9913

The Emissions Performance of the Rotapower® Engine

Paul S. Moller, Ph.D.
Freedom Motors

FREEDOM MOTORS

Freedom Motors
410 Gateway Plaza, Suite G
Dixon, CA 95620
www.freedom-motors.com

9913

The Emissions Performance of the Rotapower® Engine

Paul S. Moller, Ph.D.
Freedom Motors

ABSTRACT

This paper discusses the emissions performance of the Rotapower engine. This performance is compared to other types of engines. The attributes of this engine that make it a clean powerplant are described.

ENVIRONMENTAL CONCERNS ABOUT THE EMISSIONS OF INTERNAL COMBUSTION ENGINES DRIVE THE NEED FOR CLEANER POWERPLANTS

Internal combustion (IC) engines are everywhere, from the family SUV in America to the two-stroke motor scooters in Hong Kong to the portable power units in developing countries. Around the world legislators are responding to the increasing emissions by tightening the allowable limits on IC engines. Engine manufacturers are continually working to reduce the emissions levels produced by their power plants. Most modifications increase the complexity and the cost of the engine. The Rotapower engine is designed from its inception to be a clean burning powerplant. What is most impressive about its very low emission production is that this is accomplished without additional exhaust after-treatment or the complexities of costly direct fuel injection.

EACH EMISSION CONSTITUENT IS FORMED AND DEALT WITH UNIQUELY

There are four main emissions components that must be considered for any IC engine:

- HC - unburned hydrocarbons, which can be simplistically thought of as unburned fuel
- CO - carbon monoxide
- NOx - oxides of nitrogen, a grouping of NO and NO_2
- Particulate matter - particles suspended in the exhaust

Each of these emission constituents is produced by a different mechanism in the combustion process and therefore the means to minimize its production is different. Maximizing the combustion efficiency minimizes HC production by eliminating regions in the combustion chamber where the fuel air mix might get trapped and remain unburned. It is desirable therefore to minimize low temperature regions in the combustion chamber, which might quench the burning process, resulting in unburned fuel. Unburned hydrocarbon production increases rapidly with insufficient oxygen present as does CO. This can result when operating below the air to fuel ratio required to generate a stochiometric mixture (the mixture which results in the theoretical amount of available fuel and air necessary for complete combustion (A/F = 14.7)). It is important to get enough turbulence in the combustion chamber to ensure an even mixture and eliminate local regions where the fuel to air ratio is below 14.7. The swishing effect of the rotary engine's geometry on the air fuel mixture as its rotor approaches top dead center is of great benefit in achieving an even mixture.

Carbon monoxide is also produced when there is insufficient oxygen to fully reduce all the carbon in the fuel to CO_2. This is especially prevalent when the engine is running with an air-fuel ratio less than 14.7 (a fuel-rich mixture).

Oxides of nitrogen are produced in the environment created by the combustion process not by the process itself. They are formed in the wake of the combustion flame in the high temperature burned gases, the higher the burned gas temperature and pressure, the greater the formation of these oxides. The most important engine variables affecting NOx emissions are:

- The air-fuel ratio - NOx production is maximum when operating near the stoichiometric mixture.
- Spark timing - the point before TDC (top dead center) at which ignition occurs. Retarding the spark timing, or igniting nearer TDC, reduces the peak combustion temperature and pressure which results in reduced NOx production.
- Exhaust gas recirculation (EGR) - recirculating a portion of the exhaust gas into the combustion process increases the bulk mass of

the mass to be ignited. This reduces the combustion flame front temperature and consequently the NOx formation.

Particulate matter is of concern in engines where the fuel is injected directly into a highly pressurized combustion chamber. This injection causes the fuel to enter the high-pressure region as a mist of droplets as opposed to vapor. Some carbon portion of these droplets remains unburned because of the finite time required to complete combustion. The size of the resulting particulates is on the order of 0.1 - 20 microns. Research has shown this process can create particles that are carcinogenic. Particle sizes below 5 microns are most worrisome since they are smaller than the natural filtering mechanism in the human lungs[1].

