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AVL AUXILIARY POWER UNIT – JP-8 COMBUSTION PERFORMANCE

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ABSTRACT

This paper discusses the design and performance results of a modular designed spark ignited rotary engine Auxiliary Power Unit (APU) fueled by JP-8. This APU is intended for use onboard tactical and combat vehicles applications where packaging space and weight are at a premium. The platform is flexible and scalable to allow for application to the full portfolio of tactical and combat systems. Such an APU would enable the Army to realize significant cost savings in terms of fuel and fuel support, as well as enable enhanced operation modes of existing vehicles by enabling Silent Watch capability.

INTRODUCTION

In recent years combat and tactical vehicles have an ever increasing compliment of electronic equipment designed to support the modern warfighter with improved communication, reconnaissance and weapons capabilities. When the vehicle is in motion, the primary propulsion engine can provide such power. It is inefficient, however, to operate the prime mover at tactical idle conditions when the vehicle is not in motion simply to power electrical systems. An APU has the advantage of producing the appropriate amount of electrical power with very high efficiency because the prime mover can be sized and highly optimized for the electrical loads required.

To meet this power generation need, a power generation unit from AVL's Electric Vehicle and Range Extender (EVARE) system is adapted for combustion development using JP-8. The EVARE system consists of a rotary engine for power generation, an integrated permanent magnet electric generator, and power electronics for electrical power output. The electric generator shares a common shaft with the rotary engine to provide a compact, lightweight power unit that is extremely scalable for power generation needs.

This paper describes the EVARE unit, the adaptations made for the combustion development work, and the results of that testing.

Importance of an APU

The Department of Defense (DoD) recognizes the lack of engine efficiency during idling operation. The Defense Science Board Task Force on DoD Energy Strategy recommended an operational change for land vehicles to "Use Auxiliary Power Units (APUs), or batteries when power is needed for stationary vehicles instead of running main propulsion engines" [1].

Despite the high fuel consumption rate of combat vehicles, a study by the 2003 Marine Expeditionary Force concluded that almost 90% of the fuel was consumed by tactical wheeled vehicles (TWVs), including HMMWVs, 7-ton trucks, and the logistics vehicle system [2]. A current solicitation for the Medium Tactical Vehicle Replacement (MTVR) calls for an APU in the 6-10kW range [3] to address this concern.

Requirements for a Military APU

The system requirements for the APU have to be considered when evaluating possible solutions. From [3] some of the APU system requirements include:

- Power output from 6-10kWe for AC or DC loads.
- Fueled by JP-8.
- A variable engine speed to optimize fuel consumption.
- Target fuel consumption rate less than 1.1 gallons per hour.
- A total system weight, including auxiliary equipment, of less than 650lbs.

Design Characteristics of the AVL-APU

The AVL-APU was adapted from its originally intended use as a power unit in as an automotive range extender power unit. Typical electrical power ranges required for this application were between 10 and 50 kW, a common power range for the military applications which supported the decision to adapt it for military use. In the automotive application, weight, sound pressure, vibration and space claim were critically important due to the additions of the battery pack and electric motors and the limited space available in the BMW mini [4]. In order to improve space claim and reduce component count, the generator of the APU system was integrated to the rotary engine.

In this design, shown in Figure 1, the eccentric shaft of the rotary engine also includes the motor elements of the generator. This feature allows the generator to start the engine and eliminates the need for additional starting hardware. The combination also eliminates the mechanical connections between the power unit and generator and separate connections for the cooling system. The eliminated components save weight and complexity and result in a higher power density. Some of the characteristics of the AVL APU include:

- Lightweight, compact design. The combined weight of the rotary engine and permanent magnet generator is 29kg while the overall dimensions of this unit are approximately 240mm dia. (height and width) and 250mm in length
- The generator is a state-of-the-art permanent magnet design with an internal high voltage (320-420V), resulting in low internal currents and losses in the generator windings, a very compact package and low generator weight
- Commercial Off The Shelf (COTS) power electronics, from high voltage to low voltage (28VDC) output, share integrated cooling with engine and generator
- The rotary engine and generator uses parts and technology compatible with COTS units. These components are feasible for future high volume production in automotive, power generation and military applications.

