Performance of Spiral Groove Dry Gas Seal for Natural Gas Considering Viscosity-Pressure Effect of the Gas

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Abstract. Centrifugal compressors used for transporting nature gas are usually equipped with dry gas seals. The working medium of the seal is usually the delivered gas, that is, natural gas. In this paper, the natural gas viscosity-pressure equation is derived from the Pederson mixed gas viscosity model and Lucas viscosity-pressure model, and the real gas property of natural gas is expressed by Redlich-Kwong equation. The gas film pressure governing equations proposed by Muijderman for narrow grooves are modified and solved for the seal faces. The influences of natural gas viscosity-pressure effect on the sealing characteristics, such as leakage rate and opening force, of spiral groove dry gas seal are analyzed. Results show that the viscosity-pressure effect has significant influence on spiral groove dry gas seal. This effect reduces the leakage rate but increases the opening force, compared to the situation without considering the viscosity-pressure effect. With the pressure up to 4MPa, the viscosity-pressure effect of natural gas is weak and negligible. As the pressure increases, the viscosity-pressure effect increases. At 12MPa, the relative deviations of leakage rate and opening force caused by the viscosity-pressure effect are respectively -30.6% and 1.65%. Therefore, the analyses indicate that the viscosity-pressure effect of nature gas needs to be considered when used in high pressure situation.

Keywords: Dry gas seal, natural gas, analytical method, viscosity-pressure effect

1 Introduction

In natural gas long-distance pipelines, the compressors used for transporting natural gas are usually equipped with dry gas seals as their shaft end seals. The working medium of the seal is usually the delivered gas, that is, natural gas. Typically, the natural gas in the pipeline is a mixture of different gases, and its components is different from the nature gas sources. The physical property is different from each other. Viscosity is an important physical property for dry gas seal, and this property of the nature gas is closely related to gas components, temperature and pressure. In general, when the isothermal flow is assumed, the viscosity of the natural gas is a function of composition and pressure.

Daliri, Metet et al. [1] analyzed the viscosity variation with pressure to obtain squeeze film characteristics by modified Reynolds equation and Stoke's microcontinuum. Jaw-Ren Lin et al. [2] analyzed the effects of viscosity-pressure dependency and studied the impacts of squeezed films between parallel circular plates of non-Newtonian coupled stress fluid lubrication. According to their results, the influences of viscosity-pressure dependency raise the load capacity and lengthen the approaching time of the plates. As to the viscosity-pressure effect on the dry gas seal, Song et al [3] analyzed the effect of viscosity-pressure of nitrogen gas on the sealing performance by the Lucas model. Their results show that high pressure has significant effects on the opening force, the leakage rate and the gas pressure at the spiral groove root radius. However, nitrogen is a pure gas and does not involve the viscosity relationship of a mixed gas such as the natural gas.

As to the spiral groove dry gas seal, the Pederson mixed gas viscosity model and Lucas viscosity-pressure model are used to express the natural gas viscosity-pressure effect, and the real gas property of natural gas is expressed by Redlich-Kwong equation. The gas film pressure governing equations proposed by Muijderman for narrow grooves are modified and solved for the dry gas seal faces. The dry gas sealing characteristic parameters such as the opening force and leakage rate are obtained.

2 Model description

2.1 Geometry model

The structural model of the spiral groove dry gas seal and geometric model of seal face are shown in Fig. 1. In the geometric model, r_i and r_o are the inner and outer radii of the sealing ring, respectively, and r_g is the radius at the root of the spiral groove; ω is the angular velocity of the sealing ring; p_i and p_o are the inlet and outlet pressure, and α is the helix angle.

