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Advanced High-Performance 4-Stroke (HP4S) Engine for Military Applications

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ABSTRACT

Propulsion systems for military applications, especially for ground combat vehicles, operate in harsh environments and must fulfill a long list of challenging technical requirements. High power density, fuel efficiency, multi-fuel capability, reliability and serviceability are only a few of the top level requirements that cascade down to many sub-system requirements. As part of the Combat Vehicle Prototyping (CVP) program, the US Military is focusing on opposed piston engine technology to meet the requirements for the Advanced Combat Engine (ACE). Globally, opposed piston engines have no considerable presence in commercial applications and have been mostly replaced for military applications. This paper reviews the opportunities and challenges with opposed piston engine technology and introduces an advanced high-performance 4-stroke engine solution as alternative for the ACE.

INTRODUCTION

For more than a decade the US Military has been seeking a superior power source capable of being integrated into the main propulsion system for the next generation of combat vehicles. Attracted by the reduced heat rejection of opposed-piston engines, research and development projects have been executed to explore the benefits and potentials of the opposed piston, opposed cylinder (OPOC) architecture as well as the traditional 2-crankshaft opposed piston engine architecture. However, the question remains if opposed piston engine architectures are really the superior power source for future combat vehicles when globally they have been replaced by modern 4-stroke engines in most military applications and have no presence in commercial applications.

The propulsion system of combat vehicles consists of the power-pack and ancillary systems such as combustion air and filtration system, exhaust system, fuel tank, batteries, etc. The power-pack includes the combustion engine, transmission, generator and the cooling system and can be removed as a complete unit from the vehicle for easy maintenance and repair.

The requirements for combat vehicle propulsion systems are complex. The operating environment can be very harsh and vehicles must be able to handle extreme temperatures, a wide range of altitudes, dust and shock loads. Superior mobility requires smaller vehicles, with smaller engine compartments and high tractive power.

Critical requirements of a highly mobile combat vehicle flow down to the propulsion system, the power-pack and finally to the combustion engine; the top level engine requirements can be summarized as follows:

- High power density (power / package volume)
- High fuel efficiency (to minimize fuel tank size)
- Low heat rejection (to minimize cooling system size and fan power)
- Low combustion air consumption (to minimize the size of the intake air system, air filtration and exhaust system)
- Low electric power consumption (minimize generator size and battery capacity)

Other requirements include multi-fuel capability, serviceability and maintainability, weight, cost, etc.

Due to the reduced combustion chamber surface to volume ratio, opposed piston engines inherently reject less heat from the combustion process into the cooling system. When implementing special precautions to avoid significant heat losses from the exhaust gas to the flow optimized, generously sized exhaust belts, opposed piston engines provide less heat load into the cooling system in comparison to engines that utilize a cylinder head. However, opposed piston engines present unique challenges that must be overcome to compete against 4-stroke concepts.

Based on experience from high-performance engine development for racing trucks, pleasure craft marine and other applications, FEV has developed a high performance 4-stroke (HP4S) engine concept for automotive and other commercial applications that incorporates advanced and proven technologies. The HP4S engine meets or exceeds all requirements specified for the Advanced Combat Engine (ACE). The horizontal flat inline 6-cylinder engine is rated at 1500 hp and is scalable from 500 hp to 3000 hp for inline and V-type configurations while utilizing many common components. Variable compression ratio, thermal barrier coatings and advanced controls reduce heat rejection into the cooling system and enable the HP4S to truly be multi-fuel capable.

This paper will introduce the advanced technologies of the HP4S engine and discuss how this engine solution outperforms opposed piston engines in meeting the top level requirements for the future combat vehicle engine.

ACE TECHNICAL REQUIREMENTS

The top level technical requirements for the ACE have been published in W15QKN-14-9-1002-RPP3, Research Area 2.1:

- Multi-fuel capability: JP-8, F-24, JP-5, Jet-A, Jet-A1, DF-2 & ULSD
- Power at Rated Speed ≥ 1500 hp (JP-8)
- Peak Torque ≥ 3000 lbf-ft (JP-8)
- Torque rise: 20%
- Best BSFC ≤ 0.320 lbs/hp-hr (JP-8)
- Heat rejection ≤ 0.45 kW/kW (JP-8)
- Smoke/Opacity ≤ 8% (steady-state) & ≤ 12% (transient)
- Dimensions ≤ 43” x 23” x 63”

OPPOSED PISTON ENGINES

Opposed piston (OP) engines have a long history and most significant commercial success in the mid-20th century. A remarkable 41% break thermal efficiency was achieved with this architecture as early as 1935 [1]. The Junkers Jumo 205 and 207 have been used in commercial aircraft applications due to the high power-to-weight ratio and excellent brake thermal efficiency. Post World War II, OP engines were used in military vehicles in the Soviet Union, France, United Kingdom, Middle East, Iran and India [1]. The most successful engines were the Leyland K60, Rolls Royce K60 and the Khakiv Morozov 6-TD2, which is still in use today.

