

ADVANCED LIGHTWEIGHT TURBOCHARGED 2-STROKE MULTI-FUEL VARIABLE VALVE TIMING AND VARIABLE COMPRESSION RATIO MILITARY ENGINE

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ABSTRACT

The latest advancements in common rail fuel injection system, material science, engine control strategies, and manufacturing technologies have challenged and allowed engine designers to create a high power density, fuel efficient, reliable, and environmental friendly multi-fuel engine. To increase power density a novel high-speed 2-stroke turbocharged compression ignition engine will feed the pressurized air directly into the combustion chamber without going through the crankcase. Thus, only pressurized clean air will be used for combustion and oil consumption will be dramatically reduced. To further improve volumetric efficiency and reduce emissions, a computer controlled dynamic variable valve timing system can be incorporated such that the optimum amount of pressurized air will be available for combustion at various loads and conditions. Combustion efficiency at different loads can be optimized by adjusting the compression ratio dynamically through computer control. By controlling the fuel injection strategies through advanced engine calibration one can optimize engine horsepower, fuel economy, and emissions with multiple fuels. Parasitic losses can be minimized by reducing friction and pumping losses. Lightweight metal alloys and composite materials that have been well proven in the motorsports and aerospace industries can be used to replace a variety of engine components that are currently made of steel, iron, and aluminum to reduce the weight-to-power ratio to be close to 1. The result is a versatile, lightweight, high power density, reliable, fuel efficient, and "green" multi-fuel engine that will enable soldiers to move faster, go farther, have maximum fuel flexibility, and be safer in the battle field and other operating conditions.

INTRODUCTION

Military vehicles require speed, acceleration, and maneuverability to ensure survivability and successful mission completion. However, consistent increase in payloads has put these critical capabilities at risk. Increased payloads are desirable, but losing speed, acceleration, and maneuverability while increasing acquisition costs is unacceptable. Moreover, the operating conditions of military vehicles are unique and dangerous because they are exposed to sand, mud, oils, salt water, and potential ballistic hazards. The current propulsion systems are designed primarily to run with diesel fuel because they are typically modified land systems designed for heavy trucks or stationary land-based power generation. The weight-to-power ratios of these engines are between 3 and 5 and they have been optimized for land base civil environment and operational duty cycles. Military applications require the ability to withstand severe operational duty cycles, harsh environments, jet fuel and diesel compatible, and have extended life performance. Adapting these heavy diesel truck and power generation engines for military applications are not only sacrificing precious payload capacity and compromising the vehicle's speed, agility, and survivability, but also exposing them to much more demanding duty cycles and environments that

dramatically reduce reliabilities and shorten life spans. Thus, there is a potential need for a new engine designed specifically for the military that possess the following capabilities: (1) light weight and compact at a range of power levels such that the weight-to-power ratio is close to 1 in order to maximize payload capacity. Currently, a 700hp diesel engine weighs over 2000lbs while the proposed engine will weigh about 700lbs, therefore, an additional 1300lbs of payload capacity would be available. (2) modular engine design such that engines at different horsepower levels will share the same architecture and as many components as possible to achieve logistical commonality, (3) engine performance will be optimized for JP5, JP8, and diesel to increase flexibility and minimize the difference in performance between fuels, (4) reliable under severe military operational duty cycles in combat environment, (5) fuel efficient such that less fuel will be carried on board and payload can be increased, (6) rapid removal for mission flexibility and repair. Figure 1 and Table 1 shows a comparison of the Katech proposed military engine compares with a few state-of-the-art diesel and endurance racing diesel engines like the Audi R10 TDI and Judd.

PROPOSED ENGINE DESIGN & DEVELOPMENT

General Operation

The proposed military engine is an all aluminum turbocharged 2-stroke compression ignition engine. The engine basic geometries and operating parameters are shown in Tables 2 and 3. Rotary valves with variable timing are fitted on the side of the cylinder bore and chain driven by the crankshaft. The purpose of fitting the valves to the side of

the engine is to keep the top of the combustion chamber free of engine parts, except the injector, such that a relatively simple electro-hydraulic variable compression ratio mechanism can be integrated to the combustion chamber. A variable geometry turbocharger will be used and it, along with the valve timing and compression ratio, will be controlled by the engine management system based on engine speed and load to optimize performance while meeting emissions requirements

