Technical Report

Evaluation of the Sealability of OCTG Premium Joint Under Rapid Internal Cooling in CCS Wells

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Abstract

Oil Country Tubular Goods (OCTG) are commonly used in CO_2 injection operation in CCS wells. The operation is occasionally suspended for various reasons such as maintenance or accidents. In such suspension, the inner surface of OCTG suffers rapid cooling due to the Joule-Thomson effect. This gives rise to a concern that the OCTG connection, especially the metal-to-metal seal, would be negatively affected by internal cooling. To evaluate the impact, Finite Element Analysis (FEA) and small-scale lab experiments were conducted. It was confirmed by FEA that the seal integrity could be maintained under internal cooling while its contact intensity was lowered. In lab experiments, it was observed that the sealing performance of grease at low temperature varied with the type of grease.

1. Introduction

As we are experiencing the influence of climate changes even in our daily lives, we now understand that realizing carbon neutrality is an urgent task for humans. The industries are working in various ways to realize carbon neutrality; one technique that is particularly promising is carbon dioxide capture and storage (CCS), which means collecting CO_2 on the ground and storing it in underground storage sites almost permanently.

With regard to CCS, although there are various CO_2 emission sources and capture methods and the characteristics of storage sites in which CO_2 is contained vary, one common feature is drilling wells from the ground to underground storage sites and injecting CO_2 into the wells.

In such wells, oil country tubular goods (OCTGs) are used to inject CO_2. As the name indicates, OCTGs are steel tubes used for wells for taking out petroleum and natural gas. General OCTGs are shipped as approximately 10-meter-long steel tubes and they are connected in fields by tightening the threaded tube ends.

Considering the purpose of OCTGs, leakage of oil and gas flowing in the tubes to the outer surfaces via the connection must be avoided at all costs. Therefore, OCTG connections have been designed to retain high sealability.[1, 2]

Similarly, for CCS wells, the sealability of connection needs to be secured to prevent CO_2 leakage and the sealing mechanism of OCTG connection is considered to work effectively as well. Meanwhile, although it is known that rapid internal cooling can occur during CCS well operations, this phenomenon is not seen in usual oil and gas development. It cannot be said that the impact of such rapid internal cooling on the sealability of OCTG connection had been sufficiently evaluated.

This study investigated the impact of internal cooling on the sealability of OCTG connection from macroscopic and microscopic perspectives with finite element analysis (FEA) and also using a small-scale tester.

This paper briefly describes the basic structure and functions of OCTG connection in Chapter 2 and introduces issues of connection in CCS wells in Chapter 3. Chapter 4 outlines how this study was conducted and shows its outcomes. Finally, Chapter 5 summarizes the study.

2. Structure and Sealing Mechanism of OCTG Connections

Although there are various types of OCTG connections, joints following the standard of the American Petroleum Institute (API)[3] are widely used. Such types are called “API joints.”

In addition to API joints, various manufacturers’ proprietary

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joints are also available. Among such joints, premium joints (PJs) having metal-to-metal seals have high sealability. Nippon Steel Corporation has also worked on the research and development of PJs and the outcomes have been incorporated into the high-performance premium joints “VAM®21” and other products.[4)]

2.1 Basic structure of PJs

Figure 1 illustrates the typical structure of a PJ. In this example, the male threaded portions (PIN) provided at both ends of the OCTGs are connected to the female threaded portions (BOX) processed at both ends of short tubes called “coupling.” The joint in this combination is called a “threaded and coupled joint (T&C joint).” There is another type in which PIN is provided at one end of the OCTG and BOX is provided at the other end to directly connect one OCTG to another. This type is called an “integral joint.”

As the detailed structure, each PIN and BOX have a shoulder and metal-to-metal seal, in addition to the threaded portion. The shoulder works as a stopper when the PIN and BOX are connected and determines the relative position of the PIN and BOX.

