THE EFFECT OF DESIGN SHAPE FACTOR ON THE COMBUSTION PARAMETERS OF A ROTARY ENGINE

BY

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ABSTRACT

Comparatively, this research is motivated to investigate, through simulation, the Wankel engine performance and to focus on possible developments studies of rotary engine design. The controversial rotary engine produces a direct rotational motion. The triangular rotor shape which Felix Wankel derived from the Reuleaux triangle of complex geometry rotates continuously by keeping contact with its housing in three points separating the chambers into three where the different conventional 4-strokes occur. Near the top dead centre TDC where the volume of the chamber is minimal, critical performance of the mixture combustion is related to the shape of the chamber. An investigation of the shape factor effect on the combustion parameters of the rotary engine performance by simulation of compressible flow field in rotary engine's combustion chamber by applying the technique of Dynamic Mesh in CONVERGE CFD. In function of crankshaft angles, the change of flow field streamline, temperature and pressure of the volume is investigated.

The results showed that a constantly changing swirl was formed in the combustion chamber during the intake and compression strokes near TDC as a result of the combined effects of the pocket of the rotor and the swirls in the combustion chamber.

The very low compression ratio would yield a poor Otto-cycle thermal efficiency. The compression ratio could be increased by increasing e/R, but it would still be low for most applications. It is therefore important to consider the favorable influence of flank rounding on rotary engine performance.

Moreover, the flow behaviour during the exhaust stroke where the propagation of burned gases escapes towards the intake port chamber even though a perfect sealing was assumed. This propagation can be of an interest investigation for researchers to find the suitable possible epitrochoid shape.

خلاصة البحث

يقدم هذا البحث مقارنة لنتائج أداء المحرك الدوار Wankel بإستخدام المحاكاة (CFD) والتركيز على دراسة التصاميم المحتملة لتطوير وتحسين أداء دورة عمل المحرك وزيادة مردوده. ذلك من شـأنه أن يمكّن الباحثين من اتخاذ التدابير التصميمية الملائمة للعناصر الأساسية للمحرك. المحرك الدوار هو محرك ينتج حركة دوران مباشرة ذو مكبس ثلاثي الشكل استمده فيليكس Wankel من مثلث Reuleaux الذي يندرج ضمن الهندسة المعقدة. هذا المحرك يدور باستمرار عن طريق الحفاظ على الاتصال مع الحجرة في ثلاث نقاط ويفصل الحجرة إلى ثلاثة حيث تحدث الأشواط التقليدية الأربعة .

تبين هذه الدراسة تأثير شكل الحجرة على معاملات الاحتراق في أداء المحرك الدوار وذلك من خلال محاكاة مجال التدفق القابل للضغط في غرفة الاحتراق للمحرك بواسطة تطبيق تقنية Dynamic Mesh في برنامج (CFD CONVERGE). وأيضاً يتم تحليل سلوك خطوط التدفق ومعالجة كل من منحنى الحرارة والضغط بدلالة زاوية دوران الجذع المعقوف -العمود المرفقي.

وتظهر النتائج تأثر أداء المزيج ونسبة الانضغاط بشكل الحجرة. أدنى حجم للحجرة يكون بالقرب من المركز الميت الأعلى (TDC) وعند هذا الموضع يكون أداء احتراق المزيج حرجاً ومرتبطاً بشكل الحجرة.

تبين ممن خلال التحليل أن نسبة الضغط المنخفضة جدا من شأنها أن تسفر عن دورة محرك ذو أداء ضعيف. ويمكن زيادة نسبة الضغط عن طريق زيادة عامل الشكلe/R ، ولكنها ستظل منخفضة بالنسبة لمعظم التطبيقات.

وأظهرت النتائج تشكُّل دوامة متغيرة باستمرار في غرفة الاحتراق اثناء شوط الإفلات وتتجه نحو حجرة الامتصاص، وعلاوة على ذلك، فإن سلوك التدفق يمكن أن يكون ظاهرة ملهمة للباحثين للعثور على التصميم المناسب.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science (Mechanical Engineering)

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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LIST OF SYMBOLS

A_{max}	Area at the Top Dead Centre
A_{min}	Area at intake stroke
e	Eccentricity
K	Shape Factor
K_{gas}	Thermal conductivity (W/mK)
n	Viscosity
P	Pressure
R	Generating Radius
T	Temperature
Ɵ	Rotor rotation angle

