Development of a Small Rotary SI/CI Combustion Engine

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Abstract

This paper describes the development of small rotary internal combustion engines developed to operate on the High Efficiency Hybrid Cycle (HEHC). The cycle, which combines high compression ratio (CR), constant-volume (isochoric) combustion, and overexpansion, has a theoretical efficiency of 75% using air-standard assumptions and first-law analysis. This innovative rotary engine architecture shows a potential indicated efficiency of 60% and brake efficiency of >50%. As this engine does not have poppet valves and the gas is fully expanded before the exhaust stroke starts, the engine has potential to be quiet. Similar to the Wankel rotary engine, the 'X' engine has only two primary moving parts - a shaft and rotor, resulting in compact size and offering low-vibration operation. Unlike the Wankel, however, the X engine is uniquely configured to adopt the HEHC cycle and its associated efficiency and low-noise benefits. The result is an engine which is compact, lightweight, low-vibration, quiet, and fuel-efficient.

Two prototype engines are discussed. The first engine is the larger X1 engine (70hp), which operates on the HEHC with compression-ignition (CI) of diesel fuel. A second engine, the XMv3, is a scaled down X engine (70cc / 3HP) which operates with spark-ignition (SI) of gasoline fuel. Scaling down the engine presented unique challenges, but many of the important features of the X engine and HEHC cycle were captured. Preliminary experimental results including firing analysis are presented for both engines. Further tuning and optimization is currently underway to fully exploit the advantages of HEHC with the X architecture engines.

Introduction

The internal combustion engine enjoys widespread use as an inexpensive and reliable power conversion system. While piston engines date back 150 years, various alternative engine architectures and cycles have been considered. Today's small piston engines can be inexpensive, and have suitable reliability to serve a variety of applications including mobile propulsive power for scooters, motorcycles, all-terrain vehicles (ATVs), boats, and small aircraft including unmanned aircraft vehicles (UAVs). Small engines are also used for mobile power generation, including electric or auxiliary power, and to directly provide mechanical power for lawn and garden equipment. While piston engines enjoy prolific use, their efficiency is remarkably low. Literature indicates peak engine efficiencies of 15-18% for 30cc 1hp 4-stroke, and average part-load efficiency significantly lower [1].

The rotary engine has some advantages that make it a formidable contender for some of the markets currently served by reciprocating engines. The piston in a 4-stroke reciprocating engine momentarily comes to rest four times per cycle as its direction of motion changes. In contrast, the moving parts in a rotary engine are in continuous unidirectional rotational motion. High power density, smooth operation, simple design, low vibration, compact size, and lightweight architecture are a few of the benefits [2]. However, the rotary type engine has some drawbacks. A major problem of the Wankel rotary engine is that it does not measure up to the fuel economy of reciprocating engines in part due to the long combustion chamber shape and low compression ratio (CR). The gas sealing of the rotary engine, such as apex seals and side seals, are less efficient and durable due to poor lubrication compared to piston rings. However, these drawbacks have been steadily improved for gasoline spark-ignited (SI) rotary engines [3, 4, 5, and 6]. Recently, the rotary engine has become more attractive to applications where the typical merits of rotary engines are becoming more important (such as size, efficiency, and power density).

The LiquidPiston X Engine architecture is a rotary engine embodiment similar in some aspects to the Wankel-type engine, however, several differences lead to advantages. Merits of the X engine are described, and a comparison to the Wankel engine is provided in this paper. A primary motivation for development of the new engine architecture is the ability to embody an optimized 4-stroke cycle, dubbed the High Efficiency Hybrid Cycle (HEHC), which can change the operation of internal combustion engines fundamentally [7, 8, and 9].

The combination of this cycle's features is expected to achieve higher thermodynamic efficiency - analytical modeling studies have previously indicated that the HEHC is able to reach 50%+ brake efficiency (75% ideal cycle efficiency) with CR of 18 [10, 11, and 12].

The company has been working on new engine architectures, with a focus on rotary engines, in order to realize the HEHC cycle. The X engine platform has been developed after several years of research and development efforts. The X engine is simple, and has no reciprocating parts - features common to the conventional rotary engines. However, in contrast, the X engine has a higher CR, and a stationary conical/spherical combustion chamber suitable for direct injection (DI) and CI. As with the Atkinson or Miller cycles, the X engine takes advantage of over-expansion. This is done simply by changing the locations of intake and exhaust ports asymmetrically which allows for the extraction of more energy during the expansion stroke. Further, a power stroke of the X engine occurs 3 times per rotor revolution resulting in a high power density [12]. LiquidPiston has developed initial prototypes to demonstrate the principles of the engine, including the X1, 1370 cc (70HP) and the XMv3, 70cc (3HP).

The paper is organized as follows: 1) the HEHC cycle is reviewed, and efficiency of the cycle is discussed. While the real engine is still at relatively early stages of development, the cycle serves as a primary motivation for the development of the engine. 2) the 'X' engine architecture, including its structure and operation, is described; 3) a brief discussion of Cooling strategy, and then 4) Sealing strategy are described, as these are necessary for enabling successful operation as an engine; 5) differences between the X rotary engine and the traditional Wankel rotary engine are highlighted. 6) a summary of potential benefits of the cycle and engine is presented; 7) experimental methods and 8) results describing initial experiments with the X1 (70 HP 1.3L CI engine) and XMv3 (3 HP 70cc SI engine) are presented, and 9) we conclude discussion.

High Efficiency Hybrid Cycle (HEHC)

As the name implies, the HEHC attempts to combine (hybridize) the best features of several thermodynamic cycles, including the Diesel, Otto, and Atkinson cycles to create a highly efficient engine. In its purest form, the HEHC combines the following features:

- High CR of air (e.g. Diesel cycle)
- Constant-volume (isochoric) combustion (e.g. Otto cycle)

achieved by long-duration burn, through a dwell in volume near TDC.
- Overexpansion to atmospheric pressure (E.g. Atkinson cycle)

The HEHC cycle was developed by LiquidPiston, and is patented [7,8,9]. The X architecture, later described in detail, is designed to accomplish this cycle, and is also patented [19,20]. In the Compression-Ignition (CI) version of the HEHC cycle, fresh air (without fuel) is compressed to a high CR in a chamber of the engine. Fuel is injected into the combustion chamber just prior to top dead center (TDC) and CI takes place. The majority of combustion occurs under relatively constant volume condition, achieved by having a long duration dwell in combustion chamber volume near TDC. The combustion gas then expands to a larger volume than the initial intake volume. Figure 1 indicates a much larger area encompassed by the thermodynamic curves, when compared to the diesel and Otto cycles, thus indicating higher efficiency.

The HEHC cycle can also operate with SI, albeit with lower resulting efficiencies. In this case an air fuel mixture is compressed to a lower compression ratio, similar to standard Otto cycle engines. The reduction in CR causes a reduction in efficiency compared to CI, but the dwell in combustion volume near TDC results in higher peak pressure and efficiency than piston-engines operating with SI. This is related to the slower variation of displacement in proximity to TDC than piston engines. Overexpansion further increases efficiency, similar to Atkinson cycle. The dwell in volume at TDC allows the engine to more closely achieve true constant-volume combustion (isochoric head addition), compared to a piston implementation of the Otto cycle.

