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StarRotor Engine for Military Applications

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Overview

Jet engines and gas turbines are widely used by the military to power planes, helicopters, and tanks. These engines employ the Brayton thermodynamic cycle, which is valued because of its extremely high power density. The Brayton cycle employs a compressor, combustor, and expander (Figure 1). Traditionally, axial compressors and expanders are employed, which use high-speed spinning fans (Figure 2) to process very large volumes of air required to achieve high power output.

The StarRotor engine replaces high-speed spinning fans with gerotors (Figures 3 and 4), which are mature for liquids, but are being developed by StarRotor for applications with gasses. Each machine has an inner and an outer rotor. *N* inner rotor lobes fit *N* + 1 matching cavities in the outer rotor. The rotors spin about their respective and slightly offset axes of symmetry at different speeds with a fixed gear ratio corresponding to the different number of lobes and cavities. The volume within each cavity expands and contracts cyclically as the assembly rotates. There are no reciprocating masses, no valves, and surface speeds are low.

Gerotors have the best attributes of positive-displacement (e.g., reciprocating, screw) and dynamic machines (e.g., axial, centrifugal):

- Like dynamic machines – continuous rotation enables high throughput with low vibration and high reliability.
- Like positive displacement machines – compressing a confined gas allows higher per-stage pressure ratios and efficiency at smaller scales without excessive speeds.

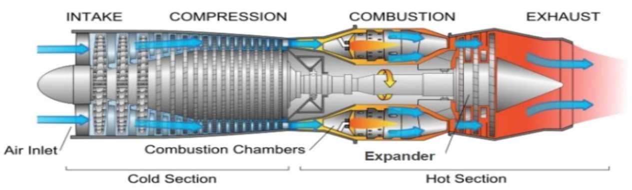

Figure 1: Conventional jet engine.

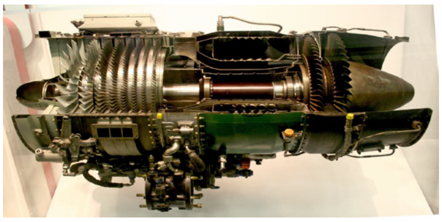

Figure 2: Axial compressor and expander in a conventional jet engine.

To adapt gerotors for gas compression and expansion, StarRotor has pioneered the following innovations: (1) a dedicated synchronizing gear prevents contact between lobes and cavities and eliminates the need for flood lubrication, (2) abradable coatings minimize internal bypass leakage, (3) advanced seals reduce internal bypass leakage, and (4) radial porting minimizes internal pressure losses. StarRotor has incorporated these features into prototype machines, demonstrating isentropic compression efficiencies greater than 86% at small scales.

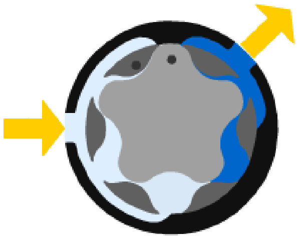

Figure 3: Star Rotor compressor.

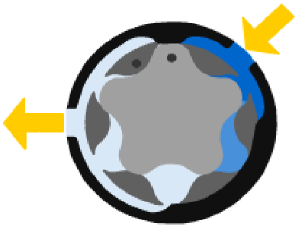

Figure 4: Star Rotor expander.

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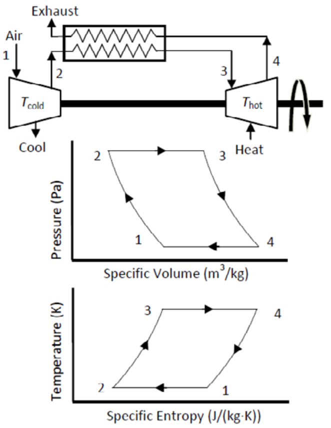

Figure 5: Ericsson cycle engine.

The StarRotor engine has the following advantages:

- efficient
- power dense
- low maintenance
- long life
- multi-fuel
- wide turn-down ratio (i.e., excellent performance over wide operating conditions)
- scalable
- quiet
- small thermal signature
- vibration free
- low cost

Innovation

Ericsson cycle

The Ericsson cycle (Figure 5) uses an isothermal compressor, isothermal expander, and a recuperator. A reversible Ericsson cycle has the following efficiency:

$$\eta = 1 - \text{Tcold}/\text{Thot} \qquad (1)$$

which also applies to the Carnot and Stirling cycles. To achieve Carnot efficiency, all three cycles require isothermal compression/expansion, which is difficult to achieve in practice.

The recuperated Brayton cycle (Figure 6) is a practical approach that nearly achieves the theoretical efficiency of an Ericsson cycle. It employs a recuperator, just like the Ericsson cycle; however, the compression and expansion are adiabatic.

