

An Assessment of Two Piston Bowl Concepts in a Medium-Duty Diesel Engine

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ABSTRACT

Two combustion systems were developed and optimized for an engine for a power cylinder of 0.8-0.9L/cylinder. The first design was a re-entrant bowl concept which was based on the combustion system of a smaller engine with roughly 0.5L/cylinder. The second design was a chamfered bowl concept, a variant of a reentrant bowl that deliberately splits fuel between the bowl and the squish region. For each combustion system concept, nozzle tip protrusion, swirl, and nozzle configuration (number of holes, nozzle flow, and spray angle) were optimized. Several similarities between combustion system concepts were noted, including the optimal swirl and number of holes. The resulting optimums for each concept were compared. The chamfered combustion system was found to have better part-load emissions and fuel consumption tradeoffs. Full load performance was similar at low speed between the two combustion systems, but the reentrant combustion system had advantages at high engine speed and load. The results suggest that the chamfered combustion system may be a better option for lower speed engine concepts of this size, but that the reentrant combustion system may be better for high speed and high power density applications.

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INTRODUCTION

In order to maximize the fuel efficiency of a diesel engine within emissions and noise constraints, it is critical that a diesel combustion system provides the best possible tradeoffs between these attributes. The key to these tradeoffs is air utilization, the efficiency with which the fuel is able to find and burn in-cylinder oxygen. This is largely dictated by the design of the combustion system.

A diesel combustion system is defined by the piston bowl design and the nozzle configuration (see [figure 1](#)) as well as the in-cylinder charge air motion (i.e. swirl) which indicates the level and angular velocity of the charge air. The type of piston bowl chosen dictates the combustion system concept. The nozzle configuration consists of four different design parameters: the number of holes, the size of those holes, the angle at which those holes exit the nozzle (spray included angle, α), and the distance that the nozzle protrudes into the combustion chamber (NTP). Hole size is a result of the number of holes and the nozzle hydraulic flow (the amount of fuel volume that flows through a nozzle at 100 bar injection pressure in either 30 seconds or 1 minute). Finally, in-cylinder charge air motion for a diesel is primarily defined by the swirl, which is a measure of the in-cylinder angular velocity.

In the current study, two combustion system concepts were separately optimized for a medium-duty engine (0.8-0.9 L/cylinder). The optimal solutions were then compared to determine which concept is best suited for this size power cylinder. The current paper discusses both the optimization of the two combustion system concepts and result of their comparison.

COMBUSTION SYSTEMS

The two combustion system concepts that were optimized and compared in the current study were a re-entrant bowl concept [[1,2,3,4](#)], which is depicted in [Figure 1](#), and a chamfered bowl concept [[5,6](#)], which is shown in [Figure 2](#). A re-entrant bowl design is a common combustion system found in passenger car application with power cylinder displacements of less than 0.5L/cylinder. This concept uses the bowl to redirect fuel down into the bowl and then towards the center of the bowl, utilizing the air in the bowl very well. Spray targeting is typically done such that a small portion of the fuel is directed into the squish region to utilize the air in that volume of the combustion chamber. The narrow throat of the bowl provides strong squish and reverse squish flow to enhance fuel-air mixing. The interaction of the swirl and the reverse squish flow provides strong mixing during the late

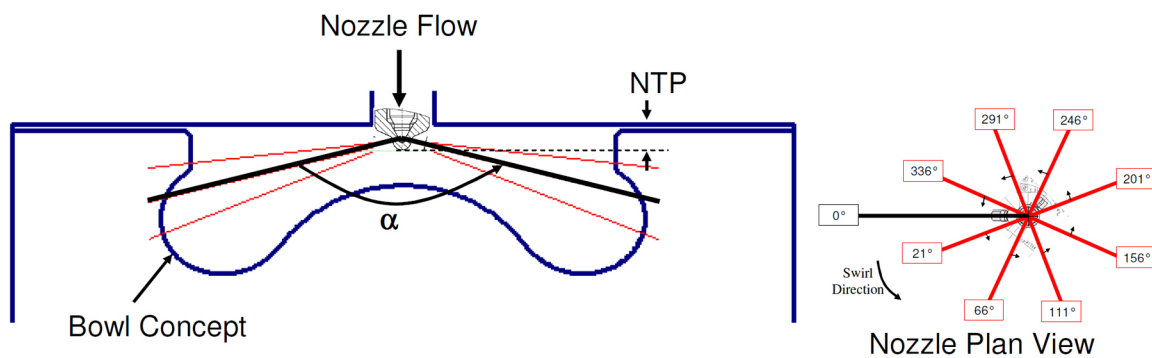


Figure 1. Combustion system example (re-entrant design)