The HEHC cycle is compatible with boosting techniques, primarily by addition of a supercharger. The effect will be in raising the pressure of the PV diagram. If true over-expansion to near-atmospheric pressure is achieved, a turbo charger cannot be used, but a supercharger will still work. In this paper we will focus on naturally aspirated cases.

The ideal gas standard HEHC thermodynamic model is presented for the purpose of comparison with ideal gas-standard Otto (constant volume heat addition) and Diesel (constant pressure heat addition) cycles. Figure 1 shows the qualitative comparison of the pressure-volume (P-V) diagram for each cycle. Analysis of ideal gas standard Otto and Diesel cycles is useful for theoretical purposes to illustrate trends in efficiency, and is a common discussion in most internal combustion engine textbooks. The ideal gas standard cycle makes a number of assumptions:

- Working fluid is ideal gas with constant specific heats
- Fixed mass of working fluid throughout cycle
- Combustion is modeled as heat addition to surroundings from external source at either constant volume (HEHC, Otto) or constant pressure (Diesel)
- Both compression and expansion processes are adiabatic and reversible
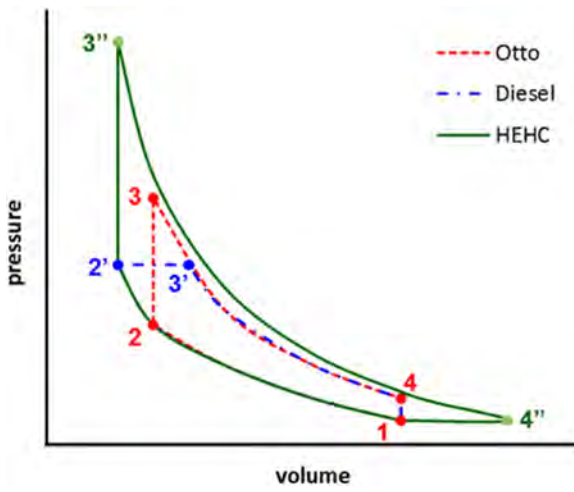- Cycle completed by heat rejection to the environment

Figure 1. p-V diagram comparing ideal air-standard cycles

Thermal efficiencies of each ideal gas cycle are explained in detail in previous papers [10, 11, 12, 13, and 14] as well as text books [15] and will not be described here. The thermal efficiencies of each cycle can be written as follows:

$$\eta_{Otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

(1)

$$\eta_{Diesel} = 1 - \left(\frac{1}{\kappa}\right)\frac{(T_4 - T_1)}{(T_{3'} - T_{2'})}$$

(2)

$$\eta_{HEHC} = 1 - \kappa \frac{(T_{4''} - T_1)}{(T_{3''} - T_{2'})}$$

(3)

where: η_{Otto}: thermal efficiency of Otto cycle

η_{Diesel}: thermal efficiency of Diesel cycle

η_{HEHC}: thermal efficiency of HEHC

κ: specific heat ratio

T: temperature

For a quantitative comparison of the cycles, the following values are chosen: the CR is 9.5 for the Otto cycle, 18.5 for HEHC and 18.5 for the Diesel cycle. The specific heat ratio of the gas is assumed to be 1.4[1]. The intake pressure (p_1) and temperature (T_1) are assumed to be 101 kPa and 300 K, respectively. The energy input during the combustion process is assumed to be 1816 kJ/kg for all three cycles. Table 1 shows a quantitative comparison of the cycles. From the analysis, the ideal thermodynamic efficiency (η) of HEHC is 38 % higher than Diesel, and 35 % higher than Otto cycle [12].

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1. The specific heat ratio depends on the mixture of gases in he chamber as well as the pressure and temperature. In real cycle simulation, this value is computed for each point in the cycle. For air-standard ideal cycle analysis, values of 1.3 to 1.4 are typically used. As long as the same value is used to compare different cycles, the trends in efficiency are shown.

Table 1. Comparison of P, T, and η for three cycles

	Cycle Point	P [kPa]	η
Otto cycle	1	101	0.59
	2	1867	
	3	9987	from Eq.(1)
	4	535	
Diesel Cycle	1	101	0.58
	2'	4439	
	3'	4439	from Eq.(2)
	4	555	
HEHC	1	101	0.75
	2'	4439	
	3"	20247	from Eq.(3)
	4"	101	

The actual efficiency for each cycle will be lower than its ideal gas standard cycle. Deviations from the ideal cycle include leakage (blow-by), heat transfer, friction, other mechanical losses, pumping losses, and specific heat and gas properties that are a function of pressure, temperature and cylinder contents (air-fuel mixture).

A 0-dimensional thermodynamics model of the HEHC and X architecture was constructed using fuel-air cycle equations adapted from [15]. The 0D model further involves the use of sub-models to describe the working chambers and ports, the thermodynamic properties of the unburned and burned gases, the mass and energy transfers across the system boundaries and the combustion process. Heat transfer is modeled using Woschni's correlations and mass transfer, including leakage, is modeled using one-dimensional compressible flow equations for flow through an orifice. Combustion (heat addition) is applied via Wiebe functions. A thorough description of the model is beyond the scope of this paper, but the results of the 0D analysis reveals that high efficiency (60% net indicated) is possible with reasonable assumptions for CR, leakage, heat transfer, and flow coefficients selected from literature. An example pressure trace and P-V diagram from simulation is shown in Figure 2 and Figure 3. In the results section, we show simulated pressure vs actual measured pressure in Figure 11.
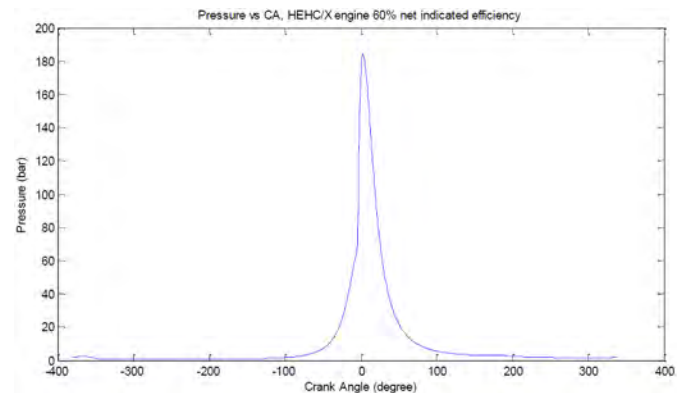

