Combustion Chamber Design Effect on The Rotary Engine Performance - A Review

Boughou Smail 1)    AKM Mohiuddin 2)

1) International University of Rabat UIR, Renewable Energies and Advanced Materials Laboratory LERMA, Technopolis Rabat-Shore, Morocco (E-mail boughou.smail@gmail.com)

2) International Islamic University of Malaysia IIUM, Faculty of Engineering P.O. Box 10, 50728 Kuala Lumpur, Malaysia (E-mail akmuddin@gmail.com)

ABSTRACT: Comparatively, this review is meant to focus on possible developments studies of the rotary engine design. The controversial engine produces a direct rotational motion. Felix Wankel derived the triangular rotor shape from complex geometry of the Reuleaux triangle. The Wankel engine simulation and prediction of its performance is still limited. The current work reviews rotary engine’s flow field inside the combustion chamber with different commercial software used. It studies different parameters effect on the performance of the engine, such as the effect of the recess sizes and the shape-factor. It is found that the engine chambers design is one of the aspects of improvement opportunities.

KEY WORDS: Rotary engine; Design geometry, Shape factor; Combustion simulation. [A1]

1. Introduction

Although the controversial rotary engine was adopted and developed by many manufacturers, it is seen that multiple attempts have been made to commercialize it. However, limited information is available about the individual projects or companies involved in the development of these engines. Some information was found in early projects at Toyo Kogyo 1 developed by Kenichi Yamamoto 2 and Muroki, Takumi 3,4. The powerful engine manufacturer could survive after the designer Yamamoto who led an engineering team and produced a commercial rotary engine vehicle at the Toyo Kogyo company, now known as Mazda.

In 2006, the Mazda company has released the RX-8 hydrogen powered RE 5. Due to falling sales and emission regulations, the Mazda CEO Masamichi Kogai comes to put an end to all the RX-8 in 2012. Nowadays, the Mazda technical research center head Mitsuo Hitomi revealed that the brand is developing integration of new fast ignition such as laser ignition and plasma ignition. Their aim is to solve the flame propagation problem of the rotary engine fuel consumption 6.

The rotary engine recently got interests for possible reliability as range extenders for electric vehicles. The rotary engine is reliable to be applied for the design architecture of UAV powertrains 12,13. The small-scale reliability to unmanned aerial vehicles UAVs. Such as for aviation of RQ-7A Shadow 200 and Sikorsky Cypher are run with a rotary engine. The low vibration is a point of fitness to UAV purposes 14. It shows an upward attraction by reducing space and weight in the future designs of the unmanned aerial vehicles.

The engine has been mounted in the work of Yewale et al 15 and tested to measure the engine performance. During the test no knock is noticed and a gradual increase in temperature is observed. The test showed the limits usability reliability of the Wankel-type rotary engine as an alternative propulsion for UAV.

For its compactness (small volume), it produces a high power compared to its weight. The rotary engine is suitable and advantageous for domains where the volume and the space taken by the engine in the power plant is of strict constrains 16,17. Such as the earlier NASA 18 applications of rotary engine research program for heavy aerials 19. Furthermore a Wankel rotary engine connected with a generator that charges the battery used in one of the designed models for hybrid propulsion systems for unmanned aerial vehicles 20. The small engines diminish the number of cylinders and giving the space for the batteries, as for example the concepts that integrate two-cylinders range extender in hybrid powertrain applications.

One area of interest of the rotary engine is the implementation into range extender for electric vehicles. As the fig. 1 shows, the range extender that uses the rotary engine as a power source may be of significant interest in the automotive application as a range extender for Electric Vehicles 21. An electric powertrain car concept 22 claimed to provide an additional 100 miles of range from a small gas tank by Mazda2 using a 0.33 – 1 cm³ (cubic capacity) single rotor engine as a range extender in its vision ZOOM-ZOOM 2030 to contribute to the electrification in all its vehicles.
Noga. M. reviewed the opportunities of range-extenders with various internal combustion engines available for use in EV. Mazda Motor Corporation has made a variety of hydrogen prototypes, which claims the rotary engine to be an optimal system for hydrogen combustion. A basic single rotor version of the engine has a displacement of 0.254 dm$^3$ and an output of 15 kW at 5000 rpm, which can be modified to increase the output to 18 kW at 7000 rpm. A single rotor rotary engine was chosen as the internal combustion engine range extender concept and connected with a generator to create the range extender system of AVL’s prototype vehicle. AVL developed range extended hybrid vehicle using rotary internal combustion engine model as shown in Fig. 2. In the other reciprocating engine research of AVL, a single-cylinder maintaining high compactness 25 kW range extender may be an alternative to a rotary engine, AVL also implemented a 1-cylinder ICE into the package of the RE unit.

As the environmental regulations that control the emissions lead to more complex vehicle architectures, it leads also to different application and design requirements for internal combustion engines. Therefore, it requires electrification development of the powertrain with an advanced combustion strategies and advanced engine architectures. This new competitive technologies, such as micro hybrids, full hybrids, electric vehicles and fuel cells are running under development in line with the traditional technology such as the BMW i3 range extender, the Honda Accord Plug-In hybrid, validations obtained at Argonne’s Advanced Powertrain Research Facility and other of many ongoing range extender application developments to reduce the overall powertrain costs with a low cost automotive engine for electric vehicles. The engine weight is to be taken into account when discussing the hybrid vehicle in order to allow the increasing of the battery size and controlling the total vehicle weight. The implementation of small rotary engines as generators to supply the energy stored in the vehicle battery gives a chance for a renaissance of the engine.

By surveying the market of small type engine designs, analysis to identify the optimal design techniques show the high fuel consumption is a challenge. Based on market survey, the distribution of the rotary engine is promoting and being under development for military applications, especially the unmanned vehicle in which the 2-stroke engine dominates. The University of Bath is developing a 225 cc Wankel rotary engine for use as a hybrid vehicle range extender (Fig. 3). The engine is competitive to be implemented as a generator to supply the energy to the hybrid vehicle battery.

Turner et al. compared the Wankel RE together with a 4-stroke piston engine the baseline model considered of BMW i3. The rotary-type engine would perform very close to the piston engine if can achieve an improvement of 12% of thermal efficiency. They finally adapted the model into further focus on the direct injection in further development of 1D/3D CFD numerical models.

