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Failure Pressure Analysis of the Head of Three-Phase Separator with Inner Corrosion Defect

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Abstract

The corrosion defects of the head of three-phase separator have an important effect on the safe operation of three-phase separator. The existing researches on the corrosion defects of the head of the three-phase separator were not comprehensive enough. Based on the nonlinear finite element analysis method, this paper analysed the equivalent stress and plastic strain in the corrosion zone and studied the influence laws of the operation pressure, the size of the corrosion defects and the distribution of double corrosion defects on equivalent stress and plastic strain, through establishing the simulation analysis model of corrosion defects in the head of a three-phase separator and based on the nonlinear finite element analysis method. The simulation results showed: the existence of corrosion defects in the head of the three-phase separator reduced the failure pressure of the head of the three-phase separator and led to earlier failure. The size of corrosion defects had little effect on the equivalent stress and plastic strain in the corrosion area of the head, and only affected the area of the stress-strain distribution. The equivalent stress and plastic strain of the double corrosion defects were basically the same at different intervals with the increase of operation pressure, and its values slightly differed only in the yield stage and the plastic deformation stage.

Keywords: three-phase separator, corrosion defects, residual strength, FEM, stress-strain

Introduction

Oil, gas and energy have made important contributions to promoting industrial production, ensuring social stability and promoting national defence. They are scarce resource on the earth, and also affect national development [1]. Although the energy structure is slowly changing, no effective alternative energy has been found yet. Reducing the costs of producing, processing, and transporting is still important. With the rapid development of the oil and gas industry, the requirement of the treatment technology of crude oil containing gas and water is also getting higher and higher. Therefore, it is urgent to ensure high efficiency separation of oil, gas and water [2]. The three-phase separator is large scale equipment which uses the principle of gravity sedimentation and separation to separate oil, gas and water [3]. It is suitable for the treatment of oil products with high water content, especially containing large amount of free water [4]. The simplified structure is shown in Fig.1. In the service three-phase separator, the usual corrosion defects are corrosion pits, which are large in number and widely distributed [5]. Corrosion zone is usually composed of multiple corrosion defects, and corrosion defects are overlapped or adjacent to each other. The current two modes would affect the limiting stress of the separator with the real corrosion defects [6]. More and more of the separator in the service process, the strength would be weakened sharply by corrosion and so on. Experts at home and abroad extensively studied the failure of three-phase separators from three aspects of corrosion reasons, failure positions and factors affecting corrosion [7]. But it was still insufficient to study the defects in the head of the separators. Because the head containing defects might cause danger, so it is very important to control the influence of the defects on the safety of the separators.

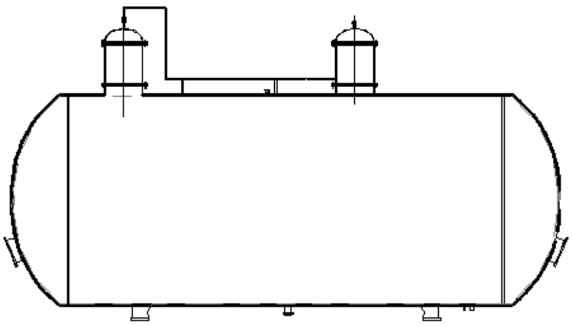

Fig.1 Simplified structure of three-phase separator

Therefore, the finite element software was used to simulate the head section of a three-phase separator with the single defect of different size and the double defects of different positions to simplified the actual working condition and combine the influence of the inner pressure of the separator. The stress and strain distributions of the head of a three-phase separator with different defects were also observed. Besides, the residual strength was evaluated and the influence of the single defect size and the location of double defects on the equivalent stress and plastic deformation at the local defects were investigated [8]. Through the risk prediction to reduce the probability of three-phase separator accident, the safety of personnel was ensured to enhance the safety level of three-phase separators and reduce the risk [9].

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Building Finite Element Models

Physical model

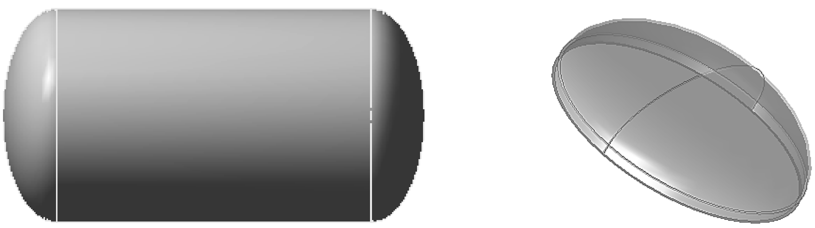
Operating parameters and geometric parameters of the three-phase separator are shown in Tables 1 and 2. The purpose of this paper is to analyze the influence of corrosion defects of three-phase separator and cylinder head residual strength, so it can be simplified as the actual three-phase separator as is shown in Figure 3.This analysis model is based on simulation of three phase separator in Table 2. so it can describes the corrosion defect accurately and can ensure accuracy of calculation result [8,10].

