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Experimental Study of Hydraulically Expanded Tube-to-Tubesheet Joints for Shell-and-Tube Heat Exchangers

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Abstract

In this paper, the hydraulically expanded tube-to-tube sheet joints for shell-and-tube heat exchangers made of three sets of commonly used tube and tunesheet materials i.e. 10# for tube and 16Mn for tubesheet, S30408 stainless steel for both tube and tubesheet, and S32168 stainless steel for the both were experimentally studied with the concentration on the relations between the tube expanding percentage, expansion pressure, pull-out force and push-out force. The tube expanding percentages within the ranges of expanding pressure from 160 MPa to 300 MPa for different materials joints were obtained. Both pull-out and push-out tests were carried out for each joint. Results show that the tube expanding percentage almost increases linearly with increasing the expansion pressures. Pull-out force is less than the push-out force and both of them increase with increasing expansion pressures. However unlimited increase of the tube expanding percentage cannot always enhance the pull-out strength of the joints because of "over-expansion". Finally, to facilitate the application, the relationships between the tube expanding percentage and expanding pressure are given, and also provided are the equations of the relationship between the pull-out force and the tube expanding percentage.

Keywords: tube-to-tubesheet joint; hydraulic expansion; tube expanding percentage; experimental research.

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1. Introduction

Tube-to-tubesheet joints play key roles to ensure reliable operation of shell-and-tube heat exchangers. Axial strength and tightness are important indicators to measure the quality of the joints' performance. In the early 1940s,

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Goodier *et al.*[1] analytically established a plane-stress model to investigate the tightness with focus on interfacial contact pressure between tube and tubesheet hole. Grimison *et al.*[2] carried out experiments to research axial strength of tube-tubesheet joints. Their analyses and experimental investigations laid some foundation for further studies of the subject. In the past few decades, a lot of studies have been spent on the joints performance. For example, Yokell[3,4] addressed the problem of correlating roller-expanded joint strength with wall reduction and rolling torque, and advocated the two stages expanding, i.e. (i) applying just sufficient pressure or torque to create firm tube-hole contact over substantially the tubesheet thickness, and (ii) then re-expanding at full pressure or torque. Allam *et al.*[5] investigated the axial strength of tube-to-tubesheet joints numerically and experimentally, and compared the pull-out force results with those estimations of simple analytical solution provided by other authors. In addition, Shuaib *et al.*[6] argued that the joint strength seemed not affected by enlarged tubesheet hole over tolerance, whereas tube wall reduction was more sensitive to tube hole enlargement.

Among the methods for joining the tube to tubesheet, hydraulically expanded method is much more commonly used for its easier fabricating and controlling. In recent decades, the performance and mechanism of hydraulically expanded joints were also extensively studied by many scholars in China. With the von Mises yield criterion, Yan Huigeng[7] and Wang Haifeng[8] obtained the analytical relations between expansion pressure and residual contact pressure. Yu Hongjie[9-11] and Tian Junli[12] researched the residual contact pressure of hydraulically expanded joint with 3D FEA models and real materials. The value and distribution of residual contact pressure between the tube outer surface and the inner surface of the tubesheet hole were found and the influence of grooves on residual contact pressure was illustrated.

In this paper, the hydraulically expanded tube-to-tubesheet joints for shell-and-tube heat exchangers were experimentally studied with the focus on the relationship between the tube expanding percentage, expanding pressure, the pull-out force and push-out force. Three sets of commonly used tube and tunesheet materials i.e. 10# for tube and 16Mn for tubesheet, S30408 stainless steel for both tube and tubesheet, and S32168 stainless steel for the both were investigated.

2. Experimental procedures

2.1. Specimens preparation

The tubes are specified as Φ25x2.5mm and the tube layout on the tubesheet is set to be triangular. There are 19 tube-to-tubesheet joints on each tubesheet specimen, as shown in the Fig. 1. Nine tubesheets specimen were prepared. Detail expanding structure of tube-to- tubesheet joint is shown in Fig. 2.

Nine tubesheet specimens were prepared for experiments which are denoted as 3A, 3B, 3C, 5A, 5B, 5C, 7A, 7B and 7C. The corresponding material combinations for the tubes and tubesheet are listed in Table 1. All tubesheet specimens have the same geometric parameters as listed in Table 2.