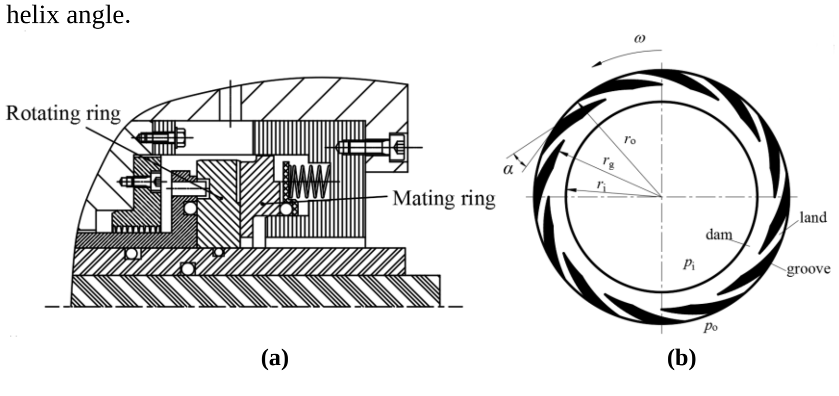


Fig. 1 Structural model of the spiral groove dry gas seal (a) and geometric model of seal face (b)

2.2 The model of natural gas viscosity-pressure effect

Lucas natural gas viscosity-pressure equation [4] has the following form,

$$\eta_o\left(p_o,T_o\right)=\frac{1+a_1{p_r}^{1.3088}}{a_2{p_r}^{a_5}+(1+a_3{p_r}^{a4})^{-1}}\eta_0 \tag{1}$$

Equation (1) is substituted to the Pederson mixed gas viscosity expression [5], which yields the model of natural gas viscosity-pressure effect:

$$\eta_{mix}=\left(\frac{T_{c,mix}}{T_{co}}\right)^{-\frac{1}{6}}\left(\frac{p_{c,mix}}{p_{co}}\right)^{\frac{2}{3}}\left(\frac{\mu}{M_o}\right)^{\frac{1}{2}}\frac{\alpha_{mix}}{\alpha_o}\frac{1+a_1{p_r}^{1.3088}}{a_2{p_r}^{a_5}+(1+a_3{p_r}^{a4})^{-1}}\eta_0 \tag{2}$$

The p_o, T_o, $T_{c,mix}$, $p_{c,mix}$ and μ are expressed as follow:

$$p_o=\frac{pp_{co}\cdot(1.0+0.031{\rho_r}^{1.847})}{p_{c,mix}\cdot(1.0+7.378\times10^{-3}{\rho_r}^{1.847}\mu^{0.5173})},\quad T_o=\frac{TT_{co}\cdot(1.0+0.031{\rho_r}^{1.847})}{T_{c,mix}\cdot(1.0+7.378\times10^{-3}{\rho_r}^{1.847}\mu^{0.5173})}$$

$$T_{c,mix}=\frac{\sum_{i=1}^{C}\sum_{j=1}^{C}n_in_j\left[\left(\frac{T_{ci}}{p_{ci}}\right)^{\frac{1}{3}}+\left(\frac{T_{cj}}{p_{cj}}\right)^{\frac{1}{3}}\right]^3\left(T_{ci}T_{cj}\right)^{\frac{1}{2}}}{\sum_i\sum_j n_in_j\left[\left(\frac{T_{ci}}{p_{ci}}\right)^{\frac{1}{3}}+\left(\frac{T_{cj}}{p_{cj}}\right)^{\frac{1}{3}}\right]^3},\quad p_{c,mix}=\frac{8\sum_{i=1}^{C}\sum_{j=1}^{C}n_in_j\left[\left(\frac{T_{ci}}{p_{ci}}\right)^{\frac{1}{3}}+\left(\frac{T_{cj}}{p_{cj}}\right)^{\frac{1}{3}}\right]^3\left(T_{ci}T_{cj}\right)^{\frac{1}{2}}}{\left\{\sum_i\sum_j n_in_j\left[\left(\frac{T_{ci}}{p_{ci}}\right)^{\frac{1}{3}}+\left(\frac{T_{cj}}{p_{cj}}\right)^{\frac{1}{3}}\right]^3\right\}^2}$$

$$\mu=1.304\times10^{-4}\left(\left(\sum_{i=1}^{c}n_i{M_i}^2/\sum_{i=1}^{c}n_iM_i\right)^{2.303}-\left(\sum_{i=1}^{c}n_iM_i\right)^{2.303}\right)+\sum_{i=1}^{c}n_iM_i$$

Where, $\{a_i, i = 1, \ldots, 5\}$ are correction factors, and P_c、T_c are the critical pressure and critical temperature obtained from the literature [5], respectively.

