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Achieving Ultra-Low Oil Consumption in Opposed Piston Two-Stroke Engines

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Abstract

The opposed piston two-stroke (OP2S) engine architecture is widely recognized for its improved fuel efficiency relative to a four-stroke engine. Achates Power Inc. seeks to demonstrate the market readiness of the OP2S engine by proving competitive in other important areas, one of which is oil consumption. Achieving oil consumption competitive to modern four-stroke engines is thus a key step in bringing OP2S technology to market. Two-stroke engines have historically suffered from higher engine lube oil consumption and subsequent emissions and durability challenges. This is primarily due to two main features of traditional two-stroke engines; the direct interaction of the piston skirt and rings with the intake and/or exhaust ports, which results in a direct leak path for lube oil to the combustion chamber and/or exhaust manifold, and crankcase-scavenged architectures which entrain oil into air being pumped through the crankcase. The OP2S engine architecture directly addresses these concerns by utilizing intake and exhaust manifolds, a closed crankcase system, and oil control rings which operate outboard of the ports. Previous work has shown the importance of careful consideration of cylinder liner, piston, and ring design in minimizing oil consumption of the OP2S architecture. This work evaluates further refinements in cylinder form, hone texture and oil retention, port sealing ring design, and oil control ring design. A Da Vinci DALOC sulfur-trace analyzer for real-time oil consumption measurement was used to generate speed vs. load maps of oil consumption of an Achates Power OP2S A48 development engine, operated under typical medium-duty conditions. The engine demonstrated oil consumption levels competitive with modern four-stroke benchmarks and completed a 100-hour durability test with no measured performance loss or increase in oil consumption. This work represents a key step towards proving the potential of the Achates Power OP2S engine architecture in the commercial and passenger vehicle markets.

Introduction

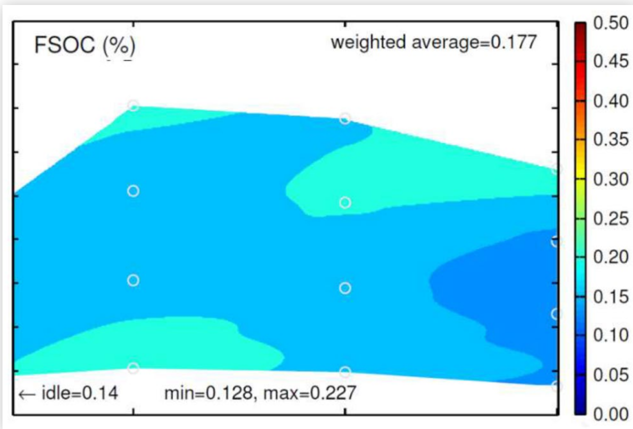
Increasing concern regarding the effects of anthropogenic climate change has brought urgency to the quest for greater vehicle fuel efficiency. The transportation sector, and internal combustion engines specifically, are one of the largest global emitters of greenhouse gases [1]. Fuel efficiency improvements in all vehicle segments represent a short-term opportunity to create large scale emissions reductions.

The opposed piston two-stroke (OP2S) has proven to be a fundamentally more fuel-efficient engine architecture [2, 3]. Achates Power, founded in 2004, has modernized the OP2S architecture and is commercializing the technology as a clear path to reduced fuel consumption and emissions. Previous results have shown fuel efficiency advantages in heavy duty [4], medium duty [5], and light duty applications [6], along with capabilities for reduced NO_X emissions and rapid catalyst light-off [7].

To be widely accepted, the OP2S architecture needs to demonstrate marketplace-competitive oil consumption for several key reasons. First, excessive oil consumption can lead to unacceptable lube oil top-up or replacement intervals. Second, ash from combusted lube oil accumulates in diesel particulate filters (DPF), resulting in additional re-generation and fuel use. Third, active sites on heterogenic catalytic surfaces can be eliminated by the lubricant-derived sulfated ash, phosphorous, and sulfur (SAPS), resulting in reduced conversion. Fourth, increased organic particulate matter (PM) from partial lube oil combustion can result in emissions non-compliance. Finally, power cylinder failure modes such as piston ring jacking are associated with excessive oil consumption and subsequent carbon deposits.

