

Visualization of the Rotary Engine Oil Transport Mechanisms

Mathieu Picard

Massachusetts Institute of Technology

Hiroyuki Hidaka

Mazda Motor Corp.

Tian Tian

Massachusetts Institute of Technology

Takayuki Nishino, Eiji Arai, and Masaki Ohkubo

Mazda Motor Corp.

ABSTRACT

The rotary engine provides high power density compared to piston engine, but one of its downside is higher oil consumption. In order to better understand oil transport, a laser induced fluorescence technique is used to visualize oil motion on the side of the rotor during engine operation. Oil transport from both metered oil and internal oil is observed. Starting from inside, oil accumulates in the rotor land during inward motion of the rotor created by its eccentric motion. Oil seals are then scraping the oil outward due to seal-housing clearance asymmetry between inward and outward motion. Cut-off seal does not provide an additional barrier to internal oil consumption. Internal oil then mixes with metered oil brought to the side of the rotor by gas leakage. Oil is finally pushed outward by centrifugal force, passes the side seals, and is thrown off in the combustion chamber.

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INTRODUCTION

The rotary engine provides a high power density and low vibration when compared to the piston engine. This makes the rotary engine a prime candidate for sports cars due to its small weight and for hybrid vehicles where packaging is critical. However, its trochoid shape leads to a more complex system to seal the gases of the different chambers, as shown in [Figure 1](#). Oil must be supplied to lubricate all the gas seals. The oil that cannot be recycled to the crankcase eventually leaves the engine with the exhaust stream. This oil consumption, which is in general higher than an optimized piston engine, must be reduced as it leads to shorter service interval, hydrocarbon emissions and catalyst poisoning.

Oil consumption can be subdivided in two contributions, which are on the same order of magnitude: (1) internal oil consumption and (2) metered oil for gas seal lubrication. Internal oil consumption is similar to piston engine oil consumption, and is caused by oil leakage from the center of

the rotor used to lubricate internal components and cool the rotor. Part of this oil finds its way to the combustion chamber through the oil seals, cut-off seal, and side seal.

Unlike the piston engine there is a second source of oil consumption; metered oil is injected next to the intake port to lubricate the apex, corner, and side seals. Part of the metered oil can be scraped to the rotor, then is moved around by the rotor motion and gas flows, and eventually is consumed before performing any lubrication to the gas seals. A good understanding of oil motion is essential in order to maximize the time it spends lubricating the seal-housing and seal-rotor interfaces before leaving the engine.

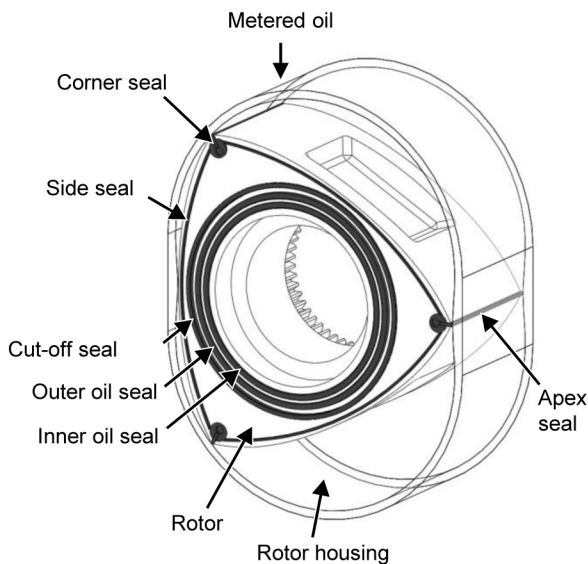


Figure 1. Rotary engine sealing system

Gas seal design, especially the apex seal, have greatly evolved from the original Wankel design to provide better sealing, first at NSU [1], then at Curtiss-Wright, and at Mazda [2, 3] including some recent modification [4]. Keeping the wear of the apex seal below an acceptable level has always been a challenge. Different materials have been tested for the apex seal and the rotor housing using wear test rigs [5, 6]. Provided proper surface treatment [7], and adequate supply of oil containing anti-wear additives [8], apex seal wear is controlled.