Table 1 Comparison of the range extender rotary and the conventional engines

| Rotary                        | Conventional                      |
|-------------------------------|-----------------------------------|
| Lightest engine               | Over-expanded SI engine          |
| Biggest battery pack          | Dual eco/boost                    |
| Urban driving                 | Combined urban-highway.          |
| Most efficient in urban       | Most efficient in combined        |
| driving                        | urban-highway.                    |

Fig. 1 Engine electrification with battery operation percentage

Fig. 2 Single rotor version as range extender

Fig. 3 AIE UK Ltd. 225CS Wankel rotary engine
An overview of detailed advantages and demerits in the report done by Chol-Bum Kweon on the heavy fueled rotary engine combustion technologies status that shows the engine not been well researched and developed in comparison with the reciprocating engine. This reports that the rotary engine promises to be a power generating for the unmanned aerial vehicles UAV due to its suitable size and light weight as well as the ground vehicles.

Conclusions on the final status of the technology are made by the NASA enablement program (1983 through 1991) of the rotary engine technology that reports the need of a design, multi-fuel capability and computational fluid dynamics CFD code methods for a better understanding and improvement of the combustion. On the basis of what had been recommended by Kweon’s review that the most advanced 3-D CFD software for the internal combustion engine simulation includes KIVA3v, CONVERGE and AVL FIRE and others.

3. Rotary engine operation performance comparison

The Wankel RE operates on the four-stroke cycle. A single-rotor Wankel engine shares some characteristics in its operation with the single-cylinder piston engine. But it is wrong to compare them on a similar displacement, because the Wankel engine operates on the four-stroke cycle unlike a single-cylinder. Therefore, it is fair to compare the Wankel with a two-cylinder, four-stroke piston engine which does a power stroke for every crankshaft revolution. A single rotor Wankel engine does two complete cycles within two revolutions of the eccentric shaft. A single cylinder piston requires two crankshaft revolutions to complete one four-stroke cycle. The comparison between a single-rotor Wankel engine and two-adjacent-cylinder piston engine, needs to take in consideration the rotor’s three faces operating in a two-lobed housing. One single-rotor behaves like a three-cylinder at the four-stroke while the cylinder number one as shows the Fig. 4.

The piston in a four stroke-cycle reciprocating engine comes to rest four times per cycle as its direction of motion changes. In contrast, the rotating parts in a rotary engine are in a continuous direction motion. Since a reciprocating engine 4-stroke Otto cycle takes place over 720° whereas the Wankel engine does two-thirds that of Otto cycle. In order to have the same number of combustion events for a given time period. Because one cycle, including intake, compression, explosion, and exhaust strokes corresponds to a crankshaft (eccentric shaft) angle of 1080° in a rotary engine. For instance, the intake ‘stroke’ having 270 degrees of eccentric shaft rotation whereas 180 degrees rotation of the reciprocating engine’s crankshaft.

The reciprocating engine runs two turns while completing the four-stroke processes, where the rotary engine runs three turns. In other word, at the reciprocating engine, the crankshaft (output shaft) makes two revolutions (720 degrees) during the four-stroke processes (Fig. 4). While in the rotary engine, the eccentric shaft (output shaft) makes three revolutions (1080 degrees) as the Table 2 summarizes.

The comparison of various rotary engine configurations demonstrates the power stroke duration of many conventional types (Fig. 5). The rotary engine has a longer process time. This causes less torque variation and differences in the flow field, which results in smooth operation. By comparison of torque variation of the rotary engine with other reciprocating engines, Timothy et al predicted the limitations of the rotary engine performance to answer whether speeding up the combustion always improve performance, and shown that a fast combustion does not necessary increase combustion rate. An eight-cylinder reciprocating (V8) engine is shown to be likely smoother as the rotary engine.

Table 2 Power stroke duration of all conventional types, 56

| Type         | Combustion process                          |
|--------------|---------------------------------------------|
| 4-stroke     | 90° out of 360° (180° out of 720°)           |
| 2-stroke     | 120° out of 360°                            |
| Wankel       | 270° out of 360°                            |
| SARM         | 320° out of 360° (160° out of 180°)          |

Fig. 4 The 4-strokes comparison between piston and rotary engines [Adapted from 55].

Fig. 5 Reciprocating vs. rotary [Adapted from 57]
4. Effects of different variables on flow fields

4.1 Eccentricity K shape factor

Modifications of the epitrochoidal shapes that are used in rotary piston machines are limited. Adequate published works are discussed here to explain various features of such machines. The study of Huai-Lung et al. indicated that the design shape factor K produces different rotor profile and different working chamber volumes. They concluded that the combustion and the compression efficiencies can be improved by increasing the K factor. As K is ratio of the rotor radius to the eccentricity (R/e), the K factor increases by enlargement of R or reduction of e. Therefore, higher K will lead to a high compression ratio. The volumetric displacement of a Wankel rotary engine is a function of the trochoid ratio and the pin size ratio. The trochoid ratio (design shape factor) K is the ratio of the fixed rotor radius R called the generating radius, to the radius of the rotating rotor e called the eccentricity (in other nomenclatures sometime denoted by r). Earlier design study of the effects of trochoid ratio and the generating ratio parameters on the displacement and compression ratio of the Wankel engine showed the relationship between the design variable K and the displacement and maximum theoretical compression ratio. Whereas increasing K (the trochoid constant) the maximum compression ratio increases. As shown in Fig. 6, increasing K factor (or R/e ratio) leads to a rotary engine with large rotor radius and small eccentricity.

Hsueh with colleagues investigated a triangular rotary engine’s internal gas flow characteristics. By using the CFD package FLUENT, they constructed a fluid analysis model as shown in (Fig. 7). They analyzed three different cases with various geometric K factor. Different K factor designs generate different rotor profiles with different working chamber volumes. The results indicate the lower is the K factor, the larger is the working chamber volume.

4.2 Effect of the recess (pocket) volume

Many parameters influence the flow field inside the rotary engine. As mentioned above, the compression ratio depends on the maximum volume, minimum volume and of the volume of the rotor pocket as well. Earlier, Yamamoto and Muroki emphasized the performance of three rotor pocket designs, and compared the effect of combustion chamber pocket shapes on HC emission. In the case where the recess is located in the rotor leading tip, the engine performance improves but HC level increases. Similar performance is observed with the centered rotor pocket. But for the pocket directed to the opposite motion direction, the unburned HC decreases.