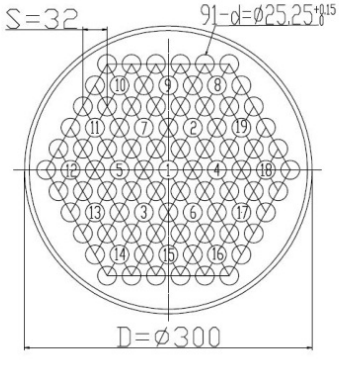


Fig. 1. Experimental specimen, mm.

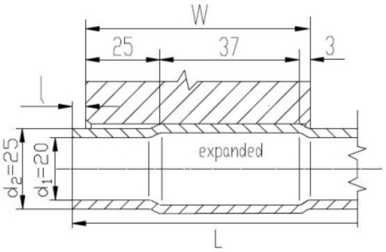


Fig. 2. The detail expanding structure of tube-to-tubesheet joints, mm.

Table 1. Specimen numbers.

Tubesheet number	Tube material/yield strength(MPa)	Tubesheet material/yield strength(MPa)
3A 3B 3C	10#/238	16Mn/375
5A 5B 5C	S30408/205	S30408/205
7A 7B 7C	S32168/210	S32168/210

Table 2. Specimen geometric size/mm.

Element	Geometric size/mm
tube	d_1=20 d_2=25 t=2.5 l=3 L=150
tubesheet	S=32 W=65 D=300

Notes: d_1-tube inner diameter, d_2-tube outer diameter, t-tube thickness, l-tube length out of tube pass, L-tube length, S-center distance, d-tubesheet hole diameter, W-tubesheet thickness, D-tubesheet diameter, P-expansion pressure

The diameter of tubesheet hole is 25.25mm with upper tolerance of +0.15mm and lower tolerance of zero. For 3A, 3B and 3C tubesheet specimens, the expanding pressures are 160MPa, 180MPa, 200MPa, 220MPa, 240MPa, 260MPa and 280MPa. While for 5A, 5B, 5C, 7A, 7B and 7C of the S30408 and S32168 stainless steel specimens, the expanding pressures are selected to be 180MPa, 200MPa, 220MPa, 240MPa, 260MPa, 280MPa and 300MPa as listed in Table 3.

Table 3. Expansion pressure for different materials combination.

Tubesheet number	Expansion pressure /MPa
3A,3B,3C	160,180,200,220,240,260,280
5A,5B,5C	180,200,220,240,260,280,300
7A,7B,7C	180,200,220,240,260,280,300

2.2. Measurements of tube expanding percentage k

Usually, there are three methods to calculate the tube expanding percentage, namely tube thickness reduction method, inner diameter control method and outer diameter control method. Among them, outer diameter control method needs to measure outside diameter of tube after expanding, and this is hard to achieve in practice. GB151-2012 *Heat Exchangers*[13] suggests to use the tube thickness reduction method to define the tube expanding percentage as shown in Eq. (1).

$$k_1 = \frac{d_3 - d_1 - b}{2t} \times 100\% \tag{1}$$

where k_1 is the tube expanding percentage, d_3 is the inside diameter of tube after expansion, d_1 is the inside diameter of tube before expansion, b is the initial clearance between diameter of hole before expansion and the outside diameter of tube before expansion and t is the tube thickness before expanding.

Steam Boiler Safety Technology Supervisory Regulations[14] provides the inner diameter control method to define the tube expanding percentage as shown in Eq. (2).

$$k_2 = (\frac{d_3 + 2t}{D} - 1) \times 100\% \tag{2}$$

where k_2 is the tube expanding percentage based on inner diameter control method, d_3 and t have the same meanings as Eq. (1) and D is the tubesheet hole diameter before expanding.

In this paper, both the tube wall reduction method and inner diameter control method are used.

Table 4. Experimental results of the tube expanding percentage.