The proper amount of metered oil needed to lubricate the apex is determined indirectly by measuring the temperature of the apex as a function of the oil flow rate [9]. Temperature of the apex is almost constant for sufficient oil flow rate, but increases rapidly below a critical flow rate [10]. This critical flow rate is defined as the minimum limit of metered oil. Although the minimum limit is known for a given configuration, it is difficult to improve the configuration to better use metered oil, as oil transport is unknown after being injected in the engine.

Oil consumption measurements for the rotary engine are scarce in the literature, and typically given for a drive cycle over a certain distance [8, 11, 12]. Although it is an important data of the engine performance, it is also difficult to relate to a specific mechanism of oil consumption in the engine.

In order to improve the rotary engine further, a deterministic method is necessary to relate oil consumption to the geometry and other characteristics of the sealing system. This was previously done for the piston engine by combining first order calculations with an experimental technique developed at MIT, called 2D laser induced fluorescence (2D LIF) [13, 14]. A laser is shot inside the cylinder through a sapphire window replacing part of the cylinder. A dye in the oil absorbs the light and reemits at a specific frequency, which is then captured by a camera. This method allows visualizing the evolution of oil film

thickness on the piston. Although windows have been installed on rotary engine for flow and combustion visualization (e.g. [15]), no observation of the oil transport have been reported.

This paper presents an understanding of the oil transport inside the rotary engine by coupling first order lubrication models and visualization of the oil transport on the side of the rotor using 2D laser induced fluorescence. The experimental setup is first presented, followed by an overall description of oil transport in the engine. The oil transport mechanisms are then described starting from inside to outside for the different regions: (1) rotor land, (2) oil seals, (3) cut-off seal, and (4) side seals and corner seals.

EXPERIMENTAL SETUP

For oil transport visualization, a single rotor engine is used (RENESIS [4]), for which the central housing is replaced by a sapphire window. Experiments are carried at 50 % load. As shown in Figure 2, the beam of a YAG laser (SOLO III, 50 mJ/pulse, 15 Hz x 2 heads) is expanded and reflected towards the engine with a beam splitter. Light is absorbed by a dye placed in the oil. The dyes chosen are pyromethene 567 and rhodamine 640 percholate to minimize the effect of temperature on the overall dye properties [16]. Light is then reemitted by the dyes. Reemitted light is filtered to filter out the laser reflection and keep only the light emitted by the dyes at 570 nm. The image is captured by a camera (ProEM: 512B, resolution 512x512). The complete optical assembly is mounted on a platform that can translate in two directions to capture any desired position on the sapphire window. Figure 3 shows the area available for visualization and a cut view of the rotor and seals. Most of the side of the engine can be spanned, except for the bearing mount on the right bottom and the intake and exhaust ports modified to be machined in the sapphire window.

Laser and camera are timed with the rotor rotation to capture one image per rotor revolution at the desired crank angle (CA). A movie is recorded and the evolution of the oil pattern can be observed over time. Rotor land oil accumulation is varying rapidly and images at different CA provide insight about the rotor land accumulation and release mechanism. However, outside the inner oil seal, the oil film is typically thin which leads to typical oil displacement from one image to the other of a fraction of a millimeter. This leads to the conclusion that an image of the oil accumulation pattern is approximately the same captured at any crank angle of the same revolution. This means that, except for the rotor land, only one image of a given position of the rotor needs to be captured and there is no need to sweep all crank angles. This reduces significantly the time involved for oil transport observations. Furthermore, as the oil displacement is small for a revolution, an image shows adequately the oil accumulation and the corresponding movie is used to determine the direction of the flow. In this paper, direction of the flow is represented with arrows on the pictures when needed.

