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COMPACT, LIGHTWEIGHT, HIGH EFFICIENCY ROTARY ENGINE FOR GENERATOR, APU, AND RANGE-EXTENDED ELECTRIC VEHICLES

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ABSTRACT

Today automotive gasoline combustion engine's are relatively inefficient. Diesel engines are more efficient, but are large and heavy, and are typically not used for hybrid electric applications. This paper presents an optimized thermodynamic cycle dubbed the High Efficiency Hybrid Cycle, with 75% thermodynamic efficiency potential, as well as a new rotary 'X' type engine architecture that embodies this cycle efficiently and compactly, while addressing the challenges of prior Wankel-type rotary engines, including sealing, lubrication, durability, and emissions. Preliminary results of development of a Compression Ignited 30 kW X engine targeting 45% (peak) brake thermal efficiency are presented. This engine aims to fit in a 10" box, with a weight of less than 40 lb, and could efficiently charge a battery to extend the range of an electric vehicle.

INTRODUCTION

Today's Diesel / heavy-fueled engines, while relatively efficient, are large and heavy, with a power-to-weight ratio of approximately .1-.2 hp/lb (see, e.g., [12]). This paper presents a new type of rotary Diesel combustion engine architecture (the "X Engine"), which is based on an optimized thermodynamic cycle: the High Efficiency Hybrid Cycle (HEHC). Together, these innovations can increase fuel efficiency by 30% or more, and significantly improve power-to-weight of Diesel engines to 1 hp/lb or better.

This paper will overview the HEHC thermodynamic cycle and rotary X engine, shown in Figure 1, and will describe the development status of the X4, a .8L Compression Ignition

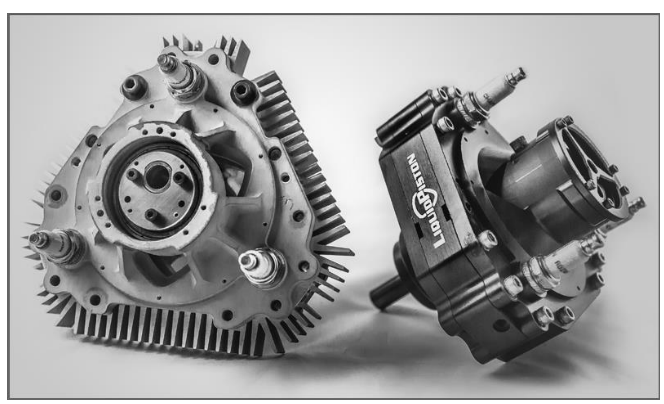

Figure 1: 70cc heavy fueled XMD engine

engine, funded by the Defense Advanced Research Projects Agency (DARPA), with aggressive targets including: 30 kW power, and power to weight of 1 hp/lb Operating on the HEHC cycle, the X4 engine can potentially achieve very high brake thermal efficiency of up to 45%. Today, small (<1.0 L) piston Diesel engines, such as the Kohler KDW1003 in use in Polaris Diesel Ranger all-terrain vehicles, typically achieve efficiency on the order of 33% peak, which drops off at part power [13]. Like other engines [7], the X-engine efficiency also improves with scale; 1-D thermodynamic models estimate 57% brake thermal efficiency for a 200 kW size engine.

The paper will also provide an overview of a second smaller X engine, the “X Mini Diesel” (XMD), a small (70cc) spark-ignited (SI) multi-fueled engine (Figure 1) that is heavy fuel compatible, which is currently being developed for insertion into a hybrid electric power supply to power the digital fire control system of the M777 Howitzer (Figure 21).

Lastly, the paper will provide an overview of applications for the engines.

Motivation

Diesel compression ignition (CI) engines, which operate at high compression ratio / high pressure, tend to be more fuel efficient than gasoline engines, but are also large and heavy. For logistical purposes, military applications prefer to operate on JP8 fuel (a heavy fuel, similar to kerosene), and increasingly demand higher efficiency and improved power-to-weight. Non-military applications also benefit from similar improvements. The work presented in this paper addresses both of these areas of efficiency and size/weight.

The X engine can scale much like other engines, and could be used for primary propulsion in vehicles. Another area of particular interest for such an engine may be as a range extender for electric vehicles. In this approach, a vehicle may be powered electrically with a small battery pack which is intermittently charged by an efficient and compact Diesel power generator based on the 30 kW X4 engine. This approach could eliminate the bulk of an electric vehicle battery pack, reducing vehicle cost and weight, while improving efficiency (on a well-to-wheel basis), and also reducing the logistical burden.

The proposed program targets of the X4 are very aggressive, as could be seen in comparison of the X4 to compiled published gasoline and diesel specific power and specific efficiency data, a sampling of which is shown in Figure 2 [8]. The green box shows the target bounds of the X4 when development is completed.

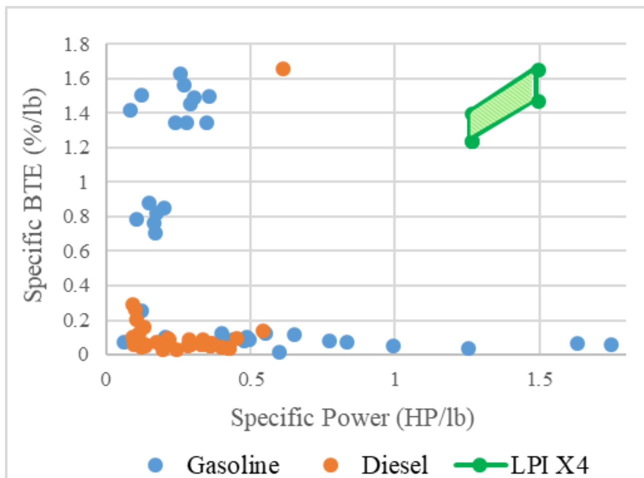

Figure 2: X4 vs. Benchmark Data

High Efficiency Hybrid Cycle

A key differentiator of the X engine is the ability to run on the High Efficiency Hybrid Cycle. In an idealized case, this thermodynamic cycle combines features from several other cycles, combining them into an efficiency-optimized cycle. The features of HEHC (referring to Figure 3) include:

1→2 High compression ratio of air (similar to Diesel cycle).