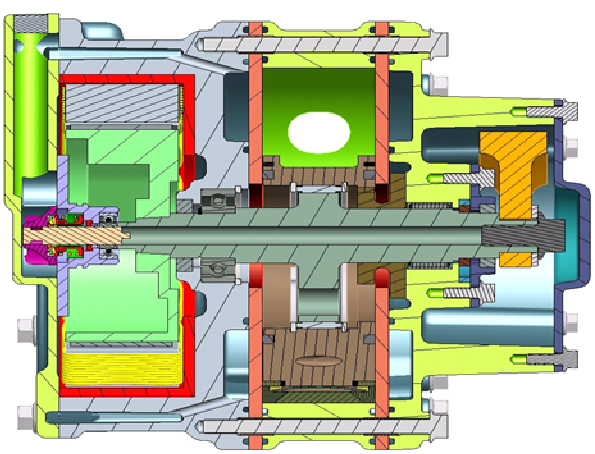

Figure 1: Layout of the APU Power Generation Unit

Design Conversions for JP-8 Fueling

For the testing and combustion development work on JP-8 rotary engine, modifications were made to the 15kWe APU base. Included in the changes are: removal of stator and power electronics, addition of a power take-off for the test bed and relocation of the fuel injector.

The purpose of this research work was to demonstrate the ability of the APU to provide power when fuelled by JP-8 and to perform combustion development to optimize the fuel consumption. Due to this focus, the electrical system, stator and power electronics, was removed as they have been proven in the range extender application. The rotor portion, including the magnets, was kept with the engine in order to maintain inertia for vibration purposes.

A power take-off was added so that there could be a direct link to the engine dynamometer for torque measurement. The modifications were made on the timing wheel side of the APU, opposite the generator. This design is shown in Figure 2.

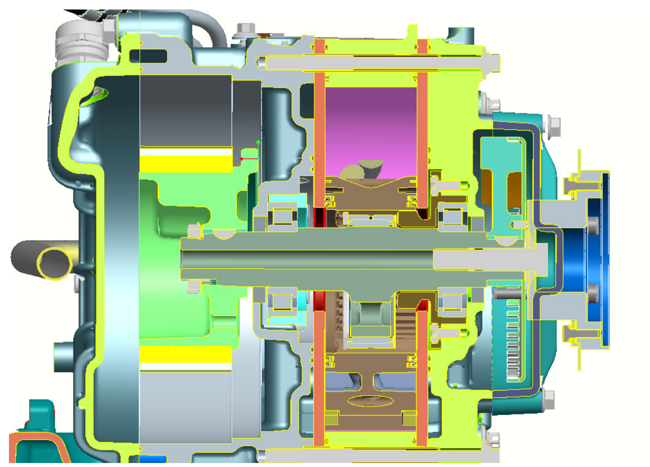

Figure 2: Modified Layout to Include the Power Take-off

The fuel injector for JP-8 was moved to allow a direct spray into the combustion chamber. The direct spray was an important consideration because the heat from the rotor could be used to vaporize the fuel. The upstream injector could be maintained for the military application as a propane injector for cold weather starts. The results discussed below focus strictly on a low pressure port fuel injector. The new location is shown in Figure 3.

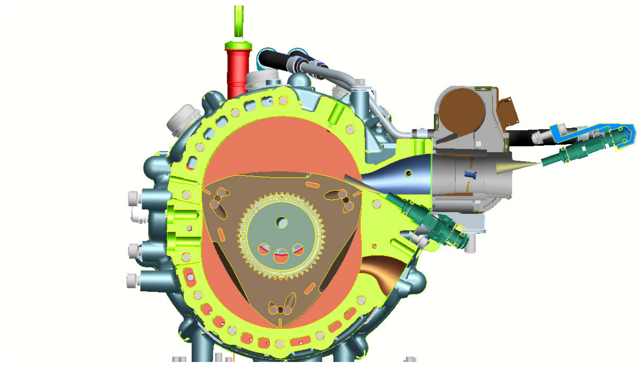

Figure 3: Locations of the Fuel Injectors

EXPERIMENTAL SETUP

The current work utilizes the AVL-APU engine described above. The engine is a single-element, rotary engine utilizing a spark-ignited combustion system. The engine specifications can be seen in Table 1below.

