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The Technological Arguments for Micro-Engines

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Abstract

There are many applications which require between 50 and 250 Watts where micro engines are the best technology to take advantage of the high specific energy of liquid hydrocarbon fuels. While there are many markets where fuel cells are seen as the frontrunner technology to replace batteries, there are many applications which would highly value the additional benefits offered by a micro engine based power pack. Furthermore, Wankel engines are the best type of engine to use for these applications due the natural fuel flexibility of the Wankel engine, the reduced number of moving parts compared to other types of engines, and the self-valving design inherent in Wankel style engines. Therefore, by combining well established, low cost manufacturing processes for making the engine and the housing and incorporating the sensors and actuators using MEMS technology on a single die utilizing the advantages of silicon carbide, a very high specific power and low cost power supply system can be built.

Keywords: Micro-engine, micro fuel cell, portable power, MEMS.

INTRODUCTION

There are many applications currently powered by batteries which could benefit from a liquid hydrocarbon fuel based power system. Remote sensors, distributed sensor networks, and handheld power tools are just a few applications where specific power and operation time are currently large problems. The cost of energy storage and conversion can take many forms, including:

- Monetary- fabrication, material, assembly
- Size- system mass, volume
- Reliability- maintenance, lifetime, shelf life
- Environmental- byproducts, disposal, exhaust, production processes

Therefore, these applications would benefit from a power supply which could leverage the high specific energy of liquid hydrocarbon fuel as compared to batteries, as is shown in Figure 1 [1]. Besides having a high specific energy, fuels have the ability to be stored for decades without loss of potency. This complements technologies like remote sensors which can run for years at a time.

The two main technologies under consideration for leveraging the high specific energy of liquid hydrocarbon fuels for portable power applications are micro engines and fuel cells. While currently batteries are used in most portable power applications, as fuel cells and micro engines become more advanced, going forward there may be a range of options for power between 50 and 250 Watts.

WANKEL ENGINE SOLUTION

In the market for 50-250 Watt portable power supplies, a micro engine based power system has advantages over other technologies currently in development for the markets stated above. Micro engine systems are able to leverage the specific energy of liquid hydrocarbon fuels at very high specific power levels. Engines such as the Wankel engine have a minimal set of moving parts, a reduced need for fuel pretreatment or reforming, do not require additional pumps or blowers, and can operate with a catalytically active glow plug ignition. All this serves to reduce the balance of plant losses and the cost of additional size and weight [2].

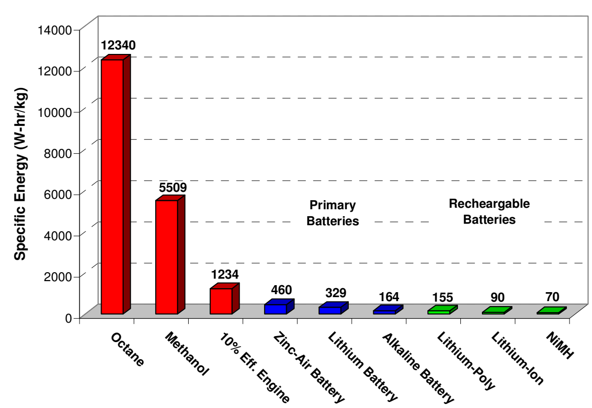

Figure 1. A comparison of the specific energy of common fuels with both rechargeable and primary batteries.

For piston type engines, including Wankel type rotary engines, efficiency is a function of the engine compression ratio, as is shown in Equation (1) below where r_v is the compression ratio and k is the ratio of the constant pressure specific heat to the constant volume specific heat [3]. Assuming a reasonable compression ratio for a Wankel engine of six, the maximum possible engine efficiency from an Otto cycle calculation shown in Equation (1) is 51.2%. Additional losses must be considered including reduced volumetric efficiencies due to poor sealing, combustion efficiency losses due to surface to volume effects and mechanical to electrical conversion efficiencies. Despite these losses, the specific energy of an engine would still be greater than that of batteries for engine operation at even 10% efficiency.

$$\eta_{th} = 1 - \frac{1}{r_v^{k-1}} \quad (1)$$

While all micro engines have the ability to produce a relatively high efficiency system which can leverage the high specific energy of liquid hydrocarbon fuels, a Wankel engine based system has additional advantages. By turning a single trochoidal rotor forming three discrete chambers within an epitrochoidal housing, as can be seen in Figure 2, the intake, compression, expansion and exhaust stages are inherently linked. Furthermore, the system is self valving, offers one power stroke per crank revolution, and has the fewest moving parts of any four stroke engine.

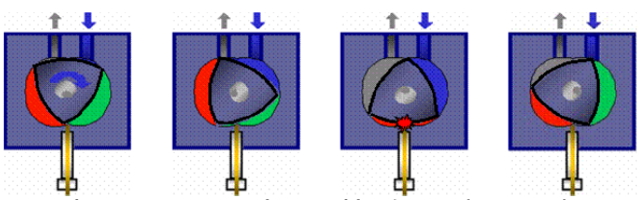

Figure 2. The four steps in the Wankel engine cycle.

