

The Achates Power Opposed-Piston Two-Stroke Engine: Performance and Emissions Results in a Medium-Duty Application

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Gerhard Regner, Randy E. Herold, Michael H. Wahl, Eric Dion, Fabien Redon, David Johnson,
Brian J. Callahan and Shauna McIntyre
Achates Power Inc

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ABSTRACT

Historically, the opposed-piston two-stroke diesel engine set combined records for fuel efficiency and power density that have yet to be met by any other engine type. In the latter half of the twentieth century, the advent of modern emissions regulations stopped the wide-spread development of two-stroke engine for on-highway use. At Achates Power, modern analytical tools, materials, and engineering methods have been applied to the development process of an opposed-piston two-stroke engine, resulting in an engine design that has demonstrated a 15.5% fuel consumption improvement compared to a state-of-the-art 2010 medium-duty diesel engine at similar engine-out emissions levels. Furthermore, oil consumption has been measured to be less than 0.1% of fuel over the majority of the operating range. Additional benefits of the opposed-piston two-stroke diesel engine over a conventional four-stroke design are a reduced parts count and lower cost.

INTRODUCTION

Opposed-piston two-stroke engines were conceived in the late 1800s in Europe and subsequently developed in multiple countries for a wide variety of applications [1,2,3,4,5]. An excellent summary of the history of opposed-piston engines can be found in [1]. Produced initially for their manufacturability, high power density, and competitive fuel efficiency, opposed-piston two-stroke engines demonstrated their versatility in a variety of applications including aircraft, ships, tanks, trucks, and locomotives and maintained their presence throughout most of the twentieth century. Historically, all types of engines have faced a number of

technical challenges related to emissions, fuel efficiency, cost and durability - to name a few - and these challenges have been more easily met by four-stroke engines, as demonstrated by their widespread use. However, the limited availability of fossil fuels and the corresponding rise in fuel cost has led to a re-examination of the fundamental limits of fuel efficiency in internal combustion (IC) engines, and opposed-piston engines, with their inherent thermodynamic advantage, have emerged as a promising alternative. This paper discusses the potential of opposed-piston two-stroke engines in light of today's market and regulatory requirements, the methodology used by Achates Power in applying state-of-the-art tools and methods to the opposed-piston two-stroke engine development process, and the performance and emissions results obtained at operating conditions consistent with a medium-duty application.

OPPOSED-PISTON TWO-STROKE ENGINE ADVANTAGES

A number of fundamental advantages of opposed-piston two-stroke engines make them attractive alternatives to common four-stroke engines. The opposed-piston (OP) arrangement, characterized by two pistons reciprocating opposite to each other in a common cylinder, has inherent heat transfer benefits compared to a standard crank-slider arrangement with a single piston and a cylinder head, and these benefits can be realized without sacrifices to engine friction or mechanical durability. First, the OP architecture creates a larger cylinder displacement for a given cylinder bore diameter, leading to a reduction in the number of cylinders compared to an engine with a standard crank-slider/cylinder head arrangement. A reduced number of cylinders decreases

the surface area available for in-cylinder heat transfer [6]. Second, an effective stroke-to-bore ratio in the range of 2:1 to 3:1 can be realized without increasing the piston speed, leading to more favorable surface-area-to-volume ratios and a further reduction of in-cylinder heat transfer. Third, the OP arrangement eliminates the cylinder head and replaces it with a second piston that can be maintained at a higher metal temperature, reducing the thermal losses to that surface of the combustion chamber.

The OP engine also has mechanical advantages compared to a standard four-stroke engine. The two moving pistons allow for piston porting, whereby the pistons uncover intake and exhaust ports at opposite ends of the cylinder and expose the combustion chamber to the intake and exhaust manifolds, respectively. The piston porting eliminates the need for poppet valves and the valve actuation mechanism, increasing the simplicity and decreasing the cost of the engine while eliminating the friction and durability concerns associated with the engine valvetrain. The nearly symmetric movement of the opposing pistons leads to excellent engine balance, even for single-cylinder configurations, and thereby reduces the loading of the crankshaft bearings for OP architectures with folded single crank or rhombic dual crank drive arrangements.