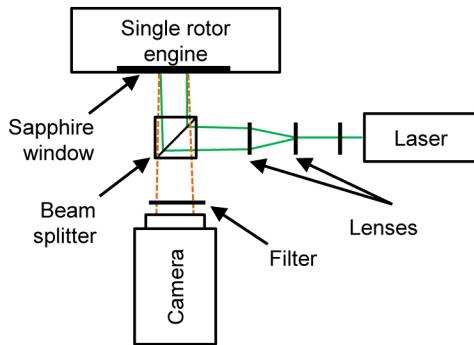


Figure 2. Schematic of the 2D LIF experimental setup

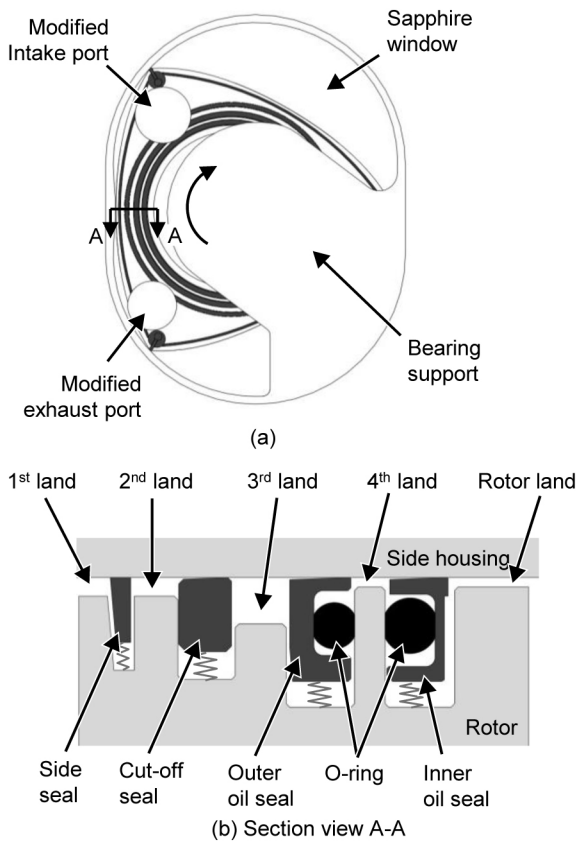


Figure 3. (a) Side view of the engine showing the available area for visualization and (b) section view of the seals

Figure 4 and Figure 5 show the typical oil accumulation pattern seen on the rotor around the gas seals and oil seals for mass production specifications. Those images show that even if some oil flow can be seen with mass production specifications, oil film thickness is small, on the order of only a few microns. Those images illustrate the challenge of understanding oil transport and reducing oil consumption of the engine, as the amount of oil in the engine is already small. In order to increase the amount of oil and better understand oil transport, oil seals and injection rate are changed. For the oil seals, three different configurations are tested using different nominal ring contact width, as seen in Table 1. Injection rate is also increased to 2 Hz for oil flow around the gas seals. Injection frequency of the side injectors and the center injector can be controlled independently. Changing specification of the seals

and injection changes the amount of oil, but does not seem change the general behavior of oil transport as can be seen by a close inspection of images taken with the mass production specification; scraping can be seen on oil seals and oil flow pattern around the gas seals is similar.