Previously published work by Achates Power reported a cycle-averaged fuel specific oil consumption (FSOC) of 0.18%, shown in Figure 1 [8]. At the time of publishing, this was the lowest FSOC published in the open literature for a two-stroke engine. Further development was required by Achates to reach a declared medium-term development goal of 0.05 to 0.10% cycle-averaged FSOC, representative of a typical four-stroke engine. This paper shows that OP2S engines can achieve competitive oil consumption to four-stroke engines.

FIGURE 1 Previously published FSOC results showing a duty cycle average of 0.18% and a maximum FSOC of 0.23% [8]

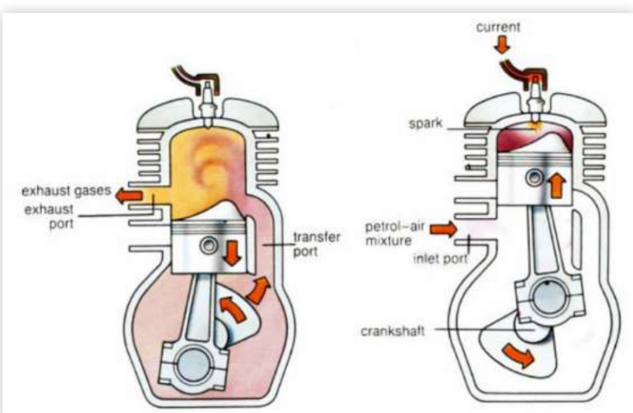


Background - OP2S Oil Consumption

It has been long assumed that two-stroke engines are not capable of four-stroke competitive oil consumption. This is largely due to the dominance of crankcase scavenged two-stroke engines, where oil is premixed with fuel, and the air-fuel mixture is inducted into the combustion chamber through the crankcase. Fuel specific oil consumption in these engines can exceed 2%. A typical arrangement of a crankcase scavenged two-stroke engine is shown in Figure 2.

Another reason for perceived high oil consumption in two-stroke engines is the piston ring and port interaction, where the compression rings traverse the ports with each cycle. It is then possible for oil present near the piston skirt and ring pack to be scraped into the ports. Such a lubricating system is often referred to as a total loss system. This configuration does not typically utilize oil scraper rings, which serve to keep the lubricating oil out of the ring and port belt area.

FIGURE 2 Traditional loop scavenged small two-stroke engine [9]

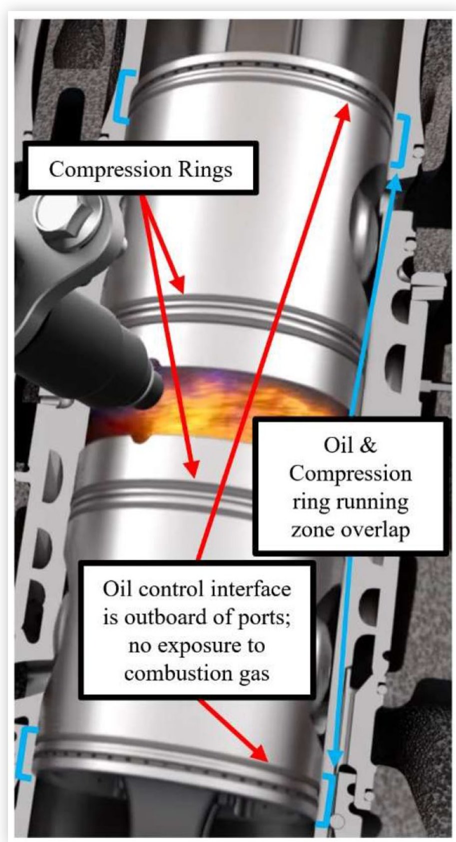


Oil scraper rings are a critical element of OP2S and four-stroke engine oil control.

The OP2S architecture utilized by Achates Power consists of a closed crankcase system similar to a four-stroke engine. This eliminates the induction of air through the crankcase. Each piston utilizes four piston rings; two for compression located at the top of the piston (referred to as top and 2nd compression ring), and two for port sealing and oil control located at the bottom of the piston skirt (referred to as 3rd and 4th or oil control ring). The lower two rings also prevent leakage from the pressurized intake and exhaust ports to the crankcase, and scrape oil away from the ports and combustion chamber. It is important to recognize that the only lube oil path from the crankcase to the ring/port area and combustion chamber is through the oil control rings; the same as a four-stroke engine. There are no other paths for lube oil into the combustion chamber or intake/exhaust manifold. For example, since there are no valves in an OP2S engine, the lube oil leak path through valve stems is not present. In addition, in an OP2S engine there exists an overlap in the running zones of the compression rings at outer dead center (during cylinder scavenging) and the oil rings at inner dead center (during combustion). This overlap zone is shown in blue in Figure 3.