Figures 5 and 6 show the PV and TS diagrams of the Ericsson and recuperated Brayton cycles are nearly identical, particularly at low pressure ratios. A traditional Brayton cycle engine does not employ a recuperator, and requires high pressure ratios to be efficient. In contrast, a recuperated Brayton cycle engine is more efficient at low pressure ratios because the compression and expansion are nearly isothermal, approximating the Ericsson cycle.

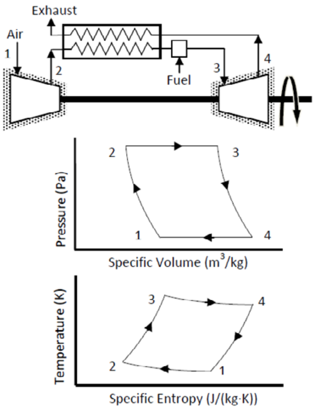

Figure 6: Recuperated Brayton cycle engine.

Conventional Machinery

Figure 7 shows the most common compressors.

Positive-displacement compressors capture a fixed mass of gas, reduce the volume, and then discharge the high-pressure gas. Best known are reciprocating compressors, which use a piston actuated by a rotating crank shaft. Large loads on the rotating crank shaft limit the speed. Further, the valves are complex and unreliable. Screw compressors have a complex three-dimensional geometry that is difficult to manufacture and seal. To seal gaps, they flood with oil, which limits the maximum operating temperature. Scroll compressors have a stationary scroll and an orbiting scroll. Because of vibrations, they are limited to small-scale applications.

Dynamic compressors employ high-speed rotating blades to compress the gas. Axial compressors have an alternating series of rotating fan blades and stators with an airfoil shape. High tip speeds are required, which requires exotic bearings. The per-stage compression ratio is low; so many stages are required to achieve high pressure ratios. Centrifugal compressors have the gas enter near the center and discharge radially. If multiple stages are required, complex flow patterns are required to collect gas from the periphery of one stage and redirect it to the center of the subsequent stage. Dynamic compressors operate efficiently only in a narrow range of speeds (Figure 8), which limits their turndown ratio (i.e., maximum/minimum speed).

Figure 9 shows the efficiency of commercial Brayton cycle engines

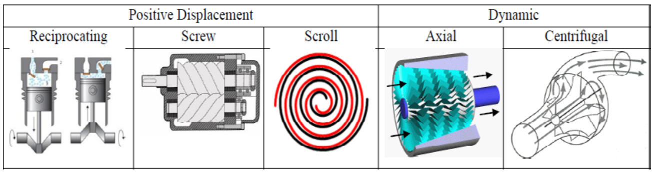

Figure 7: Summary of conventional compressors.

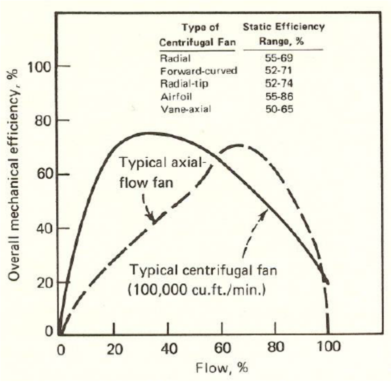

Figure 8: Efficiency of dynamic compressors [1].

as a function of power [1]. They employ dynamic machines, which do not scale down efficiently or affordably because of complex surface/volume interactions. Projecting the trendline to 1 kW, dynamic machines would be only 21% efficient. In contrast, a 1-kW (1.3-hp) StarRotor engine is projected to be 40 to 50% efficient. A 10-MW (13,300-hp) StarRotor engine is projected to be 55 to 70% efficient.

Starrotor Compressors and Expanders

StarRotor compressors and expanders employ gerotors, simple positive-displacement devices that process fluids in a compact, purely rotational, and valve-less manner. Figure 10 shows the sequential motion of the inner and outer rotor of a compressor as it goes through a single compression cycle: (1) intake, (2) compression, and (3) discharge. The same machine can also be used as an expander by reversing the direction [2-4].

It should be emphasized that all chambers work simultaneously. In Figure 10, a single rotation of the inner rotor processes five chambers, which provides extremely high volumetric capacity.

