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Sensitivity Analysis on Hydraulic Expanded Tube-to-Tubesheet Joints for Tube Layout Patterns

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ABSTRACT

The basic requirements to improve the quality of tube-to-tubesheet joints for heat exchangers are to obtain high contact pressures between the tube and the tubesheet, and low residual stresses in the transition zone of the tubes. The contact pressure and the residual stress which govern the joint quality are influenced by parameters such as mechanical properties, geometric dimension of tube and tubesheet and expansion pressures. There are two types of tube arrangements, triangular and square, which are frequently used for heat exchangers. The purpose of the present work is to investigate the joint quality according to tube layout patterns by the numerical results obtained from sensitivity analysis on the two types.

INTRODUCTION

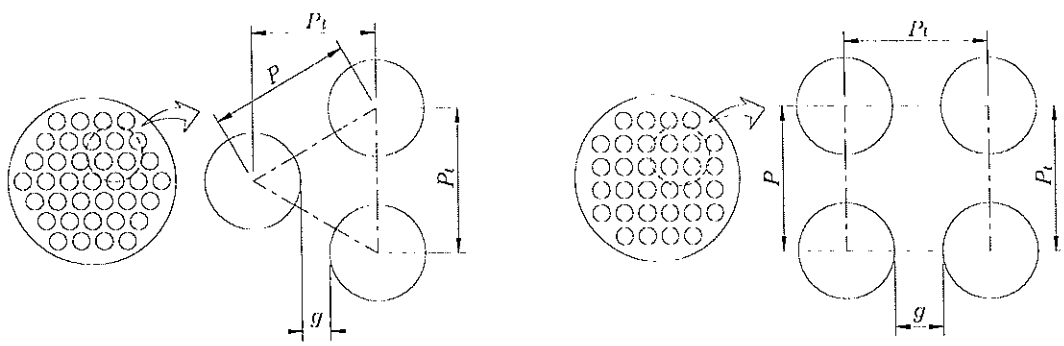
The hydraulic expansion of tube-to-tubesheet is well known for lower residual stress and more uniform joint quality in comparison with the mechanical rolling. Its technical requirements are widely known as high and uniform contact pressure for preventing leak in the interface and low residual stress in the transition zone.

To perfectly understand the tube-to-tubesheet expansion, it is important to study the parameters influencing joint quality. Many researchers analytically and numerically analyzed tube-to-tubesheet joints, considering the effect of parameters[1-6]. Usually, tube layout patterns frequently used are divided into two types, triangular and square, as shown in Figure 1 and Table 1.[7] Few works were done for the joint analysis using square pitch arrangement. This study deals with effect of expansion parameters on hydraulic expanded tube-to-tubesheet joints for both of tube layout patterns.

Most of the hydraulically expanded zone are in contact with central region of tubesheet and the primary and secondary side regions indicate the lower and the upper side joints of tube and tubesheet, respectively. Interesting regions in this study were central and secondary side region. The effect of expansion parameters on tube-to-tubesheet was investigated in the central region analysis. The axisymmetric analysis was also carried out to evaluate residual stress of tube after expansion in the secondary side transition. Effect of strain hardening and elasto-plastic behavior of materials with a plastic tangent modulus fraction 0.014 was considered in the analysis. It was assumed that the effect of adjacent tube hole was neglected.

To compare the joint quality of both tube layouts, the basic geometries and material parameters of tube and tubesheet shown in Table 2 are applied to each pattern.

P : Layout pitch P_t : Transverse pitch P_l : Longitudinal pitch g : Gap



(a) Triangular pitch layout (b) Square pitch layout

Figure 1. Tube layout scheme

Table 1. Pitches and gap in terms of pitch and tube outer diameter (d_o)

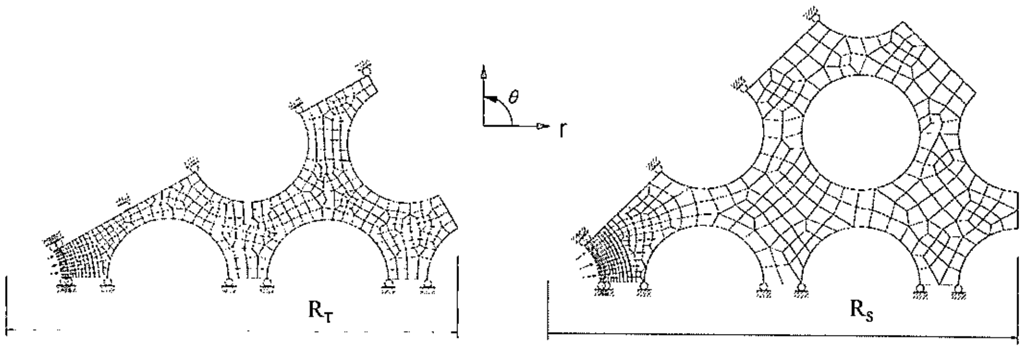
Layout pattern	P_t	P_l	g
Triangular layout	P	$P sin60°$	$P sin60° - d_o$
Square layout	P	P	$P - d_o$

