Methods for measuring residual contact pressure of hydraulic expansion joints in heat exchangers

Jingyu Jiang¹,*, Lianfa Yang²,*, Jun Wei³,*, Junjie Han⁴, and Jinjie Huang⁵, *

¹,²,³,⁴,⁵School of Mechanical and Electrical Engineering, Guilin University of Electronic Technology, Guilin, Guangxi, 541004
E-mail:*j Jingyu@163.com, y lianfa@163.com, weijun6268@163.com, d1029314600@qq.com, eJinjieHuang231@126.com

Abstract. The hydraulic expansion of the heat exchanger tube and tubesheet is an important method in the uniform expansion. Compared with other methods, the advantages of hydraulic expansion are high productivity, low labor intensity and reliable expansion performance. This paper describes several common methods for the determination of the residual contact pressure between the tube and tubesheet, and describes the principle, characteristics and the current status of the measurement at home and abroad. This paper also summarizes the development of future methods for measuring the residual contact pressure in the hydraulic expansion joint.

1. Introduction
Hydraulic expansion [1] is a method for the expansion of heat exchanger tubes using direct hydraulic pressure to expand the tube forming the tube-to-tubesheet joint. The heat exchanger tube expands outward under the pressure of liquid media, after removing the liquid media in the tube, the springback quantity of the tube is much smaller than that of the tubesheet hole due to plastic deformation. Meanwhile, the tubesheet hole is in the elastic range and will immediately springback. The contact stress in the tube-to-tubesheet joint is sufficient for the heat exchanger device to obtain enough tightness and pull-out strength, which means that the tube can fit with the tubesheet hole closely. However, the main indicators for measuring the quality of hydraulic expansion are sealing performance and pull-out performance, which are associated with the residual contact pressure. Hence, residual contact pressure is one of the important mechanical parameters to indicate the quality of the hydraulic expansion joint.

This paper discusses a variety of methods for measuring the residual contact pressure in the hydraulic expansion joint that can be divided into the following three types: theoretical and computational methods, finite element analysis methods and experimental methods.

2. Theoretical and computational methods
The residual contact pressure of hydraulic expansions can be determined by theoretical calculations.
Simplified models are usually established for analyses and computation.

In 1943, Goodier et al. [2] applied the elastic-plastic theory to simplify the tubesheet into an infinite plane with holes. The residual stress and residual deformation were preliminarily studied, and then the residual contact pressure was obtained by establishing the curve.

In 1976, Krips et al. [1] used finite circular rings for structural representation of the tubesheet, and proposed a concept of an equivalent sleeve. The ring structure is denoted as an equivalent sleeve, and a formula for the residual contact pressure was proposed:

\[
\frac{p_c^R}{p_1 - p_c} = \left(1 + \frac{(k_\delta^2 - 1)}{(k_i^2 - 1)} \right)^{-1}
\]

(1)

Where \(p_c^R\) and \(p_1\) respectively indicate the residual contact pressure and the expansion pressure, \(\mu_s\) is the Poisson’s ratio of the tubesheet material, \(K_t\) and \(K_s\) respectively indicate the ratios of outer and inner radii of the tube and tubesheet (the following parameters are the same). Krips et al. assumed that the tube and tubesheet are ideal elastic-plastic with the same elastic modulus. When the elastic moduli of the tube and tubesheet differ greatly, the formula (1) is no longer applicable.

In 1991, Yokell [3] assumed that the tube and tubesheet is ideal elastic-plastic and the thickness of the outer tube wall is infinite. Yokell established a formula for the residual contact pressure:

\[
p_c^R = p_1 \left(1 - \frac{r_1^2}{r_o^2}\right) \frac{2}{\sqrt{3}} \delta_{st} \ln \left(\frac{r_o}{r_1}\right)
\]

(2)

Where \(r_1\) and \(r_o\) respectively indicate the inner and outer radii of the heat exchanger tube, \(\delta_{st}\) is the yield strength of the tube (the following parameters are the same). The formula (2) is simple and it indicates that the residual contact pressure is associated with the yield limit, inner and outer diameters of the tube. However, the shortcomings of the formula (2) are the same as those of the formula (1), and the result of formula (2) is always smaller than that of the formula (1).

In 1992, Chaaban et al. [4] utilized statistical methods and established an empirical equation for the outer diameter of the equivalent sleeve. A more practical empirical formula was proposed, and the stress in the transition zone was analyzed by theoretical and computational methods.

In 1995, Kohlpaintner [5] assumed the heat exchanger tube to be a 19-hole tubesheet model with triangular hole patterns, and established a more perfect equation for the equivalent sleeve outer diameter. The empirical formula of the equivalent sleeve diameter was obtained to calculate the residual stress by analyzing the mechanical properties of the perforated tubesheet.