Table 1 Operating parameters of the three-phase separator

parameter	design pressure	working pressure	design temperature	operating temperature
value	1.6MPa	1.0MPa	40℃	2~10℃
parameter	main pressure part	corrosion allowance	design service life	Insulation materials
value	Q245R	2mm	30years	aluminium silicate

Table 2 Geometric parameters of the three-phase separator (unit: mm)

<table>
<tr><td rowspan="2">Cylinder parameter</td><td colspan="2">inner diameter</td><td colspan="2">length</td><td colspan="2">wall thickness</td></tr>
<tr><td colspan="2">2200</td><td colspan="2">9800</td><td colspan="2">16</td></tr>
<tr><td rowspan="2">Head type EHA2200</td><td>nominal diameter</td><td>The depth of tolerance</td><td>circular degree</td><td>convex</td><td>indent</td><td>Straight edge height</td></tr>
<tr><td>2200</td><td>$590^{+13.2}_{-4.4}$</td><td>≤11</td><td>≤27.5</td><td>≤13.75</td><td>40^{+4}_{-2}</td></tr>
</table>



(a) Global (b) Head

Fig.2 Simplified model of the three - phase separator

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The separator is affected by internal pressure, and when the internal pressure is 4MPa, we can calculate the two-way stress according to the formula (1) and formula (2).

$$\sigma' = \frac{Pd}{4\delta} = \frac{4\times10^{6}\times2200\times10^{-3}}{4\times16\times10^{-3}} = 137.5MPa \qquad (1)$$

$$\sigma'' = \frac{Pd}{2\delta} = \frac{4\times10^{6}\times2200\times10^{-3}}{2\times16\times10^{-3}} = 275MPa \qquad (2)$$

Where, σ' is tensile stress, MPa. σ'' is tangential stress, MPa. d is three-phase separator cylinder diameter, mm. P is internal pressure of three-phase separator, MPa. δ is three-phase separator thickness, mm.

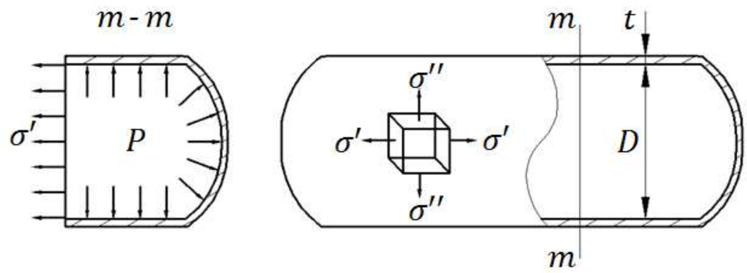
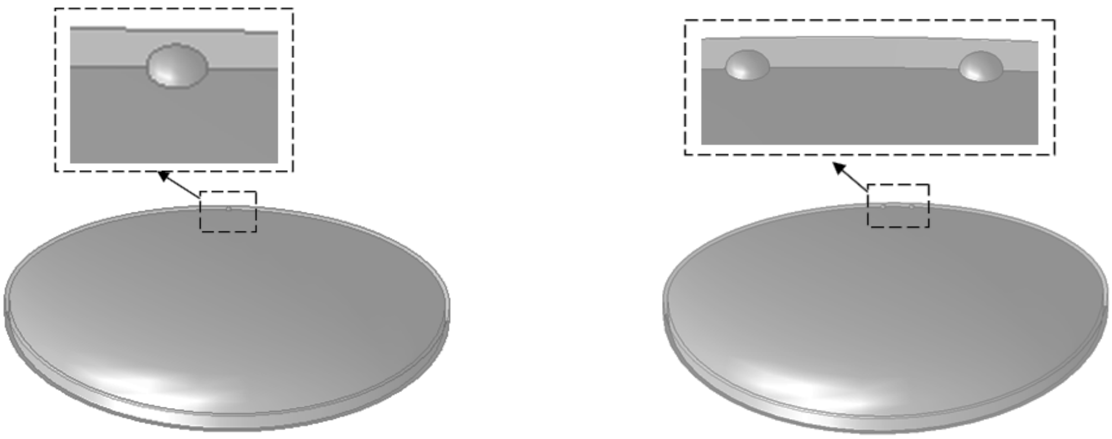


Fig.3 Simplified stress distribution of the three-phase separator



(a) Single defect （b） Double defects

Fig.4 The 1/2 model of the head part with defects

According to the geometry and load of three-phase separator, the 1/2 model of elliptical head should be built when analysing the defects of head [13]. The model of a three phase separator with corrosion defects is converted into a 8 node hexahedron element grid. In order to improve

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the accuracy of calculation, the area near the corrosion defect needs to be refined [14]. Single corrosion defects and double corrosion defects are set up in the head of the three-phase separator model, and each model is shown in Figure 4. Based on the simulation model of corrosion defects, the influence of geometric parameters of corrosion defects on the residual strength of the separator is studied by comparing and analysing the geometric parameters of the defects. In the case of a single defect, five sets of hemispherical defects with diameters of 8mm, 10mm, 12mm, 14mm, and 16mm are set. Fixed head top diameter spherical defects of 12mm, set the interval for 5°, 15°, 45°, 60°, 85°, 90°, six sets of double spherical defect model.