Other legacy two-stroke engines such as the Detroit Diesel Series 53, 71, and 92, among others, utilized a similar compression and oil control ring arrangement, however, these

FIGURE 3 OP2S cross section showing compression and oil ring operating zone



engines were ultimately unable to meet tightening emissions requirements for on-highway vehicles due to their high oil consumption and other emissions challenges. Improvements in cylinder honing and piston ring design, reductions in bore distortion using CAE tools, and architectural advantages of the OP2S enable oil consumption competitive with modern four-stroke engines.

Oil Control Overview

In considering the potential for the OP2S architecture to achieve ultra-low oil consumption, a wide variety of design parameters affecting durability, friction, and oil consumption must be considered. Important parameters for the cylinder, piston, and piston ring subsystems are summarized in Table 1.

Achates has found that to minimize oil consumption, attention must be paid to bore texture, form, and distortion, along with compression and oil control piston ring operation. Further details regarding cylinder hone and piston ring development are provided in the following subsections.

Hone Texture & Form Oil retention within a given hone texture plays an important role in lubricating the piston ring, skirt, and cylinder liner interface. As a result, this has a direct effect on power cylinder durability and oil consumption. Three typical hone texture classifications are summarized in Table 2. As honing technology has improved, plateau hones have been used in favor of peak hones to reduce wear and friction. More recently, engineered textures which provide much more direct control over the final surface have been developed.

One commonly used engineered texture is a laser etching technique developed by Gehring [10]. Instead of relying on abrasives to create the oil retention valleys in the surface finish, a laser ablates material to create laser pockets. As a result, oil retention is introduced to the cylinder bore surface in a much more controlled manner. Figure 4 shows a typical laser etch and finish hone process in a four-stroke engine.

For reference, legacy Detroit Diesel engines typically specify a coarse plateau hone, including the port bridge area, as shown in Figure 5. This results in deep helical hone etches directly intersecting ports and allowing oil leakage through the hone valleys. Achates Power has found that plateau hone textures can produce FSOC values greater than 0.4%.

Cylinder form refers to the bore diameter as a function of axial and circumferential location. It is becoming increasingly common to compensate for the thermal distortion of the cylinder that takes place as the engine goes from ambient temperature to operating temperature. The cylinder is honed to a non-cylindrical shape at ambient temperature to produce a cylindrical shape at operating temperature. This is critical for maintaining compression and oil ring conformability, a prerequisite of good oil control. Achates utilizes conjugate heat transfer and thermal/mechanical finite element analysis to quantify liner thermal distortion and compensate using cooling passages and liner form honing.

TABLE 1 Summary of power cylinder subsystem design considerations

	Design Parameter	Consideration
Cylinder	Hone Texture	*Peak, plateau, and engineered surface textures (plasma sprays, laser texturing) are commonly used. Increased oil retention generally increases oil consumption.*
	Hone Form	*Form honing (changing cylinder diameter as a function of axial and circumferential location) is becoming a common way to counteract cylinder thermal distortion.*
	Thermal Distortion	*Cylinder cooling needs to control thermal distortion and ensure uniform ring contact pressure.*
	Ports	*Ports need to be shaped, machined and deburred correctly to prevent ring and skirt damage.*
Piston	Lands & Clearance	*Top & 2nd land require adequate clearance to prevent carbon buildup and unwanted bore polishing, adequate skirt clearance required to prevent unwanted piston secondary motion while controlling clearance at all temperatures.*
	Skirt Profile	*Skirt profile needs to control piston secondary motion and resulting ring motion dynamics.*
	Skirt Coating	*Composition and texture of skirt coating needs to minimize friction and avoid excessive oil retention.*
Compression Rings	Face Profile	*Symmetric or offset barrel face can affect piston oil down-scraping and subsequent oil consumption. Offset barrel faces can also serve to reduce compression ring friction.*
Oil Control Rings	Design	*Compression or scraper ring can be used to seal port pressure from the crankcase (3rd ring position). 2-piece and 3-piece designs can be used for primary oil scraping (4th ring position).*
	Cross Section	*Scrapers typically take the form of a tapered face or Napier style downscraper to remove oil from the bore surface. Grooves on the piston ring inner diameter can also control ring twist as the ring is installed in the groove.*
	Tension	*Ring tension must find the balance between scraping and conforming to the bore adequately without adding undue friction.*