2→3 Fuel is injected, mixed and burned under approximately constant volume conditions (similar to ideal Otto cycle).

3→4 The expansion ratio can be designed to be greater than the compression ratio, enabling the engine to run over-expanded (similar to Atkinson cycle).

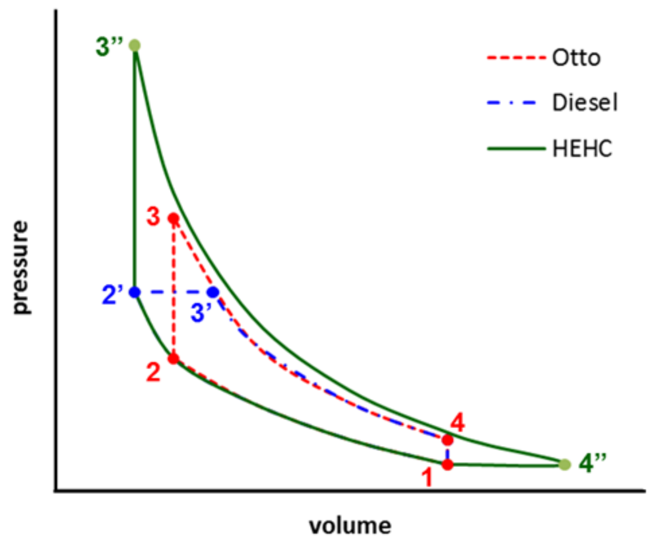

Figure 3: P-V diagram comparing ideal air-standard cycles

In the X engine, high compression is achieved by displacing and compressing the trapped air into a stationary combustion chamber in the housing. The combustion chamber can have a small volume (thereby increasing compression ratio). This chamber can be thermally isolated from the rest of the engine and could potentially run hot to reduce heat transfer during combustion. Both SI and CI, as well as indirect or direct injection (IDI and DI) type combustion is possible.

The unique geometry of the X engine causes a dwell near Top Dead Center (TDC), where the rotor is spinning, but the volume is not changing very much. This flatter volume profile gives the engine more time to combust more fully under near-“constant volume” conditions. The benefit of constant volume combustion is eloquently captured in a text by Gordon Blair [6, page 81]:

“The problem is simply that [a piston] engine cannot conduct combustion at constant volume, i.e., instantaneously at TDC, because a real burning process takes time, the piston keeps moving, and the cylinder volume changes. If this latter problem could be remedied by keeping the piston stationary at tdc while combustion took place and then moving it down on the power stroke when all is burned, the imep and power would increase by some 50%. […] I would actually encourage the world's inventors to keep on trying to accomplish this ic-engine equivalent of the ‘search for the Holy Grail’.”

The HEHC cycle has been analyzed and described previously in detail [1]. Figure 3 (adapted from [1]) shows visually a comparison of ideal Otto, Diesel, and HEHC cycles. In that work, the HEHC is shown to have approximately 30% higher efficiency than comparable Otto / Diesel cycles. More complete thermodynamic modeling of the actual engine cycle has also been completed using 1D simulation (GT Power), and the results summarized in the Modeling section below, suggests that 45% brake thermal efficiency is possible in the 30 kW size X engine.

Additional details of the cycle, X engine architecture, and development of a small SI 70cc X engine as well as the 30 kW .8L X4 engine are described in [1-3, 10]. The interested reader is also referred to view an animation of the ‘X’ engine here [4].

X engine vs Wankel

The Wankel rotary engine (Figure 4, Left) [5] was developed in the 1960s as an alternative engine architecture. The engine demonstrated excellent power to weight characteristics and exhibited low vibration even at high RPM. The engine was also very responsive, making for a fun driving sports car in the Mazda RX series. Despite these advantages, the Wankel was always plagued by poor fuel economy, emissions problems, and durability issues, especially in the apex / tip seals. These challenges are due to a number of inherent issues: 1) a narrow combustion chamber prevents adequate flame propagation, while also having high surface to volume ratio which cools the charge and reduces efficiency; 2) the engine is poorly sealed, leading to significant blowby, thereby decreasing efficiency; 3) the Wankel engine operates on the same conventional 4-stroke Otto cycle with spark ignition as a piston engine; however there are inherent challenges to operate > 10:1 compression ratio, and this engine was forced to compete with piston engines that had over one hundred years of prior development; and 4) the tip seals, in addition to being difficult to seal, are also difficult to lubricate; oil must be injected into the charge, with the majority of the oil burned in order to lubricate the gas seals.

The 'X' engine essentially "inverts" the Wankel engine (see Figure 4). While a Wankel engine has a 3-sided triangular rotor, within a 2-lobed oval housing, the X engine has a 2-lobed oval rotor in a 3-sided housing. The X engine captures the main advantages of the Wankel, including 1) high power-to-weight ratio [a one rotor X engine behaves like a 3-cylinder 4-stroke]; 2) simplicity – having only 2 moving parts – a rotor, and a shaft; and 3) like the Wankel - the X engine is inherently balanced with no oscillating components, therefore having minimal vibration. Unlike the Wankel however, there are several key differentiators which address the bulk of the older Wankel's design deficiencies:

- The combustion chamber in the X engine is located in the stationary housing, with most of the gas displaced during compression into this stationary combustion chamber. This makes the X engine uniquely suitable for high compression ratio operation with Direct Injection and