Shih et al. earlier recommended that investigating new combustion strategies might lead to improve the fuel-air mixing and distribution. They concluded in their work that two spark plugs would increase the engine efficiency. Further, they concluded that efforts should be made on the rotor pocket shape and fuel injection and intake spray in the regions next to intake and exhaust ports. In other-fashion, Nagao et al visualized the patterns of the engine combustion near TDC of the compression stroke in a transparent engine by using a spark tracing technique that consists of an optical window allowing a holographic interferometry recording camera. The results showed that the flow pattern is strongly affected by the shape of the recess.

The flow fields measured during intake and early compression of two different rotor pocket geometries in a motored rotary engine were compared by Filippis et al. The pocket geometries studied are a leading deep recess LDR (Fig. 8a) of Mazda and another one with central symmetric recess SMR (Fig. 8b). The comparison showed little difference in the regions studied. Swirling was important near the leading apex seal for the LDR rotor than in the centralized SMR rotor. Similar work of Jaber et al. proved the reliability of the concept to reducing unburned fuel and increasing lean limit of the engine.
Similarly, to determine the best pocket location, Baowei Fan et al. analyzed the effect of pocket location on combustion process and chosen a spark-ignition rotary engine and got similar information such as velocity, temperature fields and flame propagation. The table 3 shows the performance of three different pocket locations. In all designs, the main three areas of unidirectional flow field in the combustion chamber can be seen: rear, central and front.

| Pocket Location | Middle | Front      | Rear        |
|-----------------|--------|------------|-------------|
| Pressure        | Baseline | Lower peak | Higher peak |
| Flame           | Better flame development | No flame Kernel | Long combustion time |
| Flow            | Small velocity | high velocity | Small velocity |
| Consumption     | Baseline | Lowest gas consumption | Highest gas consumption and NOx emissions |

The unburned fuel of rear pocket case is less than that of other cases because of the longer combustion time that promotes the rear gas to burn. Overall, the flow field before top dead center BTDC near the spark plug of all combustion chamber geometry cases is identical.

Later on, Baowei Fan et al. investigated the effect of the turbulent swirling (Fig. 9) in both the combustion chamber and the rotor pocket caused by the intake shape. They considered a peripheral intake port combined with the effect of the shape of rotor pocket. The swirling becomes developed and unidirectional because of the small volume near the TDC and dominated by the compression processes. Large vortex structures in the center of the chamber at the intake process and dispense into small vortices in the compression process.

Poojitganont et al. in their simulation of the flow field inside the Wankel combustion chamber have focused firstly on the effect of the geometry of combustion chamber in three different shapes of geometry. The different shapes of the chamber can provide various fluid flow characteristics. The understanding of these phenomena can lead to the optimization of the suitable situation of mixing between air flow and fuel droplet inside the combustion chamber. It is concluded that the slow combustion and non-uniform mixing of fuel and air is what leads to long and incomplete combustion.

The mixture formation and flow investigation study by Izweik was one of the focus beside the investigations of diesel spray and hydrogen injection. The formation is affected by the engine’s combustion chamber design. To determine the optimal engine configuration to burn hydrogen, six rotors geometries in Table 4, with different recess shapes has been tested. The results showed that the highest-pressure has been developed with the smallest and narrowest recess “rotor no.1”. Clearly, the lowest flow velocity is the rotor that has a wider and deeper recess “rotor of KKM-407” which is fitted in an engine used in the market for light aircraft applications.

Zhou et al. modeled four different combustion chamber geometries to study the effect of various geometries of rotor recess on the flow field. The formation of fuel-air mixture is significantly affected as the results shown in Table 5. Better combustion can be obtained with a pocket located at the middle and shallower pocket. Similarly, different recess (pocket) sizes were numerically investigated by Jeng et al. As it was shown earlier that different recess geometries, the minimum volume is significantly affected, and the compression ratio CR as well (Fig. 10). The comparison of pressure-volume diagram of experimental engine with compression ratio of 10.18 shows that increasing compression ratio increases the maximum pressure.
By focusing on the effects of recess sizes with different CR- it can be concluded that:

• At lower CR (8.33) -larger recess size, the sealing leakage causes a drop of pressure in the working chamber and an increase of combustion volume.
• At higher CR (10.18) -smaller is the recess size, better fuel-air mixing is achieved, and higher is the pressure.

Table 4 Flow velocity vector, TDC-540° of shaft rotation, reproduced from 74.

| Geometry | Flow Velocity no. \( R \), [\( \text{m/s} \)] |
|----------|---------------------------------------------|
|          | 0.0                                      |
|          | 0.1                                      |
|          | 0.21                                     |
|          | 0.32                                     |

Table 5 Pocket shape effects on the performance

| Geometry 75 | Pocket position | Performance                                    |
|------------|-----------------|------------------------------------------------|
| Front      | Late combustion phase and less NOx          |
| Middle     | Better fuel atomization                      |
| Deeper     | Better flame propagation                     |
| shallower  |                                              |
| rotor      |                                              |
| Rear       | Bigger combustion Higher NOx                 |

In a rotary engine fueled with natural gas, the effects of pocket shapes on the combustion processes has been numerically investigated by Baowei Fan et al 77. Regardless the effect of the fuel type, they compared numerical results with different data obtained from the experiments using optical engine and laser ignition control system. They studied four pocket shapes: flat top pocket, trailing pocket, middling pocket and a leading pocket. The study of the flow patterns shows the combustion rate. It is seen to be faster in the case of middling pocket than the other cases.

The middling pocket was chosen to be compared with different pocket of configuration that consists of an addition of ignition slot designed in a manner to improve the flow near the spark plug. The middling pocket coupled with an ignition slot is found to perform better than a middling pocket without ignition slot. The middle of combustion chamber average flow speed and the flame propagation speed is influenced (Fig. 11).

The Flame propagation within the rotating combustion chamber in the rotary engine was also shown to be influenced by the recess shapes in the work of Harikrishnan et al 78. In their work they compared three recess geometries (Fig.12). The first recess was a baseline shaped, second with a volume in the leading side and has shallow depth in it and the third with a centrally symmetric depth. The first recess with compression ratio 9.1 considered as the baseline design. It showed that the flow and vortex formations were like that of measured data. The flame propagation travels toward the leading apex of the rotor. In the second recess with higher compression ratio of 9.6, lower trapped air–fuel mixture is noticed.
To improve the engine efficiency, various options of the rotor recess shape have been under consideration. The air-fuel mixing process and the effect of the modified combustion chamber recess has been numerically studied by Finkelberg et al. The comparison of the velocity contours at different angles for normal and modified rotor is shown in the figure 13. The proposed alternative design of the modified rotor shape leading tip stands to improve the efficiency of the rotary engine. It accelerates the flame to propagate in the working chamber.