The PIN and BOX have axisymmetric contact surfaces and they form metal-to-metal seals. The PJs’ metal-to-metal seal prevents fluid from passing through once the contact surfaces engage with each other. The seal diameter of PIN is slightly larger than that of BOX according to their design. Thus, the PIN and BOX have to be elastically deformed to be engaged. The difference of the seal diameters between the PIN and BOX is called “interference.” Without interference, the seal surfaces of the PIN and BOX are only in geometric contact and thereby, if they are subject to a high-pressure fluid, a cavity is easily created to allow the fluid to leak. On the other hand, if the interference is too high, the seal surfaces may get damaged due to sliding of the contact surfaces. Accordingly, setting an appropriate interference is very important in designing PJs.

Figure 1 shows the structure of a typical PJ. Detailed dimensions and geometric shape vary from PJ type to type.

2.2 OCTG connections and lubricants

Lubricants cannot be ignored in the discussion of OCTG connection. When OCTG connection made up, compound grease called “dope” is applied. The grease works to reduce friction between the sliding surfaces and prevent galling.

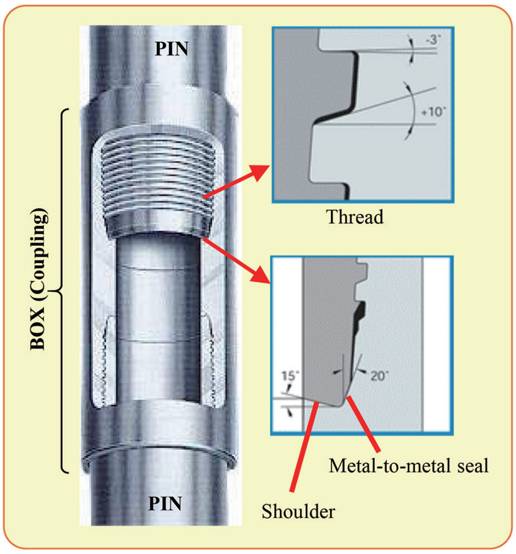


Fig. 1 Typical structure of PJ[4)]

Dope’s other function is to enhance the sealability of metal-to-metal seals; dope is filled in the micro cavities, which is supposed to exist between the seal surfaces of the PIN and BOX after they have been engaged.[5)]

There are various types of dope: API dope is produced according to the API standard[6)]. Environment-friendly dope called “yellow dope” inflicts less harm on the marine environment. In addition, in recent years, dope-free technology in which no dope is applied and solid lubricating film is formed on the surfaces of the connection is becoming increasingly popular.

2.3 How to evaluate PJ

OCTG connection—PJ, in particular—is characterized by high sealability. In extreme cases, it has gas sealability of up to 140 MPa or higher. In addition, in oil and gas wells, various types of load, such as tension and compression in the axial direction and internal and external pressure, are applied depending on the circumstances. Accordingly, in the evaluation of sealability, it is necessary to confirm that no leakage occurs under various combined loads.

For such evaluation, full scale connection is used in general and the test procedure is agreed in the industry as API recommended practice.[7)] Meanwhile, because testing using full scale connection consumes a lot of labor, resources, and time, connection evaluation is often done via FEA and other numerical methods.

3. Issues at CCS Wells

3.1 Cooling inside wells by the Joule-Thomson effect

In this section, the well environment during CCS operation is considered.

Although high-pressure CO_2 is continuously injected into the underground reservoir though CCS wells, it is impossible to continue injecting CO_2 throughout the life cycle that is assumed to be a few decades. The injection is stopped due to maintenance and inspection and the operation may be suspended due to various problems such as blowout.

In such a case, the high-pressure CO_2 remaining in the OCTGs will be released into the atmosphere and the CO_2 expands as the pressure rapidly decreases. At this time, its temperature changes because the internal energy works on the intermolecular force. This phenomenon is called the “Joule-Thomson effect” and it is known that CO_2 brings particularly large temperature drops.[8, 9)]

Simulation of an actual CCS well showed that the section near the safety valve on the bottom of the well is cooled to close to −80°C.[10)] Such internal cooling is not assumed for regular petroleum gas production wells. Therefore, no special consideration was given to such low temperature in conventional PJ development. Accordingly, to apply existing PJs to CCS wells, it is necessary to properly understand the impact of internal cooling on the PJs’ sealability.

3.2 Decrease in interference contact force due to rapid internal cooling

The impact of rapid internal cooling on PJs needs to be considered from both macroscopic and microscopic perspectives as shown in **Fig. 2**.

