Parameters Involving the Design of Tube-Tubesheet Joints

A. CHAABAN, H. MA, A. BAZERGUI
Ecole Polytechnique, Montreal, Canada

NOMENCLATURE

a	Outer diameter of tube
a_i	Inner diameter of tube
a'_i	Final inner diameter of tube after expansion process
a_o	Inner diameter of hole in tubesheet
c	Initial clearance between tube and tubesheet
t	Thickness of tube
s	Tube pitch
P	Expansion pressure
Y_{st}	Yield strength of tube
Y_{ss}	Yield strength of tubesheet
E_t	Young's modulus of tube
E_s	Young's modulus of tubesheet
P^*	Residual contact pressure
S^*_z	Maximum residual axial Stress in transition zone
S^*_h	Maximum residual hoop stress in transition zone
k	Apparent wall reduction
$L_r(m^n)$	Orthogonal array
	where r number of calculations to be performed
	m number of levels for each parameter
	n maximum number of parameters to be analyzed

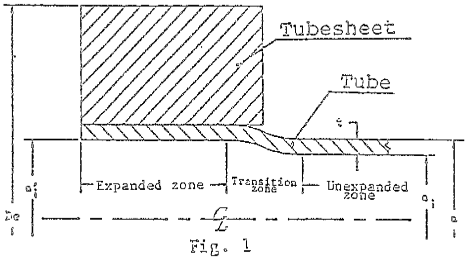

Fig. 1

INTRODUCTION

In heat exchangers, the object of the tube-to-tubesheet joining process is to provide a tight seal between the shellside and tubeside fluids, and to provide a sufficient capability of the joint to support axial loads if the tubes are required to act as stays.

Significant developments have been achieved in the evaluation of tube-to-tubesheet joints in recent years [1-5]. Soler and Hong adopted a single tube plane stress model to solve for the residual contact pressure [6]. Kalnins et al [7] adopted a single tube axisymmetrical model to solve for the residual contact pressure and residual stresses in the transition zone (Fig.1). However, the choice of the outer diameter of the annulus in the single tube

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model is still a difficult problem and may lead to significant errors in some cases particularly when non-axisymmetrical effects, such as the sequence of tube expansion, are to be considered. This particular problem has been discussed by Wang and Soler[8] and Chaaban et al[2].

The contribution of the present paper is to investigate the residual contact pressure between tube and tubesheet, the maximum residual stresses in the transition zone and the apparent wall reduction, using the nonlinear finite element method combined with a statistical analysis. On the basis of the results, empirical equations are proposed.

ANALYSIS METHOD

The Two-Step simplified method, which has been presented in recent papers by the authors [1,2], has been adopted in the present investigation. Because of space limitations, no details about the procedure, that are available in ref[2], will be included here.

Table 1. Parameters involving design of the tube-tubesheet joints

Dimension related parameters	Fabrication parameters	Material parameters
1. Thickness of tube, t	5. Expansion pressure level, P	7. Yield strength of tube, S_{yt}
2. Outer diameter of tube, a	6. Sequence of expansion process	8. Yield strength of tubesheet, S_{ys}
3. Tbue pitch, s		9. Young's modulus of tube, E_t
4. Initial clearance, c		10. Young's modulus of tubesheet, E_s

Three types of parameters are involved: dimensional, fabrication and material (see Table 1).

Different combinations of common material properties and geometries have been analyzed (see Table 2). In order to generalize the analysis, nondimensional parameters are used; the ratios t/a and s/a characterize the geometry of the seven-tube model[2]. Three nondimensional parameters, E_t/Y_{st}, E_t/E_s and Y_{ss}/Y_{st}, characterize the stress-strain curve for the materials of the tube-tubesheet joint. The calculated expansion pressure and residual stresses are normalized with respect to the yield stress of the tube, Y_{st}. Generally, the tube wall reduction is a significant indicator of the degree of expansion[9]. Since it is impractical to determine the actual wall reduction, the more appropriately termed "apparent wall reduction" [9], will be determined as follows:

$$k= [(a'_i-a_i)-2c]/2t \ \%$$

Table 2. MATERIAL PROPERTIES

		MATERIAL PROPERTY	E_t/Y_{st} (x 10E3)	E_s/E_t	Y_{ss}/Y_{st}
T1	Tube Tubesheet	Steel Steel	0.9333	1.0357	1.2667
T2	Tube Tubesheet	I-800 Steel	0.5534	0.9310	0.5344
T3	Tube Tubesheet	70:30 Cu-Ni Steel	1.2222	1.3182	1.6667
T4	Tube Tubesheet	70:30 Cu-Ni 90:10 Cu-Ni	1.2222	0.8182	0.8333
T5	Tube Tubesheet	Admiralty Steel	1.0667	1.8125	2.5333
T6	Tube Tubesheet	Steel Muntz Metal	0.75	0.5102	0.5153

