Chapter

Numerical Investigation of Elastomer Seal Performance

Sayyad Zahid Qamar, Maaz Akhtar and Tasneem Pervez

The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them.

Sir William Bragg

Abstract

Analytical models for swelling of rubberlike materials are difficult to formulate, and restricted in actual application due to their need for simplifying assumptions. Tests conducted on laboratory size samples of swelling elastomers cannot reproduce actual oil well conditions, and cannot cover all possible variations of testing parameters. However, these laboratory tests do provide useful information about material response of swellable elastomers in various conditions, serving as a basis for analytical and numerical modeling. Properly developed and robust numerical models can be used to predict near-actual performance of elastomeric seals. The current chapter describes the use of numerical (finite element) simulation to investigate swelling elastomer seal behavior in downhole petroleum applications. Variations in sealing (contact) pressure are studied for seal length, seal thickness, compression ratio, water salinity, swelling time, and type of well completion (open-hole or cased-hole). Month-long swelling experiments on samples of two actual elastomers (Chapters 3 and 7) provide input to the numerical model in terms of real material and deformation data. On the basis of these results, petroleum engineers can make informed decisions about the selection of elastomer material and seal geometry appropriate for the well type and conditions encountered. Application developers and researchers can also find this investigation useful in performance analysis and design of swelling elastomer seals.

Keywords: swelling elastomer seal, numerical simulation, seal contact pressure, different sealing parameters

1. Introduction

Effect of swelling on mechanical and structural properties of some elastomeric materials was investigated in the last chapter. How swelling elastomers behave when they are used as sealing elements in downhole applications is covered in this chapter. Swelling under actual well conditions is a complex and highly non-linear problem. It is important to know how the elastomer actually swells in a particular well, how much time is required to achieve sealing, and what sealing pressure is generated. As mentioned earlier, design and development of swelling elastomer seals is mostly based on hit-and-trial method and some laboratory tests. Analytical models for swelling of rubberlike materials are difficult to formulate, and restricted in actual application due to their need for simplifying assumptions [1–3]. Tests conducted on laboratory size samples of swelling elastomers cannot reproduce actual oil well conditions, and cannot cover all possible variations of testing parameters. However, these laboratory tests do provide useful information about material response of swellable elastomers in various conditions, serving as a basis for analytical and numerical modeling [4, 5]. Though time-consuming to run under all possible conditions, properly developed and robust numerical models can be used to predict near-actual performance of elastomeric seals.

Before this study, almost no published work is available that numerically investigates seal performance based on actual material properties and actual compression data at various stages of swelling. The current chapter describes the use of numerical (finite element) simulation to investigate swelling elastomer seal behavior in downhole petroleum applications [6]. Variations in sealing (contact) pressure are studied for seal length, seal thickness, compression ratio, water salinity, swelling time, and type of well completion (open-hole or cased-hole). Month-long swelling experiments on samples of two actual elastomers (Chapters 3 and 7) provide input to the numerical model in terms of real material and deformation data. On the basis of these results, petroleum engineers can make informed decisions about the selection of elastomer material and seal geometry appropriate for the well type and conditions encountered. Application developers and researchers can also find this investigation useful in performance analysis and design of swelling elastomer seals.

2. Mechanism of sealing

In oil wells, swelling elastomer seal is placed in the drilled hole with a certain gap between the seal and the outer casing (or formation), to ensure easy placement. With exposure to swelling fluid, the elastomer swells freely, the only driving force being dynamic swelling; through osmosis for water swellables [7], and through diffusion for oil swellables [8]. It first fills the gap between the tubular and formation; this may take a few hours to a few days depending on the elastomer type Further swelling (after filling up of the gap) generates pressure at the interface. Sealing is effective when contact pressure generated by swelling is greater than the differential fluid pressure across the seal ends in the well [9]. Swelling elastomers may be deployed in either open-hole or cased-hole completions. In open-hole configuration, the elastomer is in direct contact with the formation, while in cased-hole completions, the elastomer makes contact with the outer tubular or casing. It was concluded in Chapter 6 that among the existing hyperelastic material models, Ogden model with second degree strain energy function [10] most closely represents the behavior of swelling elastomers. Ogden-2 is therefore used in this chapter for numerical simulation of seal performance.

3. Material behavior: experimental work

As described in previous chapters, experiments were designed and conducted to find out material properties and coefficients needed for numerical simulation of swelling elastomer seal behavior. Disc samples of two elastomer types (designated as material-*A* and material-*B*) were allowed to swell for a 30-day test period in salt-water solutions of two different concentrations (6,000 and 120,000 ppm), maintained at a temperature of 50°C. Test temperature and salinities were selected to emulate medium-depth wells in the region. Swelling measurements included variations in volume, thickness, hardness, and density. Compression and bulk tests were performed to determine mechanical properties (elastic modulus, bulk modulus, Poisson's ratio, etc). Due to the quick-swelling nature of the elastomers, readings were initially taken after each day, and with increasing time periods later on (after 1, 2, 4, 7, 10, 16, 23, and 30 days of swelling).