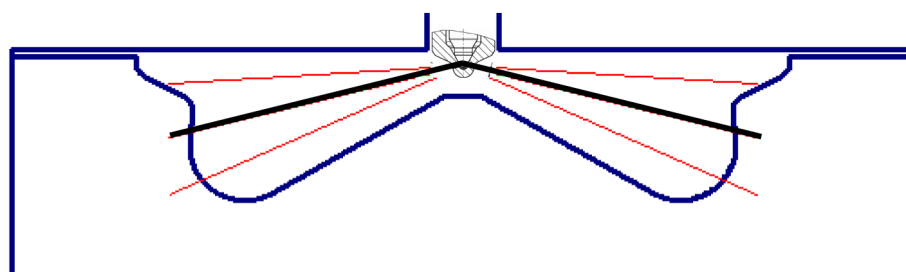


Figure 2. Chamfered combustion system concept

Table 1. Nozzle matrix

		Number of holes				
		5	6	7	8	9
Nozzle Flow Rate	A	X	X	X	X	
	B	X	X	X	X	
	C		X		X	X

phase of combustion to enhance soot oxidation and mixing, particularly at high load condition, as shown by Miles, *et al* [3]. The re-entrant bowl used in this study was based on a bowl previously optimized for a ~ 0.5 L/cylinder European engine [4], which was scaled to the larger power cylinder and its function was analytically verified through 3D CFD simulations using KIVA 3V.

The concept of the chamfered bowl is to split the fuel into two portions. One portion goes into the lower bowl, which behaves similarly to a re-entrant bowl, but with significantly less squish and reverse squish flow. The other portion of the fuel is directed up towards the cylinder head. The splitting of the fuel is intended to provide rapid fuel-air mixing by allowing the air in the squish volume to be more easily used. One of the advantages of this concept is to reduce soot-in-oil by directing the fuel upwards as it enters the squish region rather than radially towards the crevice. The chamfered bowl design used in this study was initially designed analytically and is discussed in detail in Styron *et al* [6].

Combustion system optimization typically includes two stages. Each bowl was initially optimized analytically using 3D combustion CFD and direction was provided regarding nozzle configuration and swirl. Nozzle configuration and swirl were then optimized for each bowl design by testing various heads and nozzle configurations on a single-cylinder engine. Table 1 shows the nozzle matrix used for optimization of the re-entrant combustion system, obtained based on direction from CFD analysis. The changes in nozzle flow rate going from A to B and B to C constituted approximately a 10-15% for each step. In addition, three different swirls, which were developed by modifying intake ports, were used in the optimization of the re-entrant combustion system.

SINGLE-CYLINDER TESTING

The two combustion systems were optimized on separate single-cylinder engines, both having displacements close to 0.83L. Test conditions used to optimize each combustion system differed; however, the final evaluation of the two

optimized combustion systems was conducted on a common test engine at common test conditions. Those test conditions included six mini-map points, shown in [Figure 3](#) overlaid onto a representative FTP city cycle. These mini-map points were used to project cycle emissions and fuel consumption. In addition, full load assessment was conducted at 1000, 2000 and 3000 rpm. Since single-cylinder engine friction is not representative of that observed on a multi-cylinder engine, the engine load was controlled to a net indicated mean effective pressure (IMEP720) obtained from multi-cylinder data. Boundary conditions for the test points were obtained from a surrogate multi-cylinder engine with reasonably representative turbocharging and cooling systems. Engine coolant and oil, which were externally controlled, were maintained at 90°C for all test conditions.

