Journal of Natural Gas Science and Engineering 44 (2017) 202–213

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Theoretical investigation of the compression limits of sealing structures in complex load transferring between subsea connector components

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ARTICLE INFO

Article history:
Received 1 August 2016
Received in revised form
19 March 2017
Accepted 22 March 2017
Available online 5 April 2017

Keywords:
Lenticular gasket
Subsea collet connector
The amount of compression
Load
Sealing

ABSTRACT

This paper provides a theoretical method for calculating the compression limits of a subsea connector's sealing structure to prevent natural gas leakages. The amount of compression deformation is related to the compressive load between contact surfaces. Because of the different compressive loads on the gasket under preloading and operation conditions, the amount of compression will change. Therefore, the load transmission relations between subsea connector components are first analyzed under different working conditions, and the relationship between the sealing contact load and the locking force is obtained. Secondly, a contact model between the lenticular gasket ring and hubs is established on the basis of Hertz contact theory. An analytical equation for the amount of compression is deduced. Considering the demands for sealing and strength, compression limit equations are put forward. In order to apply the compression limits equations, an optimization model is built for a locking mechanism, and the structure design parameters of one certain subsea connector are optimized. This study provides a theoretical method and guidance for the structural design of subsea connectors with a metallic lenticular gasket.

1. Introduction

Subsea production system (SPS) is one of the most important patterns of deep water oil and gas field development. Subsea production system is usually composed of wellhead trees, manifolds, jumpers, submarine pipelines etc. (Aven and Pedersen, 2014). Subsea connectors, located at the pipe end of a jumper, are the key connection facilities in subsea production system. Subsea connectors are mainly used to interlink subsea production facilities, such as jumpers and subsea trees, jumpers and manifolds, jumpers and PLETs (Bai and Bai, 2012). The key to achieving the connection between different subsea facilities is solving the sealing problem of subsea connectors. If the sealing fails, oil and gas leakage accidents will occur. To make matters worse, the leakages may result in the suspension of the subsea production system and bring about huge economic losses. In addition, subsea systems face challenges in terms of maintainability and repair costs (Vedachalam et al., 2015). Compared with production systems on land, the maintenance of subsea production system has the characteristics of great operating difficulties, long repair cycles, and high costs. Therefore, the sealing problem should receive more attention. Sealing performance is determined by the amount of compression deformation of the gasket, from which it is easy for natural gas to leak. On one hand, the amount of compression cannot be too small to ensure the sealing behaviour. On the other hand, the amount of compression cannot be too large because it would lead to the failure of the structure. This paper mainly studies the analytical method for calculating the compression limits of a subsea connector's sealing structure.

Because of both the high internal pressure medium load and high pressure of external sea water over a long period, metal seals are usually adopted as the solution for subsea connector sealing. Metal sealing is achieved through two metal flange pairs squeezing a metal gasket ring, i.e., metal-to-metal contact sealing, which is

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http://dx.doi.org/10.1016/j.jngse.2017.03.034
1875-5100/

usually used in flange connection systems. ASME Boiler and Pressure Vessel VIII 2 (2013) is the main design standard for the flange connection. This criterion describes the detailed method for calculating the bolt loads and sets gasket constants (gasket factor and minimum design seating stress) for different gasket materials and sections. Studies on metal contact sealing are usually concentrated on analyzing the influence of changes in the bolt load and contact pressure on sealing performance. Sawa et al. (1991) presented a mathematical model for determining the contact stress distribution in the flange connection based on the axisymmetric elasticity theory, and analyzed the gasket contact pressure and the flange stress. Krishna et al. (2007) developed a three-dimensional finite element model for finding the contact stresses on a gasket, and studied the influence of flange rotations on the sealing performance under preloading and operating conditions. Nelson and Prasad (2016) talked about the sealing behaviour of twin gaskets in a flange joint, studied the effect on contact stress with different bolt preloads and internal pressure by finite element method, and proposed an empirical relation to determine the bolt preload for ensuring the minimum compressive stress. Abid and Nash (2003, 2006) analyzed the stress distribution in a flange connection under different bolt loads by FEM. Roos et al. (2002), Bertini et al. (2009), Tenma et al. (2011), Kondo et al. (2013, 2014), all studied the relationship between the bolt loads and the gasket leak rate.

