KSTLE International Journal, Vol. 2, No. 1, June 2001, pp. 40-45

On the Sealing Characteristics Analysis and Design of Bi-Polymer O-ring Seals

Chung Kyun Kim†, **Young Bae Ko and Seung Hyun Cho**

Tribology Research Center, Hongik University, Seoul, Korea

Abstract : The paper deals with a non-linear finite element analysis of the thermomechanical distortions of an elastomeric O-ring seal including a temperature gradient. Axial compression of O-ring seals, as well as the influence of the temperature gradients and various O-ring seal models, are investigated based on the axisymmetric analysis. The highest temperature occurs near the interface of the O-ring between the dovetail groove bottom and the O-ring seal. The calculated FEM results indicate that the composite O-ring with the diametral ratio, 0.8 shows very stable and recommendable compared with other seal models for elevated temperatures and corrosive environments.

Key words : O-ring seal, temperature gradient, diametral ratio, thermomechanical distortions

Introduction

An O-ring is a torus, or doughnut-shaped object, generally made from elastomers. In a number of applications, elastomeric O-rings are used as pressure (or vacuum) seals to prevent leakage of gas. Elastomeric O-ring seals for static and dynamic sealing functions are capable of undergoing large deformations under compression. In a typical application, the O-ring seal is inserted into a dovetail (or rectangular) groove and then compressed a certain amount depending upon the specific application.

The leakage of elastomeric O-ring seals will occur when the pressure differential across the seal just exceeds the initial peak contact stress between two contacting surfaces. Typically, an O-ring seal restrained by dovetail or rectangular grooves cannot perfectly prevent the leakage of gas through the sealing interface between the surface of the O-ring and that of its groove wall. This may be explained by simulating non-even distributions of compressive stresses at the contact surface of an O-ring seal. The finite element analysis associated with the compression of elastomeric torroidal O-ring seals have been studied many researchers [1-3].

The sealing performance of an elastomeric O-ring has been analyzed in terms of the temperature gradients that develop between the O-ring and the groove surfaces with which it comes into contact. The thermomechanical distortions that develop in compressed O-ring seals, in common case of restrained geometry, are investigated using the finite element method. The computer simulation in this analysis includes material hyperelasticity and axisymmetry.

In this study, a numerical method was used to investigate the thermomechanical distortions of an O-ring compressed between the dovetail groove and the rigid upper plate with a cooling water jacket. O-ring is strongly influenced by the temperature gradient and pressure between the O-ring and the restrained groove. This is strongly related to the possibility of leaks occurring between the O-ring and mating surface of the upper plate.

Computer Simulation

Fig. 1 shows the FE meshes and boundary conditions for an O-ring seal uncompressed by a rigid upper plate with a cooling water jacket. The temperature of a cooling water is kept at 25 with a circulating system. With increasing pressure of the upper plate an O-ring nestles into the dovetail groove. When the pressure decreases the O-ring returns to its initial shape. This deformation is accompanied by sliding or rotating of the O-ring in its groove and therefore, may lead to leakage and wear.

The thermomechanical distortions of an elastomeric O-ring seal due to a temperature gradient which comes from the vacuum chamber have been analyzed using a non-linear FEM program MARC [4]. An elastomeric O-ring was discretized by means of axisymmetric, four-noded, hybrid, quadrilateral elements. The finite element mesh, comprising 328 solid elements for the O-ring and 584 interface elements for the unilaterial contacts, are shown in Fig. 1. Mesh refinements are introduced along the contacting regions of the O-ring against the upper plate and dovetail groove walls, which are expected to fill the corners.

The material properties of O-ring seals for the FEM analysis are given in Table 1. The structure of the upper plate and the groove is an aluminium.