Since the combustion process occurs in the gas rather than solid phase, Wankel engines are naturally flexible to the type of fuel being used, are tolerant to impurities, and can run on naturally produced fuels such as methanol or ethanol. With only minor adjustments to the carburetor, a commercial off the shelf five cubic centimeter Wankel style engine has been operated at UC Berkeley on:

- glow fuel- methanol, castor oil (up to 20%), and nitro methane
- methanol
- diesel fuel + 10% ether
- gasoline
- JP-8

This fuel flexibility is due in large part to the fact that the intake charge in a Wankel engine is not constantly exposed to the ignition source.

Due to the planar design of a Wankel engine, the rotor and housing can be manufactured using standard process such as die pressing. By using standard processes and machining many rotors and housings in parallel, the price per unit for the assembled engine can reach mass production economies of scale pricing quickly. Additional cost savings can be gained by using readily available, inexpensive materials such as steel to create the rotor and the housing.

MEMS INTEGRATION

With regards to MEMS integration, the Wankel platform is planar and the gases are circulated in a single plane. As such, all the required sensors and actuators can be contained on a single chip as opposed to multiple sensor/actuator dies located through the device. This is the series of sensors that is required to operate an engine for extended periods of time. This suite of sensors would enable the system to quickly respond to any deviations from the ideal air/fuel ratio in the combustion chamber and insure that the system was operating at peak efficiency for a given load profile.

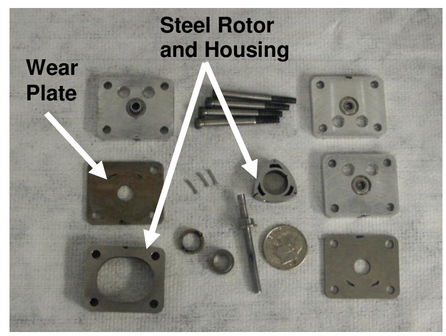

Figure 3. The parts for a micro Wankel engine compared to the size of a US dime. The wear plate shown will be outfitted with a MEMS sensor network.

The MEMS sensor network will be located on a silicon sensor plate, shown in Figure 3, which will be placed adjacent to the rotor, shown in Figure 4. The sensors will be in contact with the intake and exhaust ports, the rotor, and the combustion chamber. Because the MEMS plate can be in contact with each of the three chambers, a closed loop control of the combustion event can be achieved. This will enable a superior understanding of the combustion event than what can be ascertained by analyzing the intake and exhaust streams, which is the option commonly taken when using meso- or macro- sized sensors. A reduced dead volume and quicker response time are also advantages of MEMS sensors utilized in this design over their larger counterparts. It is the closed loop control of a single cylinder which will lead to improved energy conversion efficiency and therefore a higher specific power level.

Because the MEMS chip requires additional processing to handle challenges due to wear, friction, and sealing, a low temperature chemical vapor deposition process of silicon carbide will be utilized. Silicon carbide has the appropriate toughness, corrosion resistance, and self lubrication properties and can be integrated with silicon carbide electronics to provide real time temperature, pressure and strain sensing for closed loop control of an integrated fuel and air delivery system as well as ignition control [4]. Taking advantage of the planar nature of the Wankel engine, the sensor suite will be comprised of planar components, such as an integrated fuel vaporization and delivery system which leverages the natural instability of phase eruption to create a self-pumping system [5], or a hole-in-the-wall valve for fuel and lubricant metering [6].

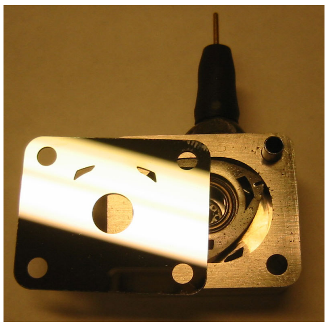

Figure 4. The UC Berkeley Wankel engine next to a silicon wear plate.

The approach of combining low cost traditional die pressing manufacturing for the rotor and housing, and high value added MEMS introduced in a single chip for the sensors and actuators, has a tremendous potential cost impact. Due to the planar nature of the Wankel style engine, where other engine types would require a series of sensors, a Wankel style system would require just one sensor suite to be installed adjacent to the combustion chamber. This directly leads to an increase in the number of engines which can be outfitted per processed wafer and a reduced overall cost of the MEMS enabled micro engine based power system using a Wankel style engine over other engine types [7].

FUEL CELLS

For many markets fuel cells are seen as the major competitor to batteries and to micro engine based power systems. Proton exchange membrane (PEM) fuel cells contain a polymer electrolyte membrane which allows hydrogen ions to pass through while forcing electrons to flow around an external circuit thereby producing electricity. There are two main types of PEM fuel cells under development for 50-250 Watt applications. The first type is a hydrogen fuel cell which converts hydrogen in gaseous form on the anode and oxygen from compressed air on the cathode. The second type is known as a direct methanol fuel cell (DMFC) system. For this type of system the fuel is a mixture of methanol and water on the anode and the oxidant is again compressed air on the cathode. Figure 5, below shows a schematic for a direct methanol PEM fuel cell system.

