

The Microgeometry of Pressure Seals

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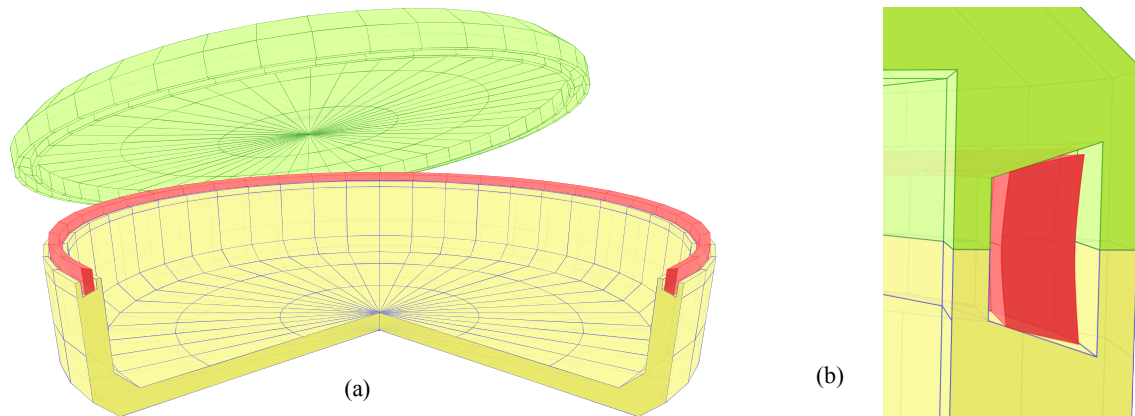


Figure 1: (a) A seal ring (red) is compressed between two parts of a container. (b) Closeup.

Abstract: Seals or gaskets that are compressed between walls of a container are important to many industrial applications. Understanding the sealing performance of such seals requires an understanding of the microscopic geometry of the sealing surfaces, because the fluid seems to seep around the undulations of such surfaces. This paper presents strong computational evidence that the microgeometry of such surfaces depends on the difference between the mechanical pressure applied to the seal and the pressure of the leaking fluid.

Keywords: Sealing and seals, microfluidics, COMSOL®, non-linear structural mechanics

1. Introduction

Sealing of fluids is a very important industrial problem. Static and dynamic seals prevent fluids in one compartment from leaking into another compartment or the environment. Sealing techniques are of utmost importance in many engineering disciplines including automotive engineering, aeronautics and astronautics, marine engineering, hydraulics and pneumatics, biomedical engineering, building construction, etc.

This paper concentrates on seals that act by compression – a piece of material (known in various situations as a gasket, an o-ring, a piston

ring, etc.) is compressed between two comparatively rigid surfaces. This compression causes the piece to press against the rigid surfaces, thus creating a seal for fluids. Such seals are used frequently in all the above disciplines, and there is a lot of information available about the geometries and materials of the seal to be chosen for various applications. [1] But the available information about compression seals is primarily of a heuristic nature. There is a clear need to create a mathematical theory of the performance of seals, to be able to analyze and design better sealing solutions.

In this paper we concentrate on the performance of compression seals for sealing pressurized containers. This paper represents one of many steps in a program for creating a theory of seal performance. The envisioned theory is in the form of a partial differential equation (PDE) that predicts the leakage rate of a seal. These equations are anticipated to be homogenized fluid flow equations of the creeping flow through crevices that an actual pressure seal experiences.

Section 2 describes the program for creating the theory of seal performance in general. Section 3 describes the problem tackled in this paper: the microgeometry of seals, and a main hypothesis of this paper: that the microgeometry depends primarily on the difference between mechanical and fluid pressure. Section 4 describes experiments using COMSOL® to test this

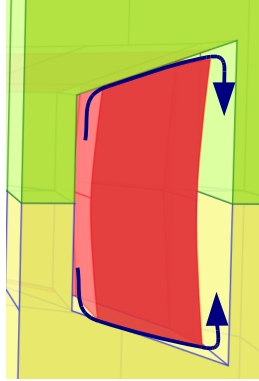


Figure 2: Fluid leakage paths in compression sealing.

hypothesis. Section 5 describes the results of COMSOL® experimentation and Section 6 discusses implications of this work in context of the larger program, and suggestions for future extensions.

