2018-01-1378 Published 03 Apr 2018

Cold Start HD FTP Test Results on Multi-Cylinder Opposed-Piston Engine Demonstrating Rapid Exhaust Enthalpy Rise to Achieve Ultra Low NOx

Samrat Patil and Ahmad Ghazi Achates Power Inc.

Fabien Redon Achates Power Inc

Christopher Sharp Southwest Research Institute

Dan Schum and John Headley Achates Power Inc

Citation: Patil, S., Ghazi, A., Redon, F., Sharp, C. et al., "Cold Start HD FTP Test Results on Multi-Cylinder Opposed-Piston Engine Demonstrating Rapid Exhaust Enthalpy Rise to Achieve Ultra Low NOx," SAE Technical Paper 2018-01-1378, 2018, doi:10.4271/2018-01-1378.

Abstract

The 2010 emission standards for heavy-duty diesel engines in the U.S. have established a limit for oxides of nitrogen (NOx) emissions of 0.20 g/bhp-hr., a 90% reduction from the previous emission standards. However, it has been projected that even when the entire on-road fleet of heavy-duty vehicles operating in California is compliant with the 2010 emission standards, the upcoming National Ambient Air Quality Standards (NAAQS) requirement for ambient particulate matter and ozone will not be achieved in California without further significant reductions in NOx emissions from the heavy-duty vehicle fleet. Given this, there is potential of further reduction in NOx emissions limit standards for heavy duty engines in the US. Recently there have been extensive studies and publications focusing on ultra-low NOx after treatment technologies that help achieve up to 0.02g/bhp-hr. at tailpipe [1].

To achieve ultra-low NOx emission levels over the composite HD FTP cycle, rapid heat energy must be provided to the diesel exhaust after-treatment system during cold start portion of the cycle, and peak NOx reduction efficiency must be maintained during the hot-start portion of cycle. Delivering this has been the challenge for conventional four-stroke heavy duty diesel engines as these are competing demands. Ultra-low NOx system solutions involving the implementation of supplemental heat sources downstream in the exhaust system comes at CO_2 penalty and adds significant cost and complexity.

The Achates Power Opposed-Piston Engine design provides an ideal solution to this challenge. The opposed-piston engine has several inherent advantages over conventional four-stroke engines, like higher BTE [2], low BMEP and internal EGR facilitating low engine out NOx and ability to provide rapid engine out temperature rise [3] for emission system while maintaining low engine out NOx.

This paper highlights the results from cold-start HD FTP testing with the 4.9L Opposed-Piston Engine. The target of this testing was to evaluate the ability of the Achates Power Opposed-Piston Engine to provide rapid engine out temperature rise by operating the engine in the mode designed to deliver exhaust enthalpy, aiding fast catalyst light-off which enables early and peak NOx conversion in the exhaust after treatment system. Rapid exhaust heat and temperature rise that was delivered exceeded SCR catalyst light-off temperature thresholds (200°C) within the first 40 seconds in the cycle while controlling the engine out NOx levels.

Introduction

Opposed-piston engines were once widely used in a variety of applications including commercial vehicles, aviation, maritime and military vehicles, due to their superior efficiency characteristics. Achates Power, Inc. has been dedicated to modernizing the Opposed-Piston Engine since its inception in 2004 and has solved various mechanical challenges faced by this engine architecture, including oil consumption, piston cooling, cylinder cooling, and wrist pin lubrication. Achates Power has also developed a unique set of performance and emissions strategies and combustion system recipes which enables the Opposed-Piston Engine to meet current and future emissions [4] while delivering excellent fuel consumption.

After overcoming the architecture's historical challenges, the Achates Power Opposed-Piston Engine now delivers a step-wise improvement in BTE over the most advanced conventional four-stroke engines [2]. In addition, with the elimination of parts such as the cylinder head and valve train, it is also less complex and less costly to produce—making it even more appealing to manufacturers.

Advantages of the Opposed-Piston Engine

The inherent advantages of the Achates Power Opposed-Piston Engine over the conventional four-stroke engine are summarized below:

Combustion System Reduced heat losses: The Opposed-Piston Engine, which includes two pistons facing each other in the same cylinder, offers the opportunity to combine the stroke of both pistons and increase the effective stroke-to-bore ratio of the cylinder, leading to lower area-to-volume of the combustion chamber. This results in reduction in heat transfer or loss from combustion to cylinder head. Additional benefit is that smaller heat rejection packaging or radiator can be used, as well as fan power consumption can be reduced to lower speeds contributing to lower fuel consumption.

