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Finite element analysis for adhesive failure of progressive cavity pump with stator of even thickness

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ABSTRACT

Compared to conventional progressive cavity pump (PCP), even thickness PCP has numerous advantages such as uniform thermal and swelling expansion, stable operation and high volumetric efficiency. However, adhesive failure occurs on the stator of even thickness PCP more often in actual working conditions, which limits its development and application. In this study, finite element models of conventional PCP and even thickness PCP with the same structural parameters are established and simulated to find the mechanism for adhesive failure. We primarily study the force conditions of adhesive interface which bonds the stator and cylinder sleeve. The results show that shear strain caused by hydraulic pressure difference and interference displacement is quite large around the adhesive interface of even thickness PCP. The too large shear strain around the adhesive interface is the main cause of adhesive failure. Based on this analysis, the relationship between the shear strain and design parameters, such as the rubber adhesion ratio, pressure difference, elastic modulus of stator, magnitude of interference and wall thickness, is investigated. Our results show that the shear strain increases greatly and adhesive failure tends to occur in certain conditions. Furthermore, two new techniques to enhance the adhesive performance are presented and validated with our finite element analysis. Our research can be of great significance for guiding the design and optimization of even thickness PCPs.

1. Introduction

At present, progressive cavity pump (PCP), which is a kind of artificial lift devices devised by Moineau in the 1930s (Saveth and Klein, 1989; Moineau, 1930), has been widely used in various oil field productions, especially in heavy oil fields, due to its numerous technical advantages such as low power consumption and low initial investment (Liu et al., 2005; Ramos et al., 2007; Wu and Li, 2010). The PCP consists of a single helical rotor rotating eccentrically inside a double threaded helical elastomeric stator of twice the pitch length. Cavities in which oil is stored are formed between the rotor and stator, and when the rotor rotates the cavities move helically. The contact line between rotor and stator seals the cavities among themselves (Moreno and Romero, 2007).

During the operation of PCP, the stator is prone to failure. The hydraulic pressure and interference displacement between the rotor and stator squeeze the elastomeric stator. The eccentrically rotating rotor impacts the stator periodically. The stator is seriously worn by the sand contained in the oil. The stator is embrittled and hardened due to the high temperature and some chemical substances (Delpassand, 1997; Feluch and Hiney, 2002; Gai and Dai, 2008).). All these factors can lead the stator to failure. The failure of stator, including wear and tear, burning pump, tear of stator and adhesive failure, is the main failure mode of PCP.

PCP usually works in heavy oil under 50–80 °C, the swelling and thermal expansion is very likely to occur for the rubber of stator (Zhang et al., 2009). For the uneven thickness stator of conventional PCP, non-uniform thermal and swelling expansion results in local serious abrasion of stator, which is the primary failure mode of conventional PCP (Zhang et al., 2009; Sheldon et al., 2010). Even thickness PCP is a good alternative to solve the problem since the thermal and swelling expansion of its stator is small and uniform (Zhang et al., 2010; Zhou et al., 2013). Even thickness PCP also shows other advantages such as stable operation and high volumetric efficiency. It has been more and more widely used in various oil field productions. However, adhesive failure occurs on the stator of even thickness PCP more often during the actual operation, which limits its development and

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application. Fig. 1 shows the actual adhesive failure cases of even thickness PCPs used in Daqing oil field. The cause of adhesive failure is complicated and its mechanical mechanism has not been found yet. No finite element simulation results in this regard have been reported previously.

In this study, finite element models of conventional PCP and even thickness PCP with the same structural parameters are established to study the force conditions of their adhesive interfaces (Liu et al., 2010). We primarily simulate and compare the stress–strain field and deformation of the adhesive interface in actual working conditions to find the mechanism for adhesive failure. The relationship between the shear strain and design parameters, such as the rubber adhesion ratio, pressure difference, elastic modulus of stator, magnitude of interference and wall thickness, is further investigated. Finally, two new adhesive methods are put forward to improve the adhesive performance. Finite element models are employed to simulate and compare the adhesive performance of different adhesive methods.