While different types of fuels have a tendency to create more of one type of emission than another, all fuels can benefit from engine attributes, which minimize the production of emissions. The Freedom Rotapower engine is based on the Wankel rotary engine, which was first patented in the late 1950's by Felix Wankel. The Rotapower engine uses the incoming fuel-air charge to cool the rotor, a concept that was put into production by Outboard Marine Corporation (OMC) for snowmobiles in the early 70's. In order to minimize rotor housing, seals, rotor and bearing temperatures, this OMC engine was, of necessity, operated at air-fuel ratios well below stoichiometric mixture. Extensive research and proprietary modifications to this engine design by Freedom Motors has allowed the rotor to operate in a lean burn mode, with air-fuel ratios greater than 20. This together with the pre-heated incoming charge inherent in a charge cooled rotary engine, has led to remarkably low production of all four-emission constituents.

ROTAPOWER ENGINE COMBINES THE BEST OF TWO-STROKE POWER WITH FOUR STROKE EMISSIONS PERFORMANCE

In applications where low cost, high power and lightweight are required, such as in the recreational marine industry, two-stroke piston engines are in widespread use. A traditional two-stroke piston engine eliminates the hardware necessary to isolate the intake process from the exhaust process, in doing so the cost and weight of the engine are substantially reduced. However, the efficiency of the combustion process is also reduced. It has been estimated that 20-30% of the fuel used in a traditional two-stroke engine is passed through to the exhaust[2]. This unburned fuel having passed through the combustion process becomes a class of compounds known as polycyclic aromatic hydrocarbons, which are known to be carcinogenic, and mutagenic[3]. In addition the oil used to lubricate the engine, which is introduced into the incoming airstream or premixed in the fuel, also can end up in the exhaust, as either unburned hydrocarbon or additional particulates.

Unburned hydrocarbon emissions from a two-stroke engine can be anywhere from 10-100 times greater than a four-stroke engine of comparable power. Figure 1 shows the comparative HC emissions of a traditional two-stroke engine versus the Rotapower engine in a personal watercraft application. An abundant amount of exhaust gas recirculation makes two-strokes produce little NOx. Two-strokes also produce high amounts of CO due to the lack of uniformity of the fuel distribution in the combustion process. The lack of mixture uniformity creates local regions of insufficient oxygen resulting in incomplete combustion of the fuel.

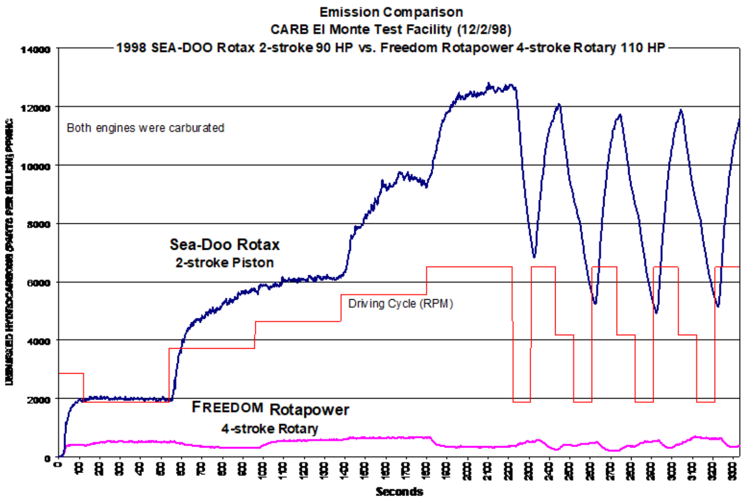


Figure 1: Comparison of HC Production

Manufacturers of two-stroke engines have gone to costly direct fuel injection to help minimize HC output. While this has cut the HC emissions of the two-stroke by 50-75% it has aggravated the problem of particulate production. In particular it has introduced the newly recognized problem of smaller particulates in the sizes (<5 microns) that are carcinogenic.

The Rotapower engine operates on the four stroke operating principle using the Otto Cycle. Engines operating on this principle inherently use fuel more efficiently. What is unique about the Rotapower engine is its ability to use this efficient cycle in a package that delivers superior power to weight ratio and power to volume ratio at a product cost comparable to that of the two-stroke engine. Table 1 below outlines these comparisons.

