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COOLING CONCEPTS FOR A FAMILY OF SMALL, HEAVY-FUEL ROTARY ENGINES FOR USE IN AUXILIARY POWER UNITS

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ABSTRACT

Military Ground Vehicle electric power demands continue to grow as new mission equipment is added. Using an Auxiliary Power Unit (APU) consumes less fuel than restarting the main engine frequently to charge batteries.

To meet the rising demand for powerful, L-3 Combat Propulsion Systems is developing a family of heavy-fuel rotary engines. Rotary engines offer superior power density making them a good choice for applications that require high power in a limited space. Heavy fuel capability simplifies logistical challenges in the field.

However, rotary engines have unique cooling challenges. Unlike a piston engine, the intake, compression, expansion, and exhaust events all take place at their respective fixed positions around the circumference of the rotor housing, leading to large temperature differences around the housing. The cooling system must be carefully developed to minimize these temperature differences in an effort to control thermal deformation, minimize thermal stress, and retain material strength.

This paper compares the advantages and disadvantages of a single-fluid cooling concept compared (oil) to a dual-fluid cooling concept (oil and water-ethylene glycol).

INTRODUCTION

In 1954, Dr. Felix Wankel became the first in the world to successfully develop a rotary engine. Since that time, rotary engines have appeared in automobiles, motorcycles, off-road vehicles, and various stationary applications (ref. Yamamoto). The rotary engine was particularly successful in the Mazda RX-7 and RX-8 sports cars, due in large part to the rotary's inherent compact size and light weight. The rotary's high power density also recommends it for other applications where weight and bulk must be avoided, such as UAV's and Auxiliary Power Units. Figure 1 (below) illustrates how the compact nature of a rotary engine helps reduce the packaging space requirements for an Auxiliary Power Unit (APU).

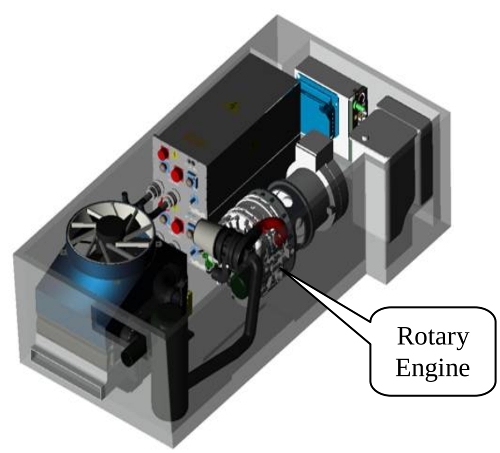

Fig. 1: Rotary Engine APU Concept

Most rotaries have used spark-ignited gasoline fuel. A few companies, such as Curtiss-Wright and John Deere, Inc., have developed spark-assisted stratified-charge rotary engines (SCREs) that use heavy fuels (diesel fuel or Jet Propellant fuel), but these efforts were stopped. An illustration of L-3's single-rotor spark-ignited heavy-fuel engine is shown below as Figure 2.

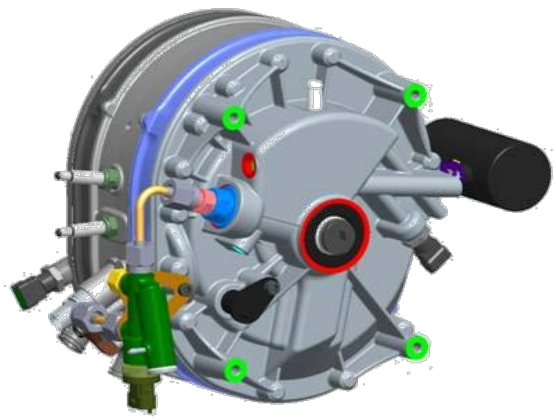

Fig. 2: Spark-Ignited Heavy-Fuel Rotary Engine

Today, the demand for a compact heavy-fuel engine is even greater. The military's desire for a single battlefield fuel has placed pressure on industry to develop new heavy fuel engines, and the proliferation of Unmanned Aerial Vehicles (UAVs), coupled with the demand for more powerful and compact auxiliary power units (APUs), has prompted engine developers to take a fresh look at SCREs. To meet this demand, L-3 Combat Propulsion Systems, supplier of engines and transmissions for a variety of military applications, has partnered with Wankel SuperTec to develop a family of small, heavy-fuel stratified-charge rotary engines.

Figure 3 (below) illustrates a packaging concept for an Unmanned Aerial Vehicle power unit.