More recent OP engine development programs have been conducted in the United States. A lightweight opposed piston, opposed cylinder (OPOC) technology was initially developed by FEV [2, 3]. Others employ the 2-crankshaft OP architecture which was initially successful in the Junkers Jumo engines, Figure 1.

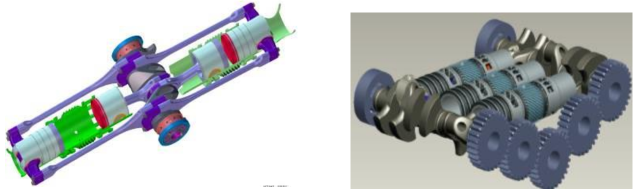

Figure 1: OP Engine Architectures, OPOC (left), 2-crankshaft OP engine [4] (right)

Technical Opportunities with OP Engines

There are numerus publications from recent developments at Achates Power and EcoMotors that explain the technical advantages of OP engines in great detail. Therefore, this paper only intends to identify the most important advantages relevant for the ACE.

Reduced total heat rejection from the engine into the cooling system is vital for future combat engines. As the heat from the cooling system must be transferred via radiators to the ambient air, the heat rejection of the engine has direct impact on the size requirement of the radiator. The cooling air flow through the cooling pack has to be provided by a mechanically or electrically driven radiator fan, since the radiator and the entire cooling pack of a combat vehicle are not in the direct airflow but must instead be protected from gunfire and other damaging debris. Consequently, the air flow rate, and thus the drive power of the radiator fan, is directly influenced by the total heat rejection of the propulsion engine.

The cooling system of a combustion engine protects relevant components from excessive temperatures and the resulting high stress levels and extreme thermal cycles. The heat flux from the combustion and hot exhaust gas is influenced by multiple factors, such as peak and average in-cylinder gas temperature, gas velocity and thermal conductivity of the combustion chamber wall material. A major contributor is the surface area for the heat to transfer from the combustion gas into the combustion chamber walls. Therefore combustion chambers with a small surface-to-volume ratio inherently reject less heat than combustion chambers with a large surface–to-volume ratio.

OP engines do not have a cylinder head as do conventional 2- or 4-stroke engines, but create the combustion chamber between the cylinder wall and the 2 opposing pistons. The surface of the cylinder head in conventional engines represents approximately 30% of the combustion chamber surface area. Hence, OP engines have approximately 30% less combustion chamber surface area and therefore an inherent advantage for low heat rejection.

Technical Challenges with OP Engines

Opposed piston engines typically apply a 2-stroke cycle, in which the exhaust gas release from the cylinder is occurring at the same time the cylinder is filling with fresh air. Uni-flow scavenging is the most effective scavenging process for 2-stroke engines, and OP engines provide an ideal opportunity for this approach with one piston opening the exhaust ports and the other piston opening the intake ports. Effective scavenging is achieved when at the end of the process the cylinder is mostly filled with fresh air and minimal amount of residual gas from the prior cycle remains in the cylinder. However, an efficient scavenging process not only ensures high in-cylinder gas purity (high scavenging efficiency), but also minimizes the fresh air loss into the exhaust (blow-through).

Figure 2 provides an example of the scavenging process. The delivery ratio (DR) on the x-axis is the ratio of fresh air passing through the intake ports versus the cylinder volume. At a delivery ratio of 1, the volume of fresh air passing through the intake ports is equal to the cylinder volume. Perfect scavenging means that the fresh air is pushing the residual gases out of the cylinder without mixing. At a DR of 1 and perfect scavenging, the cylinder is completely filled with fresh air and no air has been lost to the exhaust. In contrast to the perfect scavenging process, perfect mixing means that all fresh air entering the cylinder through the intake ports mixes perfectly and homogeneously with the residual gases. With increasing DR the purity of the in-cylinder fresh air continuously increases and approaches a scavenging efficiency of 1 at infinite DR.