Table 1: Power Unit Characteristics

Engine Type	Epitrochoidal rotary	-
Intake Port Style	Peripheral	-
Exhaust Port Style	Peripheral	-
Number of Trochoid Pistons	1	-
Displacement	0.255	L
Compression Ratio	10:1	-

The engine is naturally aspirated and incorporates a spark-ignited pre-mixed combustion system. Intake air is passed through an electronically controlled 32mm throttle body.

Fuel is delivered via a Bosch EV14 PFI injector, which is mounted between the intake and exhaust runners on the minor axis. A single injection per power stroke is used. The fuel used is Region II JP-8. The net heating value of this fuel is 43800 kJ/kg.

The existing dual sequential ignition system was utilized. The spark plugs are located in leading-trailing order on the minor axis of the trochoid housing. Two capacitive discharge coils are used which allows for adjustability of the split between the leading and trailing spark.

Lubrication for the eccentric shaft bearings, rotor bearing, and the rotor seals is provided via an electric pump. Additional lubrication for the apex seals is provided via a solenoid-operated metering pump. The lubricating oil used is a Mobil Pegasus 15w40 synthetic due to the low ash-deposit qualities. Because of the low quantity of oil introduced into the combustion chamber via oil dosing, the heat of combustion of the oil was negligible in comparison to the total heat of combustion of the fuel.

Figure 4 shows the test bed configuration that was constructed around the rotary engine.

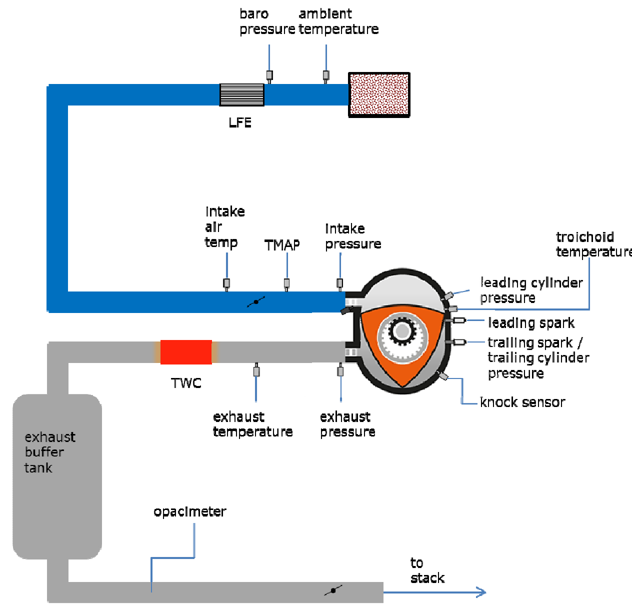

Figure 4: Schematic of Experimental Setup

The power take-off was mated to an AVL AMK 13-170 40 kW eddy current dynamometer. The dynamometer is capable of motoring the engine up to 8000 rpm, while absorbing up to120 Nm of torque.

The engine air flow is measured using a Meriam laminar flow element (LFE). The LFE is separated from the engine by a plenum with resonators to dampen the engine intake pulsations.

Fuel flow is conditioned by an AVL 753 fuel conditioner, which maintains an accurate and steady fuel temperature of 25℃. The fuel flow is measured by an AVL 733 fuel balance.

Coolant is a 1:1 volume solution of ethylene glycol and water. The coolant flow was directed through a plate-type heat exchanger and controlled by way of a PID controller. Both the inlet and outlet coolant temperatures, along with exhaust and trochoid housing temperatures were monitored, until steady state operation was achieved, after which measurements were taken.

Because of the potential interest in visible exhaust signature, the only emissions parameter that was considered was the visible smoke level. Therefore, a smoke meter is also utilized.