With regard to macroscopic impact, there is concern regarding the decrease in the interference as a result of thermal contraction of the PIN. As described in Chapter 2, the seal diameter of the PIN of PJs is slightly larger than that of the BOX, which produces interference contact force.

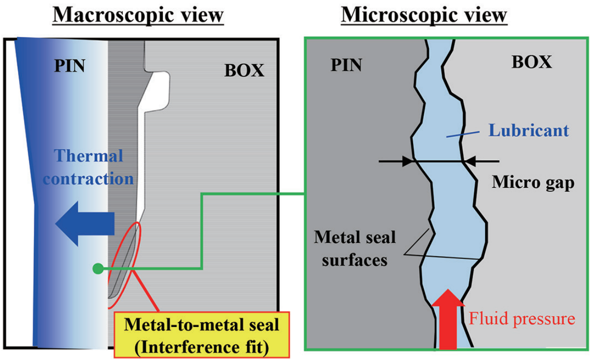


Fig. 2 The impact on sealability of PJ by rapid internal cooling[14)]

However, once the inner surface is rapidly cooled, the temperature of the PIN drops first which reduces the seal diameter due to thermal contraction. If the temperature and dimensions of the BOX have not yet been affected, the interference becomes smaller; in the worst case, the contact between the seals may be lost.

To prevent this, it is important to know how much interference is maintained in the event in which the temperature gradient between the inner and outer surface is generated due to rapid internal cooling.

3.3 Lubricant property changes at extremely low temperatures

In this section, the microscopic impact is considered. As described above, micro cavities between seal surfaces are filled with dope and that greatly enhances the sealability.

In this state, the dope is considered to sustain its fluidity; the dope is assumed to follow relative micro movement that occurs between the seals due to changes in loads applied to the PJs in a well.

However, if the seal is exposed to an extremely low temperature, the dope may congeal and may lose its fluidity. In such a case, the dope cannot follow relative micro movement that occurs between the seal surfaces, and this allows micro cavities to be formed between the seal surfaces, which may cause gas leakage.

Whether this concern is reasonable has not been sufficiently studied so far. Some researchers recommend using dope-free connections because they claim that dopes are not suitable for CCS wells.[11)] To study the validity of their claim, it is necessary to understand the rheological properties of lubricants at extremely low temperatures.

4. Sealability When the Inner Surface Is Cooled

4.1 Verification of interference contact force via FEA

Among the issues described in Chapter 3, the impact of rapid internal cooling on interference was studied via FEA.

4.1.1 Evaluation of connection sealability via FEA

As described in 2.3, FEA is widely used to evaluate the PJ's performance and knowledge such as how to model a connection has been accumulated. In our analysis, FEA techniques of PJ for petroleum gas development were applied[2)] regarding meshing, loading, and evaluation of sealability.

A 2D axisymmetric model was used for analysis and the metal-to-metal seal contact intensity was used as an index for sealability. This value is obtained by integrating the seal contact pressure along the longitudinal surface. In addition, as shown in **Fig. 3**, by applying the combined loads of axial force and pressure along the yield ellipse of the pipe body, it was evaluated whether the sealability would be maintained under various load conditions that may occur inside wells.

This approach complies with the concept on the loading scenario in API RP 5C5[7)].

4.1.2 Measurement of thermal contact resistance

Meanwhile, to incorporate rapid internal cooling and temperature gradients into the analytical model, the impact of heat transfer needed to be understood. Thermal conduction at the contact surfaces between the PIN and BOX may greatly affect the analysis results. As described in 3.3, because the area between these contact surfaces is filled with dope, thermal conduction via such dope needed to be taken into the model.

To study this, an actual OCTG material of 25Cr steel and commercially-available yellow dope were used to measure thermal contact resistance with a guarded heat flow meter technique according to ASTM1530-06. **Figure 4** shows the normalized measurement results. The figure shows that the higher the contact pressure, the smaller the thermal resistance.

4.1.3 Analysis condition settings

As the next step, concrete analysis conditions were discussed. During rapid internal cooling, the temperature inside the OCTGs becomes different from that of outside, which may reduce the seals' interference.