In reality 2-stroke engine scavenging is a combination of perfect scavenging and perfect mixing. An optimized system can achieve 80-85% scavenging efficiency at a DR of 1, Figure 2. To achieve an in-cylinder fresh air purity of >95%, as typical with 4-stroke engines, a DR of 1.4 to 1.6 are needed. This means a 2-stroke engine requires 30-50% higher combustion air flow when compared to a 4-stroke engine with the same output.

In order to avoid strong mixing of fresh air and residual gas during the scavenging process, as well as to avoid trapping of high temperature, lower density residuals in the center of the cylinder, the swirl motion of the fresh air flowing into the cylinder must be well optimized and controlled over the speed and load range of the engine.

Because the fresh air filling and the removal of residual gases from the cylinder occurs at the same time in a 2-stroke engine, the intake manifold pressure must always be higher than the exhaust pressure. Whereas turbocharging supports the scavenging process at higher load areas of the engine map, during startup and at part load the boost pressure must be provided by a mechanically or electrically driven charger.

With these requirements in mind an optimized 2-stroke scavenging system must incorporate:

- Uni-flow scavenging
- Asymmetric port timing
- Balanced swirl motion
- Mechanically / electrically assisted boosting
- Tuned sizes / volumes of intake air and exhaust system

In comparison to a 4-stroke engine, compromises have to be acknowledged in the following areas:

- High performance sensitivity with increased exhaust back pressure and increased intake air suction
- Supercharger drive power equal to approximately 3-5% of engine rated power
- 30-50% higher combustion air consumption
- In-cylinder charge motion is a result of an optimized scavenging process and cannot be optimized for improved fuel mixing / combustion

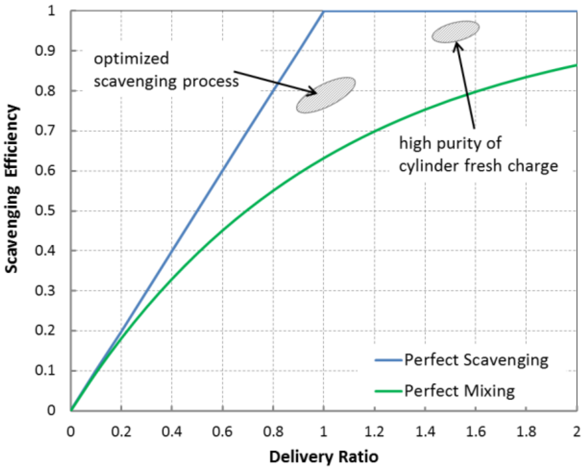

Figure 2: Example scavenging process

Modern diesel combustion systems of 4-stroke engines are characterized by 4 valve cylinder heads with a central oriented injector. Fuel is distributed in the symmetrical combustion chamber by high pressure direct injection, utilizing a nozzle with 6-8 spray holes. As fuel penetrates through the combustion chamber and toward the piston bowl the swirl intensity increases and supports improved fuel mixing, fast combustion and high air utilization, Figure 3.

OP engines require a unique combustion system with injectors installed into the cylinder wall (side injection). Fuel is penetrating from the wall toward the center of the cylinder, from higher swirl intensity to low swirl intensity. Fuel distribution is compromised by narrow spray angles required to minimize spray interference with the pistons and cylinder wall. Deep spray penetration may result in spray-to-spray interaction of the multiple injectors in one cylinder, Figure 4Figure 3. In-cylinder charge motion is mainly generated by the approaching and departing pistons and can cause significant spray deflection.