Fig. 12. Three different recess shapes.

Fig 13. Velocity contour at different angle for normal and modified rotor, reproduced from 79.

5. Computational Fluid Dynamics CFD Approaches

Fluid flow issues occur in almost every branch of engineering, ranging from the relatively simple to complicated flows. Analytical models comparison can be observed by the facilities offered by CFD. The turbulence mathematical model Large-eddy Simulation (LES) used in the computational fluid dynamics was proposed in 1963 by Smagorinsky. At the first time from meteorology background, it was intended for the simulation and the study of the dynamics of the general circulation of the atmosphere and fluid dynamics explored by Deardorff (1970).

By focusing on those that modelled the engine, some of the works cited earlier have done the simulation mainly using the environment provided by KIVA software, commercial software FLUENT, commercial code AVL FIRE, software STAR-CI, the National Instruments LabVIEW® environment and newly the Convergent science CONVERGE software.

The modelling of the three working chambers of the Wankel engine required three-cylinder elements. Consideration of the differences between the Wankel and the piston engines would be taken into account to develop an algorithm for the analogy between a single rotor rotary and a 3-cylinder 4-stroke reciprocating model. A similar equivalence method done by Peden et al. in a modelling with the AVL BOOST software. A new model was created as a derived area of the combustion chamber of the reciprocating engine. The model does a correspondence of basic geometry of the rotary engine with each of the minimum and maximum volumes of the Wankel chambers.

The application of available software of piston engines to the rotary engine confronts limitations. The single rotor is considered equivalent to the 3-cylinder 4-stroke reciprocating engine. It requires several assumptions that affects the accuracy of the model analogy which is difficult to achieve. An approach proposed by Vorraro et al. for the assessment of the performance of a modern rotary engine and developing software tools. A software tool and a data acquisition system have been developed within the National Instruments LabVIEW environment to ease and speed up the analysis of different configurations. The National Instruments LabVIEW software allows users to introduce the main design parameters for generating radius $R$ and the eccentricity $e$.

In the model constructed by Zenh et al. using the CFD software FLUENT, the high temperature zone did not travel in the combustion chamber after ignition. This is because the simulation did not well-estimate the reaction rate and the gas does not react immediately in the chamber. It needs modification of an accurate combustion model prediction in the computation.

CONVERGE a CFD code uses RNG k-$\varepsilon$ turbulence by including Automatic Mesh Refinement AMR models a grid-converged CFD. There is a strong demand of a simulation software which reduces the time of the development of rotary engine. Especially in the aero-industry such as in small aircrafts unmanned aerial vehicles UAVs.
### Table 6 Comparison of basic remarks on the accuracy of the reviewed analytical models

| Ref | Varied parameter | Test conditions | Findings |
|-----|------------------|-----------------|----------|
| (59) | | Different rotor profile | Enlargement of the rotor radius and reduction of the eccentricity; The combustion and the compression efficiencies can be improved by increasing the K factor |
| (86) | Shape factor K | Trochoid ratio | Increasing of the trochoid constant increases the maximum compression ratio. |
| (87) | | Increasing the compression ratio | Increasing the compression ratio cannot ensure an improvement of the engine performance. |
| (88) (89) (62) | | | The lower is the K factor, the larger the working chamber volume. |
| (78) | | High CR | Higher peak pressures and better mixing and fuel efficiency. |
| (63) | | Rear, Middle, Front | The unburned HC is to decrease Baseline Engine performance improves, but HC level increases |
| (67) | | Leading deep recess LDR | Swirling was important near the leading apex seal for the LDR |
| (70, 71, 73) | Recess | Rear, Central and front | The unidirectional flow field in the combustion chamber can be seen: rear, central and front. The swirling becomes developed Slow combustion and non-uniform mixing of fuel and air is what leads to long and incomplete combustion. The highest-pressure has been developed with the smallest and narrowest recess. Better combustion can be obtained with a pocket located either at the middle and shallower (deep) pocket. The minimum volume is significantly affected, and the compression ratio CR as well. At lower CR (8.33); at the larger recess size allowed increased burning area with lower compression ratio, the sealing leakage causes a drop of pressure in the working chamber; At higher CR 10.18, smaller is the recess size, better fuel-air mixing and maximum is the pressure. |
| (74, 75, 76) | | 5 Rotors geometries 4 Rotors geometries CR 8.33, 9.55 and 10.18 | |
| (77) | | Pocket coupled with an ignition slot located at the middle | The middle of combustion chamber average flow speed and the flame propagation speed is influenced. |

### 6. Current designs of rotary concepts

Recently, the rotary engine is promising for the implementation into the powerplants for UAV. The leakage flow analysis for a MEMS Rotary Engine was beside the sealing issues that are still the keys for efficient operation of the micro-engine. Kelvin et al designed, fabricated and tested the effects of sealing, ignition and thermal management on the efficiency of a mini-rotary engine. Many derived designs based upon the earlier mechanisms are showing up to the market. There are nowadays new families derived from the philosophy of Wankel engine for multi-purpose applications development worldwide, so there are essential benefits that make engineers to occupy with them. As an attempt to enhance the performance of the design of rotary devices, several examples are provided by a new method (Fig 14) that consists of a function of the angular position of pitch curve called Deviation Function \[92\].

S. Warren and Daniel C.H. Yang \[93\] found a larger variety of engine profiles using the deviation function (DF) (Fig.14) method to design the two lobed gears in most practical trajectory profile of gerotors rotary engine apex seal. This method can be used to improve the sealing of the engine by a level conformity between the housing and its rotor because of the nonconformity that prevent optimal sealing of the engine.

![Fig. 14. DF method for rotary housing generation.](image-url)
A finite element model \(^9^4\) studied the stress and deformation of a small rotary engine of 4.97 cc volume and shows the stress and deformation of the cylinder increasing with the increase of the engine speed (Fig. 15). To estimate a ratio between rotor and stationary parts that allows estimation of rotor and total heat losses, a CONVERGE CFD model was developed, and used together with GT-POWER \(^9^7\). Results indicate higher heat losses for the “X” geometry than seen in the experimental Wankel data because the engine is still under development and sensitive to seal condition and coatings used.

