Study on the stress and deformation of a diaphragm compressor cylinder head under extreme conditions

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Abstract. When a high-pressure diaphragm compressor applied in the hydrogen refueling station, the structure strength of the cylinder head are one of the most important evaluation criteria to guarantee the reliability and efficiency of the diaphragm compressor. Considering the thermal stress, this paper described a thermal-structural coupled analysis on the cylinder head of a diaphragm compressor, in which the thermal analysis was carried out, and then the structural analysis was performed based on temperature distribution. The stress and deformation of the cylinder head under high-temperature and high-pressure conditions were obtained. The experimental method was also conducted for the verification of thermal analysis. Results indicated that during the operation of the compressor, the temperature in the discharge holes was the highest, and the stress caused by high temperature and high working pressure in the discharge holes could reach a high level due to the restriction of the structure. As a result, the region where the discharge holes were opened on the cavity surface protruded into the diaphragm cavity, resulting in plastic deformation, and the plastic deformation would also result in hydrogen embrittlement, influencing the strength of the cylinder head.

1. Introduction
Hydrogen plays an important role in developing a low-emission, environment-friendly, clean and sustainable energy system [1-2]. The fuel cell vehicles (FCVs) using hydrogen as a fuel have become a research hotspot because they are recognized as zero-emission vehicles and will not affect existing grid systems. As systems and technologies become more sophisticated, the FCVs will be more competitive than pure electric vehicles, and this is why many automobile manufacturers are keen on hydrogen fuel cells. Obviously, the FCVs are one of the most potent vehicles in the future guaranteed by the development of related technologies. Hydrogen fueling stations, which apply the hydrogen fuel to the FCVs, are essential elements and important infrastructures for the operation of the FCVs [3].

In a hydrogen fueling station, hydrogen gas is compressed to a high-pressure of 5000 psi to 10,000 psi and is then stored in high-pressure vessels before being dispensed to the FCVs [4-6]. The preferred method for hydrogen gas compression is to use a diaphragm compressor because the metallic diaphragm of the diaphragm compressor completely separates the gas and hydraulic oil system to ensure the purity of the gas without any pollution to the gas [7]. The advantages of low power consumption, low cooling requirement and ideal for handling pure gases make diaphragm compressors specialized piece of equipment for hydrogen fueling stations. Normally, a hydrogen diaphragm compressor with a hydraulic drive is mainly comprised of a driven piston, a hydraulic oil system, a diaphragm set, and a compression chamber, as shown in figure 1. When the piston approaches the bottom dead center, the diaphragms are now at their closest position to the perforated plate and the gas suction process is completed. Then, the piston begins its upward stroke toward the cavity, and the
The diaphragm is then pushed to compress the gas in the gas space by the hydraulic oil. When the gas pressure reaches the discharge pressure, the discharge valve opens and the diaphragm begins to come into contact with the cavity surface, until the piston reaches the top dead center, where the oil pressure reaches its peak. After that, the piston begins its downward stroke and the diaphragm deforms downward, starting the suction process [8].

![Figure 1. The schematic of a diaphragm compressor with a hydraulic drive.](image)

Previous studies mainly focused on the two shortcomings of a hydrogen compressor: low flow rate and short diaphragm life. Wu et al. [9] analyzed the stress distribution in the diaphragm as it clung to the cavity surface and provided an optimization algorithm for the traditional generatrix equation of a cavity profile. Hu et al. [10] proposed a new generatrix for cavity profile through optimization using the complex method to decrease the maximal radial stresses on both oil and gas sides of the diaphragm clinging to the cavity surface. Wang et al. [11] designed a new generatrix that was composed of two different polynomials. Jia et al. [12] investigated the influencing factors of the diaphragm radial stress, including the radius of the groove fillet, the groove width, and the diaphragm thickness. However, when the high-pressure diaphragm compressors are applied in the hydrogen fueling stations, the demand for super high pressure also causes them to be weakened by mechanical stress during operation. The stress and deformation of the cylinder head affected by high pressure and high temperature will also affect the stress distribution of the diaphragm, thus affecting the life of the diaphragm.

This paper describes a thermal-structural coupled analysis on the cylinder head of a diaphragm compressor, in which the thermal analysis was carried out, and then the structural analysis was performed based on temperature distribution. The stress and deformation of cylinder head under high temperature and high-pressure conditions were obtained. Additionally, the experimental method was also conducted for mutual verification.

2. Numerical modelling

2.1. Geometric Model of Diaphragm Compressors

In this study, the geometric model of a diaphragm compressor was designed based on a real diaphragm compressor and was simplified before numerical modeling due to its complexity, as shown in figure 2. The 3D representation of the diaphragm compressor was obtained including the cavity, discharge valve, suction valve, valve retainers, glands, main studs, valve studs, diaphragm set, and hydraulic flange. Furthermore, the cooling channels were also provided in the cavity and the hydraulic flange for taking away the heat generated during the compression process. Table 1 shows the designed parameters for the diaphragm compressor in details.
Table 1. Main parameters of the diaphragm compressor in this study.

| Parameters                                      | Value  |
|------------------------------------------------|--------|
| Diameter of cavity (mm)                        | 560.00 |
| Diameter of diaphragm (mm)                     | 405.00 |
| Thickness of diaphragm (mm)                    | 0.50   |
| Diameter of cooling water channel (mm)         | φ18.5  |
| Discharge pressure (MPa)                       | 45     |
| Suction pressure (MPa)                         | 5      |
| Suction temperature (°C)                       | 0      |
| Cylinder head studs                            | M45×16 |
| Gland studs                                     | M16×12 |
| Tightening force moment of main studs (N·m)    | 4050   |
| Tightening force moment of valve studs (N·m)   | 64     |

Figure 2. Geometric model of the diaphragm compressor in this study.