In our analysis, the temperature of the inner surface of the tube was set to −80°C and that of the outer surface was maintained at

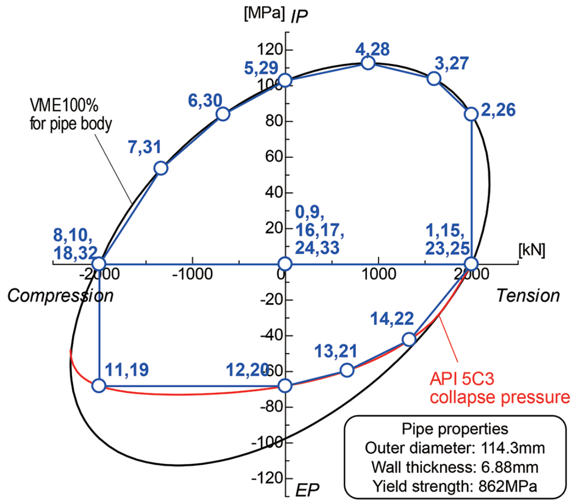


Fig. 3 Load points and loading sequence[14)]

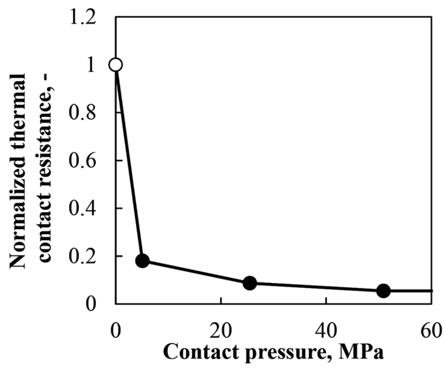


Fig. 4 Normalized thermal contact resistances applied in the FEA[14)]

25°C such that the effect would be the largest; through steady-state thermal conduction analysis, the temperature distribution inside the PJ was calculated. **Figure 5** shows the thermal transfer at the joint portion.

In addition, before cooling begins due to the expansion of CO_2, in an actual well, various loads may be applied to the OCTGs in the well. Accordingly, the loads shown in Fig. 3 were applied before and after the cooling in the simulation.

4.1.4 Analysis results

Figure 6 shows the temperature distribution in the PJ under internal cooling. The result shows that metal-to-metal seal surfaces can be cooled down to −38.9°C.

Figure 7 shows the changes in the metal-to-metal seal contact intensity through the load sequence before and after the cooling. The vertical axis is the seal contact intensity that was normalized with the value when made-up as 1 and the horizontal axis shows the loading sequence of the combined loads. Step 17 in the horizontal axis is the point of internal cooling. Before and after this step, the combined loads shown in Fig. 3 were applied.

The broken line in Fig. 7 shows the results when only the loads were applied without internal cooling and the results show that the internal cooling decreases the contact intensity. Meanwhile, the contact intensity is retained throughout the sequence and thus it is difficult to consider that internal cooling results in the complete loss of the sealability.

It is desired to improve the FEA's predictability of sealability through comparison with the results of an actual full scale test at extremely low temperatures.

4.2 Verification of the sealability at extremely low temperatures using a small-scale model tester

To evaluate the microscopic impact on sealability by the dope which is cooled to extremely low temperatures, a small-scale model tester was used.

4.2.1 Tester and specimens

Figure 8 illustrates the small-scale model tester used this time. This tester is equipped with a biaxial actuator that can apply compressive load in the axial direction and rotational torque simultaneously and independently. The equipment can also evaluate the sliding performance and sealability of the specimen by applying high-