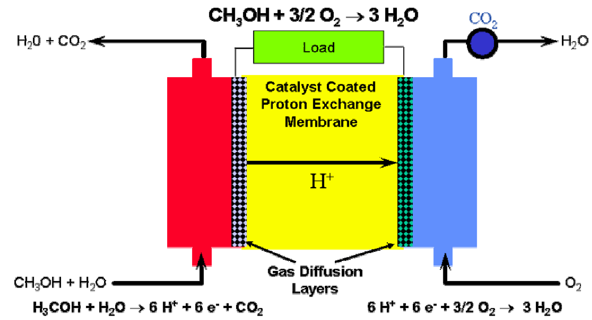

Figure 5. Schematic for a direct methanol fuel cell.

Most PEM fuel cells operate around 33% efficiency, assuming methanol as the fuel. The efficiency of a fuel cell is calculated using Equation (2) below where V_c is the cell voltage and V_{EMF} is the maximum theoretical open circuit for the cell under the given operating conditions [8].

$$\eta = \frac{V_{cell}}{V_{EMF}} \qquad (2)$$

PEM fuel cells, in order to effectively operate at relatively low temperatures, require precious metals such as platinum and ruthenium to enable the reactions to proceed. These metals act as catalysts reducing the energy required for the reaction to go forward. Due to the precious metal catalyst on both the anode and cathode, the fuel and oxidant supply for fuel cells must be ultra-pure. The fuel stocks must be free of impurities such as carbon monoxide or sulfur compounds. Otherwise, these impurities attach to the catalyst and block the site from further reactions. This reduces both the lifetime of the fuel cell system as well as the current density of the fuel cell and the specific energy of the system.

Therefore, unlike a Wankel style engine based system which is flexible to the types and purities of the fuel being combusted, a fuel cell powered system requires very specific fuels of ultra high purity. The tight restriction on the fuel stock to be used can be managed in two ways. First, there can be strict control on the source of the fuel. This is a viable option for consumer applications where the fuel source would be purchased from a select number of predetermined vendors under controlled conditions. However, for many remote power and sensing applications, these tight restrictions may not be able to be met. Second, a multi-stage fuel reformation system can be added to ensure the purity of the fuel going into the fuel cell regardless of the purity of the fuel coming into the system. This solution is both complex and expensive and not a reasonable option for many of the applications stated above.

OTHER TECHNOLOGIES

Other competing technologies for the micro Wankel engine are batteries, super capacitors, and other micro engine power projects [9] [10]. These systems have not been addressed in this paper but are based on related ideas to the micro Wankel project presented above.

Batteries and super capacitors both suffer from lower specific energy levels and naturally discharge over time making them a less ideal fit for many remote power applications. Furthermore, both batteries and capacitors require significant amounts of time to recharge. This is contrasted with fuel based power systems such as micro engines or micro fuel cells which are able to run continuously provided that there is fuel available. The instant recharge capability of fuel based systems is valuable for powering electronics which are desired to operate all day such as a laptop computer or GPS unit.

However, both micro engines and micro fuel cells will need a battery or capacitor in order to begin operation. Micro engine solutions will need either a glow plug or spark plug for combustion, which will need to be started under battery or capacitor power. A fuel cell power pack will need a battery to start up the pumps and blowers required for operation. Both solutions will be able to power their peripheral systems once they have begun but will rely on batteries or similar technologies for initial operation.

Furthermore, both fuel cells and batteries operate most efficiently under constant loads. Therefore, for varying load profiles like those produced by handheld electronics such as laptop computers, the addition of a battery or capacitor to remove any transient spikes in the power demand profile will help boost the efficiency of the system.

CONCLUSIONS

For off-the-grid power requirements between 50 and 250 Watts, there is a large advantage to using liquid hydrocarbon based fuels as the power source instead of batteries. Fuels have a high specific energy and a long shelf life, which makes them ideal for applications which are either in remote locations or which require power for extended periods of time. An ideal technology to take advantage of the high specific energy of liquid hydrocarbon fuels is micro engines, more specifically Wankel type micro engines.

Due to the planar design of a Wankel engine, well established and low cost manufacturing processes can be employed for making both the rotor and the housing. Closed loop control of the engine is possible using MEMS sensors and actuators, created on a single die, utilizing the advantages of silicon carbide. This will create a very high specific power and low cost power supply system.

Competing technologies, such as fuel cells or super capacitors have advantages over a micro engine solution for lower power or certain consumer applications. However, for applications such as remote sensors, distributed sensor networks, and handheld power tools where specific power and operation time are currently large problems, a micro engine based power system is the best solution.

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