Table 1 - Engines Comparison

Engines	Config.	Displ (L)	Bore (mm)	Stroke (mm)	HP	@ RPM	Weight (lbs)	Lbs/Hp	Hp/L
Katech Advanced Military	V12	5.71	83	88	700	@3500	700	1.00	122.6
Judd Diesel Race	V10	4.6	n/a	n/a	600	@6000	396	0.66	130.4
Audi R10 Diesel Race	V12	5.5	83	84.7	650	@4500	792	1.22	118.2
Duramax LRX	V8	6.6	103	99	300	@3000	835	2.78	45.5
Duramax LYE	V8	6.6	103	99	330	@3000	835	2.53	50.0
Detroit Diesel Series 60	I-6	14	133	168	515	@1800	2840	5.51	36.8
Yanmar 6CX-530	I-6	7.41	110	130	530	@2900	1845	3.48	71.5

Table 2 - Engine Geometry

Engine Geometry		
Bore Diameter:	83.0	mm
Stroke:	88.0	mm
Bore/Stroke:	0.943	
Rod Length:	155.0	mm
Rod Length/Stroke:	1.76	
Cylinder Volume:	476.1	cc
# Cylinder:	12	
Engine Displacement:	5714	cc

Table 3 - Engine Parameters

Engine Parameters		
# Revolution per cycle:	1	
Maximum RPM:	4000	
Maximum Piston Speed:	11.7	m/s
Peak Horsepower:	700	Hp
Peak Horsepower RPM:	3500	
Horsepower per Cylinder:	58.3	Hp
Horsepower per Liter:	122.5	Hp/L
Torque @ Max. Power:	1425	Nm
Maximum Torque:	1639	Nm
BMEP @ Max. Torque:	1802	KPa
Maximum Boost:	2.5	Bar

