THE ROTARY WANKEL ENGINE, AN ALTERNATIVE TO THE RECIPROCATING ENGINE

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1. INTRODUCTION

The reciprocating internal combustion engines, have been aiding humanity in a satisfactorily way for already more than a century, and they are going to continue doing it in our near future; this considering the advances of technology in our days. The Rotary Wankel engine is a recent development in the internal combustion engine world, and it presents to us as a different alternative to spark ignited engines.

We owe this development to Felix Wankel that in 1957 put to work the first of these motors in a functional way. The rotary engine fulfills a series of advantages that makes it a formidable contender to make some of the tasks that the reciprocating engines carry out.

The piston movement of the reciprocating engine (The one in our most common cars, →CARS) has two points where the speed is zero in a middle turn of the piston; in the superior point and in the inferior of its stroke, then so 4 times by cycle momentarily it stops and its direction of movement changes; unlike the movable parts of the rotary engine that are in continuous and linear unidirectional movement.

Rotary engines perform greater speeds of operation; absence of unbalance and vibration are some of their advantages. Their high speeds of operation allow the machine to produce the double power that a reciprocating motor of the same weight. It has a significant minor number of pieces and occupies a minor volume than a reciprocating motor with a comparable power.

With all these advantages a question arises: *Why the Rotary Wankel engine is not as used as the reciprocating engine?* The answer lies in the continuous improvement of the reciprocating engines by more manufacturers; its standardized techniques of manufacturing and a spread number of uses, which are our common day consuming. In addition to the more costly techniques of manufacture (compared to the other motors) of the rotary engines, is added the elevated fuel consumption compared to its competitors in the automotive industry and therefore its greater polluting emissions; point that has managed to improve the reciprocating engines and the gas turbine engines. Because of these features it's why this type of motor will never dominate the automotive industry, but their uses are possible in applications where the low weight power ratio and "low" volume are critical, like we can see in the competition automotive industry, aviation in general, snow vehicles, motorcycles and hobbies such as radio controlled aircrafts.

2. THE ROTARY WANKEL ENGINE

This section will discuss a brief history, the specs of the Rotary Wankel engine as an internal combustion engine, its processes, operation, parts, and general aspects of these engines.

2.1. Overview

In 1954 Dr-Ing. Felix Wankel in cooperation with NSU (First manufacturer of Wankel rotary engines) were the first able to successfully develop a rotary engine. (From now on the engine will be referred as NSU-Wankel type)

The rotary combustion engine is a power producing machine, where the piston rotates in elliptical manner according to a line that passes through the cylinder perpendicularly (axis rotation sense); it must not be confused with the "rotary" aircraft engines which are pistons cylinders arranged in a circle like the gnome engine widely used in the First World War. See: →Gnome

There are three basic types of rotary engines:

- Wankel types based on eccentric rotors (the one in study)
- Scissor action types using vanes or pistons (Like the Talo rotary engine)
  →TALO 1 →TALO 2
- Revolving block types →REVOLVING

Up to this day many types of machines to develop motive power have been designed and thought of. Most of these machines are of rotary motion but because of the difficult configurations, though the idea is simple (like the ones seen in the three basic types above) the reciprocating pistons were developed first and introduced to the most common applications.

The reciprocating engines have the following problems:

- Because of the reciprocating parts, vibration, noise and power loss increase as the engine revolutions augment.

- As a result of its mechanism engines are heavy and voluminous to give space to crank shafts and cams.
- Because it has an intake and exhaust mechanism, are needed many parts and also noise is generated.

The rotary engine does not require intake exhaust mechanism nor cranking one; for this reason it's been subject of study and research through the years. A short history will be presented:

2.1.1. History of an invention

1588
Ramelli, an Italian engineer invented a water pump which continues to be used in oil pumps and compressors. → Ramelli

1636
Pappenheim, a German engineer invented the gear pump which is still used to lubricate engines. This gear pump made it possible to dispense with the reciprocating slide valves used by Ramelli. →Gear Pump

Pappenheim drove his machine by an overshot water wheel set in motion by a stream and was used to feed water fountains. The emperor Ferdinand II granted him a "privilege" - the equivalent of a patent in respect of this invention.

Even in the 17th century, engineers were trying to solve the problem of "leak-proofing" between moving parts and this problem continues to be the Achilles heel of the rotary piston engine although Mazda would seem to have reduced this problem to manageable proportions.

1650
Otto von Guericke built a vacuum pump which employed leather washers to prevent leakage between cylinder and piston.

1782
James Watt who invented the steam engine's connecting rod crank mechanism which made it possible to convert the piston's reciprocating motion into rotary motion designed an oscillating piston machine in which a wing-shaped rotary blade performed an almost complete revolution uncovering inlet ports in a chamber separated off by a curved radial wall.
→Watt

1799
One of Watt's co-workers, Murdock, adapted Pappenheim's gear pump to create a rotary piston steam engine.
→Murdock's

1846
Elijah Galloway built the first rotary piston engine with inner epicycloid and enveloping outer line.
→Galloway's

1859
Jones, modified Pappenheim's gear pump and produced a double rotor with only two teeth per gear. Rootes compressors and pumps employ this principle.
→Jones

1900
Alotham and Franchot designed a vane compressor comprising a bust rotating inside a cycloidal housing.
→Franchot's

1901
The American, Cooley, lodged a patent for a rotary piston engine with an internal epicycloid and enveloping outer chamber.
→Cooley's

1908
The Englishman, Umpleby, transformed Cooley's steam engine into an internal combustion engine but experienced problems with gas tightness.
→Umpleby's

1923
A Swedish patent was granted to Wallinder and Skoog in respect of a true rotary piston thermal engine with toothed meshing, enveloping interior hypocycloid and internal five pointed rotor with a 5:6 rotation ratio which could be used as either a two or four stroke internal combustion engine.
→Wallinder and Scoog's

1938
Sensaud and Lavaud, (the French engineers responsible for the Traction Avant automatic gearbox which was a failure) applied for a patent for a rotary piston engine with internally meshing gears in a hypocycloid housing and a 5:6 reduction ratio. Both Renault and Citroën, at the instigation of the French Air Ministry provided backing for this project and a number of engines were built at

Batignolles. Unfortunately the engine failed to live up to expectations and the project was abandoned.
→Sensaud de lavou's

1943
The Swiss manufacturer Bernard Maillard built an air compressor based on a British patent for a rotary piston machine with a 2:3 ratio and internal hypocycloid surfaced chambers. Leakage under pressure made it impossible to use this design as a thermal engine.
Maillard's

1953 to 1954
DKM 53 (Drehkolbenmotor or "rotary piston engine). The first rotary engine is concieved. Now working for the N.S.U. company, Wankel presents full detail drawings of what was to become the Rotary engine we know today.

1954
DKM 54 .An advance on the earlier engine is designed.

18 April 1956
First production scetches made for Wankel's new Rotary engine.

1 Februrary 1957
First trial run of DKM 54.

1957 later
DKM 125 (125cc capacity) was constructed and achieved 26 horsepower at 15000rpm during testing. Another DKM engine was taken to 25000rpm in a special safety tunnel. →DMK 125

1 July 1958
KKM 125 , weighing 37lbs, is tested for the first time. →KKM 125

1954 to 1958
N.S.U. and Wankel take out 30 patents covering all aspects of the new engine design.

21 October 1958
Aircraft company Curtis-Wright pays $700,000 for an exclusive licence to produce the engine in the U.S. and a non-exclusive licence for the rest of the world (except Germany).

1958 to 1959
Curtis Wright produce two engines. The RC 1-60, a single rotor of 60 cubic inches(8 times the size of the DKM 125), and the RC 2-60, a twin rotor version of the RC 1-60. Other models produced around this time by Curtis Wright include the RC 4.3 (small, 25lb, air cooled engine), the RC1 1920 (a monsterous engine producing 800 horsepower).

1958
N.S.U. release the rotary powered Prinz. → Prinz

12 November 1959
Full Page advertisements appear in newspapers announcing the iminent arrival of a revolutionary new engine by Curtis Wright.

2 October 1960
Provisional Agreement between Mazda and NSU regarding Rotary developement and manufacture.

4 July 1961
Formal Contracts signed between Mazda and NSU regarding Rotary developement and manufacture.

1962
N.S.U. market small marine adaptaion of the rotary.

April 1963
Mazda establishes the Rotary Engine Research Division.

1963
N.S.U. Spider is launched at the Frankfurt Motor Show.
(engine-KKM 502, one rotor) →Spider

1963
Toyo Kogo gain full licence for Rotary engine design.

1964
Mazda Cosmo Sport launched at the Tokyo Motor Show.

1966
Mazda Cosmo Sport 110S exhibited at Tokyo Motor Show. Launched on 30 May 1967. (10A)

September 1967
N.S.U. Ro80 is launched at the Frankfurt Motor Show. →Ro80

1968 to 1969
C-111 project designed by GM engineer Rudi Uhlenhaut, ex Damlier. Offered 3 and 4 rotor models but did not go into production. →C-111

August 1968
Mazda Cosmo Sport 4th in Nurburgring 84 hour endurance race. →Cosmo

1969
Mazda R100 released. (10A) →R100 →R100

13 May 1970
Mazda RX2 released. (12A) →RX2

6 September 1971
Mazda RX3 released. (12A) →RX3

March 1973
Mazda RX4 released. (12A)

1974
Mazda RX4 released. (13B) →RX4

1976
Mazda RX5 released. (13B) →RX5

1978
Mazda RX7 series 1 released. →RX7 1

October 1979
Mazda RX7 series 2 released→RX7 2

October 1983
Mazda RX7 series 3 released.

1986
Mazda RX7 series 4 released.
Mazda RX7 series 5 released.

1991
Mazda RX7 series 6 released at Tokyo Motor Show. RX7 91

1991
Mazda wins the Le Mans 24 classic with its 787B R26B race cars. →787B

1999
RX-EVOLV at the 1999 Tokyo Motor Show→RX8

2.2. The Rotary Wankel combustion engine, is an Otto cycle engine

The NSU - Rotary Wankel engine is an internal combustion engine (The internal combustion engine is the most common source of power cycle) This one performs the four strokes of intake, compression, expansion and exhaust (→ OTTO)while the working chamber changes its volume and the moving parts always rotate in the same direction. The three basic moving parts in the engine are: rotor(s) and eccentric shaft; these are surrounded by the peripheral housing where the rotor tip traces out an epitroichoid curve.

But the NSU-Rotary Wankel engine also can be described by the Diesel cycle, depending on the ignition source (spark or compression source). The efficiency of both the Otto cycle engine and Diesel engine is dependent on the compression ratio; this two parameters are dependent on only upon the geometry of the engine specially on a parameter called *eccentricity ratio* described in section **2.2.3.1**. That is, when the *eccentricity ratio* is fixed the *compression ratio* is independent of the size of the engine the same as the theoretical thermal efficiency:

Otto Cycle:

$$\eta_{th,Otto} = 1 - \frac{1}{\varepsilon_{th}^{\,k-1}}$$

Equ. 1

Diesel Cycle:

$$\eta_{th,Diesel} = 1 - \frac{1}{\varepsilon_{th}^{\,k-1}}\left[\frac{r_C^{\,k} - 1}{k(r_c - 1)}\right]$$

Equ. 2

Where→. ε_{th} is the Compression ratio, and r_c is the Cutoff ratio.