Applied load process

Apply the displacement constraints in section in the contact head and cylinder. Limit axial displacement is zero. Apply the frictionless constraint in the head section which is parallel to the axial direction. And the four inner surface defects are applied 4MPa internal pressure in the model. The operating pressure presents a linear increase in the 10s from 0MPa to 4MPa.

Failure criteria

Allowable stress is the ultimate strength of materials under different conditions and working conditions, calculated according to formula (3).

For plastic material:

$$[\sigma] = \frac{\sigma_s}{n_s} \tag{3}$$

Where, $[\sigma]$ is the allowable stress, MPa. σ_s is the yield strength, MPa. n_s is the safety factor, under static loading, safety factor of plastic material is $n_s = 1.2 \sim 2.5$.

The allowable stress is the highest limit of the working stress of the component, that is to say the working

stress is not more than the allowable stress. Therefore $\sigma \le [\sigma]$, the strength condition can be checked according to the strength to confirm the allowable load.

Considering the material, the applied load, the component simplification, the reasonable degree, the importance of the component in the equipment and the working conditions, and combining the practical experience, the safety factor $n_s = 1.45$ is selected. The yield stress $\sigma_s = 245MPa$ of the Q245R material is introduced into (3) and the allowable stress is calculated through formula (4), and the safety of the in-service three-phase separator with 170MPa is evaluated.

$$[\sigma] = \frac{\sigma_s}{n_s} = \frac{245MPa}{1.45} = 170MPa \qquad (4)$$

With complex structure and working conditions of corrosion-resistant three-phase separators, the study of mechanical properties and failure pressures makes the following assumptions:

(1) The internal pressure inside the separator only.

(2) Considering the actual situation, spherical shape of the internal corrosion defects can be carried out [13].

Simulation Results Analysis

Single corrosion defect of head

As shown in Fig. 5, the influence of corrosion defects on the Mises stress distribution in the corrosion zone of the head under different running pressure is described when the 12mm hemispherical single corrosion defect is located at the top of the head in the operating pressure range of 0MPa~4MPa. At the low 0.4MPa operating pressure, the entire corrosion defect zone merely corroded the defect and there is a small stress concentration it the centre of the bottom. With the increase of pressure to 0.9MPa and 1.3MPa, there is a certain stress concentration phenomenon in the area of hemispherical corrosion defects, and the stress concentration tends to diffuse around the corrosion defect. When the running pressure is further increased to 1.7MPa~4MPa, the change of the operation pressure mainly affects the size of the whole stress zone and the surrounding stress concentration. When the operation pressure is 2.6MPa, the maximum equivalent stress at the bottom of the corrosion defect first reaches the yield limit of the material, and then the maximum equivalent stress of the material reaches the yield limit in the whole corrosion defect area. As shown in Fig. 6, the plastic strain distribution of the material at the top of the head of the corrosion zone at the top of the head is described when the running pressure of the three-phase separator is 3.2MPa, 3.6MPa and 4.0MPa under the corresponding conditions in Fig. 5. As can be seen from Figure 6, the stress concentration distribution is similar to that in the corrosion defect zone in Fig. 5. The plastic strain of the material in the corrosion zone firstly occurs at the bottom of the corrosion defect, and then gradually spreads to the whole corrosion defect zone with the increase of the operation pressure, and the plastic deformation increases gradually. But the difference from stress concentration distribution is that the influence of corrosion defects on the plastic strain of the material only affects the area of corrosion defects, and the influence on the surrounding defects is very small and can be neglected basically. Therefore, the single corrosion defects at the top of the head will lead to a certain degree of stress concentration and plastic deformation of the material in the region under different operating pressures. With the increase of operation pressure, the maximum equivalent stress of corrosion defect zone first reaches the yield limit of material, which may lead to premature failure of the head of three-phase separator.