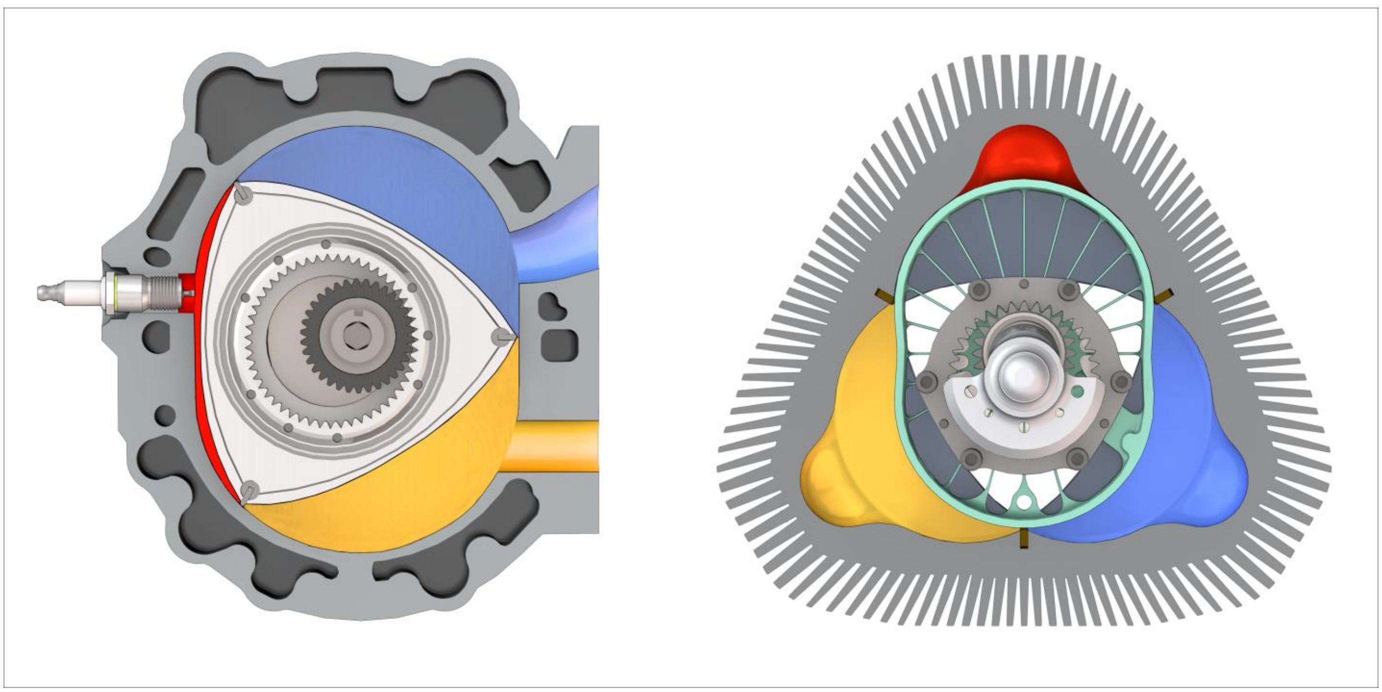

Figure 4: Wankel Engine (left) vs X Engine (right). X Engine features spherical combustion chamber and stationary apex seals which can be lubricated from the housing. Red=combustion; Blue= Intake; Yellow = Exhaust.

Compression Ignition (which is not possible in the Wankel without boosting or a second compression rotor). Additionally, the combustion chamber can take any geometry, and can be approximately spherical, optimized for surface to volume ratio, thereby improving combustion efficiency and reducing heat transfer.

- The apex seals of the X engine are located within the stationary housing, and do not move with the rotor. The seals do not experience centrifugal forces, and can be lubricated directly by metering small amounts of oil directly to the sealing surface through the housings, which means that oil consumption can be reduced to levels potentially comparable to that of a 4-stroke piston engine (essentially negligible). See oil channels for apex seals in Figure 6.
- The unique sealing geometry of the X engine has 3-5 times less blowby than the Wankel rotary. This is mainly because 1) the Wankel requires clearance at the corners between its side/face seals and its apex seals, while the X engine does not; and 2) the Wankel seals traverse across holes that contain spark plug(s), whereas the X engine does not. The sealing strategy, seal modeling, and testing validation is described in detail in [9].

As mentioned, LiquidPiston has developed two versions of the X engine, including the air-cooled SI (multi-fueled) 70cc X Mini, as well as the liquid cooled CI .8L X4 engine. The optimal efficiency benefits described in [1] cannot be fully realized in the small spark ignition (SI) engine which has been described previously in [2] and [3]. To realize the high efficiency potential, the HEHC cycle requires a high compression ratio for optimal performance. This is best achieved with compression ignition (CI) and heavy fuel. In this work, we show a step toward developing the X4 engine which runs on Diesel / JP-8, achieves state-of-the-art (or better) CI fuel efficiencies, and offers a significant weight advantage comparable to current engines of similar performance.

X4 Engine

Geometry specification

The most significant parameters defining the geometry of an X engine are the values for E, R, Rr, and engine housing thickness. E is the eccentricity, R is the radius from the centerline of the crankshaft to the center of the apex seal radius, Rr is the apex seal roller radius, and the housing thickness is the width of chosen geometry parallel to the crankshaft center line. These parameters are described in Figure 5 below, and the parameters specific to the X4 engine are shown in Table 1.