Tubesheet number	Expansion pressure/MPa	Tube wall reduction percentage control method k_1/%	Inner diameter control k_2/%
3A, 3B, 3C	160	3.21	0.65
	180	3.77	0.76
	200	4.38	0.88
	220	6.05	1.22
	240	6.53	1.32
	260	6.82	1.37
	280	8.37	1.69
5A, 5B, 5C	180	3.80	0.75
	200	4.38	0.86
	220	5.27	1.04
	240	5.93	1.17
	260	7.13	1.41
	280	7.98	1.57
	300	8.72	1.72
7A, 7B, 7C	180	3.02	0.60
	200	4.31	0.86
	220	4.50	0.90
	240	5.78	1.16
	260	6.95	1.39
	280	7.53	1.51
	300	8.95	1.79

Before expanding, each tube inside diameter d_1 and each tubesheet hole diameter are measured 5 times using inside diameter micrometer gauge along the axial direction in the expansion location. Also, outside diameter of each tube is measured 5 times by outside diameter micrometer gauge. By averaging these data， d_1, b, t and D are evaluated. Then the joints were hydraulically expanded under the specified expanding pressure. After expanding, the expanded part of each tube is measured 5 times for the diameter and averaged to get d_3. Then tube expanding percentages for different pressure and different materials combinations were calculated based on Eqs. (1) and (2) and the results are listed in Table 4.

2.3. Pull-out force and push-out force experiments

After calculating tube expanding percentage, pull-out force experiments were carried out on the expanded tubesheet, 3C, 5C, and 7C. This part of the test was divided into 3 steps, namely cutting, inserting, and drawing. The "cutting" step is to separate the expanded tubesheet into individual by Electric Discharge Machining(EDM) in order to perform the pull-out tests as shown in Fig. 3. The "inserting" step is to insert and weld a steel bar with round sectional area matched to the inside diameter of the tube in the end of each tube to avoid deformation of the clamped tube end under the axial pulling out load on the test machine as shown in Fig. 4. The welding has no influence on expanding because it is far from the joints. The clamp is shown in Fig. 5. The “drawing” step is to pull the tube out of the tubesheet as shown in Fig. 6.

Similar to the pull-out tests, push-out experiments on the specimens 3A, 5A and 7A were conducted. Instead of using the clamp in Fig. 5, a torus and four rectangular metals are used to pad the joint. Testing machine chuck declines gradually, pushing the tube out of tubesheet along the axial direction. Push-out tests are shown in Fig. 7.

Fig. 3. EDM process of joints.

Fig. 4. Joint after EDM.

Fig. 5. Clamp.

Fig. 6. Pull-out test.

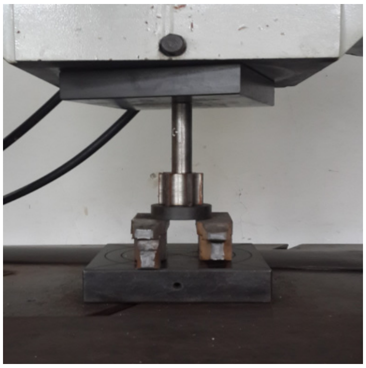


Fig. 7. Push-out test.

Experimental results of pull-out and push-out forces are listed in Table 5. In the table, there is no value of push-out force for 3A tubesheet. This is because the tube is not pushed out from the tubesheet when serious plastic deformation appears during the push-out process.

Table 5. Experimental results of pull-out and push-out forces.

Tubesheet number	Expansion pressure/MPa	Push-out force of A/MPa	Pull-out force of C/MPa
3A, 3C	160	-	8.47
	180	-	10.72
	200	-	15.15
	220	-	16.98
	240	-	17.36
	260	-	17.29
	280	-	19.25
5A, 5C	180	4.19	3.98
	200	4.41	5.26
	220	6.60	6.19
	240	8.10	6.06
	260	8.76	6.66
	280	10.49	8.14
	300	11.79	7.71
7A, 7C	180	4.05	3.13
	200	4.32	4.37
	220	4.59	4.97
	240	4.79	5.19
	260	5.91	5.65
	280	6.69	7.19
	300	10.37	7.04

3. Experimental results and discussions

3.1. Relationship between tube expanding percentage and expansion pressures

According to the experimental results listed in table 4 for 10# and 16Mn materials combination, the tube expanding percentage (k) is plotted against the expanding pressure (P) in Fig. 8. Fig. 8 (a) shows the tube expanding percentage based on the tube thickness reduction method while Fig. 8 (b) is for the tube expanding percentage based on inner diameter control method. In the figure, dots represent the experimental results, and the line is from the empirical equation (3) which fitted the data of the tube expanding percentage over the range of expanding pressure from 160MPa to 280MPa.