2.2.1. BASIC STRUCTURE AND FUNCTIONING

The basic parts of the NSU-Wankel type rotary engine is shown below in Fig 2.1

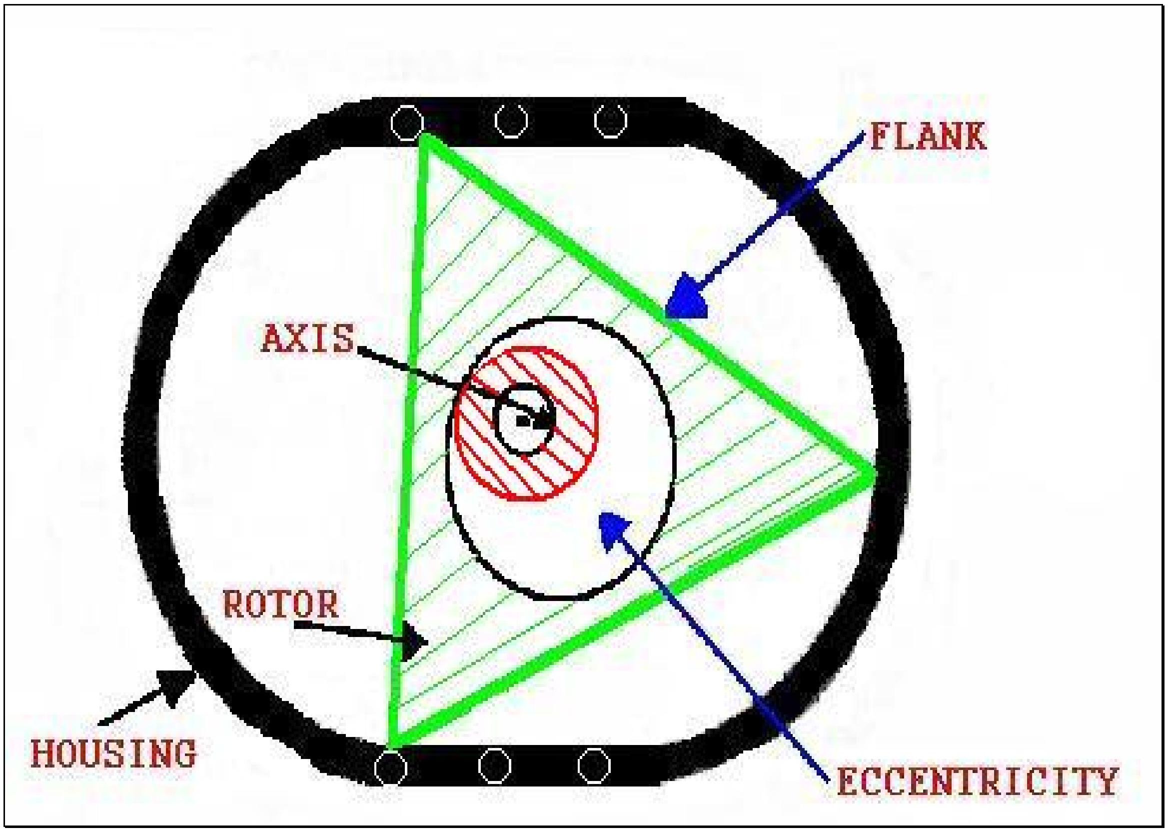


Fig. 1

The basic cycle diagram is shown below in Fig.2

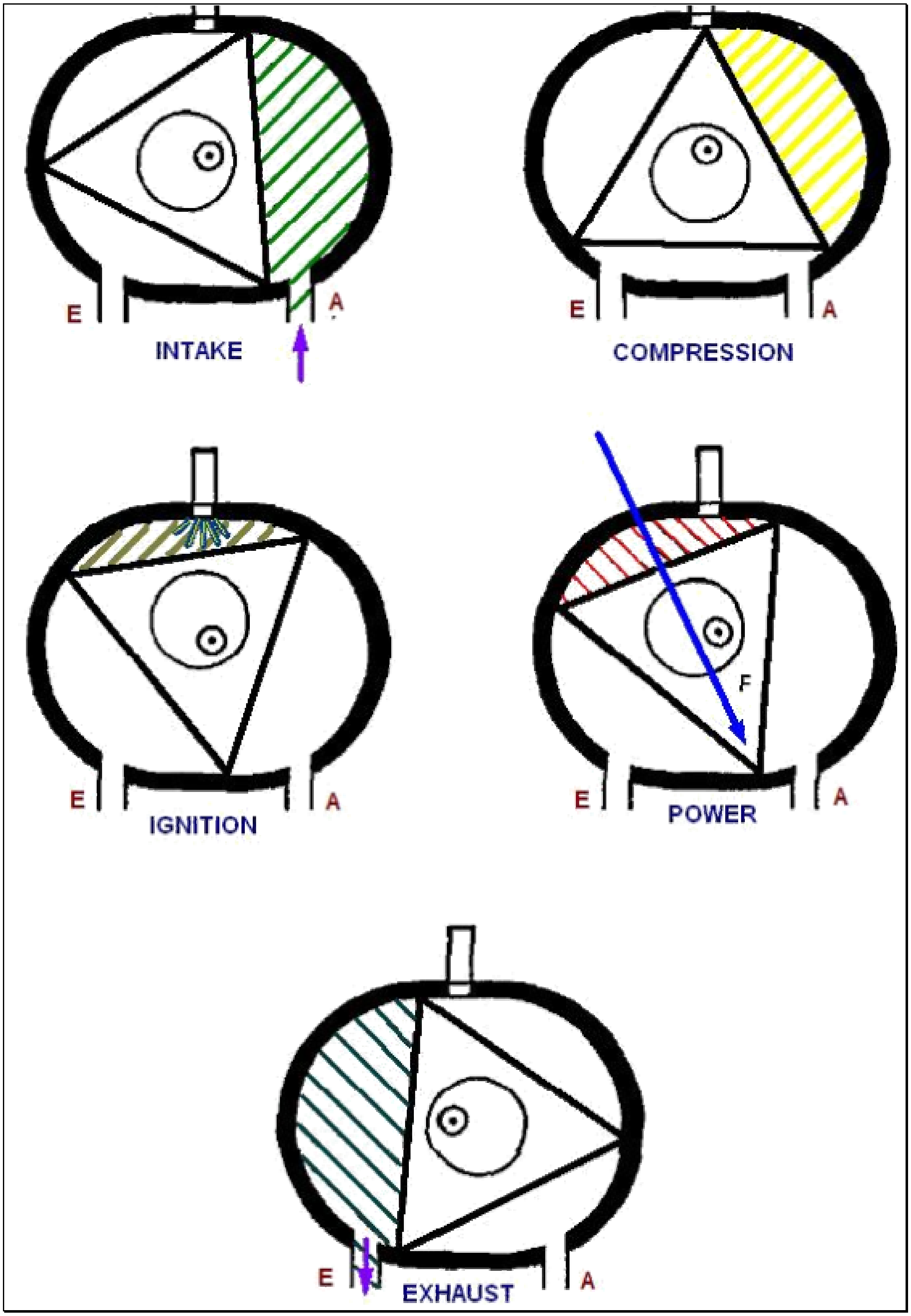
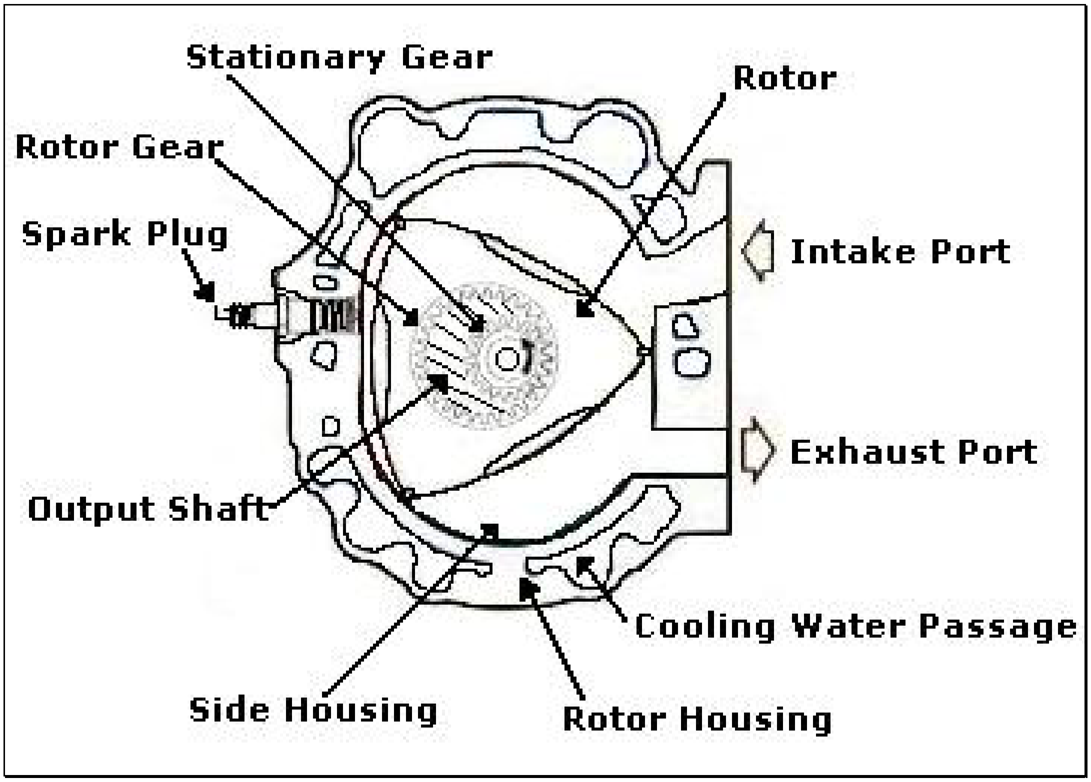


Fig. 2

As shown in the figure above, unlike the reciprocating engine, the fuel air mixture is swept along, so the four phases take place in different areas of the engine.

The basic structure of the NSU-Wankel type rotary engine is shown below in Fig.3

Fig. 3



For Better understanding of the engine in Fig.1 is shown its rotary motion and mechanical configuration. In the figure, it's shown a section of a simple rotary engine. The stationary housing (Supercedes the piston's engine cylinder) shape is an epitrochoid (An epitrochoid is generated by rolling a circle around another circle → Epitrochoid) and it is stationary. Inside the housing is a triangular rotor (Supercedes the piston in a reciprocating engine) which rotates with its apexes in constant contact with the housing inner surface. The air fuel mixture and the exhaust gases are transported inside the spaces formed by the rotor and housing. The rotor moves in an eccentricity which is integral part of an axis (Supercedes the piston engine's reciprocating piston).

2.2.2. PRINCIPLE OF OPERATION, FEATURES

Fig2. Shows the operation of the rotary engine (cycle) and the hyperlink its animated cycle → ANIMATED NSU-WANKEL ENGINE. In the intake phase; the volume of the working chamber gradually expands as the rotor rotates in sequence the volume with that pack of mixture moves and passes the intake port, having a control mass. Then in compression, the volume diminishes and the mixture's density increases; then in the compression top dead center the mixture is ignited by a spark plug (or glow plug); after this begins the expansion stroke and the exhaust port is encountered and the gases begin to be swept away as the rotor continues it's movement, and allowing all the exhaust gases outgo the engine, as a difference to reciprocating engines that can't as a reason to the space between the piston's top dead end and the valve housing.

As compared with the reciprocating engine, the rotary engine has the following basic features:

1. There are no reciprocating parts. Since reciprocating engines have reciprocating parts, there are problems of unbalance caused by the inertia of reciprocating parts and complicated engine vibration. As the rotary engine is structured by of only rotating parts, vibration is null compared to the reciprocating ones; this is done by using balancing weights which are putted in the engine to give it perfect balance. In Fig.4 can be seen the difference in number of parts between the two type engines.

   Also, since the rotary engine, does not require a cranking mechanism, it has the advantages of smooth motion, less mechanical loss, simple construction, and compactness. In Fig.5 can be observed how different in size the reciprocating and rotary engines are, this taking into account the number of cylinders and rotors of a rotary engine. Normally the rotary engines in the automotive industry have 2 rotors and the reciprocating engine four, six and eight cylinders.

2. There are no intake-exhaust mechanisms, so there is no noise induced by the opening and closing of the valves and the valve as it's positioned impedes the natural flow of gases and mixture. Another problem is that for valves at high revolutions it's difficult to follow the cams. Since the rotary engine has the

property of passing and sweeping the mixture and expulse the exhaust gases, then it's no problem at high revolutions and the exact timing of inlet and outlet of fluids is maintained at all revolutions ranges.

3. The time for one stroke is 270 degrees in terms of the rotating angle of the output shaft, and one explosion occurs at one rotation of the output shaft. The long engine stroke means that the volumetric efficiency becomes higher even at the high speed range, and reduces the torque drop. Also, the long expansion stroke means that it is better in terms of torque fluctuation. In a rotary engine that has two rotors, the expansion stroke overlaps so the torque fluctuation is as low as in the case of a six cylinder reciprocating engine.

As a resume, the rotary engine has the outstanding features of light weight, compactness, less noise and vibration, flat torque characteristics etc. For vehicles with a rotary engine it's more easy to play with the space and design of the body of the car, for performance and comfort; also, the driver will experience quieter, more comfortable and more responsive driving.

Fig. 4

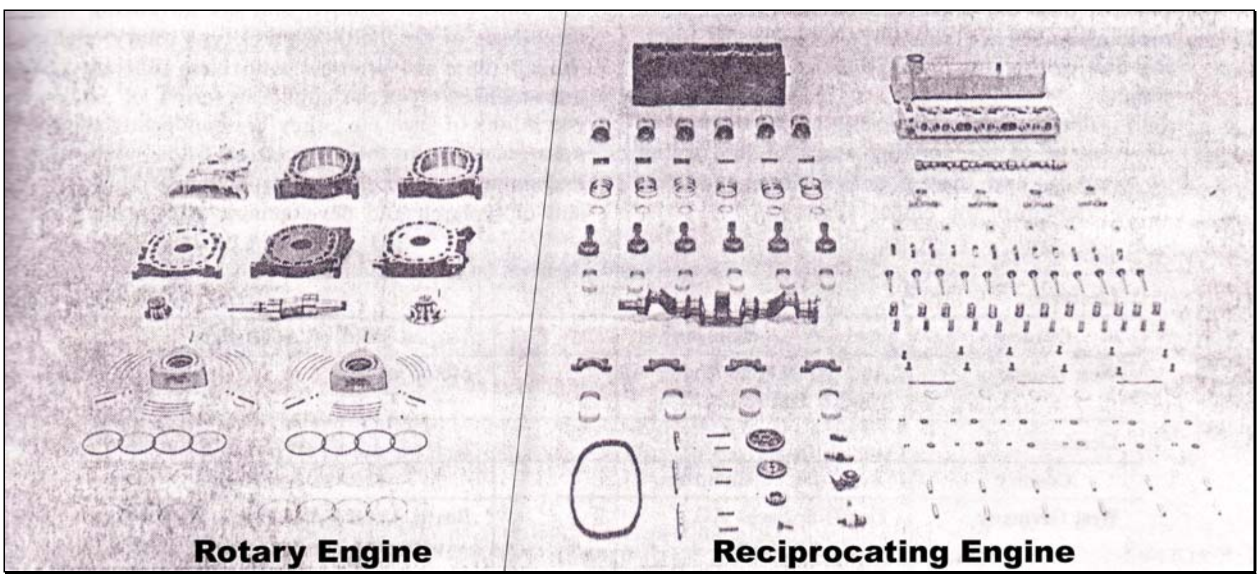
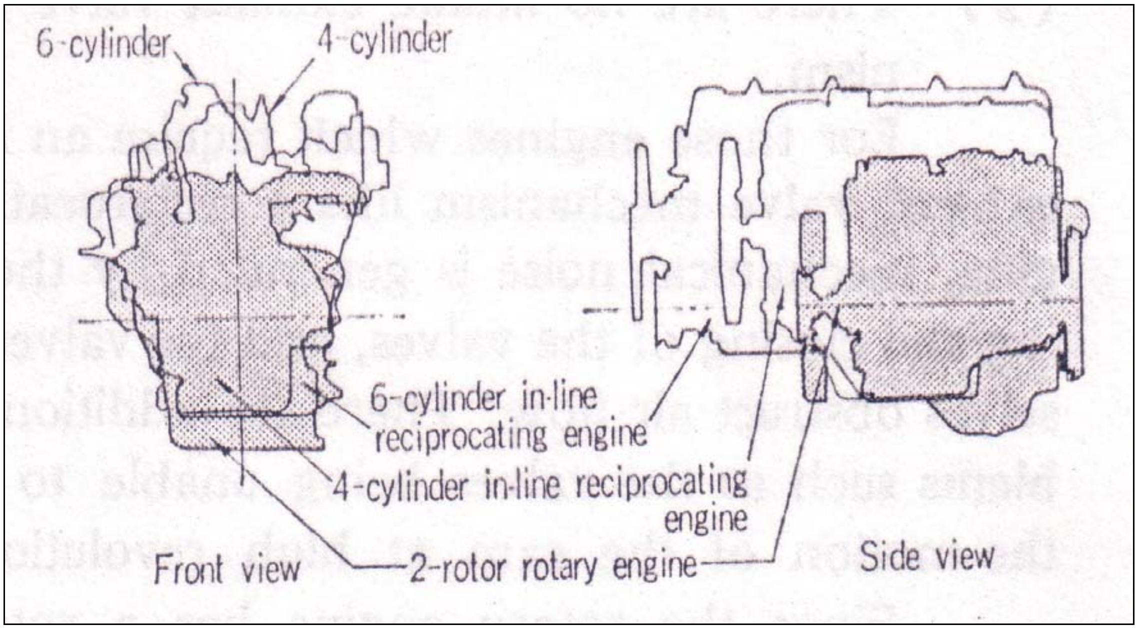


Fig. 5



All the three flanks of the rotor execute the same process in time intervals equally spaced. Thus, it gives three power pulses by each rotor rotation. Since there are three rotations of the output shaft by each rotation of the rotor, the NSU-Wankel motor gives a pulse of power by rotation of the output shaft; this showing that there are twice more power pulses in the NSU-Wankel engine than in a single cylinder Otto cycle reciprocating engine operating at the same speed. A clear advantage is that the march of the motor is but smooth and quiet (uniform).