The two-stroke cycle and its double firing frequency gives engine designers the choice of decreasing brake mean effective pressure (BMEP) levels and increasing power density compared to four-stroke engines of equivalent power output. The lower BMEP levels can be accomplished with lower peak cylinder pressures and therefore lower peak cylinder temperatures, both of which lead to design advantages. The lower cylinder pressures result in lower mechanical stress on engine components and therefore can be designed to be of lighter weight. The lower cylinder temperatures result in decreased NO_x formation during combustion, lowering the requirements for exhaust gas recirculation (EGR) and/or NO_x aftertreatment devices. The increased power density leads directly to smaller engine package size and weight, both of which are beneficial to increasing overall vehicle fuel economy and to decreasing manufacturing costs.

MODERN SOLUTIONS TO OPPOSED-PISTON TWO-STROKE ENGINE CHALLENGES

The challenge posed by the emissions regulations in the latter half of the twentieth century was difficult to overcome for two-stroke engines of any architecture and led engine manufacturers to generally favor four-stroke engine development. As demonstrated by the results reported in this paper, the emissions challenge - when revisited with modern analytical tools, materials, and engineering methods - is no

longer limiting the successful design of a clean *and* efficient OP two-stroke engine.

Since the OP arrangement has no cylinder head, the fuel injector must be installed in the cylinder liner. Historically, this has created a technical challenge compared to the common crank-slider arrangement with the fuel injector located in the center of the cylinder head. The large distances in the fuel-spray direction (*i.e.* across the diameter of the cylinder) combined with low fuel injection pressures made accessing all of the available air in the combustion chamber difficult and resulted in inefficient combustion with relatively high NO_x and soot formation. Under some conditions, however, the fuel-spray would over-penetrate and wet the cylinder walls thereby destroying the lubricant film leading to wear, fuel dilution of the oil and high oil consumption. Additionally, the interaction between the fuel spray and the traditionally high-swirl in-cylinder fresh-charge motion resulted in combustion occurring near the combustion-chamber surfaces. The near-surface combustion led to reduced thermal efficiency and increased cooling requirements because of the higher thermal loading of the piston, piston rings, and cylinder liner.

Thanks to modern development tools and advanced fuel systems, the OP architecture with a liner-mounted injector has turned from a technical challenge into a unique opportunity. The availability of fuel systems with high injection pressures and the greater ease of manufacturing asymmetric injector nozzle hole directions have enabled the fuel spray of liner-mounted injectors to better utilize the air within the combustion chamber with little-to-no wall impingement. Additionally, the ability to quickly and accurately model the fuel spray, in-cylinder gas motion, and combustion using computational fluid dynamic (CFD) software packages (*e.g.* [7], [8]) has allowed the engineering of the combustion chamber geometry and nozzle configuration to achieve clean and efficient combustion. The ability to shape two combustion chamber surfaces (the two pistons crowns) and incorporate multiple fuel injection locations on the liner has provided a larger design space than is available in common four-stroke engines.

The higher thermal loading of mechanical components compared to four-stroke engines that results from a shorter, thermally relieving gas exchange process is also addressed with modern tools and materials. As discussed previously, the combustion is designed to occur away from the piston and liner surfaces, which reduces cooling requirements of these components. Additionally, conjugate heat transfer (CHT) simulations are used to analyze the cooling circuits of the engine and engineer an effective cooling system that protects components and prevents oil degradation.