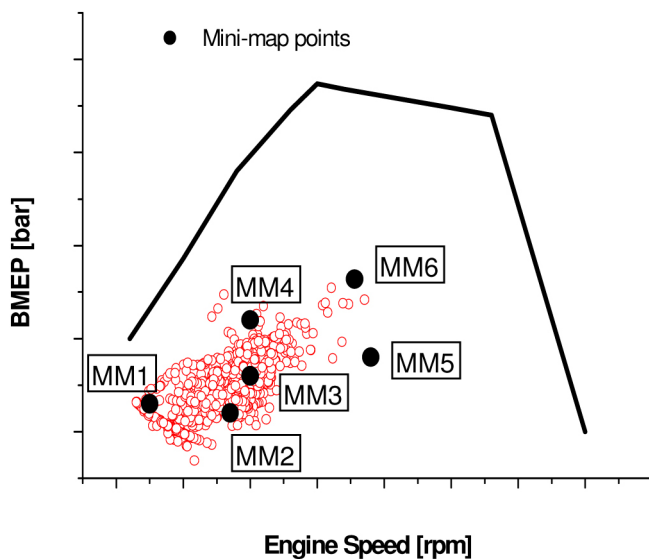


Figure 3. Mini-map Test Conditions

For a fair comparison between hardware sets, the calibration was optimized at each test condition for all hardware iterations by varying injection timing and pilot injection quantity. Injection pressure was left unchanged from a baseline value in this process, since changes to that parameter would influence the friction on a multi-cylinder engine, which couldn't be accounted for properly on the single-cylinder engine. Pilot-to-main dwell was optimized for the first several hardware iterations, but it was observed that the optimal setting remained constant as nozzle configuration and swirl were varied. Thus, the values for this parameter were held constant for all subsequent testing based on the initial optimization. The hardware was optimized by comparing fuel quantity sweeps at the full load test conditions and EGR sweeps at each of the mini-map points. Cycle projections from the mini-map points were also used to compare between different hardware sets, since the optimal hardware configuration was not always the same for all mini-map points. For brevity, most of the mini-map data in this paper will be presented as cycle projections.

RESULTS

COMBUSTION SYSTEM OPTIMIZATION

As mentioned above, the re-entrant combustion system was optimized using three heads that delivered different swirl ratios and the nozzle matrix shown in [table 1](#). In addition, the spray targeting was optimized by varying the spray angle and nozzle tip protrusion. [Figure 4](#) shows a comparison of the projected soot-NOx for various tip protrusions with a 153° spray angle. The NOx and PM data are shown as a ratio relative to a target value. Note that several NOx targets were considered as shown by the bold lines in the plot, which were based on different NOx aftertreatment efficiency assumptions. The figure shows that the optimal tip protrusion was 3.3mm. Consequently, subsequent optimization works was conducted with a 153° spray angle and a 3.3mm NTP.

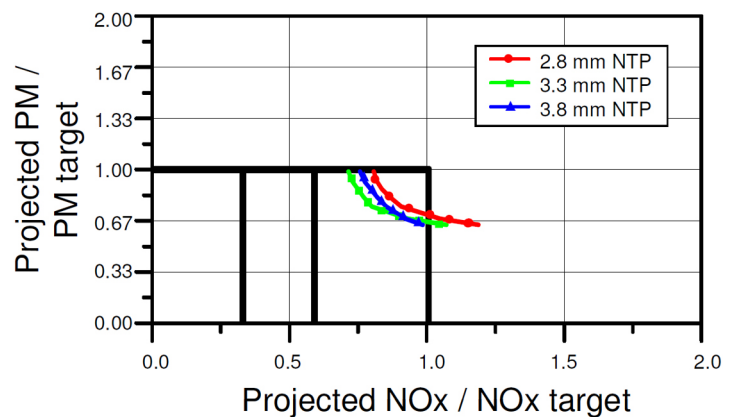


Figure 4. Projected emissions tradeoffs for various nozzle tip protrusions with a 153° spray angle

During the optimization process, an interaction between the number of nozzle holes and the swirl rate was identified. [Figure 5](#) shows the PM-NOx tradeoff as nozzle hole size is varied for various swirl rates. [Figure 5a](#) indicates that a 6-hole nozzle provides the best emissions tradeoffs for a high swirl head; however, when the swirl is reduced, the best emissions tradeoff is observed using a 7-hole (see [figure 5b](#)), although an 8-hole nozzle performs almost as well. When swirl was reduced even further as shown in [figure 5c](#), an 8-hole nozzle enables lower emissions. This suggests that the optimal number of holes increases with decreasing swirl. A probable explanation for this interaction between swirl and the number of holes is the effect swirl and the number of holes can have on entrainment of fuel from neighboring sprays (i.e. jet-jet interaction). As the number of holes increases, the gap between sprays is reduced and the likelihood of jet-jet interaction increases. Swirling flow pushes vaporized fuel causing the spray to bend and approach a neighboring spray. When the gap between sprays is small the bending of the fuel spray can lead to significant jet-jet interaction. The swirl level influences the degree to which the