Load Conditions

Contact pressure type loads relate to the compression rate of an O-ring against the upper plate in axial direction. The sealing contact pressure is better achieved by moving the base of the

---

†Corresponding author; Tel: 82-2-320-1623; Fax: 82-2-323-8793
E-mail: ckkim@wow.hongik.ac.kr

Table 1. Physical and thermal properties of O-ring seals

Material types	NBR	FFKM
Young's modulus, MPa	3	7.2
Possion's ratio	0.49	0.49
Mass density, kg/m^3	1,460	1,950
Thermal expansion coefficient, μm/m · K	94.4	229
Thermal conductivity, W/m · K	0.43	0.19
Specific heat, J/kg · K	2,000	945

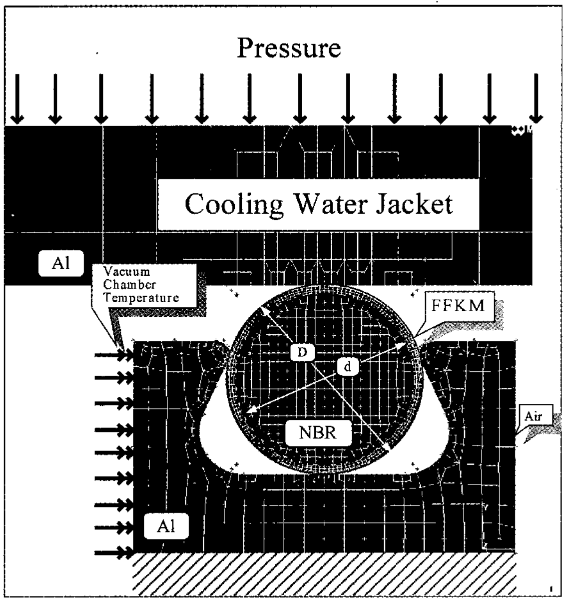


Fig. 1. FE meshes and boundary conditions.

upper plate. The thermal load which is transported from the vacuum chamber, will affect the thermomechanical distortions of the O-ring seal. The heat of the vacuum chamber is quickly conducted to the aluminium structure with a dovetail groove and the elastomeric rubber seal.

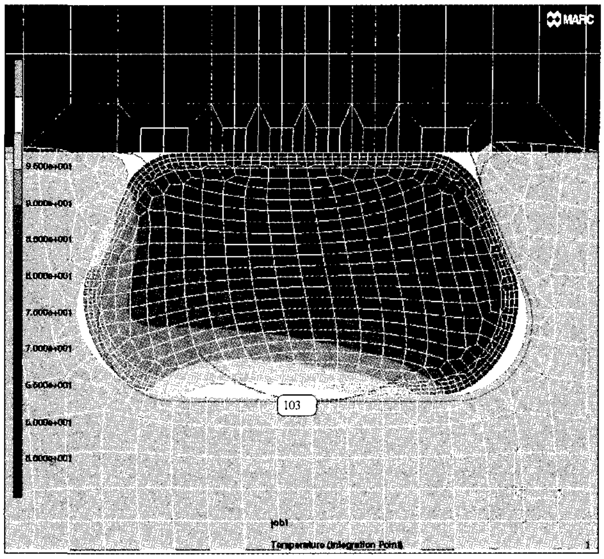
Boundary Conditions

A friction coefficient of 0.4 was assumed at each contact between O-ring, upper plate and rigid dovetail groove wall. Further, the effects of surface roughness and consequent gas penetration were not considered, so that the contact pressure at the interfaces is only considered [5].

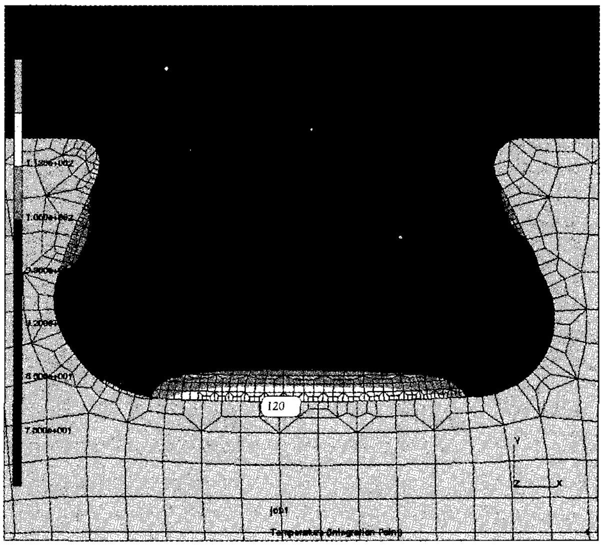
The vacuum chamber temperatures from 100°C to 400°C are applied to the left side wall of the dovetail groove structure. The other sides of the groove structure and the upper plate are exposed to the ambient temperature, 25°C.