LIST OF ABBREVIATIONS

AVL	Anstalt für Verbrennungskraftmaschinen List
BMW	Bayerische Motoren Werke
BSFC	Brake Specific Fuel Consumption
BTDC	Before Top Dead Centre
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CI	Compression Ignition
CO	Carbon Monoxide
CONVERGE	Convergent Sciences Software
CR	Compression Ratio
DI	Direct Injection
DISC	Direct Injection Stratified Charge
DoE	Design of Experiment
EV	Electric Vehicle
FAME	Fatty acid methyl esters
HEV	Hybrid Electric Vehicle
IA	Injection Angle
ICE	Internal Combustion Engine
IT	Injection Timing
LDR	Leading Deep Recess
LES	Large Eddy Simulation
MEMS	Micro Electro-Mechanical System
NASA	National Aeronautics and Space Administration
NOx	Nitrogen Oxides

QRM	Quadrilateral Rotor
RE	Range Extender
RPM	Revolution per Minute
SARM	Savvakis Athanasiadis Rotary Motor
SCRE	Stratified Charge Rotary Engine
SI	Spark Ignition
SMR	Symmetric Recess
TDC	Top Dead Centre
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
WE	Wankel Engine
WiDE	Water in Diesel Engine

CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND OF THE STUDY

In the machine science, its history and its identity, Al-Jazari was an important author to start this literature, who in 1206 wrote a treatise on clocks and mechanics, titled " Kitab al-Hiyal, (Book of knowledge of ingenious mechanical devices) (Koetsier, 2013; Koetsier & Ceccarelli, 2016).

The Wankel engine is an internal combustion engine. Unlike the conventional piston engine, with a reciprocating motion where the piston moves ups and downs, using the crankshaft to transform that motion into rotational, the controversial rotary engine produces a direct rotational motion. The rotor of the triangular shape which Felix Wankel derived from the Reuleaux triangle of complex geometry rotates continuously by keeping in contact with its housing in three points separating the chambers into three where the different conventional 4-strokes occur.

The rotor has three convex faces, each face of the rotor has a pocket in it, and the pocket increases the displacement of the engine during the compression stroke and allowing more space for air/fuel mixture. The three apex seals separate the three chambers of the engine, forming three sealed volumes of gas. The housing has an epitrochoid shape like-oval. The rotor (Figure 1.1a) will always stay in contact with the wall of the chamber. The shape of the combustion chamber is designed so that the three tips separate the housing into three volumes each subjected to combustion processes: intake, compression and ignition, combustion and exhaust. Both intake and exhaust ports are in the housing (Figure1.1b) or sided ports at the periphery. There are no valves in these ports. The output shaft (Figure 1.1c) has round lobes mounted eccentrically, this lobe acts like the crankshaft in a piston engine (J E Beard et al., 1992; Hsieh, 2015; Ishino & Niwa, 2017; Kang & Vu, 2014; Marshall, 2006; Mishra, Patel, & Joshi, 2005).

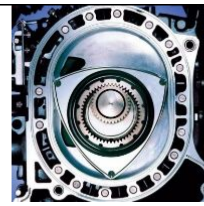
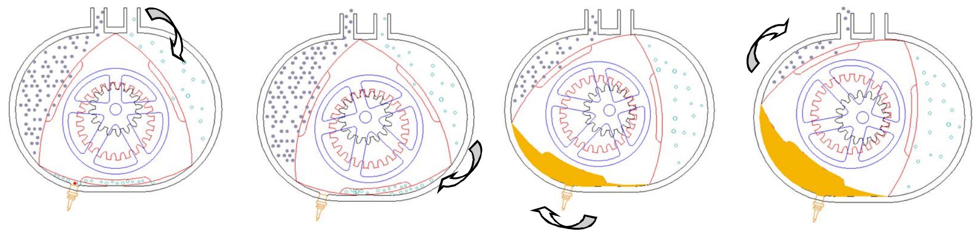
		
(a): rotor	(b): housing	(c) : Output shaft

Figure 1.1 The main engine component.

As the rotor follows its path around the housing, the force that the rotor applies to the lobes creates torque in the shaft, causing it to rotate. The intake stroke (Figure 1.2a) of the cycle, which starts when the tip of the rotor passes the intake port, as the rotor moves past the intake port, increasing the volume of the chamber. When the tip apex of the rotor passes the intake port, that chamber is sealed off, and compression begins (Figure 1.2b). The volume of the chamber gets smaller and the air/fuel mixture gets compressed, when the face of the rotor reaches the Top Dead Centre TDC where is the minimum volume of the working fluid near the spark plug (for spark-ignition SI engine) or the autoignition temperature caused by the high pressure (for compression ignition CI engine) (Figure 1.2c) , this is when combustion starts and the air/fuel mixture expands (expansion stoke) forcing the rotor to move, and the motion of the rotor creates power till the gas-air mixture is burned. That is where the tip apex passes through the exhaust port, and the burned gases are free to flow out to the exhaust (Figure 1.2d) till the volume of the chamber reaches the minimum, and the whole cycle starts again (Bracho & Montejano, 2017; Kang & Vu, 2014; Xu et al., Talbot, 2015; Zeitschrift et al., 2019).