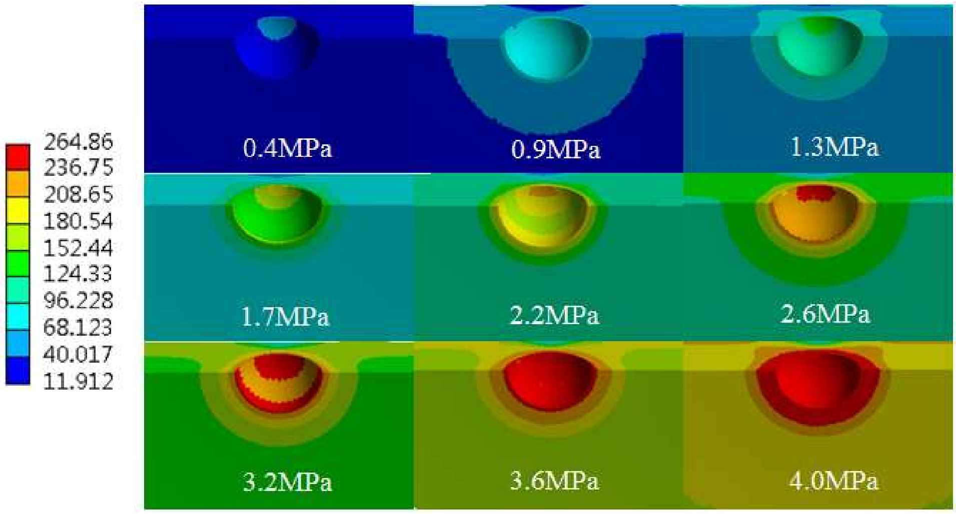

Fig.5 Von Mises stress distribution of the corroded area under different inner pressure

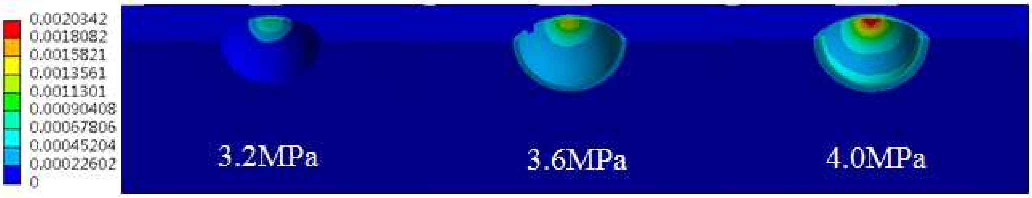

Fig.6 Plastic strain distribution of the corroded area under different inner pressure

Based on the analysis of the influence of the three-phase separator's running pressure on the corrosion defects at the top of the head, the stress distribution in the region and the plastic deformation of the material, the stress distribution in the corrosion zone and the plastic deformation of the material under different operating conditions were investigated. As shown in Figure 7 and Fig. 8, the stress distribution in the corrosion zone and the plastic deformation nephogram of the corrosion defects are described when the hemispherical corrosion defects are 8mm~16mm in diameter under the operating pressure of 4MPa. It can be seen from Figure 7 that the stress distribution of the corrosion defect area of the head is basically the same under different corrosion defect diameters. That is, the hemispherical

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corrosion defect is the centre, which expands gradually to the periphery, and the stress decreases uniformly. But compared to the other directions, the stress in the thickness direction decreases and the speed is faster. In addition, as shown in Figure 7, the greater the corrosion defects in the head, the greater the area of the high stress distribution area under the same operating pressure. Thus, the maximum equivalent stress is greater than the material yield limit, and the greater the stress zone, the greater the influence on the safe operation of the three-phase separator. Similarly, the larger the corrosion defect size in Figure 8, the greater the plastic deformation range of the head. However, the size of corrosion defects does not affect the plastic deformation area of the largest material in the corrosion zone, and the plastic deformation zone is still at the bottom of the corrosion defect.

