Numerical simulation of leakage initiation in face-type static O-ring seals

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Abstract

Elastomeric O-ring seals play a critical role in sealing fluids in variety of applications across the industries. In spite of their importance, the design of O-ring seals, like any other elastomeric seals is based on heuristic techniques that are formulated by means of existing experimental and field data. Attempts towards simulating the performance of O-rings have been limited to stress-strain analysis using commercially available finite element packages in order to find damage in O-rings. However, estimation of fluid pressure and other loading conditions that result in O-ring leakage have not been attempted. In this paper, we estimate the leak-initiation conditions of face type O-ring seals using the Fluid Pressure Penetration (FPP) technique. The analysis is performed for low squeeze values in order to simulate the loss of contact pressure in aged seals. The results thus obtained provide an insight into leakage scenarios that are frequently observed in O-rings used across the industries.

Keywords: *Sealing, fluid pressure penetration, O-ring, elastomer, finite element method.*

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Introduction

Elastomeric O-ring seals are one of the most commonly used sealing solutions in pneumatic and hydraulic systems. Applications of O-ring seals range from shipping, automobiles, aerospace, metallurgy, chemical industry, railway machinery to many other fields due to their minimalistic structure, excellent sealing performance, and less expensive manufacturing.

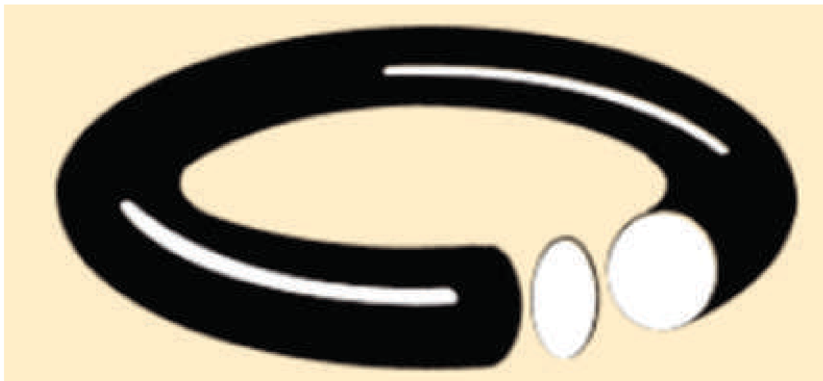


Figure 1(a). Basic O-ring with a slice [1]

These O-ring seals are generally designed by means of heuristic techniques (Parker, 2007; ERIKS, 2002; Taylor & Francis, 1984; Apple, 2009; Hitech, 2018; SAE AS568, 2003) that are formulated using data obtained from experiments and field performance history (Gillen et al., 2005; Kömmling et al., 2019; Momon et al., 2013). However, such empirical guidelines lack performance estimation capabilities, especially when the seal material, seal geometry or the loading conditions are altered.

To design an optimized O-ring seal and reduce the time and cost spent on repeated experimentations, a model that simulates the mechanics of sealing and leakage is required. Such a model will enable the prediction of fluid pressure that initiates leakage (leak initiation pressure) for any given O-ring design. Some such models that predict leak initiation are available for other seals but not for O-rings [10-14]. For O-rings, researchers have worked on numerical techniques that only predict stress fields, strain fields, and the damage inside the elastomer due to the fluid pressure and compression loading [17-21]. However, systematic estimation of leakage pressure is not pursued by researchers to the best of the knowledge of the authors. In this paper, we attempt to initiate such systematic study by means of preliminary simulations to understand the leakage behaviour of O-rings. The objectives of this paper are thus devised as follows:

- Review existing seal leakage simulation techniques [10-16] and select an appropriate model for estimation of leakage in O-rings.
- Estimate leak initiation in O-rings at different gas pressures and squeezes.
- Identify key experimental and simulation techniques required to extend and apply this work for specific O-ring applications.

Review of existing leak models

Very few researchers have attempted to develop models that estimate leakage. Most such models predict leak rate of fluid through the interface of seal and surrounding material. However, they do not estimate the loading conditions (fluid pressure and contact pressure) at which leakage initiates.

For example, Persson and Yang [10] suggested that fluid leakage occurs through the micro paths formed through the interface when micro surface protrusions of rough elastomer and metal surfaces come into contact with each other. The leak rates were estimated by calculating flow through these leak paths using percolation theory [22]. However, this theory is developed for small fluid pressures where fluid pressures play little role in deforming materials at the interface. In addition, several assumptions made in the formulation of the model and the complexity involved with the micro-mechanical modelling impede the application of this model to most practical applications.

Jolly and Marchand [11] modelled the interface as a porous medium and predicted the leak rates from Darcys' law [26] and suggested that leakage rates depend upon the permeability of the porous media. In addition, Sudhamsu et al. [12] also investigated the leakage as flow through thin porous interface and modelled the effect of contact pressure and fluid pressure on the permeability.

On the other hand, few other researchers preferred estimating leak initiation pressure (smallest fluid pressure at which leak starts to appear) instead of fluid leak rate. Models developed to predict leak initiation generally predict the fluid pressure at which the surfaces at the interface separate in order to allow for flow of fluid. Such approach enables analysing the problem in hydrostatic condition instead of the hydrodynamic flow condition that is observed in leakage fluid flow scenarios. This makes these models simpler and easier to implement in daily engineering problems.