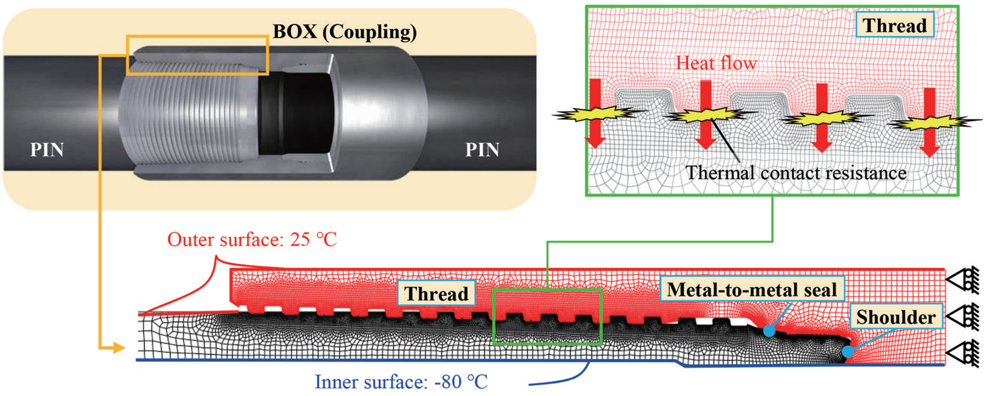


Fig. 5 Temperature gradient modelled by FEA[14)]

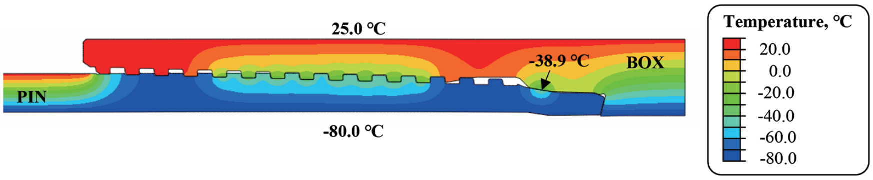


Fig. 6 Temperature distribution in the PJ under internal cooling[14)]

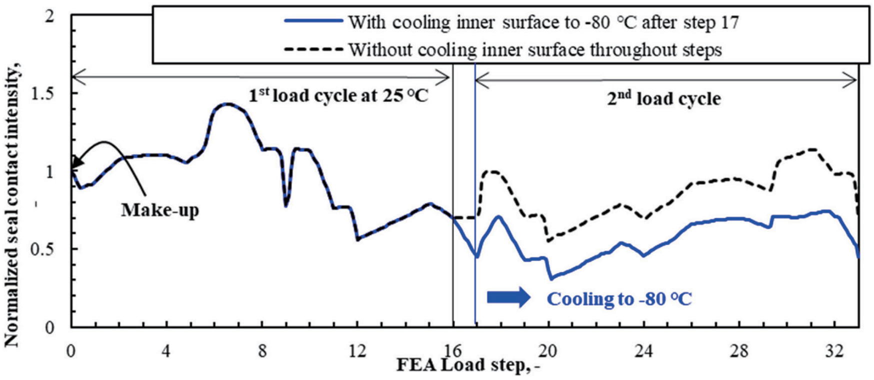


Fig. 7 Normalized seal contact intensity under combined load and inner cooling[14)]

pressure gas from under the specimen.[12)] In addition, placing a heating furnace or thermostatic bath around the test piece allows testing at various temperatures.[13)]

The specimens consists of upper and lower specimens; the upper specimen has a curved surface that simulates the PJ's metal-to-metal seal surface at its lower end. This contacts with the cone plane of the inner surface at the upper end of the lower specimen so as to form a metal-to-metal seal. As shown in **Fig. 9**, the PJ's seal surfaces are contacting with each other while helically sliding. As it simulates actual PJ's make-up, helical sliding can be applied to the specimens when the seal surfaces are brought into contact with each other.

For the specimens, stainless steel SUS420-J2 was used. **Table 1** lists the combinations of the lubricant and surface treatment for each specimen. As the lubricants, API and yellow dopes were used as well as the dope-free solution.

4.2.2 Test condition settings

As described in 4.1.4, when the inner surface of the tube was set to −80°C and the outer surface was set to 25°C, the temperature of the contact surfaces at the seal was found to be −38.9°C in a steady state.

For the sealing test at extremely low temperatures, the target temperature was determined to be −40°C or lower. A bath filled with dry ice was placed around the test piece for cooling. During internal pressure testing, it is impossible to measure the test piece's inner surface temperature. Accordingly, as shown in **Fig. 10**, thermocouples were attached to the inside and outside of a setting piece to see temperature changes. As shown in **Fig. 11**, the temperature of the setting piece's inner surface reached −40°C after cooling for 20 minutes and the temperature was held below −40°C for more than 60 minutes. Based on this result, the pre-cooling time in the sealing test at extremely low temperatures was determined to be 30 minutes.