To get the properties of the steel tubular on which the elastomer sections were mounted, strips were cut along the length of the tubular. Milling and grinding machines were then used to prepare tensile samples in line with ASTM E8M [11]. An Instron universal testing machine (150 kN) was used to conduct the tests. For the numerical simulation, coefficients for respective material models were extracted by curve fitting of the test results: stress–strain data from compression tests and pressure-strain data from bulk tests conducted on elastomer materials, and stress–strain data from tensile tests on tubular steel material. For full details of the experimental work, please refer to Chapter 7.

4. Numerical modeling and simulation

Modeling of the compression of an elastomer seal against an outer casing or a rock formation is treated as a static problem. Arrangement of the steel tubular, elastomer seal segment, and casing/formation in the pre-compression stage is shown schematically in **Figure 1**. An axi-symmetric model is used, and all materials are considered to be deformable. FE modeling is done on the software package ABAQUS [12]; CAX4RH element (4-node bilinear axi-symmetric quadrilateral hybrid) with reduced integration is used to represent the elastomer seal; and the steel tubular and rock formation are modeled using the CAX4R element (4-node bilinear axi-symmetric quadrilateral) is used to represent. In actual packers, elastomer seal element is vulcanized onto the tubular, therefore tubular and elastomer are treated as perfectly bonded in the model. Interaction forces at the

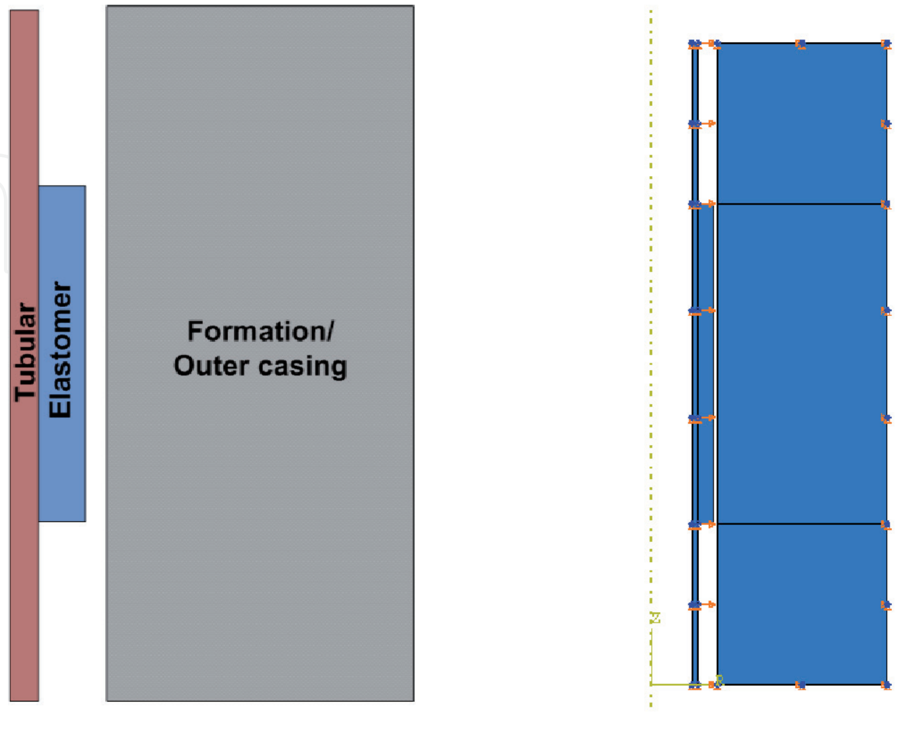

Figure 1.
Schematic diagram of model with tubular, elastomer, and formation (left); and axi-symmetric numerical model with boundary conditions (right).

elastomer-formation contact surface are split into tangential and normal components. Coulomb law is used to describe friction, with a friction coefficient of 0.4 in the tangential direction, and hard contact in the normal direction. If there is an outer casing in place of the rock formation (cased-hole), coefficient of friction is reduced to 0.1 because of the improved surface finish.

Tubular thickness and length are 7.5 mm and 800 mm respectively, elastic modulus is 210 GPa, and Poisson's ratio is 0.3. Elastomer seal is 29 mm thick and 400 mm long (same as actual swellable packer), while length variation of 100–600 mm is used to study the effect of seal length. Coefficients of Ogden hyperelastic material model are evaluated using experimental results from Chapter 6. Based on actual properties in a regional oil well, formation is modeled using Mohr Coulomb plasticity having following values: friction angle of 18°, dilatation angle of 15°, and cohesion yield strength of 7.515 GPa. For the outer steel casing, Young's modulus of 207 GPa and Poisson's ratio of 0.3 have been used.