2.3 The real gas model of natural gas

The present research adopts the Redlich-Kwong Equation [6]:

$$p=\frac{RT}{V-b}-\frac{a}{T^{0.5}V\left(V+b\right)} \tag{3}$$

And the Gas state equation can be written as:

$$PV=ZRT \tag{4}$$

Substituting Equation (3) to Equation (4) yields:

$$Z=\left[-\frac{N}{2}+\sqrt{\left(\frac{N}{2}\right)^2+\left(\frac{M}{3}\right)^3}\right]^{1/3}+\left[-\frac{N}{2}-\sqrt{\left(\frac{N}{2}\right)^2+\left(\frac{M}{3}\right)^3}\right]^{1/3}+\frac{1}{3} \tag{5}$$

The real gas state equation is:

$$\rho=pM/ZRT \tag{6}$$

The density of the natural gas of Equation (5) and Equation (6) are expressed as:

$$\rho_{mix}=\frac{pM/RT}{\left[-\frac{N}{2}+\sqrt{\left(\frac{N}{2}\right)^2+\left(\frac{M}{3}\right)^3}\right]^{1/3}+\left[-\frac{N}{2}-\sqrt{\left(\frac{N}{2}\right)^2+\left(\frac{M}{3}\right)^3}\right]^{1/3}+\frac{1}{3}} \tag{7}$$

M, N, a, b, a_{ij}, a_i and b_i are expressed as follow:

$$M=-\left(\frac{1}{3}+\frac{p^2b^2}{R^2T^2}-\frac{ap}{R^2T^{2.5}}+\frac{bp}{RT}\right)\quad N=-\frac{2}{27}-\frac{1}{3}\left(\frac{p^2b^2}{R^2T^2}-\frac{ap}{R^2T^{2.5}}+\frac{bp}{RT}\right)-\frac{abp^2}{R^3T^{3.5}}$$

$$a=\sum_{i=1}^{n}\sum_{j=1}^{n}y_iy_ja_{ij}\quad b=\sum_{i=1}^{n}y_ib_i\quad a_{ij}=\left(a_ia_j\right)^{0.5}\left(1-k_{ij}\right)$$

$$a_i=0.42748R^2T_c^{\ 2.5}/P_cT_c^{\ 0.5}\quad b_i=0.08664RT_c/P_c$$

where, a_i, a_j are pure material parameters, y_i, y_j are the mole fraction of the mixture of the pure substances i and j; k_{ij} is the binary interaction coefficient of the i, j pure substances. These parameters can be found in the literature [6].

2.4 Modified gas film pressure governing equations

The modified gas film pressure governing equations can be obtained by substituting Equation (2) and Equation (6) to the gas film pressure governing equations which are based on Muijderman narrow groove theory [7].

For sealed dam area, the equation has the form:

$$\frac{\mathrm{d}p}{\mathrm{d}r}=\frac{6\eta_{mix}S_tRT}{\pi h^3}\frac{1}{\rho_{mix}r}\tag{8}$$

For sealed groove area, the equation can be written as:

$$\frac{\mathrm{d}p}{\mathrm{d}r}=\frac{-6g_1\eta_{mix}\omega r}{h^2}+\frac{6\eta_{mix}S_tg_7RT}{\pi h_1h^2g_5}\frac{1}{\rho_{mix}r}\tag{9}$$

S_t is the mass flow rate of the gas passing through the sealing surface; h and h_1 are, respectively, the film thickness of the groove and non-groove area, and they fulfill the relationship $h_1=h+t$, where t is the groove depth of the spiral groove; ω is the angular velocity of rotation of the sealing ring; g_1, g_5, and g_7 are the spiral groove coefficients which can be obtained from the literature [7].