In conventional gerotor pumps (manufactured for over 80 years) a lubricious liquid is essential to allow sliding contact to synchronize the lobes and cavities, and to limit internal leakage through clearances. The following StarRotor innovations adapt fundamental gerotor technology for gas processing:

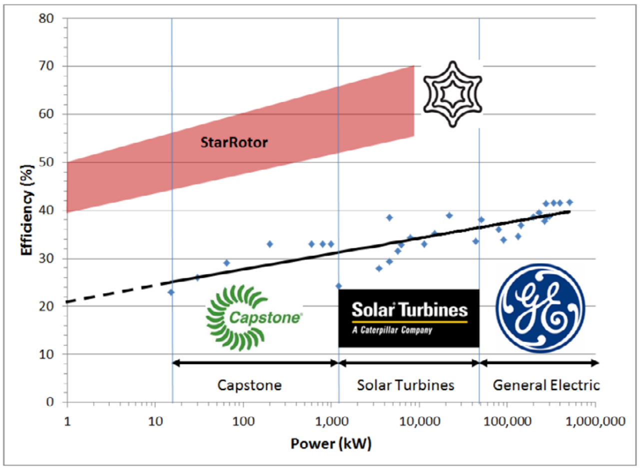

Figure 9: Efficiency of Brayton cycle engines [2-4].

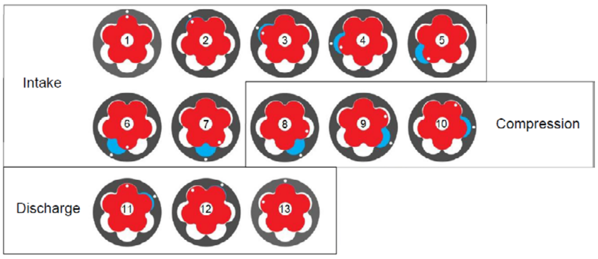

Figure 10: Gerotor compressor operation.

- **Synchronizing gear** – There is no contact between the rotors. Relative motion is maintained by a synchronizing gear outside the flow passages.

- **Abradable coating** – For tight clearances, one surface has a softer sacrificial abradable coating that wears in during initial operation. Application techniques include plasma coating (common in jet engines) and surface modification to induce turbulence.

- **Noncontact seals** – Labyrinth seals at key locations greatly reduce internal leakage.

- **Radial porting** – Unlike liquid pumps ported on their axial faces, StarRotor compressors and expanders use radial ports with optimized shapes to minimize fluid acceleration and deceleration.

StarRotor compressors and expanders have smoother and simpler gas flows than multi-stage axial machines, without the complex housing and rotor geometries of centrifugals or screws, or the oscillating masses and oil-lubricated seals of reciprocating pistons and Wankels [5].

StarRotor Engine

Figure 11 shows a recuperated StarRotor engine that employs a gerotor compressor and expander. The Wankel engine (Figure 12) uses a similar geometry, so a common question is "How is the StarRotor engine different than a Wankel engine?" Table 1 summarizes the many differences.

Efficiency

Figure 13 shows the efficiency of a StarRotor engine as a function of combustor temperature and efficiency of the compressor and expander. At the 10-kW (13-hp) scale, we have demonstrated compressor efficiency of 82%, and at the 25-kW (33-hp) scale, we have demonstrated compressor efficiency of 86%. At these compressor efficiencies and a combustor temperature of 1200 K (927°C,1700 °F), the engine efficiency is about 48%. Increasing the combustor temperature to 1600 K (1327°C, 2420°F) increases the engine efficiency to about 60%.

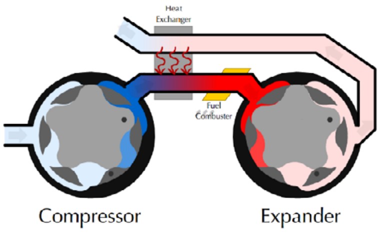

Figure 11: Star Rotor engine.

Feature	StarRotor Engine	Wankel Engine
Thermodynamic cycle	Recuperated Brayton	Otto
Pressure ratio	2 to 8	62 [5]
Outer rotor	Rotates	Stationary
Motion	Pure rotation	Rotation + orbit
Combustion	Continuous	Periodic
Seals	Noncontact	Contact
Lubricated compression space	No	Yes

Table 1: Comparison of StarRotor and Wankel engines.

To put these projected efficiencies in perspective, a 50-MW (66,600-hp) LM6000 General Electric gas turbine is 42% efficient. In contrast, the StarRotor engine can exceed this efficiency at the 50-kW (67-hp) scale.

In vehicles, diesel engines (~200 kW, 260 hp) have a peak efficiency of 45%, but under usage conditions, the efficiency is about 37% [6].

In a military setting, efficiency is extremely important. The military is the largest consumer of fuel in the United States. In times of peace, increasing efficiency allows precious funds to be used for defense rather than fuel. In times of war, the ability to deliver fuel to the battlefield can be the difference between victory and defeat. Because the logistic train is so difficult to maintain, some estimates are that battlefield fuel costs \$400/gal [7].

Characteristics

The StarRotor engine has the following characteristics:

Power dense

Because the StarRotor engine is a variant of a conventional jet engine, it has the potential to be extremely power dense.