Figure 1 also shows the ABAQUS model with all boundary conditions. Tubular is restricted to move in the vertical direction, while displacement is applied to the inner surface in the horizontal direction. When exposed to water or oil, the elastomer swells freely (in the thickness direction) until it fills the gap and comes in contact with the formation (or outer casing). Applied displacement amount is the difference between maximum free swelling in the thickness direction (from experiments) and the gap. Formation is fixed on all surfaces except the elastomer-formation contact surface.

After the gap is filled, the elastomer touches the formation and starts generating pressure. This contact pressure will develop the seal between elastomer and formation. Upper half of undeformed and deformed ABAQUS model is shown in **Figure 2**. It can be seen that after pressurization, the elastomer slides along the formation; this phenomenon occurs at the lower end also (not shown in the figure). The retaining end rings in an actual packer support the elastomer and do not allow it to slide along the gap in this way.

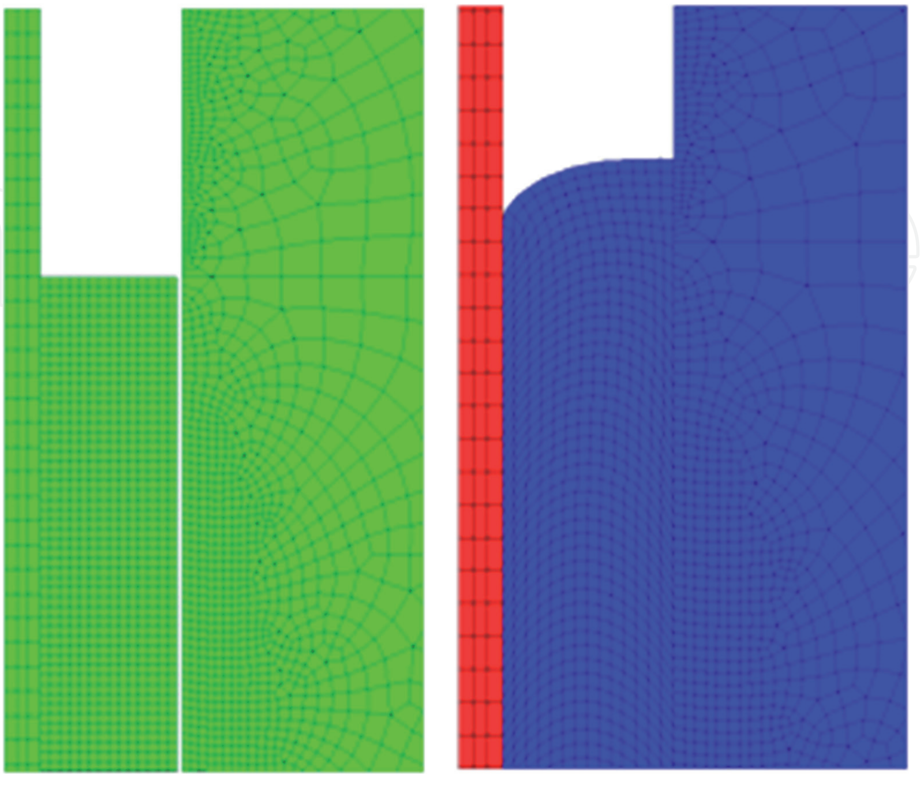

Figure 2.
Elastomer seal before (left) and after deformation (right).

5. Results and discussion

As discussed earlier, there are two factors that are necessary for superior sealing: higher value of contact pressure at the elastomer-casing interface; and good integrity and reliability of the elastomer material under the given conditions. Extended exposure to saltwater (or other medium) makes the elastomer softer (decreased hardness). Effective service life of the elastomer seal in the face of this softening effect is an important issue. Longevity investigation over a 5-year test period for a variety of water-type and oil-type swell packers has already been presented in Chapter 5.

Effect of the elastomer seal material and geometry, and the testing parameters, on seal contact pressure is presented graphically and discussed in the following sections. An expected, and notable, variation pattern can be observed in all the graphs. Seal pressure is lowest at the two ends of the rubber element, and increases nonlinearly to a maximum value near the central location.

5.1 Effect of swelling period

Figure 3 shows variation of seal contact pressure over the seal length after different swelling periods for two elastomer materials in low salinity brine. As observed for laboratory samples (Chapter 3), longer exposure results in larger amount of swelling. More swelling (increased seal thickness) generates more seal compression against outer casing or formation; increasing the contact pressure. As mentioned above, these elastomers are fast-swell type: most of the swelling occurs in the initial days, and the swelling rate goes down afterwards. Because of this, the well can become operational earlier, a highly sought-after outcome in petroleum engineering because of financial considerations. Faster swelling rate generates higher sealing pressure in the earlier days, and slower swelling for longer periods leads to lower increase in seal pressure later on.