Since the Rotary NSU-Wankel engine have a very specific and special a geometry (we refer to the internal part of the rotor housing, see Fig.3) called trochoid or epitroichoid; the housing of a single rotor engine (there exist engines with several rotors) can be seen as parallel planes separated by a cylinder of cross section of epitroichoidal form. As the epitroichoid is a well-known geometric shape, it can be made an analysis of any motor with this configuration; and in addition knowing that the rotor is an equilateral triangle. As the rotor moves within the housing, in such form that the apexes always are in contact with the rotor housing, the position of these ends also can be known.

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2.2.3 NSU-WANKEL ROTARY ENGINE GEOMETRY AND DESIGN

Since the Rotary NSU-Wankel engine have a very specific and special a geometry (we refer to the internal part of the rotor housing, see Fig.3) called trochoid or epitroichoid; the housing of a single rotor engine (there exist engines with several rotors) can be seen as parallel planes separated by a cylinder of cross section of epitroichoidal form. As the epitroichoid is a well-known geometric shape, it can be made an analysis of any motor with this configuration; and in addition knowing that the rotor is an equilateral triangle. As the rotor moves within the housing, in such form that the apexes always are in contact with the rotor housing, the position of these ends also can be known.
The epitroichoid parametric equations are:

$$x = e\cos 3\alpha + R\cos\alpha$$
$$y = e\sin 3\alpha + R\sin\alpha$$

Equ. 3

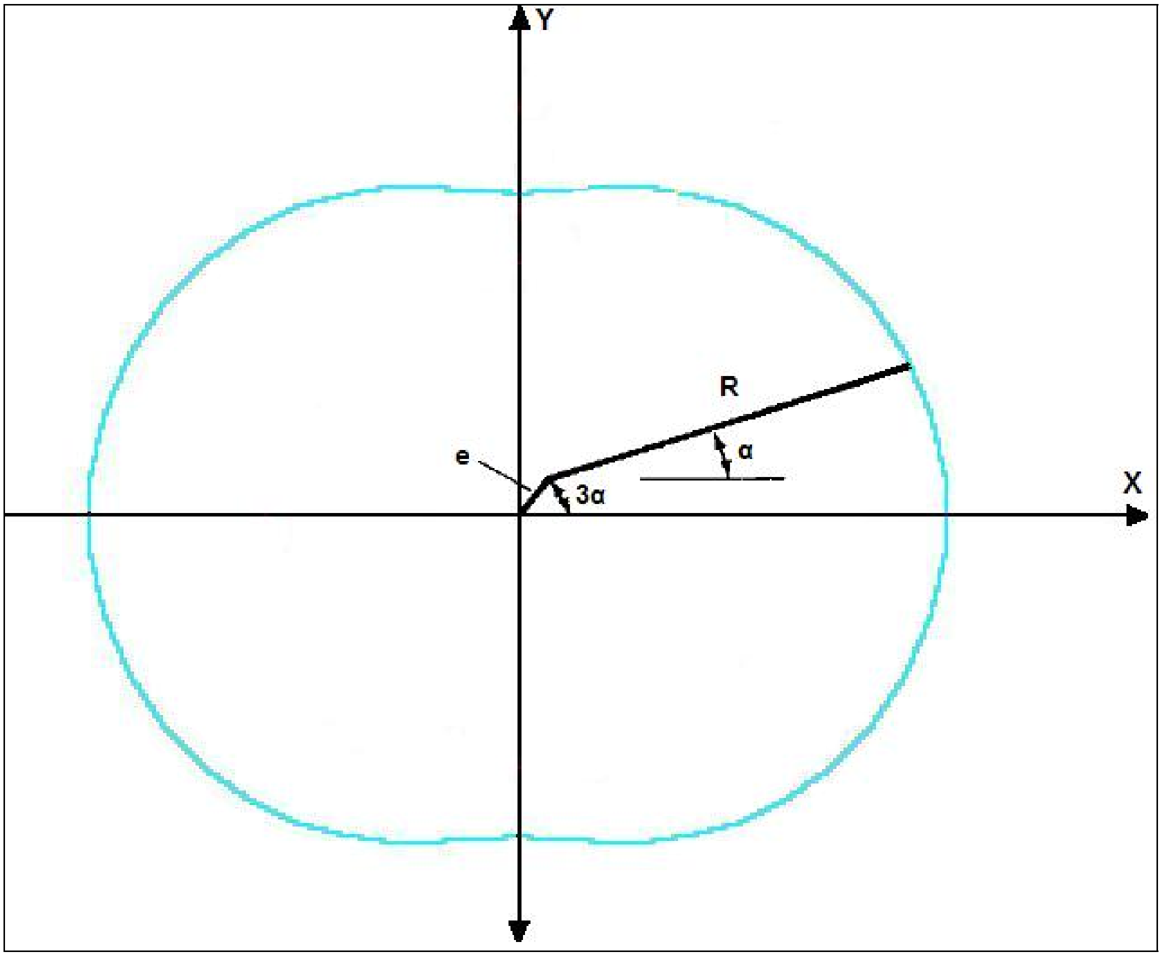

Fig. 6

Where R is the distance from the center of the rotor to the end of this, and e is the eccentricity. The previous equations give coordinates x and y defining the form of the housing when varying α. With a more detailed analysis of these engines having this form (epitroichoid) it is possible to know and to identify the movement of the rotor within the housing and know the volumes within it, the torque exerted in the rotor, the movement of the rotor in general and all the necessary information to be able to obtain the specifications of a special motor or to be able to design one with optimal characteristics, following parameters of efficiency, necessary power, the best RPMS and all characteristics of a internal combustion engine.

Knowing that the rotor shape may be thought as an equilateral triangle, as shown in Fig.1 and in Fig.3 (Flank rounding and refinement will be discussed later), and also knowing that the rotor moves inside the housing with its apexes are in constant contact with it , the position of the tips are given by the following equations:

$$x = e\cos 3\alpha + R\cos(\alpha + 2n\pi/3)$$
$$y = e\sin 3\alpha + R\sin(\alpha + 2n\pi/3)$$

Equ. 4

Where n = 0, 1, or 2 are the three values identifying the positions of the three rotor tips, each separated by 120°. Because *R* represents the rotor center-to-tip distance, the motion of the center of the rotor can be obtained from Equations (7.2) by setting *R* = 0. The equations and Figure 7.5 indicate that the path of the rotor center is a circle of radius *e*.

Note that Equations (2.1) and (2.2) can be non-dimensionalized by dividing through by *R*. This yields a single geometric parameter governing the equations, *e/R*, known as the *eccentricity ratio*. It will be seen that this parameter is critical to successful performance of the rotary engine. The power from the engine is delivered to an external load by a cylindrical shaft. The shaft axis coincides with the axis of the housing, as seen in Fig.1. A second circular cylinder, the *eccentric*, is rigidly attached to the shaft and is offset from the shaft axis by a distance, *e*, and the eccentricity. The rotor slides on the eccentric. Note that the axes of the rotor and the eccentric coincide. Gas forces exerted on the rotor are transmitted to the eccentric to provide the driving torque to the engine shaft and to the external load. The motion of the rotor may now be understood in terms of the notation of Fig.1. The line labeled *e* rotates with the shaft and eccentric through an angle 3α, while the line labeled *R* is fixed to the rotor and turns with it through an angle α about the moving eccentric center. Thus the entire engine motion is related to the motion of these two lines. Now it can be seen clearly, the rotor (and thus line *R*) rotates at one-third of the speed of the shaft, and there are three shaft rotations for each rotor revolution.

2.2.3.1. A Simple Model for a NSU-Wankel Engine

Additional important features of the rotary engine can be easily studied by considering an engine with an equilateral triangular rotor. **Fig.7** shows the rotor in the position where a rotor flank defines the minimum volume. We will call this position top center, TC, by analogy to the reciprocating engine. The rotor housing *clearance parameter*, *d*, is the difference between the housing minor radius, *R* . *e*, and the distance from the housing axis to mid-flank, *e* + *R* cos 60 = *e* + *R*/2:

$d = (R - e) - (e + R/2) = R/2 - 2e$ [ft | m]

Equ. 5

Setting the clearance to zero establishes an upper limiting value for the eccentricity ratio: (e/R)crit = 1/4. Study of Eq 2.1, at the other extreme, shows that, for e/R= 0, the epitroichoid degenerates to a circle. In this case the rotor would spin with no eccentricity and thus produce no compression and no torque. Thus, for the flat-flanked rotor, it is clear that usable values of e/R lie between 0 and 0.25.

Now let's examine some other fundamental parameters of the flat-flanked engine model. Consider the maximum mixture volume shown in **Fig.8** .For a given rotor width *w*, the maximum volume can be determined by calculating the area between the housing and the flank of the rotor. Using Eq 2.1, the differential area 2*y dx* can be written as:

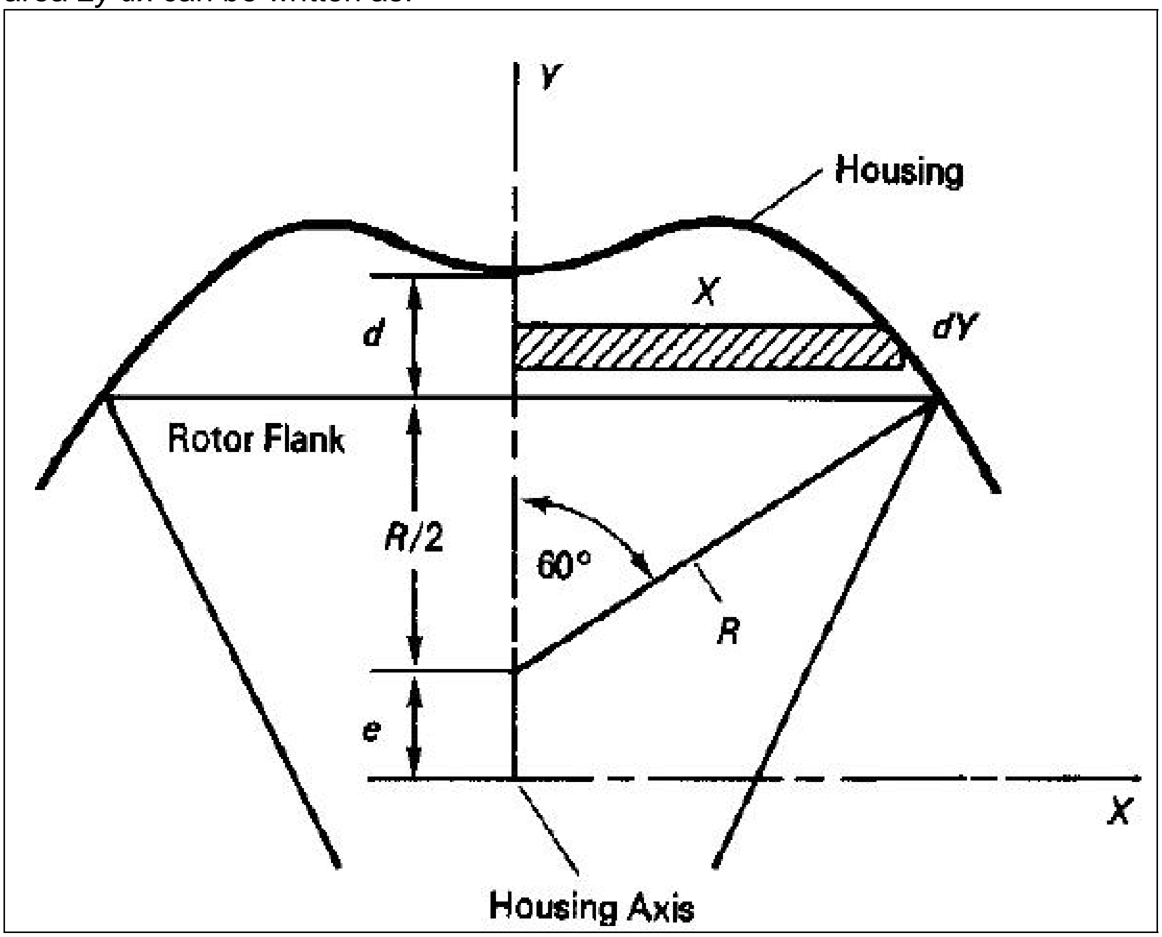

Fig. 7

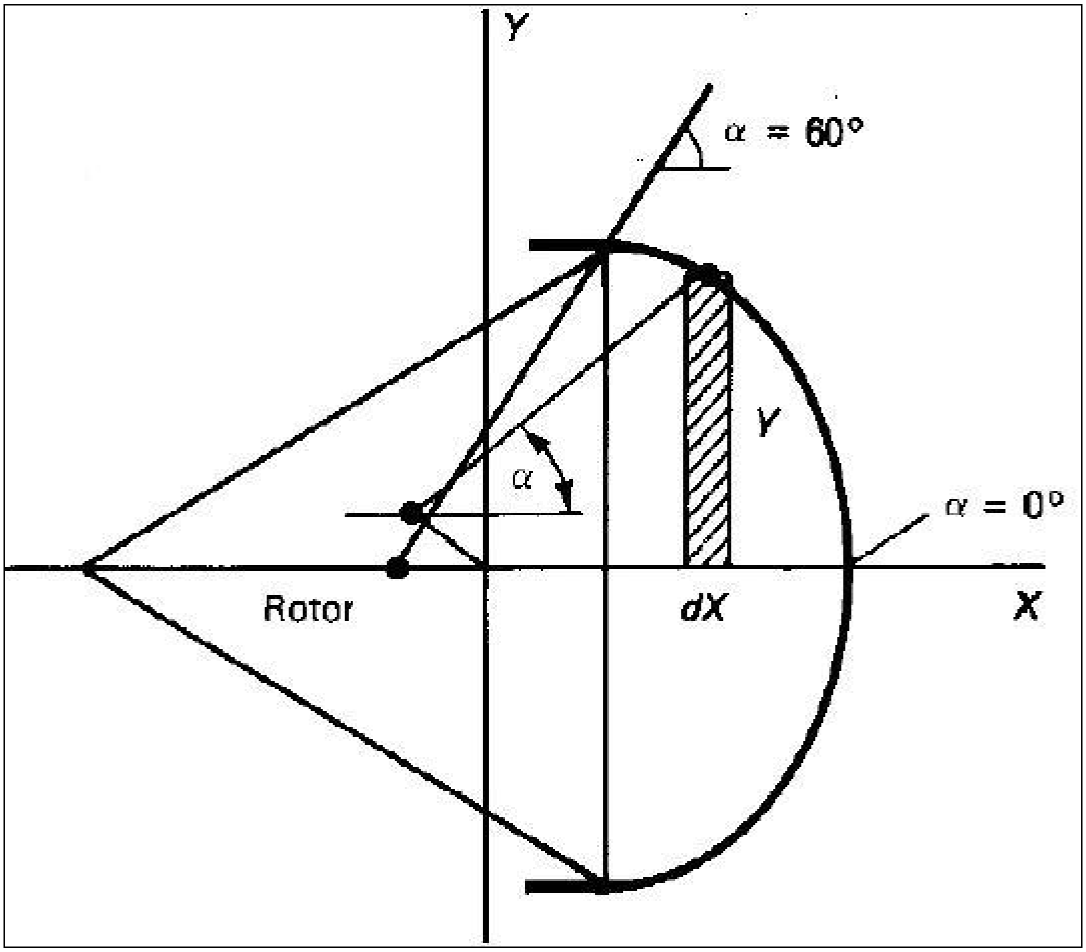

Fig. 8

$$dAmax = 2y\,dx = 2(e \sin 3\alpha + R \sin \alpha)d(e \cos 3\alpha + R \cos \alpha) \text{ [ft2 | m2]}$$