CALCULATION PROCEDURE

The calculations were done using t/a= 0.065, 0.083 and 0.109, s/a=

1.5, 1.9, 2.0,2.5 and 3.5, c/a= 0.0, 0.001, 0.003, 0.01, 0.032. These are common values as shown in the TEMA heat exchanger Standards[10]. On the other hand, three combinations of tube and tubesheet materials were selected based on practical cases (Table 2). Sets T1, T2 and T3 correspond to Y_{ss}/Y_{st}=1.2667, 0.5344 and 1.6667 respectively. The three other sets(T4, T5, T6) shown in Table 2 have not been investigated so far.

The orthogonal design method [11] was used to minimize the number of calculations while providing accurate results regarding the influence of the parameters involved. The authors have discussed in detail the usefulness of the orthogonal design method in [1]. Table 3 shows a typical orthogonal array $L_9(3^4)$. Using this array, the numerical analysis can be arranged for a maximum of 4 parameters at three levels each. This was used for sets T1, T2 and T3 of Table 2. The 27 observation points (9 for each of the three sets) were chosen and investigated as shown in Table 4. For example, for observation point No.1, the material set was T1, and the other parameters were t/a=0.065, s/a=1.5, c/a=0.032 and P/Y_{st}=0.7; the finite element analysis results were: P^*/Y_{st}=0.02, S^*_z/Y_{st}=1.54, S^*_h/Y_{st}=1.44 and k=4.44%.

Table 3. The calculations designed by using orthogonal array $L_9(3^4)$ [11]

Calcu. (i)	1 t/a	2 s/a	3 P/Y_{st}	4 c/a
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 4. Results of finite element analysis