Hydrogen embrittlement is a widely known phenomenon in high strength materials, so as for a hydrogen diaphragm compressor, it is necessary to carefully select the material used. In this study, the cavity, discharge valve, suction valve, valve retainers, and the diaphragm were all made of 316L stainless steel, and the material of hydraulic flange was 40Cr steel, while the material of the main studs and valve studs were 35CrMo steel, and the gaskets on the suction and discharge valves were made of copper. The mechanical parameters of the four materials at normal temperature and pressure conditions are shown in table 2.

Table 2. The mechanical parameters of the four materials.

| Material   | E(GPa) | μ    | \(\sigma_s\) (MPa) | \(\sigma_b\) (MPa) | \(\rho\)(Kg·m\(^{-3}\)) | \(\lambda\)(W·m\(^{-1}\)·K\(^{-1}\)) |
|------------|--------|------|--------------------|--------------------|-------------------------|-------------------------------|
| 316L       | 193    | 0.31 | 210                | 586                | 7750                    | 16.1                          |
| 40Cr       | 211    | 0.277| 785                | 980                | 7850                    | 60.5                          |
| 35CrMo     | 210    | 0.28 | 930                | 1080               | 7850                    | 44                            |
| Copper     | 110    | 0.34 | 280                | 430                | 8300                    | 401                           |
2.2. **Mesh Generation**

The cylinder head of the diaphragm compressor has a complicated structure, the outer diameter of the cavity is 560mm, while the diameter of the discharge holes and the suction holes is only 2 mm, which increase the difficulty of meshing. In addition, considering the actual operation conditions, the temperature in the discharge would be the highest, where the thermal stress could also reach a high level. So in this study, the area where the discharge holes were opened in the center of the cavity was specially divided for a finer mesh with the minimum grid length of 0.2mm, while the other parts of the cylinder head were meshed in coarser grids with the maximum grid length of 10 mm, as shown in figure 3 and figure 4. At the same time, the mesh quality was kept at a reasonable level to ensure high speed of computation.

![Figure 3. Mesh in the cylinder head.](image)

![Figure 4. Mesh in the discharge holes of the cavity.](image)

2.3. **Simulation Method**

The simulation process was divided into two parts. Firstly, the thermal analysis was carried out to obtain the temperature distribution of the diaphragm compressor cylinder head during the operation of the compressor, and secondly the static structural analysis coupled with temperature field was performed to obtain the deformation and stress results of the cylinder head.

For thermal analysis, in order to accurately simulate the temperature distribution of the diaphragm compressor cylinder head, the third boundary conditions were applied to the cylinder head including the outer surface, suction valve, discharge valve, water channels, cavity surface and the perforated plate. The environment temperature was kept as 10 °C, oil temperature was 60 °C, the suction temperature was 0 °C, and the inlet temperature of the cooling water was 12 °C. The selection of heat transfer surface is shown in figure 5.

![Figure 5. Heat transfer surfaces of diaphragm compressor cylinder head.](image)

For structural analysis, the analysis contained three loading steps, the first loading step was used to apply tightening force moment on the studs, and the tightening force moment was set up to lock in the remaining two loading steps to lock the displacement caused by pre-tightening force. This simulated the real bolt pre-tightening situation of diaphragm compressor cylinder head. In the third step, the discharge pressure load of 45 MPa was applied on the cavity surface and the perforated plate.
respectively to simulate the working condition of the compressor during the discharge process. Meanwhile, the temperature field obtained by the thermal analysis had been imported into the model in the third step.

Furthermore, in order to accurately determine the influence of thermal stress on the strength of the cylinder head, three simulated operating cases were obtained: cases 1 was the structural analysis of the diaphragm compressor cylinder head under the action of tightening force moment only, case 2 was structural analysis under combined action of tightening force moment and the working pressure of 45 MPa, and case 3 was analysis under the combined action of tightening force moment, working pressure and temperature filed.

316L stainless steel has a wide range of applications in the petrochemical industry due to its excellent corrosion resistance. However, compared with structural steel, 316L stainless steel has much lower strength and the strength is greatly affected by temperature. In this study, since the material of the cavity was 316L stainless steel and the temperature of the cavity was also significantly affected by the discharge temperature, it is necessary to consider the physical parameters and the Plastic Strain-Stress curves of the 316L stainless steel at different temperatures, as shown in figure 6 and figure 7.