High speed data were acquired via AVL Indicom v2.5. This system was used in conjunction with two pressure transducers located about the minor axis to acquire high speed pressure data, and was also used to monitor peak pressure and engine knock. High speed pressure and heat release data are not presented in this paper. The high speed data acquisition was also used to confirm injection and leading and trailing spark timing. Other data such as temperatures, mass flows, torque, and brake power were acquired with an AVL Bobcat v1.3 low speed data acquisition system.

SYSTEM EVALUATION (ENGINE PERFORMANCE GASOLINE VS JP-8 COMPARISON FOR POWER AND FUELING)

Using the current system, spark-ignited combustion with port injected JP-8 was successfully demonstrated. The results are shown in this section. Test methodology included the acquisition of steady state measurements upon stabilization of the engine oil and coolant temperatures. Each steady state point was averaged over a 30 second measurement interval. The start of injection (SOI) timing was established based on best stability and coefficient of variability (CoV). The leading and trailing spark timings used were chosen with regards to avoidance of knock, and therefore the timing was quite retarded. All data is presented on a 1080 eccentric shaft degree (ESD) basis (-540° to 540°).

Mechanical power is used partially as a metric for performance, as well as the required target electrical power capability. The electric power is estimated using a generator efficiency of 85% and a 2 kW power loss to account for assumed oil, fuel, coolant pump, and fan loads. The required mechanical power is derived using these assumptions along with the electrical power target, reference equation 1.

$$P_{mech} = \frac{P_{elec} + 2kW}{0.85} \qquad (1)$$

Engine speed was swept from 4100 rpm to 5300 rpm while maintaining constant 9 kW brake mechanical power, which corresponds to the 6 kW electrical power target. Stoichiometric operation was maintained for each point. The SOI timing was set to 150°ESD BTDC of firing for the encoder-referenced trochoid piston chamber, which translates to an injection 510°ESD BTDC of firing for the respective trochoid chamber of interest. This timing is relatively early, being that it is injected almost directly into the chamber before the following apex seal has begun to close the exhaust port. The intention was to use hot residual gas and the heated rotor face to facilitate the atomization of the JP-8 fuel. The results are shown in blue in Figure 5. The target mechanical power could be produced over a range of engine speeds. The lower target electrical power of 6 kW can be produced with a mechanical power of approximately 9-9.5 kW. The resulting volumetric fuel flow rate is 1.5 gallons per hour (gph), which can be seen in Figure 5.

A maximum brake mechanical power curve was performed over an engine speed range of 4100 rpm to 5300 rpm while maintaining stoichiometric operation. The SOI timing was maintained from the constant mechanical power test. Spark timing and throttle were limited to the detonation borderline (DBL). The results from the maximum power tests are shown in black in Figure 5, which also shows that ~13 kW mechanical power was successfully demonstrated.

