ISSN 1392–1207. MECHANIKA. 2016 Volume 22(4): 308–312

The effects of temperature on the mechanical and tribological properties of progressing cavity pump NBR stator rubber

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http://dx.doi.org/10.5755/j01.mech.22.4.16162

1. Introduction

The screw pump production system is popular in high viscosity mining due to its flexibility, reliability, strong corrosion resistance, and high volumetric pump efficiency [1]. The swelling resistance, mechanical properties, and wear resistance of stator rubber, the key component of screw pumps, directly affects the service life and performance of crude oil screw pumps. Consequently, it is important to select an appropriate material to improve screw pump efficiency and service life [2].

Temperature significantly affects the service life of screw pumps' rubber stator. On one hand, bearing the high temperature and high pressure environment under well; on the other hand, the friction between lifting fluid and the stator rubber generates heat, so that the rubber's temperature rises [3]. High temperatures cause the rubber strator to physically change, making the rubber age prematurely. As a result, the pump's working performance is adversely affected; the rubber may fall off and damage the pump even further. Sombatsompop [4] found that with an increase in temperature, rubber swelling increased. When there was a small amount of rubber and it maintained a symmetrical swelling shape, rubber swelling increased. Coronado [5] studied the effects of different biological diesel temperatures on nitrile rubber hoses, and found that temperature has little impact on rubber quality loss. Li Ping et al. [6, 7] found that swelling increased under these same conditions when the temperature rose. With a temperature increase, rubber tends to experience chemical degradation, cross linking, and fracture, which changes the rubber's properties. Wei et al. [8] found that the rubber's dynamic performance without aging decreased as the temperature increased. Persson et al. [9] found that as the temperature increased, the rubber elastic modulus decreased and the spacing of wear cratering increased. The research of Baeka et al. [10] showed that under high temperature, tear strength reduced due to accelerated rubber aging. The wear rate increased significantly and the wear rate displayed a wide change range periodically.

Little research has been conducted on the effects of temperature on stator rubber in regards to crude oil medium performance. Such research would likely have important practical significance in the oil industry. This study investigates the swelling, mechanical, and tribological behaviors of acrylonitrile-butadiene rubber (NBR) in a crude oil medium under different temperature conditions. It also provides a basis for selecting screw pump stator rubber material to prolong the pump's working life.

2. Experimental

2.1. Materials

This experiment examined three NBR samples with different acrylonitrile contents: 18 wt-% (designated N18), 26 wt-% (N26), and 41 wt-% (N41). Which were commonly used as the stator rubbers in screw pump. In order to better study the relation between masterbatch of rubber and rubber's performance, three NBR samples had the same component, the mass fraction of component was the same except carbon black, because the mass fraction of carbon black was adjusted to ensure the same hardness of three vulcanized NBR samples. The main components of NBR rubbers and their mass fractions possessed the following qualities: crude rubber 100, ZnO 2.5, stearic acid 2, dioctyl phthalate (DOP) 10, sulfur 1.5, and accelerating agent 2. All NBR samples were purchased from Shanghai Redze Chemical Co., Ltd. The hardness of the samples after vulcanizing treatment was approximately 70 Shore A.

2.2. Sample preparation

Firstly, specimens of each rubber type were prepared for swelling in crude oil for 168 h. The Crude oil medium was acquired from the Shuguang oil production factory in Liaohe Oilfield. It possessed a high solidifying point, high wax, low sulfur, and low colloid content. The specimen size was 40 mm × 20 mm × 5 mm. The crude oil immersion temperatures were 25°C, 50°C, 80°C, and 120°C respectively. The static crude oil immersion experiment used a hanging patch tester in a glass container in the JC202 thermostat (Nantong Jiacheng Instrument Co. Ltd., China). After the samples reached the desired immersion time, they were removed from the container and dipped quickly into kerosene, acetone, anhydrous ethanol, and water to remove excess oil. Then, the samples were wiped with filter paper and the swollen rubber specimens were immediately weighed in the air and in distilled water with the BS224S electrical balance with the accuracy of 0.1 mg (Sartorius, Germany).

