Advancement in Diesel Combustion System Design
to Improve the Smoke-BSFC Tradeoff

Charles E. Roberts1, Chad Stovell2, Rainer Rothbauer3, Darius Mehta4
1-4) Southwest Research Institute; Engine, Emissions and Vehicle Research Division
6220 Culebra Rd, San Antonio, Texas, 78238-5166, United States (E-mail: charles.roberts@swri.org)

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ABSTRACT: Modern diesel engines must simultaneously provide ultra-low emissions and world-class fuel economy. To meet these requirements, many new combustion strategies require that combustion occur in an oxygen-limited and/or very high EGR environment, both of which increase the tendency for particulate emissions and reduced burn-rate. The current study utilized an iterative combination of simulations and engine experiments to identify improved combustion system designs for future diesel engines. Additionally, success in reducing soot and improving burn rate in an oxygen-limited environment opens the door to new strategies for diesel combustion in the future.

KEY WORDS: (Standardized) heat engine, compression ignition engine (Free) engine combustion, diesel engine, diffusion combustion, diesel combustion system, high pressure injection, injection targeting, spray-wall interaction, piston bowl design

1. INTRODUCTION

Modern commercial diesel engines are being designed to meet extremely strict NOx and Particulate Matter (PM) regulations. The use of high levels of EGR to reduce NOx emissions has an unfortunate side effect of increasing the emissions of particulate matter (PM). For the last 10-15 years, the diesel industry has combated smoke production through use of ever-increasing fuel injection pressure. Current heavy-duty engines now regularly utilize injection pressure in excess of 250 MPa. To insure reliability and durability of ultra-high pressure injection systems, engineering, materials, and production costs have increased dramatically. The upper-limit of injection pressure may be near. Therefore, other solutions for PM control must be pursued. NOx emissions have been (at least) partially controlled by EGR, where the necessary concentrations depend upon engine-aftertreatment system strategy, where the tradeoff in engine-out NOx is balanced against the cost of NOx aftertreatment. The dominant strategy today is to utilize medium levels of EGR (approximately 20%) in combination with a urea-based Selective Catalytic Reduction (SCR) NOx aftertreatment system. The SCR system is complex and expensive, with reports that the cost of a urea-SCR system for a U.S. heavy-duty truck may exceed $9000 (Volvo). Many companies seek a lower cost, high efficiency solution to meeting NOx regulations.

Technologies being pursued include:
1. Urea-based SCR
2. Lean NOx trap
3. Combination LNT-SCR
4. In-cylinder NOx control

Of available NOx reduction technologies, SCR (1) and in-cylinder NOx control (4) stand-out as the leading candidates for production application in the short-term. The primary area of interest in this paper is in-cylinder NOx control, enabled through use of high levels of EGR (over 35% at full-load), retarded injection timing, and improved combustion system design for smoke control and fuel economy. The improvement to the combustion system is derived from enhanced air-fuel mixing, as a result of new piston bowl shapes in combination with optimized injector targeting. This program concentrated on traditional combustion system development, but utilized a multistep piston bowl design that allowed improved PM emissions, while maintaining or improving fuel consumption rate.

2. PROBLEM DEFINITION

Simultaneous control of fuel economy, engine-out NOx, and PM is a difficult task facing engine engineers of the future. This paper assumes use of a Diesel Particulate Filter (DPF) for future engines, but attempts to perform NOx control through high levels of EGR, while controlling engine-out PM with high pressure fuel injection.
and carefully matched designs for piston bowl/injector targeting.

If we assume that in-cylinder NO\textsubscript{x} will be primarily controlled through EGR rate, then the primary goals of the combustion system are to control PM and fuel consumption rate. Simultaneous reduction of each should be achievable if air-fuel mixing is very rapid, allowing fast, efficient combustion with minimal local regions of rich combustion.

Siebers, et.al., (1,2) described the behavior of a high-pressure fuel spray-jet injected into (relatively) quiescent air. Their observations showed that the penetration distance and mixing rate of the fuel/air to injection pressure, diameter of the injector hole and numerous secondary factors. Later, Dodge, et.al., (3) utilizing modified and enhanced versions of Siebers’ models and engine experiments, described a path to reduced smoke for diesel engines. The proposed solution recognized the air-fuel mixing improvement recognized when high injection pressure was utilized in combination with small injector nozzle-holes. Figure 1 shows the expected mixing rate improvements (by observing the location of unity-value equivalence ratio contours) for various nozzle holes and high injection pressures. Note that each hole-size/pressure combination yields equivalent fluid flow rates. In Figure 1, it is concluded that the decrease in volume of the fuel-rich areas with equivalence ratio greater than unity leads to reduced soot formation. Therefore, the conclusion by Dodge, et.al. was that smaller holes and higher pressures would decrease overall engine soot emissions. The proposed methodology has been advanced and optimized over the last several years.

![Fig.1 Small-holes, high injection pressure effects on air-fuel mixing in a free jet (following Dodge, et.al., (3)).](image)

More recently, the concept of “lifted flames” (4,5) has been developed to describe the combustion characteristics of the combusting, high-pressure fuel/air jet. The current model of diesel fuel/air jet combustion is a modification of the highly regarded model originally proposed by Dec, et.al., (6,7) – Figure 2.