Figure 2. Firing pressure trace from the 0D model, X1, full load, 1800rpm, and indicated efficiency 60%, peak pressure of 190bar
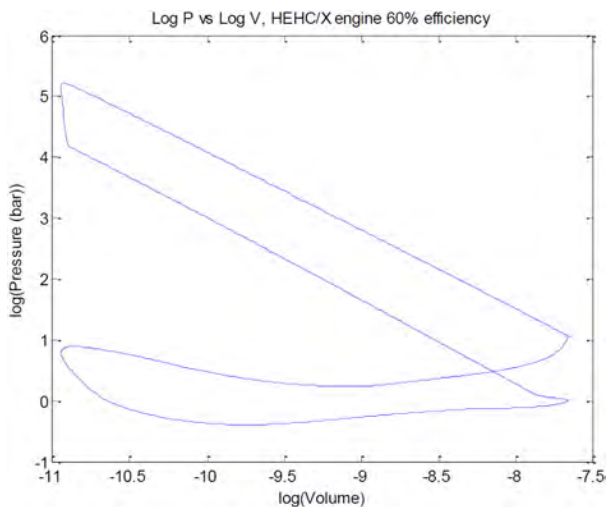
Figure 3. Firing P-V diagram from the 0D model, full load, 1800rpm, and indicated efficiency of 60%

Engine Structure and Operation

Figure 4 shows an internal view of the X1 prototype (1.35L CI/diesel) engine. An animation of an X engine and associated HEHC cycle is available to clearly show the engine operation and cycle [17]. A single-rotor X engine consists of a rotor, housing, eccentric shaft, counter balance weight, and intake/exhaust side plates and/or covers. As shown in the figure, it has a simple layout, with only two rotating parts. The X1 architecture (70hp) operates on CI. The smaller engine of the family, the XMv3 (70cc / 3HP), which operates on the modified HEHC cycle for SI operation, is a scaled down version of the X1. The description of the operating principles and components of this engine is nearly the same.

For air-standard ideal cycle analysis, values of 1.3 to 1.4 are typically used. As long as the same value is used to compare different cycles, the trends in efficiency are shown.
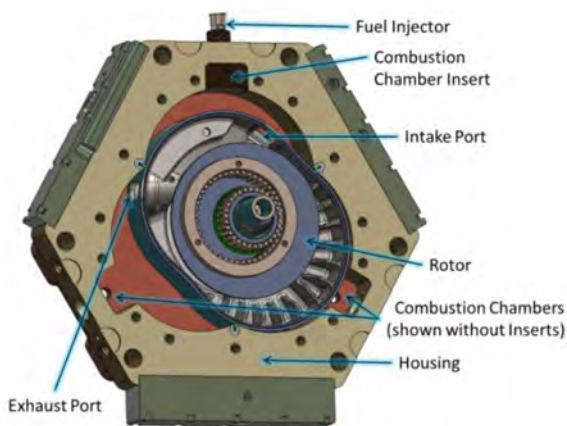

Figure 4. LiquidPiston X1 Engine view, it presents three separate combustion chambers creating 3 power strokes per revolution

Operation

The housing and rotor form three working chambers within the engine (See Figure 5). Each of these chambers successively compresses and expands as the rotor turns within it. A 4-stroke

cycle is completed within each of the three chambers, and this happens simultaneously. The processes, illustrated for the bottom-right chamber in Figure 5, include:

1. Intake,
2. Compression,
3. Combustion and Expansion, and
4. Exhaust.

The engine is ported, and gas flow is achieved by routing intake and exhaust gasses through the rotor. The X1 engine has an intake plate for one side housing, and an exhaust plate as its second side housing. Each plate has windows, allowing gas to flow from the environment (through a manifold), into a channel within the rotor.

Intake
The intake plate has three windows. Fresh air flows axially from the intake manifold, through the window. At least one of the three windows is always engaged with the intake channel within the rotor. Thus, the intake channel of the rotor is constantly supplied with fresh air from the intake manifold. The intake channel is allowed to flow gas to one of the working chambers through a port on the radial surface of the rotor. As the rotor turns, the port is moving, and is only exposed to one of the chambers at a given time. When the intake process starts, the intake port of the rotor is first exposed to a given chamber when its volume is minimal.

The location of the intake port determines the opening and closing timing of the intake. By locating the intake port so that it either closes early or late, the final intake volume will be smaller than the maximum expansion volume of the chamber, so this simple geometric change can be used to achieve over-expansion in the engine.

Exhaust
The exhaust process is similar to the intake process, but happens in reverse. The exhaust plate has three windows which allow axial flow of exhaust from an exhaust channel in the rotor to flow to the exhaust manifold, eventually exiting the engine. At all times, at least one of the three windows is engaged with the exhaust channel in the rotor, allowing unobstructed flow. Following the expansion process within the chamber, as the rotor turns, an exhaust port on the radial surface of the rotor opens to the chamber. The port opens when volume is greatest. The rotor motion causes the volume to decrease, thereby causing a flow of exhaust gasses from the chamber, through the exhaust port in the rotor, through the exhaust channel in the rotor, and finally to the exhaust manifold as the gas passes through the exhaust plate windows.

Compression
Following the Intake stroke, when the intake port of the rotor closes in one of the working chambers, the rotor motion will cause the volume in the chamber to decrease, causing compression of the gas. Eventually, at TDC, the working chamber volume will reach a minimum, and most of the gas is

displaced into a constant volume combustion chamber, which is essentially a recess within the housing. A high CR is achieved by having a small combustion chamber.

Combustion

The compression phase is followed by combustion and expansion. When the rotor approaches TDC, in X1, fuel is injected using a high pressure common rail fuel injection system. For our prototype development, we utilized automotive off-the-shelf Bosch pumps and injectors. Near TDC, the arc of the housing matches the arc of the rotor, and the volume remains approximately constant over ~20 degrees of rotor rotation. During this period, most of the gas is in the combustion chamber. There is plenty of time to inject fuel, and the engine can mix and burn a majority of the fuel under constant volume conditions, before the expansion begins. In

the XMv3 engine, the fuel and air is premixed, and a lower CR is utilized with SI. The engine is still expected to benefit from the long duration constant-volume combustion process.