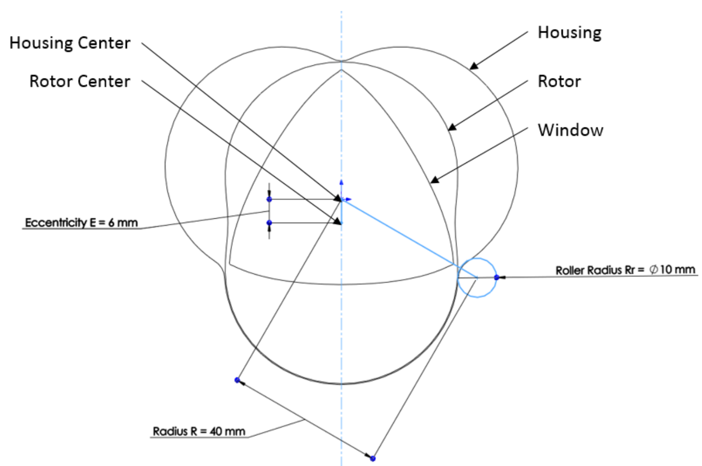

Figure 5: X Engine Generating Parameters

Table 1: X4 Design Parameters

E	13mm
R	83mm
Rr	1.46mm
Housing Thickness	45.4mm
Displacement (per chamber)	250cc
Displacement (total)	750cc

The X4 test rig is shown below in Figures 6 and 7. The size is larger than the final intent in order to make space for combustion chamber variations, and to accommodate standard diesel fuel injectors. These dimensions will be reduced in future phases of the program.

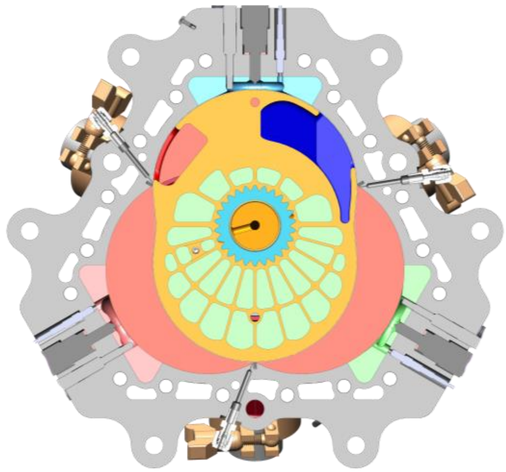

Figure 6: X4 Engine front view cross section

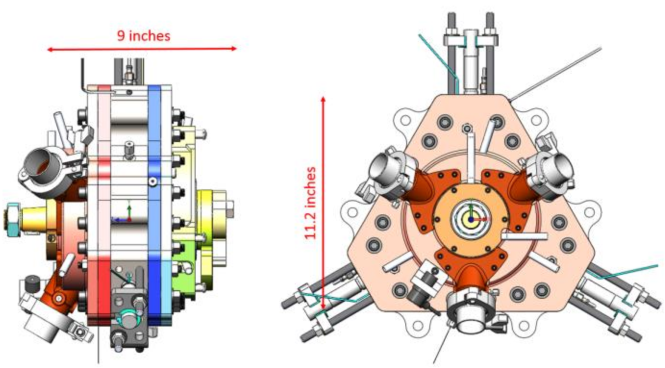

Figure 7: X4 Size

Performance Modeling

A GT Power model of the X4 engine was created to validate the chosen displacement of the engine, analyze the feasibility of meeting the 45% brake efficiency target, and provide gas load curves for component analysis. GT Power is a 1D thermodynamics and flow simulation software by Gamma Technologies which is commonly used to simulate piston engines. In order to simulate the rotary X engine, some customizations were made to account for deviation such as non-standard crank-slider mechanism, volume and surface area profiles.

A summary of important input assumptions and output results are shown in Figure 8. Case 4 shows a pathway towards the Objective (aggressive) efficiency target, and Case 1 the Threshold (conservative) target. The "Leak Area" is an equivalent blow-by orifice which represents gas leakage through the combustion seals. This value has been measured at 0.5 to 1.5 mm^2 based on motoring compression data. The friction and heat transfer values are based on prior work on the 3 horsepower X engines. Peak Cylinder Pressure of 108 bar, predicted from the GT model, was used for component design. The corresponding Pressure vs. Volume diagram for Case 1 (red) and Case 4 (blue) are shown in Figure 9.

Case No.	1	4
Burn Duration	66°	44°
Start Of Combustion timing	-30°	-16.5°
Leak areas (mm^2)	2.5	1.5
Friction	8.3% of fuel	7.8% of fuel
Heat transfer	27.9% of fuel	16.5% of fuel
Pumping loss	1.80% of fuel	1.66% of fuel
Geometric Compression Ratio	22	24
720° Indicated Thermal Efficiency	38.10%	45.50%
Brake power (kW)	24.5	32.8
Peak Cylinder Pressure (PCP) (bar, absolute)	88	108
Average cylinder P (bar)	8.52	9.46
Engine Speed (RPM)	7000	7000

Figure 8: X4 GT Power Inputs/Outputs

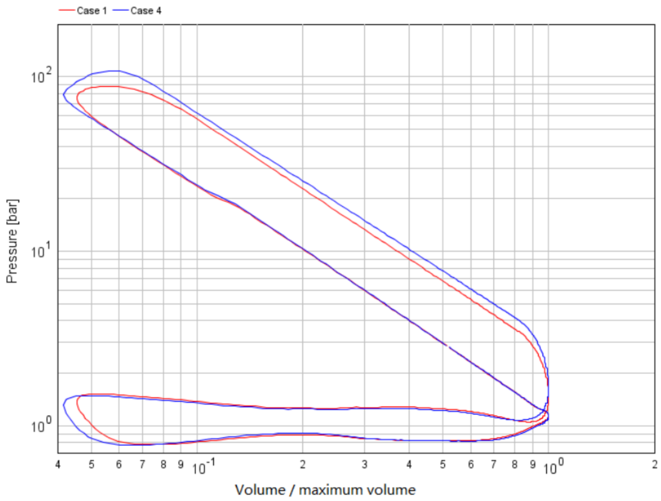

Figure 9: PV Diagram for GT Cycles

Testing

Some images of engine parts and assembly are shown in figures 10-11. LiquidPiston's AC dyno test cell with the X4 engine mounted is shown in Figure 12. The engine was equipped with in-cylinder pressure transducers, torque sensor, various thermocouples, and was controlled by a National Instruments / Drivven data acquisition / control system on an AC motoring dyno.

Some example images of pressure traces from the engine are shown in Figures 13-15. Figure 13 demonstrates the highest observed peak pressure, which exceeded 140 bar of cylinder pressure. This was achieved by combusting with an IDI type combustion chamber, at a 26:1 compression ratio, naturally aspirated.