Low maintenance

Conventional piston engines require frequent oil changes because products of incomplete combustion (carbon, acids) contaminate the lubricating oil. The StarRotor engine has extremely clean combustion, so the lubricating oil does not become contaminated with damaging combustion products.

Long life

The StarRotor engine has only three components that have the potential for wear: gears, coatings, and bearings. The synchronizing gear is lightly loaded, so it can be designed for extremely long life. The gerotor coatings will wear if the air is contaminated with grit, but it can be removed with good filtration. Hydrostatic bearings can be employed, which have no contact and therefore bearing life is essentially infinite.

Multi-fuel

Piston engines require specialized fuels (gasoline, diesel) with specific combustion characteristics (octane rating, cetane rating). In contrast, the StarRotor engine only requires a source of heat and

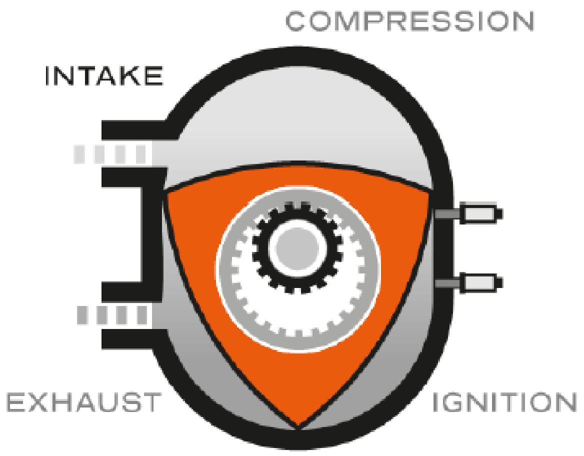

Figure 12: Wankel engine.

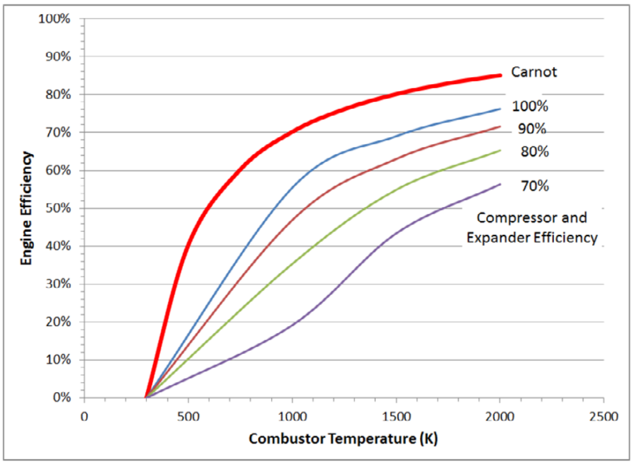

Figure 13: Efficiency of StarRotor engine as a function of combustor temperature and compressor/expander efficiency. Pressure ratio is 2.45.

therefore can use nearly any fuel including gasoline, diesel, jet fuel, hydrogen, alcohol, or vegetable oil. With appropriate combustors, even solid fuels (coal, wood) can be used.

Wide turn-down ratio

The efficiency of gerotor compressors and expanders is not sensitive to operating conditions (e.g., speed), so the engine maintains high efficiency over wide ranging operating conditions.

Scalable

Gerotor compressors and expanders are efficient even at small scale, so the engine can operate over a wide range of powers from 100 W to 10 MW (0.13 to 13,300 hp).

Quiet

The StarRotor engine fully expands the gas before releasing it, so it is quiet compared to piston engines. The tip speeds are relatively low, so it is quiet compared to gas turbines. The StarRotor engine does produce some high-frequency noise, by this is readily muffled.

Small thermal signature

Because of the recuperator, the exhaust temperature of a StarRotor engine is low, which reduces the thermal signature.

Vibration free

The inner and outer rotors of the gerotor spin about their respective centers, so there is essentially no vibration.

Low cost

The StarRotor engine has low parts count and does not require precious materials. When mass produced, it has the potential to be inexpensive.

Military Applications

The StarRotor engine has many potential military applications, such as the following:

Electric generators

The StarRotor engine can be used to power electric generators ranging from 100 W to 10 MW (0.13 to 13,300 hp).

Prime movers

The StarRotor engine can be used to power military vehicles such as trucks, armored personnel carriers, and tanks.

Drones

High efficiency and low vibration are particularly valuable to drones, which are often required to stay aloft for extended time periods while taking photographs or videos.

Personal power

The StarRotor engine can be scaled down to provide soldiers with individual power for cooling, electricity, or locomotion (exoskeletons).

Conclusion

The StarRotor engine has properties that make it particularly valuable for the military. The cost of developing the engine will be repaid in fuel savings and extra defense capability.

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