For 10# and 16Mn combination, the empirical equation of tube expanding percentage are:

$$k_1 = \frac{\left(-3.7325 + 0.0423P\right)\times 100\%}{100} \tag{3-a}$$

$$k_2 = \frac{\left(-0.75071 + 0.00854P\right)\times 100\%}{100} \tag{3-b}$$

Similarly, for S30408 and S32168 stainless steels, the relative relationships between tube expanding percentage and expanding pressure based on the experimental data are regressed in Fig. 9 and Fig. 10 respectively.

For S30408 tube and tubesheet materials, the regressed equations are:

$$k_1 = \frac{\left(-4.0357 + 0.04254P\right)\times 100\%}{100} \tag{4-a}$$

$$k_2 = \frac{\left(-0.79714 + 0.00839P\right)\times 100\%}{100} \tag{4-b}$$

For S32168 tube and tubesheet materials, the regressed equations are:

$$k_1 = \frac{\left(-5.571 + 0.0476P\right)\times 100\%}{100} \tag{5-a}$$

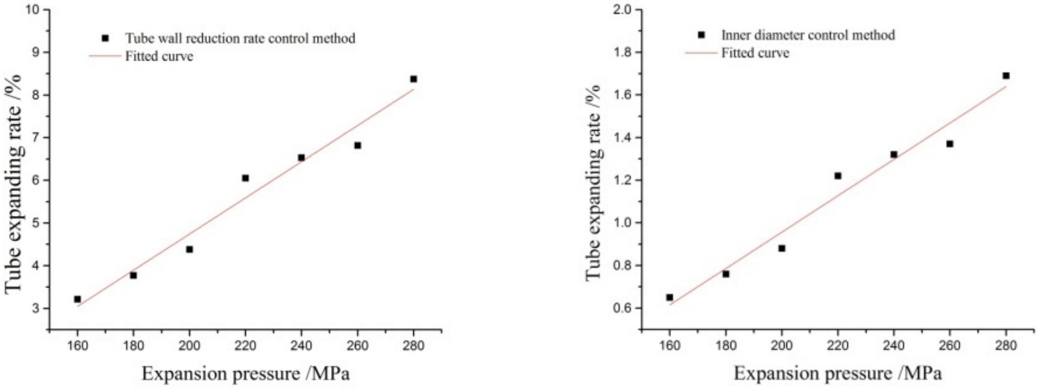
$$k_2 = \frac{\left(-1.124 + 0.009P\right)\times 100\%}{100} \tag{5-b}$$

It is clear that for whatever materials combinations and whatever calculation methods, the tube expanding percentages increase linearly with increasing the expanding pressure.

GB151-2014 recommends that the tightness expanding range of tube expanding percentage, based on tube wall reduction method, is 2%~3%, the strength expanding range is 6%~8% for carbon steel and 5%~6% for stainless steel. From table 4 and Fig. 8 (a) to Fig. 10 (a), it is seen that for 10# and 16Mn carbon steel material combination with the expansion pressure of 160MPa and for both of S30408 and S32168 stainless steel with the expansion pressure of 180MPa, the tube expanding percentage already reaches or even excesses 3% required by the standard requirement.