Engine	Max HP	Weight (lbs.)	Volume (ft^3)
Rotapower Dual	110	74	1.3 (16"x11"x13")
2Si 808 L-100[4]	100	112	3.4 (17"x28"x12")

Table 1: Power Density Comparisons

THE CHARGE COOLED ROTAPOWER ENGINE IS DESIGNED TO BE A CLEAN BURNER

While the four-stroke operating principle of the Rotapower engine easily improves upon the emission performance of the less efficient two-stroke engine, it also has several features that make it a low emission engine compared to many four stoke piston engines. Rotary engines have historically been thought of as a potentially dirty engine when compared to four-stroke piston engines. This idea stems from the fact that the combustion chamber in the rotary engine is long and thin, with a higher surface to volume ratio. This geometry is more likely to quench the burning process, resulting in higher emissions, particularly HC, than the lower surface to volume ratio geometry found in piston engines. However there are other attributes of the rotary engine, particularly with charge cooling, which offset the disadvantages caused by the shape of the combustion pocket. These include an elevated incoming charge temperature, increased rotor face temperature, exhaust recirculation, lean burn capability combined with partial charge stratification and a high exhaust temperature.

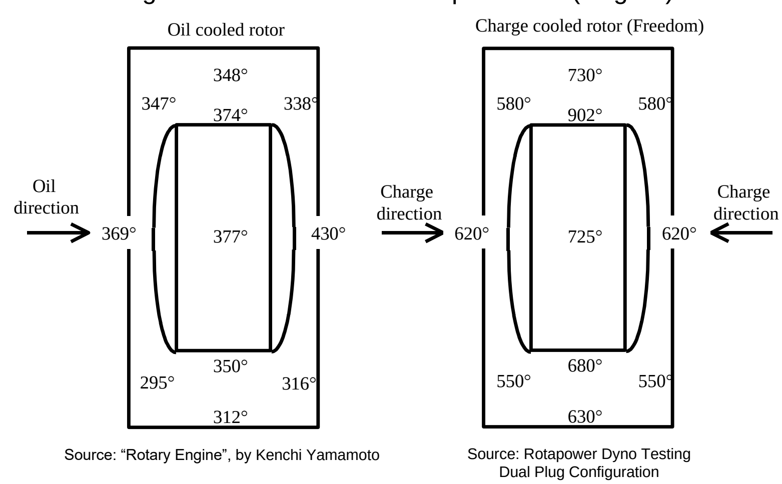
The process of using the incoming charge to cool the rotor has two effects. The first is to fully vaporize the charge. This is important because a fully vaporized mix is inherently less susceptible to quenching. Complete vaporization also reduces the possibility of particulate formation in the combustion process. The second effect is an increase of the charge temperature itself. The incoming charge is heated to approximately 250 deg. F as compared to near ambient conditions for two and four stroke piston engines. This increased temperature also reduces the tendency to quench the combustion flame. While the preheating of the charge does decrease the volumetric efficiency of the engine, this loss is balanced by the elimination of cooling hardware and the advantage of more complete combustion.

Exhaust gas recirculation is a successful technique used to mitigate NOx. In the Rotapower engine exhaust recirculation is ensured by the increased overlap of the intake cycle with the exhaust cycle at a higher power setting. Because the Rotapower engine can vary, the intake-exhaust overlap. This variable port overlap contributes to the very low amounts of observed NOx emissions.

The rotor face temperatures of the charge cooled Rotapower engine are significantly higher than its oil cooled rotor alternative. The charge-cooled rotor has combustion surface temperatures that are over 400 deg. F hotter than an oil-cooled rotor. These higher temperatures will reduce combustion quenching particularly in a higher surface to volume combustion chamber like the rotary engine. The design of the charge-cooled rotor must be capable of surviving these elevated temperatures. In addition, it must dissipate this heat in a way that minimizes its transmission to the internal rotor bearing. Freedom Motors has developed a proprietary rotor design that has demonstrated the necessary survival and heat transfer characteristics.

One of the unique characteristics of the rotary engine is that while it uses the four-stroke operating principle, it does so without the use of valves. In a four-stroke piston engine the valves can become very hot when running with lean mixtures. In part this is because the fuel in the charge helps cool the edges of the valves during normal operation. With lean mix burn, this cooling source is diminished. More importantly, lean mixtures burn slower and may still be burning as the gases exit past the exhaust valve. With no valves to overheat, the rotary can operate effectively in lean burn conditions. Additionally, the long slender shape of the combustion chamber helps maintain a partially stratified charge. With a richer, more ignitable, mixture at the spark plug, this burning mixture can readily ignite the leaner mixture elsewhere.