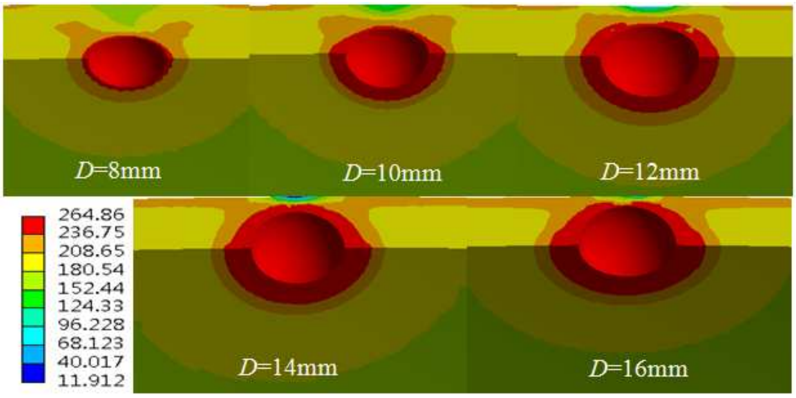

Fig.7 Von Mises stress distribution of the corroded area with different defect

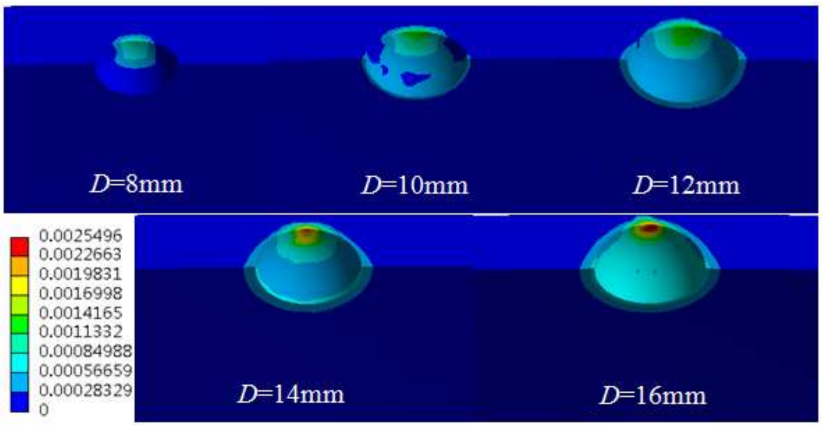

Fig.8 Plastic strain distribution of the corroded area with different defect

In order to analyse the influence of corrosion defect diameter and operation pressure of three-phase separator on the head of three-phase separator more clearly. As shown in

Figures 9 and 10, the equivalent stress and equivalent strain of corrosion defects in the head are compared when the operating pressure is 0.5MPa~4MPa and the hemispherical corrosion diameter is 0mm~16mm. In Figure 9, when the corrosion diameter is 0mm (there is no corrosion defect), the equivalent stress increases linearly with the increase of the operation pressure. When the corrosion defect diameter is 8mm~16mm, the equivalent stress increases rapidly with the increase of the operation pressure, then gradually slows down and finally decreases. That is, it undergoes the elastic deformation stage, the yielding stage and the plastic deformation stage, but the trend of change with the change of running pressure is basically the same under the condition of different corrosion defects, but only the equivalent stress value has little difference. The equivalent stress drops when the operating pressure is 3MPa. Under the condition of corrosion defects, the maximum equivalent stress at the corrosion defect of 3MPa reaches the yield limit of the material, and the further increase of the running pressure will lead to the macro deformation of the material. Similarly, in Fig.10, when the corrosion diameter is 0mm, the plastic strain at the head of the separator remains unchanged 0 with the increase of the operation pressure. When corrosion diameter is 8mm~16mm, it increases slowly with the increase of operation pressure, and when the running pressure reaches 3MPa, the index increases rapidly. That is to say, the macro deformation of the material at the head of the defect begins after the running pressure reaches 3MPa in Fig. 9. Then the plastic strain value increases sharply. The different corrosion diameters have little influence on the plastic strain at the same running pressure.

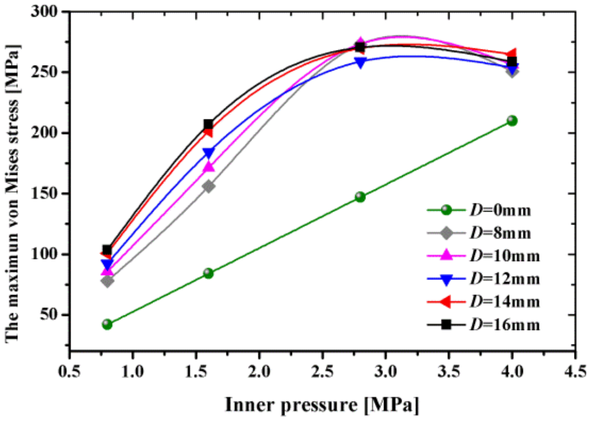

Fig.9 The chart of equivalent stress with the working pressure

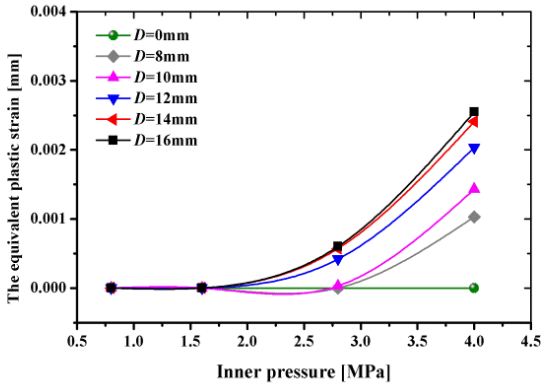

Fig.10 The chart of plastic strain with the working pressure

Therefore, for a three-phase separator with certain operating pressure range, the influence of corrosion defects at the top of the head on the stress and strain of the head will reduce the failure pressure of the separator, and lead to premature failure of separator. The size of