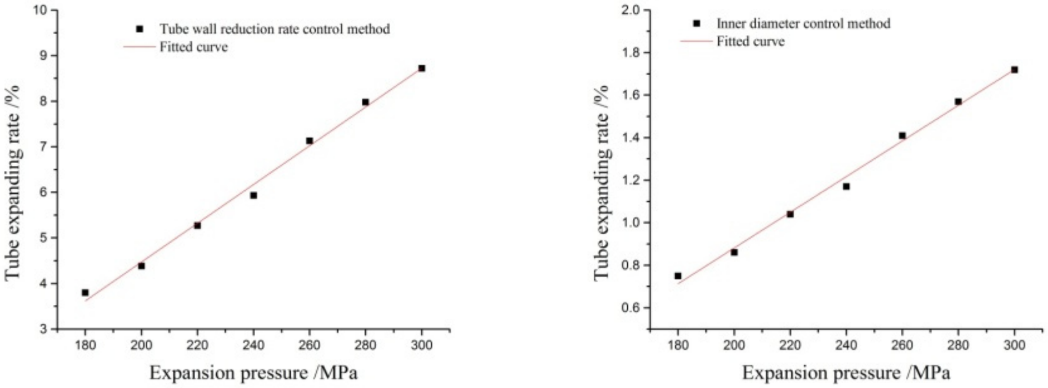
In addition, the range of tube expanding percentage based on inner diameter control method is 0.6%~1.8%. This range is similar to Liu Min's[15] results which is 0.5%~2%.

From this study, it seems that based on the standard requirements of tightness expansion, the expanding pressure should be controlled within 160-200 MPa for 10# and 16Mn combination, 180-240 MPa for S30408 stainless steel, and 180-240MPa for S32168 stainless steel. To meet the requirements of strength expansion, the expanding pressure should be higher than 220 MPa for 10# and 16Mn combination and 260 MPa for S30408 and S32168 stainless steel.



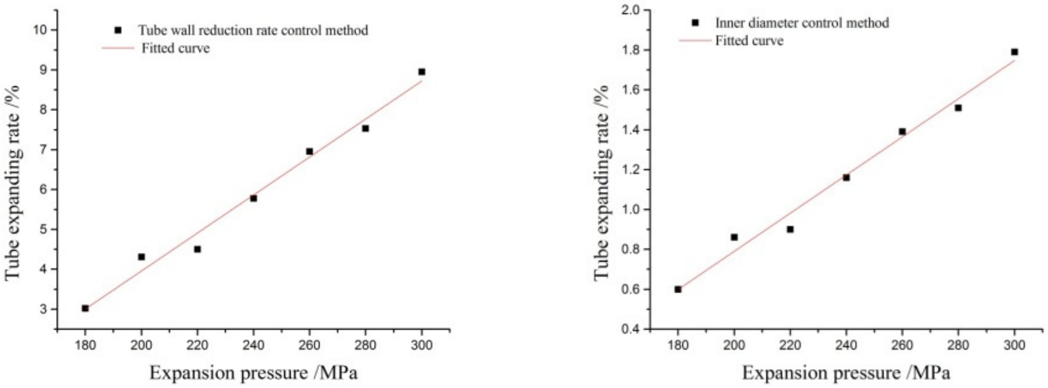
(a) (b)

Fig. 8. Tube expanding percentage changing with expansion pressures – 10# and 16Mn carbon steel.



(a) (b)

Fig. 9. Tube expanding percentage changing with expansion pressures – S30408 stainless steel.



(a) (b)

Fig. 10. Tube expanding percentage changing with expansion pressures – S32168 stainless steel.

3.2. Relationship between pull-out forces and expansion pressures

The change of pull-out force with expanding pressure for the three material combinations is plotted in Fig. 11-Fig. 13, respectively. The dots are the experimental data. Clearly, the pull-out force increases with increasing the expanding pressure, but the trend is not linear. This phenomenon is consistent with the reference[9] which found that the residual contact pressure between outside surface of tube and inside surface of tubesheet hole increased with the expanding pressure and keep a near constant level at some higher level of expanding pressure. To facilitate engineering applications, relations are obtained by fitting the experimental data as follows.

For 10# and 16Mn combination, the fitted equation for the pull-out force is:

$$q = -41.10214 + 0.43677P - 7.99107 \times 10^{-4} P^2 \tag{6}$$

For S30408 material, the fitted equation for the pull-out force is:

$$q = -8.41333 + 0.09311P - 1.29167\times10^{-4}P^2 \tag{7}$$

For S32168 material, the fitted equation for the pull-out force is:

$$q = -5.32286 + 0.05752P - 5.26786\times10^{-5}P^2 \tag{8}$$

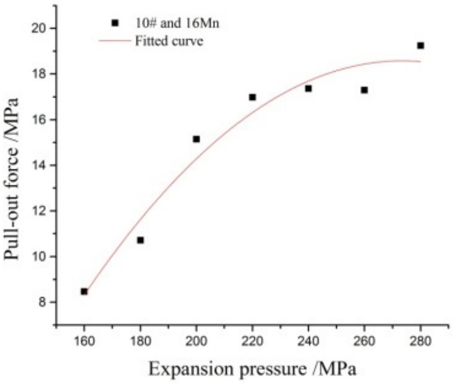


Fig. 11. Pull-out force changing with expansion pressures for 10# and 16Mn carbon steel.