2. The Theory of Seal Performance – A Program

A **seal**, as shown in Figure 1 is a piece of elastomeric material compressed between two independently moving parts of a container. If installed correctly, the seal separates the space inside the container from the environment. In this and allied papers, we investigate the performance of such a seal while sealing a pressurized fluid.

It has been observed by us (to be reported in detail in a subsequent paper), that such a seal can never seal a fluid perfectly, if the fluid is a gas – there will always be some gas leaking out of the container, even if at a very low leakage rate. It is observed (and easy to imagine), that the rate at which a seal leaks is dependent on the pressure of the fluid inside the container – in general, the more the pressure of the fluid inside the container (relative to the pressure of the environment), the faster the gas leaks. The performance of a seal can thus be described by the **sealing characteristic** – a plot depicting the leakage rate of the fluid inside the container as a function of the pressure inside the container.

Noticing that the fluid leaks despite the seal being in place, we make the following assumption: the fluid leaks through the interstices that remain between the surfaces of the seal and the container, even though these surfaces are pressed against each other. (See Figure 2). If the above assumption be true, the sealing characteristic will

be dependent on the following factors: (1) geometry of the container, (2) geometry of the seal/gasket, (3) material of the seal/gasket, (4) surface properties (like roughness) of the seal/gasket and of the container where the two meet, (5) the mechanical performance of clamps/springs or whatever is holding the apparatus together. The program of this set of papers is thus to create a methodology to which the above parameters can be input to produce an analytical model or simulation for predicting the sealing characteristic of the modeled sealing solution.

3. Seal Microgeometry

As described above, we assume that fluid leakage happens through the interstices that remain between the surfaces of the seal and the container. Locally, these interstices can be visualized as a network of connected “caverns”, formed due to non-perfect contact between the rough surfaces of the seal and container. (See Figure 3.) Any practically manufactured surface, however smooth to the human eye, will have surface imperfections, which are enough for fluid to seep through. We note that many references on sealing (for example [1]) describe the importance of surface roughness for sealing performance, and specifically claim that the smoother the seal, the better it will seal.

Since one of the two materials forming the caverns of Figure 3 is elastomeric in nature, it changes form easily with stress. This in turn, is theorized to change the shape of the caverns through which the fluid seeps. Changing the shape of these caverns has an effect on the fluid flow. In general, the narrower a cavern, the more it will “resist” a fluid from flowing, as evidenced by well known idealizations such as Poiseuille flow [2]. It is thus important to create a theory about how the cavern geometry changes with respect to various parameters, in particular with

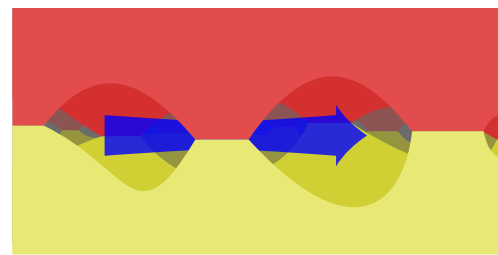


Figure 3: Surface roughness of the seal and container surfaces creates a series of caverns through which fluid can creep.

respect to the mechanical sealing pressure (intuitively, the pressure that the seal and container are pressing on each other at), and the fluid flow.

At this point, we make a second assumption: since the fluid flow is (or is expected to be) of a creeping nature, the force of viscous drag on the walls of the caverns is negligible as compared to the mechanical and fluid pressures. Thus, as far as the effect on the geometry of the caverns is concerned, viscous drag and thus fluid velocity can be disregarded. The fluid can be considered to be a static fluid having a particular pressure. (In a later paper, this pressure will be revealed to be different at different locations along the seal, but in this paper, we assume that the “micro”-scale at which a single cavern exists is too small compared to the scale over which such pressure variation is observed. Thus, the pressure variation is disregarded as well.)