Result and Discussions

A coupled thermal-mechanical analysis of an O-ring seal including a temperature gradient across the dovetail groove walls has been made to obtain temperature distributions, thermal distortions, and contact stresses.



(a) Solid NBR O-ring model



(b) Composite O-ring model, $d/D = 0.8$

Fig. 2. Distributions of temperature and geometry of the O-ring mounted in the dovetail groove and subjected to compression rate 18% and temperature gradient 300°C, simultaneously.

Temperature Distribution

Fig. 2 shows the temperature distributions for the vacuum chamber temperature, 300°C and the compression rate, 18% of the upper plate in axial direction. In Figs. 2(a) and 2(b), the maximum temperature of an O-ring occurs at the position A, which is near the contact surface between the O-ring seal and of the upper O-ring is small compared with that of the bottom contact surface against the groove bottom. This is characterized by fitting the O-ring seal with the dovetail groove.

The groove bottom. The maximum temperature of the solid Nitrile O-ring is 103°C as shown in Fig. 2(a). The maximum temperature of the composite O-ring with the diametral ratio,

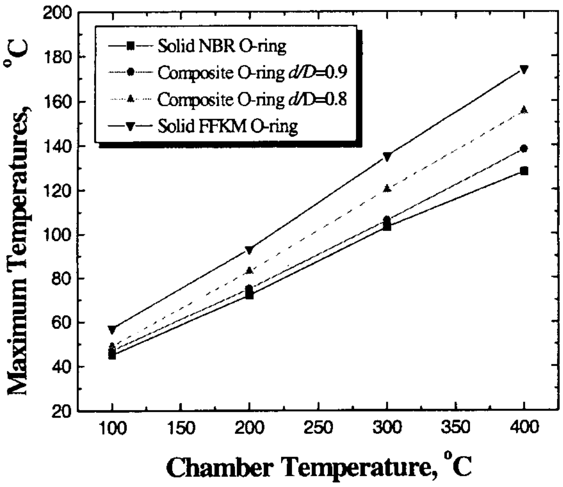


Fig. 3. Maximum temperatures in terms of the vacuum chamber temperature.

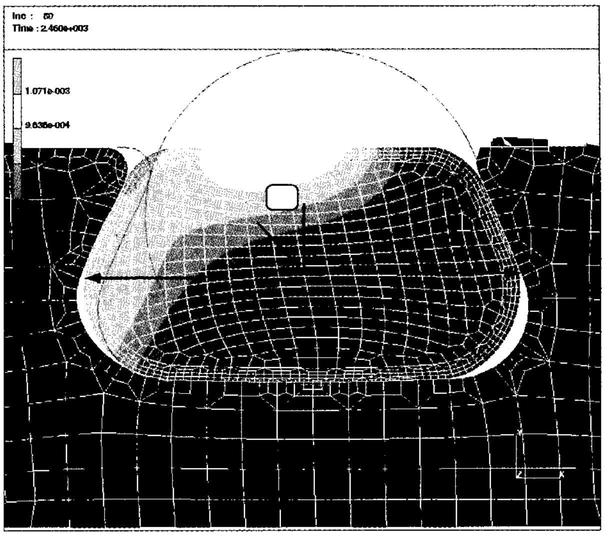
$d/D = 0.8$ is 120°C as shown in Fig. 2(b). In these figures, the maximum temperature of O-ring seals occurs near the contact position A because of the increased real contact areas at the groove bottom walls and the cooling water jacket of the upper plate. The upper contacting surface between the O-ring and the upper plate has been kept at 25°C using the cooling water jacket, which may effectively improve the sealing performance of an O-ring seal. The contacting surface area