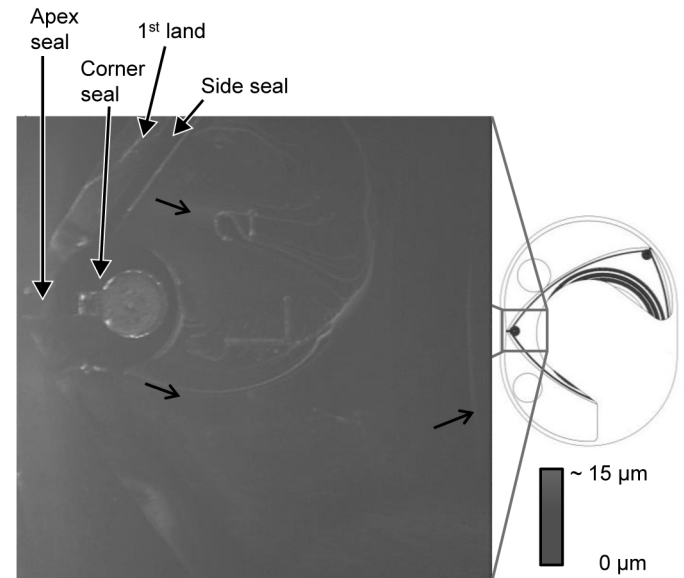


Figure 4. Gas seal oil transport 2D LIF image with mass production specifications (small oil film thickness makes it difficult to analyze oil flow pattern)

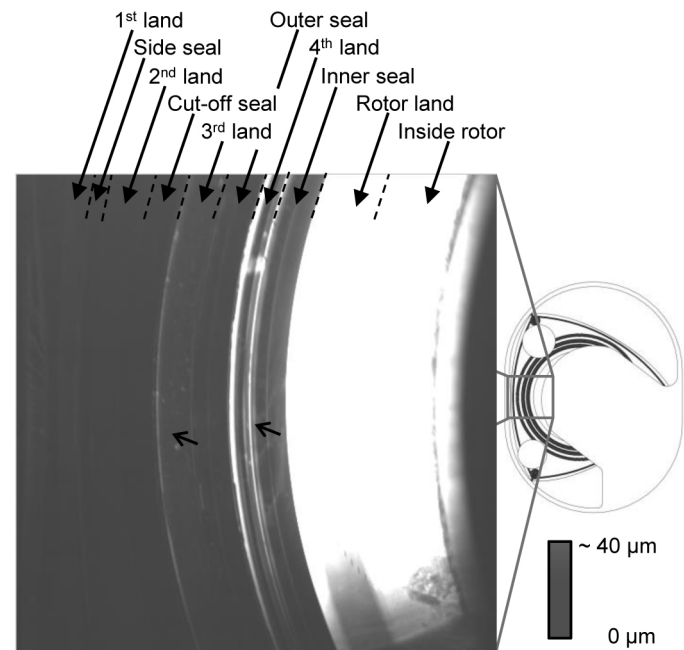


Figure 5. Oil seals and cut-off seal 2D LIF image with mass production specifications (small oil film thickness makes it difficult to analyze oil flow pattern)

Table 1. Oil seal configurations

Oil Seal Configuration	Nominal contact width (mm)	
	Inner oil seal	Outer oil seal
1 Mass production	0.2	0.2
2 Large contact inner oil seal	1.0	0.2
3 Large contact both oil seals	1.0	1.0

Oil film thickness on the rotor can be related linearly to the intensity measured by the camera. Calibration marks were added on the taper part of the seal to find the constant of proportionality between intensity and oil film thickness. To make a proper calibration, oil film thickness must be known, and thus the calibration mark must be full. However, the calibration mark was not full, as seen in Figure 6, and the calibration was not repeatable. Instead, calibration was made using the taper of the seal when it is completely full, a feature for which the geometry is known. Figure 7 shows an image taken with configuration 3 where the inner oil seal taper full. Zero oil film thickness was taken at the minimum intensity measured on an image. This method is a good estimate of order of magnitude (error of $\pm 1\text{--}2\text{ }\mu\text{m}$ depending on operating conditions) as it uses one general calibration averaged from different images, which is approximated as being independent of temperature and position on the rotor.