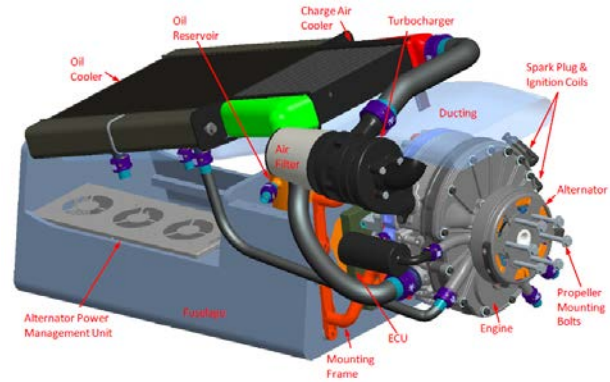

Fig. 3: Rotary UAV Packaging Concept (oil cooled)

The engine designers needed to make many architectural decisions early in the concept phase. One such decision was the choice of cooling media. This paper examines the issues associated with the use of oil or water-ethylene-glycol (WEG) as the primary cooling media and reviews the design solutions.

ROTARY ENGINE COOLING CHALLENGES

One of the primary objectives of the design effort was to create a very light-weight engine. Consequently, aluminum was specified wherever possible. Being the largest single component, the rotor housing was assumed from the beginning to be aluminum.

Unlike a piston engine, the rotary's intake, compression, expansion, and exhaust events all take place at their respective fixed positions around the circumference of the rotor housing, leading to large temperature differences around the housing. The cooling system must be carefully developed to minimize these temperature differences in an effort to control thermal deformation, minimize thermal stress, and retain material strength. Because the material in question is aluminum, metal temperatures must be held to 250 degrees Celsius or less to avoid a potentially catastrophic reduction of strength.

INITIAL COOLING CONCEPT

Pressurized oil must be present to meet the lubrication requirements of components such as the shaft and rotor. It was originally felt that engine oil could also serve as the cooling media. Oil cooling was thought to have significant advantages over WEG cooling;

Advantages of Oil over Water-Ethylene Glycol Cooling
Simplified servicing (no need to service the cooling system)
Improved field logistics (one less fluid required)
Reduced engine complexity (no separate coolant pump or radiator)
Perceived weight advantage
Perceived package size advantage

Table 1: Oil vs. WEG

Based on these results, the initial "A-Series" engines were designed to use oil as the sole cooling fluid.

A-SERIES TEST REULTS

The initial prototype engines were outfitted with thermocouples embedded in the walls of the rotor housing. Metal temperatures above the 250C bogey were not observed.

Given these favorable results, the decision was made to carry the oil-cooled concept into the next design phase (B-Series).

B-SERIES TEST REULTS

As with the previous series of prototype engines, the B-Series engines were fitted with thermocouples at various places around the rotor housing. This time, however, the results were disappointing. Experimental results revealed metal temperatures in excess of 300C in the vicinity of the combustion chamber.

IMPACT OF COMBUSTION CHARACTERISTICS ON METAL TEMPERATURES

One of the main goals in the redesign of the A-Series engine was to improve fuel economy and power by improving combustion efficiency. To this end, the injector location was significantly advanced around circumference of the rotor housing. This provided an opportunity to significantly advance fuel injection timings.

As expected, fuel economy improvements were realized. More of the injected fuel quantity was being burned earlier in the cycle and less was being wasted by burning during the exhaust phase. This was evidenced by an increase in firing pressure and decrease of exhaust gas temperature.

The unfortunate side-effect of this improvement was an increase in local metal temperatures. Because combustion was happening faster, the combustion temperatures were concentrated over a smaller arc of the rotor housing. Similarly stated, less fuel energy was being released in the exhaust gas and more was being transferred to the coolant through the rotor housing.

ANALYSIS

A Computational Fluid Dynamics (CFD) model was developed in an effort to evaluate design changes that might eliminate the issue. The model was validated using experimental data and found to be within 30C of actual temperatures. Results can be seen in Figure 4 below.

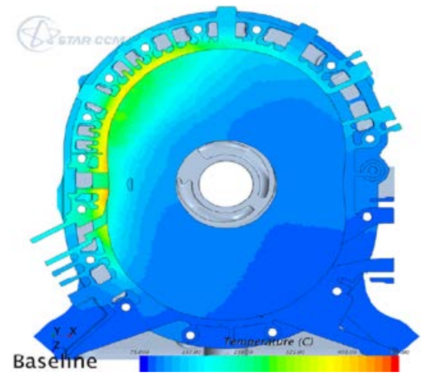

Figure 4: Rotor Housing Metal Temperatures

The baseline model predicted localized metal temperatures in excess of 300C – clearly in excess of what could prudently be tolerated.

DESIGN CHANGES

An effort was put forth to identify changes that could be made to the housing that would bring metal temperatures back into safe levels. Ten different versions of the oil-cooled housing were evaluated. Although improvements were observed, none were significant enough to renew confidence in the oil-cooled approach.

