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I Combustion Research

I.1 Medium-Duty Diesel Combustion (Sandia)

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Project Introduction

Faster combustion improves the efficiency of a diesel engine, and in medium-duty diesel engines, interactions between the fuel sprays and the piston bowl walls play a key role in determining heat-release rates. Stepped-lip pistons can promote the formation of vortices that are correlated with faster, more efficient heat-release, but this behavior is primarily observed for late injection timings at which the engine is not operating at its peak efficiency [1-3]. The objectives of this part of the project are to explain the physical mechanisms responsible for this phenomenon, to identify measures that may enhance vortex formation, and to quantify the extent to which these measures may improve the engine's thermal efficiency.

Diesel exhaust-aftertreatment systems effectively eliminate pollutants such as soot, nitrogen oxides (NO_x), and unburned hydrocarbons, but only after their temperature reaches approximately 200°C. The goal of engine operation during the first minutes after a cold start is to quickly heat up the exhaust aftertreatment system while minimizing untreated pollutants. Catalyst heating operation involves multiple injections during the later stages of combustion to maximize exhaust temperature/enthalpy and an effective catalyst heating strategy is critical for meeting increasingly strict pollutant emissions regulations. Because this mode of combustion is not well understood, efforts are devoted to developing an experimental methodology to provide initial insights into the mixture formation, combustion, and pollutant formation processes using thermodynamic measurements and high-speed imaging.

Finally, a new medium-duty diesel research engine is being constructed to enable continued research into the aforementioned topics, as well as cutting-edge research into methods of reducing wall heat loss to improve efficiency.

Objectives

This project will provide scientific understanding needed to design, optimize, and calibrate the next generations of medium-duty diesel engines that comply with increasingly stringent pollutant emission regulations while achieving thermal efficiencies exceeding 50%.

Overall Objectives

- Develop conceptual models for spray-wall interactions, combustion, and pollutant formation in direct-injection diesel engines.
- Provide scientific understanding of aspects of combustion chamber design that enable improvements in efficiency and/or reductions in pollutant emissions

- Develop conceptual models that describe fuel injection, mixture formation, combustion, and pollutant formation during catalyst heating operation.

Fiscal Year 2019 Objectives

- Develop a conceptual model for turbulent flow evolution and vortex formation in stepped-lip combustion chambers
- Identify combustion system design and/or operating parameters that are predicted to enhance vortex formation in stepped-lip combustion chambers for main injections starting near top-dead center (TDC)
- Develop an experimental approach to study catalyst-heating operation in the small-bore optical diesel engine and perform initial thermodynamic and high-speed imaging studies
- Begin construction of the new medium-duty diesel research engine

Approach

Analysis of experimental data leads to the hypothesis that promoting vortex formation will increase efficiency and reduce pollutant emissions in a diesel engine with stepped-lip pistons. Because the computational fluid dynamics (CFD) simulations (performed by a subcontractor: Wisconsin Engine Research Consultants) have demonstrated qualitative agreement with experimental results, they are applied to identify combustion system operating and design parameters that may be expected to enhance vortex formation resulting from spray-wall interactions with stepped-lip pistons. The synthesis of the experimental and simulation results leads to a conceptual model for turbulent flow evolution in stepped-lip diesel combustion chambers.

A new experimental approach is developed to study catalyst-heating operation and provide insight into mixture formation, ignition, combustion, and pollutant formation mechanisms. Thermodynamic measurements and high-speed optical and infrared imaging provide initial insights into this complex combustion regime and serve as a dataset for continued development of simulation capabilities.

A new, medium-duty diesel research engine is being constructed in 2019 to enable:

- Continued research into piston bowl geometry effects and catalyst heating operation
- Cutting-edge heat transfer research with low-thermal-mass coatings on combustion chamber surfaces

Results

Key accomplishments:

- A new conceptual model describes the key phenomena responsible for the evolution of turbulent flow and the formation of toroidal vortices resulting from spray-wall interactions in the stepped-lip combustion chamber.
- The height of the squish region is identified as a key parameter to promote vortex formation for main injections starting near TDC. A dimpled stepped-lip piston concept has been developed and simulations predict it will enhance vortex action for main injections starting near TDC.
- For catalyst heating operation, experimental data indicate that the pilot and main injections are likely the most significant contributors to unburned hydrocarbon emissions in the exhaust.