Leaner combustion: When configuring an opposed-piston two-stroke engine of the same displacement as a conventional four-stroke engine, for example, converting a six-cylinder conventional engine into a three-cylinder opposed-piston engine, the power that each cylinder must deliver is the same. The opposed-piston engine fires each of the three cylinders in each revolution while the four-stroke engine fires each of its six cylinders in one out of two revolutions. Therefore, the amount of fuel injected for each combustion event is similar, but the cylinder volume is 60% greater for the opposed-piston engine. So, for the same boost conditions, the opposed-piston engine will achieve leaner combustion, which increases the ratio of specific heat. Increasing the ratio of specific heat increases the work extraction per unit of volume expansion during the expansion stroke.

The above mentioned fundamental thermal efficiency advantages [5] are amplified by:

- Lower heat loss due to higher wall temperature of the two piston crowns compared to a cylinder head (reduced temperature difference).
- Reduced pumping work due to uniflow scavenging resulting in higher effective flow area than a comparable four-stroke or a single-piston two-stroke uniflow or loop-scavenged engine.
- Decoupling of pumping process from the piston motion because of the two-stroke architecture allows alignment of the engine operation with a maximum compressor efficiency line.

Air-System To provide enough air for combustion, Opposed-Piston Engines need to maintain an appropriate pressure difference between the intake and exhaust ports. In addition, the air demand and delivery during transient operation have greater impact on the engine performance and emissions. The advantages of such an air-systems are:

- The compressor provides high pressure ahead of the supercharger, which then further boosts intake flows resulting in low supercharger pressure ratios sufficient for high intake manifold density, reducing pumping work.
- The maximum required compressor pressure ratio is lower compared to turbocharger-only air systems of four-stroke engines.
- The use of a supercharger recirculation valve allows greater control of the flow through the engine, thus providing flexibility for precise control of boost, scavenging ratio, and trapped residuals to minimize pumping work and NOx formation across the engine map
- Lowering the flow through the engine by decreasing the pressure difference across the engine reduces the pumping penalty at low load points. This, together with having no dedicated intake and exhaust stroke for moving mass to and from the cylinders improves BSFC.
- The supercharger recirculation valve improves transient response. Facilitating EGR with a supercharger reduces the required pumping work.
- Accurate control of the engine pressure differential provides good cold start and catalyst light off capabilities. Low-speed torque is increased by selecting the appropriate gear ratios on the supercharger.

Test Bed Description

Table 1 shows the specifications for the multi-cylinder Opposed-Piston Engine used for this testing. This engine was conceived as a research test platform with flexible components and systems beyond what would be done in a production intent version. With such trade-offs made, the engine's size and friction were affected negatively. With a production design in progress for HD Class 8 truck applications, improved thermal management performance is expected over the research engine.

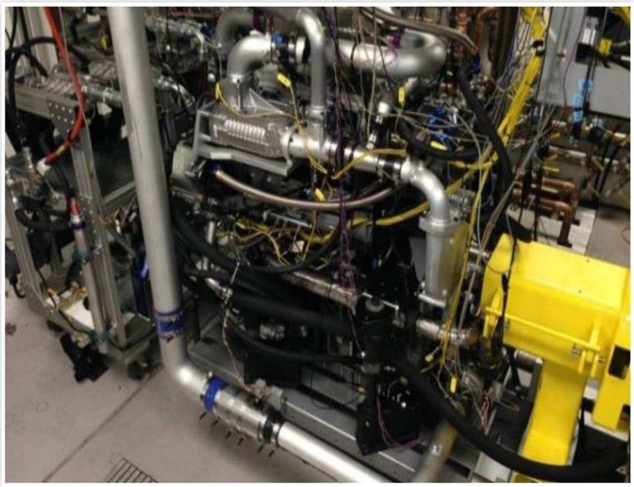
Figure 1 shows the test cell installation of the 4.9L three-cylinder Opposed-Piston Engine, for the transient cold-start testing at the Achates Power facility in San Diego, California.

Even though this engine was conceived as a research and test-platform, it powered all the accessories that were required

TABLE 1 Multi-cylinder Achates Power Opposed-Piston Engine specification

Displacement	4.9 L
Arrangement, number of cylinders.	Inline 3
Bore	98.4 mm
Total Stroke	215.9 mm
Stroke-to-Bore Ratio	2.2
Compression Ratio	15.4:1
Nominal Power (kW @ rpm)	205 @ 2200
Max. Torque (Nm @ rpm)	1100 Nm @ 1200-1600