More swelling leads to higher contact pressure, increasing the strength of the seal. **Figure 4** shows the variation in seal contact pressure for both materials in high salinity brines for the entire one month period. Progressive swelling increases the sealing contact pressure and strengthens the seal. Maximum pressure attained in each case (at the middle of the sealing element) is used for this plot. As observed and explained above, large increase in contact pressure occurs only in the first seven days; then the pressure increase becomes more gradual. A little fluctuation in the swelling pattern can be observed for material-*B* near the end of the first week. A

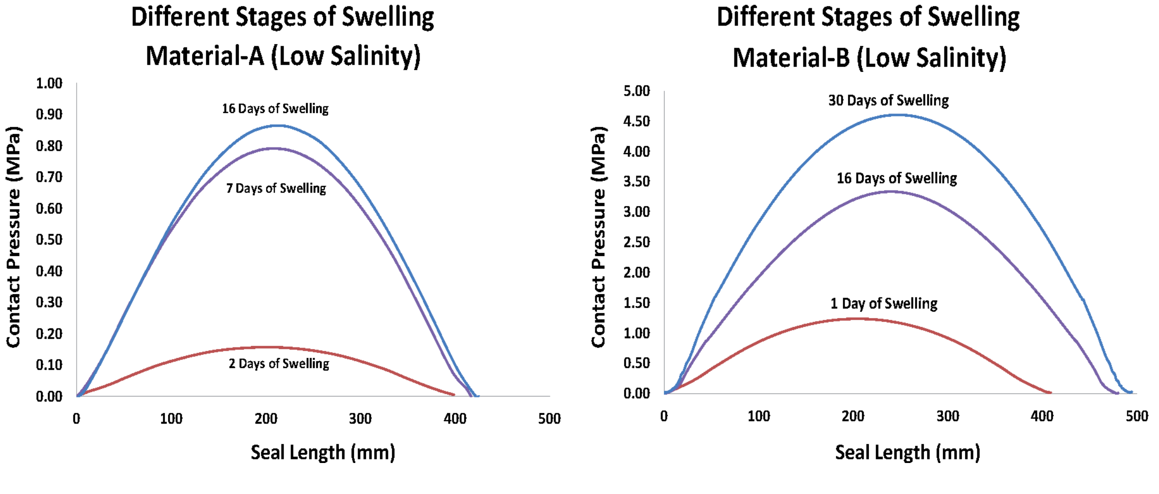

Figure 3.
Seal pressure variation for both materials at the end of different swelling periods under low salinity.

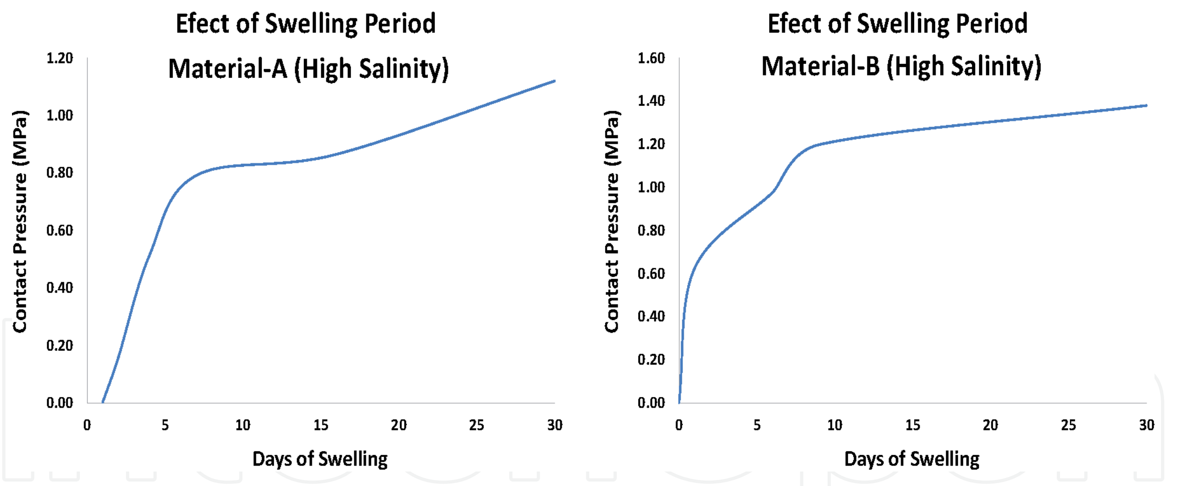

Figure 4.
Effect of swelling on sealing pressure for the entire period; both materials; high salinity.

rationale for this slight irregularity, especially for swelling under higher-salinity brine, has been presented in some earlier works by the authors [5, 13, 14]: two-way transport of salt between elastomer and salt solution, and breaking and re-forming of polymer cross-link chains. As far as choice of elastomer type goes, both materials show almost the same seal pressure performance in the case of higher-salinity wells.

