I.1.1. Ducted Fuel Injection and Cooled Spray Technologies for Particulate Control in Heavy-Duty Diesel Engines (Westinghouse Air Brake Technologies Corporation)

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Project Introduction

Heavy-duty diesel engine manufacturers are continually seeking simple, low-cost technologies to reduce emissions. Ducted Fuel Injection (DFI) and Cooled Spray (CS) technologies have emerged as promising solutions, offering the potential for nearly sootless operation. These innovations could significantly decrease harmful Particulate Matter (PM) emissions while enabling further optimization to reduce Nitrogen Oxides (NOx) and increase efficiency.

While initial experiments across various engine types have shown promise, uncertainties remain regarding the ideal geometry, scaling properties, and effectiveness of these technologies across different operating conditions. This project aims to address these knowledge gaps through experiments in both optical and metal single-cylinder engines.

In the final three months of this program, our research focused on two key areas:

1. Evaluating the sensitivity to geometry for CS inserts in a metal single-cylinder engine. We conducted a comprehensive study testing CS inserts with fuel passage diameters ranging from 2.2mm to 2.8mm under different operating modes, including EGR (Exhaust Gas Recirculation) and non-EGR conditions.

2. Performing detailed optical engine analysis to elucidate the underlying reasons for performance differences among conventional diesel combustion, CS, and DFI. This analysis included high-speed imaging and heat release measurements to provide insights into combustion behavior and soot formation processes.

The primary objective of this study was to achieve a 75% reduction in PM emissions across all operating modes while minimizing the impact on Brake Specific Fuel Consumption (BSFC). This ambitious target is crucial for meeting increasingly stringent emissions regulations and improving overall engine environmental impact. By identifying the optimal fuel passage geometry and understanding the fundamental combustion processes, we aim to significantly advance diesel engine technology, offering a path to cleaner, more efficient heavy-duty engines for off-road applications.

Objectives

Overall Objectives

- Provide critical dimensional scaling guidance for DFI and CS technologies.
- Demonstrate more than 75% PM reduction over a range of operating conditions using CS technology.

Fiscal Year 2024 Objectives

- Characterize sensitivity of performance to CS fuel passage diameter
- Elucidate underlying reasons for performance differences among conventional diesel combustion, CS, and DFI

Approach

The research approach leverages two complementary experimental setups: an optical engine at Sandia National Laboratories and a metal single-cylinder engine at Southwest Research Institute.

The optical engine at Sandia National Laboratories serves as a scientific tool for detailed investigation of combustion behavior in DFI and CS components. This apparatus is ideal for exploring the fundamentals of novel combustion strategies like CS and DFI. Recently upgraded to operate at high speed and load (up to 24bar gross indicated mean effective pressure [IMEPg], 1800RPM), the engine's optical access and state-of-the-art imaging diagnostics enable visualization of DFI and CS effects on the combustion plume.

Complementing the optical engine, Southwest Research Institute employs a metal single-cylinder engine with full-sized Wabtec engine hardware. This setup allows for rapid testing of CS prototypes across the operating map, enabling faster, lower-cost evaluations to identify optimal CS candidates. The metal engine provides validation of performance under real engine conditions, informing the selection of the best CS technology for full-scale implementation.

These two approaches work in tandem to address the project objectives: the optical engine provides insights into the underlying physics and combustion characteristics, while the metal engine allows for practical performance evaluation and optimization. Together, they enable a comprehensive understanding of CS and DFI technologies, from fundamental combustion processes to real-world performance, directly supporting our goals of providing critical dimensional scaling guidance and demonstrating significant PM reduction across various operating conditions.

Results

Figure 1A presents a bar graph comparing minimum normalized FSN for CS operation across four different fuel passage diameters: 2.8mm, 2.6mm, 2.4mm, and 2.2mm. FSN is a surrogate measurement for PM and changes in FSN correlate with changes in PM emissions. For each diameter, the graph displays data for four operating modes: Mode 3 Non-EGR, Mode 8 Non-EGR, Mode 3 EGR, and Mode 8 EGR. Mode 3 is 1500RPM 50% rated torque and Mode 8 is 1500RPM, 100% torque. Figure 1B illustrates the impact on BSFC for those same geometries at those same operating conditions. Given the primary objective to reduce PM by 75%, the data presents challenges as all geometries show higher FSN values than the target. However, the data suggest which geometries may provide the best performance for EGR and non-EGR operation, as discussed below.