Figure 2: Rotor Face Temperature (deg. F)



Charge stratification is more easily achieved in a rotary engine for a number of reasons. The intake stroke of the rotary engine is 50% longer than the four-stroke piston engine. This allows greater latitude in injecting the fuel at the critical portion of the cycle. In addition the geometry of the combustion chamber tends to keep the entire volume of the chamber from mixing, as occurs with the more cylindrical volume of the piston engine. Therefore despite using a lean overall mixture the fuel can be port injected early in the cycle and provide a richer mixture near the spark plug for good initial combustion.

The combustion process in the rotary engine always takes place at the same region of the rotor housing. Because the intake charge does not see this high heat flux region there is less chance of pre-ignition or detonation. The combustion surface temperature of the housings can, therefore, be maintained at a higher temperature by transferring less heat to the cooling system. The charge-cooled rotary engine rejects approximately one-half as much heat to the cooling system as a four-stroke piston engine does. Consequently much of this heat ends up in the exhaust. This increases the exhaust temperature where it sets up a naturally occurring thermal reactor for reduced emissions. This higher quality exhaust energy is available to be extracted as useful energy by, for example, an exhaust driven turbine.

HC and CO emissions can be eliminated from exhaust either catalytically, by the use of chemical reaction, or thermally by burning them with excess oxygen. In order to burn the residue hydrocarbons, the exhaust gases must be resident at a temperature of at least 1100 deg F. To oxidize CO requires a temperature of 1300 deg. F. With exhaust temperatures in 1400-1700 deg. F ranges, the Rotapower engine has more than sufficient thermal energy to minimize these emission components.

THE ROTAPOWER ENGINE DOES NOT PRODUCE THE CARCINOGENIC EMISSIONS OF USING DIRECT FUEL INJECTION ENGINES

All IC engine exhausts are a complex mixture of inorganic and organic products materials. However, IC engines, which inject fuel directly into the high pressure of the combustion chamber, always produce significant particulate emissions. Particulate emissions are generally much lower in properly carbureted or port fuel injected engines. Diesel engines produce particulates at a rate about 20 times greater than port injected or carbureted gasoline engines. Over 90 percent of the mass of these diesel exhaust particles is less than 2.5 microns in diameter. Because of their small size, these particles are easily inhaled into the bronchial and alveolar regions of the lung. Particulate matter has been associated with approximately 50% to 90% of the mutagenic potency of the whole diesel exhaust[5].

In diesel engines fuel is required to be directly injected into the combustion chamber under high pressure. The injection rate controls the combustion pressure rise during the expansion stroke. The fuel-air mixture would detonate if the diesel fuel was introduced into the combustion chamber via an intake charge. Research shows that the highest particulate concentrations in compression-ignited diesels are found in the core region of each fuel spray where the local air/fuel mixture is running very rich[6].

Two stroke engines manufacturers have begun introducing direct injection models to the market. Most of these models use either the Ficht or Orbital injection systems. Both systems inject fuel under pressure late in the compression cycle where little time exists for achieving uniformity of the fuel distribution. The Ficht system uses an electromechanically controlled piston while Orbital uses compressed air. The mechanism for injection may vary, however, these engines are still susceptible to particulate production due to the richer mixture of fuel in the injection region. Toyota has recently reported elevated particulate matter emissions (under 2.5 microns in size) in their direct injection gasoline engine designs[7].

The Rotapower engine has a unique advantage over the piston engine in its ability to operate on the traditional four-stroke Otto cycle using diesel fuel. Since diesel fuel has a very low effective octane rating (40 to 60) it would detonate in a piston engine where the fuel/air mixture is homogenous and combustion begins through spark ignition. The lengthy combustion chamber of the Rotapower engine provides as opportunity to slow the combustion process and allow the Rotapower engine to operate using diesel fuel. This capability was demonstrated under contract to the US Army.

Without the need for direct injection together with the total vaporization of fuel in the intake charge by charge cooling, the Rotapower engine does not produce the particulates that are common to traditional diesel or other direct injection engines.
The power to weight ratio for the diesel fueled Rotapower engine is many times greater than a traditional diesel cycle engine.