One such model, developed in Sudhamsu et al. [13], estimates the leak initiation pressure through metal-elastomer interface by using a wedge analogy. The elastomer and metal bodies are modelled using lumped elastic and mass elements. Just in the same way as a fluid separates the interface in the direction perpendicular to its flow, here, in this model a wedge block is pushed through the interface (by force representing pressure load due to fluid pressure) separating the interface in the direction perpendicular to the movement of the wedge. This simple analogy enabled the model to accurately describe leak initiation in experiments conducted on elastomer-metal interfaces using Nitrogen gas [27], However, the model contains too many parameters that cannot be measured directly through experimentation. Such parameters are to be fitted using elaborate leak experiments. In addition, the one-dimensional formulation of this model limits its usage to seals with simple geometries.

Pressure penetration model [21] is a popular fluid pressure loading technique that uses finite element analysis to estimate the separation at the interface. This technique iteratively updates the surfaces that experience fluid pressure loading as the separation at the interface progresses towards the low-pressure end of the interface. This model can be easily used as it is already implemented in the commercial FEA packages such as ANSYS and ABAQUS. However, the details of synthesis and validation of this model are not available in the scientific literature to the best of the knowledge of the authors. In spite of this limitation the intuitive approach and the simplicity of this model led several researchers into using this model for estimating leak initiation in different kinds of seals [14-16]. However, this model has not been used for estimating leakage in O-rings systematically. In the later sections of this paper, we use this model to understand the behaviour of O-ring and its performance under various design and loading conditions.

Leakage in O-ring seals

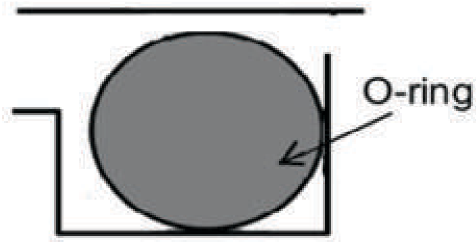


Figure 2(a). O-ring cross-section with a clearance

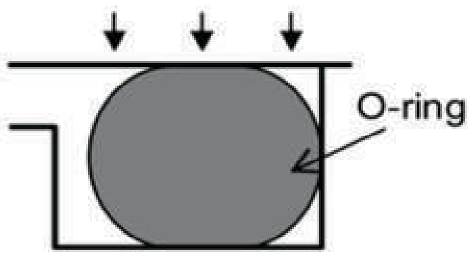


Figure 2(b). O-ring cross-section with applied squeeze

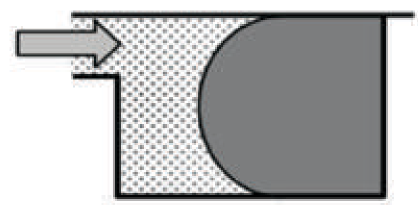


Figure 2(c). O-ring cross-section with applied fluid-pressure

Figure-2(a-c) shows a typical cross-section of a static O-ring installed in a rectangular groove. The clearance showed in Figure-2(a) is compressed(squeeze) by moving the top plate down and crushing the O-ring in the groove shown in Figure-2(b). The aforementioned squeeze is a ratio of the amount of deformation applied to the seal expressed as a percentage of the free-state cross-sectional thickness. When pressure acts from the left side it pushes the O-ring to the right and towards the enclosing metallic envelope thus closing the gap in an even more tight manner (with higher contact pressure at the interface). This in-turn makes it much more difficult for the fluid to penetrate through the interface. This "pressure-assistive sealing" generally makes O-rings very good sealing devices. However, prolonged usage of O-rings induces permanent deformation in the elastomer and reduces the contact pressures at the interface.

Under laboratory conditions, when new seals are used for testing, leakage experiments predict that O-rings will be leak proof [7-9]. However, in many real-world applications and it has been seen that seal leakage failure has caused catastrophic failures [24]. This can be attributed to the accumulation of gradual degradation in the geometry and the material of O-ring over the years of service. In order to estimate leakage in O-rings, leak simulations have to be carried out on degraded O-rings (degraded material and permanently deformed geometry). Alternatively, one can also reduce compression in new O-rings to replicate the contact pressure loss due to permanent deformation in an aged O-ring. However, such simulations have not been attempted by researchers to the best of the knowledge of the authors.

Existing literature investigates material damage caused by high stress and strain fields inside the O-ring generated due to compression and fluid pressure loading [17-21]. In the subsequent sections of the paper a parametric study of O-ring leakage at different pressures and compressions (squeeze). The amount of compressions are kept small in order to replicate the conditions that occur during permanent set in an aged seal. The methods and challenges associated with correlating these results with seals that are subjected to higher squeezes are later discussed.

Numerical modelling of elastomeric seals

O-ring made of fluorocarbon (FKM) rubber material with dimension shown in Figure-3(a) is placed into metal gland. The cut-section of the O-ring assembly with the gland dimensions with the top plate is shown in Figure-3(b). Top plate is fitted and is pushed downwards and hence creates squeeze/compression of the O-ring. Gas pressure is applied from the centre port and it tries to leak circumferentially outwards. O-ring leakage is evaluated with varying gas pressures and squeezes.

