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Effects of austenitic stainless steel tube and tubesheet hole dimensional deviations on the hydraulic expansion pressure

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ABSTRACT

The minimum hydraulic expansion pressure for the tube and tubesheet hole is calculated using the common theoretical formula and the finite element method. The effects of the tube and tubesheet hole dimensional deviations on the minimum hydraulic expansion pressure are analyzed. The minimum hydraulic expansion pressure obtained from the theoretical formula cannot guarantee a fit between the tube and tubesheet hole because the effects of dimensional deviations are not taken into account. Even if the dimensional deviations are taken into the formula, the correct pressure values cannot be obtained. Finite element analysis show that the deviations of the tubesheet hole diameter and tube outer diameter, the initial radial gaps, have significant effects on the minimum hydraulic expansion pressure. At the same time, the wall thickness deviation has a linear effect. By fitting the finite element analysis results, a correction coefficient of the theoretical formula is proposed.

1. Introduction

Shell-tube heat exchangers are widely used in petroleum refining, petrochemical industry, coal chemical industry, salt chemical industry, metallurgy, nuclear industry, and other industrial fields. The quality of the tube-to-tubesheet joints has a direct effect on the reliability and service life of heat exchangers. The joint is fabricated by either expansion only, welding only, or a combination of expansion and welding. Tube expansion methods include mechanical rolling, rubber expansion, hydraulic expansion, and explosive expansion. Compared with other techniques, hydraulic expansion has become increasingly used, since it has advantages of convenient operation and good joint quality with low residual stresses [1]. The joint strength, which is usually measured by the residual contact pressure between the tube and tubesheet hole, is strongly influenced by the expansion pressure. Another advantage of the hydraulic expansion is that the prediction to the joint strength is available by common solid mechanics theories. Therefore, many theoretical formulae have been established to calculate the expansion pressure and the residual contact pressure. Based on the assumption of elastic-perfectly plastic material, an analytic solution of the residual contact pressure was given by Krips [2]. Taking the tubesheet as an infinite thick-walled cylinder, Yokell [3] established a more concise formula. The effect of material strain hardening was considered in the model established by Allam et al. [4]. An analytic solution for power law material was proposed by Wang and Sang [5], but the formula has certain restrictions in engineering application due to its complexity.

Although the expansion pressure and the residual contact pressure can be very conveniently obtained from the analytic solutions, pressures obtained from these solutions have certain deviations compared with the actual needed values as fewer factors are considered in the solutions. Finite element method (FEM) can greatly remedy the defect of the theoretical calculation method, and the FEM has been widely used in studying the joint strength. Moreover, the result of the finite element analysis (FEA) is often used to verify and correct a new proposed analytic expression [6]. The effects of the initial radial gap between the tube and tubesheet hole and the material strain hardening on the roller-expanded joint strength were studied using a 2-D axisymmetric model and a 3-D finite element model by Merah and co-workers. The results indicated that the residual contact pressure linearly decreases with increasing the initial radial clearance for strain-hardening materials [7,8]. Wang et al. [9,10] investigated the effects of the geometry of

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grooves, expansion pressure, and operating temperature on the joint strength of hydraulically expanded joints by nonlinear FEA. Considering the effects of the initial radial gap and the material strain hardening, Huang et al. [11] derived analytic expressions for calculating expansion pressure and residual contact pressure, and the results were verified by the nonlinear FEA.

The hydraulic expansion pressure is affected by many factors, including material property, joint strength requirement, geometry and dimensions of tube and tubesheet, and roughness of tube and tubesheet hole surfaces. In this paper, the effect of deviations on the minimum hydraulic expansion pressure was investigated by theoretical calculation and nonlinear FEA. The aim of this research is to modify the formula for calculating the minimum hydraulic expansion pressure and make it more suitable for engineering practice.

2. Theoretical calculation of the minimum hydraulic expansion pressure

At present, theoretical analysis of the hydraulic expansion is established on the basis of the double-cylinder model. The hydraulic expansion process is usually divided into three stages: deformation of the tube, loading on the tubesheet, and unloading. Based on different material performance hypotheses, many formulae have been developed to calculate the expansion pressures of the three stages.