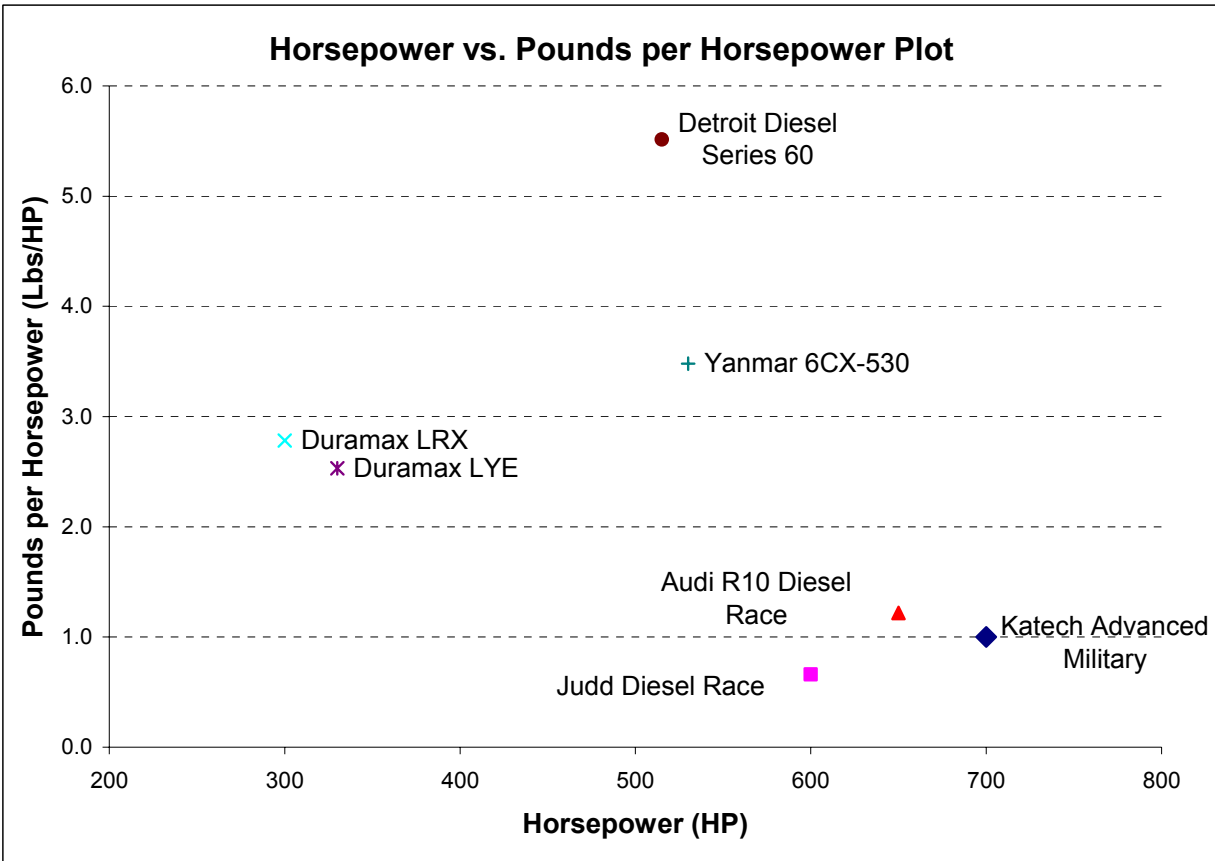


Figure 1 - Engines Comparison

1. Light Weight

- High strength cast aluminum cylinder case. A 30% weight reduction was achieved on a mass production cast aluminum cylinder case comparing to a similar cast iron cylinder case [1]. New proprietary aluminum casting processes have been developed to achieve UTS of over 400MPa and our target is to further reduce the cylinder head and case weights by 20%. A few high performance production and endurance racing aluminum diesel engines are shown in Table 4:

Table 4 – High performance production and endurance racing aluminum diesel engines

Endurance Racing Engines:	Production Engines:
Audi R10 & R15 (5.5L V12)	Honda i-DETC (2.2L I-4)
Peugeot 908 HDI (5.5L V12)	BMW XD5 35d (3.0L I-6)

Judd (4.6L V10)	Mercedes Benz OM642 (3.0L V6)
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- Integral aluminum cylinder head and bore design to eliminate the need for head gasket [2]. By removing the head gasket joint the one-piece cylinder head and bore structure becomes very stiff, lightweight, and compact. It bolts to the cylinder case around the outside to seal the water jacket, which requires much less clamping load than sealing the cylinder pressure. In combination with the advanced aluminum casting process the target weight savings over a traditional cylinder head and case unit is 60%
- The proposed rotary valve system (RVS) is more compact and lighter than the traditional poppet valve system [2]. The rotary valves will be located on the side of the cylinder case such that they will not be exposed to the peak cylinder pressure and temperature. In addition, the top of the combustion

chamber will be clear of engine parts except the fuel injector to incorporate a relatively simple electro-hydraulic variable compression ratio system. The RVS will initially be made of 2618 aluminum alloy but composite materials can be considered for future development for lower heat transfer, weight, cost, and quicker response. A sample rotary valve assembly is shown in Figure 2



Figure 2 - Sample rotary valve assembly

- Parent bore coating on aluminum cylinder case to replace heavy iron or steel cylinder liners. The coating is wear resistant and friction reduction [3]. We have had tremendous success applying the parent bore coating to endurance racing engines over the last decade. The target weight reduction is 60%
- High strength 1-piece cast aluminum main bearing housing and sump to achieve maximum structural and torsional stiffness at the minimum weight [3]. Most professional racing engines have gone to the 1-piece oil sump design to replace the heavy steel main caps and oil pan. The anticipated weight savings is over 50%
- Aluminum Metal Matrix Composite (AIMMC) pistons for strength and lightweight. 2618-T61 forged aluminum has been the material of choice for most professional racing pistons due to its high specific strength at engine operating temperature. The new generation of AIMMC has comparable density as the 2618 aluminum but has an incredible 48% higher yield strength at 200°C. In addition, AIMMC can dissipate heat quicker than the 2618 aluminum. Using advanced piston design technique the target weight savings is over 60% comparing to a current diesel piston. Lighter pistons mean less reciprocating mass and it allows the wrist pins,

connecting rods, and crankshaft to be smaller and also much lighter. Oil squirters will be required to cool the bottom of the piston for durability. Their material properties data are shown in Table 5:

Table 5 - 2618 & AIMMC Materials Properties

Alloy	2618-T61	AIMMC	Change
Density (g/cc)	2.76	2.88	4.3%
YTS @24°C (MPa)	275	480	74.5%
YTS @200°C (MPa)	179	265	48.0%
Thermal Conductivity (W/m°C)	141	150	6.4%

- CFRP covers and inlet manifold. The latest development in CFRP technology has allowed the properly formulated and constructed material to sustain in high temperature applications (up to 250°C) without sacrificing durability and strength. The weight savings over cast aluminum can be as much as 80%
- Connecting rods, crankshaft, and all other engine components will be optimized using advanced racing engine design techniques to achieve the lowest weight possible while meeting the durability requirement

2. High Power Output

- 2-stroke highly efficient compression ignition engine
- RVS for simplistic, compact, and efficient cylinder air exchange. As demonstrated on a contemporary 3.0L V10 800+hp @18000rpm Formula One racing engine [2], the latest advancements in design, materials, and manufacturing technologies have solved the traditional problems of high friction, and oil and combustion pressure sealing. Figure 3 illustrates a valvetrain and inlet tract arrangement on a V10 F1 engine tested on dynamometer