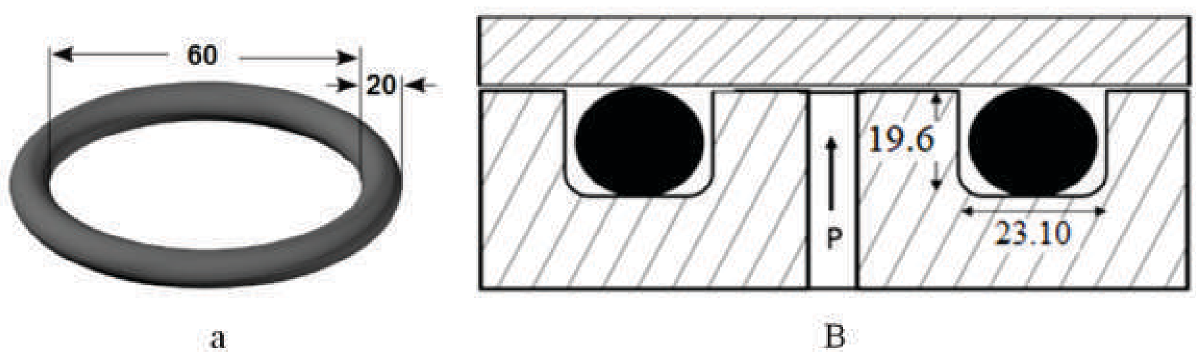


Figure 3. a) Schematic of an O-ring, b) The static O-ring flange seal assembly

Material Modelling of an O-ring:

Hyperelastic Ogden material model[25] is used to characterise the non-linear stress-strain behaviour of polymeric materials used for manufacturing of O-ring seals. The Ogden model, like other hyperelastic material models, assumes that the material behaviour can be described by means of a strain energy density function, from which the stress-strain relationships can be derived.

The potential function of the Ogden material is as follows:

$$w = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i} (\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3) + \sum_{k=1}^{N} \frac{1}{D_k} (\mathrm{J} - 1)^{2k}$$

$$\text{where} \quad J = (\lambda_1 \lambda_2 \lambda_3)^{\frac{1}{2}}$$

where λ_1, λ_2, and λ_3 are principal stretches

μ_i , α_i and D_k are the Ogden material parameters

N is the order of the model.

The material parameters corresponding to the fluorocarbon (FKM) used for leak experiments in [27] were utilized for this work.

We hence consider a three parameter Ogden model ($N = 3$) for simulation in this work. The FKM elastomer is assumed to be incompressible, thus making J equal to one ($J = 1$).

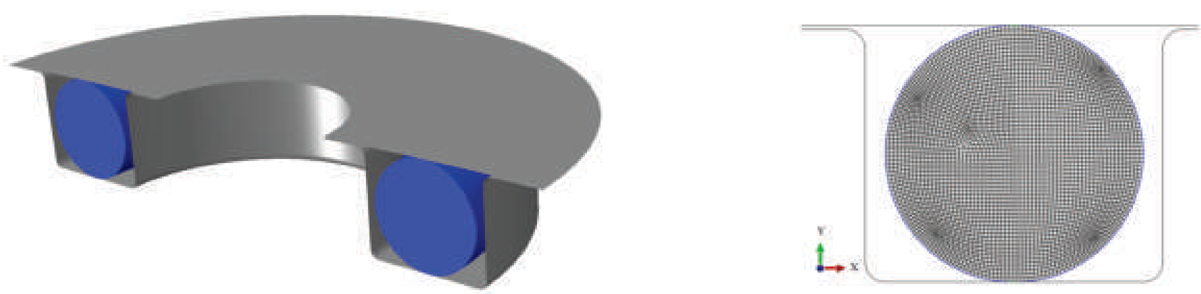
These parameters are as follows:

$$\boldsymbol{\mu_1 = 9.097215824 \quad \mu_2 = -0.376652723 \quad \mu_3 = -5.946227627}$$

$$\boldsymbol{\alpha_1 = 3.703766636 \quad \alpha_2 = 0.13111379 \quad \alpha_3 = -1.261533419}$$

Discretization of seal geometry:

ABAQUS® FE package was used for numerical analysis of O-ring assembly. Figure-4 shows the FE model built based on the installation condition of the seal assembly described in Figure-3(b). The bottom groove and top plate are in practice steel bodies and are modelled here as rigid bodies due to their relative rigidity when compared to elastomer. The rubber O-ring is meshed with four-noded axisymmetric quadrilateral elements (CAX4RH) and is modelled with incompressible third order Ogden material as discussed in section-4.1. The numerical model thus built is set to be solved using hybrid formulation and hour glass control once the loads and boundary conditions are applied.



a) Cut-section of the FEA assembly

b) Axis-symmetric analysis

Figure 4. The static O-ring flange seal assembly and FEA analysis

Application of fluid Pressure using Pressure penetration technique:

When fluid interacts with an elastomer-metal interface as shown in Figure-5a, it applies a uniform pressure loading on all the surfaces that are exposed to the fluid as shown Figure-5b. However, as the elastomer deforms due to the applied loads, new surfaces can be generated due to interface separation. In such scenario, the newly generated surfaces should also be loaded with fluid pressure and the deformation problem should be solved again to assess any further separation in the interface. This process should be continued until no additional separation in the interface is observed between two consecutive iterations. The pressure-penetration tool in commercial finite element analysis packages such as ABAQUS and ANSYS facilitate this process.