5.2 Effect of water salinity

Figure 5 shows sealing pressure curves for low and high water salinity after seven days of swelling for material-A, and after thirty days of swelling for material-B. Pressure curve for lower salinity is higher for both materials, as expected. It was found in Chapters 3, 6, and 7 that larger amount of swelling (thickness increase) takes place in lower-salinity water; this will generate larger compression ratio and thus higher contact pressure. The reason is that higher chemical potential gradient is present in the case of low-salinity solution, giving rise to more fluid influx into the elastomer at a higher rate, as explained earlier.

5.3 Pressure variation pattern

Variation trend of sealing pressure against swelling rate is shown in **Figure 6**, for the two salt concentrations. The technique is to tag the center point of the elastomer,

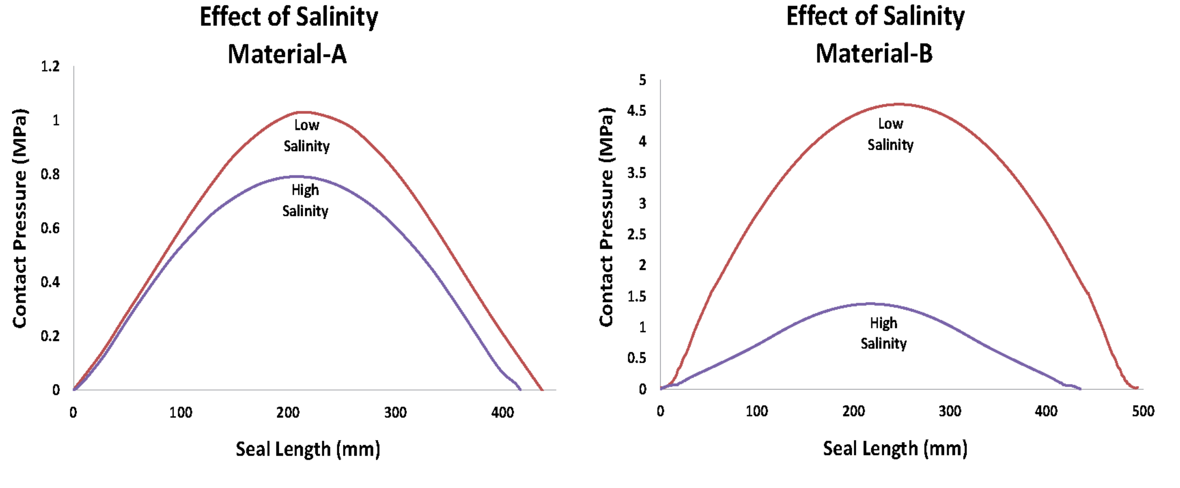

Figure 5.
Effect of salinity on seal contact pressure; material-A, 7 days of swelling; material-B, 30 days of swelling.

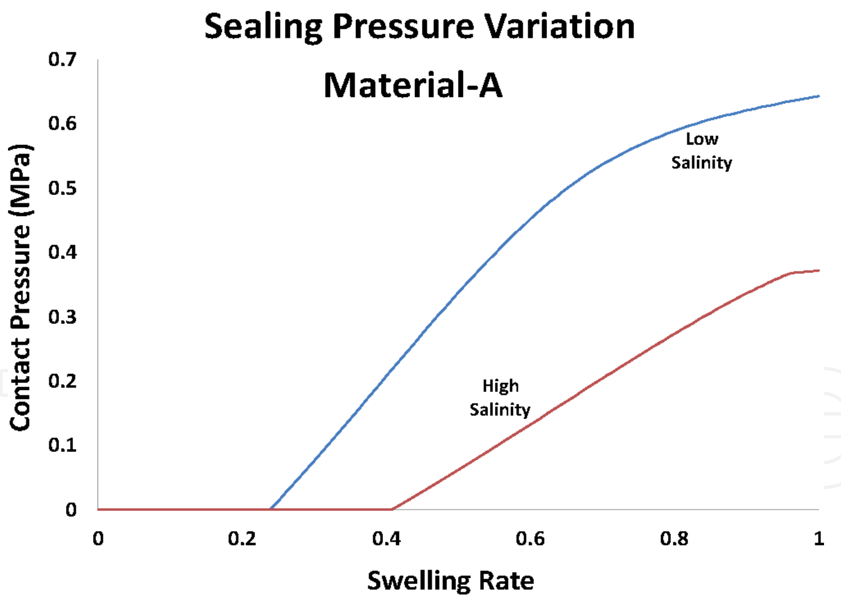

Figure 6.
Pressure variation pattern for material-A; low and high salinities.