FIGURE 1 Achates Power 4.9L three-cylinder research engine in test cell



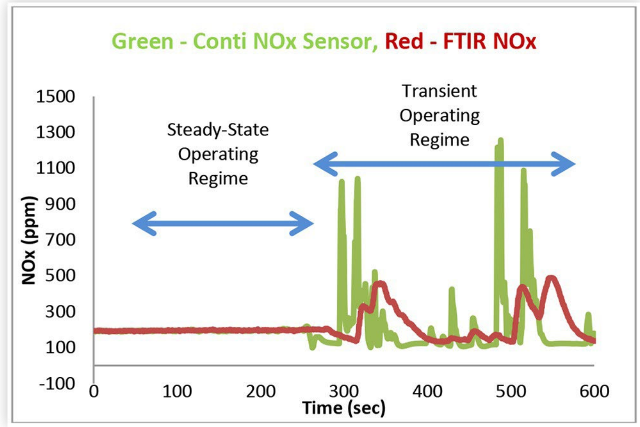
to operate it. These accessories included lubrication oil pumps, a high-pressure fuel pump, a supercharger and a supercharger drive and water pumps. The test cell setup did not include an exhaust after treatment system, but an exhaust back pressure valve was used to simulate the exhaust restriction of a typical 2010 like emission system (DOC+DPF+SCR).

Scaling the Research Engine for Comparison with a Class 8 Heavy Duty Diesel Engine When using the data from 4.9L research engine for Ultra-low NOx after treatment system simulation, the engine out exhaust parameters (exhaust flow and gas constituents) were scaled up with factor of 2.16. This scaling factor was based on the planned HD Opposed-Piston Engine design development at Achates Power (please refer to Table 2 for the specifications). To have a performance comparable to a conventional HD four-stroke engine, typically 13L to 15L, the heavy-duty Opposed-Piston Engine is designed to be 10.6L in capacity with performance characteristics mentioned below in Table 2. The Achates Power team, with experience on various light-duty and medium-duty engine designs, has high confidence in the scaling factor used and hence it was used to derive the exhaust gas constituents and flow characteristics used in the after-treatment performance simulations.

TABLE 2 Heavy-Duty Opposed-Piston Engine specifications.

Displacement	10.6 L
Arrangement, number of cylinders.	Inline 3
Bore	120 mm
Total Stroke	312 mm
Stroke-to-Bore Ratio	2.6
Compression Ratio	17.5:1
Nominal Power (kW @ rpm)	336 @ 1700
Max. Torque (Nm @ rpm)	2373 Nm @ 950
Exhaust mass flow at rated power	1412 kg/hr

FIGURE 2 Comparison between FTIR NOx and Continental NOx sensor during steady-state and transient operations



Engine-out NOx Measurement

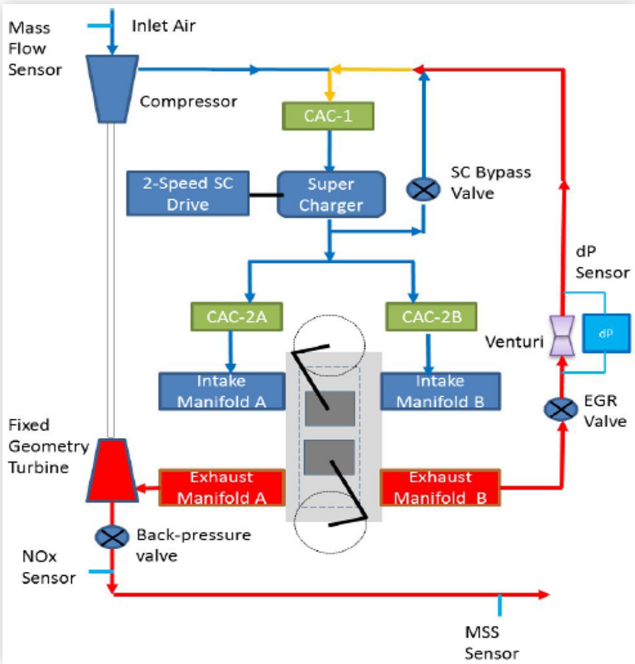
To measure engine out NOx in real-time, a Continental NOx sensor and FTIR-based gas-analyzer were used. During steady-state operations, both FTIR and Continental's NOx sensor generate similar measurement results. But during transient operations, the FTIR based analyzer system installed in the Achates Power test-cell exhibit temporal delay. The difference in performance can be attributed to both response time of the sensors, as well as transport delay. The Continental's NOx sensor is mounted immediately downstream of the back-pressure valve, whereas the FTIR sample lines are located further downstream along the exhaust pipe.

Using NOx measurements from both sensors, that was evaluated during this cold start transient testing. Figure 2, shows how the engine-out Continental NOx response differs from the test cell FTIR probe, with respect to response time and capturing the peaks.