TABLE 2 Hone texture summary

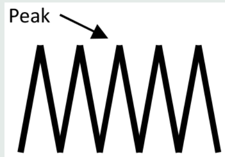
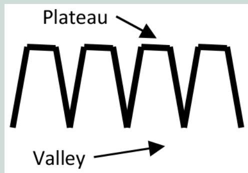
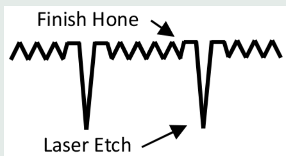
Classification	Texture Schematic
Peak hone: Peak hone geometry of a specified depth is created during honing process.	
Plateau hone: "Plateau and valley" geometry is created during honing process. Valley depth and frequency can be approximately controlled during abrasive selection.	
Laser Texturing: Hone "valleys" are produced using laser ablation while the base texture is typically a fine finish with $R_a < 0.3$ µm	

FIGURE 4 Gehring laser texturing illustration showing post-etch (top left), post-finish hone (top right), and in-engine (bottom) [10]

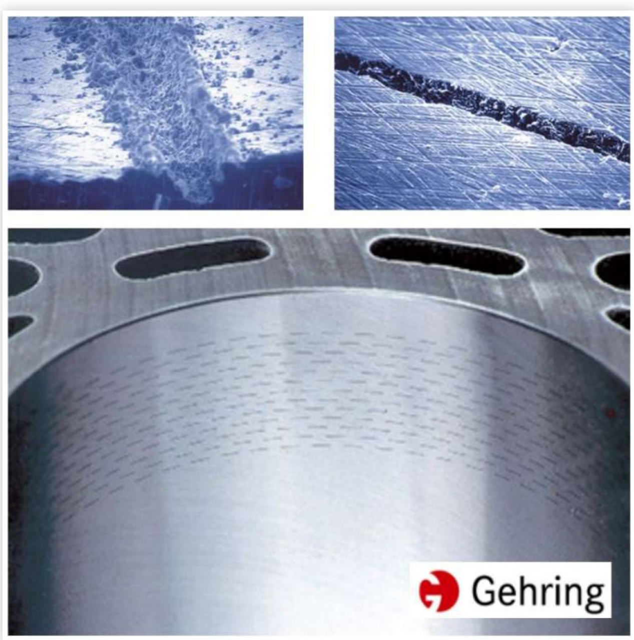
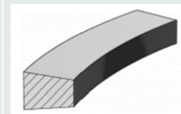
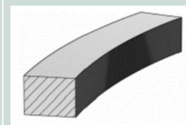
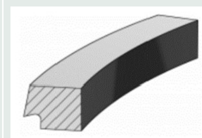
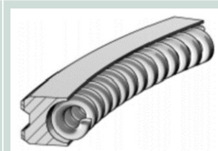


FIGURE 5 Detroit Diesel Series 53 cylinder liner, showing coarse plateau hone

Compression & Oil Control Rings The piston ring pack is a critical ingredient in controlling oil movement within the power cylinder. An OP2S specific piston ring pack was developed with Federal Mogul. The piston ring pack used in the reported results is illustrated below in Table 3.