In addition, in certain scenarios, the roughness of the elastomer and the metallic surfaces creates a need for allowing entry of fluid into the un-separated regions of the interface. In such cases, pressure penetration tool also facilitates application of fluid pressure into the un-separated interface. The extent of fluid pressure penetration into the interface in such cases is determined by the contact pressure distribution along the interface. The fluid pressure shall penetrate until a certain point into the interface where the contact pressure is just less than a given input value (known as critical contact pressure). When this critical contact pressure is set to zero, the fluid pressure is generally applied only on the separated surfaces of the interface.

The critical contact pressure is a parameter that represents the roughness of the interfacing surfaces. This makes the parameter independent of the overall geometry of the seal and the sealing envelope and enables parametric study for different geometries and loading conditions. In the analysis carried out in this paper, the critical contact pressure is considered to be zero for the sake of simplicity in illustration. However, in order to describe any leak experiment accurately, the critical contact pressure should be first determined using adequate experimental data.

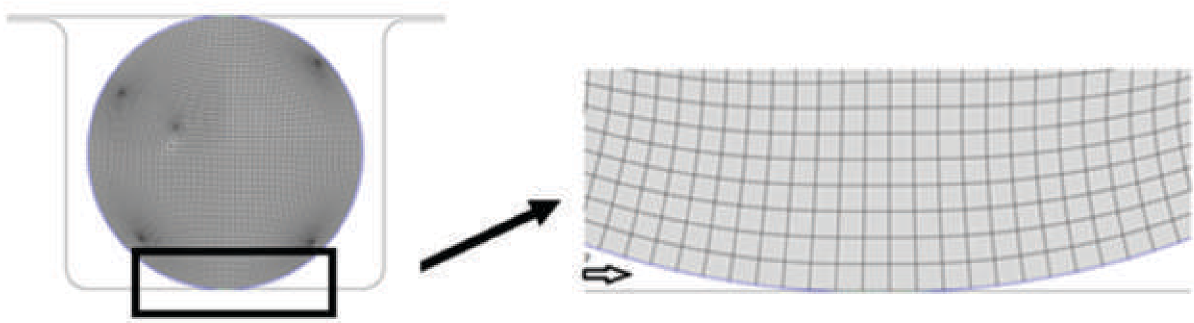


Figure 5. a) Pressure penetration Initial Loading

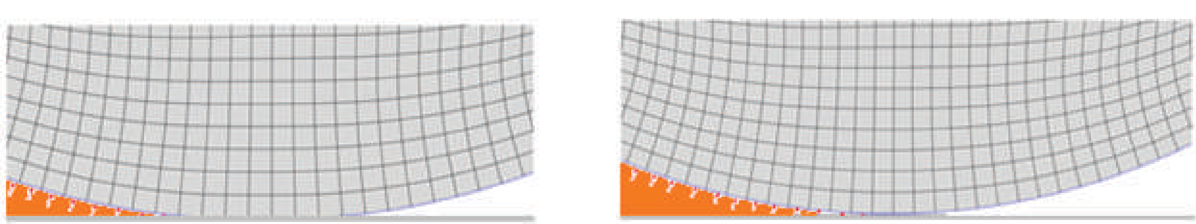


Figure 5. b) Fluid propagation

Loading and boundary Condition

The bottom groove is fixed for all the degrees of freedom and the top groove is allowed to move only vertically in order to apply varying amounts of compression. In the first step of the solution, the O-ring is compressed by moving the top plate towards the O-ring by a certain fixed amount (v) as shown in Figure-6(a).

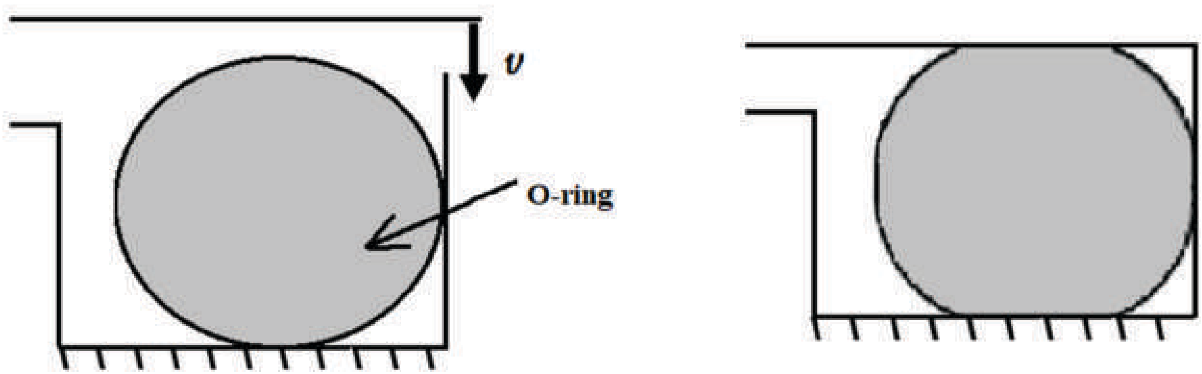


Figure 6(a). Precompression

In the second step of the solution, the compression is retained and an additional fluid pressure loading is applied using the fluid pressure penetration loading technique as shown in Figure-6(b). Once the solution for these loading conditions is complete, the separation at the interface is assessed and the analysis is re-solved number of times with higher or lower fluid pressures until the minimum fluid pressure that results in complete separation of the interface is determined.