Engine Controls and Operating Mode

Achates Power has developed proprietary controls software that addresses unique challenges faced by the Opposed-Piston Engine configuration. For air-handling control, strategies were developed to control airflow using the supercharger recirculation valve and a two-speed drive, whereas EGR is controlled by the EGR valve. For the airflow controller, air mass-flow feedback is provided by a MAF sensor mounted before the compressor. For the EGR control, EGR mass flow feedback is provided by a delta pressure sensor, which is mounted across the venturi along the EGR loop. Figure 3 provides the overview of the air handling system implemented on the 4.9L Achates Power research engine. Achates Power has developed and implemented controls strategies for controlling rail-pressure

FIGURE 3 Opposed-Piston Engine air system schematic



for the common rail system, which allows it to utilize two injectors per cylinder to inject the fuel. For the FTP transient cycle testing, a smoke-limiter, transient modifier and feed-forward controllers for air-handling and EGR were incorporated into the controls software. Details on transient air handling controls implemented for this engine are discussed in detail in prior publications by Achates Power [10].

Fast Catalyst Light-off Mode (CLO) [9]

With conventional diesel engines, the limited ability to modify trapped conditions, along with the need for stable combustion limit the potential for achieving high exhaust temperatures. This is evidenced by strategies in use for the latest heavy-duty emissions certifications, where manufacturers have implemented fuel injection directly into the exhaust stream to warm diesel oxidation catalysts or used electrical heating elements upstream of the catalysts.

In contrast, the opposed-piston engine can generate trapped conditions to achieve stable combustion (COV of IMEP <5%) and high exhaust temperatures simultaneously. Running the engine at low modified delivery ratios yields significant internal residuals, which in turn increases the trapped temperature of the charge. In this operating mode, a sufficiently high intake manifold pressure is required to achieve an adequate air-fuel ratio and good combustion stability during light-load operation, low ambient temperature operation and extreme cold starts. When coupled with a series of split and late fuel injection events, it creates a significant temperature rise in the exhaust for thermal management.

The Achates Power catalyst light-off (CLO) control scheme, designed to activate during cold starts, seeks to maximize exhaust enthalpy while retaining good combustion stability. Controlling NOx emissions during this operating mode are critical as the aftertreatment system will not yet be functioning. The NOx production needs to be minimized after a cold start while the SCR aftertreatment is getting warmed up. Hence the operating mode strategy seeks to absorb crankshaft energy with the supercharger, which also provides high boost pressure, enabling beneficial scavenging characteristics. In a vehicle application, additional energy also could be absorbed by fully engaging the vehicle's charging system, storing some of this energy for later re-use. By creating the heat within the combustion cycle, any number of crankshaft driven accessories can be used to absorb additional energy, increasing the amount of enthalpy available for warming the emissions aftertreatment equipment.

By using the variable geometric turbo, backpressure valve and the supercharger, the scavenging and trapping characteristics of the engine at idle can be altered significantly, such that majority of the fuel injected is converted into exhaust enthalpy, providing rapid temperature rise during idle and low speed & load operating points. The catalyst light-off mode (CLO) offers significant advantages that can be activated almost immediately after startup or during any extended idle where it is necessary to maintain the optimum temperatures in the aftertreatment system. In previous publications [9], it was demonstrated that turbo-out temperatures reaching 400°C were achieved during the elevated idle implemented in Catalyst light off operating mode.

Cold-start Heavy-duty FTP Testing on Opposed-Piston Engine

In a January 2015 paper [7] published at the SAE SIAT in India, Achates Power presented results showing the fuel economy of the opposed-piston multi-cylinder engine while meeting US 2010 emissions.

The results showed that the 4.9L three-cylinder OP Engine was able to achieve 43% brake thermal efficiency at the best point and almost 42% on average over the 12 modes of the SET cycle. The results from this test confirmed the modelling predictions and carved a very robust path to a 48% best BTE and 46.6% average over the cycle for a production design of this engine.

In second paper [9], published at SAE World Congress 2015, the Opposed-Piston Engine transient capabilities were assessed by testing the engine performance and emissions response under a typical transient maneuver controlling both NOx and Soot with a minimal torque lag. Additionally, the ability of the Opposed-Piston Engine to manage exhausts temperatures was also demonstrated. This was achieved using the air system control flexibility and robust combustion system developed by Achates Power. It was demonstrated that high exhaust gas temperatures can be achieved at idle-like speeds and loads. With encouraging results from steady state and transient testing, it was time to assess the Cold start FTP cycle performance of the Opposed-Piston

Engine and evaluate the fast catalyst light off ability for SCR catalyst performance.

The results from recent study by Southwest Research Institute (SwRI) [1] indicates that for a conventional four-stroke HD powertrain, this can be achieved by the addition of a supplemental heat source, like a diesel fuel mini-burner or electric heat catalyst/element in front of the SCR catalyst inlet in the exhaust after treatment system. Such a system solution results in a CO_2 penalty, and adds cost and complexity. The study highlighted the limitations for the conventional HD diesel engine, in achieving Ultra-low NOx levels at the expense of CO_2 emissions. This trade-off has been considered as the main hurdle to the adoption and implementation of Ultra-low NOx regulations in the HD commercial vehicle and HD Off Highway industry.