Equ. 6

Dividing by *R*2 and differentiating on the right-hand side, we obtain an equation for the dimensionless area in terms of the eccentricity ratio and the angle α:

$$Amax/R^2 = -2 \int_0^{60} [(e/R)\sin 3\alpha \_ + \sin\alpha][3(e/R)\sin 3\alpha + \sin\alpha]d\alpha \text{ [dl]}$$

Equ. 7

In order for the differential area to sweep over the maximum trapped volume in **Fig.8**, the limits on the angle α must vary from 0° to 60°. Thus integration of **Equ.5** with these limits and using standard integrals yields:

$A\text{max}/R^2 = \pi\,[(e/R)^2 + 1/3] - 3^{1/2}/4[1-6(e/R)]$ [dl]

Equ. 8

Similarly, using Figure **Fig.7** and the differential volume shown there, the nondimension-alized minimum area can be written as:

$A\text{min}/R^2 = \pi\,[(e/R)^2 + 1/3] - 3^{1/2}/4\,[1 + 6(e/R)]$ [dl]

Equ. 9

These maximum and minimum volumes (area-rotor width products) are analogous to the volumes trapped between the piston and cylinder at BC and TC in the four-stroke reciprocating engine. In that engine the difference between the volumes at BC and TC is the displacement volume, and their ratio is the compression ratio. A little thought should convince the reader that the analogy holds quantitatively for the displacement and compression ratio of the rotary engine. Therefore, subtracting **Equ.9** from **Equ.8** gives the displacement for a rotor width *w* for one flank of the flat-flanked engine as

$\text{disp} = 3 * 3^{1/2} w R^2 (e/R)$ [ft^3| m^3]

Equ. 10

And forming their ratio yields the compression ratio as:

$$CR = \frac{A\text{max}/R2}{A\text{min}/R2} = \frac{\pi\,[(e/R)^2 + 1/3] - 3^{1/2}/4[1-6(e/R)]}{\pi\,[(e/R)^2 + 1/3] - 3^{1/2}/4\,[1 + 6(e/R)]} \quad [dl]$$

Equ. 11

Thus the displacement increases with increases in rotor width, the square of the rotor radius, and with the eccentricity ratio, whereas the compression ratio is independent of size but increases with increase in eccentricity ratio.

2.2.3.1.1 The Circular-Arc-Flank Model

While the triangular rotor model represents a possible engine and is useful as a learning tool, such an engine would perform poorly compared with one having a rotor with rounded flanks. A more realistic model is one in which the triangular rotor is augmented with circular-arc flanks, as shown in **Fig.9**. The radius of curvature, *r*, of a flank could vary from infinity, corresponding to a flat flank, to a value for which the arc touches the minor axis of the epitroichoid. Note that the center of curvature of an arc terminated by two flank apexes depends on the value of *r*. It can also be seen from **Fig.9** that *r* is related to the angle, θ, subtended by the flank arc by:

$$r \sin(\theta/2) = R \sin(\pi/3) = 3^{1/2}R/2 \quad \text{[ft | m]}$$
or
$$r/R = 3^{1/2}/[2\sin(\theta/2)] \quad \text{[dl]}$$

Equ. 12

Thus either the included angle θ, or the radius of curvature, *r*, may be used to define the degree of flank rounding for a given rotor radius *R*.

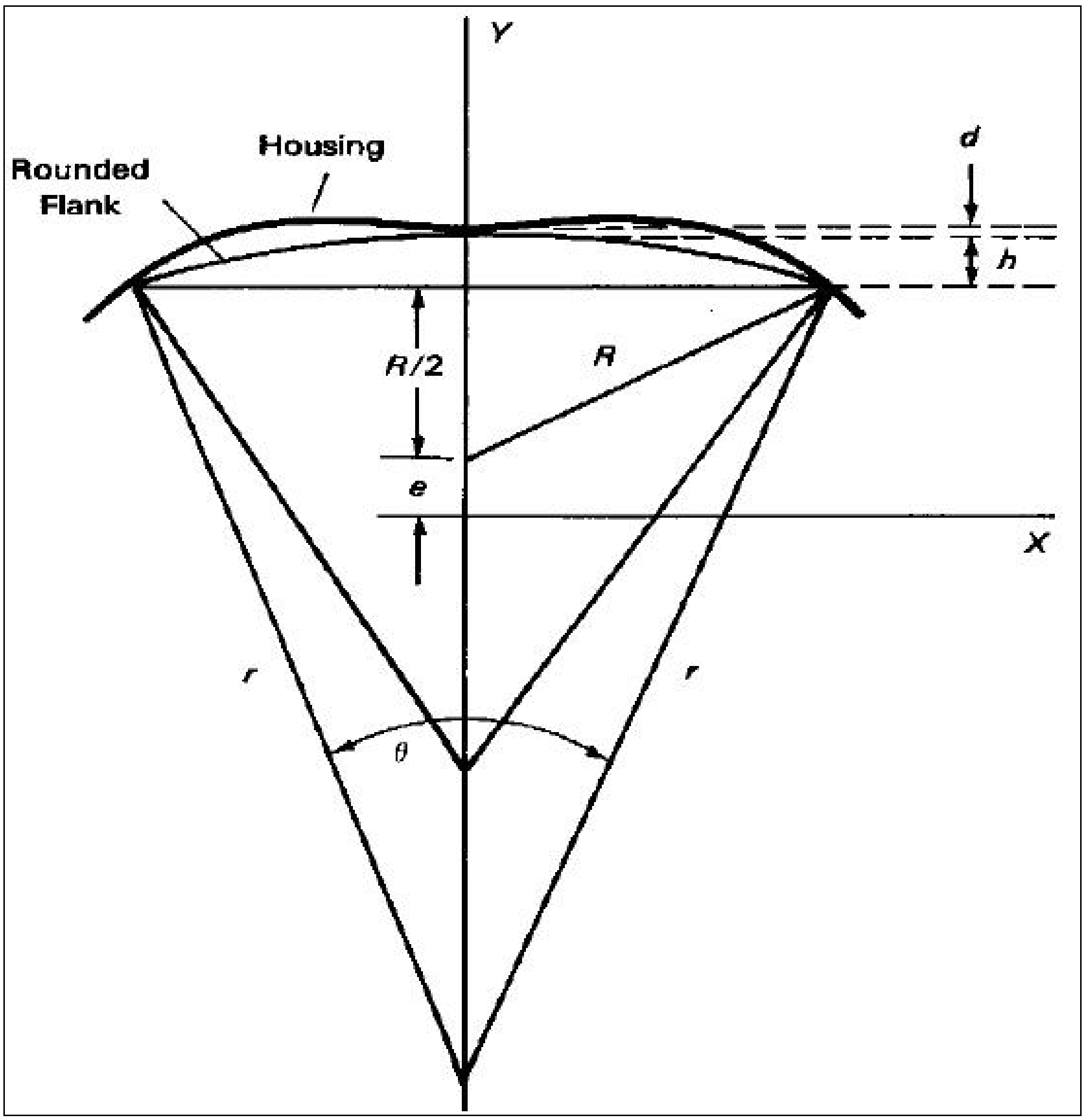

Fig. 9

Clearance with Flank Rounding

The additional area obtained by capping a side of a triangle with a circular arc is called a segment. The segment height, *h*, shown in **Fig.9**, is the difference between *r* and the projection of *r* on the axis of symmetry:

$h/R = (r/R)[1-\cos(\theta/2)]$ [dl]

Equ. 13

Substitution of Equation **Equ.12** *in* Equation **Equ.13** yields:

$h/R = 3^{1/2} [1-\cos(\theta /2)] / [2\sin(\theta /2)]$ [dl]

Equ. 14

It is evident from the figure that the clearance for the rotor with circular arc flanks is the difference between the clearance of the flat-flanked rotor and *h*. Thus, using Equation **Eq 2.3**, the clearance is given by

$d/R = 1/2-2(e/R)-3^{1/2} [1-\cos(\theta /2)] / [2\sin(\theta /2)]$ [dl]

Equ. 15

In a real engine, of course, the clearance must be non-negative.

Added Volume per Flank Due to Rounding

The segment area is the difference between the pie-shaped area of the sector subtended by its included angle, θ, and the enclosed triangular area. The sector area, or volume per unit rotor width, is the fraction of the area of a circle of radius, *r*, subtended by the angle θ; i.e., $\pi r^2(\theta /2\pi) = r^2\theta/2$. Thus using **Equ.11**, the dimensionless segment volume is:

$$A_s /R^2 = (A_{sec} . A_{tri}) /R^2 = (r/R)^2 (\theta-\sin \theta) /2$$
$$= (3/8)(\theta -\sin \theta) /\sin^2 \theta /2 \quad [dl]$$

Equ. 16

Displacement and Compression Ratio

It was pointed out earlier that the displacement of the flat-flanked engine is the difference between the maximum and minimum capture volumes, and is given by **Equ.9**. This is true also for the engine with rounded flanks. The additional volume added to the rotor by flank rounding subtracts from both of the flat-flanked maximum and minimum capture volumes, leaving the difference unchanged. Thus the displacement of one flank of a rounded-flank engine is:

$$Displacement = 3 * \sqrt{3} * w * R^2 * \left(\frac{e}{R}\right) [ft^3 \mid m^3]$$

Equ. 17

Likewise, the ratio of the maximum and minimum capture volumes given by **Equ.8** and **Equ.9**, corrected for the segment volume from **Equ.15** provides a relation for the rounded-flank engine compression ratio:

$$CR = \frac{\pi\,[(e/R)^2 + 1/3] - 3^{1/2}/4\,[1 - 6(e/R)] - As\,/R^2}{\pi\,[(e/R)^2 + 1/3] - 3^{1/2}/4\,[1 + 6(e/R)]\,.\,As\,/R^2} \quad [dl]$$

Equ. 18

The added rotor volume due to rounding subtracts from the flat-flanked capture volumes and therefore reduces the denominator of **Equ.18** more than the numerator. As a result, the compression ratio is greater for rounded-flank than for flat- flanked engines. Rotary engines usually have the maximum rounding possible consistent with adequate engineering clearances. . High compression ratio in rotary engines requires a low R/e ratio, which means a small rotor radius and high eccentricity. For instance, an R/e ratio of 11.5 gives a theoretical compression ratio of 30:1. However, the higher R/e ratio also results in a higher maximum tip angle (the angle at which the rotor apex is in contact with the epitroichoid chamber) and higher surface to volume ratio at maximum compression. The higher tip angle is detrimental to sealing effectiveness, as well as seal durability [8]. The higher surface to volume ratio in the combustion chamber will accelerate heat loss. Therefore, every rotary engine design is a compromise between sealing effectiveness, surface to volume ratio, and compression ratio.

Recess Volume

Eq 2.18 accounts for flank rounding but not for the recess usually found in rotor flanks. The additional capture volume associated with the recess is seen in **Fig.10**. Its influence on the displacement and compression ratio may be reasoned in the same way as with the segment volume. The recess increases both minimum and maximum mixture volumes by the same amount. It therefore has no effect on displacement and it decreases the compression ratio. While flank recession reduces the compression ratio for given values of θ and *e/R*, it improves the shape of the long, narrow combustion pocket forming the minimum capture volume. Rotary engines usually have more than one spark plug, to help overcome the combustion problems associated with this elongated shape.

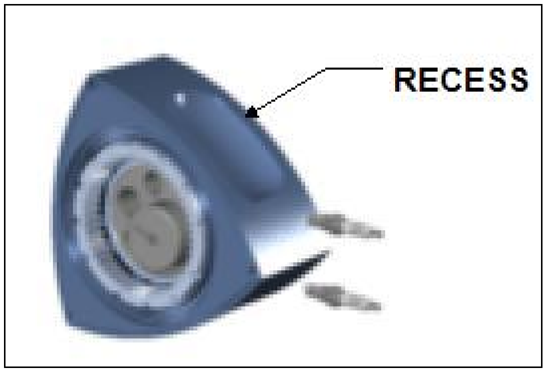

Fig. 10

Power

It has been noted that the displacement volume associated with one flank of the rotary engine produces one power stroke during each rotor revolution and during three shaft rotations. Because there are three flanks per rotor, a rotor executes one complete thermodynamic cycle per shaft rotation. Thus the power produced by a single rotor is determined by the displacement volume of a single flank and the rotational speed:

$$\text{Power} = \frac{(\text{disp } [cm3/Rev])(\text{MEP } [kN/cm2])(N\ [Rev/min])}{(60\ [sec/min])(100\ [cm/m])} \qquad [kW]$$

Equ. 19

or

$$\text{Power} = \frac{(\text{disp } [in3/Rev])(\text{MEP } [lb/in2])(N\ [Rev/min])}{(12\ [in/ft])(33{,}000\ [ft\text{-}lb/HP\text{-}min])} \qquad [HP]$$

Equ. 20

Circumferential velocity of rotor vertex

The circumferential velocity is obtained from **Equ.3** as

$$\upsilon = \left\{ \left(\frac{dx}{dt} \right)^2 + \left(\frac{dy}{dt} \right)^2 \right\}^{1/2}$$

Equ. 21

$$\upsilon = \frac{N}{3} \left(9e^3 + R^2 + 6eR\cos 2\alpha \right)$$

Equ. 22

*Where N is the rotating angular velocity of the output shaft in (rad/sec)

In the rotary engine, the rotor always rotates in the same direction eliminating the zero-speed point.