Expansion

Finally, as the rotor continues turning, the volume is expanded. The gas pressure pushes on the rotor which translates to brake torque. The expansion process continues until the maximal expansion volume is reached, and the exhaust port of the rotor opens. If the intake and exhaust ports are asymmetrically located, the effective expansion ratio can be significantly higher than the compression ratio, allowing more energy of the gas to be converted into useful work. This Over-expansion also has the effect of lowering average temperature in the chamber, reducing cooling needs. Additionally, the exhaust pressure can be near atmospheric - so it has lower temperature and lower pressure than traditional engine exhaust.
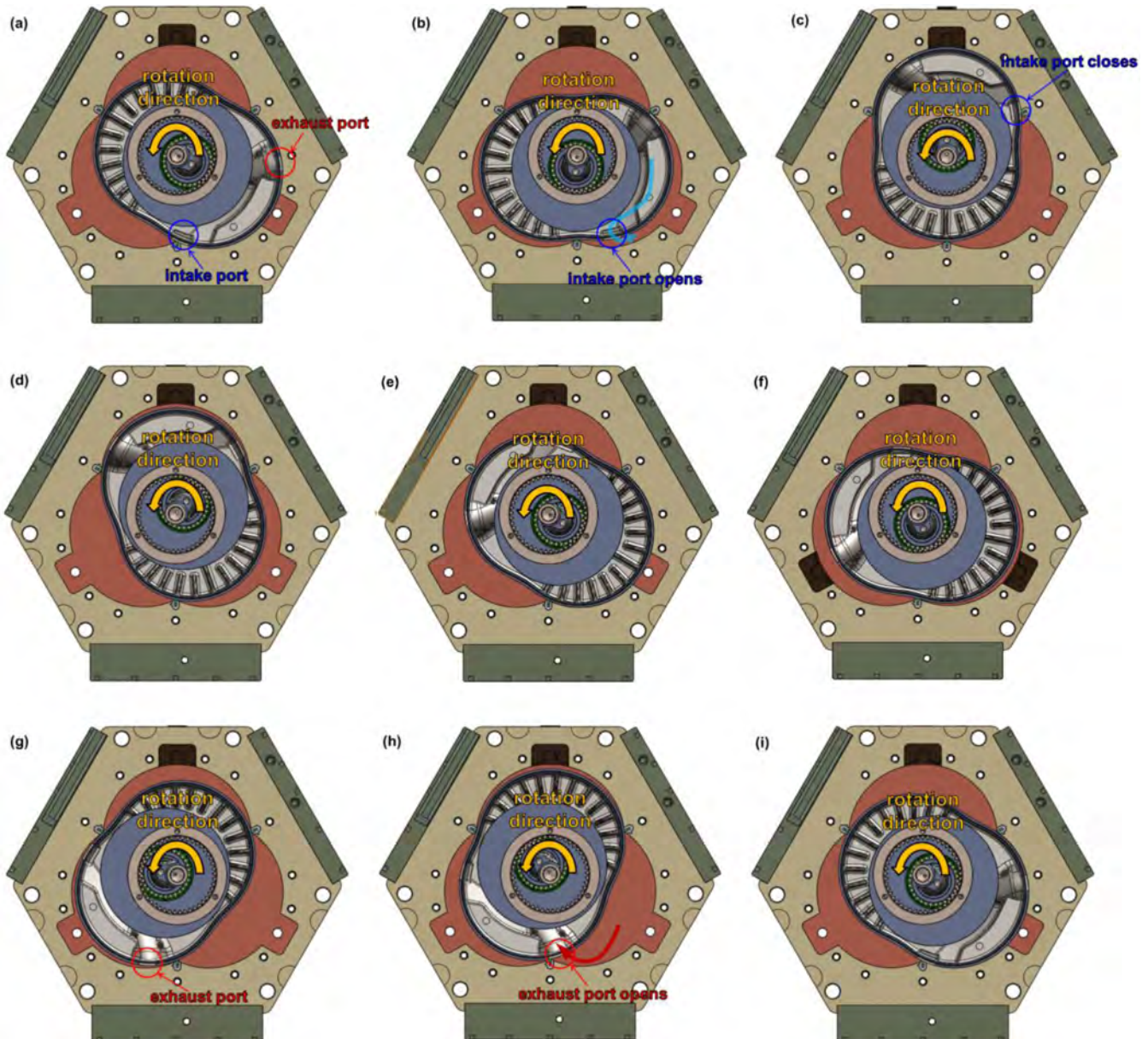

Figure 5. Operation of X1 engine: (a) just before intake port opens, (b) intake stroke starts, (c) intake stroke completes, (d) compression stroke starts, (e) compression stroke completes and combustion occurs, (f) expansion stroke starts, (g) expansion stroke completes, (h) exhaust stroke starts, and (i) exhaust stroke completes

Sealing

The rotor seals in rotary engines perform the same duties as the piston rings in a reciprocating engine because they provide a seal for the combustion gases. Figure 6 shows the main gas sealing components of the X1 engine. These consist of a face seal on each side of the rotor, three apex seals, and stationary O-rings in the housing. Face seals are installed into the grooves on the rotor face with springs. Two-piece apex seals are used in the X1 engine for better gas sealing performance compared to one-piece apex seals. While dimensionally different, the seals are similar to Mazda RX-8 seals.
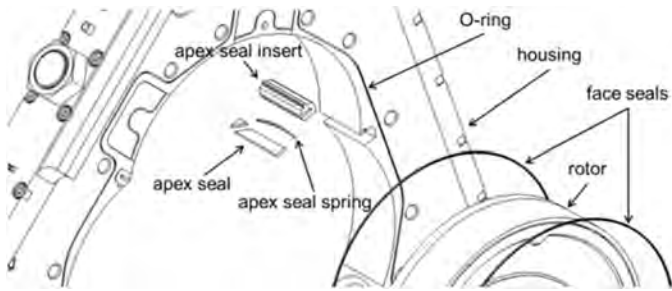
Figure 6. Main gas sealing components of X1 engine

The gas seals are initially loaded with spring force, but in operation, the gas forces acting on the seals far exceed the spring forces. Since apex seals of a conventional rotary engine are inserted in radial slots at each rotor apex, the significant portion of the force that works on the apex seal is centrifugal force [2], which is one of the major constraints for designing apex seals in conventional rotary engines. However, there is no centrifugal force on apex seals of the X1 engine because the apex seals are inserted at the housing which is a stationary part. This also changes the lubrication strategy, as stationary apex seals can be lubricated with small quantity of oil metered directly at the seal location through the stationary main housing or side housings.

Cooling

The over-expansion process of HEHC reduces the average cylinder temperature, and exhaust is cooler. On the other hand, higher combustion temperatures are reached during constant volume combustion. It should be noted that even with constant-volume combustion, peak temperatures and pressures in the naturally aspirated HEHC case are lower than a turbo-charged diesel engine. Cooling is necessary to prevent overheating of components and premature wear, especially due to degradation of the oil film at the seal interfaces. Unlike the Wankel-type engine, combustion is spread across three chambers of the housing, and each of these chambers also sees a cool intake stroke, so heating issues of the housing are expected to be less than heating issues of the rotor. Traditional cooling strategies, for example water jacket in the housing and

oil cooling via passages in the rotor, can be utilized. The initial X1 prototype was run without any cooling, as this prototype was designed only to demonstrate the basic operation of the cycle. The XMv3 engine utilizes an air cooling strategy, with air blown axially through the rotor across a plurality of ribs. Computational Fluid Dynamics (CFD) simulations showed that at 10,000 rpm and full load with a heat rejection of 55% of LHV of fuel, the rotor temperature was kept below 200C (max lubricating oil temperature) with a flow rate of 130CFM.

Skip-cycling is a control strategy which may be uniquely suitable to rotary compression-ignition engines [10]. If such control is utilized, the non-firing cycles will have an additional cooling effect on the engine.