Table 2. Material properties and dimensions of tube and tubesheet

Tube outer diameter	18 mm
Tube thickness	1 mm
Tubesheet inner diameter	18.2 mm
Tube yield stress	300 MPa
Tubesheet yield stress	450 MPa
Tube young's modulus	210 GPa
Tubesheet young's modulus	210 GPa

ANALYSIS OF CENTRAL REGION

Figure 3 shows the geometry and boundary conditions for finite element analysis in central region. The plane stress condition is assumed. Due to the symmetry, only one-twelfth of the triangular pitch layout is modeled and one-eighth of the square. The constraints are free on outer boundary of the tubesheet, where the expansion pressures don't have an effect on tubesheet during expansion. The biquadratic plane stress 8-node element (CPS8) in ABAQUS, commercial nonlinear FEM code, was used to perform the analysis. Small sliding was assumed in the contact interface between tube and tubesheet and a coefficient of friction was equal to 0.2.



(a) Triangular model (b) Square model

Figure 3. Two-dimensional finite element mesh for tube and tubesheet

The parametric study is significant to determine the optimal design criteria of tube-to-tubesheet joints. The design parameters are considered as follows : initial clearance between tube and tubesheet, Poisson's ratio, plastic tangent modulus, yield strength and Young's modulus of tube and tubesheet, ligament thickness of tubesheet, strain hardening of material, tube expansion pressure.

Effect of ligament efficiency(η) to contact pressure is compared in Figure 4. The pitches of two patterns were varied from 23 to 37mm, or $0.17 \leq \eta \leq 0.48$. The expansion pressure of 250MPa was loaded at the inside of tube. It is seen that the triangular layout pattern has higher contact pressure than square at the same ligament efficiencies.

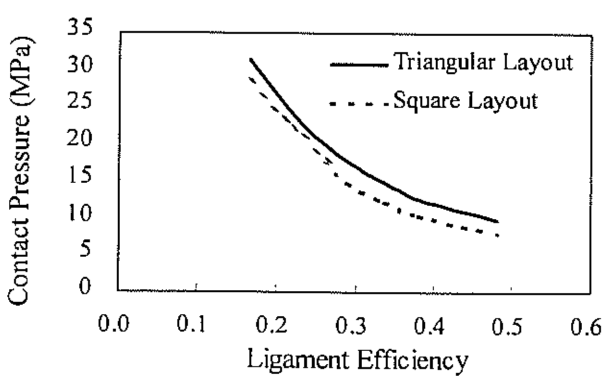


Figure 4. Effect of ligament efficiency

Table 3 shows the results of sensitivity analysis for the tube layout patterns. The values of the parameters are changed from –5% to 5% based on the value in Table 2. The reference value of contact pressures to be compared are 22.605MPa for triangular tube layout and 20.798MPa for square in the condition of 250MPa expansion pressure and 25mm pitch. A parenthesis in the table represents the change rate of contact pressure against the reference contact pressure.

Table 3. Contact pressures for variations of design parameters

Unit : MPa

Parameter		Triangular layout		Square layout	
		-5%	5%	-5%	5%
Expansion pressure		19.162(-15.2%)	26.095(15.4%)	17.436(-16.2%)	24.211(16.4%)
Tube Young's modulus		20.625(-8.8%)	23.714(4.9%)	18.875(-9.2%)	21.859(5.1%)
Tube thickness		22.081(-2.6%)	23.070(2.1%)	20.325(-2.3%)	21.215(2%)
Tube yield stress		24.295(7.5%)	20.126(-11%)	22.496(8.2%)	18.318(-11.9%)
Tubesheet Young's modulus		24.499(8.4%)	20.855(-7.7%)	22.638(8.8%)	19.098(-8.2%)
Clearance		22.857(1.1%)	22.353(-1.1%)	21.051(1.2%)	20.545(-1.2%)
Tubesheet yield stress		22.584(-0.1%)	22.618(0.06%)	20.784(-0.07%)	20.805(0.03%)
Plastic tangent modulus fraction	Tube	22.899(1.3%)	22.313(-1.3%)	21.089(1.4%)	20.508(-1.4%)
	Tubesheet	22.606(0%)	22.605(0%)	20.798(0%)	20.798(0%)
Poisson's ratio	Tube	22.851(1.1%)	22.359(-1.1%)	21.048(1.2%)	20.547(-1.2%)
	Tubesheet	22.359(-1.1%)	22.851(1.1%)	20.547(-1.2%)	21.048(1.2%)
Friction coefficient		22.605(0%)	22.605(0%)	20.798(0%)	20.798(0%)

