Prediction of Leakage Rates Through Sealing Connections with Metallic Gaskets

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Abstract. According to fractal theory, the leakage model of metallic gaskets was developed in order to predict leakage rate of metallic gasket sealing connections. The relationship among the leakage rate, the fractal dimension, the compressive stress and the scale coefficient obtained by experiment, is approximately the same as that by the sealing model of metallic gaskets, which indicates that the sealing model of metallic gaskets established in this paper is reasonable. The research results not only are helpful for the development and application of metallic gaskets, but also contribute to the establishment of the design criterion and the design method of metallic gasket connections.

1. Introduction

The bolted flange connections with metallic gaskets are widely used in the processing equipments, which are usually operating in harsh conditions, such as high-temperature, high-pressure and corrosion medium. The failure of sealing systems will lead to enormous pecuniary loss, serious environment pollution and even personal injury. Mostly, such failures are not caused by the strength of flanges or bolts but by the leakage of the connections. Conventional designs of the connections with metallic gaskets are usually based on the gasket factors or the linear sealing stresses [1, 2], in which the strength of the elements is taken into consideration for the designing criterion while the quantitative leakage and tightness are not.

Systematical researches on the nonmetallic gasket performances and the tightness of bolted flange connections started in Fluid Sealing Laboratory at Nanjing University of Technology in 1980. A tightness analysis method was developed, and a safety assessment method of gasket sealing system based on the criterion of the maximum allowable leakage rate was presented. The connections designed according to the tightness designing method are not only structurally safe but also tight [3]. Over the past 30 years, many institutions have plunged much manpower and funding on evaluating the performance of the metallic gaskets. Although a number of theoretical analysis and numerical calculations have been published, most of them are focused on the strength of the flanges and the deformation compatibility equations of the connections [4]. Investigations on characterizing the fractal mechanism of the sealing surface topography and leakage model of metallic gaskets have been conducted since 2006 [5, 6].
This paper is an extension of our previously developed leakage model based on incompressible viscous fluid laminar flow theory and fractal geometry. According to our previous model and current experimental results, formula for the leakage rates calculation of metallic gaskets has been obtained. The tightness design method of bolted flange connections has been further developed. The maximal allowable leakage rate was used as the design criterion.

2. The leakage model of metallic gaskets

2.1. Relationship between the real area of contact and the compressive stress

According to the research results in Ref.[5], the contact between the flange and the metallic gasket sealing surfaces can be modeled as the contact between a rigid smooth flat surface and a rough fractal surface [see Figure 1].

![Figure 1. Contact between the rough surface and the smooth surface](image)

In Ref.[7], the contact model of sealing surfaces of the flange and the metallic gasket has been established on the basis of the modified M-B model. The Eq.(1) defines the link between the average compressive stress of the gasket $S_G$ and the dimensionless real contact area $A_r'$.

When $D\neq1.5$,

$$S_G = \frac{4}{3} \sqrt{\pi} E \left[ g_1(D) c^\alpha \right]^2 g_2(D)^{\alpha(D^2)} A_r'^{\alpha(D^2)}$$

$$+ \left( \frac{2-D}{D} \right)^{\alpha(D^2)} \left[ a_{e}^{(2-D)/2} \ln^{a_{e}^{(2-D)/2}} \right]$$

$$+ \frac{1}{2} \left( \frac{2-D}{D} \right)^{\alpha(D^2)} \left[ a_{p}^{(2-D)/2} \ln^{a_{p}^{(2-D)/2}} \right]$$

$$+ \frac{2}{3} \left( \frac{2-D}{D} \right)^{\alpha(D^2)} \left[ a_{e}^{(2-D)/2} \ln^{a_{e}^{(2-D)/2}} \right]$$

$$+ \frac{1}{3} \left( \frac{2-D}{D} \right)^{\alpha(D^2)} \left[ a_{p}^{(2-D)/2} \ln^{a_{p}^{(2-D)/2}} \right]$$

$$+ \frac{1}{4} \left( \frac{2-D}{D} \right)^{\alpha(D^2)} \left[ a_{e}^{(2-D)/2} \ln^{a_{e}^{(2-D)/2}} \right]$$

$$+ \frac{1}{6} \left( \frac{2-D}{D} \right)^{\alpha(D^2)} \left[ a_{p}^{(2-D)/2} \ln^{a_{p}^{(2-D)/2}} \right]$$