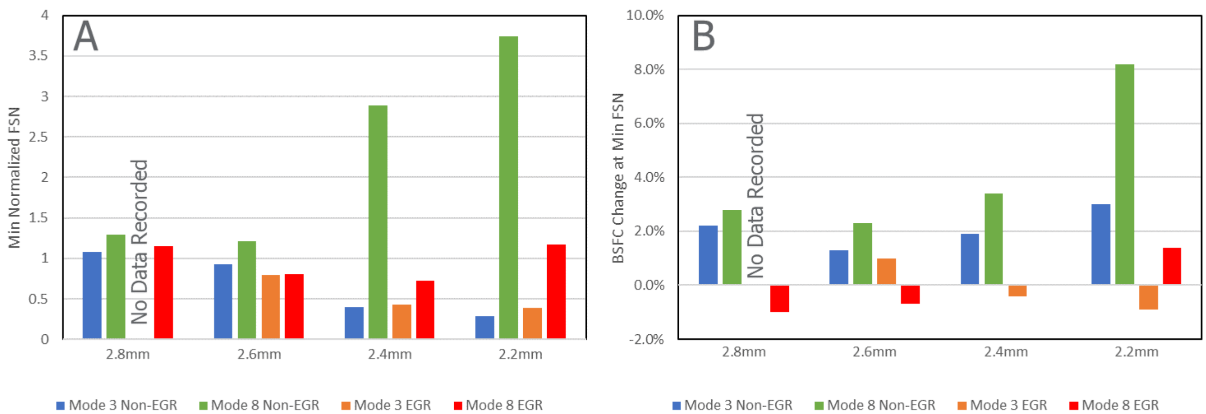

Figure 1. Impact of CS fuel passage diameter on (A) Min Normalized FSN and (B) BSFC change at Min FSN for different engine operating modes with and without EGR.

For EGR operation, the 2.4mm geometry appears most promising. It shows the lowest FSN values for both Mode 3 EGR and Mode 8 EGR, coming closest to the PM reduction target. The BSFC impact is relatively low, with Mode 3 EGR showing a slight decrease and Mode 8 EGR showing no change from the baseline. This geometry offers significant PM reduction potential and good BSFC response under EGR conditions.

For non-EGR operation, either the 2.6 or 2.4mm geometries perform best. The 2.6mm geometry shows a small FSN reduction at Mode 3 and a small FSN increase at Mode 8 while the 2.4mm geometry shows significant FSN reduction at Mode 3 with a significant FSN increase at Mode 8. Further studies should evaluate these CS inserts at other operating modes to determine which provides the best overall performance.

An unusual phenomenon is observed with the 2.4mm and 2.2mm geometries in non-EGR Mode 8, where FSN values are significantly higher compared to other conditions. This suggests that smaller CS geometries might struggle with emissions control in high-load non-EGR conditions. Further investigation into the combustion characteristics and fuel-air mixing for these geometries in Mode 8 could provide insights into this behavior and potential mitigation strategies.

Given the project's objective of PM reduction, the 2.4mm CS geometry appears to be the most promising for both EGR and non-EGR operations, as it comes closest to achieving the PM target. Its performance is particularly good in EGR operation, where it also shows a BSFC advantage in Mode 3. However, its high BSFC impact in non-EGR operation, especially at Mode 8, is a significant drawback. Further research should focus on understanding and potentially mitigating the high FSN values for CS at high load. Additionally, investigating the mechanisms behind the BSFC improvement in Mode 3 EGR operation for the 2.2mm geometry could lead to optimizations that balance FSN reduction with fuel efficiency across all operating conditions.

Optical-Engine Results **–** Sandia efforts during the previous reporting period showed that both CS and DFI performed better than conventional diesel combustion (CDC), and DFI performed better than CS at Mode 4 for both EGR and non-EGR conditions (Klingbeil, 2023). Sandia efforts during this final reporting period focused on analysis of timeseries and optical-imaging data to better understand the underlying reasons for the observed performance differences among CDC, CS, and DFI.