The Achates Power Opposed-Piston Engine design does not have the limitations of the conventional four-stroke engine. Its inherent ability to control trapped conditions and low heat rejection enable superior conversion of fuel into exhaust enthalpy while controlling NOx production, can be leveraged to help achieve Ultra-low NOx like emissions with a simplified after-treatment system.

The focus of the testing on the 4.9L research engine was to demonstrate that capability. In CLO operating mode, which is activated at start-up, the engine calibration is modified to increase the exhaust enthalpy until the SCR catalyst light-off temperature is achieved. As we did not have thermal mass of an actual after treatment system in the test cell during this testing, turbo out temperature exceeding 300 °C was used as a proxy to indicate that the SCR catalyst has reached light-off. At this point the engine operation strategy switches from CLO to normal operation. During the idle or low-speed and low-load points on the FTP cycle, where turbo out temperature can fall below the light-off threshold, the engine controls strategy switches back to CLO to ensure that temperatures are maintained above 200°C for entire duration of the cycle to guarantee peak NOx reduction by the SCR catalyst.

The engine out data of exhaust constituents were used as inputs for aftertreatment system simulations, with different components and configurations to identify a simplified solution that can help achieve Ultra-low NOx levels.

Engine Out Temperature Comparison Between the Achates Power Opposed-Piston Engine and Conventional Four-stroke HD Engines Used in ARB Low NOx Testing Figure 4 shows measured turbo out temperature, for the cold-start HD FTP portion, comparing ARB Low NOx baseline engine (13L HD engine), modified ARB Low NOx final engine and Achates Power Opposed-Piston Engine. Once the turbo out temperature exceed the close coupled SCR catalyst light-off threshold, the Achates Power OP engine is able to maintain the temperature above for entire duration of cold-start HD FTP cycle. This allows continuous dosing or introduction of DEF enabling peak NOx reduction.

Figure 5 focuses on the first 400 seconds of the cycle, wherein the CLO engine operating mode was active, demonstrating that the turbo out temperature of the Opposed-Piston Engine exceeded 200°C within the first 40 seconds of the cycle and reached 250°C in less than 80 seconds of the cycle.

FIGURE 4 Cold-start FTP Turbo out temperatures comparison.

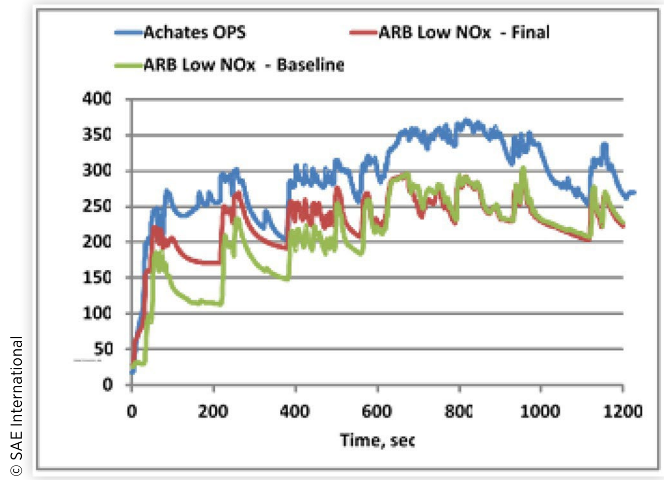
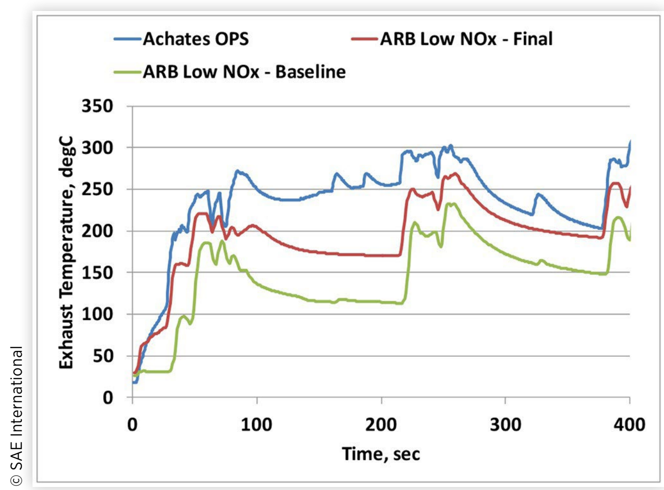