TABLE 3 Achates piston ring configuration summary

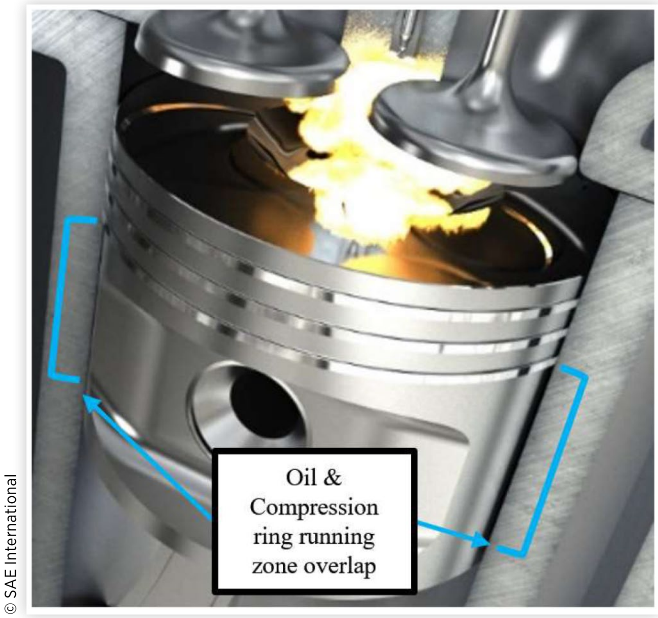
Description	Cross Section
Top compression ring, full keystone, fully inlaid GDC Chrome + microdiamond face coating, chrome bottom flank coating, offset barrel	
2nd compression ring, rectangular, GDC chrome + microdiamond face coating	
Napier scraper ring, located in third piston groove below ports. Serves to seal port pressure and downscrape oil.	
2-piece LKZ oil control ring, located in fourth piston groove. Serves as main oil scraping ring.	

OP2S vs. Four-Stroke Oil Control

There are two additional key details when considering the means of oil transport and consumption within an OP2S engine compared to a four-stroke engine. While fundamentally, both engines must pass oil through the oil control ring(s) to consume oil, the overlap between the compression ring running zone and the oil ring running zone is much larger on a four-stroke engine. In both engines, the oil ring running zone is exposed to a fully or partially flooded surface on each piston downstroke. In the case of the OP2S engine, this area of the cylinder liner is only exposed to in-cylinder gases in a small overlap area below the ports. In the case of the four-stroke engine, this area is re-exposed to in-cylinder gases each revolution. As a result, any transport mechanism related to oil on the cylinder wall being vaporized by the combustion gas will be much more prevalent in a four-stroke. This difference in overlap can be visualized by comparing Figure 3 with Figure 6 below.

Additionally, the importance of oil ring scraping edge geometry and bore conformability in reducing oil consumption is well documented. As a result, reducing cylinder liner distortion in the oil ring running zone directly reduces oil consumption and/or reduces the required oil ring tension for adequate bore conformance. Bore thermal distortion is typically highest at rated power conditions (maximum temperature), where oil consumption is typically measured. In the OP2S design, the oil control rings are located at the bottom of the piston skirt and operate outboard of the ports. This part

FIGURE 6 Four-stroke engine cross section showing oil and compression ring running zone overlap



of the liner has no direct contact with combustion gas, resulting in inherently low thermal distortion. In a four-stroke engine, the oil ring is located directly underneath the compression rings and is exposed to the thermal deformations present in the bore at the top of the piston stroke, approaching the cylinder head. Due to the inherently lower distortion present in the OP2S oil ring running zone, lower oil consumption can be achieved for a given ring tension, or a lower ring tension can be used to achieve the same conformability, resulting in lower oil control ring friction.

Finally, piston skirt lubrication on OP2S engines is of interest because the skirt and bore interaction occurs above (inboard) the oil control rings. Although this zone is not "fully flooded" as is found in a four-stroke engine, Achates has found that low piston skirt wear rates comparable to four-stroke engines can be achieved with careful skirt profile design and bore distortion minimization. The oil film and subsequent hydrodynamic lubrication that occurs between the piston skirt and the cylinder liner can be maintained without the excess influx of oil present in a fully flooded environment.

These differences in the operating environment of the oil control ring(s) facilitate low oil consumption with the OP2S architecture. Since the transport of lube oil past the oil control rings is the same in OP2S and four-stroke engines, it must be possible to achieve competitive oil consumption to a four-stroke. Once lube oil is metered correctly past the oil control rings, the oil must be best utilized to maximize durability and minimize friction.

Four-Stroke Oil Consumption Benchmark

Previously published data of model year 2003-2004 heavy duty engines is shown below in Table 4 [11]. The data was obtained using a volumetric oil consumption measurement method over the course of a 308-hour test based on an 8-mode AVL drive cycle. From this data we conclude that an engine which has a cycle averaged FSOC value less than 0.06% is competitive in the marketplace. Furthermore, while published data is not available for current market offerings, modern engines have not observed substantial further reductions in oil consumption.