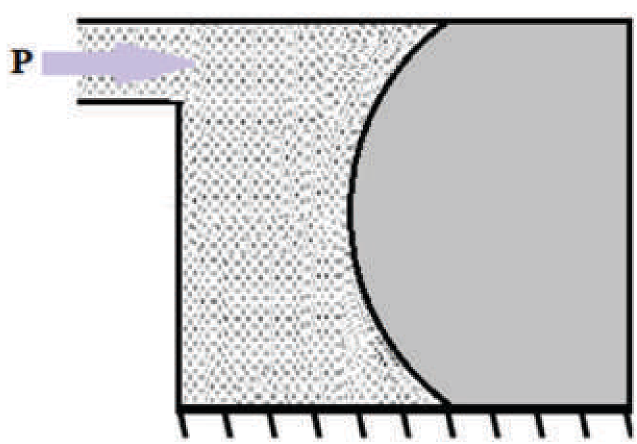


Figure 6(b). Pressure Penetration

Results of Numerical simulation

Displacement loading conditions with four different squeeze values (ranging from 0.5% to 2%) were applied on O-ring. Figure-7 shows the von mises stress contours in O-ring material under the influence of pure compression loading for 2% squeeze. With increasing amount of squeeze, it can be observed that the maximum von-mises stress increases as shown in Figure-10.

The critical contact pressure is a parameter that

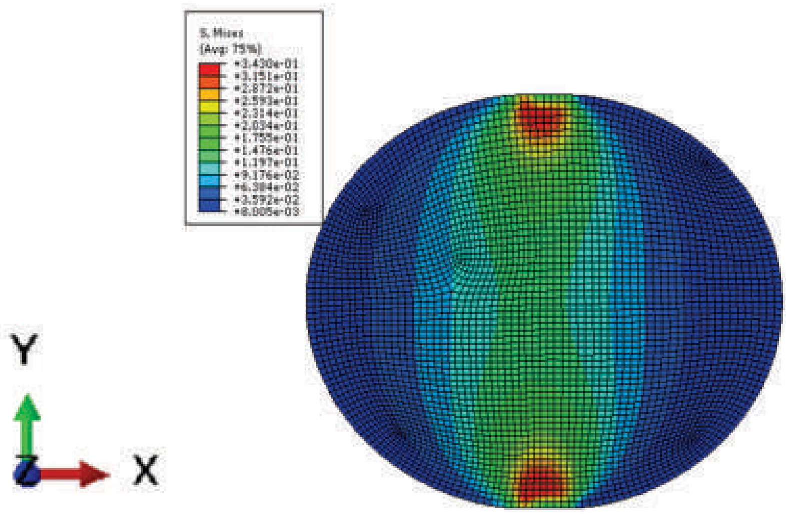


Figure 7. Von-mises stress in the elastomer for 2% squeeze

It is also observed that O-ring flattens for some length at the O-ring and metal interface, known as contact length as shown in Figure-8. At the contact region the maximum contact stress increases with increase in squeeze and the maximum contact stress lies near the centre of the contact length as shown in Figure-9.

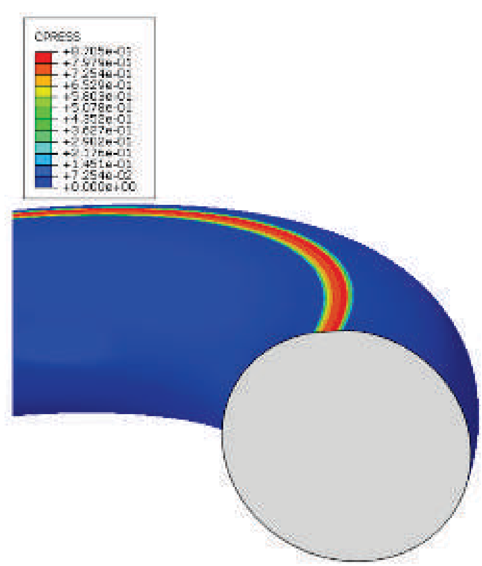


Figure 8. Contact stresses on the contact length for 2% squeeze

For a particular squeeze value, the contact stresses vary throughout the contact length. Figure-9 shows the contact stress profile for four different squeezes varying from 0.5 to 2%. The contact stress profile increases in area with increase in the squeeze value.