The maximum and minimum values of the peripheral speed are:

$$\upsilon_{\max} = \frac{N}{3} \left(3e \ + R \right)$$

Equ. 23

When α=0 (On mayor axis)

$$\upsilon_{\min} = \frac{N}{3} \left(-3e \ + R \right)$$

Equ. 24

When α = π/2 (On minor axis)

Acceleration of rotor vertex

The x and y components of the vertex acceleration a_x and a_y are:

$$a_x = \frac{d^2x}{dt^2} = -\frac{N}{1}\left\{e\cos 3\alpha + \frac{R}{9}\cos\alpha\right\}$$

Equ. 25

$$a_y = \frac{d^2y}{dt^2} = -\frac{N^2}{1}\left\{e\sin 3\alpha + \frac{R}{9}\sin\alpha\right\}$$

Equ. 26

The magnitude of the acceleration is a_c is:

$$a_c = (a_x{}^2 + a_y^2)^{1/2} = \frac{n^2}{9}\{(81e^2 + R^2 + 18eR\cos 2\alpha)\}^{1/2}$$

Equ. 27

The acceleration is divided into the parallel element a_r and the vertical element a_α , to the generating radius, as:

$$a_r = a_x\cos\alpha + a_y\sin\alpha = -\frac{N^2}{9}(R + 9e\cos 2\alpha)$$

$$a_\alpha = a_x\sin\alpha - a_y\cos\alpha = N^2 e\sin 2\alpha$$

Equ. 28 **Equ. 29**

Generally, the inertia force is given by the product of acceleration and mass. The inertia force acting on the apexes seal can be obtained by multiplying **Equ.28 & Equ.29** by the mass of the apex seal.

Problems regarding rotary engines

A significant problem facing rotary engines is leakage, either past the rotor tips or over the rotor face. Leakage reduces the engine efficiency (by reducing the compression ratio) and increases the effect of incomplete combustion. Sealing mechanisms have been created to reduce this problem in large-scale engines. These sealing systems consist of spring-loaded tabs at the rotor apexes and across the rotor face. The tabs maintain contact between the rotor and epitrochoid walls and sealing for the chambers. Apex seals have been fabricated for almost all engines but face seals no. However, it should be noted that the smallest commercially available rotary engine (the 5000 mm 30. S. Graupner) does not use a face seal.

Advances

Continued engineering research on the rotary engine has resulted in performance improvements through improved seals, lean-burn combustion, fuel injection, integral electronic control, improved intake design, weight reduction, and turbo charging. Despite vehicle weight increases, the Mazda RX-7 with a two-rotor 80-in.3 -displacement engine improved 9.4% in fuel consumption and 8% in power output between 1984 and 1987 (ref. 6). During this time period, the addition to the engine of a turbocharger with intercooling increased its power output by 35%. Reference 8 reports that the Mazda RX-Evolv, a year-2000 concept car, has a naturally-aspirated rotary engine called .RENESIS.. The two-rotor, side intake and exhaust engine is reported to have reduced emissions and improved fuel economy and to have attained 280 horsepower at 9000 rpm and 226 N-m torque at 8000 rpm.

EQUATION SUMMARY

PARAMETER	EQUATION
Displacement	$V_s = 3\sqrt{3}Rwe$
Theoretical Compression ratio Theoretical Compression ratio	$CR = 1 + \frac{9\sqrt{3}\,\mathrm{Re}}{e^2\pi + eR\left(8\cos\theta - 3\sqrt{3}\right) + \theta\left(\frac{2R^2}{3} + 12e^2\right)}$ $CR = \frac{\pi\left[(e/R)^2 + 1/3\right] - \sqrt{3}/4\left[1 - 6(e/R)\right] - A_s/R^2}{\pi\left[(e/R)^2 + 1/3\right] - \sqrt{3}/4\left[1 + 6(e/R)\right] - A_s/R^2}$
Power	$Pow = \frac{V_s * MEP * N}{60 * 1000}$
Maximum and minimum values of the peripheral speed	$\upsilon_{max} = \frac{N}{3}(3e + R)$ When α=0 (On mayor axis) $\upsilon_{min} = \frac{N}{3}(-3e + R)$ When α = π/2 (On minor axis)

Acceleration of rotor vertex	$a_r = a_x \cos\beta + a_y \sin\beta = -\frac{N^2}{9}\left(R + 9e\cos\frac{2}{3}\beta\right)$ $a_\beta = a_x \sin\beta - a_y \cos\beta = N^2 e \sin\frac{2}{3}\beta$
Maximum Tip Velocity	$u_{\max} = \frac{2\pi n_E\left(\frac{R}{3}+e\right)}{1000}$ Where n_E =output shaft speed (rev/s)
Thermal efficiency	$\eta_{th,Otto} = 1 - \frac{1}{\varepsilon_{th}^{k-1}}$

Table. 1

Tab.1 lists the basic equations used to calculate rotary engine parameters

3. NSU –WANKEL 49PI O.S 0.3 ENGINE

The engine that is characterized in this project is a NSU-Wankel made by the Japanese company O.S, renamed manufacturer of model engines. The engine was designed by Graupner in West Germany and O.S manufactures it with the Graupner seal on its engines.

3.1. NSU –WANKEL 49Pi EXPERIMENTAL PARAMETERS

The engine parameters as the Eccentricity Ratio, that is e and R are measured experimentally by taking the distance from the center of the engine to the point where the shaft pinion and the rotor (gear) have contact, that is in the pitch circles of both shaft pinion and rotor, where the circular pitch is:

$$p_c = \frac{\pi * d}{N}$$

Equ. 30

The contact point can be seen in the pinion and gear but attention must be paid because often the center of the rotor does not coincide with this point. See hyperlink: Wankel parameters . After disassembling the engine it was seen that it didn't follow the regular mechanics of normal Wankel engines instead of having a pinion joined to the shaft and the rotor working as the gear with its corresponding gear teeth that moved the pinion that is the shaft; the engine has an eccentricity in the shaft fixed to the rotor, thus as the rotor moves the shaft does it as well Wankel 49Pi. All the full engine pictures as well as the disassembly and the first test stand are shown in the following hyperlink; Disassembly and test stand.

The objective of seeing the engine parts is to know how the engine works gear and pinion or shaft with eccentricity, if it has apex and housing seals and to measure the engine to calculate in experimental manner the NSU-Wankel 49Pi parameters. The 3d views and drawing with all the engine parts are shown opening the following hyperlink: 3D View and parts.

The measurements were taken with a Mitutoyo electronic digital caliper Mitutoyo Caliper with an LCD resolution of 0.01mm and an accuracy of ± 0.02mm. The parameters in **Tbl.1** and their uncertainty are calculated in the excel sheet ENGINE PARAMETERS. Because the shaft and its eccentricity geometry interfere with a proper measuring of *e* and *R*; so 2*(e+R) this is the major axis and also it was measured 2*(R-e) its minor axis or diameter. In measuring the rotor rounding angle θ the following procedure was performed:

1. First the rotor was put over a paper and its rounding was traced on the paper 15 times.
2. With each trace was by geometry calculated the exact radius of the circle which a portion is the rounding of the rotor, that is tracing the mid point of the arc section then finding the radius passing through the mid line that draws the arc perfectly.
3. After having the radius, 2 lines from the center of the circle or point where the radius from any point of the arc section ends, were traced 2 lines up to the end points of the arc section.
4. After having the circle section, that draws the arc section, θ was measured.

From the picture can be seen the steps to measure θ Theta experimentally. After having all the measurements of the important parameters the engine characteristics are calculated with the following theory of error:

3.2. UNCERTAINTY CHAPTER

The error is the difference between the measured value Xm and the true value Xt:

$$\text{Error} = \varepsilon = Xm - Xt$$

Equ. 31

The objective of this chapter is to experimentally obtain the parameters of the NSU-Wankel 49 Pi engine and all of its characteristics. This made with the proper method that is, calculating the uncertainties that this kind of measurements and experiments present. The error ε is bounded by an uncertainty.

$$-u \leq \varepsilon \leq +u$$

Equ. 32

Where u is the uncertainty estimated at odds of n:1. This is that 1 on n will have an error with an offset of the uncertainty.

$$Xm - u \leq Xt \leq Xm + u$$

Equ. 33

There are two kinds of error, the Bias and Precision errors. The Bias errors are systematic errors and are those that occur the same way in each measurement. Precision errors are the random errors and are different in each successive measurement but have an average value of zero.

After determining the Bias and Precision errors in the measurement, both must be combined to obtain the total uncertainty.

$$U_{tot} = \left(U_{Bias}{}^{2} + U_{Precision}^{2}\right)^{1/2}$$

Equ. 34

3.2.1. PRECISION UNCERTAINTY

To calculate the precision error must be calculated the distribution error. As the sample is small (15) that is, less that 30 samples, the t-student probabilistic distribution is used.

$$t = \frac{\bar{x} - \mu}{S_i / \sqrt{n}}$$

Equ. 35

Where $\bar{x}$ the sample is mean, S_i is the sample variance of each parameter and *n* is the number of samples, so the precision uncertainty is calculated in the following way:

$$\bar{x} - t_{\alpha/2,\nu} \frac{S_i}{\sqrt{n}} \leq \mu \leq \bar{x} + t_{\alpha/2,\nu} \frac{S_i}{\sqrt{n}}$$

Equ. 36

$$U_{\mathrm{Precision}} = t_{\alpha/2,\nu} \frac{S_i}{\sqrt{n}}$$

Equ. 37

With a 95% of confidence, this means 1-α=0.95; α/2=0.025 and looking in the t distribution table with ν degrees of freedom, where ν = n-1. We have:

$$U_{\mathrm{Precision}} = t_{0.025,14} \frac{S_i}{\sqrt{15}}$$

Equ. 38

The value of t is in the excel sheet.

3.2.2. BIAS UNCERTAINTY

The bias uncertainty is obtained from the manufacturer; this knows the calibration of their products and equipment. In the case of the Mitutoyo caliper the uncertainty is 0.02 mm. The coverage of the uncertainty is unknown, but this suggests that 95% coverage is a reasonable assumption.

3.2.3. PROPAGATION OF UNCERTAINTY

In this case, several quantities were calculated and, significant numbers of formulas have to be applied to reach our goal of knowing the engine characteristics by experimental way.

Finding the uncertainty in a result due to uncertainties in the independent variables is called *finding the propagation of error.* For uncertainties in the independent variables, the procedure rests on a theorem, that is exact for a function *y* of several independent variables (x_i), with standard deviations. The theorem states that the standard deviation of *y* is:

$$\sigma_y = \sqrt{\left(\frac{\partial y}{\partial x_1}\sigma_1\right)^2 + \left(\frac{\partial y}{\partial x_2}\sigma_2\right)^2 + \ldots\ldots\ldots\ldots + \left(\frac{\partial y}{\partial x_n}\sigma_n\right)^2}$$

Equ. 39

The theorem can be applied to results of *y,* which is a function of several independent measured variables (x1,x2,x3…xn) Each measure value has some uncertainty (u1,u2,u3,….un), thus it can be found the uncertainty in the required variable *y,* which is called u_y .

$$u_y = \sqrt{\left(\frac{\partial y}{\partial x_1}u_1\right)^2 + \left(\frac{\partial y}{\partial x_2}u_2\right)^2 + \ldots\ldots\ldots\ldots + \left(\frac{\partial y}{\partial x_n}u_n\right)^2}$$

Equ. 40

In this manner are calculated both precision and bias uncertainties followed by the total uncertainty of each parameter in the experiment.

3.3. O.S NSU-WANKEL ROTARY ENGINE 49PI FEATURES

O.S is a Japanese company that is one of the world leading companies that manufacture model engine and steam locomotives. This company has 65 years of transcendence and built the first model engine.

The engine analyzed in this project is built by O.S, but it was designed by Graupner. The first NSU-Wankel model engine was built in 1970 its picture can be seen clicking in the Hyperlink First, and the difference between the modern one and the first one can be seen by means of better heat transfer by improved fins and a better carburetor.

The basic engine parts are shown. The PI abbreviation is because of the engine's peripheral inlet. The engine features of the engine are high specific power output, its total freedom of vibration, its relative low noise level and its compact shape. The planetary rotation of the rotor is controlled by an eccentric shaft, an internally-toothed gear and a fixed pinion mounted centrally on the rear cover plate. The engine is fitted with a conventional throttle type carburetor that gives progressive control from idling to full power.

The ignition is by means of a glow plug instead of the conventional spark plug that our cars have on their engines. The glow plug is initiated by a 1.5 V power source connected to it. When the battery is disconnected, the heat retained within the combustion chamber. Ignition timing is 'automatic': under reduced load, allowing higher rpm, the plug becomes hotter and, appropriately, fires the fuel/air charge earlier; conversely, at reduced rpm, the plug become cooler and ignition is retarded.

Mounting the engine: Firmly bolt the engine's radial mounting flange to the model or to a rigid test stand, using a self locking nut or a secondary nut locked to the first one. Make sure that the three cap screws securing the mounting flange to the engine itself are tight and are fitted with spring washers. The engine is normally mounted so that the carburetor is horizontal on the right side and the glowplug on the left (i.e. when viewed from astern). The engine should receive a free flow of cooling air. Do not obstruct airflow with an oversized spinner. If the engine is cowled, make sure that the air entering at the front is able to escape easily: the outlet area for the cooling air should not be less than the entry area and should preferably be larger. Position the fuel tank so that when full, the fuel level is approximately in line with the fuel jet. Keep the fuel line short, i.e. install the tank as close as possible to the back of the motor.

Fuel: For this engine, use top quality methanol-based model engine fuel containing approximately 25% castor-oil and between 5% and 15% nitromethane

Propeller: The suitability of the prop depends on the size and weight of the model and type of flying. Determine the best size and type after the engine has been run in. Check the balance of the propeller before fitting it to the engine. Unbalanced propellers cause vibration and loss of power. Wooden propellers are to be preferred. Some nylon propellers are not strong enough to withstand the high power output of these engines and a thrown blade can be very dangerous. As a starting point, we recommend 9x5~6, 9.5x5 and 10x5 for general use.