FIGURE 5 Turbo out temperatures during the first 400 seconds of the Cold-start HD FTP



This ability of the Opposed-Piston Engine, to generate rapid exhaust heat, leads to after treatment architectures, like close-coupled SCR catalyst, wherein peak NOx reduction can start very early (less than 100 seconds) in the cold-start cycle. Catalyst durability and reliability are often cited as concern to a close coupled solution, due to exposure to extreme high temperature excursions. But the Achates Power Opposed-Piston Engine design has great degree of control on the exhaust temperature range across the speed and load map, addressing this concern. Figure 4 and Figure 5 highlight that the current production HD four-stroke diesel engines are unable to provide sustained rapid exhaust heat (above 200°C) until 400 seconds into the cycle resulting in peak NOx reduction happening halfway or 600 seconds into the cycle. As majority of the NOx emissions over composite HD FTP cycle comes from the untreated NOx at cold-start portion of the cycle, reducing the time to light-off is critical to achieve further NOx reduction.

Engine Out NOx Emissions Comparison Between the Achates Power Opposed-Piston Engine and Conventional Four-stroke HD Engines Used in ARB Low NOx Testing In addition to providing rapid heat for catalyst light-off, to achieve Ultra-low NOx levels at tailpipe, it is essential to control the generation of engine out NOx during a cold start. The Achates Power catalyst light-off control scheme seeks to maximize exhaust enthalpy, while retaining good combustion stability yielding low NOx levels. This is achieved by controlling the amount of internal EGR, needed to elevate the trapped temperatures along with the injected fuel and boost.

Figure 6 compares the engine out NOx emissions from the Achates Power Opposed-Piston Engine and the conventional four-stroke HD engine (used in the SwRI ARB low NOx project), over the first 400 seconds of the cold-start cycle.

In the HD FTP maximum tailpipe NOx emission happens when the SCR catalyst is yet to warm up for NOx reduction, which is typically the first 300-600 seconds. The cumulative engine out NOx emission from the Opposed-Piston Engine, during this period, is considerably lower than the conventional four-stroke HD engines tested at SwRI for the ARB low NOx project, as illustrated in Figure 6.

Figure 7 shows that around 400 seconds into the cycle, the Opposed-Piston Engine emits more cumulative engine out NOx, compared to the conventional four-stroke HD engine. This is because the engine operating mode switches from catalyst light-off mode to normal operating mode. This switch is triggered when turbo-out temperature exceeds 300°C, as this was used as the proxy to indicate down-stream SCR catalyst has reached light-off temperature. The rationale behind this strategy is that, after providing sufficient and rapid exhaust heat, the engine operation should change to provide the maximum fuel efficiency. The SCR catalyst is a robust component, such that once the temperature is conducive and it is at peak NOx conversion efficiencies (above 95%), it can consume slightly additional NOx without impacting tailpipe emissions. Additional testing and tuning is underway at Achates Power to further optimize this strategy to provide the best cold-start performance for NOx control and fuel efficiency.

FIGURE 6 Cumulative engine out NOx comparison - first 400 seconds of cold-start HD FTP

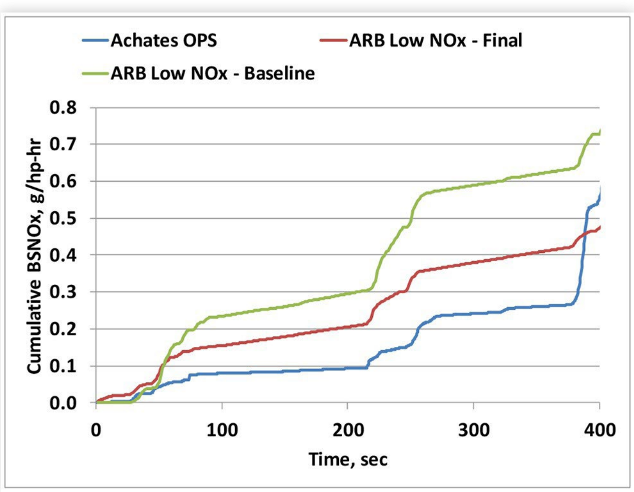
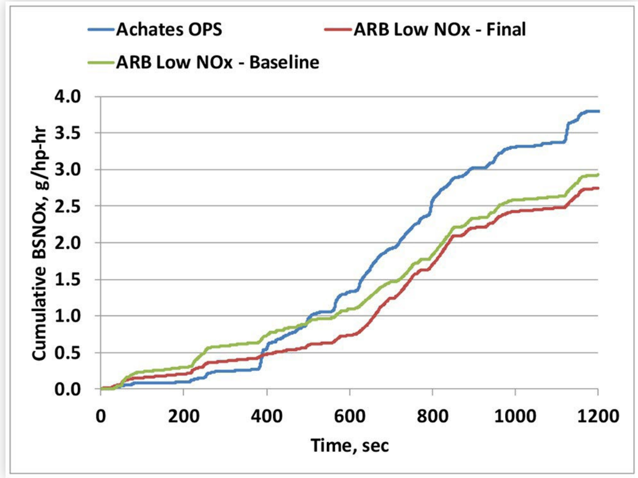