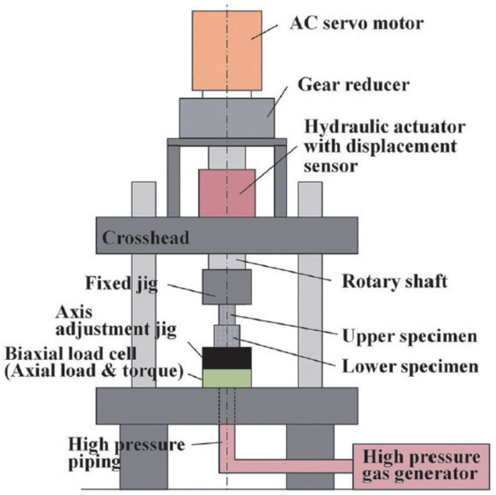


Fig. 8 Schematic of testing setup[14)]

Table 1 Combinations of surface treatments and lubricants

No.	Surface treatment		Lubricant
	Upper specimen	Lower specimen	
1	Cu plating	As machined	Yellow dope
2	Cu plating	As machined	API dope
3	Special plating	As machined	Dope free

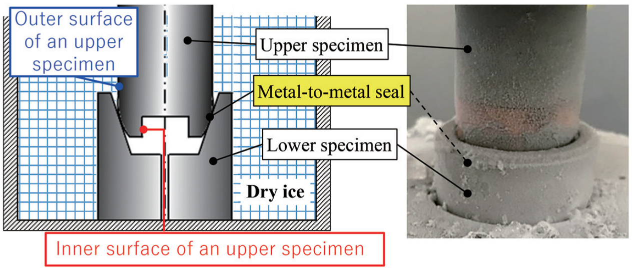


Fig. 10 Cooling by dry ice[14)]

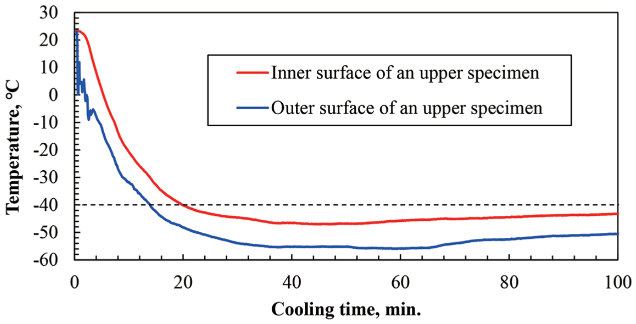
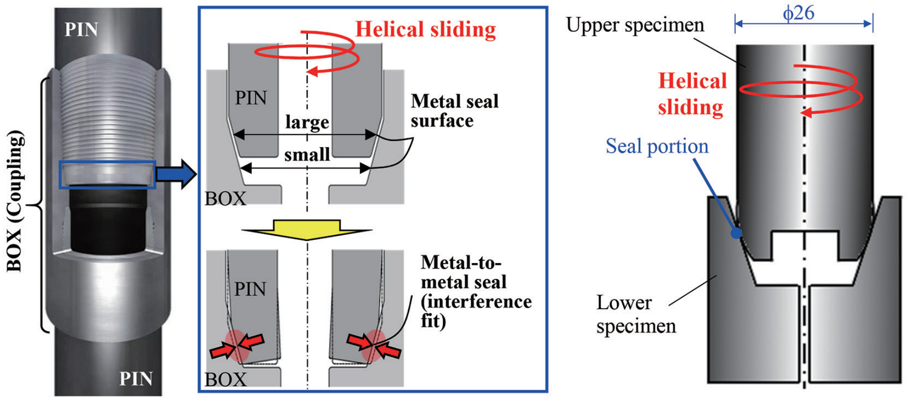


Fig. 11 Temperature of inner and outer surfaces of the specimen[14)]



(a) Premium threaded connection

(b) Specimen for gas tightness tests

Fig. 9 Schematic of metal-to-metal seal of PJ and test specimen[14)]

Figure 12 shows the test sequence. First, the seal surfaces were brought into contact at ambient temperatures while having them helically sliding. This is because joints are made up at ambient temperatures in actual CCS wells. The circumferential velocity at the contact surfaces was set to 24.7 mm/s and displacement of 0.17 mm/s was given in the axial direction at the same time so as to achieve helical sliding. Then, when the compressive force reached 7.5 kN, the rotation was stopped. These values simulated those at the actual PJ's metal-to-metal seal. FEA simulating this test showed that the mean contact pressure of the seal surfaces at this time is as high as 687 MPa.