Differences from Wankel

The X engine shares some advantages of the rotary engine architecture similar to the Wankel, for example the simplicity of having two major moving parts; the low-vibration / purely balanced rotor; and the advantage of not having any oscillating masses, thereby reducing need for flywheel and making the engine more responsive (see Figure 7). However, there are significant differences as well:

1. The thermodynamic cycle of the Wankel engine is the Otto cycle, but the implementation is inferior to the traditional piston engine; the X engine, on the other hand, is optimized to work on the HEHC cycle with the advantages of that cycle, either CI or SI;

2. The 'X' engine compresses all of the gas into an isolated combustion chamber. This combustion chamber can be small, leading to a higher CR than is possible with the Wankel engine.

3. The isolated combustion chamber can have an approximately spherical geometry, e.g., it will have a low surface area to volume ratio. Given that engines lose a large part of their heat during the combustion process, the 'X' engine will have a favorable surface area during this part of the cycle, leading to lesser heat transfer losses. Although during the expansion the surface area could be greater than a regular piston engine with higher heat loss, but the majority of heat transfer takes place during the combustion and the beginning of the expansion stroke

4. The X engine, operating like an inverted-Wankel engine, has apex seals which are stationary in the housing, whereas the apex seals in the Wankel engine are in the rotor. Thus, the X engine does not have centrifugal loading of the seals and allows direct metering of lubrication to the seals. This approach has been demonstrated in the lab to significantly reduce wear of the engine, while supplying 10x less oil to the engine compared to Wankel engines.
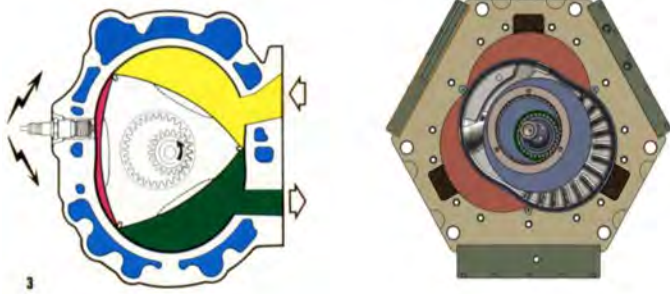
Wankel Engine
- Low Compression ratio
- No constant-volume combustion
- No over-expansion

LPI X1 Engine
- High Compression ratio
- Constant-volume combustion
- Over-expansion

Figure 7. Comparison of LiquidPiston X architecture and Wankel

Potential Benefits

Given the early stage of development of these engines, many of the benefits outlined below require more work to be verified, but the potential benefits are presented here with associated supporting logic. Initial results from testing will be discussed in the Results section below.

Efficiency

The primary advantage of the X engine is that it is optimized to work on the HEHC cycle, taking advantage of a high CR, low surface area during combustion, constant-volume/long duration combustion, and over-expansion, and skip-firing control to maintain high efficiency even at low-loads.

Size and Weight

A single rotor forms three chambers within the housing. For each rotation of the rotor, three 4-stroke cycles are executed simultaneously, leading to 3 combustions per revolution of the rotor. The rotor is geared 3:2 with the shaft, leading to 1.5 combustion events per revolution of the shaft. Thus, the compact engine with 2 moving parts behaves like a 3-cylinder 4-stroke diesel engine (See Figure 8).

Figure 8. size comparison of a 40hp X engine with a typical naturally aspirated industrial diesel engine Isuzu D201 (35hp)

Low Vibration

The rotor is purely balanced on its center of rotation. The rotor spins on an eccentric shaft, so it can be balanced by oppositely mounted counter balances on the shaft. In X1, this is done by having 2 counter-balances, one on each side of the engine. In XMv3, the bearings were weighted to act as counter balances. The vibration forces and moments of the XMv3 was analyzed in comparison to a 30cc commercial lawn and garden 4-stroke engine (single cylinder), and are compared in Figure 9. The vibrational forces are reduced by two orders of magnitude.

Multi-Fuel Capability

A variety of strategies exist to enable multi-fuel capability in the X engine. The engine couples a high CR with long-duration burn process. A variety of fuels can be accommodated under CI if a suitable fuel injector is capable of supplying the variety of fuels. The engine can also utilize combustion chamber inserts, which can be used to quickly switch out the chambers, thereby varying the CR, combustion chamber geometry, and fuel injectors which are coupled to the combustion chamber. Alternatively, a single combustion chamber can house a small piston to vary the CR on the fly, as well as also hosting a glow plug, spark plug, and fuel injector.
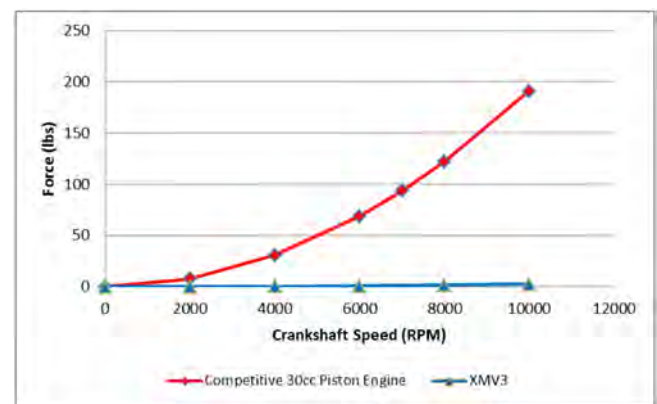

Figure 9. Modeled v brational forces of single-cylinder 30cc piston engine vs XMv3 rotary engine

Noise

The four primary causes of noise in a 4-stroke diesel engine are [21]:

1. rapid pressure rise during combustion;
2. poppet valves causing metal-to-metal contact as the valves open and close;
3. the rapid pressure drop when the exhaust gasses in the cylinder are open to atmosphere; and
4. Piston slap causes a metal-to-metal contact between the piston and the cylinder bore.

The HEHC cycle utilizes an over-expansion process, in which the gas may be expanded all the way until atmospheric pressure is reached, significantly reducing exhaust noise. X engines in the lab have been run without mufflers (open headers), and little difference in exhaust noise is heard whether the engine is motoring or firing. Further, the X engine

does not have poppet valve noise or piston slap. Combustion noise can be further reduced by introducing fuel over a longer period of time (either injecting a low rate for a longer duration, or having multiple injections). This is allowed by the long dwell time at TDC volume. LPI has not formally measured noise levels, as the dyno and supporting components are in some cases louder than the engine itself. Anecdotally, however, it appears the X engine is quiet, as firing noise is comparable to motoring.

Cost and Durability

Notably, the core engine has only five primary parts, of which two are moving parts. The low part count is expected to reduce manufacturing costs, especially in labor to assemble the engine. Initial prototypes were designed for manufacture primarily with CNC milling, and little consideration was given to higher volume casting / manufacturing techniques. This is left for future work.