When $D=1.5$,

$$S_G = 3^{-\alpha/4} \sqrt{\pi} E \left[ g_1(D) c^\alpha \right]^2 g_2(D)^{\alpha(D^2)} A_r'^{\alpha(D^2)}$$

$$+ \frac{1}{2} \left( \frac{2-D}{D} \right)^{\alpha(D^2)} \left[ a_{e}^{(2-D)/2} \ln^{a_{e}^{(2-D)/2}} \right]$$

$$+ \frac{1}{3} \left( \frac{2-D}{D} \right)^{\alpha(D^2)} \left[ a_{p}^{(2-D)/2} \ln^{a_{p}^{(2-D)/2}} \right]$$

where,

$$g_1(D) = \frac{(4-2D) \ln 2}{(2D-3) \ln 2}$$

$$g_2(D) = \frac{2}{3-2D}$$

$$g_3(D) = \frac{2}{3}$$

$$C = \frac{A_r'}{A_s}$$

$$a_{e}^{(2-D)/2} = \frac{a_{e}^{(2-D)/2}}{A_s}$$

$$a_{p}^{(2-D)/2} = \frac{a_{p}^{(2-D)/2}}{A_s}$$

$$A_r' = \frac{A_r'}{A_s}$$

$S_G = \frac{E}{A_s} \cdot A_r'$ is the true contact area, mm$^2$; $A_s$ is the geometry area of gasket, mm$^2$; $A_r'$ is the
dimensionless true contact area, $a_c$ is the critical area of contact spot changed from elastic deformation into elastic-plastic deformation, mm$^2$; $a_{pe}$ is the critical area of contact spot changed from elastic-plastic deformation into plastic deformation, mm$^2$; $b$ is the width of gasket, mm; $C$ is the scale coefficient, $D$ is the fractal dimension, $E$ is the composite elastic modulus ($E_f \approx E_g$), MPa; $E_f$ is the Young’s elastic modulus of flange material at room temperature, MPa; $E_g$ is the Young’s elastic modulus of gasket material at room temperature, MPa; $k_y$ is the scaling factor ($k_y = H / \sigma_y$), $\sigma_y$ is yield strength of gasket material, $H$ is hardness of gasket material, $\mu$ is the Poisson’s ratios, $\phi$ is the material properties constant ($\phi = \sigma_y / E$), $\psi$ is expansion coefficient of size distribution range ($\psi > 1$), and $S_G$ is the average compressive stress of gasket, MPa.

2.2. Leakage model based on fractal parameters

The gas flowing the bolted flange and metallic gasket seals can be considered as predominantly incompressible laminar flow [8, 9]. In Ref. [8], according to the fractal geometry and the incompressible viscous fluid laminar flow theory, the leakage model of the metallic gaskets based on the fractal parameters has been established. The maximum volumetric leakage rate of all passages of the sealing surface is given by

$$L_V = \frac{p_1 - p_2}{9 \pi \eta \phi} \frac{D}{7 - 4D} \left( \frac{2 - D}{D} \right)^{\frac{7 - 3D}{2}} \frac{1}{\psi^2} (2 - D)(3D - 5)$$

where, $L_V$ is the volumetric leakage, cm$^3$·s$^{-1}$; $p_1$ is the pressure inside rig, MPa; $p_2$ is the pressure outside rig, MPa; $\eta$ is the dynamic viscosity, kg·(s·m)$^{-1}$.

Ref.[9] presents the detailed derivation of this equation by assuming that the sealing surface of the flange is smooth and each hole on the surface of the gasket is not only a leak passage but also a cosine wave through, and it doesn’t deform under the compressive stress.

In practice, the surfaces of the flange and the metallic gasket are not smooth. The irregularities/asperities on the surfaces may interlock into each other due to the contact and the compressive force which greatly reduces the leak passages. The longitudinal section of a passage is irregular. The irregularity changes when the compressive stress increases. So the actual leakage rate is less than the leakage rate calculated according to Eq.(3). In order to eliminate the effect of these factors, the function of compressive stress $S_G$ was used to modify Eq.(3). According to Ref.[8], the function $\xi = C_1 e^{-C_2 S_G}$ can be obtained, so the volumetric leakage rate can be calculated by the following formula:

$$L_V = C_1 \frac{p_1 - p_2}{9 \pi \eta \phi} \frac{D}{7 - 4D} \left( \frac{2 - D}{D} \right)^{\frac{7 - 3D}{2}} \frac{1}{\psi^2} (2 - D)(3D - 5) e^{-C_2 S_G}$$

Where $C_1$ and $C_2$ are regression coefficients which can be obtained from the experimental data. $C_1 = 0.7768$, $C_2 = 0.0481$.

3. Test Verification

3.1. Test apparatus and procedure

In order to validate the established leakage model, we have performed some tests on a fully automatic testing machine for gasket performance, as shown in Figure 2. The machine consists of a frame, two test flanges, a loading device, a gas supplying device, a leakage rate measuring device, a controlling
device and a data acquisition device. The testing machine is fitted with a sealing cylinder that creates a low pressure chamber (called as leak detection chamber) just outside the gasket to be tested, and the gasket leakage rate is measured. The chamber is sealed with two rubber O-rings mounted between the flanges and the sealing cylinder. An additional function of the chamber is to accumulate the gas leaking through the gasket. According to the state equation of ideal gas, the leakage rate can be obtained by measuring the change of the pressure and the temperature of the gas in the chamber and the volume of the chamber over time. All test parameters such as the compressive gasket stress, gasket deformation, test medium pressure, and the pressure/temperature of the leakage fluid accumulated in the leak detection chamber, are measured with high precision sensors. The measurement range of the leakage rate is from $10^{-6}$ to 0.1 Pa m$^3$s$^{-1}$.