2.3. Characterization techniques

2.3.1. Hardness & swelling test

Sample hardness was measured with the TH200 Shore durometer with an accuracy of 0.1 Shore A (Beijing Time High technology co. Ltd., China). Sample mass was weighed with weighing electronic balance with a 0.1 mg precision. The volume change rate (*VCR*) was calculated using the following equation:

$$VCR = \frac{(m_2 - m_4) - (m_1 - m_3)}{m_1 - m_3} \times 100\% \quad (1)$$

where m_1 is the sample weight in air before the swelling experiment; m_2 is the sample weight in air after the swelling experiment; m_3 is the sample weight in water before the swelling experiment, and m_4 is the sample weight in water after the swelling experiment – all in mg.

2.3.2. Tensile and tribology test

The NBR specimens' mechanical properties were tested before and after swelling by using Shanghai non-metallic material testing machine plant XQ-250 rubber strength testing machine. The specimens displayed an ASTM-B dumbbell shape, 2 mm thickness, 500 mm/min tensile speed, and 20 mm gauge length. The tensile fracture permanent deformation (TS_F) was calculated using Eq. 2; all results in this paper are the average of three or more trials.

$$TS_F = \frac{L_2 - L_0}{L_1 - L_0} \times 100\% \quad (2)$$

L_0 is the dimensioning spacing before stretching in mm; L_1 is the dimensioning spacing after tensile fracture in mm; L_2 is the dimensioning spacing that the NBR of tensile fracture which was stood for 3 minutes already.

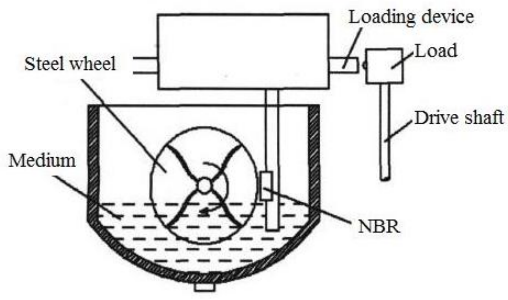


Fig. 1 Schematic of the ring- on-block wear testing machine

In accordance with mutual movement of the metal rotor and rubber stator, the tribological behavior of the NBR samples in crude oil was measured using an ring- on-block tester, as shown in Fig1 (Jinan Shidai Shijin Test- ing Machine Group Co. Ltd., China). During the test, the tester speed was 200 r/min and the time was 7200 s. Thesteady-state friction coefficient of the samples was recorded. The worn specimen was successively dipped into kerosene, acetone, anhydrous ethanol, and distilled water to remove excess oil. Samples were weighed before and after the wear experiment using an electrical balance.

2.3.3. Morphology test

Specimens were examined with a field emission scanning electron microscopy (FE-SEM, Hitachi JSM-6360, Japan). Swollen surface morphology and tensile fracture surface morphology samples were saw-cut from rubber specimens; they had sizes of approximately 8 mm × 8 mm × 5 mm, were mounted on aluminum stubs (ø25 mm × 5 mm) after cleaning, and then coated with gold in a JEOL JEE-400 Vacuum Evaporator. The swollen surface and tensile fracture surface images were magnified 500 and 200 times.

3. Results and discussion

3.1. Effect of temperature on the swelling behavior of NBR

Fig.2 shows the NBR samples' volume change rate (VCR) variants in crude oil at different temperatures. As the temperature rose, the VCR of N18 and N26 increased in a linear relationship. After swelling for 168 h at 120°C, N18 exhibited 29.13% VCR and N26 exhibited 7.14% NCR.N41's VCR decreased as the temperature rose; its VCR was almost zero at 120°C.

According to the similar dissolving principles, the more similar the rubber and solvent's solubility parameters (SP), the more easily the medium can permeate the rubber's three-dimensional network structure, thus resulting in increased swelling.N18 displayed 8.7 ～ 8.8 SP, N26 displayed9.4 ～ 9.9, and N41 displayed 10.3 ～ 10.5; the crude oil SP value in the experiment was 7.6, so N18 exhibited the largest VCR at the same temperature in crude oil, and N41 exhibited the lowest VCR.