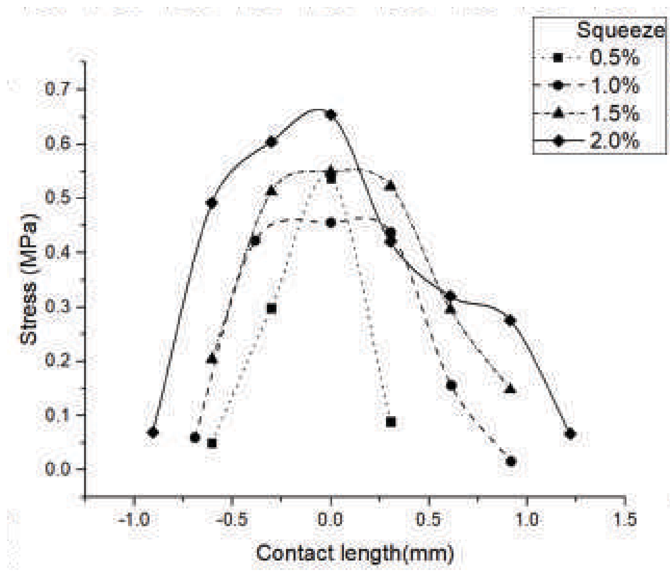


Figure 9. Contact pressure profile vs the contact length at different squeezes

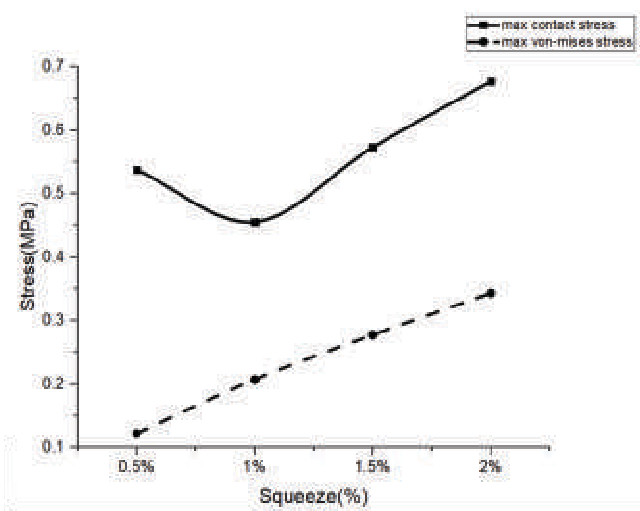


Figure 10. Maximum von-mises and maximum contact stress

With the application of fluid pressure, the separation of surfaces at the interface starts to occur. Interface separation in turn, decreases the contact length (*l*). The fluid pressure is increased until the interface separates completely. It is assumed that this complete separation enables fluid flow or leakage. The fluid pressures at which leak initiates for any given squeeze can be thus found out using this process. Figure-11 shows the effect of increase in fluid pressure on the contact length. For the constant squeeze value of 2%, increase in fluid pressure decreases the contact length until the seal starts leaking at 0.15 MPa.