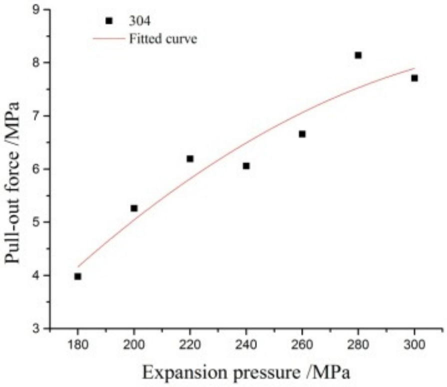


Fig. 12. Pull-out force changing with expansion pressures for S30408 stainless steel.

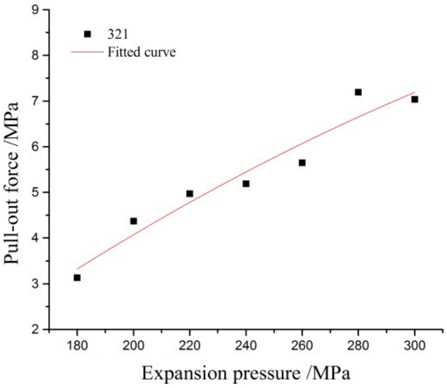


Fig. 13. Pull-out force changing with expansion pressures for S32168 stainless steel.

3.3. Relationship between push-out forces and expansion pressures

Figure 14 and Fig. 15 show the relationships between push-out forces and expansion pressures respectively for both S30408 and S32168 steel combinations. Obviously, push-out forces increase with the expanding pressures. Comparing Figs. 12-13 and Figs. 14-15, it is found that in general, the pull-out forces are larger than push-out forces especially when the expanding pressures are higher. This result is consistent with reference[16]. It is interesting to note that the pull-out forces have a different trend from the pull-out forces regarding the effects of the expanding pressure.

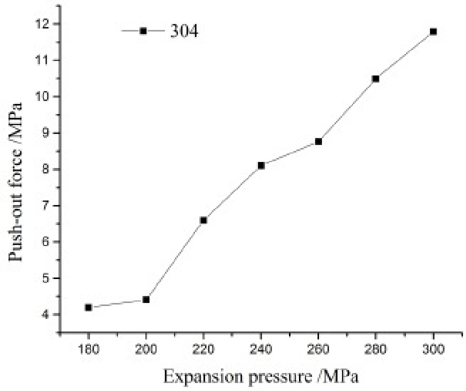


Fig. 14. Push-out force changing with expansion pressures for S30408 stainless steel.

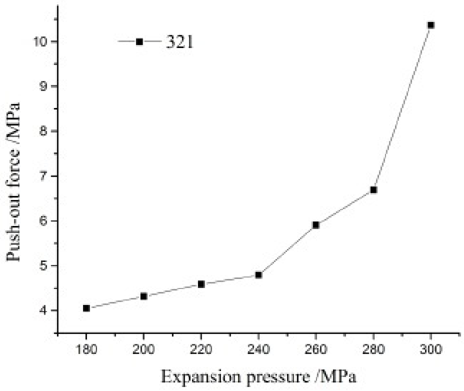


Fig. 15. Push-out force changing with expansion pressures for S32168 stainless steel.