Figure 3 - Rotary valvetrain and inlet tract arrangement on a V10 F1 engine tested on dyno

- In a poppet valve system if a valve or a valve spring should be broken, there is a high possibility that the broken pieces will damage the cylinder and extend the damage to the rest of the engine. On the contrary, RVS has no protruding parts into the cylinder and the broken seals or bearings will be kept out of the cylinder and not interfere with the operation of the rest of the engine
- The proposed RVS has significantly less friction than poppet valve system due to less moving parts, less contact area, and they run on sealed roller bearings. Because it does not require oil lubrication, no oil from the valvetrain will be sucked into the combustion chamber and it dramatically reduces HC and NOx emissions [4]. RVS has lower inertia and higher system stiffness than poppet valve system for better dynamic stability and performance.
- Valve timing is no longer limited by the piston-to-valve clearance. Instead, the geometries of the rotary valve will determine the timing of the valve events and they could be optimized per engine configuration. Figure 4 shows a section view of the cylinder head assembly with an overhead rotary valve installed

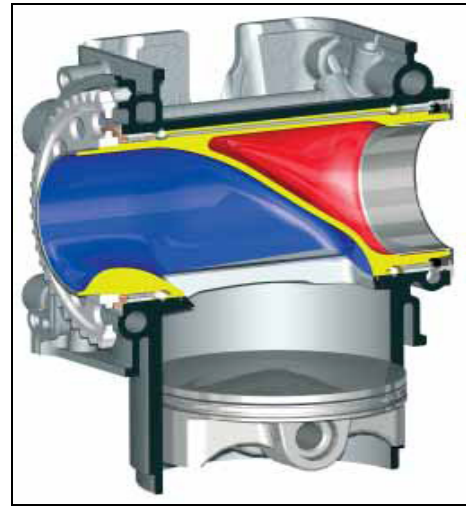


Figure 4 - Rotary valve cylinder head section view

- Inherent tumbling effect on intake air improves burn rate and combustion efficiency while maintaining or increasing volumetric efficiency [2]. This is a great advantage to the high speed 2-stroke CI engine because the speed of the combustion process will dictate the maximum rpm the engine can run and where the peak horsepower occurs. Figure 5 demonstrates a CFD simulation of the tumbling flow inside the cylinder at 6000rpm

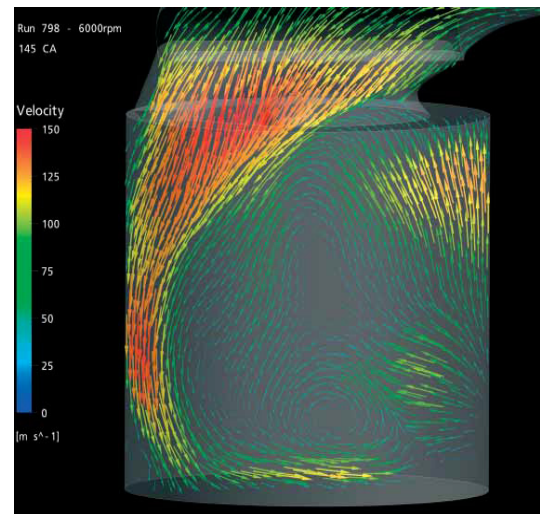


Figure 5 - CFD simulation of the tumbling flow inside the cylinder at 6000rpm

- Variable valve timing (VVT) will be electro-hydraulic actuated to maximize power with acceptable emissions at all speeds and loads [5] [6]. VVT will also be used to control EGR. Valve event strategy will be critical to the overall balance between performance and emissions. The target valve timing adjustment is +/-30° crank angle
- Minimize parasitic losses through advanced components design, friction and pumping losses reduction. A crank-driven multi-stage dry sump system will be fitted to the engine in order to generate slight vacuum in the oil pan. Katech Inc. internal testing have demonstrated that an effective dry sump system can reduce parasitic losses by over 5% as shown in Figure 6

