Freedom Motors
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The Rotapower® rotary engine (simple and compound)

Freedom Motors has developed a family of rotary engines ranging from single-rotor 27cc and 150cc displacement models to multi-rotor versions of its 530cc and 650cc displacement engines. These Rotapower® rotary engines have been successfully tested in a number of applications.

The Rotapower® rotary engine is based on the Wankel rotary engine patented design that has the following attributes:

- High power for its weight and volume
- Very few moving parts
- Operates on the four stroke principle
- Very low vibration

There have been two fundamentally different approaches to cooling the rotor used in this engine:

- Oil cooled rotors were used by GMC, Mazda, NSU, Syrano, and Ingersoll-Rand
- Charge or air-cooled rotors were used by Outboard Marine Corporation (OMC), Norton Motors, Infinite Engine Company (IEC), Fichtel-Sachs, and currently by Freedom Motors

The oil cooled rotor requires a complex composite side-seal to retain the oil in the rotor. This limits rotor operating temperature and initially was subject to failure. Power is absorbed as the oil is accelerated during its passage through the rotor.

The charge cooled rotor is much simpler and consequently can be more reliable but has a lower volumetric efficiency due to preheating the incoming charge. It has a significantly higher rotor surface temperature which reduces combustion quenching. This tends to mitigate the rotary engine's higher combustion surface to volume ratio which reduces combustion efficiency by quenching the combustion process.

In both rotor cooling approaches, the simple rotary engine has a higher specific fuel consumption (SFC) than that of the highly developed four-stroke piston engine used in the automobile. However, the simple rotary's SFC is competitive for many utility, recreational, or commercial four-stroke piston engine applications which use a rich fuel/air mixture to preserve the low cost valves that are vulnerable to the slow burning nature of a lean fuel-air mixture. The rotary is valveless.

Summary of limitations of the existing simple Wankel type rotary engines include:

- Loud exhaust as the exhaust port opens abruptly
- High surface to volume ratio compromises combustion efficiency due to quenching
- Inability to use compression ratios above 9:1 due to increasing the combustion chamber surface to volume ratio
- Lower volumetric efficiency with charge cooled rotors
- Oil cooled rotors have power loss and added cost

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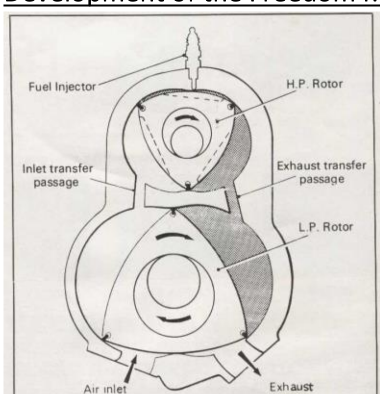
Compounding the rotary engine. The unique attributes of the existing simple Rotapower® engine make it an attractive candidate where high power relative to weight and volume are important such as a range extender for electric automobiles. However, in its present simple form the higher SFC, louder exhaust noise, and elevated exhaust temperature limit its use in some applications. Freedom Motors has addressed these limitations by compounding the simple engine to extract and efficiently utilize a portion of the normally wasted energy in the exhaust gases.

A compound rotary engine is created by using two rotors in series where the first compression/expansion (CE) rotor supercharges a second power rotor. Following combustion in the power rotor, the exhaust gases reenter the CE rotor where additional expansion takes place. Rolls-Royce was the first company to demonstrate a compound rotary engine. In the RR design, a large compression/expansion rotor was used in conjunction with a smaller power rotor. The two rotors were connected by a chain drive and operated on separate crankshafts as shown in the following figure. The resulting engine was substantially smaller than the diesel fueled piston engine RR was hoping to replace. Unfortunately, RR was forced into a Chapter 11 reorganization which prevented further development. It did achieve a SFC of 0.35 lb/hp*hr which is the lowest SFC recorded by a rotary engine, but substantially higher than a turbocharged piston engine using the diesel cycle. NASA Lewis projected that fuel consumption for a turbo-compounded rotary engine could be as low as 0.3 lb/hp*hr (see NASA TM 105562).

