Fatigue life analysis of cracked gas receiver of emergency cut-off system in gas gathering station

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Abstract. Small-scale air compressor and gas receiver are used as the driving gas of the emergency cut-off system in gas gathering station. Operation of block valve is ensured by starting and stopping compressor automatically. The frequent start-stop of compressor and the pressure fluctuation pose a threat to the service life of gas receiver, and then affect normal operation of the emergency cut-off system and security of gas gathering station. In this paper, the fatigue life of a pressure vessel with axial semi-elliptical surface crack in the inner wall is analyzed under the varying pressure by means of the theory of fracture mechanics. The influences of the amplitude of pressure fluctuation and the initial crack size on the residual life of gas receiver are discussed. It provides a basis for setting the working parameters of gas receiver of emergency cut-off system and determining the maintenance cycle.

1. Introduction

Emergency cut-off system is the most important guarantee for the safe operation of gas gathering station. For the gas field with gas collection technology of multi-well, high pressure and normal temperature, the emergency block valve is installed at the entrance of single well and exporting position in gas gathering station, and pressure monitoring points are located on the total throttle organ, separator and output position. When the pressure at the monitoring point exceeds the set value, block valves would cut off gas supply automatically to achieve overpressure protection of gas gathering station. In the early days, nitrogen gas that was supplied by nitrogen cylinders was used as gas supply and to drive emergency block valve on or off in the emergency cut-off system. Due to the large amount of nitrogen consumption, nitrogen cylinders needed to be replaced frequently. This led to overspending of manpower and material resource, and inconvenient management. Therefore, the air supply system, which is composed of small air compressor, gas receiver, dryer, filter screen, pressure regulator etc., is installed and used as gas supply of emergency block valve. The compressor can start and stop automatically, and avoid the emergency cut-off system in gas gathering station being influenced by climate and road. This new system could reduce demand of the material and financial resources due to the frequent replacement of nitrogen cylinders, abate operation cost of pneumatic valves, and ensure safe and stable operation of gas gathering station. But as gas supply of emergency cut-off system, gas receiver charges and discharges frequently and always stands the relatively large pressure difference. Accompanied by the fact that defects, such as corrosion, machining cracks and so on appear inevitably during service period, the safe operation of gas receiver is threatened [1].
In this paper, based on the theory of fracture mechanics, the fracture and fatigue properties of gas receiver with longitudinal surface cracks inside wall are analyzed, and the influences of the amplitude of pressure fluctuation and the initial crack size on the residual life of gas receiver are discussed. The results provide the basis for setting working parameters of gas receiver and determining the maintenance cycle properly.

2. Problem description
Gas receiver is generally made of steel Q345R, yield strength $\sigma_s = 345\text{MPa}$, and elastic modulus $E = 210\text{Gpa}$. The inner diameter of gas receiver $D_i = 800\text{mm}$, wall thickness $t = 7\text{mm}$, design pressure is 2.2MPa, and test pressure is 2.75MPa. When the supply gas pressure is lower than the set value (1MPa), compressor runs and inflates gas receiver; when the pressure exceeds the upper limit (2MPa), the compressor stops.

During the serving process of gas receiver, bulk defects and plane discontinuity may exist because of corrosion, incomplete welding, air gap and other reasons. Under the condition of internal pressure, the hoop stress of gas receiver is much higher than the axial stress ($\sigma_\theta = pD_i / 2t$, axial stress $\sigma_z = pD_i / 4t$, where $p$ is internal pressure), and the stress of the inner surface of the cylinder is higher than that of the outer surface. Therefore, the axial crack in the inner wall of the cylinder is more dangerous. Lin & Smith [2] and Carpinteri [3] had demonstrated that the initial surface defects with any shape would develop into a semi-elliptical crack with aspect ratio of 0.6 to 0.7 after several cycles of fatigue crack propagation. So, the axial crack in the inner wall of a tank is taken as a semi-elliptical surface crack, which can represent the actual crack properly, as shown in Fig.1.

![Figure 1 The sketch of semi-elliptical surface crack in the inner face of tank shell.](image)

3. Fracture properties
Gas receiver that contains a longitudinal semi-elliptical surface crack is subjected to internal pressure. Considering the effect of air pressure on both the inner wall of tank and the crack surface, the stress intensity factor $K_I$ of the crack can be expressed as [4]:

$$ K_I = \frac{pD_i}{2t} \sqrt{\pi a} \cdot \frac{0.97}{E(k)} \cdot \left[ M_1 + M_2 \left( \frac{a}{t} \right)^2 + M_3 \left( \frac{a}{t} \right)^4 \right] g \cdot f_o \cdot f_c $$

(1)