Improving the efficiency of diesel engines requires fundamental understanding of the processes that govern fuel-air mixing rates. For engines with stepped-lip pistons, interactions between the fuel sprays and the piston bowl have a dramatic effect on flow and mixing. Continued analysis of experimental and CFD simulation results has resulted in a conceptual model that describes key phenomena that drive the evolution of turbulent flow in a particular stepped-lip combustion chamber. This model is shown on a vertical plane containing a single spray axis in Figure I.1-1. It describes how the stepped-lip piston bowl geometry redirects the spray's outward, downward momentum and how shear in the boundary layer between the penetrating spray and the wall generates vorticity (local rotation of the flow).

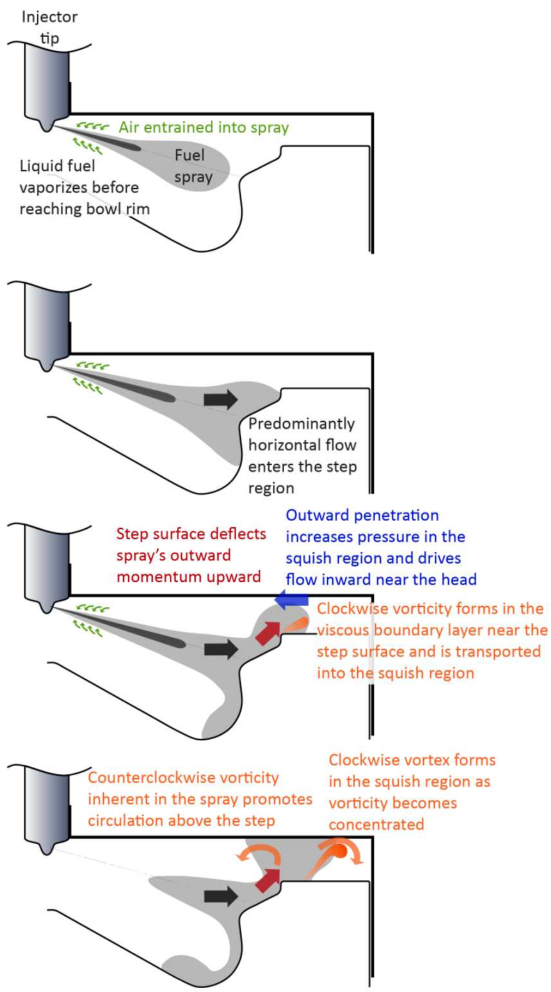

Figure I.1-1: Conceptual model describing the evolution of turbulent flow in a stepped-lip combustion chamber. Note that the effects of combustion are not considered in this version of the model.

The spray's momentum transports this vorticity to the squish region, where a toroidal vortex forms. At the same time, the outward penetration into the squish region creates an adverse pressure gradient that drives flow back inward near the cylinder head. This backflow, combined with the counterclockwise vorticity in the upper portion of the spray, results in a toroidal vortex above the step region.

This conceptual model applies to conditions for which the stepped-lip piston effectively creates vortices: at relatively late main injection timings. While injections starting near TDC advance the combustion phasing and improve the engine's efficiency, the strength and longevity of the toroidal vortices becomes weaker and the mixing-controlled portion of the combustion event becomes slower [4]. Thus, it is hypothesized that measures that promote vortex formation for near-TDC injection timings will increase fuel-air mixing rates and therefore result in further efficiency improvements. A further CFD investigation focuses on whether combustion system operating and design parameters can promote vortex formation at the near-TDC injection timing. The only parameter predicted to achieve this is the space in the squish region (between the piston top and the cylinder head). A modified stepped-lip geometry is created to achieve this increase in squish region space; the resulting geometry is called a dimpled stepped-lip (DSL) piston and is shown in Figure I.1-2.

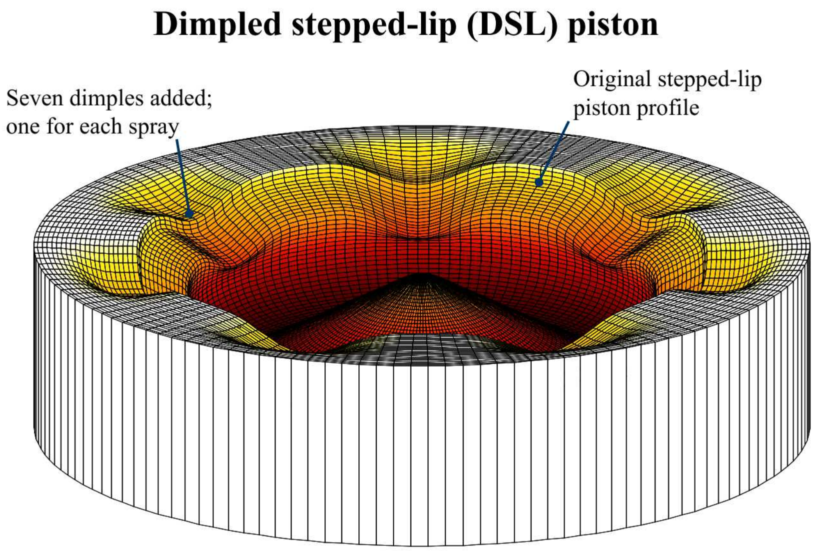

Figure I.1-2: The dimpled stepped-lip piston. This design was created to test the hypothesis that increased space between the top piston surface and the cylinder head will promote vortex formation as the fuel sprays separate from the piston surface.