In Fig. 3, the maximum temperature distributions of four O-ring seal models are presented as a function of the vacuum chamber temperature from 100°C to 400°C. The maximum temperature of an O-ring seal increases linearly as the operating temperature of the vacuum chamber increases. The solid NBR O-ring and the composite O-ring with the diametral ratio, $d/D = 0.9$ have the similar temperature characteristics due to a maximum temperature limit of the base materials. The maximum temperature limit of a Nitrile rubber is just around 130. These results indicate that the temperature distributions of a solid perfluoroelastomer, FFKM and the composite O-ring, $d/D = 0.8$ can effectively endure the sealing performance problems for the increased operating temperatures. But if we consider the very high price of perfluoroelastomer O-ring seals, the composite O-ring seal with a diametral ratio, d/D = 0.8 is efficient and cheap for elevated temperatures and chemical environments, especially.

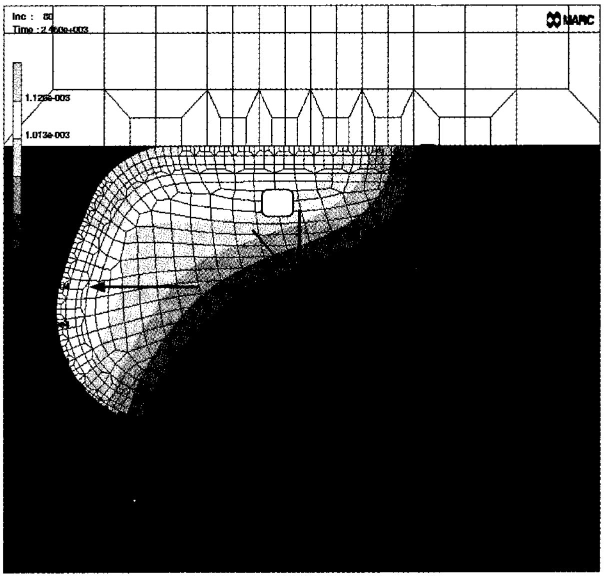
Thermomechanical Distortion

We assume symmetry of the deformation about the axial direction as well as the radial one. The angle, θ of the initial contacts between the upper plate, O-ring seal and dovetail groove is chosen so that the distortion at the center of the toroidal shape of the O-ring seal is zero as shown in Fig. 4.

The thermomechanical distortion between O-ring seal and groove wall is strongly related to a sealing performance as long as O-ring seals have been existed. During the sealing processes, O-ring will be distorted due to non-uniform temperature distributions conducted from the vacuum chamber and the upper cooling jacket.