Starting: Fill the fuel tank and open the needle-valve 2 to 3 turns from the closed position. Prime the engine fairly liberally with fuel through the carburetor. Turn the propeller through one complete revolution and prime again. Repeat this procedure once more so that all three chambers formed between the rotor flanks and housing, are primed. Now rotate the prop through several revolutions so that any excess of fuel is blown through the exhaust port. This will leave the chambers with just about the correct proportion of fuel and air for starting. An alternative priming procedure, that some users may find preferable when an electric starter is being used, is to simply finger-choke the intake (throttle fully open) while turning the prop for six revolutions. Now close the throttle to between one-quarter and one-third open, connect glowplug lead and apply electric starter. After starting, allow the engine to warm up for 5~6 seconds, then remove the plug lead, open the throttle fully and adjust the needle-valve. Adjust for rich, reduced-rpm running when the engine is new (see paragraph below on "Running-in") otherwise adjust for full power. When re-starting the engine hot, do not prime: simply close the throttle and apply the starter: it will burst into life again immediately.

Things needed: Glowplug battery, battery leads, fuel tank, fuel bottle (for refilling the tank), electric starter, and silicone tubing to connect the tank to the carburetor.

SPECIFICATIONS

■ Displacement	4.97 cc (0.303cu.in.)
■ Bore	———
■ Stroke	———
■ Practical R.P.M.	2,500〜18,000 r.p.m.
■ Power output	1.27bhp / 17,000 r.p.m.
■ Weight	335g (11.8oz.)

Table. 2

3.4. EXPERIMENTAL DATA

Knowing the uncertainties relation between all the variables in the experiment, the uncertainty of *R* and *e* are calculated as followed:

$$Var\ (2*(R+e)) = Var(2*R)+Var(2*e)$$

Equ. 41

$$Var\ (2*(R+e)) = 4*Var(R)+4*Var(e)$$

Equ. 42

With the **Equ.42,** the sample variance of R and e are calculated, this, by having the other equation: Var (2*(R-e)) thus obtaining the other equation needed for the two unknowns sample standard deviation of *R* and *e*. These standard deviations are used to calculate the error between all the relations involving only *R* and *e,* like the eccentricity ratio, compression ratio, etc.

The standard deviation of the eccentricity ratio can be calculated with the following equation, knowing the STD deviations of our engine parameters:

$$s\left(\frac{e}{R}\right)=\sqrt{\left(\frac{\partial\left(\frac{e}{R}\right)}{\partial R}s_R\right)^2+\left(\frac{\partial\left(\frac{e}{R}\right)}{\partial e}s_e\right)^2}$$

Equ. 43

The results of segment volume, eccentricity ratio, compression ratio, and displacement, and efficiency were calculated with the experiment parameters and following the propagation of uncertainty like in the estimate of the standard deviations of the eccentricity ratio in the last paragraph. The average values of e*, w, R* and *θ are* used to calculate the engine parameters.

3.4.1. SEGMENT VOLUME

The value of the segment volume calculated due to rotor rounding can be analyzed by its formula, if the radius r is infinite, the rounding is null, thus having a triangular rotor and θ very small and a dimensionless segment volume value of zero, the maximum volume, occurs when the clearance is set to zero, in our case having:

$$4\left(\frac{e}{R}\right)-1=\frac{-2\sqrt{3}\left(1-\cos\left(\frac{\theta}{2}\right)\right)}{\sin\left(\frac{\theta}{2}\right)}$$

Equ. 44

In case of the NSU-Wankel O.S 0.3 49PI the maximum value of the angle θ that can be obtained is: 59.5922º or 1.040 radians. The difference between the maximum value of θ and the mean sample value obtained in the experiment is 0.2174 radians, theoretically a maximum value of θ and a minimum value of the clearance *d* should be obtained; but always there has to exist a clearance in order that a good combustion process by means of flame propagation take place. If the clearance has a null value the combustion chamber will be cut in two and the spark due to the spark or glow plug or other means of ignition wouldn't be able to occur in a satisfactory way, so our value of θ equal to the mean value of 0.822631 radians, this is close enough for maximizing the compression ratio and having a combustion chamber of adequate dimensions.

The clearance of a simple model of the engine in the experiment would be *d=(R-e)-(R*cos(60)+e)=(R-e)-(R/2-e)=5.06099mm.* The real engine has a clearance of $d = R/2-2*R*(e/R)-R*3^{1/2}\,[1-\cos(\theta/2)]\,/\,[2\sin(\theta/2)] = 1.09239$mm, this improving the compression ratio of the real engine to the simple model in a 230.41%, this is that a simple model engine with the same parameter will have a compression ratio of 3.1820 compared to the real 7.3318 CR.

3.4.2. ECCENTRICITY RATIO

As described in section 2.2.3.1 the eccentricity ratio lies between 0 and 0.25. If the ratio is big (around 0.25) there is a result in high maximum tip angles (the angle at which the rotor apex is in contact with the epitrochoid curve or housing) and also a higher surface to volume ratio (this means increasing the compression ratio but making the combustion chamber larger), but the higher tip angle is a detrimental to sealing effectiveness, as well as seal durability.

An appropriate value of the eccentricity ratio is about 0.125. The O.S 0.3 49PI engine has (e/R) mean value of 0.133 which; knowing the other engine parameters is a good value taking into account its consequences. A rotary engine is a compromise between sealing effectiveness, surface to volume ratio and compression ratio.

3.4.3. COMPRESSION RATIO

The typical compression ratio in small rotary engines is around 7, this telling that a mean value of 7.33 of the 49PI engine is satisfactory. The compression ratio in a working rotary engine is never as high as the theoretical compression ratio. All rotary engines have a rotor cut-off ratio to allow the combustion reaction to propagate at the onset of the power stroke. The compression ratio also gives the Otto efficiency of the engine, which has a mean value of 54.92% which is appropriate for an engine this size.

3.4.4. DISPLACEMENT

The real displacement of the O.S 0.3 49PI rotary NSU-Wankel engine is 0.303 in^3, which gives a displacement of 4.965228 cm^3, the mean value calculated is 4.908998 cm^3 knowing that with a 95% of confidence the value of the displacement will be between 4.947256 cm^3, the maximum value can be taken to compute the errors between the real and experimental data.

Absolute error $= \left| realvalue - \exp erimentalvalue \right|$

Equ. 45

Relative error $= \dfrac{\left| Absoluteerror \right|}{\left| \mathrm{Re}\, alvalue \right|}$

Equ. 46

The absolute error for the experiment is 0.018 cm^3 and the absolute error is 0.00362 cm^3, showing that the engine parameters are prevailed by the mathematical model of an engine with epitroichoidal housing and a circular arc flank rotor moving about an eccentricity *e.*

3.4.5. POWER AND PERIPHERAL SPEED VALUES

The power curve (line in this case, as a reason of a linear model) is calculated and shown in the in the excel sheet ENGINE PARAMETERS in the power section. The curve starts at the engines idle speed (2500RPM) and starts with 0.124HP and at 14300 RPM the engine brings 0.711HP, the slope of the line is 4.97E-5 BHP/RPM. These values of power for an engine of this size are high, knowing that a lawnmower engine has a top power of about 1HP. The 17000 RPM that is on the manufacturer manual as the speed where 1.27 BHP are performed can’t be reached because in Bogotá, Colombia South America the atmospheric pressure is 75 kPa, this as a reason of the altitude of the city (2600m above sea level) thus having a decrement in air density and oxygen in the air. The RPM shown are the practical RPM which the engine performs at Bogotá.

The maximum peripheral velocity is the circumferential velocity which is the derivate of the position, in the engine is easy to do so because the path that the rotor apex describes as it rotates is an epitrochoid.

$$v = \left\{ \left(\frac{dx}{dt} \right)^2 + \left(\frac{dy}{dt} \right)^2 \right\}^{\frac{1}{2}} = \frac{\omega}{3} \left(9e^2 + R^2 + 6eR \cos \frac{2}{3} \beta \right) \quad \text{Where } \beta = 3\alpha$$

Equ. 47

Where $\omega = \frac{d\beta}{dt} (rad / \sec)$, the maximum speed occurs on the mayor axis and depends on the engine speed. The maximum speeds behave linearly as the rotor angular speed increases, giving a minimum of 1427m/s at 2500RPM or idle speed and a value of 8823 m/s at 14300 RPM, the slope of the line is 0.6267 m/s/RPM. These speeds are very high as a reason of the high angular velocities developed in the engine.

The minimum peripheral speed occurs on the minor axis and goes from 654m/s at 2500 RPM to 3741m/s at 14300 RPM. The speed behaves in a linear way and the line has a slope of 0.2616m/s/RPM. The relation between the increment in the maximum and minimum speed as the RPM increase are not the same and the maximum speed grows 2.4 times faster than the minimum speed as the angular velocity grows.

The effect of having these high speeds on the tip of the rotor result in high stresses in these parts and an appropriate lubrication and material selection and design of the apex seal have to be crucial parameters in the engine.

3.4.6. ACCELERATION OF ROTOR VERTEX

The equations of the acceleration of the rotor vertex and the velocities are useful to analyze the inertia forces acting on the apex seal, this force can be obtained by multiplying the acceleration by the mass of the apex seal.

The notation used to obtain the equations is that β=3α, this to imply that the direction of one component of the acceleration is perpendicular to the center of the epitrochoid in the β direction. The β acceleration is function of the sine function, this tells that depending on the location of the vertex there is an acceleration or deceleration of the vertex. The *r* acceleration is negative; this is directed towards the center of the epitrochoid thus the negative sign and the dependence of the angle makes it increase or decrease.

When β =0 also α is zero and the cosine term is unity and the sine term is null, this shows that the a_β acceleration is zero because of this term. The reason for it is that there is a change in the sign in the equation due to the *sine* function. In the Excel sheet in the acceleration curves show how it changes according to the angle but it has to be considered that the rotor vertex 0 is at one third of the angle graphed and from zero to 90º it accelerates, from 90º do 180º it decelerates, from 180º to 270º it accelerates again and finally from 270º to 360º it decelerates again. This means that the vertex accelerates from the maximum axis to the minimum axis and it decelerates in going from the minimum axis to the maximum distance point or axis.

The acceleration in the direction towards the center (radial acceleration), like in a circular motion its term is negative, but in the epitroichoidal movement when the *cosine* of the angle plus its constants due to the double derivate of the trajectory functions are negative and greater than the rotor radial term and with negative sing the same sign in the whole function becomes positive, and as a consequence the acceleration changes its sign. This particular change in vector acceleration direction occurs in between 17º before and after the 90º and the 270º degrees position; when the vertex approaches the minimal distance from the center (minor axis point) it begins to accelerate in a radial manner in the opposite direction, therefore the apex seal having a sudden change in force direction. Aided by the excel sheet and the **Fig.11** the inertia forces in the apex seal can be analyzed.

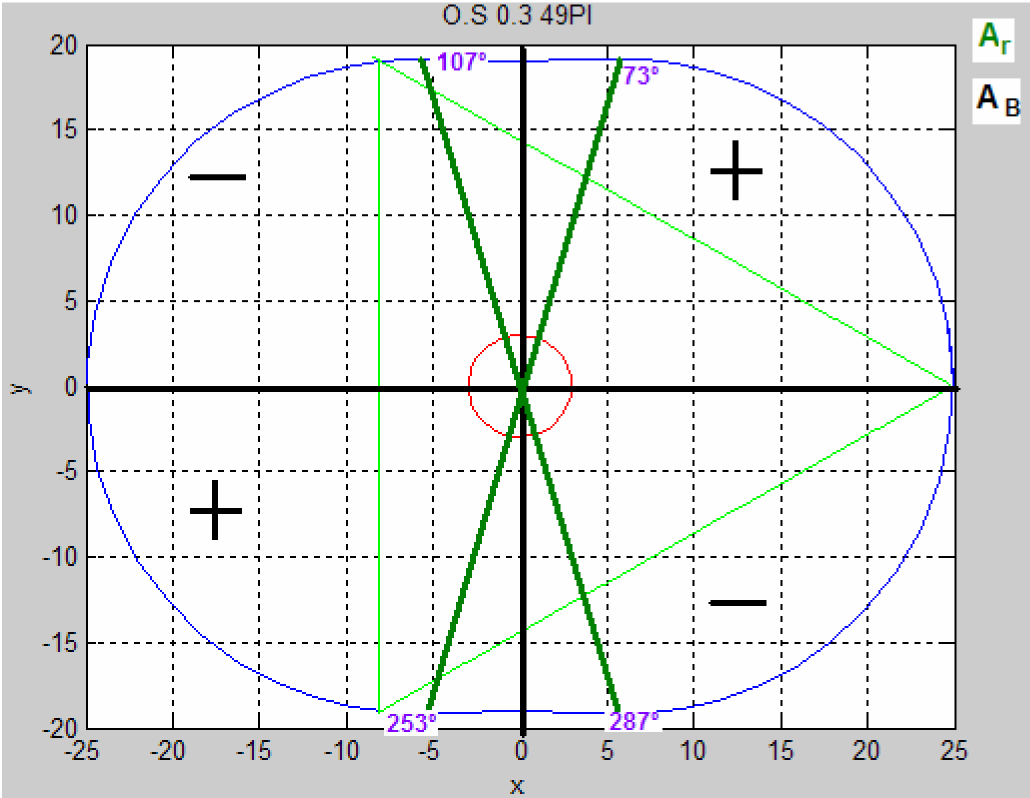

Fig. 11

3.4.7. OTTO CYCLE ANALYSIS

The first item analyzed in order to reach a complete Otto cycle analysis is how much fuel the engine consumes at al the speed range. To do so, a measurement on the fuel density had to be performed; with the aid of a Blau Bran pycnometer, with a volume of 10.215 $cm^3 \pm 0.001\ cm^3$. With an Ohaus scale with an uncertainty of $\pm$0.001gr; the weight of the empty pycnometer is measured and the weight of the full of fuel pycnometer is also measured. The difference is the volume weight and the volume is given by the calibrated pycnometer. A statistical analysis is performed and the mean density value is obtained with the corresponding uncertainty. A $\rho = 863.110 \pm 1.020\ kg/m^3$ is obtained. The density is needed to evaluate de value of the mass rate of flow entering the engine, this measuring the volume rate of flow.

The second item is the exhaust temperature (temperature in point number 4 in the Otto cycle). The description is shown in the Excel Sheet, in the OTTO part. As a result of the repeatability of the experiment it is difficult to reach an exact speed on the engine to evaluate an exact point. In the experiment performed in the test stand the speed was fixed to 14000 RPM and the temperature at the exhaust was measured with an Omega thermocouple; the temperature measured was 863.15 ºK and the ambient temperature 283.15ºK. Concepts regarding the fuel are of extreme importance, Chapter 4 tells everything involving nitromethane, where the low heating value appears and other important and relevant properties. In the hyperlink the picture of the test stand and the experiment can be viewed.

The Otto cycle analysis is performed with a very good accuracy assuming that the engines work within an air cycle; this has been corroborated by experimental means.