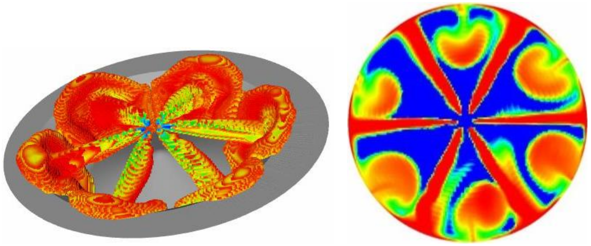

Figure 3: 4-stroke diesel engine injection / combustion system

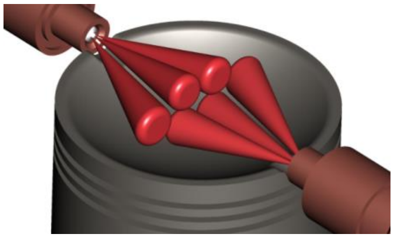

Figure 4: **2**-stroke OP Diesel engine injection / combustion system

In addition to the gas exchange and direct injection / combustion challenges, OP engines also have unique mechanical design challenges. Large ports in the cylinder liner provide sufficient flow area to optimize the scavenging process. The opening and closing of the ports is controlled by the pistons, where one piston controls the intake ports and the other piston, in the same cylinder, controls the exhaust ports. The ports are opened for approximately 90-120° crankangle as the pistons travel through bottom dead center, otherwise the ports are closed by the piston skirts. Gas sealing needs to be ensured between the combustion chamber and the ports, the ports and the crankcase, as well as from the ports to the piston wrist pin. Oil sealing needs to be provided from the crankcase to the ports and from the piston wrist pin to the ports, Figure 5. To provide these sealing functions OP engines require long piston skirts with typically 2 or more piston rings in the upper part of the piston skirt (combustion chamber seal) and 2 piston rings at the bottom of the skirt to provide sealing to the crankcase. The skirt is completely closed to seal the wrist pin to the ports. The following technical challenges result from these unique piston sealing requirements:

- Increased friction due to increased number of piston rings
- Increased oil consumption due to oil loss into the ports while providing sufficient lubrication to the upper compression rings
- Increased overall engine height, due to long pistons and long liner to provide complete sealing between crankcase and ports at BDC
- Tall piston and unconventional wrist pin bearing lead to increased oscillating masses

A general challenge for 2-stroke engines is the constant force applied to the connecting rod as a result of the compression and expansion stroke and the piston inertia when traveling through BDC. The piston does not lift from the connecting rod as it would during the gas exchange process in a 4-stroke engine. This condition is especially challenging for the piston wrist pin bearing and special design features are required to ensure proper lubrication of the loaded area in the bearing.

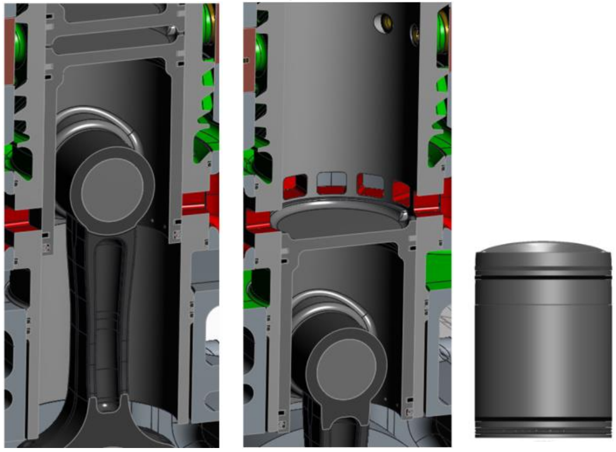

Figure 5: Sealing of scavenging ports

As discussed above, asymmetric port timing is required for optimum scavenging of a 2-stroke OP engine. Asymmetric port timing is achieved in a 2-crankshaft OP engine through an asynchronous timing of the crankshafts. The crankshaft with the exhaust port controlling pistons runs ahead of the crankshaft with the intake port controlling pistons. This leads to unbalanced share of the torque generation between the intake and the exhaust crankshaft. An 8-10 degree offset between the crankshafts results in approximately 70% torque generation of the exhaust crankshaft and only 30% contribution from the intake crankshaft, Figure 6

Also, the crankshaft offset leads to a torque reversal when the intake crankshaft travels over TDC, because of the high in-cylinder combustion pressure present at that time. A gear train connects the crankshafts with each other and the torque of both crankshafts is transferred to a power take off (PTO) gear between the crankshafts. This leads to very high torque fluctuations in the gear train, Figure 7. The relatively oversized gear train is heavy, results in mechanical losses in the transmission of the crankshaft torque to the PTO and provides a source of high vibration and noise.