(a) Solid NBR O-ring model

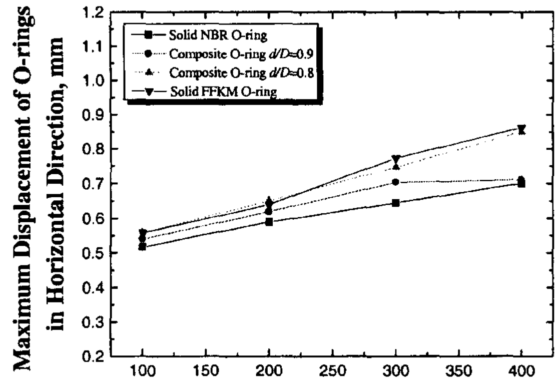


(b) Composite O-ring model, $d/D = 0.8$

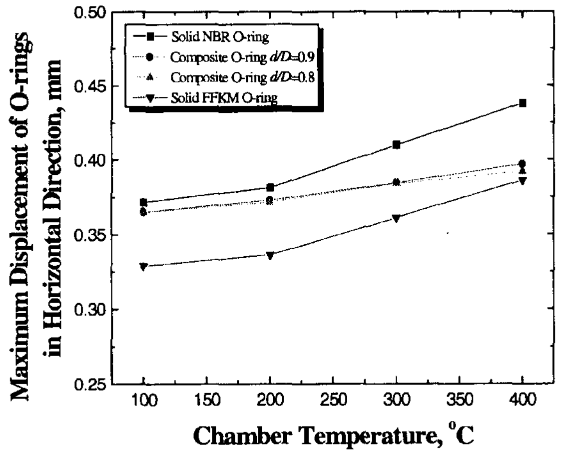
Fig. 4. Deformed profiles of an O-ring seal.

Fig. 4 shows the deformed geometry of the O-ring seal which is distorted to the CCW direction. The deformed zone B of the O-ring seal, which is exposed to a high temperature of the vacuum chamber, shows more expanded profiles compared with that of the right side zone C. This may try to rotate the O-ring seal to the CCW direction, which is known as a thermomechanical distortion.

The computed results indicate that non-uniform temperature gradients are strongly related to the shifted positions of the concentrated contact stresses and the maximum temperatures from the center line of symmetric O-ring seals. Therefore, the maximum displacement of the O-ring seal occurs at the left side zone B. During heating and cooling processes of the vacuum chamber system, the repeated thermal loads due to heatings transported from the vacuum chamber and coolings



(a) For a distorted zone B



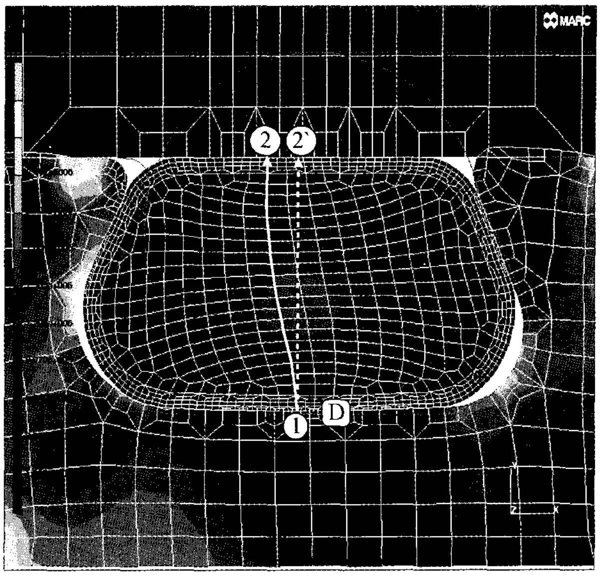
(b) For a distorted zone C

Fig. 5. Maximum displacements of an O-ring seal in the horizontal direction as a function of a vacuum chamber temperature.

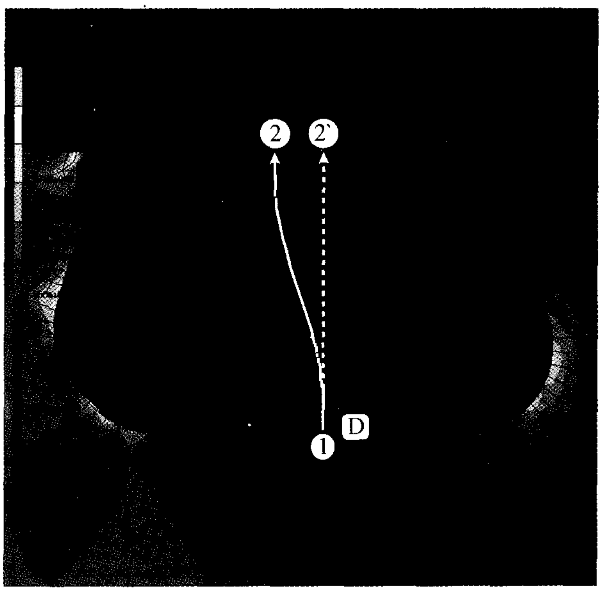
conducted from the water jacket may lead to a thermomechanical distortions in axial direction of elastomeric toroidal O-ring seals. This distortion may produce a gas leakage along the contact surface between the O-ring seal and the upper plate, and the thermal failure of the seal.