Considering the above simplifications, the forces which affect the microgeometry of the seal caverns are: (see Figure 4)

(a) The **mechanical sealing pressure** S , which is the pressure with which the seal and the container are pressing on each other. This is defined to be the average stress in a direction normal to the seal-container contact at a location “sufficiently inside the seal”, taken to mean enough inside that the local variation in stress due to the undulating contact will have disappeared.

(b) The **fluid pressure** P , which is the fluid dynamical pressure inside the fluid. This is exactly the pressure on the parts of the seal and parts of the container that are in contact with the fluid.

(c) The forces conveyed through direct contact between the container and the fluid.

Imagine a thought experiment where we setup an apparatus similar to Figure 4. We could fix the mechanical sealing pressure S simply by

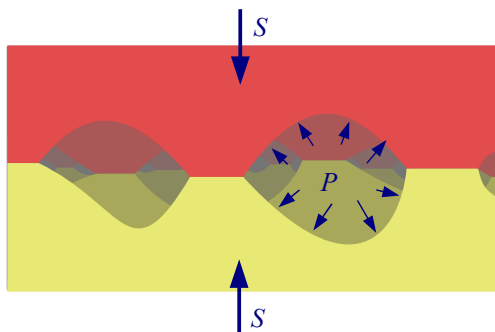


Figure 4: Mechanical sealing pressure S and fluid pressure P

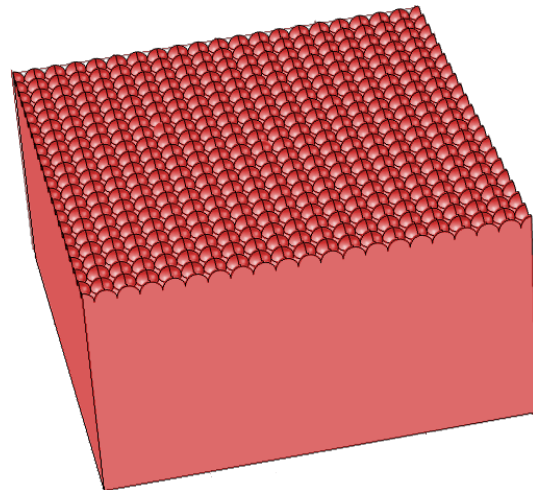


Figure 5: Idealization of a seal with a rough surface.

pressing down on the apparatus. We could fix the fluid pressure P by introducing fluid at a certain pressure. On the other hand, we do not have independent control over the forces conveyed through direct contact, unless we manipulate the contacts directly. Such manipulation being impossible at the microgeometry scale, we theorize that fixing the mechanical sealing pressure S and the fluid pressure P fixes the geometry completely. This thought experiment has led us to believe that the microgeometry is a function only of S and P .

Continuing our thought experiment, if we keep the mechanical sealing pressure S constant and increase the fluid pressure P , we intuitively expect the caverns to grow wider, and the area of contact between the seal and container to reduce. The contact between the seal and container will be broken at the point that the fluid pressure P equals the mechanical sealing pressure S . If fluid pressure P increases beyond this point, the seal is pushed away from the container, and the seal gap is no longer a creeping flow domain. Since this effect occurs around the situation described by $S - P = 0$, we make the following hypothesis:

“The microgeometry of sealing is, to a first order of approximation dependent only on the difference between the mechanical sealing pressure S and the fluid pressure P .”

This is the central hypothesis of this paper, which we shall call the **pressure difference hypothesis**. The rest of this paper tests all the above assumptions about microgeometry, including the pressure difference hypothesis, using simulation studies.