FIGURE 7 Engine out NOx comparison during cold-start FTP



After Treatment System Solution

As stated in the paper published by SwRI[1], various after treatment architectures, configurations and catalyst formulation were evaluated on the 13L HD ARB low NOx engine, and the solution that helped achieve 0.02g/bhp-hr. at tailpipe is shown in Figure 8.

In this architecture, a fuel mini-burner was used upstream of SCRF to help it achieve the fast catalyst light-off by raising the temperature at the expense of fuel efficiency and CO_2.

Achates Power's transient testing shows rapid temperature rise above the SCR catalyst light off temperature of 200°C, just 40-50 seconds in the cold start HD FTP. This lends itself to after treatment architectures with SCR catalyst that are close-coupled to the engine. Figure 9 gives a pictorial representation of the after-treatment system simulated with the scaled cold-start transient data from the 4.9L research engine. The configuration consisted of adding a close-couple light-off SCR (LO-SCR) with gaseous ammonia introduction upstream of it. Downstream is a typical chassis mounted conventional HD after treatment system in Class 8 HD truck application with DEF delivery system.

FIGURE 8 Final ARB Ultra-low NOx system by SwRI

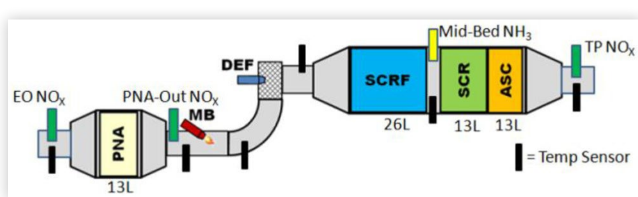
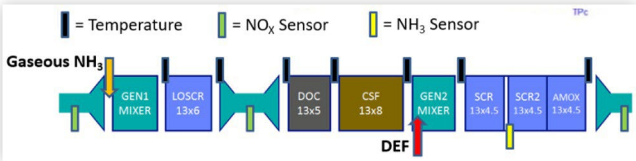


FIGURE 9 Low NOx solution simulated with the Opposed-Piston Engine



© SAE International

As you can see, a close-coupled LO-SCR is used to take advantage of the rapid heat release and initiate good NOx reduction very early into the cold-start cycle. For simulation of this system, target was set to 0.06g/bhp-hr. for the cold-start cycle and 0.01g/bhp-hr. for the hot-start cycle, which will enable 0.02g/bhp-hr over composite HD FTP cycle.

The exhaust after-treatment simulation was done using a 2-D simulation for monolithic catalysts and filters. The tool also accounted for effect of aged catalysts, while solving for energy, mass and soot balance in the catalyst channels. The simulation does assume the single channel performance as representative for the entire catalyst and homogenous gas mixing in front of the catalyst. The cold-start and hot-start HD FTP data (engine out mass flow, NOx, THC, CO, CO_2, O_2, H_2O and temperature) from the Achates Power 4.9L engine was scaled to a 10.6L HD engine output, before using as an input to this simulation tool.

The initial simulation results, for tailpipe NOx emissions, were very encouraging and indicated reaching 0.03g/bhp-hr. Although this is above the 0.02g/bhp-hr. target, with continued efforts of calibration and tuning improvements on engine and after-treatment we are confident we can reach the 0.02g/bhp-hr. target. Achates Power is working with leading industry substrate and catalyst coating providers to evaluate if using advanced SCR catalyst with lower light-off temperature threshold can help reach the 0.02g/bhp-hr. NOx target.

Achates Power and Southwest Research Institute are currently working on further testing and development of a HD Opposed-Piston Engine and Ultra-low NOx emission system to demonstrate these benefits in practical, on-road application.

Summary/Conclusions

Opposed-Piston diesel engines have inherent efficiency advantages when compared to a traditional internal combustion engine. The testing and simulation results in this paper show that this advantage extends to cold start transient performance from exhaust emissions perspective. The cold-start HD FTP test results on the 4.9L research engine, demonstrate the capability of the Opposed-Piston Engine to control engine-out emissions and provide rapid heat release to help achieve ultra-low NOx levels at tailpipe. This advantage of the Opposed-Piston Engine, simplify the emission after treatment system solution to achieve ultra-low NOx levels, by potentially eliminating the need for supplemental energy source, like electrically heat catalyst, diesel fuel mini-burner, etc. that add cost and complexity.