![Fig. 15. Small rotary engine finite model and stress distribution](image)

There are three types of commonly studied rotary concepts, which are Wankel type, LiquidPiston (Fig. 16) and SARM for drones and range extenders. LiquidPiston: a rotary engine, four-stroke of “X” architecture with intake and exhaust through rotor shaft \(^9^5-9^8\). The LiquidPiston’s “X” architecture is a rotary engine that similar in some aspects to the Wankel. The X engine shares some advantages of the rotary engine architecture similar to the Wankel, for example the simplicity of having two major moving parts and the advantage of not having any oscillating masses making the engine more responsive and smoother. In many ways, the “X” engine can be thought of as an inverted Wankel concept. The rotor in both engine types is mounted on an eccentric shaft, so that its center moves on a circle.

![Fig. 16. Components and Fluid motion comparison between the “X” LiquidPiston engine and Wankel engine](image)

A quadrilateral deformable rotor QRM was studied by Hsieh et al \(^1^0^1\). The high-sealing of roots rotor with variable trochoid ratio. Unlike Wankel engine that has a rigid triangular rotor, the novel rotary engine has a deformable rotor quadrilateral QRM and rhombus orientation \(^1^0^2\) (Fig. 18). It is seen that both engines have epitrochoidal stator profiles, but different rotor motion processes and the way it rotates inside the housing is related to the eccentricity that equals to zero in the case of QRM, the summary is presented in the Table 7.

![Fig. 17. Comparison between QRM and Wankel engine100](image)

|                      | QRM                  | Wankel               |
|----------------------|----------------------|----------------------|
| Chamber shape        | Epitrochoid          | Epitrochoid          |
| Rotor shape          | Quadrangle           | Triangular           |
| Rotor flexibility    | Deformable           | Rigid                |
| Rotor speed          | Equal shaft speed    | One-third shaft speed|
| Rotor motion         | Pure rotation        | A combination of rotation plus curvilinear translation |
| Power transmission   | Gearless             | Internal gear        |
A three-chamber rotary engine epitrochoidal concept is presented by Szorenyi 103–105. It is declared to suit for aircraft and applications due to its multi-fuel capability, lower vibration levels (Fig. 18) than Wankel and reciprocating engines, and its compact dimensions 106. This concept has shown a thermal efficiency that is greater than the reciprocating engine of 0.46% and greater than the Wankel engine by 0.38%.

For a combustion performance improvement, a modification in the combustion chamber design is needed. This requires changes in the epitrochoid housing design. Felix Wankel proposed both two-lobes and three-lobes epitrochoids and other designs did not get enough chance to prove their reliability. For instance, with considerations of the combustion characteristics only limited cavity designs are applicable. That is to say that designers should look for compatible highest compression ratios taking into account the fuel anti-knocking properties.

The importance of swirling in the combustion process is seen to be significant. The reciprocating engine benefits from the longer intake time from TDC to BDC, which is smaller for the rotary engine. The shape of the combustion chamber (recess) and the arrangement of spark plugs influence Wankel engine performance. The rotor pockets geometries had been modified and displaced towards leading tip. When the pocket is located towards the leading edge of the rotor, it produces recirculation within the pocket and leads to faster mixture combustion.

Numerical modeling studies of rotary engines are very rare due to dynamic modeling difficulties of eccentric flow field motion as well as the limited availability of the software that could simulate the engine rotation. Some new codes are promising for the internal combustion engine simulation, such as the AVL and Convergent science CONVERGE code.

Rotary engines are being disadvantageous compared to reciprocating engines because of the less demand in the market due to its high emission and fuel consumption. That is why there are currently only a few areas of application and a very limited spread of the rotary engine. However, for some UAV special applications, it might be a good alternative to conventional engines, which is worth to be considered.

### References:

1. Yamamoto K, Kuroda T. Toyo Kogyo’s Research and Development on Major Rotary Engine Problems. Epub ahead of print 1 February 1970. DOI: 10.4271/700079.
2. Yamamoto K, Muroki T. Development on Exhaust Emissions and Fuel Economy of the Rotary Engine at Toyo Kogyo. In: SAE Technical Paper Series. Epub ahead of print 1 February 1978. DOI: 10.4271/780417.
3. Muroki T, Gotou S, Morita K. A Study of an Outline of Combustion for a Direct Injection Stratified-Charge Rotary Engine. In: SAE Technical Paper Series. Epub ahead of print 1 September 1990. DOI: 10.4271/901600.
4. Moriyoshi Y, Muroki T, Xu W. A Study on Combustion Characteristics of DISC Rotary Engine Using a Model Combustion Chamber. In: SAE Technical Paper Series. Epub ahead of print 1 March 1994. DOI: 10.4271/941028.
5. Ohkubo M, Tashima S, Shimizu R, et al. Developed Technologies of the New Rotary Engine (RENESIS). In: SAE Technical Paper Series. Epub ahead of print 8 March 2004. DOI: 10.4271/2004-01-1790.
6. Sam McEachern. It’s Official - Mazda is Working on a New Rotary Engine » AutoGuide.com News, https://www.autoguide.com/auto-news/2017/09/official-mazda-working-new-rotary-engine.html (2017, accessed 13 April 2019).
7. John B. Hege. The Wankel rotary engine: a history, https://www.jstage.jst.go.jp/article/geriatrics/56/1/56_56.Content/sl/-article/-char/ja/ (2001).
8. Chen T. Research and Development Work on Rotary Combustion Engines in China. Epub ahead of print 1 February 1988. DOI: 10.4271/880628.
9. Thompson GJ, Wowczuk ZS, Smith JE. Rotary Engines – A Concept Review. In: SAE Technical Paper Series. Epub ahead of print 27 October 2003. DOI: 10.4271/2003-01-3206.
10. A. Murphy B, A. Fraser E, A. Doman D. Review of Recent Toroidal Rotary Engine Patents. Recent Patents Mech Eng 2013; 6: 26–36.
11. Ozcanli M, Bas O, Akar MA, et al. Recent studies on hydrogen usage in Wankel SI engine. Int J Hydrogen Energy 2018; 43: 18037–18045.
12. Bongermino E, Mastrorocco F, Tomaselli M, et al. Model and energy management system for a parallel hybrid electric unmanned aerial vehicle. In: 2017 IEEE 26th International Symposium on Industrial Electronics (ISIE). IEEE, pp. 1868–1873.
13. Bongermino E, Tomaselli M, Monopoli VG, et al. Hybrid Aeronautical Propulsion: Control and Energy Management. IFAC-PapersOnLine 2017; 50: 169–174.
14. Griffis C, Schneider J. Unmanned Aircraft System Propulsion Systems Technology Survey, https://commons.erau.edu/publication/72 (2009, accessed 15 May 2019).
15. Yewale GL, Tapkire A, Radhakrishna D, et al. Endurance Testing for Wankel Rotary Engine. SAE Tech Pap Ser 2017; 1: 1–5.
16. Eiermann D, Nuber R, Soimar M. The Introduction of a New Ultra-Lite Multipurpose Wankel Engine. In: SAE Technical Paper Series. Epub ahead of print 1 February 1990. DOI: 10.4271/900035.
17. Louthan L. Development of a Lightweight Heavy Fuel
Rotary Engine. Epub ahead of print 1 March 1993. DOI: 10.4271/930682.