The equations used to analyze the cycle are used knowing that in the cycle takes place first an isentropic compression, where the atmospheric temperature is known (T1) and then the temperature in point 2 (compressed air) can be known by:

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} = T_1(CR)^{k-1}$$

Equ. 48

The pressure in point 2 (compressed air) can be known having that the pressure at the intake (1) is the atmospheric pressure where the test is being performed (In Bogota the pressure is 75kPa) The relation to calculate the pressure is the following :

$$P_2 = P_1\left(\frac{V_1}{V_2}\right)^{k} = P_1(CR)^{k}$$

Equ. 49

The next process in the cycle is an isochoric heat addition (constant volume). But for simplicity first the temperature at exhaust must be measured, this has to be performed at the nearest point where the exhaust gases are expulsed by the rotor (nearest point to the exhaust chamber) With the exhaust temperature the temperature in point 3 is calculated:

$$T_3 = T_4\left(\frac{V_1}{V_2}\right)^{k-1} = T_4(CR)^{k-1}$$

Equ. 50

The pressure in point 3 (point after heat addition) is calculated with the following equation:

$$P_3 = \frac{T_3 P_2}{T_2}$$

Equ. 51

Process 3-4 is an isentropic expansion, then the pressure in pint 4 (exhaust) is calculated:

$$P_4 = \frac{P_3}{\left(\frac{V_1}{V_2}\right)^k} = \frac{P_3}{(CR)^k}$$

Equ. 52

The thermal efficiency of the cycle can be alternatively found as follows, assuming constant specific heat of air:

$$\eta_{th} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$$

Equ. 53

The heat addition is found as follows (The qh in the experiment eas calculated with the air fuel ratio and the low heating value of the nitromethane):

$$q_H = C_v(T_3 - T_2) \text{ Or } q_H = LHV\left(\frac{1}{AF_{ratio}}\right)$$

Equ. 54

The mass flow and volume flow are found from the following relations:

$$\dot{V} = \frac{V_s N}{2(60)} = \frac{3\sqrt{3}wR^2\left(\frac{e}{R}\right)N}{2(60)}$$

Equ. 55

$$\dot{m} = \frac{3\sqrt{3}wR^2\left(\frac{e}{R}\right)N}{2(60)}\frac{P_{atm}}{RT_{atm}}$$

Equ. 56

Work and power are obtained:

$$work = w_k = q_H\eta_{th}$$

Equ. 57

$$Pow = \dot{m}\,w_k = \frac{3\sqrt{3}wR^2\left(\frac{e}{R}\right)N}{2(60)}\frac{P_{atm}}{RT_{atm}}q_H\eta_{th}$$

Equ. 58

The indicated mean effective pressure and brake mean effective pressure useful to calculate the developed power are found as follows (Brake horsepower=BH and developed power = Pi):

$$IMEP = \frac{w_k}{V_s} = \frac{w_k}{3\sqrt{3}wR^2\left(\frac{e}{R}\right)} = \frac{1}{2}\frac{P_{atm}}{RT_{atm}}q_H\eta_{th}$$

Equ. 59

$$BMEP = \frac{BH}{\frac{V_s}{2}\frac{N}{60}}$$

Equ. 60

$$Pi = \dot{m}\,w_k \quad \text{Or} \quad Pi = IMEP\left[3\sqrt{3}wR^2\left(\frac{e}{R}\right)\right]$$

Equ. 61

4. NITROMETHANE

4.1. FUEL PROPORTIONS

All mixes are described on a percentage by volume basis which seems to be standard in the glow engine fuel business. Standard American volume equivalents are: 1 gallon= 4 quarts= 128 fluid ounces= 231 cubic inches. A typical mix, called 10% fuel, is 10% nitromethane, with 25% castor oil and 65% methanol- all by percentage volume so that a gallon of 10% looks like the tabulation below.

12.8 oz. nitromethane	10%
32.0 oz. castor oil	25%
83.2 oz. methanol	65%
128.0 oz. total (gallon)	**100%**

Table. 3

The calculation for oil, as an example, is 25% of a gallon which equals 0.25 x 128 oz. or 32 oz., and the calculation for nitromethane at 10% is 0.10 x 128 oz. or 12.8 oz. The nitro and oil are carefully mixed with about half gallon of methanol and then the gallon is completed with methanol- thus avoiding directly measuring the methanol.

Methanol (wood alcohol, methyl alcohol, and meths (methylated)) is the first oxidation product of methane, CH_4, and has the chemical name CH_3OH. Further oxidation produces formaldehyde, then formic acid, and finally carbon dioxide and water (CO_2 & H_2O), which is ultimate--you cannot burn water! All of these products occur in the engine and produce heat which does the work. Methanol is a colorless and almost odourless liquid which is a violent poison and is highly flammable. It burns with a pale blue flame which is not visible in daylight. You could be on fire with methanol and nobody could see the flames. Methanol produces 55,550 net BTU per gallon, a 3450 OF flame temperature in air, has a near 43 OF flash point (does not evaporate below 43 OF), and a 725 OF ignition temperature. The addition of castor oil and nitromethane will slightly lower the ignition temperature of the mix. 1300 OF to 1500 OF temperature is indicated by the "color" of a hot glow plug coil. The flammable limits of methanol (% vapour in air by volume) are 6.7% lower and 36.0% upper. So if lean or rich on a cold day (43 0F flash point), your engine will be a real bear to start. A gallon of methanol requires about 560 standard cubic feet of air for combustion, resulting in exhaust gasses composed of 78.4 standard cubic feet of carbon dioxide (CO_2), 156.9 cu ft of water (H_2O) at 212 OF (vapour), and 445.5 standard cubic feet of nitrogen (N_2). The nitrogen comes from air, 21% oxygen (O_2) and 78% nitrogen (N_2), which must be pushed through the engine to provide oxygen for combustion of the fuel. Good methanol is both anhydrous (free of water), and hygroscopic (absorbs water from air and is soluble in water). It should never be exposed to humid air (most air is humid) for more than a few minutes. Dry methanol is a good fuel; while wet methanol is a dog- will still burn, but not well. Good dry methanol has a gravity of 0.7914 and anything higher shows water. Pure water has a gravity of 1.0000, so the properties can considerably change if exposed to humid air for a long period of time, ruining a good combustion.

Castor oil is the "classic" oil for glow fuel; a vegetable oil from the beans of a plant called RICINUS COMMUNIS. Chemically it is $C_{11}H_{10}O_{10}$, viscous, clear to yellow, and about the same weight as water. Medically it was an old fashioned laxative and if 75 year old memory serves was pretty potent! Castor oil as a lubricant is exceptional because of heat resistance, cling, and lubricity. The coefficient of friction for steel, using castor oil as lubricant is 0.095, which is better than all other oils listed in the handbooks. Compare to wet ice, with a coefficient of friction of 0.05 to 0.15, where the lower number is the most slippery and one of the most slippery surfaces known the comparative coefficient of friction is very good Castor oil at 10% would lubricate an engine, but it is raised to 25% so that the oil can also act as a coolant. It does not enter into combustion, just pumps through the engine the same as nitrogen. The castor "smoke" you see in the air is mostly fine droplets of oil. Traces of true smoke may be produced in a very hot engine. Castor oil smoke has a pleasant odor, while most of the synthetic oils have a perfume-like odour associated with their smoke. The two together produce a definite and unique flying-field odour and a special color.

The main difficulty of the synthetic oils is that there are so many of them, each manufactured for a specific purpose, but not for glow engines. Any other oil will surely cause problems. The big negative with castor is that it polymerizes to a tacky varnish when left on surfaces and exposed to air- makes messy airplanes and or test stands, splashing every piece of equipment with oil. Synthetic oils seem to reduce or soften this polymerization when mixed with castor oil.

Nitromethane (CH_3NO_2) is a colorless liquid, sweet smelling, soluble in methanol, and normally stable- but with the chemical potential to detonate. When mixed in methanol it gives the mixture the "alcohol" smell and taste and provides some oxygen for combustion beyond the induced air. The OSHA exposure limit is 100 ppm over an eight hour period, so exposure time must be limited as well as avoid ingestion in any circumstance. Nitromethane (mix) is about $90000 Colombian pesos per gallon, this is about $30.US dollars price very elevated.

4.2. DANGERS

It is necessary to know the dangers involved with the use of nitromethane mixtures so that the necessary precautions can be taken and understood, reducing them to a degree that makes the use of such fuels acceptable under the circumstances in which will be normally operated. Knowing the dangers the manipulation of these fuels can be done, resulting in harm prevention, but if not, then it is possible through lack of simple precautions to suffer, so bear them in mind at all times. After combustion, mixtures containing nitromethane exhaust relatively large amounts of nitric acid in vapour form, making the use of a proper gas mask essential by the person that is manipulating the engine, and for those close to it in the running area; this if the place where the engine works is not properly ventilated. The reason for this is that nitric acid, when inhaled, causes a muscular reaction making it impossible to breathe. Dropping a can of nitromethane will not cause an explosion in a can, due to its construction of light weight material, will not have sufficient rigidity, but an amount in a thick-rigid walled container may.

4.3. COMBUSTION

The "old hands" say that the nitromethane "activates" the methanol, but it is unknown what the activation means are. A theory is that the exothermic reaction results from the strong nitrogen-oxygen bonds, the presence of oxygen and nitrogen in the structure leads to a very special combustion.

The molecular balance for the combustion of methanol (CH3OH) is: (CH3OH) + 3/2O2 --> CO2 + H2O = 2(CH3OH) + 3O2 --> 2CO2 + H2O or two mols of methanol require 3 mols of molecular oxygen (two volumes of molecular methanol vapor require 3 volumes of molecular oxygen for complete combustion), but oxygen comes in a package called air which is 21% molecular oxygen and 78% molecular nitrogen. There is 3.76 times as much N2 as O2 in air. 3O2 + (3.76 x 3N2) or 14.26 "mols air" are required to burn 2 mols of methanol. Fuel/air ratio for methanol is 1/7.14. The molecular balance for the combustion of nitromethane, (CH3NO2) is: 4(CH3NO2) + 3O2 --> 4CO2 + 6H2O

+ 2N2. 4 volumes of nitromethane vapour require 3 volumes of molecular oxygen for complete combustion, which are 14.28 volumes of air as above. The Air/Fuel ratio and all the combustion is explained in the excel sheet NITROMETHANE. Nitroethane (C2H3NO2) will provide available oxygen the same as nitromethane, but will not provide as much extra oxygen per unit volume. Compare methanol fuel/air ratio with nitromethane fuel/air ratio, 1/7.14 for methanol and 1/6.78 for nitromethane. The nitromethane is providing some oxygen for combustion and needs less induced air to burn; in fact, twice as much output is available from pure nitromethane as from pure methanol for the same amount of air. So the nitro is a chemical form of super-charging. With an increase in hp there is a corresponding increase in rpm, with an additional increase in induced (carburetor) air, with a compound increase in output hp. I am working on an algorithm to relate % nitro to % increase in engine output-- realizing that no two of these little engines are the same or will experience the same operating conditions. How much output increase is very difficult to calculate, but we know with increase in % nitro we gain in output, engine operating temperature, and the cost of fuel and knowing this the increase in power can be very costly.

The conclusion is that nitromethane provides extra oxygen above that provided by combustion air and therefore improves hp output. The practical rule is to provide no more nitromethane than needed for your plane, your engine, and your flying wants. Most of us can get along on 5% or 10% nitromethane fuel. 10% nitro is actually 13.3% nitro if you look only at combustibles- the oils do not enter into combustion so can be thrown out of the calculation for effective percent of nitro methane air and the other reactants and products present in the reaction.

To move from 5% fuel to 10% fuel, the start point is with the 5% gallon which holds 6.4 oz nitro. Now add enough nitro to make a 10% mixture (larger container now needed). The new mixture will have a volume of 128 oz plus whatever nitro is required to make a 10% mix. This sets up small algebra problem-- algebra at the RC field. If "x" is the added nitro, then (128 oz + "x" oz)(0.10) = "x" oz + 8.4 oz. This equation translates to 10% of the new volume is equal old nitro plus the added nitro. The approaching to a true 10% mix by simultaneously adding oil and methanol. The above algebraic approximation puts it within 2% of being right, if not simultaneous equations must be performed. This is easy making a matrix and solving a linear system.

4.4. GENERAL ASPECTS IN GLOW PLUG ENGINES

This is an attempt to explain how the combustion takes place in a glow plug engine. First it will be explained some basic thermodynamic and basic combustion phenomena in layman terms. The Heat Engine; all heat engines are based on the fact that hot gas expands more than cold gas. This means that you take a "cold" gas compresses it. After it has been compressed you heat it up, usually by some sort combustion. After that the gas is expanded. The good part is that you get more work from expanding the warm gas then was used to compress the cold gas. You end up with positive work. This is the heat engine. This is how your car engine work and also how your glow plug engine works. There are several ways of solving the 'heat adding part', but we will talk about how that happens in the glow engine. In the glow plug engine the gas you use is mixture of air, fuel and oil that will compress, combust and expand, and hopefully give some positive work.

The fuel that is used is normally liquid. But for any thing to burn it has to be in a gaseous form. So the liquid fuel has to vaporize before it can combust. A little physics: When substance goes from liquid to gas heat has to be supplied (this is usually referred to as boiling). This heat will help cool the engine and the incoming air. This cold gas will make the compression easier. This heat is called Heat of vaporization.

When you burn a fuel it will let of heat. This is what we call heating value. It the table you it is called ‘lower heat value'. There is also a higher heating value, but when talking about piston engines, always and only look at the lower heating value. Looking things up in tables look only for the lower heating value to compare numbers. Else the data obtained will be wrong.

To get the most from a burning mixture, it is best to burn the fuel completely as well as all the oxygen. When this balance is right, is what is called stoichiometry. How many kg of air needed for 1 kg of fuel?

This is where it gets interesting! What is putt into the engine is a mixture of air and fuel. So the heating values isn't that interesting, when in comes to performance in heat engines. What is interesting is how much heat it can put into the cylinder. It has to be remembered the mixture is putt and is air and fuel but not just fuel. By having a mixture with lots of heat it will also be more power. As it can be seen in the table below having methanol and gasoline is almost equal in mixing value. But nitromethane is in a totally different thing. Now you it might be realized why nitromethane is putt in the fuel.

Now, it is time to explain some fundamental aspects regarding combustion in glow plug engines. Example: First there is a quiescent fluid, this means a mixture of air and fuel, all in gas phase, everything in the container is still, no movement of the gases, but the gas is well mixed, then a spark will perform ignition on one side of the container, now a flame would be seen and a flame front propagating through the fluid will occur. What will be seen is a light emitting sheet travelling through the fluid concentrically from the spark onwards.