The effects of changing injection timing with the stepped-lip piston, as well as the effect of changing the bowl geometry on the flow structure is visualized in Figure I.1-3. Toroidal vorticity is shown on a vertical cutting plane for a crank angle approximately 5 degrees after the end of the main injection. Interactions between the fuel spray and the piston bowl have strongly influenced the structure of the turbulent flow above the piston. The DSL piston effectively restores the rotational flow topology that is lost with the stepped-lip piston when the main injection timing is advanced to near TDC. Continued research efforts will be devoted to developing a DSL-like piston for the new medium duty diesel engine to test the hypothesis that enhanced vortex formation will lead to thermal efficiency improvements.

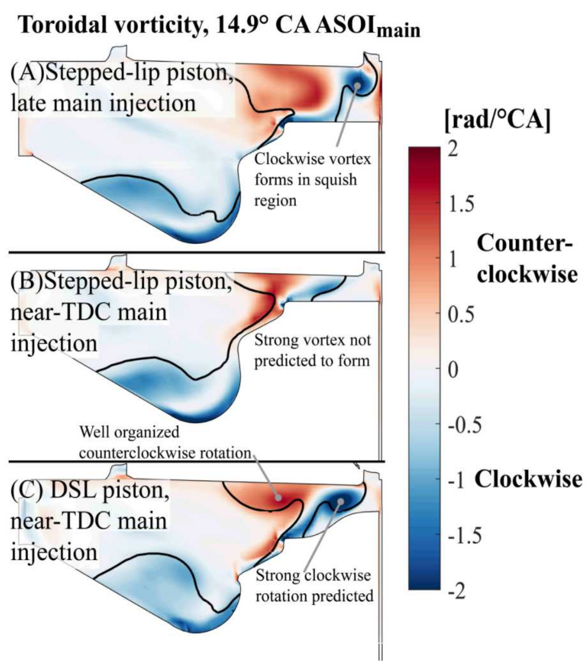

Figure I.1-3: Toroidal vorticity (vorticity vector perpendicular to the page) for a vertical plane containing a spray axis. (A): Stepped-lip piston, main injection starting in the expansion stroke. (B): Stepped-lip piston, main injection starting near TDC. (C): DSL piston, main injection starting near TDC.

Fuel injection strategies for catalyst heating operation often include one or more pilot injections, a main injection, and one or more post injections. The variable quantity and timing of each injection event create an excessively large parameter space, so these initial studies are performed with a pilot-main-post injection strategy to provide insight into sources of unburned hydrocarbon emissions. The quantities and timings of each injection event are controlled as follows:

Table I.1-1: Injection timings and quantities for initial study of catalyst heating operation

Pilot timing	Pilot quantity	Main timing	Main quantity	Post timing	Post quantity
Fixed at 15 CAD ATDC	2 mg	Fixed at TDC	3, 5, 7 mg	Vary between 10-30 CAD ATDC	2, 4, 6 mg

These various injection strategy calibrations are utilized in the running engine while maintaining a coolant temperature of 30°C. Unburned hydrocarbon emissions levels are measured and the emissions index of unburned hydrocarbons (EIHC) is shown for each variation of post injection timing in Figure I.1-4. EIHC levels are also shown for pilot-main injection strategies using dashed lines. While adding a post injection to a pilot-main injection strategy, the amount of unburned hydrocarbons per kilogram of fuel injected decreases. Regardless of injection strategy calibration, EIHC tends to increase as post injection timing is retarded. Increasing the main injection quantity typically reduces unburned hydrocarbons, particularly for late post injection timings.