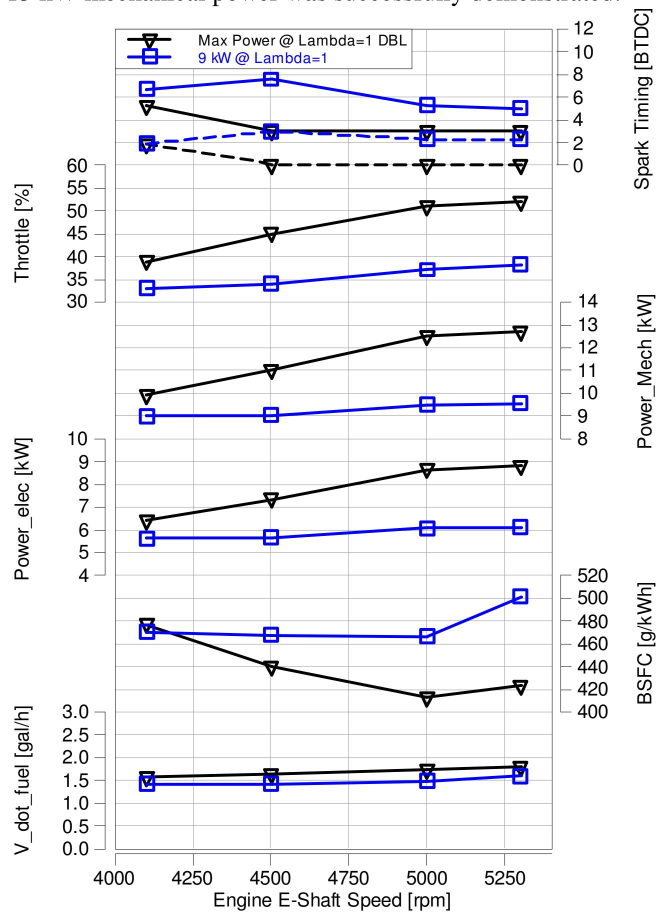

Figure 5: 9 kW and DBL performance with λ=1. Leading and trailing spark timing are shown as solid and dotted lines respectively.

The specific fuel consumption is lower at higher loads due to the higher volumetric efficiency at partially un-throttled conditions. Although DBL was reached before wide open throttle (WOT) could be achieved, the mechanical power achieved translates into electrical power within the target range.

Results from a demonstration of maximum power using spark-ignited JP-8 with enrichment are presented in Figure 6. Engine speed was varied from 4000 rpm to 5300 rpm. At 4500 rpm and above, the estimated 10 kW electrical power is achievable using enrichment.

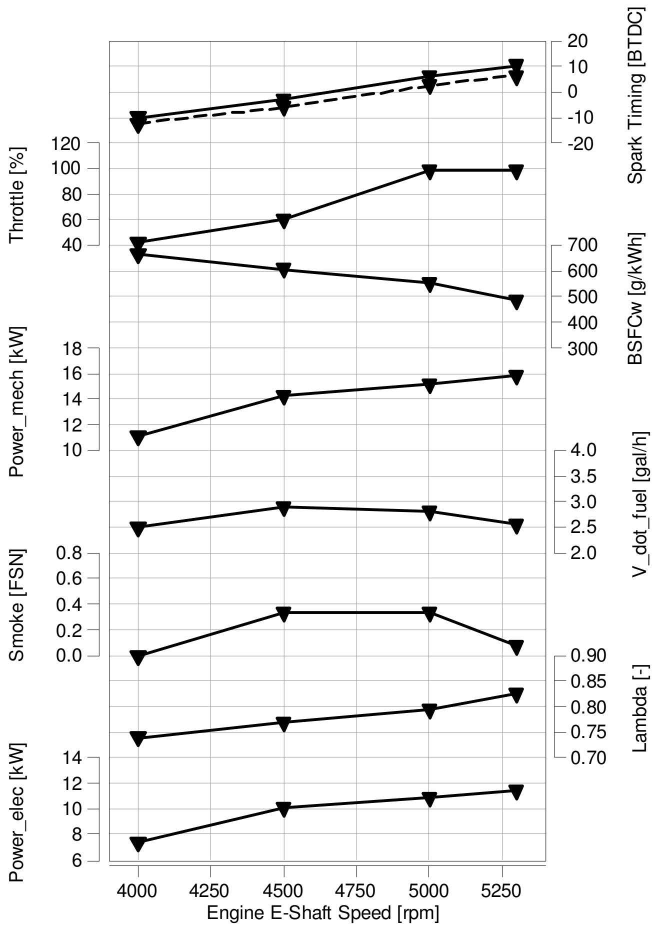

Figure 6: Maximum power sweep with λ<1.

With maximum power output, visible signature is a parameter of interest. The measured filter smoke number (FSN), shown in Figure 6, is under the visible smoke limit.

To avoid unacceptable levels of knock, enrichment was necessary at these points. The advent of severe knock is most likely due to inadequate mixing, which can be aided by an optimized fuel injector location, change in fuel injector type, or different injector spray patterns.

WOT operation was not obtainable at engine speeds lower than 5000 rpm. However, at 4500 rpm and 60 % throttle, the estimated electrical power potential met the target of 10 kW. Because of the relatively long combustion duration when compared with a reciprocating engine, it is more advantageous to operate the rotary engine at higher loads while at higher engine speeds, thus reducing the time for engine knock to occur.