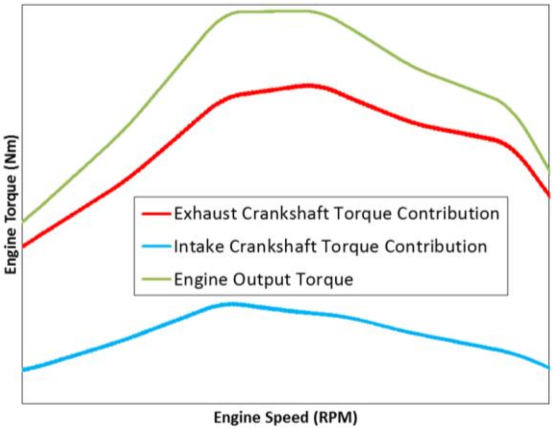

Figure 6: OP engine torque contribution from intake and exhaust crankshaft

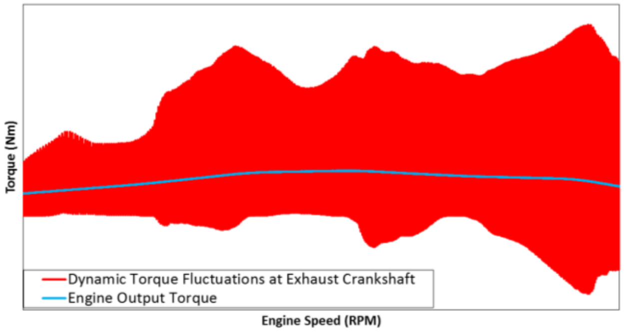

Figure 7: OP engine torque fluctuations in gear train

High Performance 4-Stroke Engine (HP4S)

In modern commercial and military applications 4-stroke diesel engines are used as the primary source for propulsion power. Power density and fuel efficiency of these engines have continuously improved over the past decades. Some applications, such as racing trucks, military combat vehicles, and high performance pleasure craft, reach specific power outputs of 80-100 kW per liter displacement. Brake thermal efficiencies of >45% (BSFC <0.31 lbs/hp-hr) are common in today's on-highway heavy-duty applications.

Based on state-of-the-art technologies applied in light-duty, medium-duty and heavy-duty applications, FEV has developed a high performance 4-stroke (HP4S) diesel engine meeting the performance and packaging requirements of the ACE, Figure 8. The main specifications of the HP4S engine are:

- Inline 6 cylinder
- Horizontal-flat installation
- Bore/stroke: 146/140 mm
- Rated speed: 3000 rpm
- Rated power: 1500 hp
- Max. Torque: 4300 Nm (3200 lbf-ft)

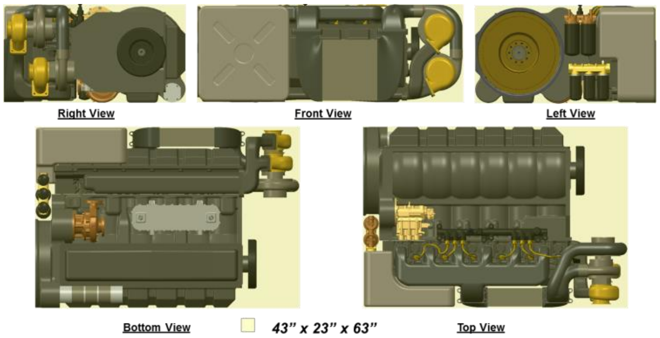

Figure 8: HP4S Engine

The HP4S engine utilizes advanced technologies to meet, and in some areas exceed, the requirements of the ACE. A summary of these technologies is shown in Figure 9 and described in the following sections.

Diesel engines typically operate at a compression ratio between 15:1 and 19:1. Applying a high compression ratio provides an improvement in cold start capability and an increased thermodynamic efficiency. However, especially in high performance engines, it is desirable to operate at lower compression ratio to minimize peak cylinder pressures, as well as mechanical and thermal stresses. To allow the advantages of both approaches FEV has developed a novel design to adjust the compression ratio with the connecting rod. The variable compression ratio (VCR) conrod is actuated by oil pressure supplied from the crankshaft and increases or decreases the effective length of the conrod via an eccentric wrist pin bearing. This technology allows the HP4S engine to operate at high compression ratio at low load and part load and switch to low compression ratio at high loads. Peak cylinder pressures can be reduced by up to 50 bar, resulting in significantly lower mechanical loads and reduced heat transfer due to lower peak temperatures in the combustion chamber.

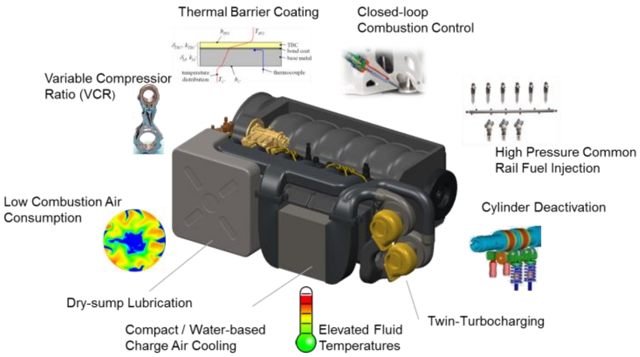

Figure 9: Advanced Technologies applied in the HP4S Engine

The HP4S engine includes a 4 valve cylinder head with centrally located fuel injector and fully symmetric combustion chamber. Along with high pressure common rail fuel injection (>2000 bar) and optimized piston bowl geometry the fuel /air mixing is well optimized for fast and complete combustion while operating at air fuel ratios (AFR) less than 20.