Where:
\[ E(k) = \left[ 1 + 1.464 \left( \frac{a}{c} \right)^{1.65} \right]^{1/2}, \quad M_1 = 1.13 - 0.09 \frac{a}{c}, \]

\[ M_2 = -0.54 + \frac{0.89}{0.2 + \frac{a}{c}}, \quad M_3 = 0.5 - \frac{1}{0.65 + \frac{a}{c}} + 14 \left( 1 - \frac{a}{c} \right)^{24}, \]

\[ g = 1 + 0.1 + 0.35 \left( \frac{a}{t} \right)^2 (1 - \sin \theta)^2, \quad f_\theta = \left[ \sin^2 \theta + \left( \frac{a}{c} \right)^2 \cos^2 \theta \right]^{1/4}, \]

\[ f_c = \left[ D_0^2 + D_i^2 \right] \frac{2t}{D_0^2 - D_i^2} + 0.5 \sqrt{\frac{a}{t}} 2t. \]

In which \( a \) and \( c \) are the minor axis and major axis of the semi-elliptical crack, respectively, m. Here \( a/c \) is specified as 0.7; \( E(k) \) is the complete elliptic integrals of the second kind; \( \theta \) is circumferential angle of the crack front. The dimensionless stress intensity factor \( K_{\text{non}} \) is defined as:

\[ K_{\text{non}} = \frac{K_t}{pD\sqrt{\pi a}} \]  

(2)

For the axial semi-elliptical surface cracks with \( a/t = 0.2, 0.4 \) and 0.6, the distributions of \( K_{\text{non}} \) along the crack front are calculated and shown in Fig.2. It can be seen that the \( K_{\text{non}} \) varies along the position of the crack front, and the larger \( K_{\text{non}} \) leads to faster growth rate of the crack. As a result, the shape of the crack front is flattened gradually as the crack propagating gradually. Based on the \( K_{\text{non}} \) at the deepest point of crack, the fatigue propagation process of crack is studied, and the fatigue life of gas receiver under different working parameters is predicted.

![Figure 2 Distribution of \( K_{\text{non}} \) along crack front under different crack depth.](image-url)
4. Fatigue life
By means of the formula derived by Paris, the crack growth rate in the tank inner wall could be estimated by Eq. (3).

\[
\frac{da}{dN} = C(\Delta K_i)^m
\]  

(3)

Where: \( N \) is the number of load cycles, \( \Delta K_i \) is the range of stress intensity factor at the crack tip, MPa·m\(^{1/2}\); \( C \) and \( m \) are material constants related to working conditions, and chosen as \( C = 7.97 \times 10^{-10} \) and \( m = 3.52 \) for steel Q345R. Fracture toughness at room temperature is \( K_{IC} = 108 \) MPa·m\(^{1/2}\). Substituting Eq. (1) into Eq. (3), and integrating from \( a_0 \) to \( a_c \), the fatigue life of gas receiver could be obtained.

Here the surface crack with depth \( a_0 = 0.1t \) is taken as an example, and the gas receiver is judged as failure when the deepest point of semi-elliptical surface crack penetrates tank wall, that means the critical crack size is \( a_c = t \). The number of pressure cycles of the gas receiver varying along with the amplitude of the pressure fluctuation is shown in Fig.3. It can be seen that the fatigue life of gas receiver decreases sharply with the increase of the amplitude of pressure fluctuation. Under the condition that the compressor runs as \( p < 0.6 \) MPa and shuts down as \( p > 2.2 \) MPa, the fatigue life of gas receiver would be only 11751 cycles. If the gas pressure is adjusted so that the compressor runs below 1.2 MPa and stops above 1.8 MPa, the fatigue life of gas receiver would increase to 371107 times. Therefore, reducing the amplitude of pressure fluctuation can improve the service life of gas receiver greatly.

![Figure 3](image1.png)

Figure 3 Fatigue life vs. the amplitude of internal pressure fluctuation.

![Figure 4](image2.png)

Figure 4 Fatigue life vs. initial crack depth.
Figure 4 shows the variation of the fatigue life of gas receiver with initial crack depth when the amplitude of pressure fluctuation is set as 0.6MPa. With the increase of the initial crack depth from 0.14mm ($a/t = 0.02$) to 4.2mm ($a/t = 0.6$), the number of residual cycles of gas receiver decreases from 260699 to 4112. With the increase of crack depth, the remaining life of gas receiver decreases sharply.

5. Conclusion
Based on the theory of fracture mechanics, the fracture properties of the axial semi-elliptical surface cracks in the inner wall of gas receiver under the action of internal pressure are studied. The influences of the amplitude of internal pressure fluctuation and initial crack depth on the remaining life of gas receiver are analyzed. It is found that the shape of the crack front is flattened gradually in the process of fatigue crack propagation. The residual life of gas receiver decreases sharply with the increase of either the amplitude of fluctuating internal pressure or the initial crack depth. Therefore, measures should be taken to ensuring safe operation of gas receiver as the following two aspects: improving the operating parameters to reduce the pressure fluctuation, and enhancing flaw detection to limit the defect size in the inner wall of gas receiver.

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