where maximum pressure occurs, and then record the change in pressure as the amount of swelling increases. As mentioned earlier, the elastomer keeps on swelling until it just touches the formation; further swelling causes it to exert increasing pressure because of the compression. This increase in pressure is faster at first, and then drops down to a more gradual change. Elastomer swelling is higher in low salinity brine, and therefore has the higher pressure curve. For both salinities, pressure variation pattern is similar, but there are obvious differences in the magnitude of contact pressure generated.

5.4 Effect of seal length

In order to investigate the effect of length of sealing element on contact pressure, simulations are run for lengths of 100 mm, 200 mm, 300 mm, 400 mm, 500 mm and 600 mm with same set of boundary conditions. Maximum pressure obtained from each simulation is plotted in **Figure 7**; after three days of swelling for material-A, and after seven days of swelling for material-B in high salinity solution. Increase in seal length gives higher contact pressure. As expected, for a fixed amount of seal compression, larger contact area between elastomer seal and outer casing yields higher sealing pressure. As for the slight fluctuation of contact pressure for material-*B* (under high salinity), it may be due to the factors related to the nature of swelling described above.

5.5 Effect of seal thickness

How thick the elastomer seal element should be is an important decision in downhole petroleum applications. Based on actual field data, different thicknesses (10 mm to 29 mm) are used to investigate the effect of seal thickness on contact pressure. As an example, **Figure 8** shows simulation results for different seal thickness for both materials under low salinity after seven days of swelling. One observation appears to be counter-intuitive: pressure is higher for smaller seal thickness. The reason is the way the simulation is conducted: magnitude of seal compression is kept constant, while simulation is run for different values of seal thickness. Compression ratio (seal compression δ divided by seal thickness t) is therefore larger for thinner seals; thus the observed behavior. This

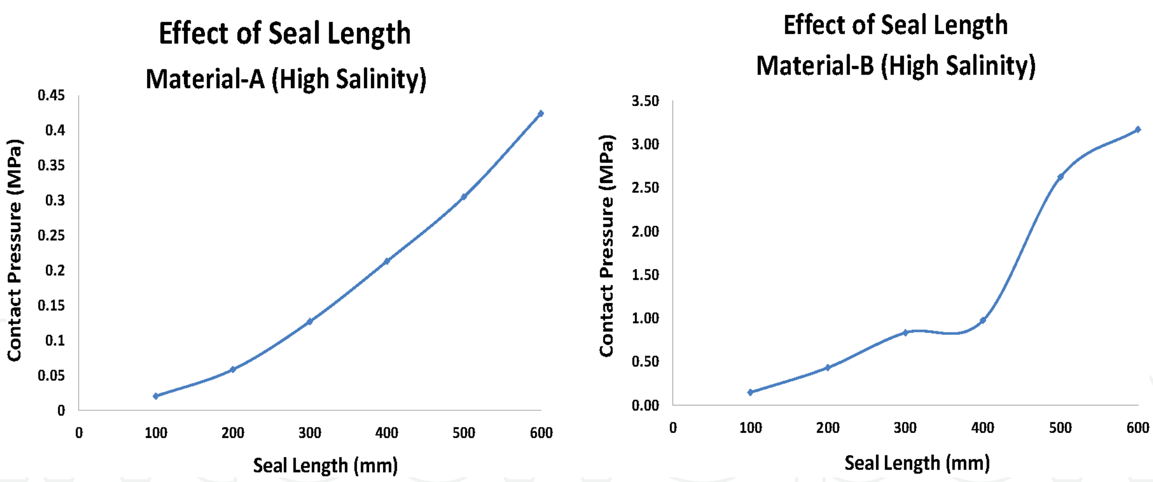

Figure 7.
Effect of seal length on seal contact pressure; high salinity; material-A, 3 days of swelling; material-B, 7 days of swelling.