The speed which the flame propagates is called the *laminar flame speed.* Methanol burn pretty fast, gasoline burns about 10-20% slower, but it must be remembered that the laminar flame speed is dependent on air / fuel ratio, pressure and temperature. All in all if numbers are putt behind combustion duration and the speed that the engines have. It will be seen that things don't add up. If the gas burned with laminar flame velocity the engine would not rev. Example follows: If it's known that an engine runs at 15000 rpm, this is 250 r/sec and this for a NSU-Wankel engine are 83.33 combustion's per second, it will be assumed that the combustion duration is 140 ° in the housing that makes the entire combustion time per cycle to 4.67 ms. Say that the flame has to travel 1 cm this makes the flame velocity of about 214.13 cm/s. This is about 5 times to slow if the *laminar flame velocity is used*. So things must go faster.

When a fluid (gas or liquid) flows slowly, it usually flows with a laminar flow pattern. When the flow speed increased its flow pattern is turbulent (irregular). If the smoke is observed coming from a cigarette, the first part of the smoke is smooth, there are smooth flow lines, later on there will be a transition to a more irregular pattern. This is the transition from laminar to turbulent flow. If a flame is ignited in a turbulent flowing environment, the burn rate increases considerable, it makes the flame go so fast as it will bridge up the gap between the laminar cases to the turbulent case. Turbulence makes the flame go faster, there is also evidence that strong turbulence will stabilize the combustion, if the mix is uneven, strong turbulence will stabilize this. How turbulence is created is not very hard to imagine that the flow inside an engine that has 83.33 cycles per seconds should be turbulent. But there still are mechanisms that control the burn rate in the engine.

The squish area is the outer part of the combustion chamber, during the last part of the compression stroke the gas that resides below the squish area will be forced towards the center of the combustion chamber. This high velocity movement will generate high intensity turbulence during combustion. By changing the area of the squish band the amount of gas that is forced is changed and effectively changing the turbulence.

4.5. MIXTURE PROPERTIES

	Methanol	**Nitromethane**	**Gasoline(isooct)**
Stoichiometric A/F ratio	6.45:1	6.78:1	~14.5:1
Lower Heating value [MJ/kg]{kWh/kg}	19.9 {5.5}	11.3 {3.1}	43 {12}
Heat of vaporization [MJ/kg]	1.17	0.56	0.18
Heating value mixture[MJ/kg]	3.08	6.6	2.96
Formula	CH3OH	CH3NO2	CH8H18
Mol. Wt	32	61	114
Oxygen. Wt %	49.9	52.5	0
Specific energy	3.1	6.6	2.9
SE ratio	1.06	2.3	1

*SE: Specific energy is the ratio of heating value to air fuel ratio relative to isooctane. High heat of vaporization cools the incoming charge and increases volumetric efficiency.

Table. 4

The simplest alcohol is a liquid with low heat content compared to gasoline and it has also a significant higher heat of vaporization. Methanol also has a low ignition point. It will ignite at about 500°C. This is a fairly low temperature. It explains why a glow plug is working; these engines are ignited by surface ignition from the glow plug coil. Nitromethane is used as fuel but it's very special. One special thing is that is requires very little air to burn. This is nice when it is blend with other fuels. It will be able to get more heat into the cylinder. By adding more fuel you get more cooling from the added fuel to the mixture. Another fact of Nitromethane is that it can be a mono propellant. That means that nitromethane can burn in the complete absence of air. In other words the engine can run only on nitromethane, this is like in the moon where there is no oxygen but the low temperatures won't make it able to reach the ignition temperatures. Nitromethane burns very quickly and has a high tendency to knock. That is one reason why it isn't good to run exclusively on Nitromethane and take into account that a large amount of Oil will slow the rate of combustion down.

Usually the glow fuel can be divided into three different categories according to Nitromethane content: No Nitro (0-5%), Low Nitro (~15%) and High

Nitro (~30%). The question what is the difference between these fuels? In the first case you are only combusting pure methanol. Maximal power is obtained by running 1:4 fuel/air ratio. This means running fuel rich, and getting lots of fuel cooling. Secondly when running 15% nitromethane, this makes it possible of running even richer with more heat being released in the cylinder; I also make for a faster combustion. Third running on 30% nitro, here it is added more fuel and get more cooling. It should also perform a more rapid combustion.

The *laminar flame speed* for methanol it is about 40[cm/s] at room temperature and pressure.

- *Important Fuel Properties:*

Table. 5

• Heating value – lower and higher HV
• Density
• Flash point – temperature at which the
• Vapour pressure of fuel in air is flammable
• Distillation curve (volatility)
• Most fuels are blends (even natural gas)
• Viscosity (affects spray behaviour)
• Combustion properties
• Octane number (gasoline)
• Cetane number (diesel)
• Additives (MTBE and lead)

It is usually use as a mixture with methanol to reduce peak flame temperatures. Its high heat of vaporization results in significant cooling of the air fuel mixture entering an internal combustion engine. The fuel energy delivered to the combustion engine is 2.3 times that of iso-octane for the same mass of air. For these reasons nitromethane is a fuel commonly used in drag racing in both cars and boats.

5. EXPERIMENTAL DATA AND TESTS

The experimental data obtained in order to have the complete knowledge and certain behaviour of the engine in our laboratories and global position were performed building a test stand that fulfilled all the needs in order to calculate accurately torque, power, thrust, and fuel consumption.

To accomplish all this test stand built can measure torque by measuring the weight needed to level the force that the engine at a given speed and laboratory conditions produce. This knowing the phenomenon that is present in aircrafts and will be explained later. The stand consist on a car mounted on a railed base that by reaching the equilibrium of the forces between a weight on a basket transmitted by a pulley and the thrust that the engine performs gives the thrust that the engine is producing. The torque is measured by obtaining the counteract torque that the engine is performing at certain speeds and conditions; the engine is mounted on bearing that permit its free rotation, then if a force (weight) at a certain radius (produced torque) counteracts and makes a zero rotation then the same torque that the engine is giving is reached and the power is the product between the torque and the angular velocity. The fuel consumption is just the measurement of the time that the engine at certain speed takes to consume 10mL of nitromethane, this having a levelled tank connected to the engine.

5.1. TORQUE EFFECTS IN PISTON AND TURBOPROP ENGINES

The torque problem comes from Newton's basic law of motion which states that "For every action there is an equal and opposite reaction." Therefore, as a helicopter's engine spins the main rotor in one direction, the helicopter body wants to spin in the opposite direction. However, the smaller rotor on the tailboom creates a force, or more correctly a *moment* (which is the force multiplied by the distance between the main and tail rotors), that counteracts the induced spin of the body and keeps the helicopter in equilibrium.

Propeller-driven aircraft do indeed suffer from the same effect. When viewed from the front, most propellers turn counterclockwise, so the rest of the plane has a tendency to rotate clockwise, or left-wing down.

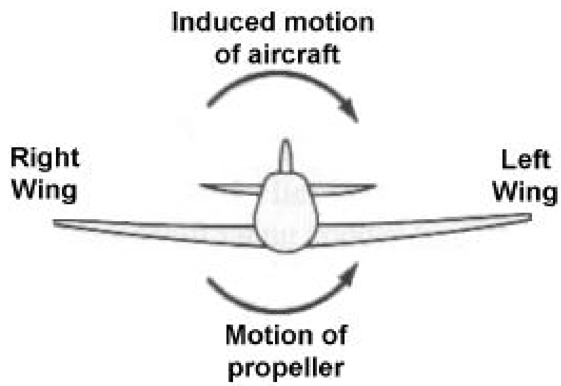

Fig. 12

Torque induced on an aircraft due to propeller rotation

While helicopters use a separate device to address this problem, this tendency is usually counteracted by pilot control inputs alone on an airplane. Since the plane wants to roll to the left, he will apply right aileron (i.e. deflect the left aileron down, right aileron goes up) to increase the lift on the left wing creating a right-roll moment. This moment counteracts the rolling motion induced by the propeller torque and returns the aircraft to a wings-level configuration.

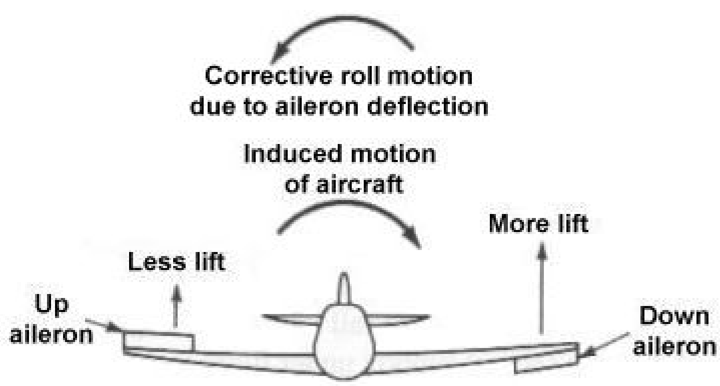

Fig. 13

Corrective roll motion created by deflecting the ailerons

However, this aileron deflection has the effect of making the aircraft asymmetric, or uneven, because one side of the plane produces more lift than the other. When this situation occurs, that side of the aircraft also produces more drag than the other. This increase in drag on the left side of the plane causes it to yaw to the left, an effect known as adverse yaw To correct for this yaw effect, the pilot must also apply right-rudder (rudder deflects to the right) to counteract the adverse yaw and keep the nose pointed straight ahead.

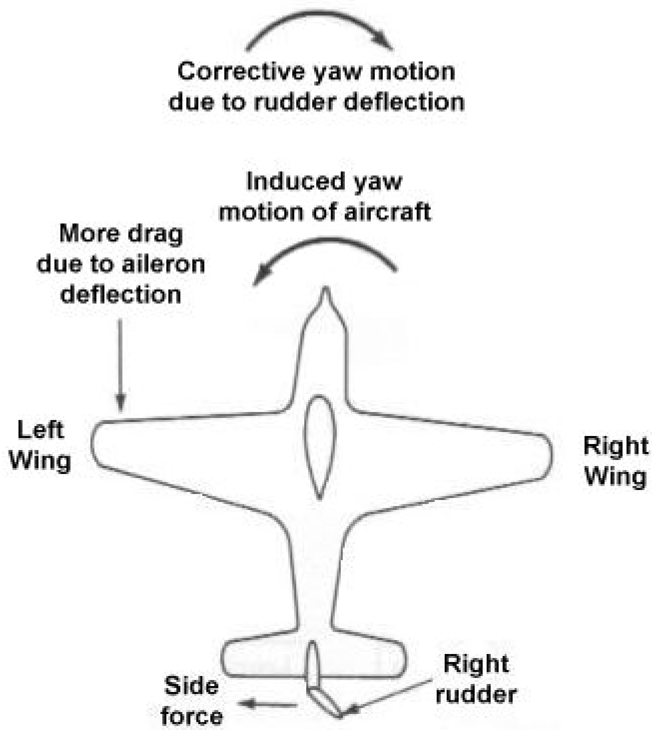

Fig. 14

Corrective yaw motion created by deflecting the rudder

We might expect that dealing with all these balancing motions and corrective measures would be somewhat tiring to the pilot, but the effect is not that great for most aircraft. Pilots usually maintain trim by instinct and familiarity with the flight characteristics of the particular aircraft. However, *torque-roll* has caused many accidents when the pilot entered a flight regime he was not familiar with. For example, when the engine fails, the torque effect disappears and the pilot must realize how this changes the flight characteristics.

A more common example comes from the operation of piston aircraft from aircraft carriers. When a pilot misses the landing wires on a carrier deck, he goes to full power to take off again and go around for another attempt. This sudden increase in power also generates a sudden increase in torque that the pilot may not be prepared to compensate for. Complicating the issue even more is that landing occurs at relatively low speeds. When the speed of the air flow passing over the aileron and rudder is slow, these surfaces loss much of their effectiveness and may not be able to counteract the torque.

Another method of counteracting the torque effect is the use of contrarotating propellers, or propellers that rotate in opposite directions. As piston engines became increasingly powerful in the 1940s, some single-engine aircraft required contrarotating propellers to remain controllable. The Supermarine Seafire and Maachi M72 are examples of aircraft with such powerful engines that they needed twin contrarotating props on the same shaft to cancel the torque effect. Contrarotating props also offer advantages in eliminating other assymetrical effects and were found to give aircraft much better handling characteristics.

In addition, the torque effect can be completely eliminated on multi-engined aircraft in a similar manner. Most twin-engined or four-engined piston aircraft use propellers that rotate in opposite directions to negate the torque effect. By rotating the right engine clockwise and the left engine counterclockwise, for example, the torques will cancel without any corrective action being necessary.

Finally, keep in mind that any rotating component creates assymetrical forces and moments on aircraft. Even the rotating fans and turbines in modern jet engines will do so, but these effects are usually so small that they are difficult to notice. In addition, modern fly-by-wire control systems probably correct for these effects automatically.

The knowledge of these phenomena was used to design the test stand and the mechanism which measures the contrarotating moment which gives the torque and power curve of the engine at different speeds.

5.2. PERFORMANCE TEST OF THE 49PI NSU WANKEL ENGINE

The technical drawings of the test stand are opened with the hyperlinks:

1. Base
2. Car
3. Track
4. Rod and pulley
5. Isometric parts
6. Isometric 1
7. Isometric 2

These drawings show the parts and how they are assembled in order to have the test stand used for these experiments. With the pictures taken of the experiments and the experiment protocol hypothesis and technical document the experiment procedures can be better understood. The picture TEST STAND TEST shows all the test pictures in the laboratory and with the final test stand. The first pictures show the test stand assembled with the engine and fuel tank, show the torque test, that show the engine running the container filled with the BBS that are used as the weight to counteract the torque action of the engine and the position of the rod in which there is no contact with the test stand stops, this is that the net torque is zero then the weight in the container plus the container and the cord that suspends the container. The other pictures show the thrust measure where the weight putted to the car counteracts the thrust performed by the set engine and propeller thus the car positioned in a central position on the rails where it can be seen zero net force acting on it.

All the experiment characteristics are specified in the following documents:

1. Hypothesis.
2. Experiment protocol.
3. Technical report.

6. FINAL COMMENTS

All the conclusions of the experiments are resumed in the documents hyperlinked above all the work done previously was helpful to understand how the engine worked its origins and characteristics. To develop resume and obtain all the pertinent parameters of these engines as well as study profoundly a certain type of engine the O.S 49PI made for model aircraft engine, disassemble it measure it and put it to test in all its power made possible the understanding of these types of engines. Through out time it can be seen the introduction of this kind of engines in new technologies and uses as can be seen in the fifth slide of the resume presentation.

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