(a) Intake (b) Compression (c) Ignition and power (d) Exhaust

Figure 1.2 Basic Working Principle of a RE (“Animated Engines - Wankel,” n.d.).

1.2. STATEMENT OF THE PROBLEM

The hydrocarbon emission is one of the most serious drawbacks of the Wankel engine. The combustion chamber shape may also lead to incomplete combustion of the air-fuel mixture; This would result in a larger amount of unburned hydrocarbons – in form of flames escaping from the seals and released into the exhaust

The Wankel engine is disadvantageous in some aspects like sealing and lower power output at low speeds. Also, a rotary engine generally has lower thermodynamic efficiency due to the long shape of their combustion chamber. They emit high CO, CO_2 and HC emissions.

1.3. RESEARCH OBJECTIVES

The objectives of this research work are as follow:

1) To study the effect of the shape factor K on the compression ratio CR of the rotary engine;
2) To investigate the effect of the Shape Factor K on the flow in-cylinder of rotary engine using computational fluid dynamics CFD;
3) To validate the design of the rotary engine with the published data.

1.4. RESEARCH QUESTIONS

1. What are the various designs possible for the rotary engines?
2. What are the effects of design geometries on the rotary engine performance?
3. What is the optimum shape for the rotary engine performance?

1.5. RESEARCH HYPOTHESES

The various designs in the literature showed a variety of possible solutions to the rotary engine problems. Starting from the design of the housing of the engine, the rotor shape; the rotor recess (pocket) and the relation between the chambers design and the performance.

H1 The rotary engine designs rely on the shape factor K;

H2 The design geometries effect the compression ratio and therefore the in-cylinder pressure of the rotary engine combustion chamber;

H3 The shape of the rotary engine needs further improvement especially near top dead center TDC during combustion of the air-fuel mixture.

1.6. SIGNIFICANCE OF THE STUDY

The results from this research show that the combustion parameters, mainly the compression ratio characteristics are affected by the shape of geometry. It seems that the variation of the shape parameter affects the flow field. The result of this simulation will be utilized for validation with other simulation tools.

1.7. LIMITATIONS OF THE STUDY

Since that a good envelope gives smooth rotation, the basic geometrical characteristics of a Wankel RE are the variations of the working chamber-volume as a function of the angular displacement of the output shaft (rotor).

1. In this research on the Rotary engine geometry, the study does not involve different fuel feeding of the engine nor their effects on combustion and flow performance.

2. It is limited to the investigation of the epitrochoidal-based housing and does not consider the apex seal profile.

1.8. DEFINITION OF TERMS

Wankel rotary engine: Wankel derived from the Reuleaux triangle of complex geometry, rotates continuously by keeping in contact with its housing in three points separating the chambers into three where occurs the different conventional 4-strokes.

The Rouleaux's triangle, made by three circulars, keep contact with all the sides of the square or any other shape, as the curve does not have to be circular, because it depends on the eccentricity of the rotor while rotating.

The casing shape called an epitrochoid is dependent on the path of the apex seal during engine operation. The geometry of epitrochoid and its conjugate envelope are derived from expressions of contact between the rotor and the chamber and simulated the pressure processes.

Trochoid: defined as the path of a point fixed in a circle which rolls- without slipping- on a fixed circle. The Trochoids are called epitrochoids if the moving circle is outside the fixed circle and called hypotrochoids if the moving circle is inside the fixed circle: pinion located inside an internal (annular) gear

K Shape Factor: Defined as the ratio of the rotor radius called the generating radius, R and the eccentricity, e of the rotor while producing the rotational motion.

CHAPTER TWO

BACKGROUND AND REVIEW

2.1. INTRODUCTION

2.1.1. General Overview

The hybridization, hydrogenation and electrification afterwards are the trends in the battery-based electric vehicles and the hydrogen-based technologies (Alberto Boretti, 2017). Nowadays, the electrification implementation in transport vehicles become one of the solutions towards zero-carbon transportation as the electricity is considered zero emissions solutions. The fossil fuels mainly dominate the multi-sources electricity generation.