In 1996, Huigeng Y et al. [6] assumed that there is no strain enhancement in the tube during the expansion. Elastic-plastic analysis method was utilized to establish a two-dimensional single-tube model. The residual contact pressure \(p_c^R\) was given by:

\[
p_c^R = (1 - 2c) p_1 - \delta_{st} \ln K_t
\]

(3)

Where \(c\) is associated with parameters such as \(E_t\), \(E_s\), \(K_t\), \(K_s\), \(\mu_s\), \(\mu_t\), etc. \(E_t\) and \(E_s\) respectively indicate the elastic modulus of the tube and tubesheet. \(\mu_t\) indicates the Poisson's ratio of the tube.

In 2001, Huigeng Y et al. [7] realized that the elastic-plastic theory utilized for hydraulic expansion analysis would generate large errors. The calculation of the deformation curve and the slope after the drawing was performed and the value of residual contact pressure was calculated. The accuracy of this method is related to the material and the degree of deformation of the tube.

In 2007, Laghzale N E et al. [8] proposed a new elastic-plastic model which can accurately predict the residual contact pressure. With the single-tube sleeve model, they assumed that the model of the tube and tubesheet is ideal. Meanwhile, the strain hardening was not neglected.
In 2010, Chen G et al. [9] focused on the analysis of two theoretical and computational models for the residual contact pressure: an ideal elastic-plastic model and a power hardening material model. The two models of the tube were numerically simulated, and the results of the numerical analysis were compared with those of the theoretical model in this analysis.

In summary, the formulas proposed by Krips, Yokell, and Huigeng Y et al. are derived on the basis of the ideal elastic-plastic model. Hence, the calculated value of the residual contact pressure is smaller than the actual one. Although the formula established by Huigeng Y et al. is simple and requires fewer known parameters for materials, however, the effect of gaps is neglected. It is more accurate that Laghzale N E et al. took the strain hardening of the material into account.

3. Finite Element Methods
The finite element method (FEM) is a numerical method for solving problems of engineering and mathematical physics. Within the linear and nonlinear finite element analysis, the residual contact pressure can be obtained.

In 1984, Scott et al. [10] used stress corrosion, X-ray diffraction and other methods to study the residual stress and residual deformation in the expansion joint. Scott studied the stress state at the contact surface of the expansion by the finite element analysis and studied the change in strength and length of this joint during hydraulic expansion.

In 1992, Chaaban et al. [4] utilized finite element methods to perform finite element analysis. Referring to Figure 1, the 7-hole plane stress model and the axisymmetric model were used to determine the residual contact pressure, and the residual stress in the transition zone was analyzed.

In 2003, Feng W H et al. [11] simulated the hydraulic expansion process by the nonlinear finite element analysis. Referring to Figure 2, the 1/12 of the finite circular disk with 19 holes was taken as the computation model for the tube and the tubesheet. ANSYS was used for further processing, it was found that the residual contact pressure increases with expansion pressure in the range of 250-270 MPa and reaches the maximum when the expansion pressure reaches 270 MPa was summarized.

In summary, the model adopted by Scott and Chaaban et al. is a single-tube model, which is different from the models adopted by Feng W H and Zheng W et al. ANSYS was found a utilization in processing
the distribution of residual contact pressure during the expansion process.

4. Experimental methods

During the hydraulic expansion, the pressure is evenly distributed on the inner wall of the tube. Hence, not only the value of the residual contact pressure is calculated, but also the circumferential strain on the outer surface of the single-tube model is measured.

In 1996, Huigeng Y, L Ge et al. [13, 14] conducted further research and got a theoretical solution of the residual contact pressure on the basis of the principle of unloading and related parameters. Huigeng Y, L Ge et al. adopted Elastic unloading methods to verify the correctness of the theoretical solution of the residual contact pressure.

In 2003, Yi Lu et al. [15] used electrical resistance strain gauges to measure the circumferential strain on the outer surface of a single-tube model, as shown in Figure 3. Yi Lu proposed a new method for measuring the residual contact pressure, by which the relevant parameters of the entire measurement system can be calibrated. Hence, the influence of various factors was eliminated. In addition, the accuracy of the algorithm proposed from Yi Lu was verified in the literature [7].

![Image of single-tube model and strain gauges]

Figure 3. The strain gauge distribution and full-bridge connection

In summary, the errors between the experimental results from Huigeng Y, L Ge et al. and the theoretical results are within a reasonable range, hence, the methods with resistance strain gauges are feasible. According to Yi Lu, the factors such as the structural size of the model, the accuracy of the attachment position of the strain gauge and the sensitivity coefficient of the strain gauge are eliminated.

5. Conclusions

Theoretical analyses and calculations for different types of tubes are needed for the methods for measuring the residual contact pressure in the hydraulic expansion joint, and the finite element simulation software should be used for analyses to improve efficiency and accuracy. It is also necessary to conduct experiments to further verify whether the experimental and theoretical values are within reasonable errors. Some of the hydraulic expansions mentioned in this article are liquid bag expansions. Hence, further researches on pure hydraulic expansions are needed. Most of the objects simulated in the existing literatures are single-tube models, however, multi-tube expansions are required in actual productions. In addition, the residual contact pressure after multi-tube expansion is different from that after single-tube expansion, and it is worth further study.

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