From the results, parameters can be divided into three categories according to the degree of influence to contact pressure. First, the parameters proportional to the contact pressure, expansion pressures, Young's modulus of tube and tube thickness. Second, the parameters in inverse proportion to contact pressure, yield stress of tube and Young's modulus of tubesheet. Last, the parameters which only have little influence on contact pressure, initial clearance, Poisson's ratio, plastic tangent modulus fraction of materials, and friction coefficient. The most influential parameters on contact pressure are expansion pressure, yield stress of tube and Young's modulus of tube and tubesheet.

The value of contact pressure in triangular layout was always higher than that in square under the same condition. It means that joint quality of triangular layout is superior to square if the expansion condition is the same both for layouts. In order to obtain the same joint quality as triangular layout, higher expansion pressure must be applied to the inner side of square pitch tube.

The average wall thinning ratio of tube can be obtained here. The ratio can be represented as "Expansion ratio = (initial tube thickness - tube thickness after expansion)/(initial tube thickness)×100(%)". Table 4 provides the tube wall thinning ratio of the two tube layout patterns after expansion of 200, 250 and 300MPa. It is noticed that tube wall thinning ratio of triangular layout is a little higher than that of square in each expansion pressure. Though the tube wall thinning is not prominent in hydraulic expansion, higher wall thinning in the same expansion condition means getting higher performance and better joint quality in tube expansion within design limit. Based on the above results, it is said that the case of the triangular layout pattern is easy to obtain a good joint quality compared with square.

Table 4. Average tube wall thinning ratio for variations of expansion pressure

Expansion pressure (MPa)	Initial tube thickness (mm)	Triangular layout		Square layout	
		Expanded Tube thickness (mm)	Tube expansion ratio (%)	Expanded tube thickness (mm)	Tube expansion ratio (%)
200	1	0.9924	0.76	0.9925	0.75
250	1	0.9918	0.82	0.9919	0.81
300	1	0.9898	0.1	0.9902	0.98

ANALYSIS ON THE SECONDARY SIDE REGION

The axisymmetric single tube model shown in Figure 5 was used in the analysis of secondary side transition. Its materials are the same as the central region analysis shown in Table 2 and the pitch is 25mm. The isoparametric-axisymmetric 8-node element (CAX8) was used to perform the analysis due to the symmetry of geometry. The average contact pressure in the previous central region analysis was used to obtain radius of single tube model (R), which is 16.6mm for triangular and 17.4mm for square obtained by trial and error. The expansion pressure is applied to tube below 3mm from the top of tubesheet to avoid bulging of tube.

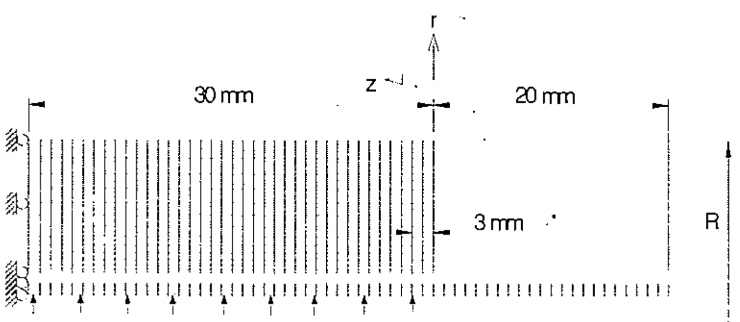
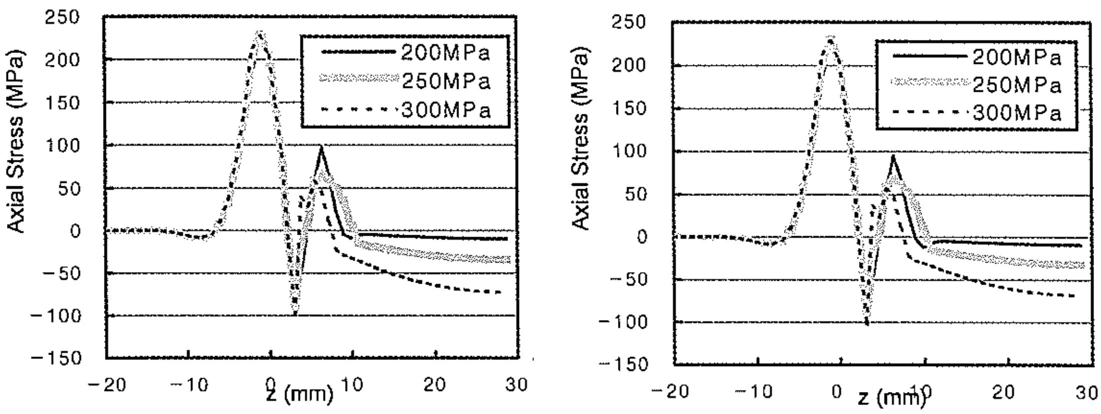