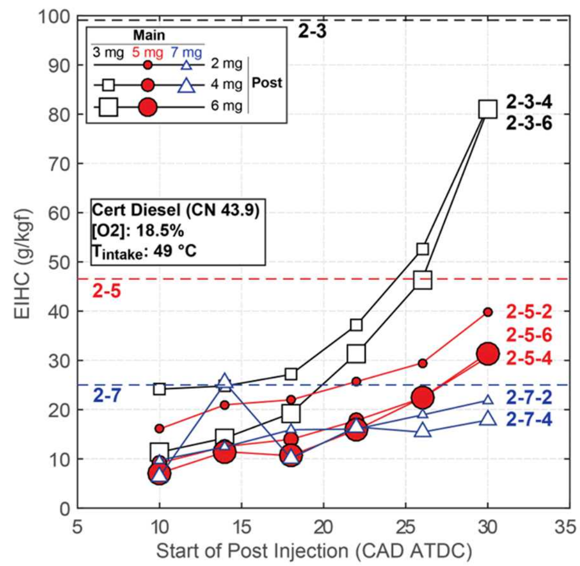

Figure I.1-4: Emissions Index (EI) of unburned hydrocarbons as a function of the crank angle at which the post injection starts. Adding a post injection to a pilot-main injection strategy always decreases the mass of unburned hydrocarbons formed for the given fuel mass.

These results show that the pilot and main injections are significant sources of unburned hydrocarbons, and that the ability of a post injection to oxidize these hydrocarbons is diminished for late injection timings and small main injection quantities. Results from high-speed imaging experiments (not shown) suggest that combustion of the pilot and main takes place primarily within the piston bowl. Furthermore, early post injections can interact directly with the bowl contents, but late post injections are targeted above the bowl and are not observed to interact with the bowl contents. Thus, late post injections may be limited in their ability to reduce unburned hydrocarbon emissions.

Conclusions

The DSL piston design provides evidence that changes in piston geometry can enhance the formation of the vortices that form by interaction with the bowl surface. DSL-like piston designs will be developed to test the hypothesis that stronger vortices can increase heat-release rates and thereby efficiency.

Experimental evidence suggests that the pilot and main injections are important sources of unburned hydrocarbon emissions in catalyst heating operation.

Key Publications

1. Busch, Stephen, Perini, Federico, Reitz, Rolf D. Reitz, and Eric Kurtz. "Effects of Stepped-lip Combustion System Design and Operating Parameters on Turbulent Flow Evolution in a Diesel Engine" *SAE Journal of Engines*, in press.
2. Perini, Federico, Busch, Stephen, Kurtz, Eric, Warey, Alok, Peterson, Richard C., and Rolf D. Reitz. "Limitations of Sector Mesh Geometry and Initial Conditions to Model Flow and Mixture Formation in Direct-Injection Diesel Engines." *SAE Technical Paper* 2019-01-0204, 2019, DOI: https://doi.org/10.4271/2019-01-0204.
3. Perini, Federico, Busch, Stephen, Zha, Kan, Reitz, Rolf D., and Eric Kurtz. "Piston Bowl Geometry Effects on Combustion Development in a High-Speed Light-Duty Diesel Engine." *SAE Technical Paper* 2019-24-0167, 2019, DOI: https://doi.org/10.4271/2019-24-0167.

References

1. Busch, Stephen, Zha, Kan, Kurtz, Eric, Warey, Alok, and Richard C. Peterson. "Experimental and Numerical Studies of Bowl Geometry Impacts on Thermal Efficiency in a Light-Duty Diesel Engine." *SAE Technical Paper* 2018-01-0228, 2018, DOI: https://doi.org/10.4271/2018-01-0228.
2. Busch, Stephen, Zha, Kan, Perini, Federico, Reitz, Rolf D., Kurtz, Eric, Warey, Alok, and Richard C. Peterson. "Bowl Geometry Effects on Turbulent Flow Structure in a Direct Injection Diesel Engine." *SAE Technical Paper* 2018-01-1794, 2018, DOI: https://doi.org/10.4271/2018-01-1794.
3. Zha, Kan, Busch, Stephen, Warey, Alok, Peterson, Richard C., and Eric Kurtz. "A Study of Piston Geometry Effects on Late-Stage Combustion in a Light-Duty Optical Diesel Engine Using Combustion Image Velocimetry." *SAE Technical Paper* 2018-01-0230, 2018, DOI: https://doi.org/10.4271/2018-01-0230.
4. Busch, Stephen. "Light- and Medium-Duty Diesel Combustion." In *Advanced Combustion Engines and Fuels: 2018 Annual Progress Report*, 30-35. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Office.

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Acronyms, Abbreviations, Symbols, and Units

CFD	computational fluid dynamics
DSL	dimpled stepped-lip
EIHC	emissions index of unburned hydrocarbons
NOx	nitrogen oxides
SL	stepped-lip
TDC	top-dead-center