2.5 Solution of gas film pressure governing equations

Boundary conditions of Equation (8) and Equation (9) are:

$$p\big|_{r=r_i}=p_i\,,\quad p\big|_{r=r_o}=p_o$$

The pressure distribution $p(r)$ of end face film is obtained, and the end face opening force F is obtained by integrating over the entire end face:

$$F=\int_{r_i}^{r_o}p\left(r\right)2\pi r\mathrm{d}r\tag{10}$$

The leakage rate S_t is expressed as:

$$S_t=\frac{\pi h^3\left(p_g^{\ 2}-p_i^{\ 2}\right)}{12\eta R_cT\ln\left(\frac{r_g}{r_i}\right)}\tag{11}$$

3 Analytical model and verification

3.1 Model verification

The results from Equation (2) and Equation (7) obtained in this paper are compared with the literature data, and they are illustrated in Fig. 2 with different pressure conditions. The results show that the average deviation of the natural gas compressibility factor, viscosity with the National Institute of Standards and Technology database (NIST) [8] are 0.344% and 1.45%, respectively.

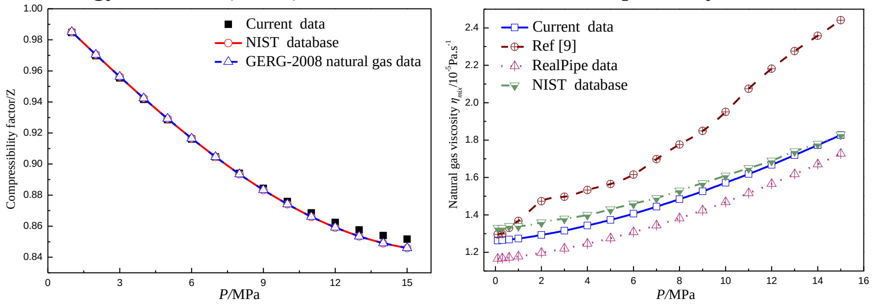


Fig. 2 The comparison between the current data and references data [9-10]

3.2 Property parameter

The parameters of natural gas components and seal face geometric are listed in Table 1 and Table 2, and these parameters are from the literature [5,11].

Table 1 Natural gas components and parameters

Component	CH_4	C_2H_6	C_3H_8	I- C_4H_{10}	N- C_4H_{10}	CO_2	N_2
Molar	0.812	0.043	0.009	0.0015	0.0015	0.076	0.057

Table 2 Basic parameters of numerical calculation

Parameter	Value	Parameter	Value
Outer radius, r_o/mm	77.78	Radius of groove root, r_{g2}/mm	69
Inner radius, r_i/mm	58.42	Spiral groove angle, α_1/°	15
Number of groove, n	12	Groove depth, h_{g1}/μm	5
film thicknesses, h_0/μm	3.0	groove width ratio , γ	1

3.3 Relative errors

As shown in Section 2.5, the leakage rate S_t and opening force F of the natural gas with the viscosity-pressure effect and the real gas property can be obtained from Equation (9) and Equation (10). Furthermore, two additional cases are analyzed, i.e., ideal gas case by setting Z=1 and viscosity-pressure effect ignorance case with constant viscosity. To express the effect of natural gas viscosity-pressure on spiral groove dry gas seals, the relative errors are used:

E_1 = ((the leakage rate of G_1-the leakage rate of G_3)/(the leakage rate of G_3))×100%.

E_2 = ((the leakage rate of G_2-the leakage rate of G_4)/(the leakage rate of G_4))×100%.