Figure 2 shows apparent heat-release rate (AHRR) and bulk-gas-averaged in-cylinder temperature (T_{bulk}) plots for CDC vs. the best-performing DFI and CS configurations (both had an inside diameter of 2.5 mm) at their optimal injection timings for the EGR condition. It is evident that although CDC and DFI have nearly identical start-of-combustion timings, the AHRR for DFI reaches larger values sooner than CDC and drops more quickly late in the cycle. It is believed that the enhanced mixing enabled by DFI facilitates faster reaction rates earlier in the cycle, leading to the higher T_{bulk} values. This combustion-phasing advance for DFI yields higher efficiency and likely improved soot oxidation at the cost of slightly increased NOx emissions. The net result is favorable for DFI, with DFI providing an 81% lower cost function than CDC (Klingbeil, 2023). Results for CS have similar trends to DFI, but the benefit is not as great, and the DFI cost function is 75% lower than that for CS at this condition. Observations and results from analysis of timeseries data for the non-EGR condition are similar (Mueller et al., in preparation).

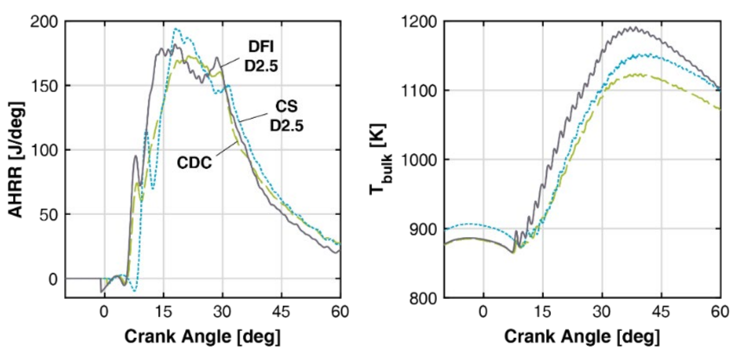

Figure 2. Apparent heat-release rate (AHRR) and bulk-gas-averaged in-cylinder temperature (T_{bulk}) for CDC vs. the best-performing DFI and CS configurations (both had an inside diameter of 2.5mm) at their optimal injection timings for the Mode 4 EGR condition.

The in-cylinder imaging data give additional insights into the improved performance of CS and DFI relative to CDC. Figure 3a shows the evolution of the raw flame liftoff length (defined as the distance from the injector orifice exit to the standing premixed autoignition zone) for the different combustion strategies at the Mode 4 condition with EGR. In general, the longer the liftoff length, the more distance and time are available for mixing before autoignition, which should enhance combustion rate and reduce soot formation. It is evident that DFI has the longest liftoff lengths early in the injection event, followed by CS and then CDC, which is consistent with the observations from Figure 2 and the rank-ordering of each strategy's performance based on the cost-function analysis in last year's report.