18. Oron H (Elbit S. UAV Engines in the next decade-Turbine Engines, Piston Engines and the newly Combat Proven Rotary Engine. In: A Lecture at the 6th Symposium on Jet Engines and Gas Turbines, http://www.der-wankelmotor.de/Sp/ref/hemi.pdf (2006).

19. Meng PR, Hady WF, Barrows RF. An Overview of the NASA Rotary Engine Research Program. SAE Tech Pap Ser. Epub ahead of print 1984. DOI: 10.4271/841018.

20. Xiaqing L, Minxiang W, Rui L. Modeling and Simulation Study of Intake System Characteristics of Wankel Engine for UAV. IOP Conf Ser Mater Sci Eng 2019; 692: 012045.

21. Fraidl GK, Beste F, Kapus PE, et al. Challenges and Solutions for Range Extenders - From Concept Considerations to Practical Experiences. In: SAE Technical Paper Series. Epub ahead of print 9 June 2011. DOI: 10.4271/2011-37-0019.

22. VISNIC B. No Title, https://www.sae.org/news/2018/10/mazda-2030-electrification-plan.

23. Noga M. Application of the internal combustion engine as a range-extender for electric vehicles. Combust Engines 2013; 154: 781–786.

24. Wakayama N, Morimoto K, Kashiwagi A, et al. Study of Intake System Characteristics of Wankel Engine for UAV. Pharm Bus Mater Sci Eng 2019; 692: 012045.

25. Koetsier T, Ceccarelli M. Essays on the History of Mechanical Engineering. Cham: Springer International Publishing. Epub ahead of print 2016. DOI: 10.1007/978-3-319-22680-4.

26. Norbert B, Bogdan-Ovidiu V, Dan M, et al. Analysis of Range Extended Hybrid Vehicle with Rotary Internal Combustion Engine Using AVL Cruise. In: Burnete N, Varga BO (eds) Proceedings of the 4th International Congress of Automotive and Transport Engineering (AMMA 2018). Cham: Springer International Publishing, pp. 312–319.

27. AVL Range Extender specifications, wwwavl.com/rangeextender.

28. Hubmann C, Beste F, Friedl H, et al. Single Cylinder 25kW Range Extender as Alternative to a Rotary Engine Maintaining High Compactness and NVH Performance. SAE Int. Epub ahead of print October 2013. DOI: 10.4271/2013-32-9132.

29. T. Sams, B. Sifferlinger. AVL rotary range extender, 2013.

30. Jeong J, Lee W, Kim N, et al. Control Analysis and Model Validation for BMW i3 Range Extender. Epub ahead of print 28 March 2017. DOI: 10.4271/2017-01-1152.

31. Jeong J, Karbowski D, Rousseau A, et al. Model Validation of the Honda Accord Plug-In. Epub ahead of print 5 April 2016. DOI: 10.4271/2016-01-1151.

32. Lohse-Busch H, Duoba M, Rask E, et al. Ambient Temperature (20°C, 72°C and 95°F) Impact on Fuel and Energy Consumption for Several Conventional Vehicles, Hybrid and Plug-In Hybrid Electric Vehicles and Battery Electric Vehicle. Epub ahead of print 8 April 2013. DOI: 10.4271/2013-01-1462.

33. Agarwal A, Lewis A, Akehurst S, et al. Development of a Low Cost Production Automotive Engine for Range Extender Application for Electric Vehicles. Epub ahead of print 5 April 2016. DOI: 10.4271/2016-01-1055.

34. Noga M. Application of the internal combustion engine as a range-extender for electric vehicles. Combust Engines; R. 52, nr, https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-84c4e340-9ab8-4491-9683-feeb83f8d824 (2013, accessed 21 April 2019).

35. Vamhagen S, Same A, Remillard J, et al. A numerical investigation on the efficiency of range extending systems using Advanced Vehicle Simulator. J Power Sources 2011; 196: 3360–3370.

36. Bartrand TA, Willis EA. Performance of a Supercharged Rotary Injection Stratified-Charge Combustion Engine. J Symp Gen Aviat by AIAA FAA Ocean City, New Jersey, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/1990001666.pdf (1990).

37. Ribau J, Silva C, Brito FP, et al. Analysis of four-stroke, Wankel, and microturbine based range extenders for electric vehicles. Energy Convers Manag 2012; 58: 120–133.

38. Mittal V. Design Parameters for Small Engines Based on Market Research. In: SAE Technical Paper Series, pp. 1–7.

39. Turner M, Turner J, Vorrago R. Mass Benefit Analysis of 4-Stroke and Wankel Range Extenders in an Electric Vehicle over a Defined Drive Cycle with Respect to Vehicle Range and Fuel Consumption. Epub ahead of print 2 April 2019. DOI: 10.4271/2019-01-1282.

40. Vorra R, Turner M, Turner JWG. Testing of a Modern Wankel Rotary Engine - Part I: Experimental Plan, Development of the Software Tools and Measurement Systems. Epub ahead of print 15 January 2019. DOI: 10.4271/2019-01-0075.

41. Advanced Innovative Engineering (UK) Ltd. 225CS - 40BHP - Wankel Rotary Engine. 225CS - 40BHP - Wankel Rotary Engine | Advanced Innovative Engineering (UK) Ltd, https://www.aieuk.com/225cs-40bhp-wankel-rotary-engine/ (2015).

42. Kweon C-BM. A Review of Heavy-Fueled Rotary Engine Combustion Technologies. US Army Res Lab, http://www.arl.army.mil/arreports/2011/ARL-TR-5546.pdf (2011).