Due to the inefficiency of throttled combustion in an IDI type chamber, DI was explored next. Figure 14 demonstrates an example of DI compression ignition, at a 20:1 compression ratio, showing firing (green) vs motoring (red). So far the engine has been run at up to 5.5 bar Indicated Mean Effective Pressure (IMEP), up to 3,500 Revolutions Per Minute (RPM).

Future work

The engine testing to date demonstrates stable operation at up to 150 bar of peak cylinder pressure. Seals were demonstrated to have successfully held up to such pressure. Upon disassembly, nothing remarkable was observed in the rotor, gear, bearings, shaft, and housings. Engine testing so far has been conducted without any cooling, just to verify the structural integrity and basic operation of the core components. A cooling system with a water jacket in the housing and oil cooling of the rotor was recently developed for the engine, and testing for the cooled system is currently ongoing. Cooling of the engine is necessary to run the engine for longer periods at hotter conditions, necessary to do measurements of peak efficiency as well as further work for optimization.

Packaging the engine with balance of plant components (fueling, cooling, control & lubrication systems), as well as optimizing for power and efficiency, remains as future work.

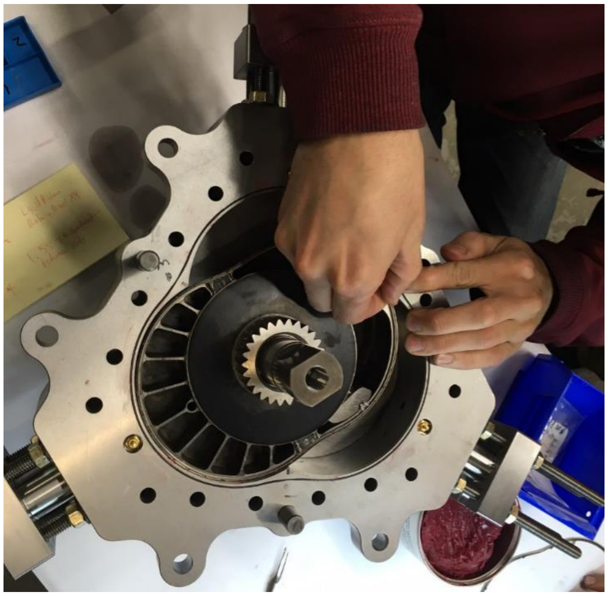

Figure 10: Rotor Assembly

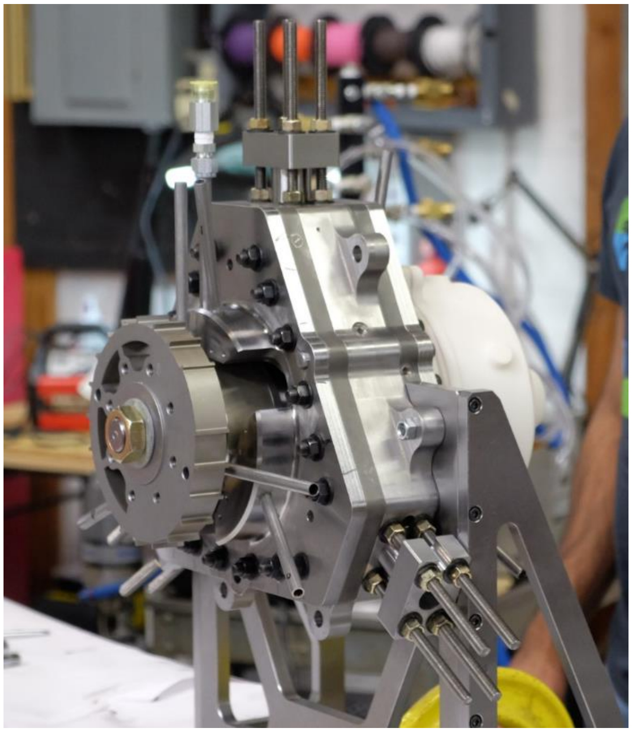

Figure 11: X4 assembly, view from Flywheel Side

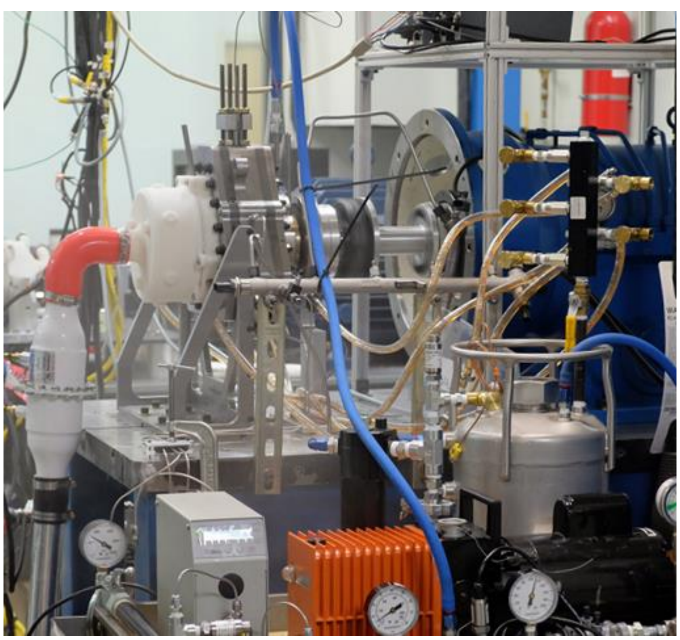

Figure 12: X4 Test Setup

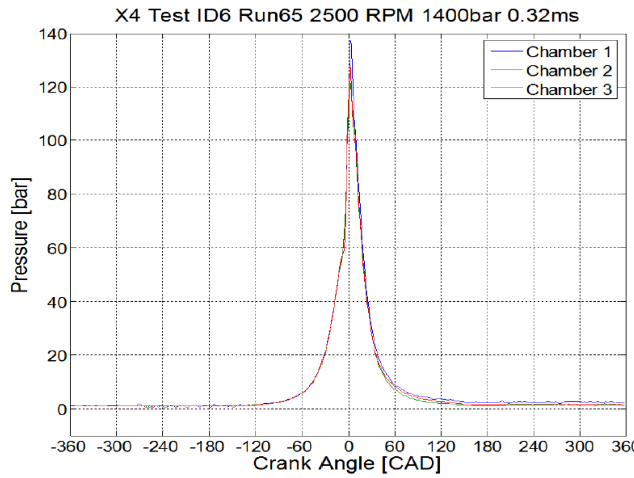

Figure 13: Highest Pressure Cycles (26:1 compression ratio, IDI combustion)