2. Finite element modeling and simulation method

In our previous work, a three dimensional finite element model of PCP has been established successfully (Zhou et al., 2013). The computed laden torque and volumetric efficiency for the given design parameters are in good agreement with experimental result of laboratory test, which can verify our model and simulation method (Zhou et al., 2013). Zhang et al. (2010) studied the force condition and deformation of the stator. The results of two-dimensional plane strain model are consistent with those of three-dimensional model. For simplicity, two-dimensional plane strain finite element models of PCPs are used in the present work.

Conventional PCP (GLB500) and even thickness PCP (DGLB500) with the same structural parameters are simulated and compared. The models of these two types of PCPs are shown in Fig. 2. The gray parts of the models are the stators of PCPs. The inner and outer radius of circular arcs is 21 mm and 31 mm, respectively. The eccentricity of the rotor is 7.5 mm. In our previous experimental research, we measured the stress–strain curve of the rubber used in the PCPs. Both Yeoh model and linear elastic model are employed to describe the constitutive relationship of stator. The Yeoh model is a hyperelastic material model for the deformation of nearly incompressible, nonlinear elastic materials such as rubber. It can be described by the following equation (Ali et al., 2010)

$$U=\sum_{i=1}^{3} C_{i0}(\bar{I}_1-3)^i+\sum_{i=1}^{3}\frac{1}{D_i}(J-1)^{2i} \tag{1}$$

As Fig. 3 shows, when the strain is small, the Yeoh model is close to the linear elastic model; when the strain is large, the Yeoh model can describe the constitutive relationship of stator more accurately. Thus, in our current work, we use both linear elastic model and Yeoh model. The elastic modulus of linear elastic model is 4.0 MPa, while the Poisson ratio is 0.499 (nearly incompressible). The corresponding parameters of Yeoh model C_{i0} and D_i are 0.667, -0.326, 0.17, 3×10^{-3}, 3×10^{-3} and 3×10^{-3}, respectively. The inside parts of the models are the rotors of PCPs. Since the elastic modulus of the metal rotor is 210 GPa, which is much larger than that of elastomer stator, the rotor is supposed to be rigid in our model. The magnitude of interference can be changed by adjusting the radius of rotor. Both the rotor and the stator are meshed with the element type of CPE4R. In our simulation, the default interference is 0.3 mm and the friction coefficient is 0.25. Since we primarily study the static interaction between rotor and stator, the kinematic velocity is not taken into consideration. In actual working conditions, the stator is bonded to the fixed steel cylinder sleeve, which is the outside part of our models. The deformation of cylinder sleeve is very small and it can be supposed as rigid. The force condition of the stator's outside boundary is equal to that of adhesive interface.

Fig. 1. Cases of adhesive failure of even thickness PCP used in Daqing oilfield.

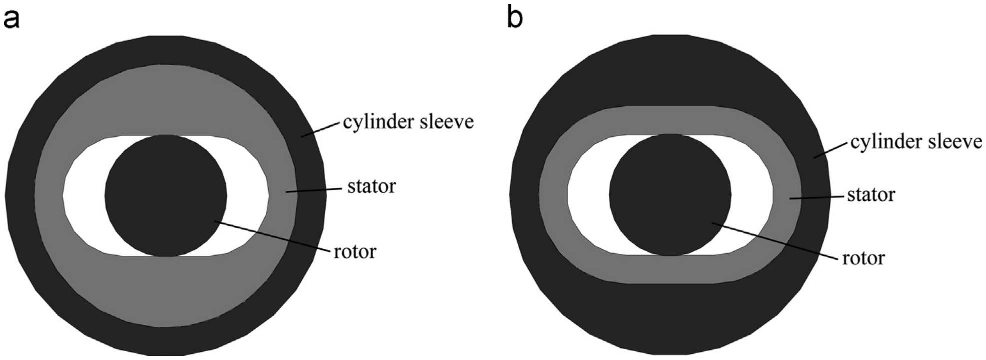

Fig. 2. Finite element models of conventional PCP and even thickness PCP.