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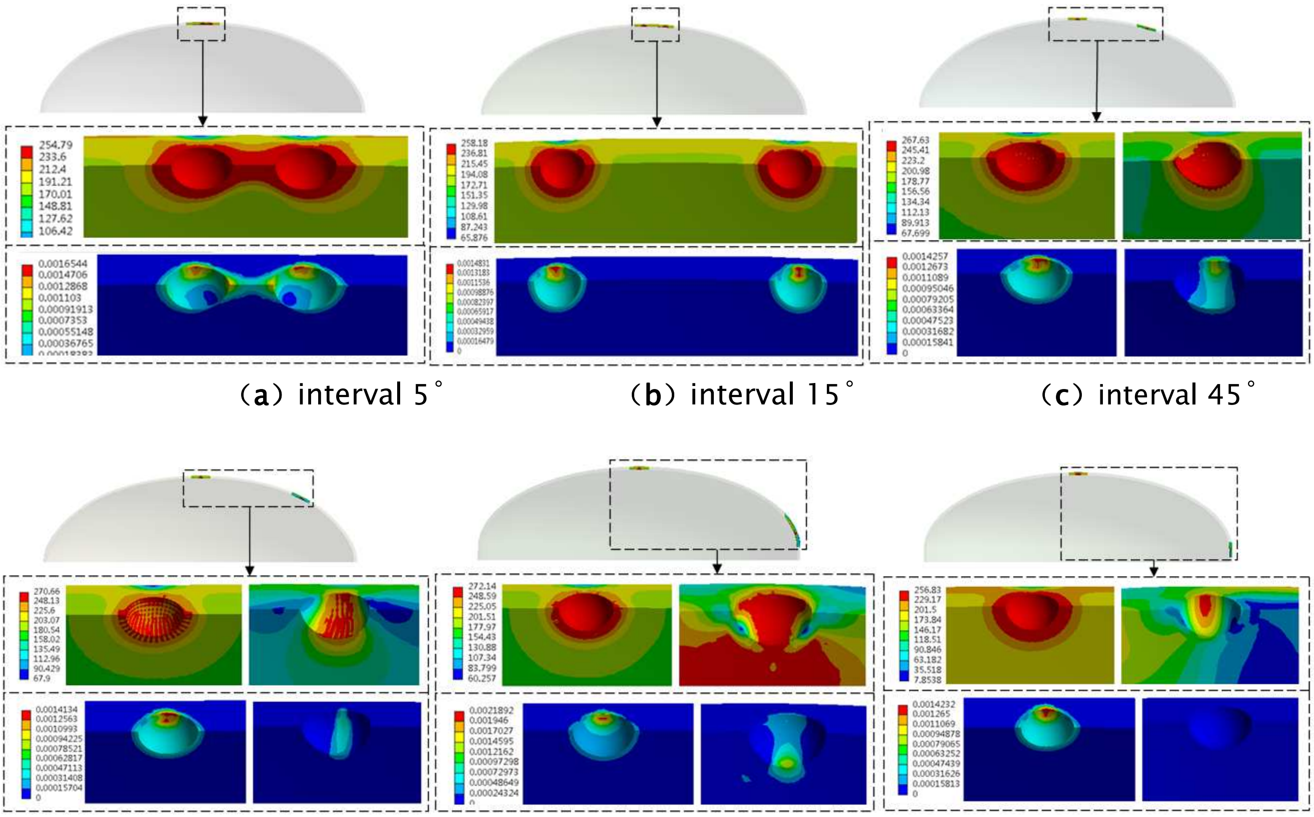
corrosion defects affects the stress concentration and the plastic deformation area of the material. Besides, it has a certain influence on the premature failure of the separator.

Double corrosion defect of head

In the 3.1 section, the influence law of corrosion defects on the stress and strain of the head of the three-phase separator is obtained by changing the running pressure and the diameter of corrosion defects. But only a single corrosion defect is discussed and analysed. However, there is more than one corrosion defect in reality. Therefore, in this section, the influence of double corrosion defects on the stress and strain of the head is studied and analysed.



(a) interval 5° (b) interval 15° (c) interval 45°

(d) interval 60° (e) interval 85° (f) interval 90°

Fig.11 Equivalent stress and strain of double corrosion defects at different intervals

For a single corrosion defect, stress concentration first occurs at the bottom of the spherical defect and gradually affects the entire internal surface of the defect, and the plastic strain first occurs at the bottom of the defect and becomes the largest region of the corrosion defect strain. For double corrosion defects, as shown in Figure 11, when the diameter is the 12mm and the running pressure is 4MPa, the distribution angle between the