E_3 = ((the opening force of G_1-the opening force of G_3)/(the opening force of G_3))×100%.

E_4 = ((the opening force of G_2-the opening force of G_4)/(the opening force of G_4))×100%.

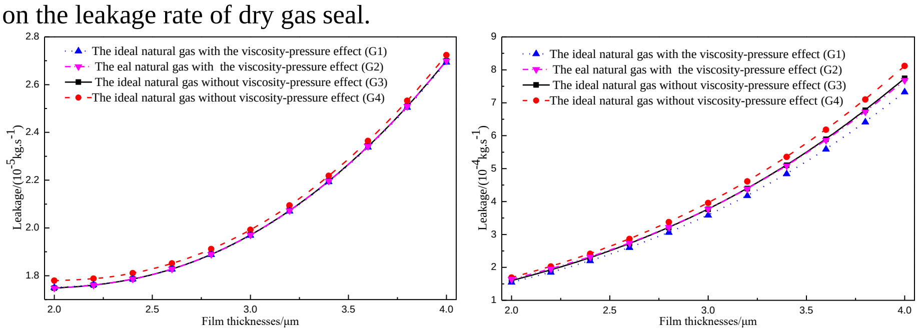
where G_1 is the ideal gas with the viscosity-pressure effect; G_2 is the real gas with the viscosity-pressure effect; G_3 is the ideal gas without viscosity-pressure effect; G_4 is the real gas without viscosity-pressure effect.

4 Results and discussion

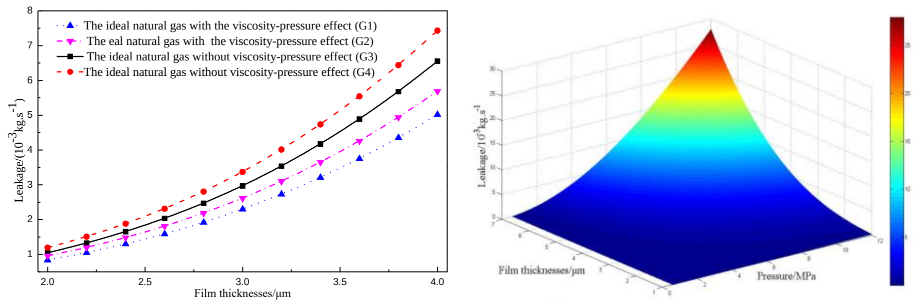
The boundary condition of internal pressure is 0.1013MPa and the external pressure p_o is respectively 0.6 MPa, 4 MPa, or 12 MPa. The sealing performance is calculated at different film thicknesses. The results are shown in Fig. 3 and Fig. 4.

4.1 Leakage rate

The leakage rates of G1 to G4 under different pressures and film thicknesses are shown in Fig. 3. It can be seen from the Fig. 3（a）-（c) that the leakage rate increases with the increase of film thickness and pressure. Fig. 3(d) is a three-dimensional (3-D) map of pressure, film thickness, leakage rate, from which it can be seen that the interaction between the leakage rate and the two parameters, i.e. the film thickness and pressure is obvious. When the pressure reaches 0.6 MPa, the averages of E_1, E_2 are, -0.070% and -1.193%, respectively. Negative values of E_1 and E_2 indicate that the viscosity-pressure effect reduces the leakage rate. The reason is that as the pressure increases, the viscosity increases and the gas flow decreases, which results in the decrease in the leakage rate. The $|E_2|$, where $|\ |$ stands for absolute value, is greater than the $|E_1|$ indicates that the viscosity-pressure effect induces a stronger influence on real natural gas spiral groove dry gas seal compared with the assumptions of ideal gas. When the pressure reaches 12 MPa, the averages of E_1 and E_2 are -28.622% and -30.6%, respectively. The results show that the viscosity-pressure effect has influence on the leakage rate of dry gas seal.