43. Willis EA, Park B, Mcfadden JJ. NASA ’s Rotary Engine Technology Enablement.

44. Convergent Science. CONVERGE Manual v2.4. 2019.

45. Marshall T. Rotary lobe pumps - a piece of history. World Pumps 2006; 2006: 32–34.

46. Mishra TP, Patel YD, Joshi UA. Design of lobe pair profile of an external rotor lobe pump 1 Introduction. 2005; 1–11.

47. Kang YH, Vu HH. A newly developed rotor profile for lobe pumps: Generation and numerical performance assessment. J Mech Sci Technol 2014; 28: 915–926.

48. ISHINO Y, NIWA T. A Novel Rotational Internal Combustion Engine with a Single-Lobe Peritrochoid Rotor (Design Fundamentals and Motoring Test of a Prototype Engine). Trans JAPAN Soc Aeronaut Sp Sci Aerosp Technol JAPAN 2017; 15: a117–a126.

49. Beard JE, Yannitell DW, Penmock GR. The effects of the generating pin size and placement on the curvature and displacement of epitrochoidal gerotor. Mech Mach Theory 1992; 27: 373–389.

50. Hsieh C-F. A new curve for application to the rotor profile of rotary lobe pumps. Mech Mach Theory 2015; 87: 70–81.

51. Zeitschrift MA, Band M, Link P, et al. Rotors of variable regular polygons.

52. Bracho J, Montejano L. Rotors in triangles and tetrahedra. J Geom 2017; 108: 851–859.

53. Xu X, Xu H, Deng H, et al. An investigation of a hypocycloid mechanism based twin-rotor piston engine. Proc Inst Mech Eng Part C J Mech Eng Sci 2015; 229: 106–115.