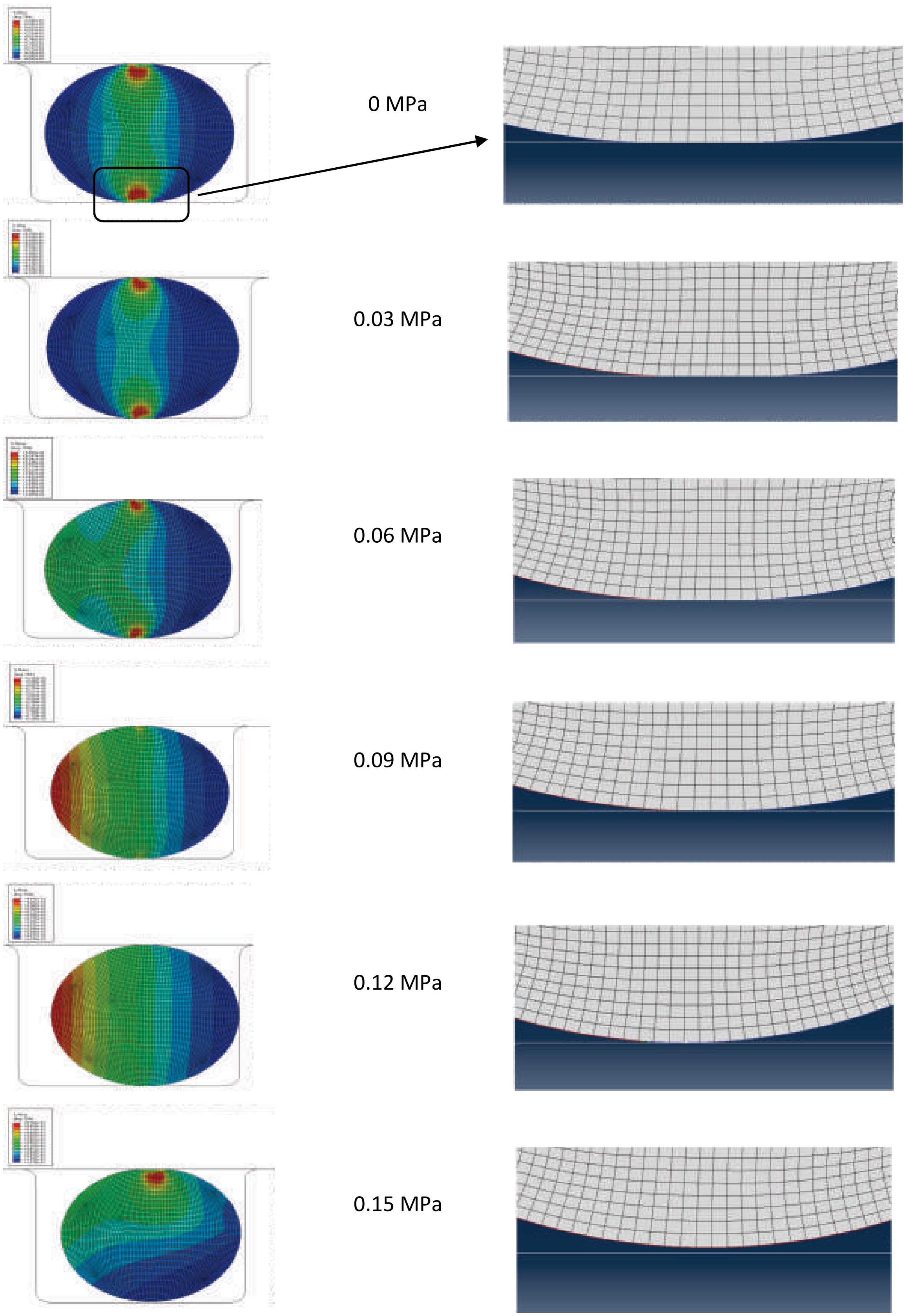


Figure 11. Fluid pressure and contact length

In Figure-12, each curve shows variation of contact with x-position (axes shown in Figure-7) for a given fluid pressure at 2% squeeze. Multiple curves are drawn for different fluid pressures and it can be observed that the contact stress profile decreases with increase in fluid pressure. Similarly, it can be observed that the maximum contact pressure throughout the interface decreases with increase in fluid pressure as shown in Figure-13. The leak initiation pressure is thus found out for different amounts of squeeze and is shown in Figure-14. It can be observed that the leak initiation pressure monotonically increases with increase in squeeze.