Figure 5. Finite element mesh for the analysis of transition zone

Figure 6 provides the distribution of residual axial stress at the inside of tube after expansion at 200, 250, and 300MPa in the secondary side transition. The distributions of residual axial stresses in each expansion pressure are almost same in non-contact area of tube and tubesheet while they show the variation from the top of tubesheet where the tube begins to attach tubesheet during expansion. The tensile stresses may be critical because of the stress corrosion cracking problem at the inside of tube. The maximum residual tensile stresses are 229.26, 229.32, and 227.06MPa for the triangular layout and 229.73, 230.4, and 228.31MPa for the square in each expansion pressures. It can be said that the triangular and square layout patterns have a very similar stress distribution in the secondary side transition.

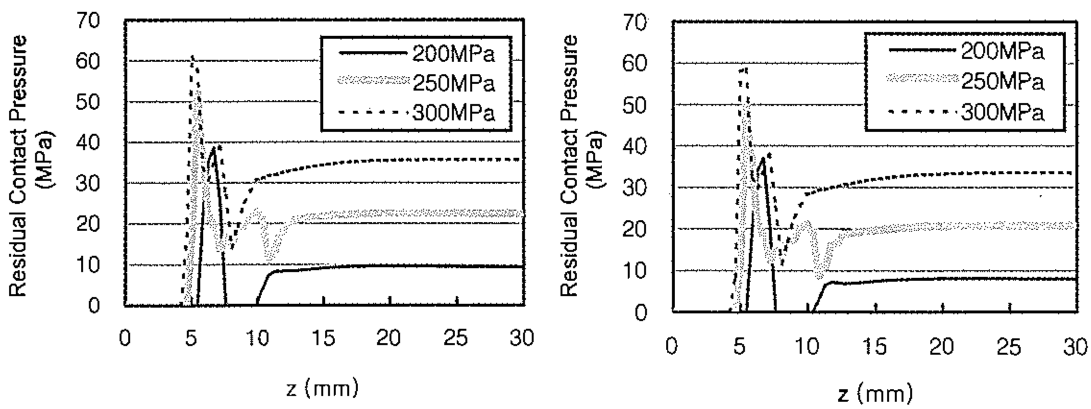


(a) Triangular layout

(b) Square layout

Figure 6. Distribution of residual axial stress on the inside of tube

The distribution of contact pressure in the secondary side transition is provided in Figure 7. The contact between tube and tubesheet begins below 5mm from top of tubesheet in both layout patterns. The maximum contact pressures are 38.5, 51.6, and 60.9MPa for triangular layout and 36.9, 49.7, and 58.4MPa for square at the expansion pressures of 200, 250, and 300MPa, respectively. This result is similar to the central region analysis. In secondary side transition, triangular layout has a little higher contact pressure than square under the same expansion condition.



(a) Triangular layout

(b) Square layout

Figure 7. Contact pressures in the secondary side transition

CONCLUSIONS

The finite element analysis was used to perform the parametric study on the hydraulic expansion for tube-to-tubesheet joints considering the tube layout patterns. Expansion parameters are divided into three types : proportional, inverse proportional and indifferent factors for increasing contact pressure. The most influential parameters among these are expansion pressure, yield stress of tube and Young's modulus of tube and tubesheet regardless of tube layout. The triangular layout has a higher contact pressure than square and has residual stress distribution on tube similar to square under the same expansion conditions such as expansion pressure, materials, geometries. These mean that the triangular layout can obtain the same joint quality as the square by applying to lower expansion pressure than square in manufacturing process under the same expansion parameter conditions. It also obtained better joint quality than square for the same expansion pressure.

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