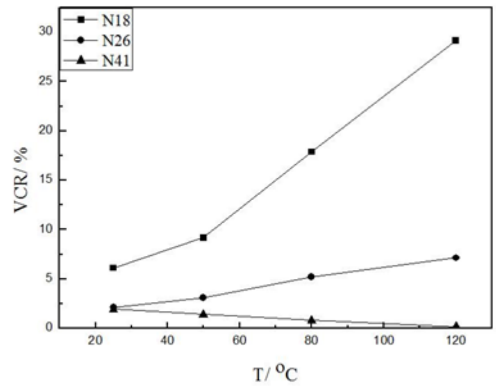


Fig. 2 The effects of temperature on the VCR of NBR

With the increase in temperature, crude oil viscosity decreased, the interactive force between particles weakened, the liquidity and the kinetic energy of crude oil molecules became reinforced [11], and the crude oil more easily permeated the rubber's three-dimensional network structure [12]. On the other hand, temperatures also prompted nitrile rubber chain elongation, rubber net structure expansion, molecule interval enlargement, and larger quantities of crude oil entering the NBR molecular structure. As a result, the volume change rates of N18 and N26 increased gradually; for N41, the volume change rate slightly decreased with rising temperatures. With increasing acrylonitrile content, the rubber molecule chain flexibility reduced. The molecular network structure expanded under high temperatures, causes chain ruptures, cross linking, the internal structure of rubber mess, the precipitates of NBR increases, resulting in reductions in rubber volume.

Fig. 3 displays N26 surface topography after swelling for 168 h at different temperatures in crude oil. The crude oil permeated the rubber's three-dimensional network from the rubber surface, and diffused inside. The N26 surface uplifted first, then uniformly; pits and precipitates increased. When crude oil reached 120°C, cracks appeared near the precipitate.

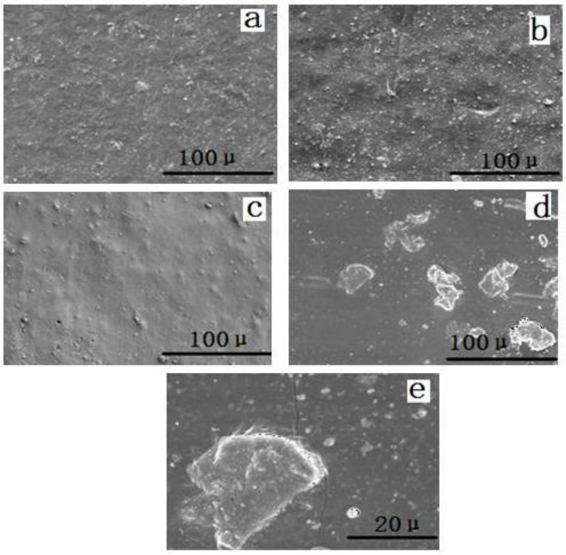


Fig. 3 Surface topography of N26 immersed in crude oil with different temperature for 168 h: a - 25°C; b - 50°C; c - 80°C; d - 120°C; e - 120°C

3.2. Effect of temperature on the mechanical behavior of NBR

Tensile strength and tensile fracture permanent deformation indicate rubber quality. Fig. 4, a shows the tension strength change curve at different temperatures for 168 h. Tensile strength depends on the chemical bond force on the main chain and the force between them. With the increase of acrylonitrile content, the nitrile groups (-CN) increased, the density of the Polar group and the molecular weights per unit area increased, and molecular spacing decreased. There are advantages to the cross linking reaction; it became more slip resistant [13], resulting in higher tensile strength. Fig. 4, a reveals that the swollen rubbers' tensile strength declined as the temperature rose. With increasing crude oil temperatures, it was possible to investigate the rubber's aging and main change ruptures. Rubber tensile strength dropped rapidly.