![Figure 2. Test equipment for gasket performances evaluation](image)

1. pressure sensor  2. servo cylinder  3. force sensor  4. displacement sensor  
5. 6. pressure gauge  7. valuator  8. buffer vessel  9. high-pressure tank  10–12. valve

Samples are flat metallic gaskets made of 10 steel. Their outer and inner diameters are 0.06 m and 0.04 m respectively, and their thickness is 0.003 m. The roughness parameters of the samples are listed in Table 1.

| No. | $R_a$ /μm | $D$ | $C$ |
|-----|----------|----|----|
| I   | 0.58     | 1.220 | 0.0078 |
| II  | 0.40     | 1.459 | 0.0069 |
| III | 0.31     | 1.560 | 0.0065 |

The test temperature is the room temperature (About 22 ℃). The testing gas is 99.9% nitrogen. Other testing conditions are listed in Table 2.

| No. | $S_G$ /MPa | Gas pressure /MPa |
|-----|------------|-------------------|
| I   | 125, 187, 250, 312 | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 |
| II  | 62, 125, 187, 250 |  |
| III | 62, 125, 187, 250 |  |

3.2. Experimental results and discussion

3.2.1. Relationship between the leakage rate and the compressive stress

The relationships between the leakage rate $L_v$ and the compressive stress $S_G$ for samples I–III under the different medium pressure are shown in Figure 3(a)–(c), respectively. The experimental results show that there $\log(L_v)$ is almost proportional to $S_G$ under the same medium pressure which means the larger the compressive stress $S_G$ is, the less the leakage rate $L_v$. Furthermore, we can see that the slopes of the plots are almost the same under different medium pressure.
3.2.2. Relationship between the leakage rate and the medium pressure
Figure 4(a) –(c) illustrate the relationships between the leakage rate and the medium pressure of samples I–III under the different gasket compressive stresses. Under the same compressive stress, the leakage rate and the medium pressure is linearly related, larger medium pressure accompanies with larger leakage rate. But the leakage rate increases significantly with the increment of the medium pressure when the compressive stresses are smaller. On the contrary, when the gasket compressive stresses are larger, this tendency is subtle.

Figure 3. Relationship between the leakage rate and the compressive stress
Figure 4. Relationship between the leakage rate and the medium pressure

- **Figure 3**: Relationship between the leakage rate and the compressive stress
- **Figure 4**: Relationship between the leakage rate and the medium pressure

![Figure 3](image1)

![Figure 4](image2)
3.2.3. Relationship between the leakage rate and the fractal dimension

The relationships among the leakage rate, the fractal dimension and the scale coefficient for samples I~III when \( S_C = 0 \) and \( p = 6, 8 \) and \( 10 \) MPa are shown in Figure 5 and Figure 6. It can be found from them that the relationship among \( \log(L_V) \), \( D \) and \( C \) is linear. According to Ref.[4], it can be seen that the smoother the sealing surfaces are, the less the leakage rate is.

4. Leakage rate prediction

Some predictions have been carried out, by which Eq.(4) was validated. Figure 7 illustrates the comparison between the results of leakage rate predictions and the experimental data presented on Figure 3 when \( S_C = 0 \) for samples No.01~No.03.

It can be found from that the leakage rates predicted by Eq.(4) are close to the experimental results, which supports the established leakage prediction model represented by Eq.(4). The essential reason for the error of prediction is mostly due to the selection of leak detection methods and the experimental noises when doing on sites tests.

5. Conclusions

The contact model of the sealing surfaces of the flange and the metallic gasket has been established on the basis of the modified M-B model, and the link between the contact area and the compressive stress has been obtained. A sealing model of metallic gaskets has been used based on the laminar flow theory of the incompressible viscous fluid and the fractal geometrical theory.

Experimental investigations on the sealing performance of metallic gaskets have been carried out. The effects of the compressive stress, the medium pressure, and the surface topography on the sealing performance have been evaluated. The modified sealing model we proposed is reasonable because the leakage rate, the fractal dimension, the compressive stress and the scale coefficient in our model are highly consistent with the experimental data.
Based on the research results, it is possible to design the metallic gasket connections and evaluate the tightness of the connections by adopting the maximal allowable leakage rate as a criterion. The results are not only helpful for the machining of the metallic gasket and flange sealing surfaces, but also contributing to the design and the safety assessment of metallic gasket connections.

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