After that, after cooling for 30 minutes as described above, gas was injected into the lower specimen and the pressure was continuously increased until the gas started leaking through the seal. The gas was a mixture of 95% nitrogen and 5% helium and a helium leak detector placed outside the specimen was used to detect gas leakage. The gas pressure when the gas started leaking is considered as an index for sealability; that is, when leakage occurs at lower pressure, the sealability is low and when the leakage does not occur until the pressure becomes high, the sealability is high.

Tests at ambient temperatures and at 180°C were also conducted to compare the results with test results at extremely low temperatures. 180°C is the temperature in high-temperature testing with the OCTG connection evaluation procedure defined by the API.[7)]

4.2.3 Test results

Figure 13 shows the sealability test results. To see the differences from the sealability at ambient temperatures, the figure shows the relative sealability that was obtained by dividing the leaked pressure in each temperature range by the value at ambient temperatures.

As shown in Fig. 13, for the API dope, the sealability deteriorates at extremely low temperatures while for the yellow dope, the sealability improves at extremely low temperatures. Meanwhile, the sealability deteriorates at high temperatures for both types of dopes.

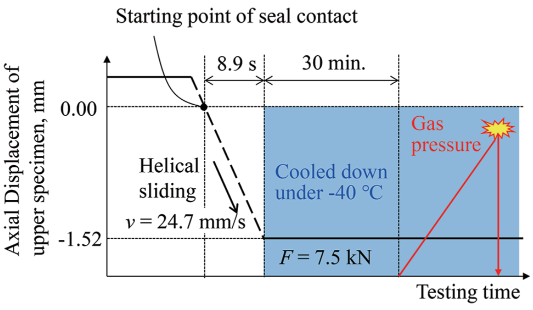


Fig. 12 Sealability evaluation test sequence[14)]

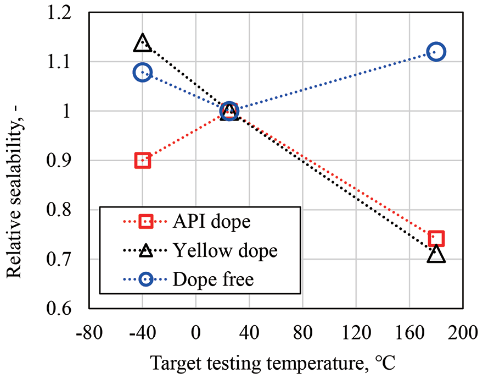


Fig. 13 Sealability evaluation test results[14)]

On the contrary, when the solid lubricating film was applied, the sealability is the lowest at normal temperatures and it improves both at extremely low temperatures and high temperatures.

4.2.4 Dynamic viscoelasticity measurement

Based on the results in 4.2.3, to understand differences in the tendency of changes in the sealability when the API and yellow dopes were cooled, the dynamic viscoelasticity properties were measured to investigate the temperature dependence of the dynamic viscoelasticity for each lubricant.

For the measurements for the dopes, MCR302 manufactured by Anton Paar and 25-mm parallel plates were used. The measurements were conducted in nitrogen atmosphere at a frequency of 1 Hz and at a temperature increase/decrease speed of 3°C/sec.

For the solid lubricating film, RSA-III manufactured by TA Instruments was used. The storage modulus (E') and loss modulus (E") were measured in nitrogen atmosphere at a frequency of 1 Hz and at a temperature increase/decrease speed of 5°C/sec.

All types of measurements were started from 25°C; the specimens were first cooled to −80°C and then the temperature was increased to 25°C.