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two corrosion defects is 0° (a single defect), or 5°, or 15°, or 45°, or 60°, or 85°, or 90°, the stress nephograms of the head are contrasted. As shown in Figure 11 (a), when the interval between the two defects is 50°, the stress concentration occurs at the same time between the corrosion defect and the two defects and the plastic strain first occurs at the bottom of the two defects and the edge of the two defects. Therefore, there is a certain interaction between the two corrosion defects at the interval of 5°, and the stress and strain have a little symmetry. As shown in Figure 11 (b), the interval between two corrosion defects is 15°, the stress concentration first appears on the inner surface of the defect, and the plastic strain appears at the bottom of the defect first. There was no stress concentration between the two corrosion defects. Therefore, the interaction between the defects is not significant when the interval between two corrosion defects is 15°. It can be seen from Fig.11(c)~(f), As the spacer angle increases further, the stress concentration phenomenon also appears on the inner surface of corrosion defects first. With the increase of the interval, the stress concentration region of the non top defect decreases gradually, and plastic strain also occurs at the bottom of the top of the head at the same time. The interaction of double corrosion defects can still be neglected.

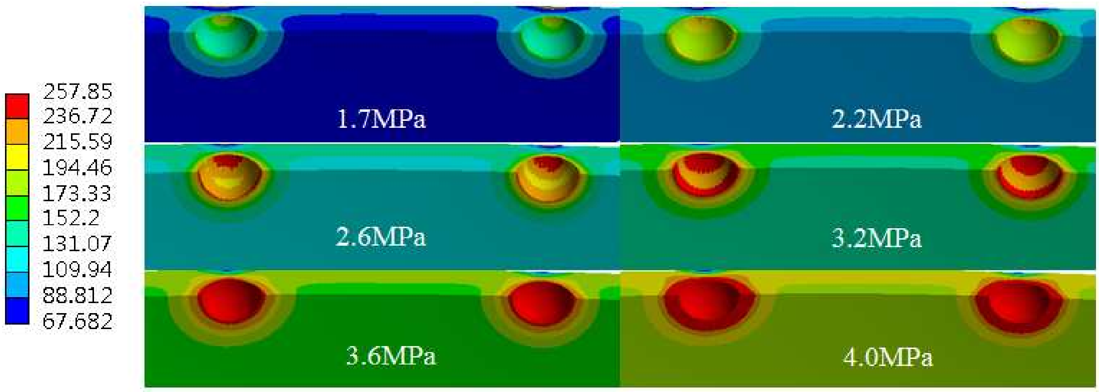

Fig.12 Von Mises stress of the area with double defects under different inner pressures

The double corrosion defect interval is 15°. The influence of the corrosion defects of double head on the stress and strain under the different operating pressure of the three-phase separator is shown in Figure 12 and figure 13. As shown in Figure 12, when the running pressure is 1.7MPa, the stress concentration occurs in the interior of the double corrosion defects, and the two corrosion defect shows obvious stress concentration in the centre. When the running pressure increases to 2.2MPa, the stress concentration phenomenon begins to appear between the corrosion defect edge zone and the two corrosion defect. As the running pressure continues to increase, the stress concentration between the corrosion defect area and the defect is becoming more and more obvious. In

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Fig.13, the strain nephogram of the head corrosion under different running pressure is known, When the running pressure increases to 3.2MPa, slight plastic deformation begins to occur at the bottom of the spherical corrosion defect. As the running pressure continues to increase, the plastic deformation is gradually extended to the whole corrosion defect. However, no obvious plastic deformation occurs between the two corrosion defects. Therefore, under different operation pressure, the interaction between corrosion defects at intervals of 15° is not obvious and can be ignored. It also confirms the conclusion in Figure 11.