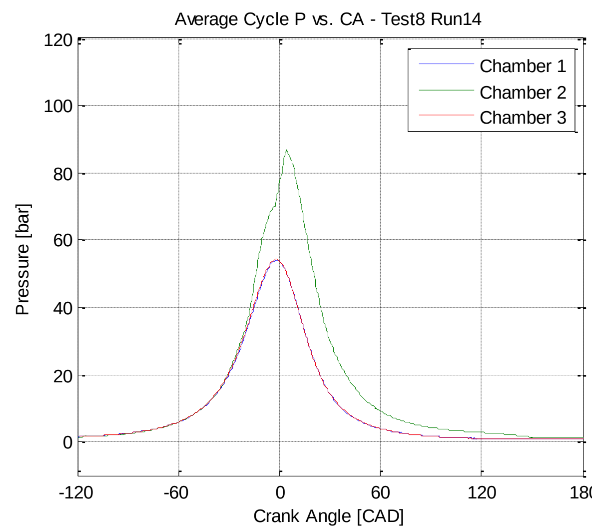

Figure 14: Example firing vs motoring traces, 20:1 compression ratio (Direct Injection). Firing trace has a first (pilot) injection at -55 and a second injection at -11 degrees after top dead center.

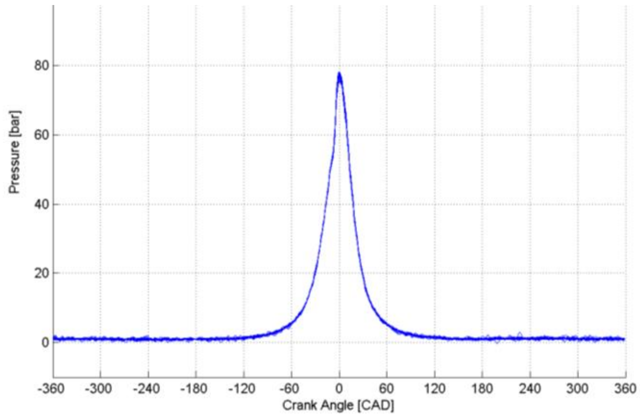

Figure 15: Example of Pressure (bar) vs. Crank Angle (deg.) of 50 consecutive firing cycles overlaid, showing COV IMEP of 0.4%. This data had early fuel injection with objective of increased cylinder pressure rather than increased IMEP.

X Mini Engine

As mentioned above, LiquidPiston has also developed a small 70cc X engine called the X Mini Diesel (XMD), shown in Figures 16 - 18. This TRL-6 engine is air cooled, and operated on spark ignition, and is therefore compatible with a variety of different fuel types. The engine has been run on gasoline, kerosene, and Jet A fuels.

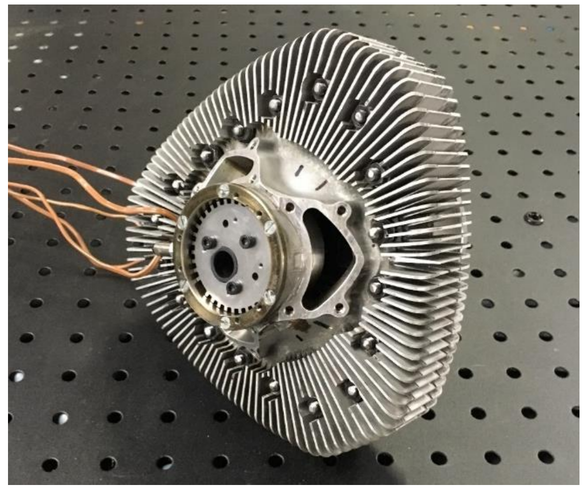

Figure 17: XMD 70cc SI engine

Specifications			
Model	X Mini Alpha Prototype	X Mini Beta Prototype	Mature Design
Type	70cc SI-HEHC cycle air-cooled rotary engine		
Fuel	Port injected, multi-fuel (Gasoline, JP8, Kerosene, etc.)		
Compression Ratio	9:1		
Power (hp) / RPM	3.0 hp / 10 k	3.6 hp / 9 k	5 hp / 14 k
Dimensions	6.6”x6.2”x5.4”= 221 in³	6.6”x6.2”x5.4”= 221 in³	6”x6”x5”= 180 in³
Dry Weight ++	5 lb.	4.5 lb.	4 lb.
Peak Efficiency SFC (g/kW-hr)	18% 460 g/kWh	22% 378 g/kWh	25% 333 g/kWh
Specific Power	.6 hp/lb.	` .8 hp/lb.	1.2 hp / lb.
Time between overhaul	30+ hours	150 hours	1000 hours

++Engine core, excluding fuel / ignition / cooling systems

X Mini Engine

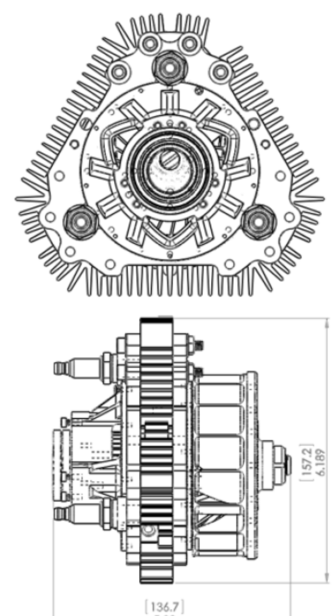

Figure 16: X Mini engine specifications. Alpha prototype = today; Beta prototype = near term target; compared with Mature design targets

Figure 18: X Mini engine powered go-kart (small vehicle demo)

Applications

The X engine is scalable, from a few hp, up to a thousand hp, and applications are generally similar to piston engines. The engine could be used, for example, for primary propulsion (Figure 18) or for hybrid electric power or range extension of an electric vehicle (see e.g. Figure 19).