The air system of the HP4S engine applies twin turbocharging and utilizes a water-based charge air cooler integrated into the engine package. Twin turbocharging provides not only packaging advantages when compared to a larger single turbocharger; it also improves transient performance due to low rotational inertia. In combination with cylinder deactivation, at part load only one turbocharger is required to provide the boost pressure thus operating within the high efficiency area of the compressor map and avoiding surge conditions. The charge air cooler (CAC) is typically part of the cooling pack, however integrating the CAC into the engine package has significant advantages. Significantly reduced volume in the charge air system (compressor outlet to intake valves) allows a much faster pressure build-up during load changes and thus an improvement in transient performance without excessive smoke emissions resulting from insufficient combustion air. There are no installation and maintenance connections for the air system between the engine and the cooling pack. Furthermore, with the CAC included in the space claim of the ACE, additional package space is available in the cooling pack.

A critical requirement for combat engines is the ability to operate on a large range of fuel types (multi-fuel engine). Even when considering standardized fuels, such as DF-2, JP-8, JP-5, the ignition and burning characteristics are vastly different. Figure 10 shows an example of the ignition and combustion behavior for three diesel fuels with different cetane numbers (CN). Diesel fuel in the US typically has a CN between 40-45, whereas in Europe the CN of diesel fuel is typically in the low 50s. According to MIL-T-83133, JP-8 and JP-5 have no CN requirement specified and 5% less heating value than diesel fuel. The CN of diesel fuel describes its ignition behavior; specifically fuels with high CN have a shorter ignition delay than low CN fuels. Long ignition delays cause a significant amount of premixed combustion, resulting in steep pressure rises and the possibility for excessive peak cylinder pressures, which could lead to engine damage. It is therefore desirable to have the ability to adjust the fuel injection parameters based on the actual combustion characteristic of the fuel in use. The HP4S engine is equipped with in-cylinder pressure sensors to evaluate the burn characteristics and apply real-time controls to adjust injection timing, injection duration injection pressure and compression ratio to compensate for the combustion behavior of the fuel. This approach maximizes the performance of the HP4S engine and provides true multi-fuel capability.

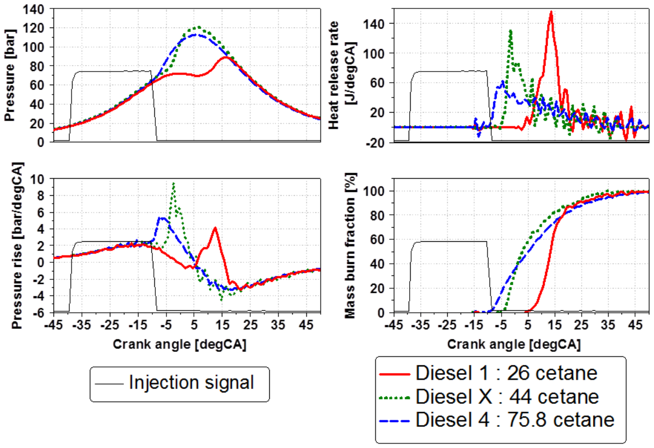

Figure 10: Combustion behavior of diesel fuels with different cetane numbers

The common rail system used in the HP4S engine uses individual unit pumps to provide the high pressure fuel to the common rail. The unit pumps are engine oil lubricated and thus do not rely on the fuels lubricity. The number of unit pumps can be varied based on the engine configuration and performance (scalability).

The valve train of the HP4S engine can be configured with valve deactivation features. At part load (e.g. < 40%) three of the six cylinders can be deactivated to improve fuel economy by deactivating the valve actuation and fuel injection.