Figure 6. Physical parameters of 316L stainless steel.
3. Experimental validation
To obtain the temperature distribution of the compressor cylinder head during working processing, a test rig was built by utilizing a two-stage diaphragm compressor, and the second stage cylinder head of the compressor was taken as the research object. The main parameters of the diaphragm compressor in the test rig were in accordance with Table 1. The rotational speed is 420 rpm, and the gas flow-rate of the diaphragm compressor is 200 Nm$^3$/h. The nominal suction and discharge pressure of the second stage is 5 MPa and 45 MPa, respectively, and the suction temperature is 0 °C. In addition, the inlet temperature of the cooling water is 12 °C. During the operation of the compressor, Five Pt100 temperature transducers were mounted on the cylinder head to measure the temperature in the cylinder head outer surface, and the measurement accuracy is 0.02% FS.

4. Results and discussion
4.1. Results of the steady-state thermal analysis
Figure 9 and figure 10 show the comparison of the temperature between the simulation results and the experimental results at the same measuring point on the cylinder head. It is indicated that the simulated temperature at each point was consistent with the experimentally measured temperature, and thus verifying the validity of the thermal analysis model.

Figure 11 is the temperature distribution in the cavity and cavity surface. Results show that due to the effect of cooling water channels and the large difference in suction temperature and discharge temperature, the temperature distribution in the cavity was uneven. The temperature in the discharge holes was the highest, and the maximum temperature was 257 °C. And the temperature gradient around the discharge holes of the cavity was also large.
4.2. Results of the structural analysis

Figure 12, figure 13 and figure 14 describes the equivalent stress distribution of the diaphragm compressor cavity at three different operating cases, and the area where the discharge holes are opened in the center of the cavity surface is separately divided for a more intuitive comparison. This shows that the maximum stress of the discharge holes under the action of tightening force moment only (case1) was about 64 MPa, while the maximum stress of the discharge holes under the combined action of tightening force moment and working pressure (case2) was 72 MPa, and under the combined action of tightening force moment, working pressure and temperature filed (case3), the maximum stress of the discharge holes was 385 MPa, which was approximately six times higher than that with case1, and was much higher than the yield strength of 316L stainless steel at 250 °C. Results indicates that during the operation of the high-pressure diaphragm compressor, both the high working pressure and high discharge temperature would affect the strength of the cylinder head, and the influence of high temperature was even worse.
The axial relative displacement of the diaphragm compressor cavity surface three different operating cases is presented in figure 15, figure 16, and figure 17. A negative displacement indicates that the cavity surface protrudes into the gas space, and a positive displacement indicates that the cavity deforms in a direction away from the gas space. It reveals that when only the tightening force moment of the studs applied on the cylinder head, due to the asymmetrical structure of the cavity, the maximum displacement was located at the edge of the cavity near the side of the suction valve. While when the temperature field was applied in the model, the position of the maximum deformation transferred to the center of the cavity surface, the region where the discharge holes were opened on the cavity protruded into the gas space, and the deformation could reach about 0.46 mm. Figure 18 shows the deformation of the cavity surface at a magnification of 50 times. Results indicate that during the operation of the high-pressure diaphragm compressor, the temperature at the discharge holes was the highest, and the thermal stress of the discharge holes could reach a high level due to the restriction of the structure and thus results in plastic deformation of the cavity surface.
From above analysis, we can see that the load transmission method C in which the compressor package was simplified as a super-element was more accurate than method B in which the compressor package was simplified as mass elements. It maybe because both of the mass and stiffness of the compressor package were taken into account in the super-element of method C, but the stiffness of the compressor package was not considered in method B. Besides, simplifying the compressor package as a super-element can greatly save the computational time compared to the whole coupled model of the offshore platform and compressor package. Therefore, it is advisable to simplify the compressor package to a super-element when performing vibration analysis for the offshore platform.

5. Conclusion
In this paper, the strength of a diaphragm compressor cylinder head were discussed focusing on the stress and deformation of the diaphragm compressor cavity under high-temperature and high-pressure conditions, and a thermal-structural coupled analysis considering both the heat transfer analysis and structural analysis was presented. The main conclusions are given below.

- When the pressure ratio was too high, the discharge temperature of the high-pressure diaphragm compressor could reach above 200 °C, and the highest temperature was located in the discharge holes of the cavity surface, where the temperature gradient was also large.
- During the operation of the compressor, both the high working pressure and high discharge temperature would affect the strength of the cylinder head, and the influence of high temperature was even worse. The place with the lowest strength of the cylinder head was located at the discharge holes, and the stress of the discharge holes could reach a high level, which would be higher than the yield strength of 316L stainless steel.
- Considering the restriction of the structure and the material of the cavity, the region where the discharge holes were opened on the cavity surface would protrude into the gas space due to the high pressure and high temperature in the discharge holes, resulting in plastic deformation in the discharge holes, and the deformation can reach about 0.46mm.
- The diaphragm compressor is one of the most promising compressors for the hydrogen refueling stations. However, method must be taken to reduce the excessive temperature of the cylinder head discharge holes, thereby avoiding the plastic deformation of the cavity. The thermal-structural coupled analysis is an effective method to predict performance of the diaphragm compressor.

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