Fig. 4, b shows the TS_F change curves of swollen rubber at different temperatures after 168 h of crude oil immersion. As the temperature increased, the TSF curve decreased. With more acrylonitrile content, Nitrile Groups (-CN) increased, crosslinking density increased, the internal forces between the molecules of NBR became enlarged, the chain molecules became more tangled, the tensile fracture permanent deformation gradually declined, and rubber resilience decreased. When the temperature rose, more crude oil permeated the rubber, rubber size increased, the entanglement chain stretched, the crosslink band orientation fractured and rearranged, the resilience property enhanced, and the TS_F curve decreased.

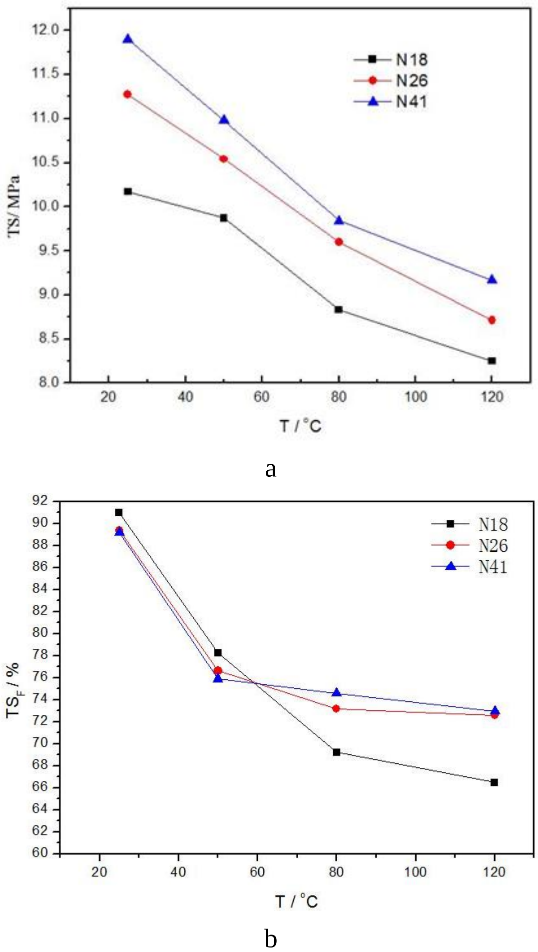


Fig. 4 Variation of tensile strength and tensile fracture permanent deformation at different temperatures

The microstructures of the tensile failure section were examined with a scanning electron microscope. Fig. 5 shows the tensile fracture morphologies of NBR at 120°C after being immersed in oil for 168 h. The figure shows that the crack extends inward from the surface. The rubber surface exhibits more cracks and potholes, and some cracks penetrate the rubber. Therefore, tensile fractures started at the surface and gradually expanded inward. The surface cracks appeared due to swelling; the actual area reduced, which bore the stretch weight. The actual tensile stress increased, so it accelerated the crack growth and decreased tensile strength.

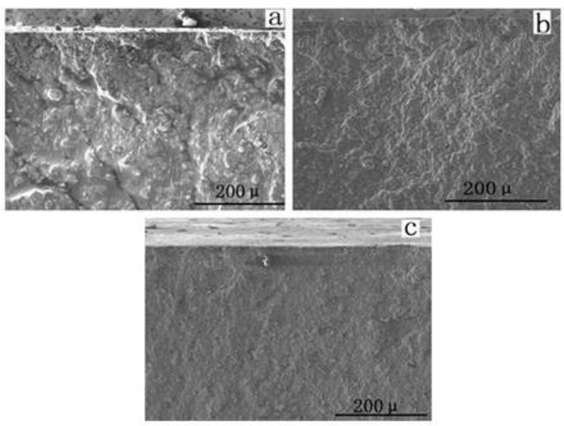
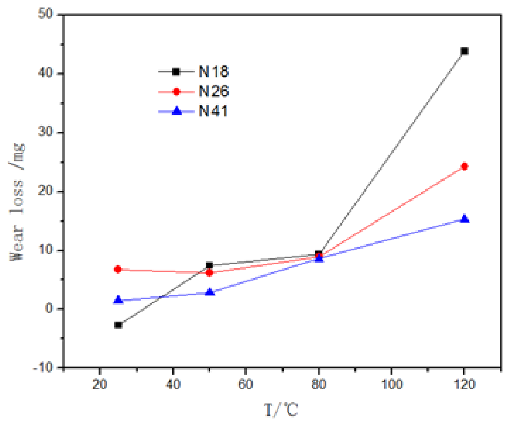