TABLE 4 Four-stroke oil consumption benchmark data

Engine Model	Duty Cycle FSOC (%) (300-hour test)
Caterpillar C15	0.075
Cummins ISX	0.05
Detroit Diesel Series 60	0.1
Volvo D12	0.045

Experimental Apparatus

The majority of Achates' oil consumption development is conducted on the single-cylinder A48 research platform. This platform is highly modular and allows for a variety of cylinder, piston, and ring configurations to be tested. Data presented in this paper was gathered on the single cylinder A48-1 research engine, of which details can be found below in Table 5.

To accurately and repeatedly measure real-time oil consumption a Da Vinci Lubricant Oil Consumption (DALOC) analyzer was applied. This measurement system is based on a sulfur-trace technique and it has been introduced in a number of past references [8, 12]. An image of the analyzer is shown below in Figure 7.

It is well established in the marketplace and it has certain advantages over other oil consumption measurement techniques:

- Each steady-state oil consumption condition can be measured in real-time over a few minutes instead of many hours for any volumetric or gravimetric technique
    - Steady-state oil consumption data has a test-to-test repeatability of 1-2%

TABLE 5 Achates A48-1 Engine Specifications

Displaced volume	1.63 L (swept volume)
Number of Cylinders	1
Number of Pistons	2
Bore	98.4 mm
Stroke (per piston)	108 mm
Stroke to Bore Ratio	2.2:1
Speed Range (rpm)	1200-2200
Compression Ratio	18.6:1
Maximum Power (kW)	90
Maximum Torque (N·m)	310
Oil	Chevron DELO 400 SAE 30 CF SJ
Fuel	Zero-sulfur fuel used for DALOC testing

FIGURE 7 Da Vinci Lubricant Oil Consumption analyzer

- Each transient cycle, the engine oil consumption can be measured in real time instead of over many hours for any volumetric or gravimetric technique
    - Transient oil consumption data has a repeatability from test-to-test of 1-2%
- It compares favorably to radioactive-tracer techniques in that the sulfur already present in the oil is used as the tracer, rather than a hazardous material
- It compares favorably to unburned lubricant base stock oil-vapor techniques in that it is more robust and repeatable
    - The latter measurement devices exhibit sensitivities around the stability of the tracer (burned/unburned fraction of oil-vapor), sensitivities towards temperature and pressure variations in a test cell, and other repeatability sensitivities

The oil consumption rate is calculated in real-time by performing a sulfur mass balance around the engine as a control volume, and using the measured sulfur concentration in the lubricant oil and fuel, according to Equation 1 below:

$$\dot{m}_{OC} = \frac{\dot{m}_{fuel}\left([S]_{exh} - [S]_{fuel}\right) + \dot{m}_{air}[S]_{exh}}{[S]_{oil}} \quad (1)$$

Where the quantities are defined as follows:
$\dot{m}_{OC}$ = Engine-out oil consumption rate
$\dot{m}_{air}$ = Air mass flow rate
$\dot{m}_{fuel}$ = Fuel mass flow rate
$[S]_{fuel}$ = Fuel sulfur mass fraction
$[S]_{oil}$ = Oil sulfur mass fraction
$[S]_{exh}$ = Exhaust sulfur mass fraction

Method

A 13-mode speed/load map reflecting a medium-duty engine application was used to generate an oil consumption map. Each speed/load point was repeated for a total of three measurements over a two-day testing span. The 13 test modes and drive cycle weightings are summarized below in Table 6.

Results & Discussion

Real-time oil consumption measurements were taken across all speed and load points across two different test days. FSOC results are reported as a function of engine load for A, B, and C speeds, respectively, in Figures 8, 9, and 10.

Averages for all points taken at each speed and load are shown below in Figure 11.