A unique feature of rotary engines, including the X engine, is the ability to run at high speed, with little to no vibration, while maintaining high volumetric efficiency, due to a lack of valves. This means that more power can be attained from smaller displacement, and makes these engines especially interesting for applications where power is more valuable than torque. For example, the 'X' engine, at approximately 1 hp/lb is about 5-10 times lighter and smaller than comparable piston engines in terms of power. The torque advantage of the X engine, which is a function of {volume x vol. efficiency x brake efficiency}, is not dependent on RPM, and therefore the "specific torque" is only 2-3 times better than a piston engine. Given the particular advantage in power, this makes the engine particularly interesting for generating electric power.

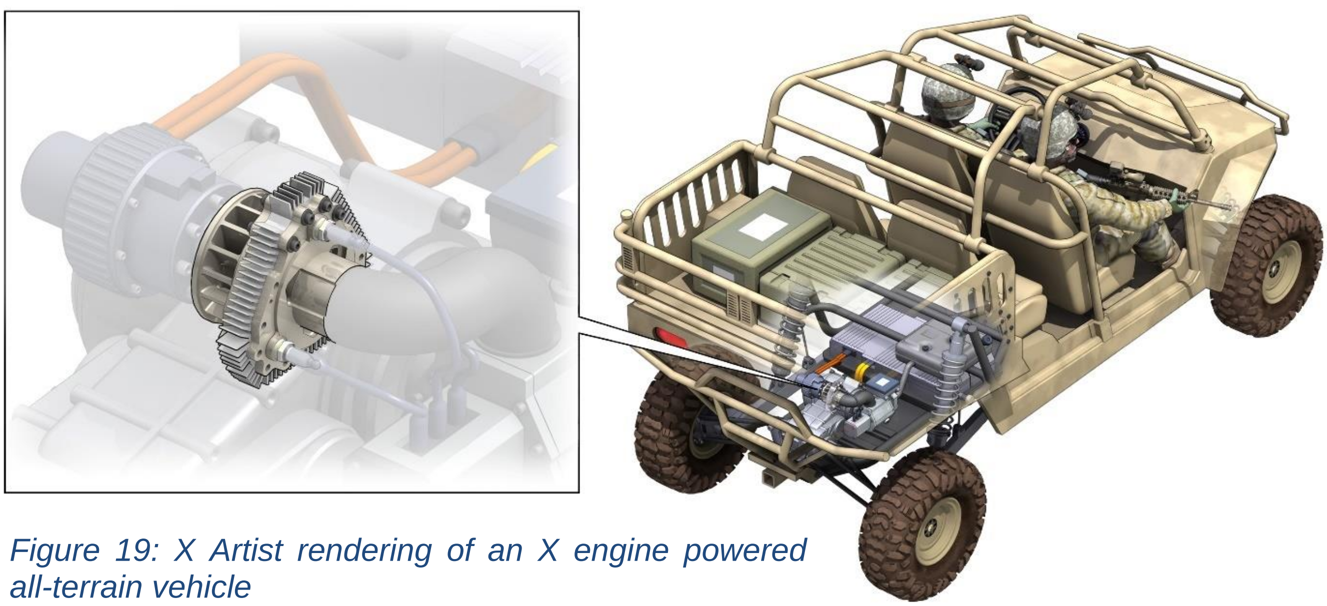

Figure 19: X Artist rendering of an X engine powered all-terrain vehicle

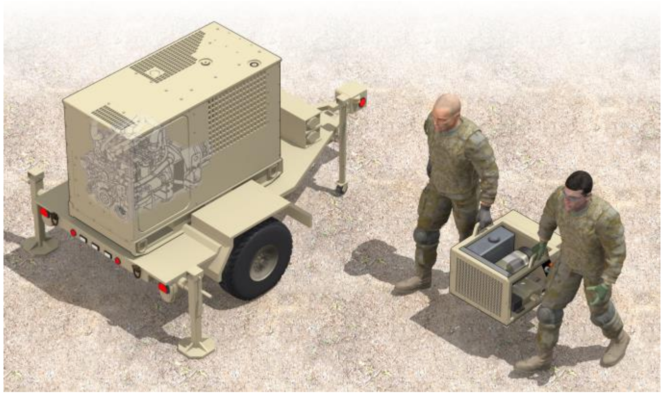

Figure 20: Artist depiction of (Left): 30 kW AMMPS Generator, which weighs 2215 lbs., vs (Right): a 30 kW generator that weighs 150 lbs., based on the X4 engine.

Further leveraging the lightweight aspect of the X engine, consider that alternators become smaller, lighter, and more efficient when operated at higher speed. The X engine, operating at high speed, can therefore be coupled with extremely lightweight and efficient alternators, making an overall electrical power generation system compact, lightweight, and efficient. Such a system can be used for hybrid electric power / range extension, allowing the use of smaller batteries and offering ability to rapidly refuel the system (as opposed to a purely electrical power supply, in which a battery would take a long time to charge); or as a mobile power generator for expeditionary applications (see Figure 20).