Although the formulae based on the elastic-perfectly plastic material assumption do not involve the material strain hardening and the initial radial gap, they are widely used in engineering practice because of their simple forms. When the tubesheet material around the expanded hole is represented by an annular sleeve, the minimum expansion pressure $P_{\min}$ can be estimated using the following equation [12].

$$P_{\min} = \frac{1}{\sqrt{3}} R_{p0.2} F_p \left(k^2 - \frac{1}{K_1^2} \right) \tag{1}$$

Where $R_{p0.2}$ is the yield strength of the tube material; $k = d_o/d_i$ is the ratio of the tube outer diameter to the inner diameter; K_1 is the equivalent diameter ratio, which reflects the effect of tubesheet material around the tube; F_p is the magnification factor effected by non-compression zone of the tubesheet holes.

When the tubesheet holes are arranged in an equilateral triangle, the equivalent diameter ratio K_1 can be calculated by the following formula

$$K_1 = 2\sqrt{3}H \Big/ D - 2.464 \tag{2}$$

Where D is the tubesheet hole diameter; H is the tube pitch, which is the distance between the adjacent holes, as shown in Fig. 1.

The magnification factor F_p can be calculated by the following formula

$$F_p = 1 + D\sqrt{K_1 - 1} \Big/ 2l \tag{3}$$

Where l is the length of the expanded tube.

Dimensional deviations of the tube and tubesheet hole inevitably exist in manufacturing, but they are not taken into account in Eq. (1). For cold-drawn tubes of austenitic stainless steel with high dimensional accuracy, the outer diameter deviation ε_d and the wall thickness deviation ε_S [13] are listed in Table 1. The tubesheet hole diameter D and deviation ε_D [14] corresponding to the tube are also listed in Table 1.

In order to consider the effects of the dimensional deviations, a tube with diameter = 25 mm and thickness = 2 mm was taken as an example. The tubesheet holes are distributed in an equilateral triangle pattern. The tubesheet hole diameter D and tube pitch H are 25.25 and 32 mm respectively. The length of the expanded tube is 268 mm. The minimum expansion pressure can be calculated using Eq. (1) when the deviations of ε_d, ε_S, and ε_D are taken into account. The mechanical property of materials is listed in Table 2. The calculated results are shown in Fig. 2. The initial radial gap c is equal to $(D - d_o + \varepsilon_D - \varepsilon_d)/2$.

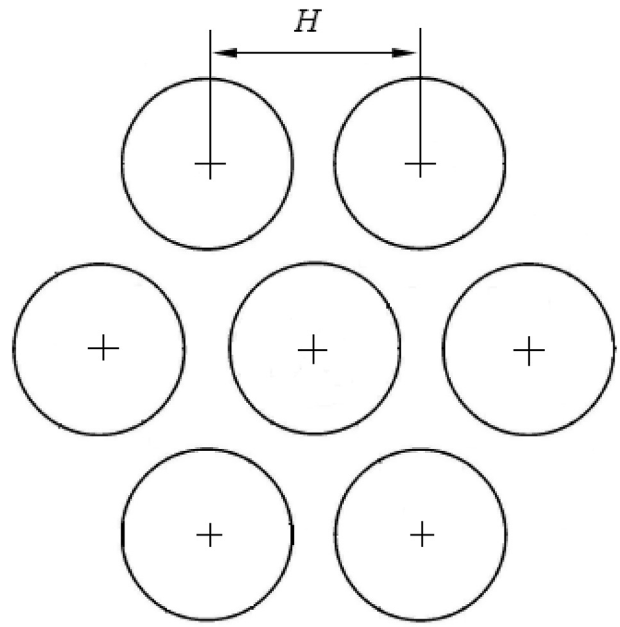

Fig. 1. Tubesheet holes arranged in an equilateral triangle.

It can be seen from Fig. 2 that the wall thickness deviation has a significant effect on the minimum expansion pressure under the same initial radial gap. Otherwise, the initial radial gap has little effect. Whether the above results are correct or not need to be further validated. To further study the effect of the deviations on the minimum expansion pressure, the expansion process was simulated.

3. Finite element analysis

A number of finite element (FE) models have been proposed and employed to simulate the expansion process. In the simulation, 3-D geometry of the real joint may be simplified by a configuration of either a 2-D plane stress or an axisymmetric model [15]. In this study, a 2-D axisymmetric model was established to study the effect of size deviations on the minimum expansion pressure.

3.1. Finite element model

The tube-to-tubesheet joint analysis can be simplified by considering a single tube surrounded by an annular sleeve representing the tubesheet, and the equivalent sleeve diameter can be calculated from the equation proposed by Kohlpaintner [16].