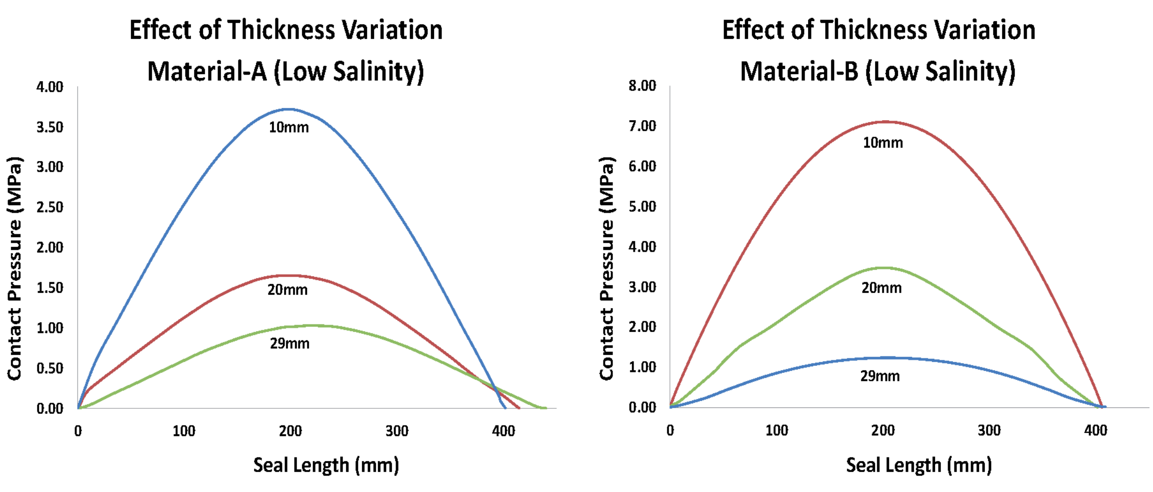

Figure 8.
Effect of seal thickness on sealing pressure; both materials; low salinity; 7 days of swelling.

misperception can be avoided by using the expression *compression ratio* instead of *seal compression*; as done in the following sub-section.

5.6 Effect of compression ratio

Figure 9 shows the variation of maximum sealing pressure versus compression ratio in for both materials in low salinity solution after seven days of swelling. As expected, sealing pressure is higher when larger compression ratio is larger. In actual downhole operations, higher value of seal pressure is naturally preferred, as it represents better seal performance. In applications where swellable elastomers and solid expandable tubulars (SET) are used conjointly, compression ratio is a result of elastomer swelling, or tubular expansion (larger expansion ratio), or a combination of the two [15, 16].

5.7 Effect of well completion type

As explained in Chapter 2, swelling elastomers are used in many applications for remediation as well as new installations using both open-hole and cased-hole completion strategies [17–19]. In selecting a suitable swell packer, it is important to consider the effect of well completion type on contact pressure. **Figure 10** shows

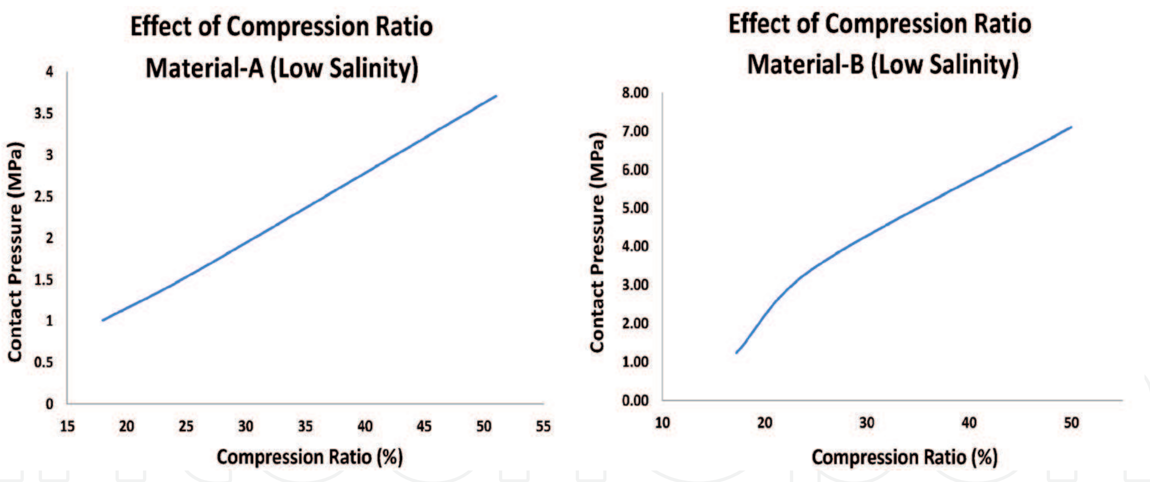

Figure 9.
Effect of compression ratio on seal contact pressure; both materials; low salinity; 7 days of swelling.

