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Study on the diaphragm fracture in a diaphragm compressor for a hydrogen refueling station

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ABSTRACT

When a diaphragm compressor applied in the hydrogen refueling stations, the diaphragm fracture occurred frequently in the edge and middle region of the outer circular groove of the perforated plate. The unstable operation of the plunger pump caused the oil shortage in the oil cylinder, so the diaphragm would cling to the perforated plate while the piston reached the bottom dead center. Thus, the diaphragm in the groove region would endure the radial stress caused by the large deflection deformation and the additional stress caused by the perforated plate's groove. In this paper, a theoretical calculation method combined with the thin-plate large deflection theory and the thin-plate small deflection theory was proposed to analyze the two kinds of the radial stresses. The experimental and numerical methods also were conducted for mutual verification. Furthermore, the influencing factors of the diaphragm radial stress were investigated, including the radius of the groove fillet, the groove width and the diaphragm thickness. The results indicated that the radial stress caused by the large deflection deformation is similar to that caused by the small deflection deformation. The maximum radial stress of the diaphragm increased slowly with the increase in the radius of the groove fillet. But with increasing the diaphragm thickness or decreasing the groove width, both the deflection and the radial stress of the diaphragm had an obviously decrease.

Introduction

With the rapid progress of fuel cell vehicle in the world, a number of hydrogen fueling infrastructure stations have been built to provide hydrogen fuel for vehicles [1–3]. In a hydrogen fueling station, hydrogen gas is compressed to achieve a high-pressure of 5000 psi to 10,000 psi and is stored in high-pressure vessels [4–10]. There are mainly two methods for the hydrogen compression, the mechanical hydrogen compressor and the electrochemical hydrogen compressor. The advantage of the electrochemical hydrogen compressor is that hydrogen separation and compression are achieved in a single one step process, so the electrochemical hydrogen compressor in a polymer-electrolyte-membrane (PEM)-cell is more effective than mechanical hydrogen compressor just for some specific applications, such as low power applications, and the mechanical hydrogen compressors are more suitable and efficient for normal applications [11–13]. However, the leakage of mechanical compressor and dispenser are currently the main contributors to the total risk of a hydrogen

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Nomenclature

C	integral constant
D	bending rigidity, N/m^2
E	Young's modulus, MPa
F	average reacting pressure, MPa
H	deflection of the diaphragm, mm
H_0	deflection of the diaphragm in the center or deflection of the perforated plate, mm
M_i	the radial moment of the diaphragm, Nm
p	suction pressure, MPa
Q_i	shear stress of the cross section of a circle with radius r_i, MPa
q	support reaction, N
r	radius of the diaphragm, mm
r_1	radius (length) of the OA, mm
r_1	inside radius of outer groove (length of the OB), mm
r_1	outside radius of outer groove (length of the OC), mm
r_1	radius (length) of the OA, mm
R	radius of the perforated plate, mm
t	thickness of the diaphragm, mm
w_1	deflection of part AB
w_2	deflection of part BC
w_3	deflection of part CD
Z	deflection exponent of the perforated plate's generatrix
ε_r	radial strain of the diaphragm
ε_t	circumferential strain of the diaphragm
θ	deflection angle of the diaphragm or deflection angle of the perforated plate's generatrix, °
μ	Poisson's ratio
σ_a	allowable radial stress of the diaphragm, MPa
σ_{Gr}	radial stress of the diaphragm's lower surface, MPa
σ_{Fr}	radial stress of the diaphragm's upper surface, MPa
σ_r	radial stress of the diaphragm, MPa
σ_t	circumferential stress of the diaphragm, MPa

fueling station [14,15]. So the diaphragm compressor has become the best choice for compressing hydrogen because it ensures gas purity without any leaking [16]. Moreover, the mature leak-detecting system of diaphragm compressor also can reduce the risk to a minimum. Compared with other types of compressors, the special structure of the diaphragm compressor provides a lower compression index and higher volumetric efficiency, which are both beneficial for energy saving. Meanwhile, the periodic maintenance of the seals and diaphragms of the compressor is relatively easy [17].

However, the frequent diaphragm failure is a shortcoming of a diaphragm compressor. A fracture is the most common mode for a diaphragm failure. A diaphragmatic fracture usually occurs in three positions: the edge of the diaphragm, the center of the diaphragm and the region contacting the outer groove of the perforated plate [18]. The first two are caused by the cavity profile of a diaphragm and researched in previous studies. The generatrix equation for the cavity profile of a diaphragm compressor has a significant influence on the diaphragm's fatigue life. The traditional generatrix is a single exponential polynomial. Wu et al. [19] analyzed the stress distribution in the diaphragm as it came into contact with the cavity surface and provided an optimization algorithm for the traditional generatrix equation of a cavity profile. Ban [20] analyzed the stress variation in the diaphragm during the compression process using an iteration method. Wang et al. [21] designed a new generatrix that was composed of two different polynomials. The stress distribution of the diaphragm in the cavity with the new generatrix was more uniform than with the traditional one, although the cavity volume hardly increased and the compressor's flow rate was still extremely low. Altukhov et al. [22,23] found that the diameter of the discharge holes in the cavity was the significant factor that influences diaphragm's fatigue life. Li et al. [18,24] indicated that exceeding the radial stress is the root cause of diaphragm failure. A new generatrix of the cavity profile of a diaphragm compressor, together with an optimization algorithm, was developed. The research results indicated that the diaphragm exhibited low radial stress, as it clung to the cavity when the new generatrix was employed. However, little research has been conducted on the diaphragm's fracture occurred in the third position, which is caused by the outer groove of the perforated plate.

Thin-plate large deflection theory and thin-plate small deflection theory are the main basis for the theoretical analysis of the diaphragm radial stress as it clung to the perforated plate [21,25]. Von Kaman's equations describe the thin circular plate under uniform loads [26]. Many valid methods have been subsequently developed for thin plate, including the finite element method [27], perturbation and variation methods [28], the locally transversal linearization method [29], and the modified iteration method [30].

Previous studies and diaphragm failure cases indicate that exceeding the radial stress is the root cause of diaphragm failure. The purpose of this study was to research the diaphragm fracture caused by the outer groove of the perforated plate. A theoretical calculation method combined with the thin-plate large deflection theory and the thin-plate small deflection theory was proposed to analyze the diaphragm radial stress as the diaphragm clung to the perforated plate due to the lack of hydraulic oil. Meanwhile, the numerical simulation also was applied to research on the diaphragm radial stress, and the experiments had been carried out to verify the theoretical and numerical methods. Furthermore, the influencing factors of the diaphragm radial stress were investigated, including the fillet of groove, the groove width and the diaphragm thickness. The results indicated that the maximum radial stress of the diaphragm could be decreased obviously with increasing the diaphragm thickness or decreasing the groove width when the diaphragm clung to the perforated plate.

Analysis of diaphragm fracture

The structure of the diaphragm compressor is shown in Fig. 1. When the piston is at the top dead center, the oil pressure