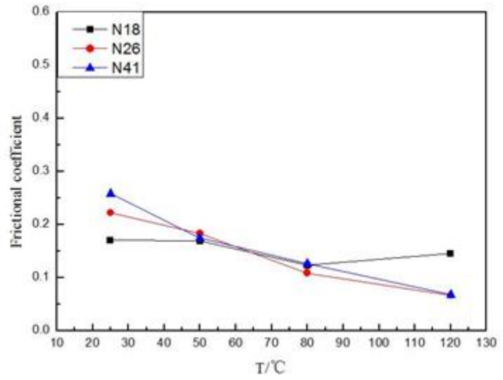
Fig. 5 Tensile failure section morphology of three NBR samples immersed in crude oil at 120°C for 168 h: a - N18; b - N26; c - N41

The high-temperature crude oil entered the rubber center because of the perforative crack, that made structure changing of NBR. Relative to N18, N26 crack depth was smaller. The actual bearing area increased, so the tensile strength increased. After analyzing the tensile fractures of N41 from SEM morphologies, it was observed that the crack and extension layer did not exist on the surface. N41 fractured overall, so the tensile strength was the highest of the three.

3.3. The effects of temperature on the tribological behavior of NBR



a



b

Fig. 6 The wear loss (a) and frictional coefficient (b) of the swelled NBR samples in crude oil at different temperatures

Fig. 6, a illustrates the wear mass of swelled NBR samples in crude oil under different temperatures. With increasing temperatures, NBR wear mass increased (especially at120°C), elastic modulus decreased, viscoelastic parameters increased, friction force increased, and wear mass increased. At 120°C, NBR aged and tear strength decreased, so the wear mass significantly increased. This was in agreement with the observation by Zuevetal [14].

Fig. 6, b shows the frictional coefficient variation of NBR samples in different crude oil temperatures. They displayed the same changing trend: the frictional coefficient decreased as the temperature increased.

During the wear process, oil molecules that had permeated the rubber's three-dimensional network structure moved from the inside to the surface under shear force. Oil molecules lubricated by forming an oil film on the rubber surface. The swelling quantity increased with the rise of the soaking temperature, and the oil film on the rubber surface became larger. There were more holes and cracks on the rubber surface after swelling; as the frictional resistance decreased, the coefficients of friction decreased. Increasing temperatures intensified the oil's molecular motion, thus increasing NBR swelling. The molecular network structure changed and molecule chains elongated and fractured.

4. Conclusions

This study investigated the effects of temperature on the swelling and tribological behaviors of NBR rubbers. Increasing acrylonitrile content had the following effects: VCR declined; with increasing temperatures, the VCR of N18 and N26 rubbers increased linearly, but the N26 change was smaller; for N41 rubber, the volume change rate slightly decreased; tensile strength increased; tensile fracture permanent deformation decreased; with the increase in temperature, the tensile strength and the tensile fracture permanent deformation of all three NBR rubbers decreased; the force of interaction between molecules enlarged. The wear mass of NBR increased with the rise of immersing temperature, but the friction coefficient declined. Therefore, high-acrylonitrile NBR has good heat resistance, swelling resistance, mechanical properties, and wearing capacity, but poor resilience.

Acknowledgements

The authors wish to acknowledge the financial support of the National Natural Science Foundation of China (Contact NO. 50875178), Liaoning Natural Science Foundation (Contact NO. 2013020039).

