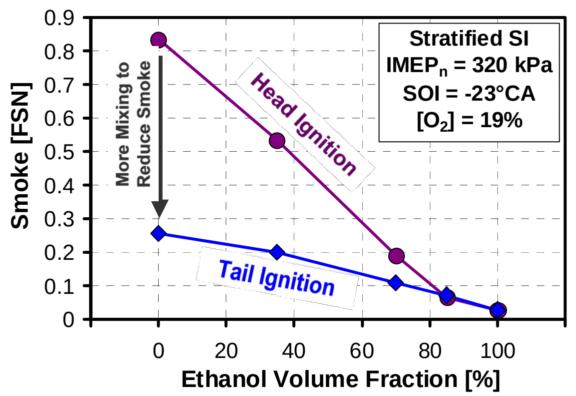

Figure 1. [Engine-out smoke level as a function of volume fraction of ethanol in gasoline for operation with single injection at two different levels of stratification, as controlled by the spark timing relative to the fuel-spray development.]

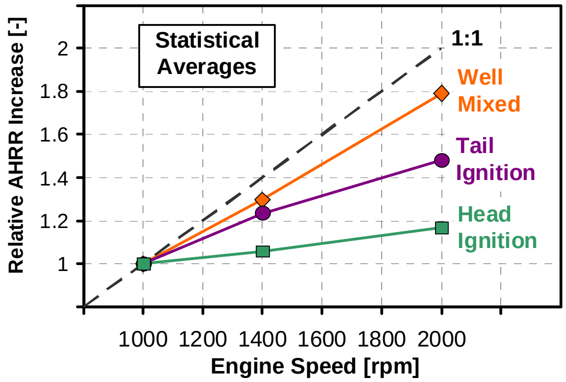

Figure 2. [Scaling of peak heat-release rate (in kW) with engine speed for well-mixed stoichiometric E70 operation and for two different levels of stratification using gasoline (tail ignition) and E70 (head ignition).

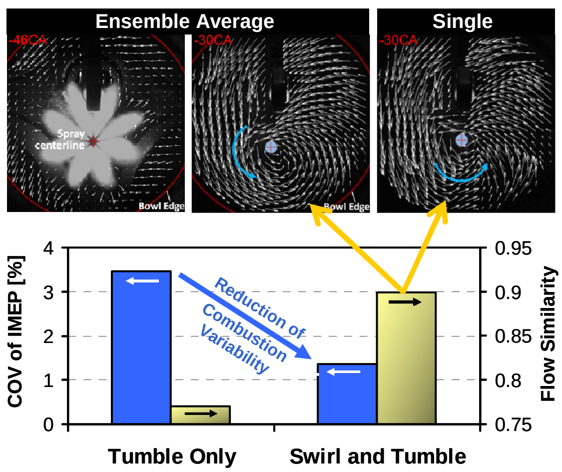

Figure 3. [Spray-swirl interaction causes flows that are more repeatable from cycle-to-cycle. The increased flow similarity is correlated with a reduction of combustion variability for spray-guided stratified-charge operation using gasoline. 2000rpm, $IMEP_n$ = 370 kPa, intake $[O_2]$ = 19%.]

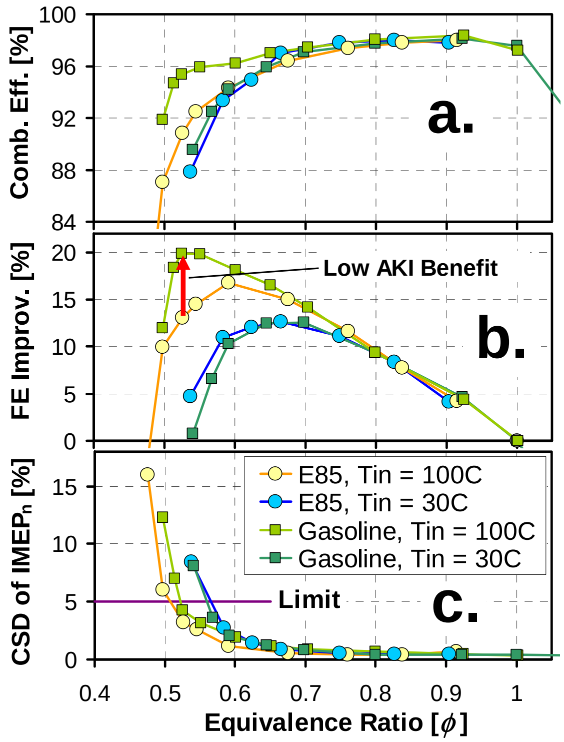

Figure 4. [Combined effects of fuel type and intake heating on lean SI operation. a) Combustion efficiency. b) Fuel-economy improvement relative stoichiometric operation. c) Relative $IMEP_n$ instability.]

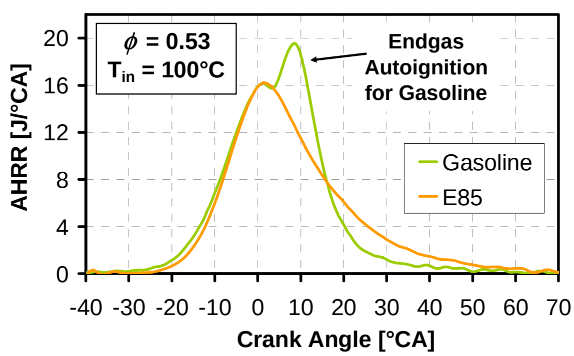

Figure 5. [Effect of fuel type on late-cycle combustion for lean well-mixed SI operation using pre-heating of the intake air.]