3.4. Relationship between pull-out forces and tube expanding percentages

The tube expanding percentage is the most commonly used method to judge the joint strength in engineering practice. The ultimate goal is to achieve the reliable joints. In order to provide a reliable reference to engineers, the relationship between pull-out force and tube expanding percentage is plotted in Fig. 16-Fig. 18. From the figures, it is found that the trends are similar to Fig. 11-Fig. 13. For 10# and 16Mn carbon steel, the pull-out force increases with the tube expanding percentage. But for S30408 or S32168 stainless steel joints, when the tube expanding percentage reaches 8%, the pull-out force began to decrease. This indicates that unlimited increase of the tube expanding percentage cannot always enhance the pull-out strength of the joints, instead it may reduce the pull-out force of the joints because of "over expansion". Therefore, over expansion of the joints is not better for the joint strength.

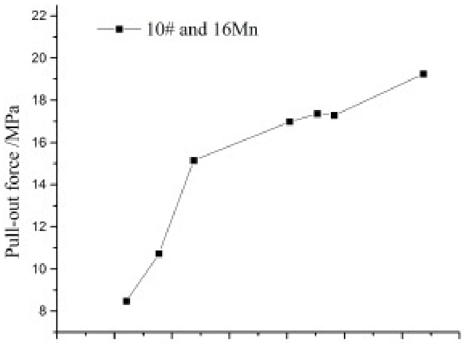


Fig. 16. Pull-out force changing with tube expanding percentages for 10# and 16Mn carbon steel.

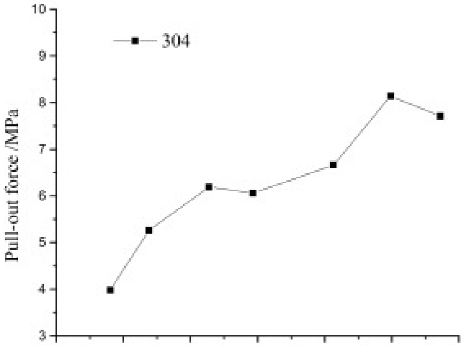


Fig. 17. Pull-out force changing with tube expanding percentages for S30408 stainless steel.

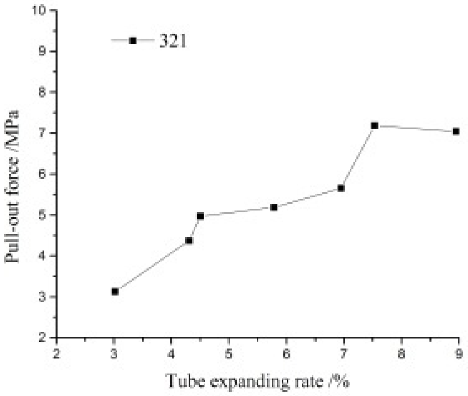


Fig. 18. Pull-out force changing with tube expanding percentages for S32168 stainless steel.

It should be pointed out that standards require that in order to ensure pull-out strength, the tubesheet hole should be slotted for strength expanding. However, according to the present experimental results, it is found that even if the tubesheet hole is not slotted, the pull-out force is far more than 4MPa for 10# and 16Mn joints, when expansion pressure reaches 160MPa or more, meeting the standard requirement. And for stainless steel S30408 or S32168, when expansion pressure reaches 200MPa or more, the requirement of pull-out force is satisfied. Therefore, in terms of the pull-out strength, tubesheet hole does not have to be slotted for hydraulically expanded method.

4. Conclusions

In this paper, the hydraulically expanded tube-to-tubesheet joints for shell-and-tube heat exchangers were experimentally studied. Three sets of commonly used tube and tubesheet materials were investigated. For the conditions studied here, i.e. the tube size of Φ25x2.5mm and the tubesheet thickness of 65mm with the expanded length of 37mm, the following conclusions are drawn.

(1) Tube expanding percentage increases with the increasing expansion pressure. For the tightness expansion with the expanding percentage of 2%-3%, the expansion pressure of 160MPa is sufficient for 10# tube and 16Mn materials combination and 180MPa for the stainless steel combinations.

(2) The pull-out force is less than push-out force, but both of them increase with increasing expansion pressure.

(3) Unlimited increase of the tube expanding percentage cannot always enhance the strength of the joints, instead it may reduce the pull-out force of the joints because of “over expansion”.

(4) The relationships between the tube expanding percentage and expanding pressure are given, and also provided are the equations of the relationship between the pull-out force and the tube expanding percentage.

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