References

1. **Wang, S.J.; Li, F.B.; Sun, S.H.** 2005. Research on the On- line Monitoring Technology for Progressing Cavity Pumping (PCP) Operation, China Mechanical Engineering 15(14): 1276-1279.
2. **Oglesby, K.D.; Arellano, J.L.; Scheer, G.** 2003. Fourteen Years of Progressing Cavity Pumps in a Southern Oklahoma Waterflood, SPE-80919-MS.
3. **Wei, J.D.; Shi, G.C.** 1993. Influence of the temperature and viscosity of the testing medium on the volumetric efficiency of screw pumps, CPM 21(9): 15-20.
4. **Sombatsompop, N.** 1998. Swelling characteristics of some natural rubber based elastomers, Progress in Rubber and Plastics Technology 14(4): 208-225.
5. **Coronado M.; Montero, G.; Valdez, B.** 2014. Degradation of nitrile rubber fuel hose by biodiesel use, Energy 68(8): 364-369. http://dx.doi.org/10.1016/j.energy.2014.02.087.
6. **Li, P.; Chen, Y.** 2008. The influence factors of the screw pump stator rubber performance on oil filed, China Rubber Science and Technology Market 13: 23-25.
7. **Chen, Y.; Li, P.** 2008. Stator NBR of Screw pump and its swollen property research, China Rubber Science and Technology Market 12: 21-23.
8. **Wei, Y.T.; Nasdala, L.; Rothert, H.** 2004. Experimental investigations on the dynamic mechanical properties of aged rubbers, Polymer Testing 23(4): 447- 453.

http://dx.doi.org/10.1016/j.polymertesting.2003.09.006.

9. **Persson, N.J.; Tosatti, E.** 2000. Qualitative theory of rubber friction and wear, ChemPhys 112(4): 2021-2029. http://dx.doi.org/10.1063/1.480762.
10. **Baek, D.K.; Khonsari, M.M.** 2008. Fretting behavior of a rubber coating: Effect of temperature and surface roughness variations, Wear 265(5/6): 620-625. http://dx.doi.org/10.1016/j.wear.2007.12.002.
11. **Liu, Z.M.; Xiang, J.; Zhang, P.** 2014. Effect factors summarization of crude oil viscosity chang, Technology and Development of Chemical Industry 43(11): 36-39.
12. **Mathew, L.; Joseph, U.K.; Joseph, R.** 2006. Swelling behaviour of isora/natural rubber composites in oils used in automobiles, Bulletin of Materials Science 29(1): 91-99. http://dx.doi.org/10.1007/BF02709362.
13. **Zhang, K.; Wang, F.; Zhu, L.** 2013. Thermal-oxidative aging of nitrile rubber 5171 sealing element, Equipment Environmental Engineering 10(4): 1-4.
14. **Zuev, Y.S.; Chelmodeev, A.D.** 1968. Effect of temperature and concentration of aggressive media on rubber wear in an abrasive flow, Polymer Mechanics 4(1): 70-74. http://dx.doi.org/10.1007/BF00859167.

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THE EFFECTS OF TEMPERATUR ON THE MECHANICAL AND TRIBOLOGICAL PROPERITES OF PROGRESSING CAVITY PUMP NBR STATOR RUBBER

S u m m a r y

This study used immersion and wear experiments to examine the swelling and tribological behaviors of nitrile-butadience (NBR) rubber with three acrylonitrile contents (N18, N26, and N41) in crude oil at varying temperatures. The results showed that in a crude oil medium with increasing temperatures, the N18 volume change rate (VCR) increased linearly, the N41 VCR decreased slightly, and N26 experienced a smaller change. As the temperature rose, the tensile strength and tensile fracture permanent deformation of NBR reduced. As the soaking temperature rose, the NBR wear loss increased and the friction coefficient decreased. When the rubber was soaked in crude oil, swelling gradually spread from the external portion to the internal portion. Due to its compact structure, NBR with high acrylonitrile content exhibited good heat resistance, swelling resistance, mechanical properties, and wearing capacity, but a poor resilience.

Keywords: nitrile butadiene, temperature, swelling, mechanical property, tribological behavior.

Received November 06, 2015
Accepted July 04, 2016