（a）0.6 MPa （b）4 MPa

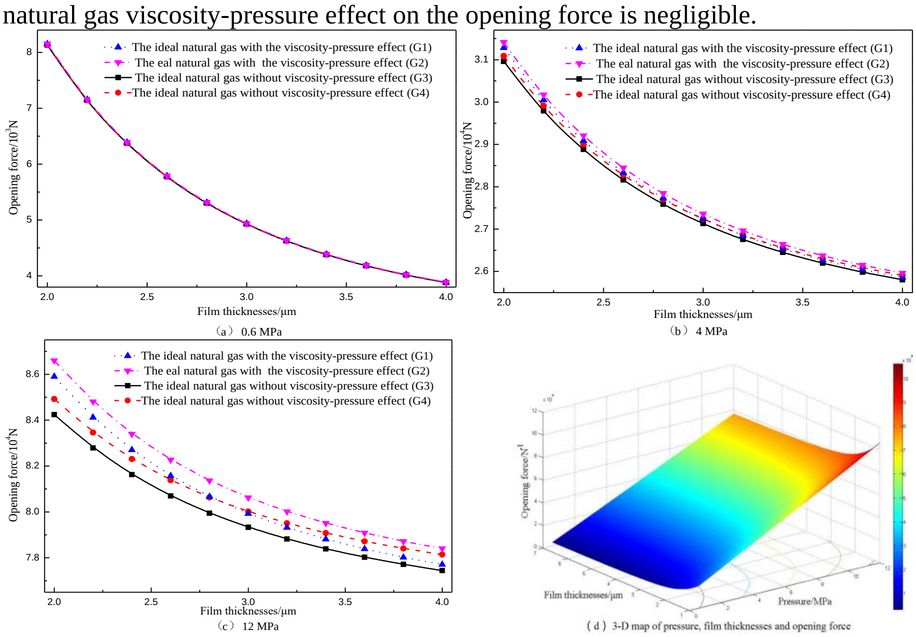


（c） 12 MPa （d） 3-D map of pressure, film thicknesses and leakage

Fig. 3 Leakage at different film thicknesses and different p_o

4.2 End face opening force

The opening force of G_1 to G_4 under different pressures and film thicknesses are shown in Fig. 4. The result in Fig. 4（a）-（c） show that the opening force increases with the increase of pressure but decreases with the increase of the film thickness. From the three-dimensional (3-D) map of pressure, film thickness and opening force, it can be seen that the effect of pressure on the opening force is more obvious compared with the film thickness. E_3, E_4 is greater than 0, indicating that the viscosity-pressure effect of natural gas raises the opening force. At 0.6 MPa, the opening forces of the G_1 to G_4 almost overlap. As the pressure increases, the relative error of the opening force of G_1 to G_4 increases. When the pressure reaches 4 MPa, the average values of E_3, E_4 are 0.503%, 0.8120%, respectively. When the pressure reaches 12 MPa, the average values of E_3, E_4 are 0.901%, 1.6472%, respectively. It is shown that under 4 MPa, the effect of natural gas viscosity-pressure effect on the opening force is negligible.



（a） 0.6 MPa （b） 4 MPa （c） 12 MPa （d） 3-D map of pressure, film thicknesses and opening force

Fig. 4 Opening force for kinds of gas at different film thicknesses

5 Conclusions

For spiral groove dry gas seal of conveying natural gas centrifugal compressor, the natural gas viscosity-pressure effect is analyzed based on the narrow groove theory of the spiral groove. The conclusions of the present research are listed as follows: (1) The viscosity-pressure effect reduces the gas leakage rate but increases the opening force. (2) Up to 4MPa, natural gas viscosity-pressure effect is weak. As the pressure increases, the viscosity-pressure effect increases. (3) At 12MPa, the relative deviations of leakage rate and opening force caused by the viscosity-pressure effect are respectively 30.6% and -1.6472%. The viscosity-pressure effect of nature gas needs to be considered when used for high pressure situation.

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