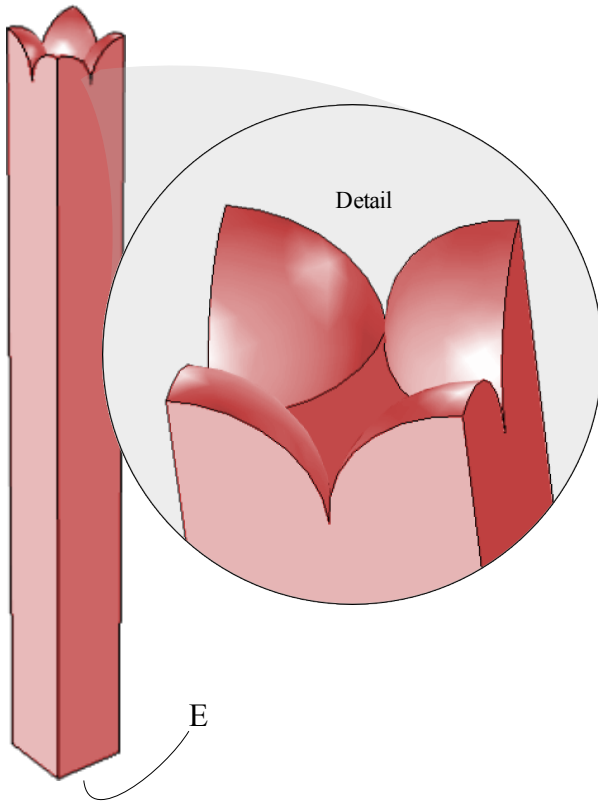


Figure 6: One cell in the idealized periodic surface structure of an elastomeric seal. The surface undulations are hemispherical. The long “stalk” is provided so that at the far end “E”, a uniform sealing pressure is achieved, and the pressure variations due to the undulations have disappeared.

4. Simulations

The primary purpose of simulations is to verify the above hypotheses. Even though the actual variations in surfaces are expected to be of a random nature, we assume an elastomeric seal with a periodically varying surface. (Figure 5). The periodically varying surface is assumed to be built out of hemispherical protrusions ($\varphi = 2\mu\text{m}$) arranged in a square lattice. For the purpose of simulation, only one of the cells of

this arrangement (Figure 6) need be simulated, with the appropriate symmetry boundary conditions.

The container wall is simplistically assumed to not have any surface variations of its own. In general, since the container is expected to be very hard with respect to the elastomeric seal, we expect the variation of the microgeometry to be due to the seal, rather than the container.

This model is programmed in COMSOL® using the Structural Mechanics Module and the Non-Linear Structural Materials Module. The elastomer is chosen to follow the Mooney-Rivlin two parameter model with constants $C10 = 0.39\text{MPa}$, $C01 = -0.05\text{MPa}$. The initial bulk modulus is set to 100GPa to approximate incompressibility.

A rigid block (modeling the container, not shown in the diagram) is in contact with the undulating surface. On the undulating surface of the seal, an additional fluid pressure is defined as a boundary load. A particular displacement towards the container is prescribed at the far end “E” of the elastomer. Many simulations are run, for various values of displacements and fluid pressures.

5. Results

Figure 7 depicts a typical simulation result. It is seen that there is a large mechanical pressure variation near the undulating surface, but near the end “E”, the variation has died down completely. Comparing with Figure 4, we see that the average mechanical pressure recorded on the surface “E” can be taken to be the mechanical sealing pressure S .

Figure 8 depicts results for various displacements of the far end for a constant fluid pressure. It is seen that, as the displacement is increased, the geometry becomes more constrained. The region of contact, also depicted, goes on increasing. The value of $S - P$ also goes on increasing.

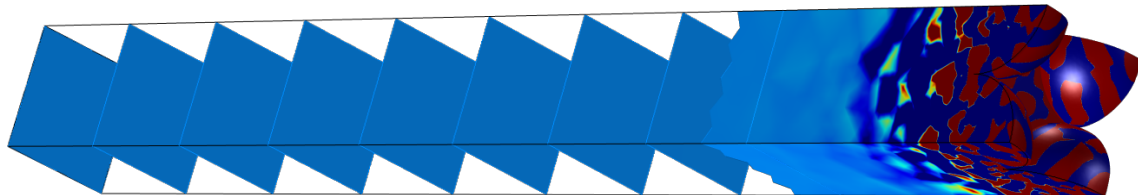


Figure 7: Mechanical pressure inside the elastomeric seal for an end deflection of 61nm and fluid pressure of 0.3MPa . Large variation is seen near the undulating surface, but the variation dies out quickly away from the surface, to give an average pressure at the end “E” equal to the mechanical sealing pressure S .