In Figs. 5(a) and 5(b), the maximum displacements of the distorted zones B and C in the horizontal direction are presented in terms of the vacuum chamber temperature, respectively. In Figs. 5(a) and 5(b), the maximum displacement of the distorted zone B is much higher than that of the distorted zone C for various types of O-ring seals. In Fig. 5(a), the FEM results show that the maximum displacement of the Nitrile rubber material O-ring seal is very stable and small for the limited temperature. This is strongly related to a low Young's modulus, high thermal conductivity, and low expansion coefficient. This means that thermal loadings are more influential factors compared to mechanical pressures. But the maximum displacement of a perfluoroelastomer O-ring seal is high compared with that of the Nitrile rubber material as shown in Fig. 5(a).

In Fig. 5(b), the FEM results show that the maximum displacement of the perfluoroelastomer O-ring seal is very stable and small for the increased temperature. This is strongly related to a high Young's modulus, low thermal conductivity, and high expansion coefficient. This means that mechanical contact pressures are more important parameters compared to thermal loadings. But the maximum displacement of the Nitrile rubber material is high compared with that of a perfluoroelastomer O-ring seal as shown in Fig. 5(b).



(a) Solid NBR O-ring model



(b) Composite O-ring d/D=0.8

Fig. 6. Stress distributions of a composite O-ring seal.

From the calculated results, the thermomechanical distortion of the composite O-ring seals shows more stable as the diametral ratio, *d*/*D* of the composite O-ring seal is increasing. This means that a Nitrile rubber which shows a low Young's modulus and low mass density is recommendable as a core material of the composite O-ring seals.

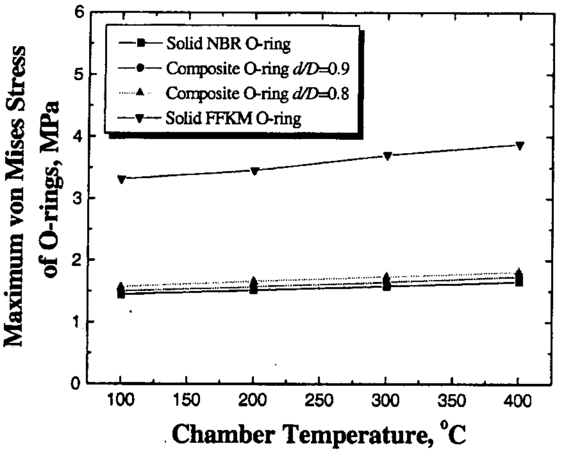


Fig. 7. Maximum von Mises stress of an O-ring seal in the horizontal direction as a function of a vacuum chamber temperature.

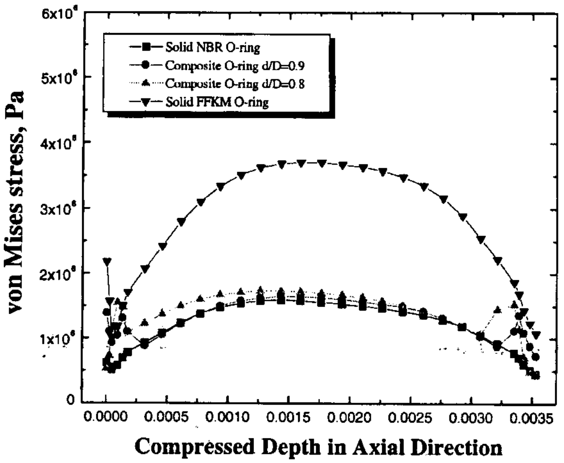


Fig. 8. von Mises stress along the compressed depth, ①→② in axial direction for a temperature gradient, 300.