Development of the Freedom Motor compound Rotapower® rotary engine.



ROLLS ROYCE two-stage design utilising two-rotors.

FM initially designed, built, and dyno tested a 294cc compound rotary engine using a 530cc compression/expansion (CE) rotor in a design similar to Rolls-Royce.

Very limited testing showed a small improvement in SFC, a 93% reduction in noise, and a significant reduction in exhaust temperature. The major difference from the Rolls-Royce design was having both rotors operate on the same crankshaft which reduced its complexity and size. This early design was followed by a second fundamentally different compound engine design that used equal size 530cc rotors also operating on a common crankshaft. The noise was reduced over 95% while the exhaust temperature was reduced by over 35%. Fuel consumption was not quantified due to inadequate funds being available to optimize the port timing program required to significantly reduce fuel consumption.

This compound version maintained the compact form of the simple rotary engine while using components common to both the compressor/expander (CE) section and the power section. By supercharging the intake charge, the issue of volumetric efficiency was eliminated. It also allowed the compression ratio of the power rotor to be lowered which reduced the surface to volume ratio of the

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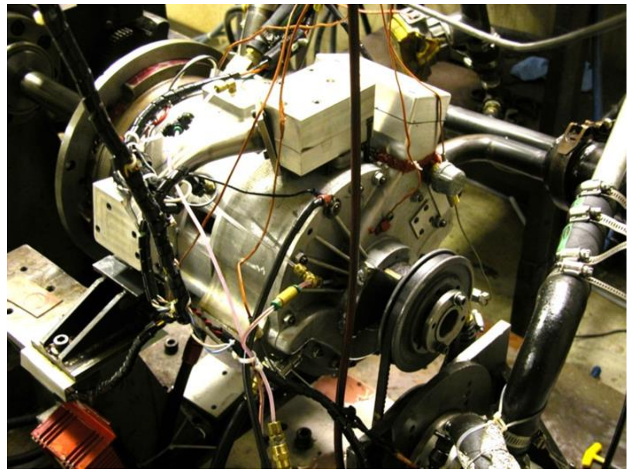
Freedom Motors 294cc Compound Rotary Engine on Dyno stand



Freedom Motors 530cc Compound Rotary Engine on Dynamometer

combustion chamber. As exhaust gases exited the power rotor, they reentered the CE rotor with its 15:1 expansion ratio. This, together with the 7:1 power rotor expansion ratio resulted in an effective overall 18:1 expansion ratio (very extended Atkinson cycle). Consequently, the exhaust gases left the exhaust port of the CE rotor at low pressure, with little acoustical energy. With the added ports and their associated timing, the parameters involved in optimizing thermal efficiency have been significantly increased. A modest decrease in SFC was noted, but this engine will need significant additional development to achieve the expected 20% to 25% reduction in SFC that NASA believes could lead to a SFC as low as 0.3 lb./hp.*hr.

More recently the U.S. government is moving to have a one-kilowatt co-genset installed in every home in the U.S. with access to natural gas (80 million homes). For this application, FM is creating a compound version of its 27cc engine. The government's goal for this Combined Heat and Power (CHP) application is a thermal efficiency of 37% and a noise level of 55 dba. Existing engines of this size (approximately 2HP) are unlikely to achieve a thermal efficiency greater than 25%, simultaneously, achieving the 55 dba noise level could prove nearly impossible with any reasonably sized muffler and muffling enclosure. It is believed that achieving 37% thermal efficiency will not only require that the engine be compounded, but that it also operate at a higher combustion temperature through reduced heat transfer from the combustion process to the rotor housings and rotor. This would require a thermal barrier coating (TBC) to all components exposed to the combustion process. The engine would also need a solid lubricant similar to the PS 400 coatings developed by NASA. FM successfully developed a way to use this solid lubricant in its rotary engine under a SBIR Phase II contract (1995 NASA Contractor Report 195445).

FM plans to concentrate on completing the development of a compound version of its 27cc Rotapower® engine as the list of potential candidates for this model continues to grow.