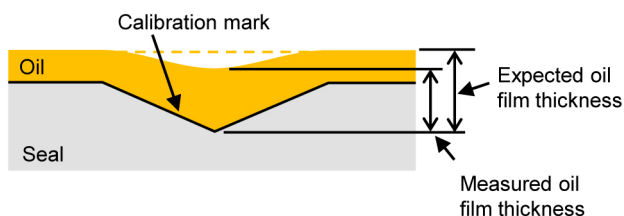


Figure 6. Difficulty with calibration marks

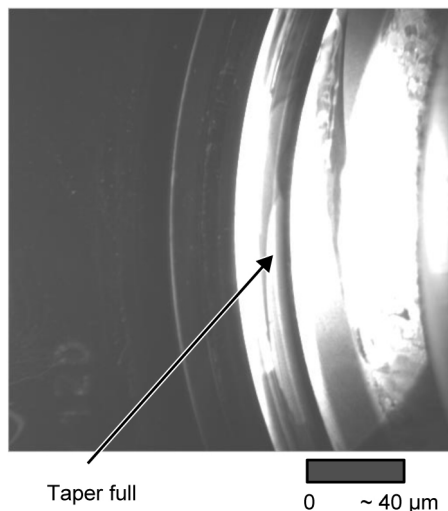


Figure 7. 2D LIF image of the oil seal configuration 2 showing part of the inner oil seal taper completely full

ROTOR SIDE OIL TRANSPORT

A summary of the oil transport mechanisms on the side of the engine is shown in Figure 8, based on the understanding developed from the 2D LIF engine experiments. Oil path starts from the right of the figure with the supply of oil from inside the rotor splashing on the side housing. Oil accumulates in the rotor land during inward motion, supplying oil to the inner seal. Some oil is allowed to pass the inner oil seal (IOS) during inward motion. Most of it is returned to the rotor land during outward motion, but some of it is scraped to 3rd land. As the grooves are sealed by O-rings on both side of 3rd land, oil must be recycled back to the housing. Some of this oil is able to pass the outer oil seal (OOS) in a similar fashion. Once passed the OOS, oil on the rotor can be either scraped out by the cut-off seal (COS) or pass under it. Oil mixes with metered oil that was able to reach the side of the rotor by passing around the corner seal (CS). Oil is then pushed out by inertia, passes the side seal (SS), and reaches 1st land. Finally, oil evaporates or is thrown off in the combustion chamber and leaves with the exhaust stream, resulting in oil consumption.

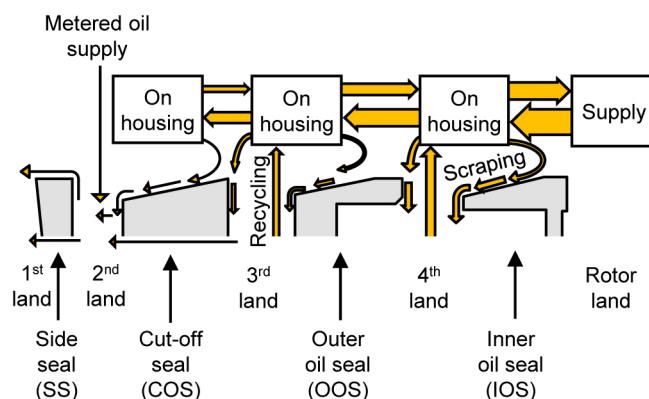


Figure 8. Summary of oil transport on the rotor side

The subsequent sub-sections detail the understanding of the oil transport mechanisms from inside the rotor to the combustion chamber, supported by experimental observations and order of magnitude calculations.

Rotor Land

Oil accumulation in the rotor land is important as it provides the supply for the oil seals and generates pressure due to relative motion between rotor and housing that can lift the IOS. Due to the eccentric motion of the rotor, the radial motion of a given location on the rotor land is alternatively moving inward, and outward. Figure 9 shows the mechanism of oil accumulation and release caused by this motion. During inward motion, oil that is on the side housing due to splashing inside the rotor is scraped by the IOS and accumulates in the rotor land. Inertia is pointing outward when the rotor starts moving inward, which contributes to the supply of oil towards the rotor land. When the rotor starts moving outward, oil is released and the rotor land is quickly emptied.