The weighted drive cycle average for the speed/load points reported in Figure 11 is 0.04% FSOC, a 78% reduction in oil consumption compared to previously published results [8]. FSOC at rated power (C100) averaged 0.052% FSOC, a 77% reduction. In addition, all speed/load points are competitive

TABLE 6 13-mode speed/load map for oil consumption mapping

Mode	Engine Speed	Load (%)	Cycle Weight Factor (%)
1	Idle - 1000	0	15
2	A - 1400	100	8
3	B - 1800	50	10
4	B - 1800	75	10
5	A - 1400	50	5
6	A - 1400	75	5
7	A - 1400	25	5
8	B - 1800	100	9
9	B - 1800	25	10
10	C - 2200	100	8
11	C - 2200	25	5
12	C - 2200	75	5
13	C - 2200	50	5

FIGURE 8 FSOC (%) at A speed (1400 rpm) from 25% to 100% load

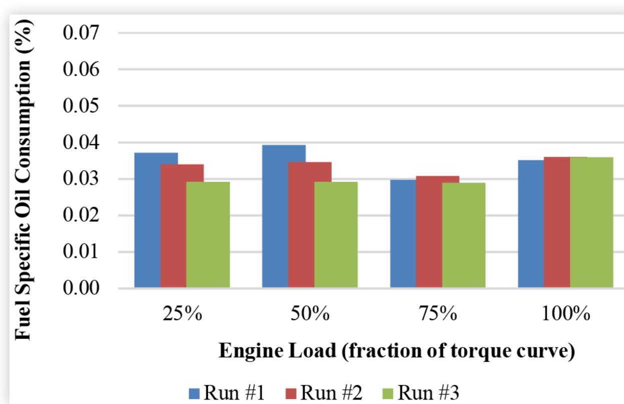


FIGURE 9 FSOC (%) at B speed (1800 rpm) from 25% to 100% load

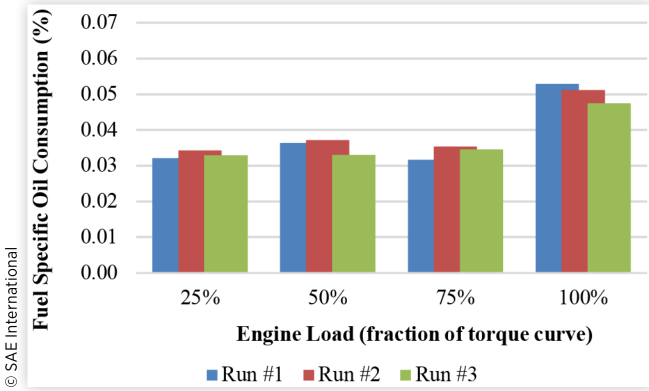


FIGURE 10 FSOC (%) at C speed (2200 rpm) from 25% to 100% load

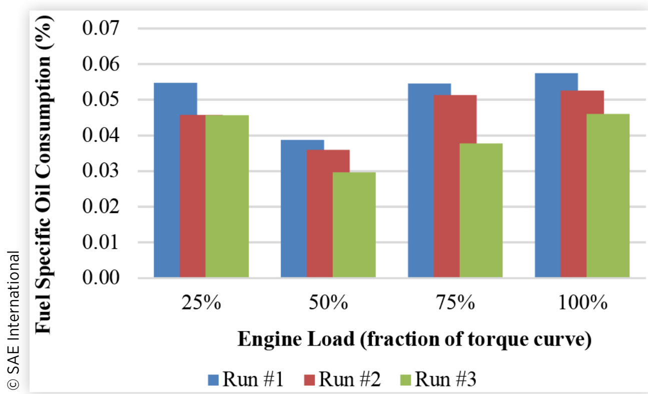
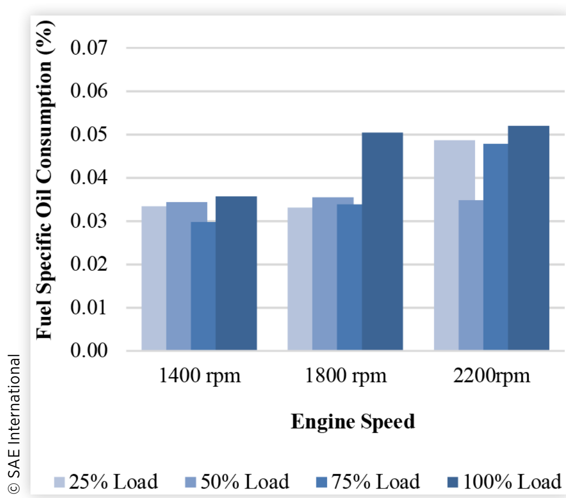


