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Engine experiments using a CFD-improved dimple stepped-lip piston in a diesel engine

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INTRODUCTION

Diesel piston-bowl shape is a key design parameter that affects spray-wall interactions and turbulent flow development, which, in turn, affects the engine's thermal efficiency and emissions behavior. Previous simulations and experiments in a small-bore diesel engine with a stepped-lip (SL) piston showed that efficiency increases are due to faster mixing-controlled heat-release, which were correlated with the strength and longevity of squish-region vortices [1, 2]. These vortices are believed to promote fuel-air mixing, leading to increased heat-release rates, but their strength and longevity decreased with advanced injection timing. Simulations predicted that a dimple stepped-lip (DSL) piston can enhance vortex formation at near-TDC injection timings, which is hypothesized to further improve peak thermal efficiency and reduce emissions [2].

In a previous study [3], engine experiments showed that a baseline DSL piston bowl was able to achieve a 1.4% thermal efficiency gain when compared against a SL piston, but soot emissions increased dramatically, with no penalty in NOx emissions. A design sensitivity study using non-combusting CFD simulations was performed to improve the design of the DSL bowl. This led to a DSL bowl with shallower, narrower, and steeper-curved dimples that are further out into the squish region, leading to stronger and more rotationally energetic vortices for early injection timings. This improved bowl is fabricated and used in the current study in a medium-duty diesel engine, and its performance is compared against that with the production SL piston.

EXPERIMENTAL SETUP

Experiments were performed in the Sandia Off-Road Diesel Research Engine facility. The facility consists of a 0.83L single-cylinder engine (99 mm bore × 108 mm stroke) derived from a Ford 6.7L medium-duty eight-cylinder diesel engine with a compression ratio of 16.35:1. Multiple sub-systems allow precise control of virtually all operating parameters, allowing well-characterized experiments. The fuel is delivered by a centrally mounted 8-hole piezo-injector. Results were obtained with certification diesel fuel (CN = 46). Further details about the engine configuration, experimental procedure, and data processing method can be found in [3, 4].

Engine experiments were performed with both the baseline SL piston and the improved DSL piston. The surface area of the DSL piston is approximately 1.3% smaller than that of the SL piston due to scaling down of the bowl and stepped area. The spray clocking angle, injector protrusion depth and engine compression ratio are kept constant. A dual-pilot, single-main injection strategy with constant dwell between each injection is used and block-shifted in an injection timing sweep. Two engine loads were performed with two EGR rates and two rail pressures: 3.91 bar IMEPn, 40% EGR rate, and 882 bar; and 8.55 bar IMEPn, 20% EGR rate, 1615 bar, corresponding to low- and part-load, respectively.

RESULTS AND DISCUSSION

Thermodynamic analyses were performed and the thermal efficiency results of both pistons are shown in Figure 1. At part-load operation, the DSL piston bowl leads to ~0.5% higher thermal efficiency than the SL bowl at the earliest injection timing of 2.7 CAD after top-dead-center compression (aTDCc). As injection timing is retarded, the DSL piston achieves lower thermal efficiency than the SL piston. This is consistent with the results in our previous study [3], as the DSL piston was designed to enhance vorticity at early injection timings, which is hypothesized to enhance thermal efficiency. At low-load operation, the DSL piston leads to ~0.4% lower thermal efficiency than the SL piston at the early injection timing. The degree of constant volume combustion is systematically improved by ~0.7% by the DSL piston relative to the SL piston at both operations, indicating faster mixing controlled heat release, which tends to increase the efficiency. But, energy balance analysis shows that wall heat transfer is higher in the DSL piston, despite a 1.3% reduction in piston surface area, likely due to the more energetic squish-region vortices leading to higher convective heat losses. Therefore, while vortex enhancement is important

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to obtain a higher mixing-controlled heat release, it needs to be balanced with wall heat transfer losses to further improve thermal efficiency.

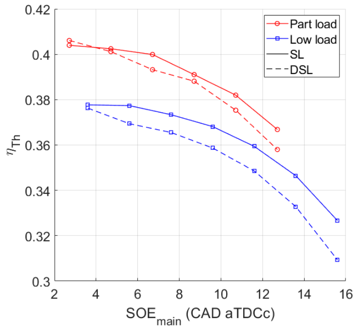

Figure 1. Thermal efficiency for the baseline SL (solid) and improved DSL pistons (dashed) for two injection timing sweeps at low- (red) and part-load conditions (blue).

Figure 2 shows the emissions for the same experiments as those of Figure 1. At both low- and part-load operations, soot is significantly reduced by the DSL piston at the earliest injection timing by 45%, likely due to improved air utilization and soot oxidation. At part-load operations, NOx increases slightly by 9% at the earliest injection timing, but decreases below SL piston values with later injection timing. NOx could be easily reduced back to production piston values by adjusting the EGR rate. This can be seen in the low-load operation, which uses a 40% EGR rate, causing a reduction of NOx over the entire injection sweep. At part-load operation, unburned HC and CO emissions are lower than the SL piston values at early injection timings. As injection is retarded, slightly higher CO emissions are obtained with the DSL piston, whereas HC emissions stay below the SL piston values. At low-load operations, both CO and unburned HC emissions are higher with the DSL piston than with the SL piston.

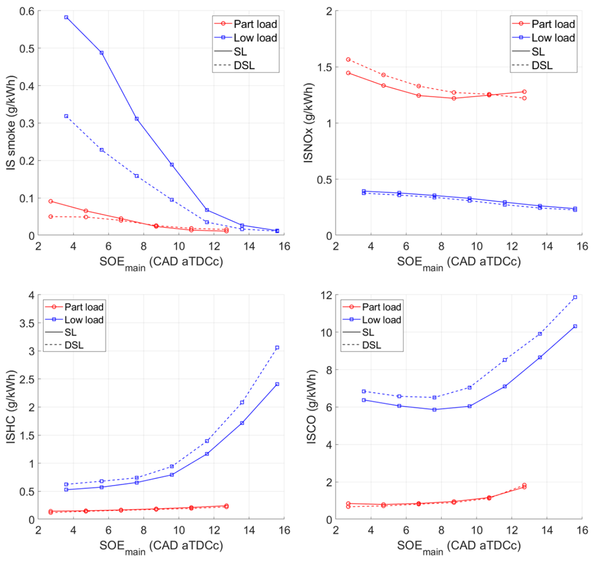

Figure 2. Smoke (top-left), NOx (top-right), unburned HC (bottom-left), and CO (bottom-right) emissions for the baseline SL piston (solid) and the improved DSL piston (dashed) for two injection timing sweeps at low- (red) and part-load conditions (blue).

CONCLUSIONS

An improved DSL piston that enhances vortex formation at near-TDC injection timings was evaluated experimentally at the Sandia Off-Road Diesel Research Engine Facility and the engine performance was compared to that obtained with a production SL piston. For early injection timings, the DSL piston leads to 0.5% higher thermal efficiency, 45% less soot, 16% less unburned HC emissions, and 20% less CO emissions than the SL piston, with a small penalty on NOx emissions for part-load operation. The marginal improvement in efficiency is caused by increased wall heat transfer losses in the DSL piston. At low-load operation, thermal efficiency is reduced, with 45% less soot, higher CO and unburned HC emissions, and lower NOx emissions.

This study shows that vortex enhancement may not necessarily lead to improved thermal efficiency as it can lead to increased wall heat transfer losses. Therefore, future design optimization of the DSL piston will need to focus on balancing vortex enhancement and wall heat transfer losses in order to further improve thermal efficiency.

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