Wankel engines have a reputation in aviation for reliability - in the unlikely event of engine failure, it is typically a slow process, where the engine makes less power over time, whereas piston engines have been known to catastrophically fail. The general simplicity of the engine lends itself to durability as there are fewer parts to break, and the engine is easier to service. The primary wear component in the X engine, similar to the Wankel Rotary, is the apex seals. However, unlike the Wankel engine, the X engine apex seals are stationary, and located in the housing. These seals may be built to be serviceable without complete engine disassembly. Furthermore, the unique direct lubrication strategy is expected to be tribologically favorable over the Wankel, further reducing wear of sealing components. Initial X engine prototypes have only undergone initial testing, and significant work remains to prove the long-term durability of the engine. Thermal management including maintaining a good oil-film for all sliding (including sealing) surfaces in the engine will be critical, but similar issues have been largely addressed in commercial rotary engines.

Thermal Signature

As a higher efficiency cycle, the HEHC allows more energy to go to mechanical work, and less is lost as heat. The over-expansion process of the HEHC cycle reduces the exhaust temperature. The XMv3, which is air cooled, mixes cooling air with the exhaust stream, significantly reducing the exhaust gas temperature, which may be desirable in certain applications. The lower exhaust temperature may not be compatible with certain catalytic emission systems and is an important consideration for future work.

Experimental Methodology

Engine experiments were conducted at LiquidPiston's engine dynamometer test facility. Figure 10 shows an instrumented X1 prototype engine. A complete specification of the X1 and XMv3 engines is summarized in Table 2.
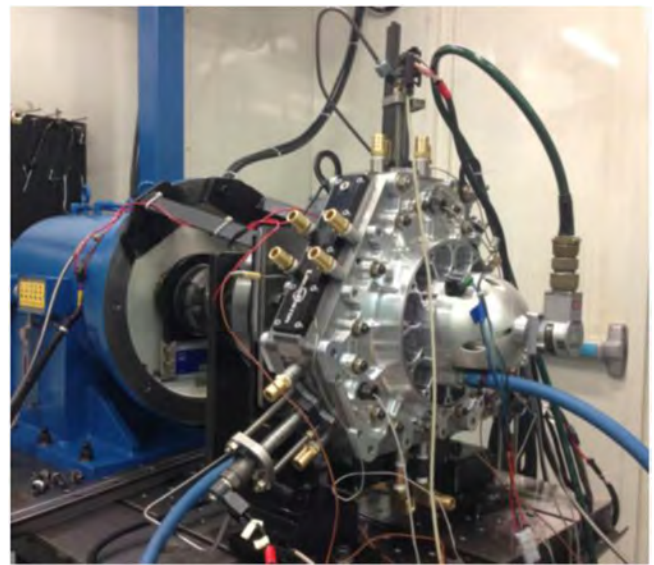

Figure 10. X1 engine setup on the dynamometer during development

The engine test cell and laboratory is operated and maintained according to the indications and recommendations of the code of federal regulation (CFR 40 part 1065). The engine was operated using a custom DRIVVEN control system capable of actuating start-of-injection (SOI) timing, injection duration, fuel rail pressure, and number of injection events. The DRIVVEN system also allows recording both high speed data (crank angle-resolved signals such as chamber pressures, injector current signals, and instantaneous engine torque, etc.) and low speed data (time-based signals such as intake air temperature, exhaust gas temperature, oil pressure, etc.) In-chamber pressure measurements were recorded from each chamber using Kistler 6052C piezoelectric pressure transducers. Typically fifty engine cycles were acquired for each condition. In order to avoid the effect of fuel characteristics on combustion, a synthetic diesel fuel with Cetane of 61 was utilized for diesel experiments. Standard pump gasoline was utilized for gasoline experiments.

Table 2. specifications of engines under development

	X1	XMv3
Ignition	Compression	Spark
Displacement [L]	1.37 (0.457 x 3)	.070 (.023x3)
CR	18:1	9:1
Expansion Ratio	27:1	11:1
Intake Charge Type	Natural Aspiration	Natural Aspiration
Fuel Injection System	Common Rail	PFI or Carburetor
Rotor [#]	1	1
Chamber [#]	3	3
Combustion Chamber	Bowl-In Shape	Recessed Dome
Cooling	None	Internal and external Air cooled
Power (estimated)	70 hp @ 7200 rpm	3 hp @ 10,000 rpm

The test cell is also equipped with California Analytical Instruments (CAI) emission bench capable to analyze CO_2, CO, HC and O_2 from the raw exhaust. This bench will be used for the finer tuning required for the engine emission compliancy calibration.

Results

X1

The X1 engine is a naturally aspirated 1.37L, single rotor, three chamber, DI diesel engine with a Bosch common rail fuel injection system. The CR of this engine is 18:1, but it can be easily changed by replacing the combustion chamber inserts located in the housing. Typically, 35 bar of compression (motoring) pressures are attained when running naturally aspirated at 1800 RPM. Net indicated efficiency of the firing engine was computed by integrating pressure trace over the entire cycle (including intake and exhaust strokes). The X1 engine has demonstrated net indicated efficiency of 33% at medium loads (Lambda = 3), at 1800 RPM. The results are achieved during the first stages of the engine development. The next stages of development regard the calibration of the engine for higher and lower loads. Unfortunately, no data are available to be presented in this paper.

The first stage of development (calibration at light-medium loads) collected a total of 10+ hours on the engine. Upon teardown, wear on gas seals is observable but not measurable. The ongoing testing at higher load and eventual durability tests will provide deeper information regarding the wear of the different components. The 0D model, calibrated to the data, indicates that the engine is sealing comparably to production rotary engines in literature. An example firing trace and comparison to the 0D model is provided in Figure 11. The 0D model has been calibrated on the test data, tuning the equivalent leak area and heat transfer parameters, and achieving r^2 of 98% indicating a close fit between model and data.

It is important to note that several solutions are under analysis to improve efficiency, such as:

• Increment of combustion efficiency;
• Advanced injection strategies;
• Reduction of pumping losses;
• Sealing improvements;

As of now, the fuel injection system is not well matched for the given combustion chambers, and significant wall-wetting is observed. The fuel spray pattern is optimized for a bowl-shaped piston. Naturally aspirated engines require fine tuning and adjustments of the intake and exhaust manifolds, and this work has yet to be done. These combined improvements represent an achievable path to the 60% efficiency goal.
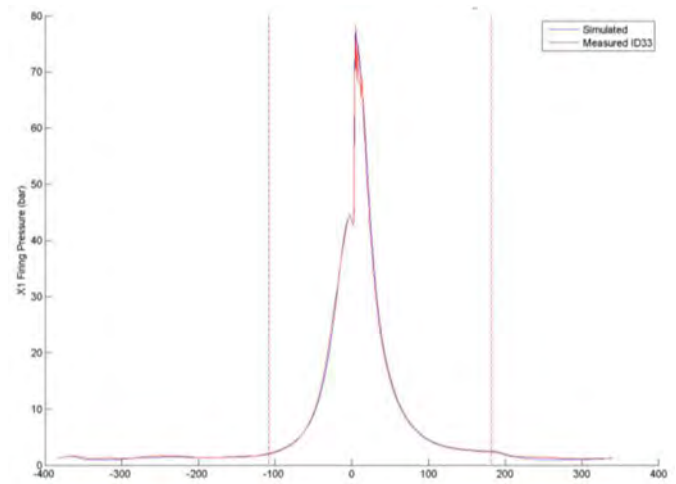

Figure 11. firing trace of X1 test results (red) and the 0D model comparison, 1800rpm, 50% load. Pressure (bar) vs CA (degrees). Red dashed lines show intake port closing (IPC) (left) and exhaust port open (EPO) (right).