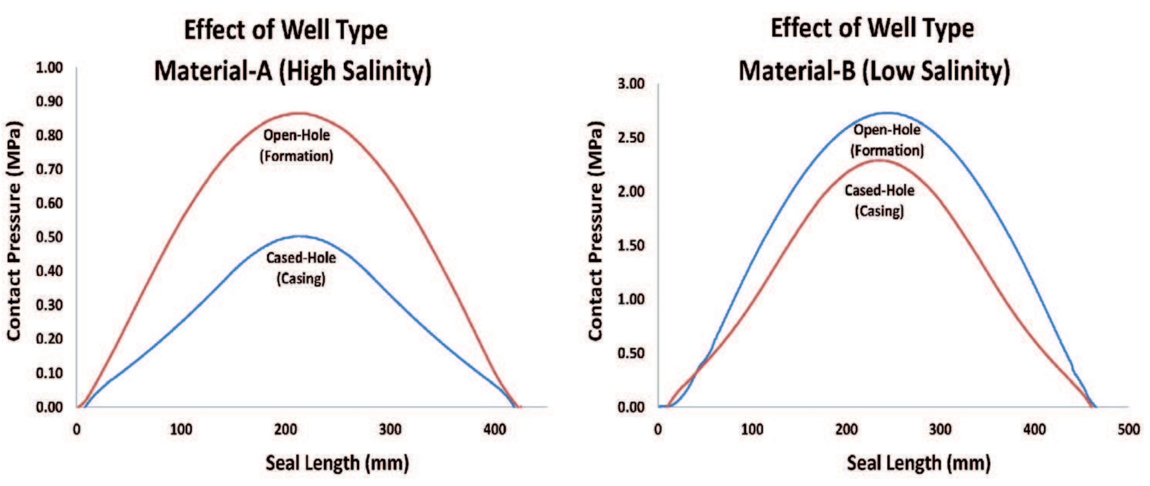

Figure 10.
Effect of well completion type on seal contact pressure; material-A, high salinity, 16 days of swelling; material-B, low salinity, 9 days of swelling.

this in a graphical format for material-*A* after 16 days of swelling in saltwater of higher concentration, and for material-*B* in low concentration solution after 9 days of swelling. These simulation results are in good agreement with actual behavior in oil wells. In open-hole configuration, when elastomer is in direct contact with rock formation, there is higher contact friction due to larger surface roughness of the formation; sealing pressure is therefore higher. For cased-hole completions, the elastomer seal makes contact with the outer casing, which is smooth and has much better surface finish compared to the formation. The lower friction coefficient yields lower sealing contact pressure.

5.8 Selection of appropriate seal

Three factors are critical in proper selection of swell packer or elastomer type in actual oil or gas wells: rate of swelling, as it influences how early full sealing is achieved and the well goes into production; magnitude of seal contact pressure, as it is needed to withstand the differential pressure in the well; and durability (long-term integrity) of the elastomer seal. On the basis of the various simulation results described above, some significant observations can be made about the proper choice of elastomer seals for actual oil well conditions: (a) If the well is a higher-salinity type, magnitude of swelling would be small, and ensuing seal pressure would be low. This seal will not be effective against large differential pressures. Furthermore, rate of swelling will be low, requiring longer well completion time, leading to time and cost overruns. (b) It appears that larger seal length yields higher sealing pressure. However, very large seal length is not practical: longer packers will be more costly, and their deployment in the wells would be more difficult. A much better design would be to have a series of well-spaced elastomer sections on the steel tubular rather than a single-element seal of very large length. (c) Seals of larger thickness will naturally generate larger pressures as they will fill the small annular gap quickly. Nevertheless, deploying a large-thickness packer to the target location in the well can cause obstruction related problems. A minimum amount of annular clearance has to be kept to insert measurement and remediation tools when needed. If quick water shutoff is required, fast swelling elastomer under the given temperature and salinity conditions should be used with an optimally large seal thickness. Optimum packer design needs a judicious balance of elastomer type (fast-swelling) and a seal thickness that is not too large. (d) In the case of an open-hole completion, roughness of the rock formation helps generate higher contact pressure; elastomers that are not fast-swelling may be used to good effect.

6. Conclusions

Finite element simulations have been carried out to investigate sealing performance of downhole applications, for two different swelling elastomer materials that are kept in low and high salinity brine solutions. Required experimental data about swelling and compression tests is reported in Chapters 3 and 7. Finite element simulations are conducted to study the performance of elastomer seals (contact pressure) under different parameters such as well completion type (open-hole or cased-hole), seal configuration (length, thickness), downhole conditions (saltwater concentration, temperature, differential pressure), swelling time, and compression ratio. Contact pressure increases with the amount of swelling (or swelling time), at a faster rate in the first few days, and more gradually later on. Pressure curves are higher for low-concentration brine. Seals of larger length yield higher contact pressure. Larger values of compression ratio (not necessarily thicker seals) generate higher sealing pressure. Higher pressures are observed in the case of the elastomer seal swelling against rock formation (open hole) rather than an outer steel casing (closed hole).

This investigation can benefit petroleum engineers in proper selection of elastomer type and seal geometry for existing conditions in an oilfield. Reported results can also help in performance assessment and design improvement of swelling elastomer seals and packers.

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