Significant progress has been made in the development of low thermal conductivity surface materials over the past decade. A primary application for these materials is the turbine blades of aircraft engines and commercial gas-turbines to allow higher gas temperatures and thus an increase in thermal efficiency. New ceramic materials include high-purity zirconia-based materials for improved high temperature sintering resistance, and low-K compositions utilizing pyrochlores, perovskites, or advanced oxide defect cluster ceramic composites for improved high-temperature heat insulation. These coatings are applied to heat exposed surfaces by Physical Vapor Deposition (PVD) methods. Coating thicknesses of up to 2 mm significantly reduce base material temperatures. Thermal Barrier Coatings (TBC) will address the thermal management issues of the HP4S engine in two ways. First, the low heat conductivity coating will reduce the heat flux into the base material and the cooling fluid. Second, the coolant fluid temperature can be increased without exceeding temperature and stress limits of the structural components such as the cylinder head and piston. Operating the engine system at higher coolant temperatures will decrease the required airflow through the radiator and reduce the driving power required of the radiator fan.

HP4S Engine Performance Predictions

Performance simulations of the HP4S engine have been conducted with GT-Power. The gas exchange process, including turbocharger matching has been optimized to meet the full load requirements of the ACE, Figure 11. At rated speed of 3000 rpm the output power is 1500 hp. A maximum torque of 4300 Nm (3170 lbf-ft) is available from 1500 rpm to 2100 rpm, meeting the ACE torque rise requirements of 20%. The HP4S engine maintains maximum power up to 5,000 ft altitude and more than 1200 hp is available up to 12,000 ft, Figure 12.

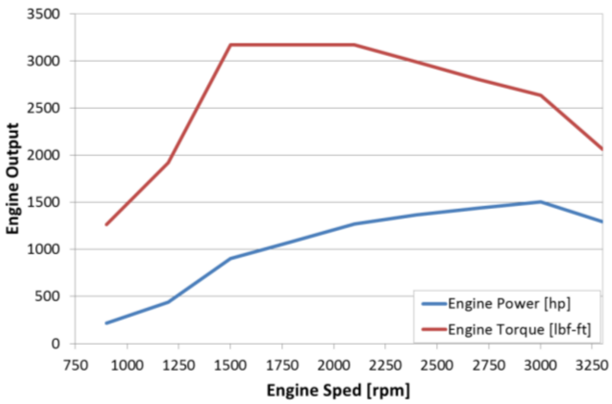

Figure 11: HP4S engine full load performance

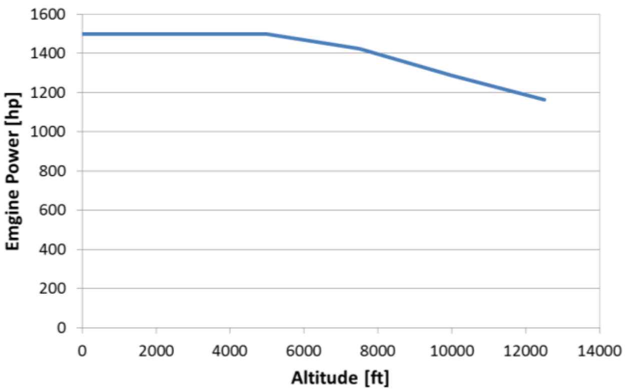

Figure 12: HP4S engine altitude capability

The 2 step VCR connecting rod offers high fuel efficiency with the best point at 193 g/kWh (0.317 lbs/hp-hr). Up to approximately 70% load the engine operates at a compression ratio of 19:1. At higher loads the compression ratio is reduced to 14.9:1 to maintain peak cylinder pressures below 250 bar, Figure 13.

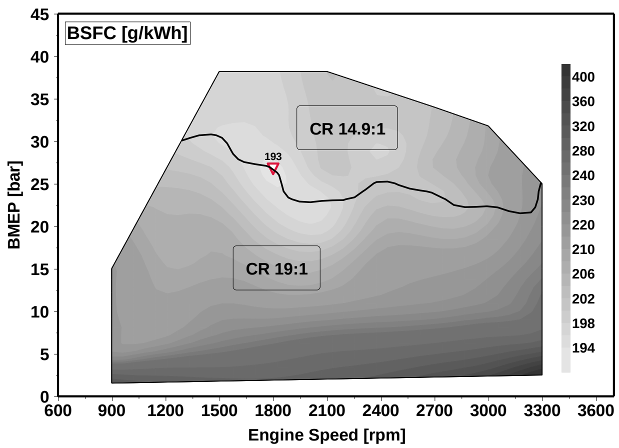

Figure 13: HP4S engine fuel efficiency

One of the critical requirements for the ACE is the low heat rejection into the cooling system. A challenging target of 0.45 kW heat per kW output power has been established. The HP4S engine the requirement over the relevant, high load area of the engine map. At lower engine loads the specific heat rejection is >0.45 kW/kW, but the absolute heat transfer into the cooling system is much below the capability of the cooling pack sized for the high engine loads, Figure 14.