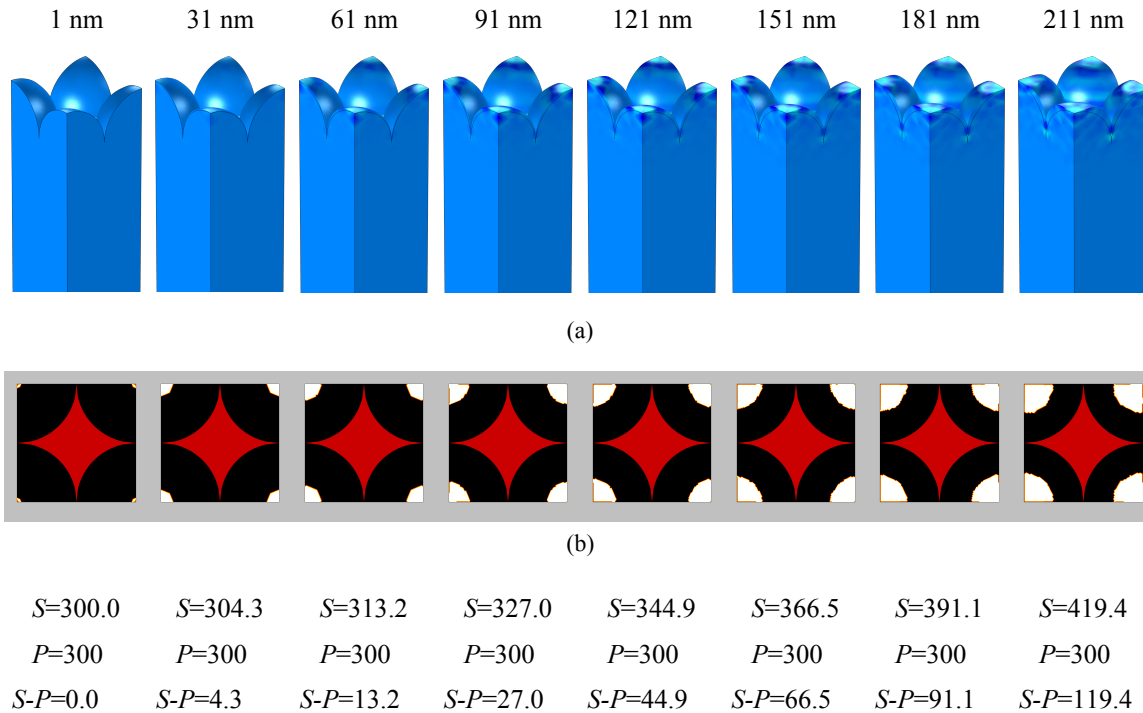


Figure 8: Seal microgeometry for end deflections from 1 nm to 211 nm, with a constant fluid pressure $P=300$ KPa. The sealing pressure S (all pressures in KPa) goes on increasing with increasing deflection, and so does $S - P$. (a) Microgeometry distortion. Color represents mechanical pressure in the solid body. (b) Contact (represented by white) between the elastomeric seal and rigid container. The contact starts at the corners and moves towards the center, indicating that the geometry of the cavern gets more and more compressed as $S - P$ increases.

Thus, a changing value of $S - P$ coincides with a change in geometry.

Figure 9 depicts results for a particular displacement of the far end “E” for various fluid pressures. It is seen that, there is no change in the microgeometry of the cavern. Also, $S - P$ remains constant throughout, even though S and P are individually changing by large amounts.

This constancy of $S - P$ coincidental with constancy of the microgeometry is observed at all simulated conditions. This result is strongly in favor of the pressure difference hypothesis presented in section 3. In fact, looking at the exactness of the results achieved, the **pressure difference hypothesis** can be made stronger:

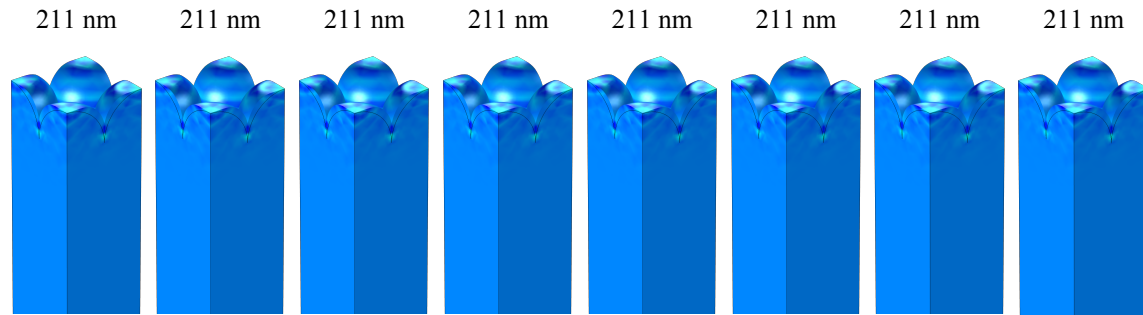
“The microgeometry of sealing is dependent only on the difference between the mechanical sealing pressure S and the fluid pressure P .”

Thus, it seems that the pressure difference hypothesis is not an approximation, but an exact result!

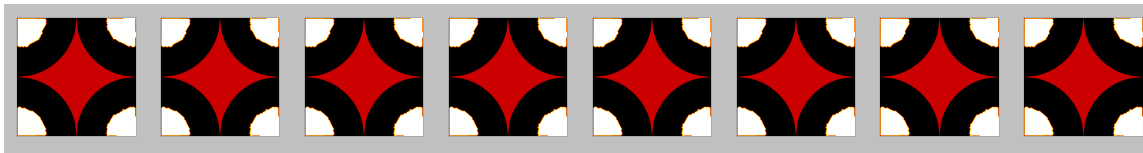
6. Discussion

In the larger context of creating a program for seal analysis, the present work fits as follows. Fluid flowing through the interstices between the seal and the container, considered to be the primary source of seal leakage, can be modeled as some partial difference equation. This partial differential equation is expected to be similar to the models of fluid flow through a porous domain, the difference being that the porous domain in this case forms a 2D manifold instead of a bulk 3D domain. Just like the permeability of a porous medium is dependent on the pore geometry, the microgeometry of a seal is expected to affect the permeability parameter of such a partial differential equation.

In this context, this paper strongly suggests that the permeability parameter will be dependent on the mechanical sealing pressure and the fluid pressure. This guides the creation of laboratory measurements to measure the permeability parameter. The permeability parameter has to be measured at various sealing pressures and fluid



(a)



(b)

$S=419.4$	$S=519.4$	$S=619.3$	$S=719.3$	$S=819.3$	$S=919.3$	$S=1019.2$	$S=1119.2$
$P=300$	$P=400$	$P=500$	$P=600$	$P=700$	$P=800$	$P=900$	$P=1000$
$S-P=119.4$	$S-P=119.4$	$S-P=119.3$	$S-P=119.3$	$S-P=119.3$	$S-P=119.3$	$S-P=119.2$	$S-P=119.2$

Figure 9: Seal microgeometry for fluid pressures from 300 to 1000KPa, at a constant end deflection of 211nm. The sealing pressure S goes on increasing with increasing fluid pressure, but $S-P$ is a constant. All pressures in KPa. (a) Microgeometry distortion. There is no noticeable difference in the various situations. Over these 8 simulations, the maximum the cavern surface has moved (averaged over the surface) is 0.112 pm, whereas the surface itself has moved an average of 0.175 nm as against the reference configuration. (b) Contact between the elastomeric seal and rigid container – no noticeable difference.

pressures. Furthermore, this paper provides strong evidence that the permeability parameter will depend only on the difference between the two pressures. This reduces the tabulation workload from a 2D to 1D table, thus reducing the number of independent studies that need to be conducted in the laboratory.

In other papers in this series, the authors intend to use the above insight to build an analytical theory of seal performance. The strong numerical evidence towards the validity of the pressure difference hypothesis also suggests that a mathematical proof of the pressure difference hypothesis should be attempted. Similarly, laboratory work to verify the pressure difference hypothesis (from the point of view of the porosity parameter) can also be conducted.

9. References

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