Improvement of ICEs technologies, hybridization of cars and narrowing the wide use of ICE fuel cell can be directed towards electrification and hydrogen-based mobility. There are several ways to classify ICE based on basic engine design (Molino et al., 2018).

At present, the market of Wankel engines is limited to special applications. Therefore, this fact explains the absence of developed commercial software products to simulate and predict this engine performance. While the reciprocating-piston engines performance is widely simulated using software products, many projects of the rotary engine tried to survive, as Yanmar motors team released their rotary engine application to the market in 1969 after the agreement with the main developer of the Wankel rotary engine at that time NSU Motorenwerke AG a German manufacturer of automobiles (Kamo et al., 1987; Yamaoka et al., 1976).

As facts, those are sufficient indications of the technological difficulties confronted in the development of rotary engines and seen recently when the Mazda company has released the RX-8 (Ohkubo et al., 2004; Okimoto, 2002). Hydrogen RE powered since 2006 but due to falling sales and emission regulations, the Mazda CEO Masamichi Kogai comes to put an end to all this RX-8 in 2012 (Autoevolution, 2014). Nowadays, the technical research centre head Mitsuo Hitomi at Mazda revealed the brand is developing integration of new fast ignition such as laser ignition and plasma ignition for the flame propagation problem of the rotary oil consumption (Sam McEachern, 2017).

Although the novel engine was adopted and developed by many manufacturers, it is seen that multiple attempts have been made to commercialize this rotary engine, however, limited information are available about the individual projects or companies involved in the development of these engines, some information was found in early projects at Toyo Kogyo developed by Kenichi Yamamoto & Muroki (1978), Kenichi Yamamoto and Kuroda (1970) and Moriyoshi, Muroki and Xu (2010); Muroki (1984); Muroki, Gotou and Morita (1990). The brand could survive with its small and powerful engine by their engine designer Yamamoto who led the engineering team that produced a commercial rotary engine vehicle at the company Toyo Kogyo now known as Mazda, and later became its president and chairman.

2.1.2. Recent Rotary Applications

Since the early reviews of T. Chen (1988) and John B. Hege (2001) on the rotary engine philosophies focused either on the early experiments since 1957 to 2000, also the patent's concepts classification of Thompson et al., (2003) and Murphy et al., (2012) , or else on the alternative fuels by Ozcanli M. et al (2018) that may improve this engine type performance, it is appropriate to briefly mention the technologies that are either in production or under investigations at the research level.

The Wankel engine recently got interests of possible reliability as range extenders for electric vehicles; small scale reliability to unmanned aerial vehicles and the design suitability for various feeding strategies (hydrogen) have attracted and brought its concept into new investigations.

In the classifications done by El-Sayed (2016) of aircraft and propulsion system fundamentals of aircraft and rocket propulsion, the unmanned aerial vehicles (UAV) can be classified according to different tasks and need different engine types depending on the area they are used (Çoban & Oktay, 2018). Such as for aviation, RQ-7A Shadow 200 and Sikorsky Cypher that made from the Wankel rotary engine low vibration a point of fitness to UAV purposes (Griffis & Schneider, 2009). The RQ-7 Shadow, a UAV (Figure 2.1) utilized by the Marine Corps and Army for reconnaissance purposes, is powered by UEL's AR741 rotary engine and functions on aviation fuel.

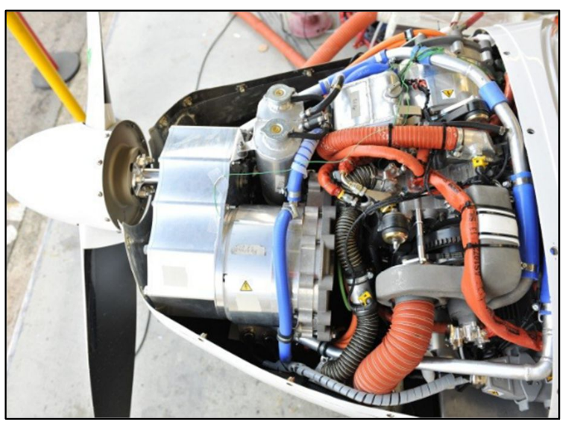


Figure 2.1 RQ-7 Shadow, an unmanned aerial vehicle (UAV).

The engine has been mounted in the work of Yewale et al. (2017) and tested to measure the engine performance. During the test no knocking has been noticed and a gradual