BY COMPARISON, THE ROTAPOWER ENGINE IS THE BEST OVERALL PERFORMER IN MINIMIZING EMISSIONS PRODUCTION WITHOUT AFTER-TREATMENT

The engines discussed in this paper utilize different arrangements for the conversion of fuel into mechanical power. The combustion process of each is different enough such that the emission constituents vary from engine to engine. Figure 3 compares the untreated emissions from various engines of similar power output operating with different fuels. The emission production is measured in grams per horsepower-hour, which allows for the accurate comparison of engines of somewhat different sizes. The comparisons are made for untreated exhaust emissions. Some of the engines can utilize after-treatment to reduce these values, some may not. Two-stroke engines, for example, cannot use the traditional after-treatment offered by catalytic converters. The oil in the exhaust of a two-stroke engine quickly clogs up the converter. In addition, the low exhaust temperature drastically reduces the efficiency of catalytic type after-treatment. While the four stroke piston engines and diesel engines can use after-treatment, doing so increases cost and, eventually, the efficiency of the these subsystems degrades.

The Rotapower engine is able to minimize the production of all four major emission constituents without the additional cost of after-treatment and in doing so can maintain optimum emissions performance throughout the engine lifecycle at much less cost.

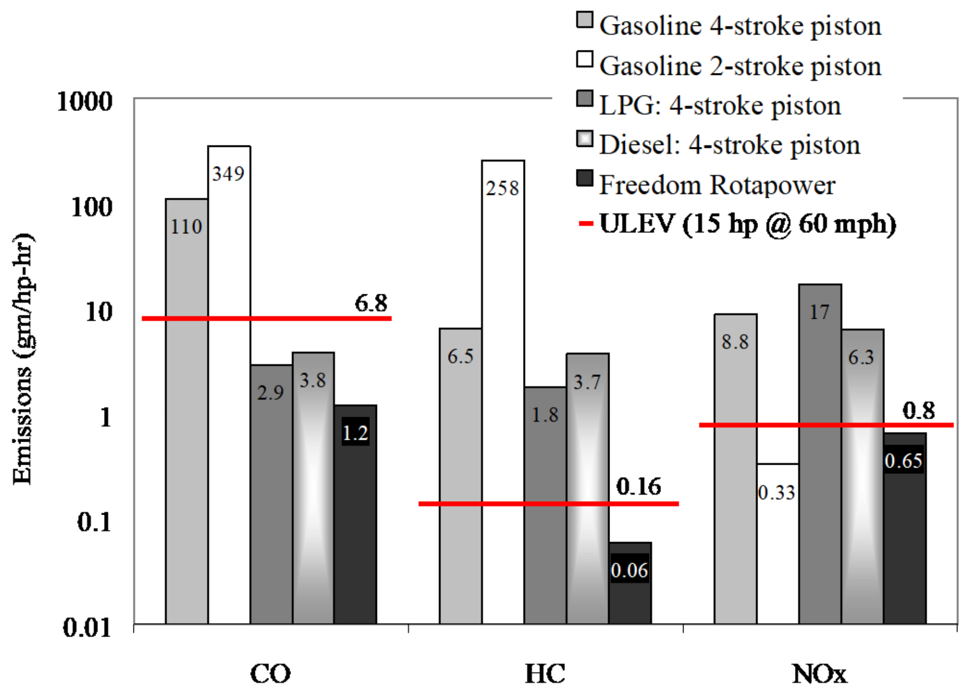


Figure 3: Comparative Emissions Performance [8, 9]
ULEV is the California Ultra Low Emission Vehicle Standard

REFERENCES

[1] CARB Staff Report, "Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant", June 1998, page 4
[2] State of California, Air Resources Board, Staff Report, "Public Hearing to Consider Adoption of Emissions Standards and Test Procedures for New 2001 and Later Model Year Spark-Ignition Marine Engines", October 23, 1998, page 15
[3] Hilchey, Tim, "EPA Studies How to Clean Up the Wakes of Motor Boats." New York Times, May 17, 1994
[4] 2-Si International Specification Sheet, "808 L-100"
[5] CARB Staff Report, "Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant", June 1998, page 4
[6] Heywood, John B., Internal Combustion Engine Fundamentals, page 632
[7] CALSTART, "Toyota Introduces Direct-Injection Gas Engine", News Notes, 7/3/98
[8] SAE 931541, "Baseline and Controlled Exhaust Emissions from Off-Highway Vehicle Engines"
[9] Burke, Andy, Ph.D., Letter of Witness to Rotapower Engine Testing, Institute of Transportation Studies, UC Davis, 1/10/97

FREEDOM MOTORS
410 Gateway Plaza, Suite G,
Dixon, CA 95620

www.freedom-motors.com