A performance comparison between WOT stoichiometric operation using 87 octane gasoline and DBL operation using JP-8 is shown in Figure 7. The same engine speed range is used, as well as the same injector and location. However, due to the adequate atomization of gasoline, and its resistance to knock, the SOI was set to 67.5°ESD BTDC. This translates to 427.5°ESD BTDC of the respective trochoid piston chamber of interest. At that point, the exhaust port has fully closed and chamber temperature will be decreased.

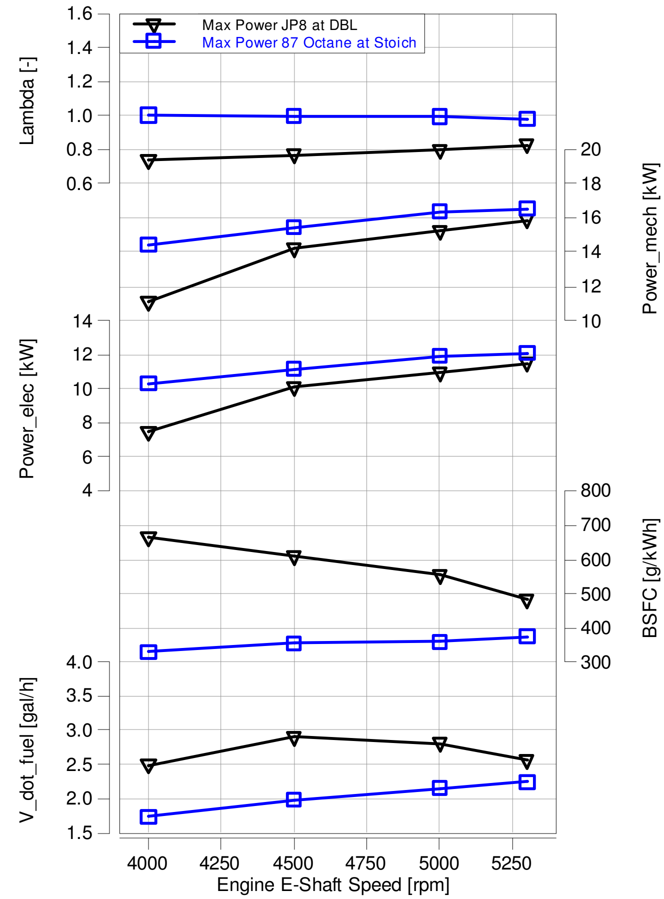

Figure 7: Performance comparison between stoichiometric operation on 87 octane gasoline and DBL operation on JP-8.

Similar maximum power can be obtained with either fuel at 5300 rpm. However, JP-8 fuel lacks knock resistance and has a high boiling point compared to gasoline. This characteristic is exacerbated by the PFI injector's large droplet size, which contributes to poor in-cylinder mixture preparation. This ultimately necessitates fuel enrichment to reduce the tendency to knock, which results in a fueling penalty (0.3 gallons per hour).

CONCLUSIONS AND POTENTIAL FUTURE WORK

The conversion of the AVL-APU from a gasoline based range extender power source, to a JP-8 compatible auxiliary power supply has demonstrated its initial phase. This design shows the ability to provide a range of power capability with minimal impact on package space by increasing rotor width or adding an additional rotor. The combustion system is flexible but still has potential for improvement.

The data indicates that a better means for atomization of JP-8 is required. This can be accomplished through:

- Use of a different injector type e.g. gasoline direct injection
- Optimizing the spray pattern of either injector
- Reducing the hot spots in the chamber
- Increase fuel inlet temperature

Future development concerning the optimization of the design for the challenges presented by military applications will continue to focus on the combustion optimization of the system.

REFERENCES

[1] "More Fight – Less Fuel", Report of the Defense Science Board Task Force on DoD Energy Strategy, February 2008

[2] "Breaking the Tether of Fuel." Marine Corps Gazette. August 2006.

[3] Attachment 2 System Specification from Solicitation Number M67854-13-R-0211. Auxiliary Power Unit (APU) for the Medium Tactical Vehicle Replacement (MTVR) (6-10kW), May 2013

[4] F. Beste, R. Fischer, R. Ellinger and T. Pels, "The Pure Range Extender as Enabler for Electric Vehicles", 21st International AVL Conference "Engine & Environment", 2009