While batteries are improving on average several percentage points each year, consider that even today's best batteries, e.g. Tesla's Model 3 battery pack, offers specific energy of only 168 Wh/kg. This compares to Diesel fuel, which has a specific energy of 13,762 Wh/kg, a difference of 82-fold. A hybrid electric power system based on the X engine therefore combines the advantages of 1) a compact, and efficient engine architecture; 2) a high speed alternator that is compact and efficient; and 3) leveraging fuel that has very high specific energy content, compared to battery-only solutions.

A small 2 kWe hybrid electric power system is currently under development for the M777 Howitzer, under funding from the Army under the Rapid Innovation Fund by PM-TAS (see Figure 21). The engine has been demonstrated as a generator in "breadboard" configuration (Figure 22, Page 12), and is being matured to TRL 6+ under the Rapid Innovation Fund program.

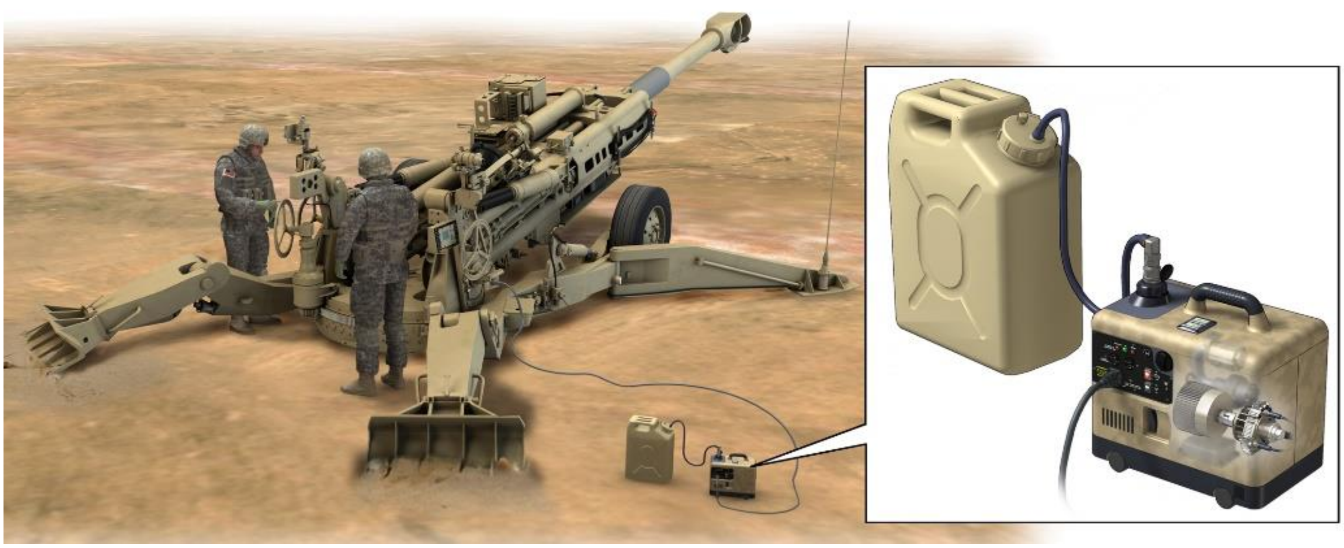

Figure 21: Artist Rendering of Compact Artillery Power System (CAPS), hybrid electric power generator for M777 Howitzer

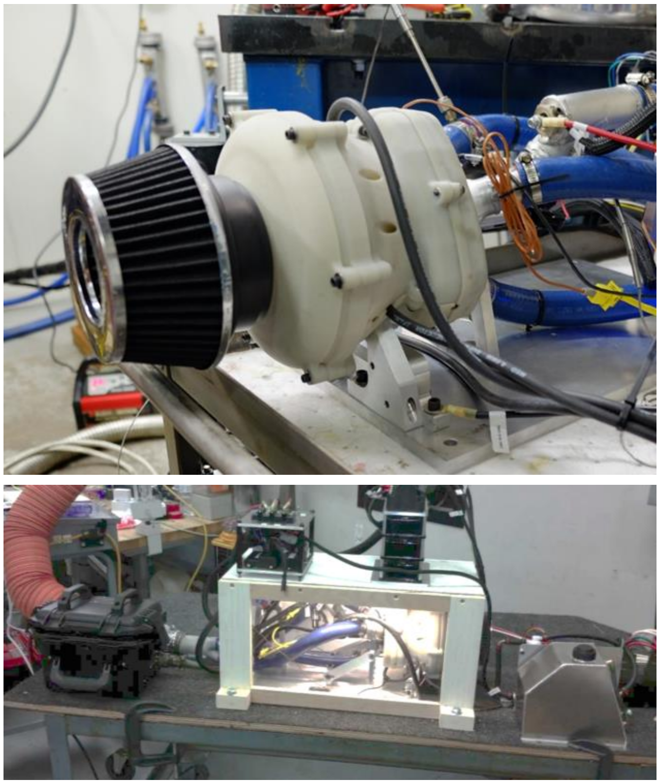

Figure 22: 2kW X Mini Diesel (XMD) engine (Top), inserted into a Generator "Breadboard" (Bottom)

Conclusions

This paper presented the rotary X engine and HEHC cycle, especially focusing on a new 30 kW compression ignition version of the engine that is currently under development. Preliminary results demonstrate the X4 platform is capable of operating with compression ignition on Diesel fuel. Future work will include optimizing the power and efficiency of the engine, addition of a cooling system, and optimizing the packaging of the engine to achieve 1 hp/lb. A smaller spark ignited (heavy fueled / multi-fueled) engine, was also presented, including current status of integrating the engine into a hybrid electric power supply for the M777.

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Definitions/Abbreviations

CI	compression ignition
SI	spark ignition
HEHC	High Efficiency Hybrid Cycle
E	eccentricity
Rr	roller radius
R	radius
PCP	peak cylinder pressure
IDI	indirect injection
DI	direct injection
TDC	top dead center
DARPA	Defense Advanced Research Projects Agency
COV	coefficient of variation
IMEP	indicated mean effective pressure

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