WATER-ETHELYNE GLYCOL (WEG) COOLING

WEG has a number of advantages over oil as a cooling fluid. It has superior heat transfer characteristics, it requires less pump power due to its lower viscosity, and does not require the precise pressure regulation of the lube oil system.

A number of WEG-based designs were evaluated. Results show that metal temperatures are significantly lower compared to oil. Consequently, the decision was made to switch from an oil-cooled rotor housing to a WEG-cooled version. The current design features axial-flow coolant passages, although radial-flow designs are being considered for future design iterations.

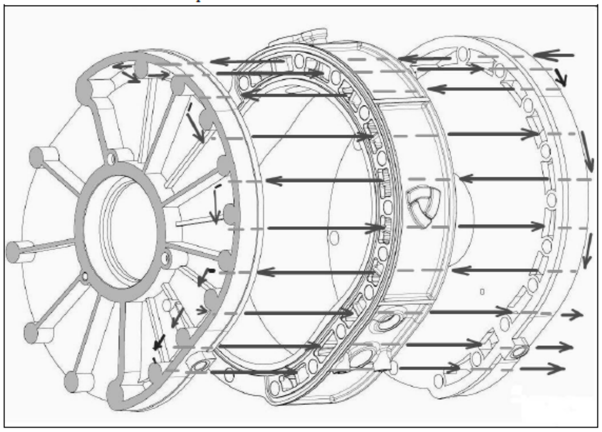

Fig 3: Axial-flow WEG Coolant Passages

PACKAGING

The decision to switch to WEG cooling meant that a heat exchanger, pump, and plumbing had to be added to the system. However, because the bulk of the cooling burden was being transferred to the WEG circuit, the oil circuit, including the heat exchanger, could be significantly downsized. A study was launched to establish how the conversion to WEG cooling would affect heat exchanger size and total package size.

Cooling requirements and specifications were gathered. These data were used to estimate heat exchanger size. The study showed that the superior effectiveness of the WEG cooling circuit led to 39% reduction in heat exchanger volume.

Specification	Oil Cooled Version	Water Cooled Version	
		Water Cooler	Oil Cooler
Fluid	15W-40 Oil	50-50 WEG	15W-40 Oil
Heat Rejection	34 kW	25 kW	9 kW
Flow Rate	46 Liter/min	30 Liter/min	7 Liter/min
Cooler Inlet Temp	123 C	115 C	140 C
Cooler inlet Pressure	30 psig	30 psig	80 psig
Cooler Pressure Drop	15 psig	15 psig	15 psig

Table 2: Cooling System Design Specifications

Description	Percent Change Relative to Oil-Cooled Concept
Height	-32%
Width	-16%
Thickness	+7%
Total Volume	**-13%**
Cooler Dry Weight	-45%
Liquid Volume	+70%
Liquid Weight	+110
Total Wet Weight	**-28%**

Table 3: Heat Exchanger Volume and Weight Comparison

The illustration below shows how the two heat exchangers would fit in the within the cross section of an Abrams APU compartment.

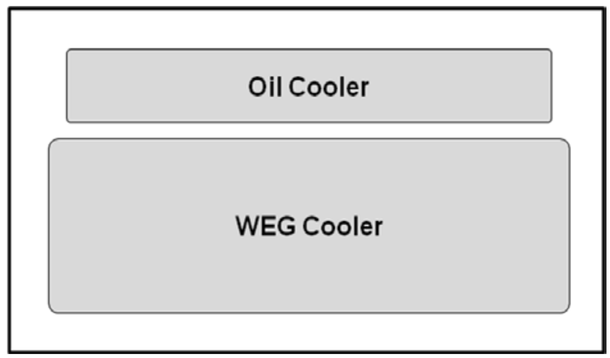

Figure 4: Heat Exchanger Packaging

In addition to a new heat exchanger, the WEG circuit would require its own pump and coolant lines. The weight impact of these additional components was estimated. The weight of oil and WEG was included to arrive at a “wet” weight comparison. Results showed that despite an increase in part count, a WEG-based system would be one kg lighter than the oil-only system.

ADDED BENEFIT

For the purposes of this investigation, the rated power of this single-rotor, 350 cc engine was assumed to be 33.5 kW (45 bhp). As shown in the previous sections, the B-Series oil-cooled engine could not achieve rated power without pushing rotor housing metal temperatures to unsafe levels.

SUMMARY

The original design assumptions for a 350cc single-rotor heavy-fuel rotary engine included an oil-cooled rotor housing. As combustion development efforts progressed, less and less fuel energy was being lost to the exhaust gasses, and more was being transferred to coolant (oil). As a result, desired power levels could not be achieved without violating material-related metal temperature limits.

ACKNOWLEDEMENT

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