Figures 14 and **15** show the measurement results. Regarding the API dope, the viscosity rapidly increases at −10°C or lower and the dope loses its fluidity. Meanwhile, the changes in the viscosity of the yellow dope are rather mild; the fluidity is considered to have been retained in the temperature range in this lab experiment. With regard to the solid lubricating film, the viscoelasticity properties exhibited few changes throughout the temperature range.

Based on the results above, it can be considered that the API dope's sealability deteriorated at extremely low temperatures because the fluidity was lost as a result of rapid increase of the viscosity and thereby the dope could not follow microscopic relative movement of the seal surfaces, forming micro cavities.

Meanwhile, regarding all lubricants for which the dynamic viscoelasticity was measured, the trajectory when the temperature decreases almost matches that of the temperature increase. Accordingly, the impact of cooling on the dope's sealability seems to be reversible. In other words, even if the sealability temporarily deteriorates due to cooling, once the temperature returns to normal, the dope's sealability may also return to its original state.

5. Summary

The sealability of PJs in CCS wells—the behavior under internal cooling that occurs as a result of CO_2 pressure drop in OCTGs, in particular—was studied.

Regarding the interference contact force at the seals, it was confirmed via FEA that temperature differences between the inside and outside of OCTGs lower the contact intensity. The level of contact intensity required to retain the sealability needs to be evaluated in the future through comparison with the results of full scale testing at extremely low temperatures.

In addition, the impact of changes in the lubricant properties at extremely low temperatures on the metal-to-metal seals' sealability was evaluated using a small-scale model tester. The results demonstrate that the behavior varies between lubricant types.

Furthermore, the dynamic viscoelasticity of the lubricants was measured. Based on the results, the deterioration of the sealability for the API dope at low temperatures seems to be caused by loss of

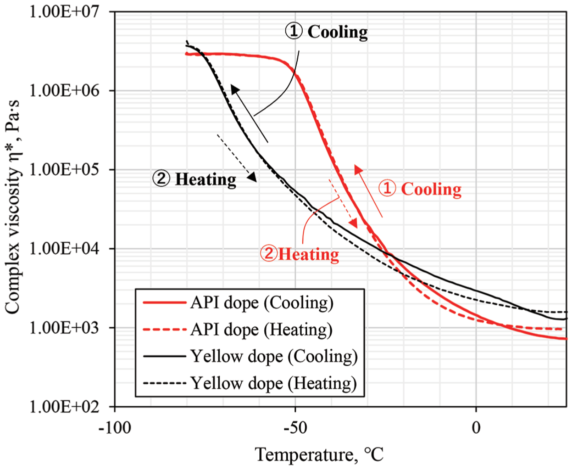


Fig. 14 Dynamic viscoelasticity measurement results of dopes[14)]

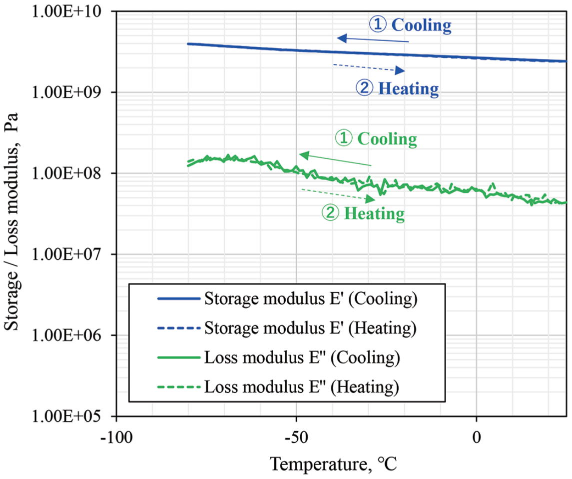


Fig. 15 Dynamic viscoelasticity measurement result of dope-free coating[14)]

the fluidity due to rapid increase in the viscosity.

Meanwhile, regarding the yellow dope, because the fluidity was retained at a certain level even at low temperatures, the sealability is well retained.

For all cases, the impact of cooling is reversible; even if the temperature in CCS wells temporarily lowers to extremely low due to problems during operations, when the temperature returns to ambient temperatures, the sealability seems to return to the original state.

Acknowledgments

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