XMv3

A small, 70cc engine, the XMv3, is currently undergoing initial testing by LiquidPiston. This engine (shown in Figure 12) has potential applications in the lawn and garden industry, as well as moped, watercraft, UAV, and small generator markets. Like its larger brother, the engine executes a 4-stroke HEHC cycle. As this engine is designed for lower-cost markets, the first version developed is a SI engine with a lower compression ratio of 9:1. For development, a PFI injector is used to modulate fuel into the intake, however the engine is designed to accommodate a carburetor. Three spark plugs are used to ignite the fuel air mixture (one for each chamber). The engine utilizes a near-constant volume combustion process and over-expansion of gas products to improve efficiency and reduce noise output.

Figure 12. XMv3 engine in comparison to an iPhone for scaling

The intake process described previously was for the larger X1 engine. For the 70cc XMv3 engine, which is designed to be air

cooled, the intake is configured differently, wherein intake gasses flow through the main shaft axially (see Figure 13). The side plates still have three windows, but these windows are configured for cooling air to flow through the rotor, driven by a fan on the shaft (see Figure 13 and Figure 14). Exhaust gas is allowed to enter into the rotor through the exhaust port, but is immediately diluted and blown out of the engine by the cooling fan. The intake channel is insulated from the exhaust. The long pathway for intake serves as a plenum to allow mixing of air and fuel and absorbs the intake air pulses (an effect of the early or late closing of the intake port). The interested reader can view the assembly and operation of the XMv3 in this video [18].
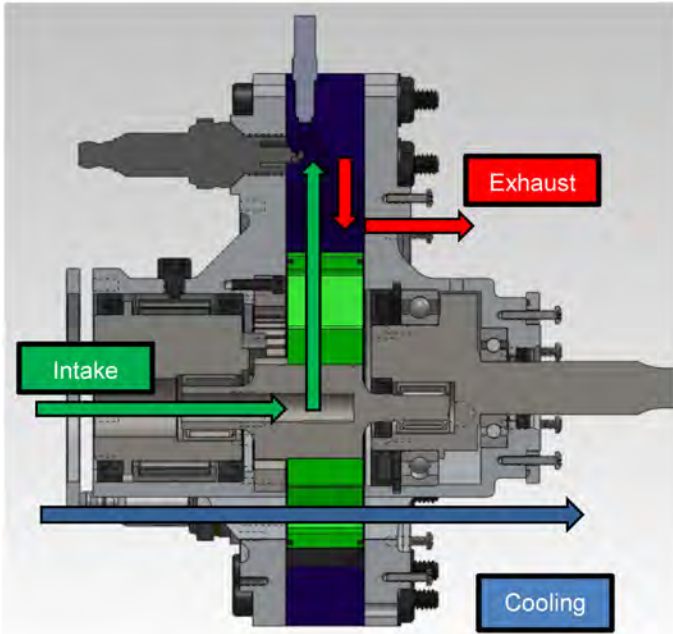
Figure 13. XMv3 section view and flow configuration
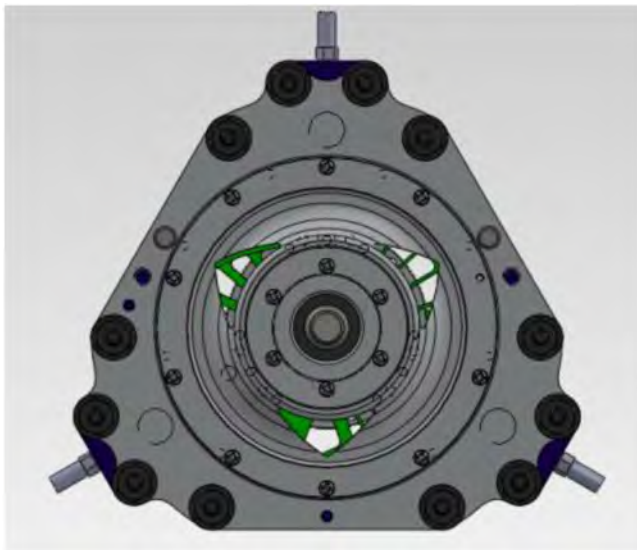
Figure 14. front view of XMv3 and opening in the plates for the internal cooling flow

Intake and exhaust port areas are shown in Figure 15. The XMV3 has approx. 40% larger intake area than a SI single cylinder 30cc 4-stroke lawn and garden engine measured as a baseline. It is important to remark that the XMv3 has three chambers with a displacement of 23cc each. A single set of intake and exhaust ports operates for all the three chambers. Furthermore, the ports open and close rapidly as they are not cam-driven. A great advantage of rotary engine is the lack of reciprocating motion. It has the potential to be relatively vibration-free, which would be especially useful in hand-held and UAV and mobile power applications, where the weight of mounting brackets and frame can be reduced. Accelerometer test results indicated a reduction of more than one order of magnitude on the shaking force.

The XMv3 engine (See Figure 12) is a proof of concept engine designed to demonstrate the scalability of the HEHC cycle and X engine, as well as operation in steady-state with air cooling. Initial motoring results show good motoring pressures (>16 bar) at higher RPMs, indicating that sealing is less of an issue, especially at higher RPM. Figure 16 shows the peak motoring pressure for XMv3 and a 30cc piston engine. Leakage problems are present for XMv3 at low speed, and improvements to sealing are in development. The steep ramp of pressure at low speed could affect the potential rope starting of this engine until leakage is reduced. At higher RPM, the pressures are notably higher than in the piston engine due to improved breathing and a slight boosting effect from the delayed intake-port closing.
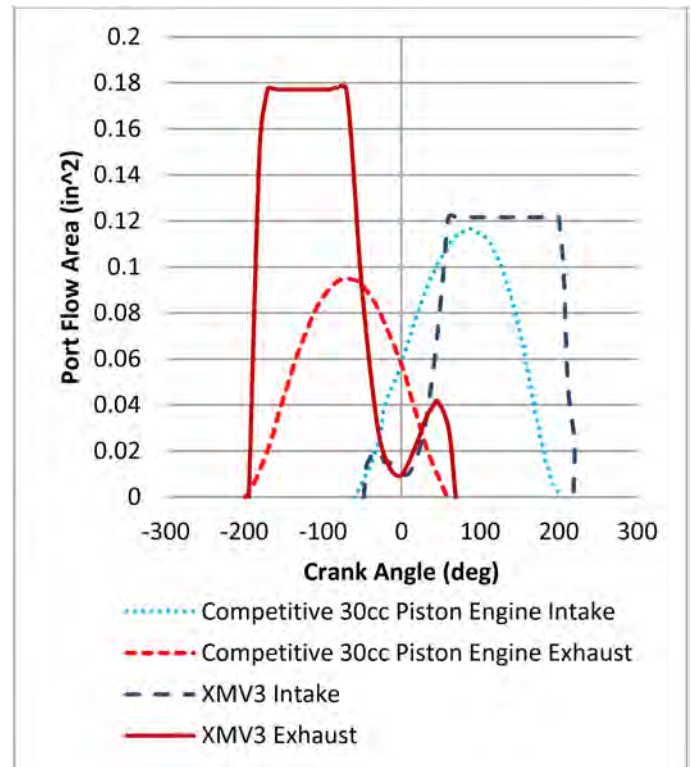