According to different cross-section shapes of the metal gaskets, the common metallic sealing types include flat gasket seals, cone gasket seals, C ring seals, lenticular gasket seals, and octagon gasket seals. There have been a number of studies on different types of metal seals, with most concentrating on the calculation of the locking force and the influence of its changes on sealing performance. Murtagian et al. (2004) introduced the metal-to-metal seal on a tubular connection, and investigated the effectiveness of stationary metal-to-metal seals with respect to contact pressure and load history. Prodan (1982) presented the flange joints with a lenticular gasket and deduced the formulation of bolted preload. Gong et al. (2015) talked about the relationship between the bolt preload and the ring contact pressure distribution on flange joints with a lenticular gasket, established a self-tightening coefficient calculation model, and analyzed the effect of lenticular gasket stiffness and bolted flange stiffness on self-tightening coefficient. Peng et al. (2015) introduced a subsea connector with metal cone gasket, established the calculation model for preload under different conditions, and made an optimized design for the connector locking mechanism. The sealing type of the subsea collet connector studied in this paper is lenticular ring gasket. The previous researches on lenticular ring gaskets have focused on the relationship between the locking force and contact load. And up to now, no literature considers the theoretical relationship between contact load and compression deformation for lenticular gasket. In fact, the sealing performance is directly decided by the compression deformation, the value of which is related to the compressive load, namely contact load between contact surfaces. According to contact theory, the contact load is related to the contact pressure and contact width. In summary, there is an uncertain relation between compression deformation and the contact parameters, such as the contact load, contact pressure, and contact width. Because the metal sealing is face to face, we cannot use test methods to measure the contact pressure distribution and contact width, and the relationships between deformations and the contact pressure as well as the contact width cannot be obtained by tests. In most cases, the Finite Element Method (FEM) is adopted to calculate the contact force and width. However, Finite Element Method takes a long time to conduct trials to determine appropriate design parameters, and this method is usually suitable for verification. Therefore, it is necessary to investigate the theoretical relationship between compression deformation and the contact parameters when studying the sealing problems of subsea connectors.

In the present work, an analytical method for calculating compression limits is developed firstly for the sealing structure of the subsea collet connector with a lenticular gasket. Because of different compressive loads on the gasket under the preloading and operation conditions, the amount of compression will change accordingly. Therefore, first of all, mechanics analyses under different working conditions are implemented, and load transmission relations between subsea connector components are analyzed. The computational equation for the locking force is deduced, and the relationship between the contact load and the locking force is established. Secondly, the theoretical relationship between the sealing contact load and the amount of compression is obtained from the contact model among the lenticular gasket ring and hubs on the basis of Hertz contact theory (Johnson, 1987). Taking the requirements for sealing and strength into consideration, a design principle for the lenticular gasket structure is proposed to determine the limits of the amount of compression. Finally, an analytical equation for calculating compression limits is developed. The contact model is verified by utilizing the finite element method. In addition, this study provides an application case to employ the analytical method for calculating compression limits. In the case, an optimized mathematical model is built for the locking mechanism, and the structural design parameters of one certain subsea connector are optimized by using the load transmission relations and compression limit equations.

2. Theoretical investigation of the limits of compression

2.1. Working principle of the subsea connector structure

As shown in Fig. 1, a horizontal type of subsea collet connector is composed of two parts, i.e., the male connector and the female connector. The structure of the subsea collet connector is axisymmetric. The male connector includes one male-hub, twenty claws, one actuator ring, two fastening bolts, and a seal ring, whereas the female connector consists of one female-hub and one alignment basement. The male connector is welded on the jumper pipe ending, whereas the female connector is located on the pipe end of such subsea production facilities as Manifolds and Trees. The two parts join together and form one sealing channel to realize the connection between different production facilities.

The sectional view in Fig. 2(a) shows the status before locking, whereas Fig. 2 (b) shows the status after locking. The working principle of the subsea collet connector is as follows: the external force provided by the running tool pushes the actuator ring to move, and the moving actuator ring forces the claws radially inwards to lock the male-hub and female-hub. At the same time, the seal ring is squeezed by the male-hub and female-hub, which forms a reliable sealing channel. Various parts transfer forces through contact surface to achieve reliable locking of the subsea connector. As shown in Fig. 2(b), the leakage position is usually at the gasket contact surface, so the sealing problem should receive considerable attention.

The sealing principle of a subsea connector is that contact loads, derived from extrusion between hubs and gasket, cause hub surface and gasket surface deformation, which will fill the microscopic clearance between the contact surface of hubs and gasket, thereby achieving sealing performance. The gasket in this article is a lens type, and the contact region is between the spherical surface of the gasket and conical surface of the hubs. Therefore, the axial cross-section of the subsea collet connector can be regarded as a circular arc in contact with an inclined plane. The width of the contact line is marked as 2b. When it rotates 360° around the center axis, a