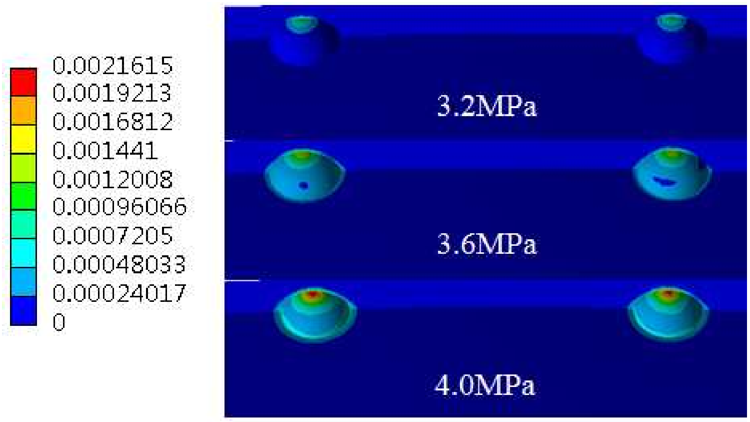
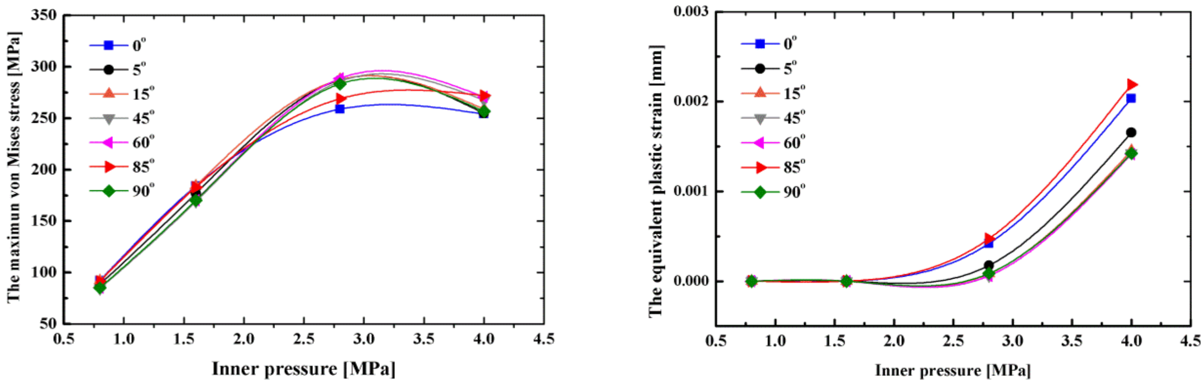


Fig.13 Plastic strain of the area with double defects under different inner pressure



(a) Local von Mises stresses (b) Equivalent plastic strain

Fig.14 Stress-strain of multiple sets of double defects with the internal pressure

As shown in Figure 14, the influence of operation pressure on equivalent stress and equivalent strain of double head corrosion defect area is described under different interval conditions. From Figure 14(a), in the case of double head corrosion defects at different intervals, the equivalent stress presents a parabola tendency to increase first and then decreases with the increase of operating pressure. That is to say, in elastic deformation stage, the equivalent stress in the corrosion area of the head increases gradually with the increase of operation pressure, But in the plastic deformation stage, it gradually decreases with the increase of the running pressure. It conforms to the basic principle of material deformation. In addition, it can be seen from Figure 14 (a) that in the elastic deformation stage, the effects of the equivalent corrosion force on the double corrosion defects at different intervals are basically the same, but there is some difference in the plastic deformation stage. The equivalent stress at other distribution angles is greater than that of the interval 0° (a single corrosion defect), but the effects of different intervals are very small. Because the head material undergoes the elastic deformation stage, the yielding stage and the plastic deformation stage with different operation pressure. Therefore, in Figure 14 (b), the equivalent effects of the double head corrosion defects appear to remain the same at first, then slowly increase, and finally increase rapidly with the increase of operating pressure. In the elastic deformation stage, the equivalence effect of the defect angle almost has no influence. In the yield stage, the difference of the effects of different defect angles increases gradually with the increase of the operation pressure. Except under the interval 85°, the equivalent effects under the rest of distributions are less than 0°, but the gap is still small. In the plastic deformation stage, the equivalent stress remains almost the same at different interval angles. Therefore, the change in the location of the double head defects has almost no influence on the stress and strain in the defect region in the elastic deformation stage. The yield stage and the plastic deformation stage have smaller effects. Compared with intervals of 0°(single defects), other intervals (double corrosion defects) will increase the head stress at the same operating pressure, and then reduce the failure pressure in the corrosion defect zone.

Conclusions

The equivalent stress and the plastic strain and strain distribution in the flaw area of the three-phase separator with spherical defects show: With the increase of internal pressure, the stress concentration appears at the bottom of the spherical defect and gradually affects the whole area of the defect, And the thickness direction decreases faster than other directions, so that the top surface of the head is low stress area. The maximum equivalent stress in the corrosion zone reaches the yield limit, which may lead to the deformation or failure of the head.

Change the size of the single spherical defect at the top of the three-phase separator head. In the initial stage, the equivalent stress of the defect zone increases with the increase of the diameter of the spherical defect at the top of the head. Subsequently, the range of equivalent stress decreases, but the influence of defect size is not obvious. It is obviously larger than the equivalent stress at the top of the head when there is no defect. The size of the head of the three-phase separator significantly affects the equivalent stress and plastic deformation in the defect zone. However, there is little difference in equivalent stress and strain near the diameter of 14mm and 16mm.

Change the location of double spherical defects on the head of the three-phase separator. At interval of 5°, the interaction between the two defects is significant. The stress concentration occurs simultaneously between the interior of the spherical defect and the two defects. With the increase of internal pressure, it continues to affect the whole area. If the angle is greater, the interaction between the two defects is weaker, and the interaction of the two defects can be neglected. The change of the double defect position has a little influence on the strength of the defect zone. To some degree, the increase in the number of defects will have an effect on the failure pressure.

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