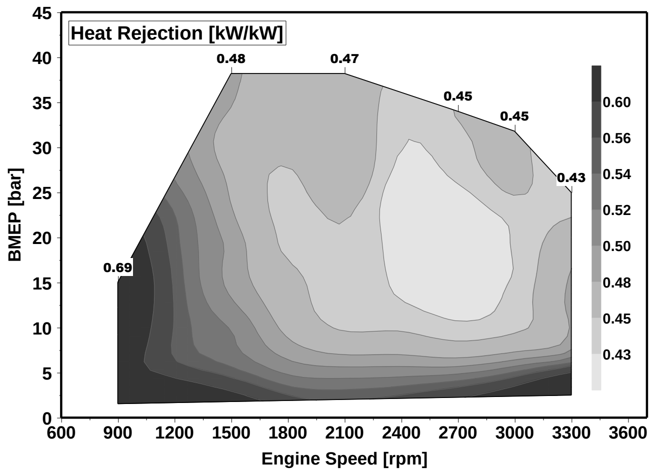

Figure 14: HP4S engine heat rejection

HP4S Engine Scalability

The HP4S engine provides a modular and flexible architecture that allows derivative solutions of the ground combat vehicle engine (ACE) for other military applications. The intent is to maximize part commonality across a wider range of applications to reduce production cost as well as maintenance and logistic costs, Table 1.

Table 1: HP 4S engine configurations

Cylinder Configuration	Installation Orientation	No. of Cylinders	Power Capability	Rated Speed	mean piston speed	BMEP	Applications
I-6	horizontal flat	6	1500 hp	3000 rpm	14.0 m/s	32 bar	Combat Vehicle
I-4		4	1000 hp				
I-6	vertical / conventional	6	900 hp	2200 rpm	10.3 m/s	26 bar	Tactical truck
I-4		4	600 hp				
V-12		12	3000 hp	3000 rpm	14.0 m/s	32 bar	Marine / PowerGen
V-8		8	2000 hp				

Comparison of HP4S and OP Engine

A high performance 4-stroke engine as described in this paper has many advantages over an OP engine for combat ground vehicle applications. A requirement for 30-50% less combustion air consumption allows the size of the air filtration system, intake air piping to engine, charger air cooling system as well as the exhaust system to be reduced by approximately 40%. This leads to a significantly smaller overall propulsion system and consequently to a smaller and lighter vehicle. The lower combustion air requirement also permits a reduced charge air cooling and lower radiator fan power consumption. Unlike the 2-stroke OP, the turbocharged 4-stroke engine does not require an electrically or mechanically driven supercharger for startup and part load operation. A 1500 hp OP engine requires approximately 30-40 kW of power to drive the supercharger, which must be considered in the specification of the electrical system.

The HP4S engine does not suffer the many unique and fundamental mechanical challenges of a 2-stroke OP engine, such as a piston design requirement that provides sealing of the combustion chamber. This piston design not only leads to increase in engine size (length from crankshaft axis to combustion chamber), it also increases the parasitic losses due to increased oscillating inertia, larger number of friction components (main bearings, conrod bearings, pistons), and a difficult trade-off between low lube oil consumption and piston ring durability / reliability.

ABBREVIATIONS

ACE	Advanced Combat Engine
BDC	Bottom Dead Center
CAC	Charge Air Cooler
CN	Cetane Number
CVP	Combat Vehicle Prototyping
DR	Delivery Ratio
HP4S	High-Performance 4-Stroke
NAMC	National Advanced Mobility Consortium
OP	Opposed Piston
OPOC	Opposed Piston, Opposed Cylinder
TDC	Top Dead Center
VCR	Variable Compression Ratio

The weight of the 1500 hp HP4S engine would be approximately 300-400 kg less than the weight of a 2-crankshaft OP engine due to the reduced number and size of structural components such as the crankcase and the crankshafts, and the highly loaded gear train. The weight of these additional components by far overcomes the weight reduction that would otherwise result from the elimination of the cylinder head.

Summary

This paper discussed some of the fundamental benefits and drawbacks of OP engines in regard to meeting future requirements for advanced, high performance combat vehicle engines. It also introduces a new advanced high performance 4-stroke engine that incorporates known and proven technologies from automotive, heavy-duty and industrial engine applications. Applying these technologies to an engine architecture that has been tailored specifically for combat vehicle applications provides a power source that meets or even exceeds the targets specified for the ACE.

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