![Dec model for diesel combustion (adapted from 6,7).](image)

It should be noted that the flame-liftoff distance is a strong function of injection pressure, ambient temperature and density, and EGR concentration. Figure 3 (adapted from original paper (5) shows liftoff lengths for flames in ambient environments with temperature 1000K and density of 14.8 kg/m\textsuperscript{3}. Injection pressure was ~138 MPa and nozzle hole size was 180 micron. Also shown in the figure is the strong effect of oxygen concentration (EGR) on flame lift-off length. Note that modern diesel engines utilize up to 20% EGR at high load conditions, with EGR targets approaching 40% for some future applications. With this in mind and referring to Figure 3, the flame liftoff distance for a future diesel engine (EGR ~40%, or O\textsubscript{2} ~15%) could be over 30% greater than the non-EGR case (EGR ~0%, or O\textsubscript{2} ~21%). Because larger flame lift-off distances can be correlated to increased air entrainment in the fuel/air jet, longer liftoff lengths are often targeted for reduction of smoke from the flame.

![Fig.2 Dec model for diesel combustion (adapted from 6,7).](image)

Figure 4 shows results from Siebers, et.al.(5), where flame-produced soot, as measured by soot incandescence, is nearly extinguished when sufficient air is entrained into a fuel-air jet. The term, $\phi_r$, represents the percentage of stoichiometric air entrained into the fuel jet. Note that for stoichiometric air fractions above 50%, soot formation is effectively zero. This is in agreement with other research, including that of Roberts (8), where premixed flames exhibit no soot when diluted with air to equivalence ratios below approximately 2.2. Comparing “typical” flame lift-off lengths for modern diesel engines (10-20 mm) to expected air entrainment, it is clear that increases in injection pressure may be utilized to further decrease engine smoke by increasing lift-off length and thus improving air-fuel mixing and entrainment in the injection jet.
Fig. 3 Flame liftoff distances as function of oxygen concentration (0% O\textsubscript{2} = 0% EGR, 15%O\textsubscript{2} = ~40% EGR). Image adapted from (5).

Fig. 4 Flame Lift-Off Length Requirements for Future Diesel Engines (from Siebers, et.al. (5))

Figure 5, based upon the work of Dodge, et.al. (3), extends the steady-state analysis methods of Siebers to include a mixing rate time limit for soot production. Dodge introduces the “Mixing Parameter, MP1” which represents the fraction of total injected fuel not mixed sufficiently with air in the fuel jet within a time of less than 0.5ms. The basis of the analysis is that fuel and air which are quickly mixed beyond stoichiometry will not soot. Based upon this strategy, as shown in Figure 5, injection pressures of approximately 450 MPa are required to insure adequate mixing of the fuel/air jet such that smoke is eliminated.

Fig. 5 Soot Potential based upon Mixing Parameter Value, as described by Dodge, et.al., (3).

Although the smoke reduction strategy described above shows a path to low-smoke engines, it fails to recognize some limitations of modern engine design, especially in regard to excess injection system pressure and the limited distance between the piston bowl edge and the fuel injector nozzle. As injection pressure is increased, the cost of the fuel system increases rapidly, while it becomes increasingly difficult to insure injection system durability. Beyond technical challenges to building high-pressure injection systems, the flame liftoff distance impacts the location of the flame plume in the combustion bowl. Production 14-16L heavy-duty diesel engines have injector-to-bowl distances of approximately 45mm at top-dead-center, and almost never exceed 55mm for piston positions within 10 CAD from TDC. Therefore, at very high injection pressures and high EGR rates, the flame liftoff distance can approach the available combustion chamber injector-to-bowl distance. Hence, the majority of the flame (and air entrainment) may occur for fuel-air mixtures that interact strongly with the piston bowl. This problem becomes even more severe for smaller bore engines. Implications of these challenges are that combustion and design engineers must approach new engine designs with multiple solution methods, including injection system pressure and design, coupled with optimization of piston bowl and injection plume interactions.

### 3. PROGRAM DESCRIPTION

#### 3.1. Objective

The target of this program was to study a combustion system for future diesel engines that would provide higher cycle-efficiency through fast burn rates, while being robust to engine smoke and NO\textsubscript{x} production. The study utilized a 15 liter displacement, in-line 6-cylinder heavy-duty diesel engine. The engine was modified to include the following technologies and operational characteristics:
1) ~270 MPa injection pressure from 2-valve-type unit injectors  
2) Two, series turbochargers, with intercooling and aftercooling  
3) Low-pressure-loop cooled EGR system

The turbocharging and EGR systems were designed to provide air and EGR flow with minimal pumping losses. The engine was equipped with pressure transducers and rocker-arm strain gages on all 6 cylinders, allowing detailed combustion analysis. Additionally, the test facility included 5-gas emissions capability (including EGR measurement) and an AVL smoke meter (all PM results correlated from smoke number). The engine was tested over the entire speed-load range. However, for brevity, this paper will focus upon results at a medium speed, high load condition. Details of the test condition are shown in Table 1.