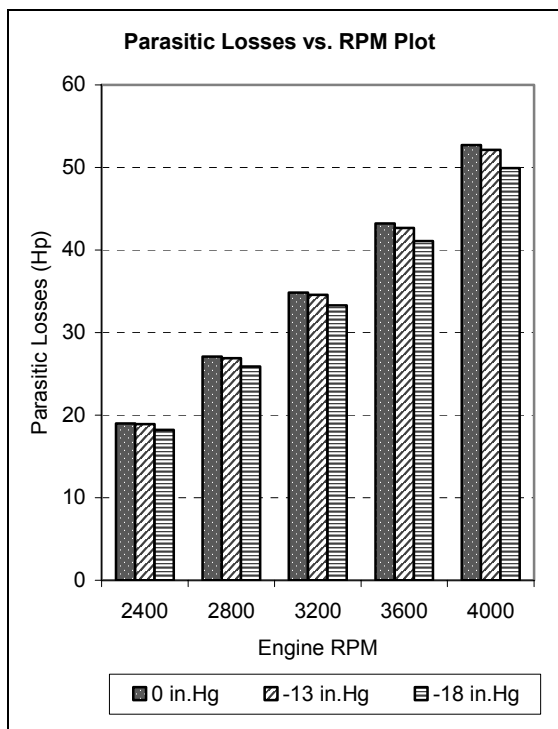


Figure 6 - Parasitic losses at various pan vacuum settings

- Variable geometry turbocharger (VGT) to improve low speed, part-load performance and emissions, and transient response [6] [7]. It was demonstrated that VGT was particular effective when applied in conjunction with VVT
- Integrated air-water intercooler for maximum charge density
- Turbo and intercooler will be sized to the displacement and target output of the engine

- Apply advanced CAE to determine initial intake and exhaust port geometries, valve timing, and optimize combustion characteristics
- Maximize power using in-cylinder and port pressures optimization technique. By simultaneously measuring the pressures in the intake port, exhaust port, and cylinder the valve event and the fuel injection timing can be phased to minimize pumping losses, maximize volumetric and combustion efficiencies
- Variable compression ratio (VCR) – engine calibration will decide based on load and speed if the engine should be running at low or high compression. High C.R. can improve cold start and low to medium load performance; low C.R. at full load to reduce maximum cylinder pressure and NOx emissions [8]. The C.R. will also be adjusted to enhance performance in transient conditions. The proposed compression ratios are 15 and 20 to 1. The VCR will be hydraulically driven by a solenoid valve controlled by the engine management system

3. JP5, JP8, and Diesel Optimization

- Advanced engine calibrations for maximum performance for JP5, JP8, diesel, and possibly other fuel of choice. Each fuel will have its own calibration because of their different combustion characteristics at different engine speeds and loads [9]. Engine calibration includes the control of the fuel injection timing and duration, VGT, VVT, and VCR
- 200MPa or higher piezoelectric direct injection system for maximum fuel atomization [10] and combustion efficiency
- Work closely with engine management system and fuel injector developer to develop custom applications for fuel mapping and control strategies
- Variable compression ratio - VCR will improve multi-fuel performance due to its ability to adjust for the different combustion characteristics of each fuel

4. Reliability

- Custom engine design for military applications. It is critical to mission success and the safety of its crew to have 100% reliability. Traditionally military engines were designed with a wide safety margin in order to achieve reliability. However, large safety margin usually means heavy engine components and it will reduce speed and the payload capacity of the vehicle. Through the use of advanced materials, design and manufacturing technologies the same

reliability can be achieved with lighter components at higher efficiency.

- Custom engine calibrations for JP5, JP8, and diesel to ensure acceptable reliability while optimizing performance
- Extensive dyno durability testing to simulate real world operational duty cycle and conditions

5. Modularity

- Scalable engine architecture with common reciprocating and valvetrain components for engine outputs between 120 and 700hp to simplify procurement and inventory logistics
- Each pair of cylinders will produce about 120hp
- The preferred engine configuration is horizontal opposed for perfect balance [11] [12]. However, vee and inline configurations can be accommodated if space, installation, or serviceability are a concern

6. Emissions

- To meet future emissions requirement with minimum performance loss. Some engines lose as much as half of their maximum output in order to meet emissions requirement [12]
- Perform emissions testing along with cylinder pressure testing to facilitate engine calibration
- Apply fuel injection strategies in combination with VGT and VVT to control the amount of EGR [6] [7]
- Use of effective Diesel Particulate Filter (DPF) technology and strategy to reduce visible smoke under transient conditions [3] [13]

CONCLUSION

Today's military operations demand the most powerful, efficient, and reliable power plant to maximize mission success. In light of Katech Inc.'s successful endurance racing heritage and expertise in advanced engine development, a lightweight highly efficient military engine design was proposed with state-of-the-art technologies. As a result of the proposed design and development, a family of advanced military engines could be available for service from 120 to 700hp with weight-to-power ratio equal to 1, multi-fuel optimized, reliable, modular, emissions compliance, and fuel efficient.

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