An engine and exhaust after-treatment solution, that is simplified and cost competitive, that can meet the most stringent tailpipe NOx limits (less than 0.02g/bhp-hr.), is a win-win for transportation and heavy machinery industry as well as the Air quality improvement efforts by regulatory bodies around the world. Therefore, the Achates Power Opposed-Piston Engine design can help encourage wide scale adoption and implementation of the tighter ultra-low NOx emission norms while giving the fuel efficiency benefits to the end-user.

References

1. Sharp, C., Webb, C., Yoon, S., Carter, M. et al., "Achieving Ultra Low NOX Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine - Comparison of Advanced Technology Approaches," *SAE Int. J. Engines* 10(4):1722-1735, 2017, doi:10.4271/2017-01-0956.
2. Abani, N., Nagar, N., Zermeno, R., Chiang, M. et al., "Developing a 55% BTE Commercial Heavy-Duty Opposed-Piston Engine without a Waste Heat Recovery System," SAE Technical Paper 2017-01-0638, 2017, doi:10.4271/2017-01-0638.
3. Low Emissions and Rapid Catalyst Light-Off Capability for Upcoming Emissions Regulations with an Opposed-Piston, Two-Stroke Diesel Engine - Redon F., Kalebjian C., Michael Wahl - Presented at Emissions 2012, Global Automotive Management Council.
4. Nagar, N., Sharma, A., Redon, F., Sukumar, B., and Walker, A. P., "Simulation and Analysis of After-Treatment Systems (ATS) for Opposed-Piston 2 stroke Engine," presented at Emissions 2016, Troy, MI, 2016.
5. Herold, R.E., Wahl, M.H., Regner, G., Lemke, J.U., and Foster, D.E., "Thermodynamic Benefits of Opposed-Piston Two-Stroke Engines," SAE Technical Paper 2011-01-2216, 2011, doi:10.4271/2011-01-2216.
6. Naik, S., Johnson, D., Fromm, L., Koszewnik, J. et al., "Achieving Bharat Stage VI Emissions Regulations While Improving Fuel Economy with the Opposed-Piston Engine," *SAE Int. J. Engines* 10(1):17-26, 2017, doi:10.4271/2017-26-0056.
7. Naik, S., Redon, F., Regner, G., and Koszewnik, J., "Opposed-Piston 2-Stroke Multi-Cylinder Engine Dynamometer Demonstration," SAE Technical Paper 2015-26-0038, 2015, doi:10.4271/2015-26-0038.
8. Kalebjian, C., Redon, F., and Wahl, M., "Low Emissions and Rapid Catalyst Light-Off Capability for Upcoming Emissions Regulations with an Opposed-Piston, Two-Stroke Diesel Engine", presented at Emissions 2012 Conference.
9. Redon, F., Sharma, A., and Headley, J., "Multi-Cylinder Opposed Piston Transient and Exhaust Temperature Management Test Results," SAE Technical Paper 2015-01-1251, 2015, doi:10.4271/2015-01-1251.
10. Sharma, A. and Redon, F., "Multi-Cylinder Opposed-Piston Engine Results on Transient Test Cycle," SAE Technical Paper 2016-01-1019, 2016, doi:10.4271/2016-01-1019.

Contact Information

Samrat Patil
Achates Power
4060 Sorrento Valley Blvd. San Diego CA 92121
Phone: +1 858.535.9920 ext. 375
patil@AchatesPower.com
Web: www.AchatesPower.com

Disclaimer

The statements and opinions expressed in this paper are solely those of the authors, and mention of trade names, products, and organizations does constitute endorsement or recommendation for use.

Acknowledgments

The author would like to thank SwRI team for offering advice, guidance and support for data analyses during this Cold-start HD FTP testing. The author would also like to thank the co-authors at Achates Power for the support and assistance provided during the transient testing and simulation phase.

Definitions/Abbreviations

API - Achates Power Inc.

OP - Opposed-Piston Engine

SwRI - Southwest Research Institute

BTE - Break Thermal Efficiency

HD FTP - Heavy-Duty FTP Transient Cycle

EONOx - Engine Out NOx

ULNOx - Ultra-low NOx at tailpipe (0.02g/bhp-hr.)

SCR - Selective catalytic reduction catalyst

DEF - Diesel exhaust fluid

CLO - Catalyst Light-off

DOC - Diesel Oxidation Catalyst

DPF - Diesel Particular Filter

Lo-SCR - Light -off SCR

ARB Baseline engine - HD 2014 MD13TC engine

ARB Ultra-low NOx final engine - HD 2014 MD13TC engine, with modified calibration and Ultra-low NOx after-treatment.

ISSN 0148-7191