**Table 1. Engine Operating Point**

| Engine Variable | Value | Comment |
|-----------------|-------|---------|
| RPM             | 1500 rpm | Mid-speed |
| BMEP            | 1.5 MPa | High Load |
| EGR rate        | ~38% | Constant NOₓ = 0.27 g/kWh |
| Air-Fuel Ratio  | ~18/1 | |

**Table 2. Combustion System Design Parameters**

| Design Parameter | Value or Range | Comment |
|------------------|----------------|---------|
| Combustion Bowl Design | Conventional vs Two-Step | Represents traditional vs high EGR design |
| Injector Spray Angle | Narrow, Baseline, Wide | Baseline = ~145 deg |
| Number of Nozzle holes | 6, 7, 8 | Hole size adjusted for constant nozzle flow |

**Fig. 6** Conventional Piston Bowl Design  
**Fig. 7** General Two-Step Piston Bowl Design

The study also encompassed three areas of combustion system design, as outlined in Table 2. The bowl designs consisted of conventional (as a baseline) versus a two-step design, both shown schematically in Figures 6 and 7. The injector spray angles were varied from narrow to wide, in increments of approximately 5 degrees, as shown in Figure 8. Additionally, injector hole number was varied from 6 to 8, as shown in Figure 9. It should be noted that the hole size was determined such that each injector tip had the same net flow area (regardless of hole number), such that the expected injection duration from each tip would be nominally equal.

**Fig. 8** Injector Spray Angles tested for this program  
**Fig. 9** Injector hole combinations tested for this program

### 4. RESULTS

The results from the program are presented in three sections: First, an initial comparison of the two-step piston design versus the conventional piston is made. Second, the injection spray angle was varied and results are presented. Finally, the effect of number of injector holes is presented. All results are normalized to the operating condition corresponding to two-step pistons with the baseline spray angle and 8-hole injector tips.

#### 4.1. Conventional Versus Multi-Step Piston

The target of this program was to develop a combustion system for future diesel engines that would provide high cycle-efficiency with reduced soot emissions. Both of these objectives can be met with a combustion system that provides fast mixing of injected fuel with air, such that combustion rate is improved while smoke production is decreased due to local increases in air-fuel ratio. The conventional piston was very similar to designs seen in many OEM combustion systems. The bowl and injection system were designed to allow excellent fuel economy for injection timings near Top-Dead-Center. However, to meet future emissions standards for NOₓ and PM, it may be necessary to increase EGR levels and retard injection timing compared to modern diesels. For example, to meet low engine-out particulate targets, injection timings as late as -10 deg BTDC may be required. Note in Figures 10 and 11 that the two-step piston design provides improved fuel consumption at injection timings that produced low particulate emissions. Also, note that the fuel economy was very good for the conventional piston (injection timing 5 deg BTDC), but had high BSPM.
4.2. Injector Spray Angle Study

Injector spray angle was varied to establish the sensitivity of the two-step piston design to injection spray angle. Figure 12 illustrates the targeting of the injection plume and its relation to piston position for the narrow, baseline, and wide injection spray angles and piston position of -20 deg BTDC. Figures 13 and 14 show the results of injection spray angle for the two-step piston as a function of injection timing. Recall that the previously-discussed piston bowl study had generally resulted in a target injection timing of 10-12 degrees ATDC. In this timing range, the baseline and narrow injection angles provided lowest particulates at nearly equal fuel consumption. It is assumed that the wide-angle injection spray deposited too much fuel above the piston bowl for late injection timings, as can be seen in Figure 12, which shows the location of the fuel plume during the middle of combustion.
4.3. Effects of Number of Injector Nozzle Holes

Injector nozzle hole number was varied to determine the sensitivity of engine smoke and fuel consumption to the air-fuel mixing rates achieved for various injector hole numbers. For all tests conducted, the total flow area of the injector tip was held constant. Figures 15 and 16 show particulate and BSFC response to injection timing. At advanced timings, the 6-hole injector exhibited lowest smoke, followed by the 7- and 8-hole injectors. This trend may be expected, due to the fact that higher hole numbers would have a higher tendency to display plume-to-plume interactions within the bowl at advanced timings. The trends reversed at the retarded timing conditions, where the 8-hole injector displayed an advantage in BSFC, as well as particulate emissions. Here, it is presumed that the 8-hole injector provided better utilization of available air above the bowl and that plume-to-plume interactions were much less severe.

5. CONCLUSION

This study compared potential combustion system designs for future, high-EGR engines. The conclusions from this program are:

1. The two-step piston was compared to an optimized conventional piston at mid-speed, high-load conditions. The two-step piston provided better BSFC at retarded injection timings necessary for low smoke.
2. Injection spray angle was varied to study the sensitivity of the two-step piston to spray-angle/piston-interactions. It was found that the best spray angle would target the two-step piston such that the injection plume would be split into roughly equal upper and lower wall-jets.
3. Injector hole number was varied from 6-8, with 8 holes giving best BSFC/smoke tradeoff for late injection timings, where smoke production was minimized.

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