Contact Stress

In Fig. 6, the contact stress distributions between the O-ring seal and the restrained dovetail groove are shown for the vacuum chamber temperature of 300°C. In this figure, the compression rate of an O-ring is 18% and the diametral ratio(=d/D) of the composite O-ring seals is 0.8. As shown in Fig. 6, the maximum contact stress occurs at the contacting surface D between the groove bottom wall and the O-ring seal. This may be influenced by the distorted O-ring and the differential expansion rate between the seal and the restrained groove depending on the temperature gradient.

The sealing capability of an elastomeric O-ring seal depends upon the contact stresses that develop between the O-ring and the surface of the rigid upper plate with which it occurs when the pressure differential across the O-ring seal just comes into contact. The gas leakage of the O-ring seal will exceeds the initial peak contact stress.

In Fig. 7, the maximum von Mises stress of an O-ring seal was presented in terms of the vacuum chamber temperature from 100°C to 400°C. In this figure, the maximum von Mises stress of the seal increases linearly as the vacuum chamber temperature increases. The maximum von Mises stress of the perfluoroelastomer O-ring seal shows 3 times higher than that of other O-rings. This means that the solid perfluoroelastomer O-ring seal has a high stiffness compared with other O-ring models and the thermal stability of the FFKM O-ring is excellent. But the flexability of the FFKM O-ring is not good compared with other O-ring models.

In Fig. 8, von Mises stress along the line ①→②, which is given in Fig. 6, was presented for various materials of O-ring seals. In this figure, von Mises stresses of solid O-rings which are made using a Nitrile rubber and a perfluoroelastomer show very stable along the depth in axial direction, ①→②. But von Mises stress distributions of the composite O-ring with the diametral ratio, d/D = 0.8 and 0.9 show very unstable near the interfaces between the core ring and the outer ring, which is made by a perfluoroelasromer. The peak stresses were occurred at the interface between two mating elastomers. To increase the stress stability of composite O-ring seals, the damping compounds should be added at a bonding layer.

Conclusions

The FEM results for the temperature distributions, thermomechanical distortions, and contact stresses for an O-ring seal compressed between the O-ring and the upper plate with a cooling water jacket have been presented. The operating temperature of the vacuum chamber varies from 100°C to 400°C and the elastomeric O-ring seal is compressed between two rigid plates up to about 18%.

The highest temperature occurs near the interface of the O-ring between the groove bottom and the O-ring seal. In general, the temperature gradient of the O-ring seal does not affect to von Mises stress because of the geometric characteristics of the dovetail groove. The thermomechanical distortions of the composite O-ring seal show more stable for the increased diametral ratio. This means that a Nitrile rubber which shows a low Young's modulus and low mass density is recommendable as a core material of the composite O-ring seals.

The calculated FEM results indicate that the composite O-ring with the diametral ratio, 0.8 shows very stable compared with other seal materials for the elevated temperatures and corrosive environments. Under these applications, the composite O-ring seals may be recommended if we consider very high prices of solid perfluoroelastomer O-ring seals.

Acknowledgment

This work was supported by grant No. 2000-30400-004-1 from the University-Industry Collaborative Research program of the Korea Science & Engineering Foundation.

References

1. Green, I. and English C., Analysis of Elastomeric O-ring

Seals in Compression Using the Finite Element Method, Tribology Trans. Vol. 35, No. 1, pp.83-88, 1992.

2. Green, I. and English C., Stress and Deformation of Compressed Elastomeric O-ring Seals, International Conference on Fluid Sealing, Firenze, Italy, pp.83-95, 1994.
3. Kim, C. K. and Hwang, J. T., Contact Stress Analysis of an O-ring Seal in a Dovetail Groove, Proceedings of the KSTLE, pp.25-21, 2000.
4. MARC Analysis Research Corporation, Computer Program MARC, California, USA, 1994.
5. Metcalfe, R., Baset, S.B., Lesco, R. and Selander, W.N., Modelling of Space Shuttle Solid Rocket O-rings, Proc. 12th Int. Conf. on Fluid Sealing (BHRA), Brighton, UK, pp.147-163, May 10-12 1989.