Cylinder scavenging, which is a primary difference between two- and four-stroke engines, is a technical challenge for all two-stroke engines. In order to achieve a once-per-revolution firing frequency, the OP two-stroke engine must accomplish cylinder charging and scavenging in roughly one-third of an engine revolution, as opposed to a full revolution in four-stroke engines, and must do so without the aid of a direct mechanical displacement pump (*i.e.* the piston). Instead, the blower-scavenged two-stroke engine requires an external pressure differential between the intake and exhaust ports to induce flow through the cylinder that allows the fresh charge to replace the exhaust products. Compared to other two-stroke architectures that use loop-scavenging, the opposed-piston engine with intake and exhaust ports being located far apart at opposite ends of the cylinder employs the more efficient uniflow scavenging [9]. The development goal for scavenging is to minimize the external pumping required to purge the exhaust residual from the cylinder while creating the charge motion for subsequent fuel/air mixing during injection. Complete characterization of the scavenging process is possible with the use of efficient and accurate CFD software packages available today (*e.g.* [8], [10]). Optimization of port, cylinder, and piston geometries and their effects on the developed in-cylinder flow field can be accomplished in software without time-consuming and costly hardware fabrication and testing.

With regards to emissions, one of the opportunities afforded by the two-stroke scavenging process is the ability to retain some portion of the burnt charge in the cylinder after combustion (“internal” EGR) as a means to control NO_x by simply reducing the pumping work applied by the aircharge system. This helps improve fuel efficiency at part load. For high rates of EGR, the use of cooled external EGR is still required, but the engine's supercharger provides an efficient method to pump the EGR from the exhaust to the intake.

High oil consumption is a traditional challenge for two-stroke engines and can be problematic for two reasons. First, aerosolized oil is a significant source of particulate emissions in compression-ignition two-strokes, and second, additives in the oil create ash residue that tends to contaminate after-treatment devices. The engineering goal is to develop a piston-liner and ring-liner interface that uses as little oil as possible without compromising durability. Fortunately, many of the technologies developed to reduce oil consumption in four-stroke engines apply equally to two-stroke engines: improvements in cylinder bore materials, cylinder bore finishing, piston ring technologies, crankcase breathing systems, management of cylinder bore oil impingement, synthetic oils, and low ash and phosphorus oils are all technologies that have been developed for four-stroke engines but are equally applicable to two-stroke engines. As a side benefit, the lack of a valvetrain in two-stroke engines obviates the need for anti-scuffing oil additives such as zinc

dialkyl dithiophosphates (ZDDP). For the work reported here, an advanced oil consumption analyzer has been used [11], making research and development of these oil-control technologies quicker and much more focused.

The lubrication of wrist pin bearings is another well-known two-stroke challenge as the oil replenishing of the continuously loaded wrist pin bearing is difficult. Several techniques have evolved utilizing bearings with substantially greater surface area and ladder grooves as well as special coatings that aid boundary lubrication.

THE RENAISSANCE OF THE OPPOSED-PISTON TWO-STROKE ENGINE

The renaissance of the opposed-piston two-stroke engine has been aided by three circumstances: the increasing demand and regulatory requirements for highly fuel-efficient and clean internal combustion engines, the thermal efficiency benefit of OP engines that is not found with other engine architectures, and the development of designs that have overcome the challenges and limitations of previous implementations. The fundamental thermal efficiency benefits of this engine [6] along with its low emissions, small package size and weight, and low cost relative to current four-stroke engines make it an attractive alternative for future commercial and passenger vehicles. The following sections summarize the performance and emissions results of an Achatas Power opposed-piston two-stroke engine that meets low engine-out emissions levels with acceptable oil consumption while achieving fuel consumption levels that exceed those of the current state-of-the-art four-stroke engine.

DATA ACQUISITION AND CORRELATION

SINGLE CYLINDER RESEARCH ENGINE

The custom single-cylinder research engine, shown in [Figure 1](#), has been manufactured in-house and is tested on a 300 hp AC dynamometer. The engine has a trapped compression ratio of 16.7, a bore of 80 mm, and a stroke of 212.8 mm, resulting in a displaced volume of 1.06 L. The fixed liner geometry creates a fixed swirl ratio and port timing, and the piston geometry and injection spray pattern has been specified based on analytical combustion simulation results. A common-rail fuel injection system is capable of creating injection pressures up to 2000 bar and can produce multiple injection events per engine cycle. The maximum cylinder pressure is limited to 160 bar, and the maximum liner temperature is limited to 200 °C.