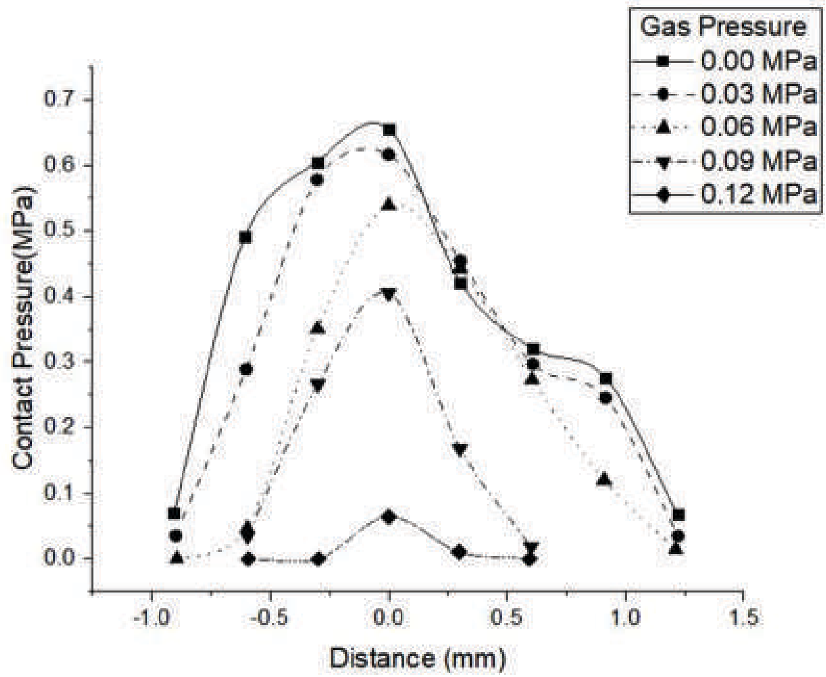


Figure 12 Contact pressure profile at different gas pressure

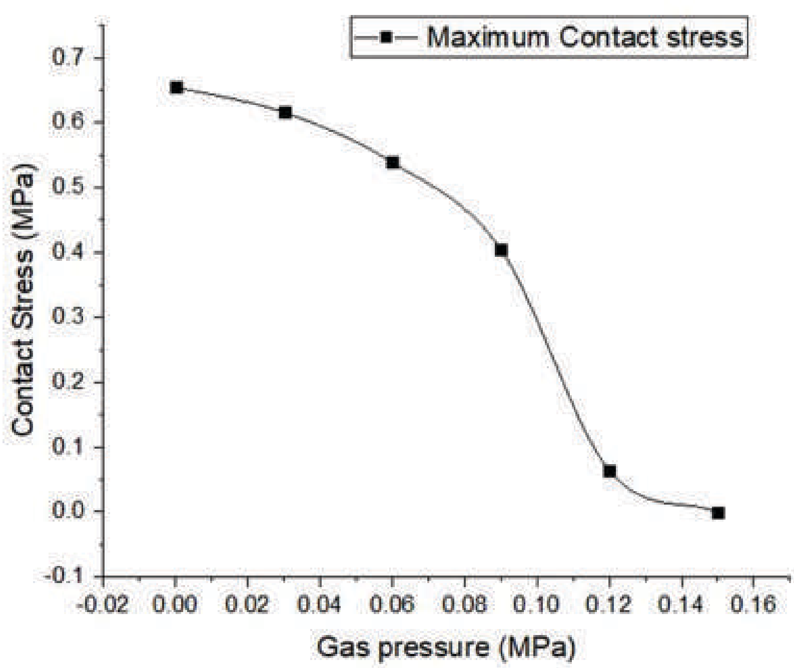


Figure 13 Maximum contact stress at different gas pressure for 2% squeeze seal

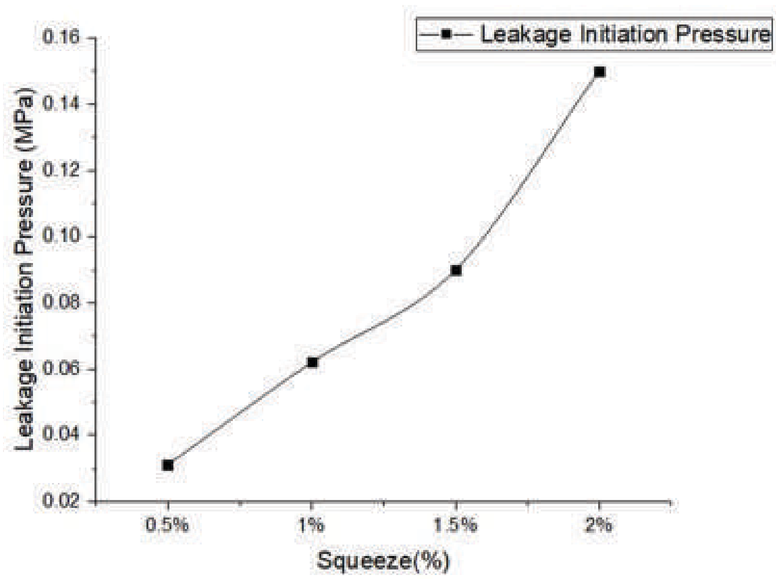


Figure 14. Leak initiation pressure at different Squeezes

Significant observations from numerical study

Figure-14 shows leak initiation pressure at squeezes until 2%. When squeezes more than 2% are applied, it has been observed that the contact pressures increase with fluid pressure as shown in Figure-15. For this reason, O-rings are known for their "pressure-assistive" sealing properties especially when high squeeze percentage is applied on the O-ring. O-rings that are used in applications across the industries, thus use, squeezes greater than 5% [1-4] thus enabling pressure assistive sealing. However, the effective squeeze decreases as the O-ring undergoes permanent deformation with time. When the effective squeeze falls below a certain value, the seal loses its "pressure-assistive" nature and hence is prone to leakage, especially at higher fluid pressures. When the analysis illustrated in this paper is coupled with ageing studies it should be possible to accurately determine the life of the seal after which leakage is imminent.

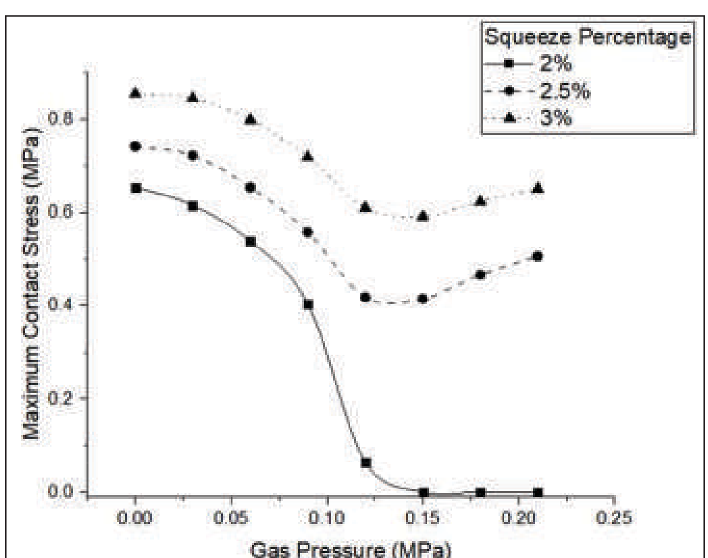


Figure 15. Maximum contact stress at different gas pressure for different squeeze seal

Although fluid pressure penetration tools have been used by researchers to estimate leak in different seals, the technique has been rarely validated using leakage experiments. In addition, leakage experiments on O-rings have been seldom conducted. It is important to conduct such experiments as they can be useful not only in understanding the behaviour of O-rings but also in validating the fluid pressure penetration technique and associated studies such as the one conducted in this paper.

The critical contact pressure parameter of the fluid penetration technique is a measure of the roughness and other irregularities present on both the interfacing surfaces. In order to determine this value, one needs to fit the results obtained by pressure penetration model with data for leakage experiments. Once the value of this parameter is determined, it is expected to remain unaltered with the size and geometry of the seal and the interface as long as the surface roughness parameters remain the same. This provides an opportunity to use this model to optimize design of the O-ring assembly. However, this capability of the pressure penetration technique has to be validated by means of leakage experimentation on different O-ring assemblies.

Summary and Conclusions

In this paper, models for estimation of leak through different sealing interfaces are briefly reviewed. Fluid pressure penetration technique is utilized to estimate leak initiation in face type static O-ring seals. The results show that O-rings seal effectively at high squeezes but are prone to leakage at small squeezes. This indicates the tendency of O-rings to fail when the effective squeeze drops below the threshold limit due to ageing of the material. For effective use of this technique in specific applications, the critical contact pressure parameter of the pressure penetration model and the contact pressure decay due to ageing in O-rings should be evaluated before conducting leakage simulations such as those illustrated in this paper. This will allow accurate prediction of leak initiation in both new and aged O-ring assemblies of different sizes that are designed to seal fluids of different pressures.

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