54. Bertrand TA, Willis EA. Rotary Engine Performance Limits
55. Automotive Council UK T (NAIGT). New Automotive Innovation and Growth. www.automotiv council.co.uk/wp-content/uploads/2010/12/Tech-Road-Maps-RD-Capability-Final.pdf.
56. Savvakis S, Gkoutzamanis V, Samaras Z. Description of a Novel Concentric Rotary Engine. SAE Tech Pap Ser 2018; 1: 1–17.
57. Jason Siu, autoguide. Mazda’s Rotary Engine Celebrates 50th Birthday » AutoGuide.com News. Auto news, https://www.autoguide.com/auto-news/2017/05/mazda-s-rotary-engine-celebrates-50th-birthday.html (2017, accessed 15 February 2019).
58. Maiti R, Sinha GL. Limits on modification of epitrochoid used in rotary piston machines and the effects of modification on geometric displacement and ripple. Ingenieur-Archiv 1990: 60: 183–194.
59. Ma H, Kuo C, Chen C. Chamber Contour Design and Compression Flow Calculations of Rotary Engine. 2010; 39: 35–50.
60. Hsieh C-F. Dynamics Analysis of the Triangular Rotary Engine Structures. J Eng Gas Turbines Power 2018; 140: 112804.
61. Hsieh C-F, Cheng H-Y. Effects of Various Geometric Designs on the Flow Characteristics of a Triangular Rotary Engine. Mech Eng Res 2015; 5: 1–11.
62. Hsieh C-F. Dynamics Analysis of the Triangular Rotary Engine Structures. J Eng Gas Turbines Power 2018; 140: 112804.
63. Yamamoto K, Muroki T, Kobayakawa T. Combustion Characteristics of Rotary Engines. Epub ahead of print 1 February 1972. DOI: 10.4271/720357.
64. Shih TI-P, Schock HJ, Ramos JI. Fuel-Air Mixing and Combustion in a Two-Dimensional Wankel Engine. SAE Tech Pap Ser; 1. Epub ahead of print 2010. DOI: 10.4271/870408.
65. Li Z, Steinthorsson E, Shih TI-P, et al. Modelling and Simulation of Wankel Engine Flow Fields. Epub ahead of print 1 February 1990. DOI: 10.4271/900029.
66. Nagao A, Ohzeki H, Niura Y. Present Status and Future View of Rotary Engines. In: Automotive Engine Alternatives. Boston, MA: Springer US, pp. 183–201.
67. DeFilippis M, Hamady F, Novak M, et al. Effects of Pocket Configuration on the Flow Field in a Rotary Engine Assembly. SAE, Tech Pap Ser, 1. Epub ahead of print 2010. DOI: 10.4271/920300.
68. Jaber N, Mukai M, Kagawa R, et al. Amelioration of Combustion of Hydrogen Rotary Engine. Int J Automot Eng 2012; 3: 81–88.
69. Sprague SB, Park SW, Walther DC, et al. Development and characterisation of small-scale rotary engines. Int J Alterm Propuls 2007; 1: 275.
70. Wei FB, Peng PJ, Xian LY, et al. Effect of Pocket Location on Combustion Process in Natural Gas-Fueled Rotary Engine. Appl Mech Mater 2013; 316–317: 73–79.
71. Fan B, Pan J, Yang W, et al. Effects of different parameters on the flow field of peripheral ported rotary engines. Eng Appl Comput Fluid Mech 2015; 9: 445–457.
72. Zhang Y, Liu J, Zuo Z. The Study of Turbulent Fluctuation Characteristics in a Small Rotary Engine with a Peripheral Port Based on the Improved Delayed Detached Eddy Simulation Shear-Stress Transport (IDDES-SST) Method. Energies 2018; 11: 642.
73. Poojitganont T, Izweik HT, Berg HP. The Simulation of Flow Field inside the Wankel Combustion Chamber. 2006; 1–6.
74. Izweik HT. Cfd Investigations of Mixture Formation, Flow and Combustion for Multi-Fuel Rotary. 2009.
75. Zhou N-J, Pei H-L, Gao H-L, et al. Effects of Rotor Recess Geometries on Combustion Process in Diesel Rotary Engine. In: Volume 3: Combustion Science and Engineering. ASME, pp. 255–259.
76. Jeng D-Z, Hsieh M-J, Lee C-C, et al. The Numerical Investigation on the Performance of Rotary Engine with Leakage, Different Fuels and Recess sizes. Epub ahead of print October 2013. DOI: 10.4271/2013-32-9160.
77. Fan B, Pan JF, Pan ZH, et al. Effects of pocket shape and ignition slot locations on the combustion processes of a rotary engine fueled with natural gas. Appl Therm Eng 2015; 89: 11–27.
78. Harikrishnan TV, Challa S, Radhakrishna D. Numerical Investigation on the Effects of Flame Propagation in Rotary Engine Performance With Leakage and Different Recess Shapes Using Three-Dimensional Computational Fluid Dynamics. J Energy Resour Technol 2016; 138: 052210.
79. Finkelberg L, Kostuchenko A, Zelentsov A, et al. Improvement of Combustion Process of Spark-Ignited Aviation Wankel Engine. Energies; 12(12). Epub ahead of print 2019. DOI: https://doi.org/10.3390/en12122292.
80. Smagorinsky J. GENERAL CIRCULATION EXPERIMENTS WITH THE PRIMITIVE EQUATIONS. Mon Weather Rev 1963; 91: 99–164.
81. Deardorff JW. On the magnitude of the subgrid scale eddy coefficient. J Comput Phys 1971; 7: 120–133.
82. Turner M, Peden M, Turner JWG, et al. Comparison of 1-D Modelling Approaches for Wankel Engine Performance Simulation and Initial Study of the Direct Injection Limitations. In: SAE Technical Paper Series. Epub ahead of print 3 April 2018. DOI: 10.4271/2018-01-1452.
83. Vorraro G, Turner M, Turner JWG. Testing of a Modern Wankel Rotary Engine - Part I: Experimental Plan, Development of the Software Tools and Measurement Systems. SAE Tech Pap Ser 2019; 1: 1–16.
84. Moiz AA, Som S, Bravo L, et al. Experimental and Numerical Studies on Combustion Model Selection for Split Injection Spray Combustion. SAE Tech Pap Ser; 1. Epub ahead of print 2015. DOI: 10.4271/2015-01-0374.
85. Spreitzer J, Zahradnik F, Geringer B. Implementation of a Rotary Engine (Wankel Engine) in a CFD Simulation Tool with Special Emphasis on Combustion and Flow Phenomena. SAE Tech Pap Ser; 1. Epub ahead of print 2015. DOI: 10.4271/2015-01-0382.
86. Beard JE, Pennock GR. The Effects of Design Parameters on the Displacement and Compression Ratio of the Wankel Rotary Compressor. Int Compress Eng Conf. Epub ahead of print 1990. DOI: http://docs.lib.purdue.edu/iccc/686.
87. Beard JE, Pennock GR, Stanisic MM. The Effects of the Design Parameters on the Generated Curvature and Displacement of Epitrochoidal Gerotor Pumps. In: SAE Technical Paper Series. Epub ahead of print 1 September 1989. DOI: 10.4271/891831.
88. Hsieh C-F. Dynamic property of the triangle rotary engine mechanism. In: Proceedings of the ECCOMAS Thematic Conference on Multibody Dynamics 2013. 2013, pp. 153–161.
89. Hsieh C-F, Cheng H-Y. Effects of Various Geometric Designs on the Flow Characteristics of a Triangular Rotary Engine. Mech Eng Res; 5. Epub ahead of print 5 January 2015. DOI: 10.5539/mer.v5n1p1.
Analysis for a MEMS Rotary Engine. In: Microelectromechanical Systems. ASME, pp. 327–334.
91. Fu K, Knobloch AJ, Martinez FC, et al. DESIGN AND EXPERIMENTAL RESULTS OF SMALL-SCALE ROTARY ENGINES. In: ASME International Mechanical Engineering Congress and Exposition. 2001, pp. 11–16.
92. Tong SH, Yan J, Yang DCH. Design of deviation-function based gerotors. Mech Mach Theory 2009; 44: 1595–1606.
93. Warren S, Yang DCH. Design of rotary engines from the apex seal profile (Abbr.: Rotary engine design by apex seal). Mech Mach Theory 2013; 64: 200–209.
94. Hu DY, Zhou HT, Zhao B, et al. Finite element analysis of cylinder stress and deformation of a small rotary engine. IOP Conf Ser Mater Sci Eng 2019; 504: 012075.
95. Shkolnik A, N Shkolnik - US Patent App. 10/221 690, 2019 U. Rotary engine with intake and exhaust through rotor shaft, https://patents.google.com/patent/US10221690B2/en (accessed 27 April 2019).
96. Littera D, Nickerson M. Development of the XMv3 High Efficiency Cycloidal Engine. SAE Tech Pap 2015-32-0719, https://www.sae.org/publications/technical-papers/content/2015-32-0719/ (2015).
97. Costa TJ, Nickerson M, Littera D, et al. Measurement and Prediction of Heat Transfer Losses on the XMv3 Rotary Engine. SAE Int J Engines; 9. Epub ahead of print 2016. DOI: 10.4271/2016-32-0033.
98. Shkolnik A, Littera D, Nickerson M, et al. Development of a Small Rotary SI/CI Combustion Engine. Epub ahead of print 11 November 2014. DOI: 10.4271/2014-32-0104.
99. Costa TJ, Nickerson M, Littera D, et al. Measurement and Prediction of Heat Transfer Losses on the XMv3 Rotary Engine. SAE Int J Engines; 9. Epub ahead of print 2016. DOI: 10.4271/2016-32-0033.
100. Al-Hawaj OM. Geometrical analysis of a quadrilateral rotary piston engine. Mech Mach Theory 2015; 93: 112–126.
101. Hsieh C-F, Hwang Y-W. Study on the High-Sealing of Roots Rotor With Variable Trochoid Ratio. J Mech Des 2007; 129.
102. Al-Hawaj. ROTARY MECHANISM WITH ARTICULATING ROTOR. US 8,904,991 B2, Al-Hawaj , https://patentimages.storage.googleapis.com/f1/56/b3/5301b49fd3205b/US8904991.pdf (2014).
103. King P. The Szorenyi Three-Chamber Rotary Engine Concept. In: 18th Australian International Aerospace Congress: HUMS - 11th Defence Science and Technology (DST) International Conference on Health and Usage Monitoring (HUMS 2019): ISSFD - 27th International Symposium on Space Flight Dynamics (ISSFD). Melbourne: Engin, pp. 24–26.
104. King P. The Development of the Szorenyi Four-Chamber Rotary Engine. In: SAE Technical Paper Series. Epub ahead of print 8 October 2017. DOI: 10.4271/2017-01-2413.
105. Chen H, Pan C, Xu X, et al. Development of rotary piston engine worldwide. In: Future Energy, Environment and Materials II, pp. 158–163.
106. Espinosa LF, Lappas P. Mathematical Modelling Comparison of a Reciprocating, a Szorenyi Rotary, and a Wankel Rotary Engine. Nonlinear Eng 2018; 8: 389–396.