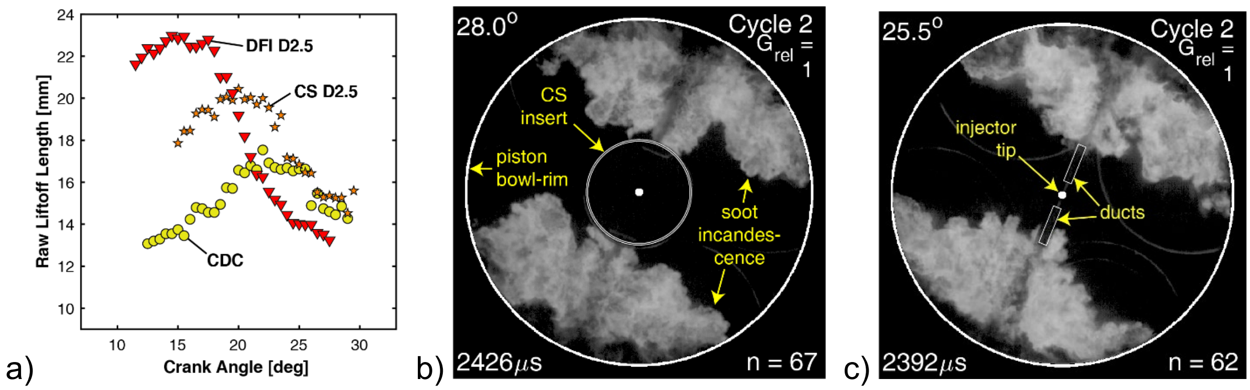

Figure 3. Data for Mode 4 EGR condition with optimal injection timings and insert/duct-module geometries. a) Raw liftoff length. b) and c) Images of in-cylinder soot incandescence for CS and DFI, respectively, acquired two crank-angle degrees before the end of injection. Number in upper-left corner of each image frame is the crank angle after top-dead-center of the compression stroke.

Given the many similarities between CS and DFI, it is interesting that their cost-function values should be so different. High-speed in-cylinder imaging of soot incandescence provides some potential explanations for this result. Figure 3b and 3c show images of in-cylinder soot incandescence for CS and DFI, respectively, for the EGR condition, with each image acquired two crank-angle degrees before the end of injection. The CS image shows that sooty combustion products have reached the circumference of the CS insert where the inlet passages are located, meaning that these combustion products could be drawn into the insert instead of fresh charge-gas, likely leading to increased soot formation. Conversely, Figure 3c and later images for DFI show that sooty combustion products do not make it back to the duct inlet at this time nor by the end of injection, meaning that fresh, oxygen-containing charge gas is mixed with the injected fuel for the entire injection event, likely leading to faster mixing and combustion, attenuated soot formation, and enhanced soot oxidation.

Conclusions

The CS testing on the metal engine has demonstrated significant potential for reducing PM emissions across a broad operating range. Throughout this 39-month project, CS inserts have achieved over 50% reduction in PM emissions on the duty cycle, with some operating conditions showing up to 80% reduction. The research presented in this report highlights the critical importance of fuel passage diameter as a key design feature. Results indicate an optimal diameter range of 2.4 to 2.6mm for best overall performance. Interestingly, anomalous data observed during the study suggests the presence of competing physical phenomena that may cause CS inserts to underperform under certain conditions. Optical imaging of flame liftoff length and soot incandescence has provided valuable insights into the root causes of performance differences across CDC, CS, and DFI. Further investigation and understanding of these phenomena could potentially lead to the development of even more effective DFI and CS designs, offering enhanced PM reduction capabilities.

Key Publications

Klingbeil, A., Tinar, T., and Ellis, S. (May 3, 2024). "Cooled Spray Technology for Particulate Reduction in a Heavy-Duty Engine." ASME. J. Eng. Gas Turbines Power. September 2024; 146(9): 091024. https://doi.org/10.1115/1.4065365

Klingbeil, A, Tinar, T. " Investigation of Fuel Passage Geometry on Performance of Cooled Spray Inserts for Particulate Reduction in a Heavy-Duty Engine." Proceedings of the ASME 2024 ICE Forward Conference. ASME 2024 ICE Forward Conference. San Antonio, TX, USA. October 20–23, 2024.

Mueller, C.J., et al., “An Optical-Engine Investigation of Conventional Diesel Combustion, Cooled Spray, and Ducted Fuel Injection Technologies for Heavy-Duty Engines,” manuscript in preparation, November 2024.

References

Klingbeil, A., “Ducted Fuel Injection and Cooled Spray Technologies for Particulate Control in Heavy-Duty Diesel Engines,” U.S. DOE Vehicle Technologies Office Decarbonization of Off-Road, Rail, Marine, and Aviation (DORMA) 2023 Annual Progress Report, December 2023.

Mueller, C.J., et al., “An Optical-Engine Investigation of Conventional Diesel Combustion, Cooled Spray, and Ducted Fuel Injection Technologies for Heavy-Duty Engines,” manuscript in preparation, November 2024.

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Acronyms, Abbreviations, Symbols, and Units

BSFC	Brake Specific Fuel Consumption
CDC	Conventional Diesel Combustion
CS	Cooled Spray
DFI	Ducted Fuel Injection
EGR	Exhaust Gas Recirculation
FSN	Filter Smoke Number
NOx	Nitrogen Oxides
PM	Particulate Matter