Figure 15. Intake and Exhaust porting / minimum restriction area in XMv2/3 compared to a Competitive SI single cylinder 30cc engine.
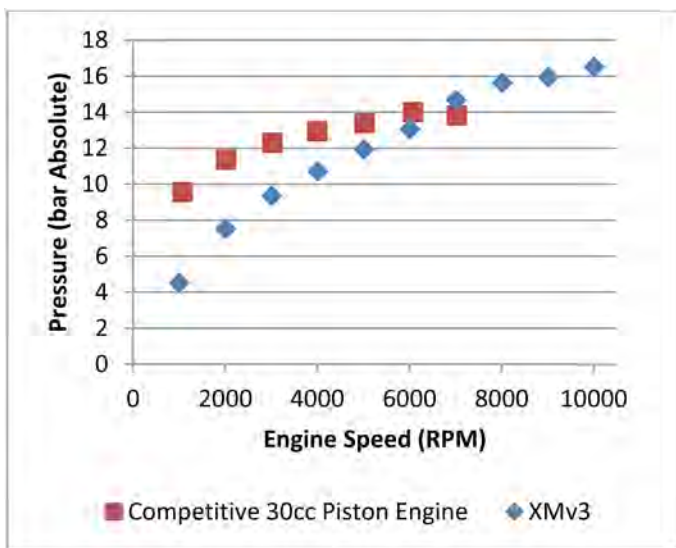
Figure 16. Peak motoring pressure for engine speed from 2000 to 7000 rpm for the XMv3 and single cylinder 30cc competitive engines. As speed increases, the effect of leakage is reduced. At 10,000 RPM the XMv3 engine has demonstrated 15-16 bar compression pressures.

The newly developed engine was fired for the first time recently, and measured net indicated power of 1.33hp at 8000rpm with 25 BTDC spark advance. Indicated efficiency is 10% (see Figure 17). With continued development, this engine, weighing 3.5 lbs., is expected to produce 3-5hp (3HP at 14% brake efficiency / 10000 RPM, 5HP at 20% brake efficiency).
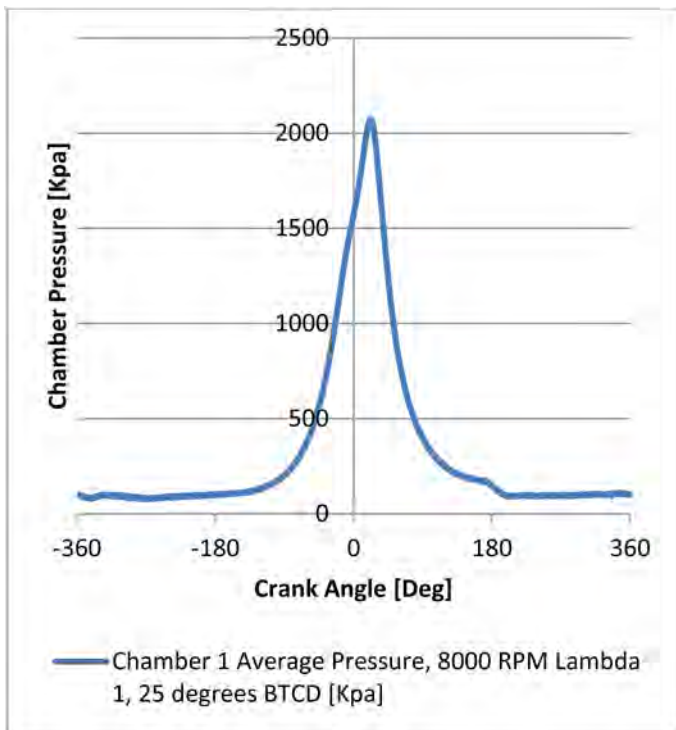
Figure 17. Firing trace for XMv3, SI, 8000 rpm full load

The need for three spark plugs could generate a problem for packaging or off-the-shelf components. The proposed ignition system for this application would rely on a micro controller or engine control unit (ECU) already implemented on small engines. The approach here is a minor modification of a standard electronic ignition. As with existing multi-cylinder

systems, this requires an angle sensor, storage capacitor, controller, and coil-on-plug per cylinder. The modification required is to change the sequencing of the plugs, which is done in software, as well as the number of plugs. Additionally, a low-voltage generator or pickup coil is needed to supply power to the ignition circuit as well as the controller. This may already be part of existing battery-less systems.

Further development of the engine includes improving sealing and volumetric efficiency, as well as finer engine calibration. The HEHC for SI will not be able to reach the 60% efficiency level. The goal for the XMv3 is to achieve high power density (3-5hp for an engine that weighs 3.5 lb) and higher efficiency (20% to 25%) than a 4-stroke SI piston engine of the same displacement, with the added advantages of low vibration and low noise.

Conclusions

In this paper we reviewed the HEHC cycle and presented model results indicating the feasibility of achieving 60% net indicated efficiency in a 1.3L 3-chamber CI design. We introduced the 'X' rotary engine architecture as a potential embodiment of this cycle. The rotary engine has more flexibility in its arrangement and can more readily execute the HEHC cycle.

The X architecture is a rotary engine which allows for high power density and low vibration operation. In addition, several other advantages of the X configuration are the reduction in number of moving parts, fuel flexibility, and easy scalability, low vibration, and low noise levels. While the engine is in early stages of development, the supporting logic was presented to discuss at least the feasibility of achieving these objectives with the X engine and HEHC cycle.

Two X engines are under development: X1 with CI HEHC, and XMv3 with SI HEHC. The X1 presents a displacement of 1.3L and at the initial development phase has demonstrated 33% indicated efficiency at medium load at 1800rpm, diesel fueled.

The smaller XMv3 presents a displacement of 70cc operating on SI, gasoline fueled. XMv3 is, at this stage, capable to provide 10% indicated efficiency and 1.4hp indicated power at 8000 rpm, full load.

Those initial results indicate that the target HEHC efficiency of 60% is not yet achieved, but they support the feasibility of development of this engine architecture and the potential for rapid improvement.

Future work and publications will focus on demonstrating efficiency and power density benefits, including running the engines at full load and in continuous (steady-state) operation over a wide range of engine speeds.

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