FIGURE 11 Average FSOC values for all speed and load points



with or lower than benchmark four-stroke FSOC numbers. Generally, FSOC increased with both speed and load, particularly at B speed (1800 rpm). A consistent decrease in oil consumption with progressive repeated data points was observed, particularly at B100 and C100. This is believed to be due to an ongoing hone break-in effect; Achates has observed considerable oil consumption reduction between new and broken-in hardware states. This is due to initial reductions in hone surface roughness and corresponding oil retention. With fully broken-in hardware, repeatability in FSOC measurements would improve.

A 100-hour accelerated durability test was completed on a duplicate set of hardware to the test engine used for these results. The engine completed the test successfully with no scuffing or accelerated wear on the cylinder liner, piston skirt, and piston rings. No unitizing of the LKZ oil ring was observed, and no deposits or ring sticking occurred in the 3rd and 4th oil control rings. Achates will report further results from longer duration durability tests upon completion.

Conclusions

The Achates OP2S engine has demonstrated lube oil consumption competitive to a modern four stroke engine. This represents a significant step toward integrating the OP2S engine architecture into the vehicle as a system. Fundamentally, OP2S engines transport oil into the power cylinder using the same mechanisms as a four-stroke engine. Piston rings traversing the ports and causing excessive oil consumption has been a historically difficult challenge to overcome. Achates has overcome this by combining CHT and FEA tools to understand and control piston and cylinder thermal distortion, together with improvements in compression and oil control ring technology. Achates remains focused on completing successful long duration durability tests in the near future.

References

1. U.S. Energy Information Administration, "July 2018 Monthly Energy Review," 2018.
2. Warey, A., Gopalakrishnan, V., Potter, M., Mattarelli, E. et al., "An Analytical Assessment of the CO2 Emissions Benefit of Two-Stroke Diesel Engines," SAE Technical Paper 2016-01-0659, 2016, doi:10.4271/2016-01-0659.
3. Herold, R.E., Wahl, M.H., Regner, G., and Lemke, J.U., "Thermodynamic Benefits of Opposed Piston Two-Stroke Engines," SAE Technical Paper 2011-01-2216, 2011, doi:10.4271/2011-01-2216.
4. 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.
5. 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.
6. Hanson, R., Strauss, S., Redon, F., and Salvi, A., "Progress in Light-Duty OPGCI Engine Design and Testing," in *SIA Powertrain Conference*, 2017.

7. 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.
8. Callahan, B.J., Wahl, M.H., and Froelund, K., "Oil Consumption Measurements for a Modern Opposed-Piston Two-Stroke Diesel Engine," in *Proceedings of the ASME 2011 Internal Combustion Engine Division Fall Conference*, Morgantown, WV, 2011.
9. Cameron, K., "Two-Stroke Engines: Defining Their Purpose," *Cycle World*, n.d., accessed July 25, 2018, https://www.cycleworld.com/2015/04/06/two-stroke-motorcycle-engines-explained-tech-talk-by-kevin-cameron.
10. Gehring Technologies, "Laser Honing," Gehring L.P., n.d., https://www.gehring.de/en-ww/laser-honing.
11. Froelund, K. and Ross, M.G., "Laboratory Benchmarking of Seven Model Year 2003-2004 Heavy-Duty Diesel Engines Using a CI-4 Lubricant," SAE Technical Paper 2005-01-3715, 2005, doi:10.4271/2005-01-3715.
12. Froelund, K., Menezes, L.A., Johnson, H.R., and Rein, W.O., "Real-Time Transient and Steady-State Measurement of Oil Consumption for Several Production SI-Engines," SAE Technical Paper 2001-01-1902, 2001, doi:10.4271/2001-01-1902.

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Definitions/Abbreviations

CAE - Computer Aided Engineering

CHT - Conjugate Heat Transfer (Analysis)

DALOC - Da Vinci Lubricant Oil Consumption

DPF - Diesel Particulate Filter

FEA - Finite Element Analysis

FSOC - Fuel-Specific Oil Consumption

OP2S - Opposed Piston Two-Stroke

PM - Particulate Matter

SAPS - Sulfated Ash, Phosphorus, and Sulfur

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