		(1) Sequential Case								(2) Simultaneous Case							
		Conditions				Results				Conditions				Results			
OBS	CASE (Table 2)	t/a	s/a	c/a	P/Y_{st}	P^*/Y_{st}	S^*_z/Y_{st}	S^*_h/Y_{st}	k %	t/a	s/a	c/a	P/Y_{st}	P^*/Y_{st}	S^*_z/Y_{st}	S^*_h/Y_{st}	k %
1	T1	0.065	1.5	0.032	0.700	0.021	1.540	1.437	4.440	0.065	1.5	0.032	0.700	0.043	0.987	0.813	4.130
2		0.065	2.5	0.003	0.800	0.033	0.470	0.300	0.464	0.065	2.5	0.003	0.800	0.041	0.897	0.577	0.515
3		0.065	3.5	0.010	0.900	0.057	0.427	0.480	1.290	0.065	3.5	0.010	0.900	0.064	0.853	0.777	1.430
4		0.083	1.5	0.010	0.800	0.053	1.107	0.783	1.450	0.083	1.5	0.010	0.800	0.078	0.960	0.637	1.510
5		0.083	2.5	0.032	0.900	0.064	1.230	1.293	4.380	0.083	2.5	0.032	0.900	0.078	1.753	1.853	4.820
6		0.083	3.5	0.001	0.700	0.001	0.303	0.133	1.250	0.083	3.5	0.001	0.700	0.006	0.510	0.363	0.175
7		0.109	1.5	0.003	0.900	0.086	0.713	0.513	0.620	0.109	1.5	0.003	0.900	0.116	0.847	0.627	0.672
8		0.109	2.5	0.000	0.700	0.009	0.014	0.030	0.011	0.109	2.5	0.000	0.700	0.011	0.014	0.039	0.014
9		0.109	3.5	0.032	0.800	0.028	1.960	2.123	4.750	0.109	3.5	0.032	0.800	0.037	1.733	1.773	5.460
10	T2	0.065	1.9	0.032	0.700	0.021	1.315	1.387	5.150	0.065	3.5	0.032	0.700	0.023	1.342	1.408	5.090
11		0.065	2.5	0.003	0.700	0.014	0.399	0.221	0.544	0.065	2.5	0.003	0.689	0.021	0.796	0.552	1.020
12		0.065	1.9	0.010	0.700	0.018	0.779	0.714	1.960	0.065	3.5	0.010	0.689	0.018	0.758	0.689	1.940
13		0.083	1.5	0.010	0.689	0.020	0.807	0.716	2.330	0.083	2.0	0.010	0.689	0.025	0.933	0.613	1.890
14		0.083	2.5	0.032	0.689	0.013	1.394	1.496	5.180	0.083	2.5	0.032	0.699	0.022	1.219	1.158	5.050
15		0.083	1.9	0.003	0.616	0.018	0.781	0.574	0.789	0.083	3.5	0.003	0.700	0.017	0.716	0.536	0.786
16		0.109	1.5	0.003	0.689	0.009	0.853	0.634	0.604	0.109	2.0	0.003	0.689	0.016	0.783	0.615	0.646
17		0.109	2.5	0.010	0.689	0.005	0.853	0.800	1.640	0.109	2.5	0.010	0.700	0.014	0.905	0.504	1.690
18		0.109	1.5	0.032	0.689	0.008	1.214	1.132	2.160	0.065	2.0	0.032	0.616	0.011	1.166	1.025	4.380
19	T3	0.065	1.5	0.032	1.000	0.083	1.500	1.450	4.290	0.065	1.5	0.032	1.000	0.100	1.356	1.139	4.270
20		0.065	2.5	0.003	1.055	0.077	0.689	0.517	0.529	0.065	2.5	0.003	1.055	0.091	0.833	0.606	0.620
21		0.065	3.5	0.010	1.111	0.093	1.183	1.011	1.450	0.065	3.5	0.010	1.111	0.104	1.111	0.994	1.440
22		0.083	1.5	0.010	1.055	0.113	1.178	1.100	1.580	0.083	1.5	0.010	1.055	0.139	1.000	0.667	1.630
23		0.083	2.5	0.032	1.111	0.121	2.022	2.144	5.210	0.083	2.5	0.032	1.111	0.131	1.906	2.044	5.050
24		0.083	3.5	0.003	1.000	0.065	0.528	0.389	0.513	0.083	3.5	0.003	1.000	0.074	0.678	0.489	0.551
25		0.109	1.5	0.003	1.111	0.152	0.867	0.611	0.663	0.109	1.5	0.010	1.111	0.093	1.239	1.217	1.780
26		0.109	2.5	0.010	1.000	0.089	1.322	1.333	1.850	0.109	2.5	0.003	1.000	0.176	0.839	0.622	0.702
27		0.109	3.5	0.032	1.051	0.091	1.150	1.250	4.800	0.109	3.5	0.032	1.051	0.120	2.150	2.270	6.530

STATISTICAL ANALYSIS AND EMPIRICAL EQUATIONS

The statistical analysis was performed using SAS 5.18 (Statistical Analysis System)[12]. The 27 sets of data for the 27 observation points (Table 4) were analyzed in the following manner:

First, a correlation analysis was performed in order to show the strength of a relationship between any two variables. The correlation coefficient is a number that ranges from -1 to +1. A positive correlation means that, as the value of one variable increases, the value of the other variable will also tend to increase. A correlation coefficient near zero means there is little correlation between the two variables. Table 5 presents the results of the correlation analysis. For example, in the case of the simultaneous expansion process, the correlation coefficients between P^*/Y_{st} and t/a is 0.215.

Table 5. Correlation coefficients

(1) Sequential case

	t/a	s/a	c/a	P/Y_{st}	E_t/Y_{st}	E_s/E_t	Y_{ss}/Y_{st}
P^*/Y_{st}	0.120	−0.090	−0.105	0.764	0.716	0.332	0.434
S^*_z/Y_s	0.009	−0.239	0.790	0.254	0.276	0.106	0.085
S^*_h/Y_s	−0.001	−0.160	0.785	0.205	0.240	0.027	0.006
k	0.060	−0.177	0.957	0.056	0.043	0.028	0.031

(2) Simultaneous case

	t/a	s/a	c/a	P/Y_{st}	E_t/Y_{st}	E_s/E_t	Y_{ss}/Y_{st}
P^*/Y_{st}	0.215	−0.300	−0.104	0.680	0.734	0.272	0.400
S^*_z/Y_s	−0.123	0.044	0.728	0.409	0.213	0.255	0.219
S^*_h/Y_s	−0.082	0.172	0.717	0.376	0.196	0.243	0.212
k	−0.097	−0.096	0.977	−0.005	−0.046	−0.083	−0.091

In order to derive useful empirical equations, a nonlinear multiple regression analysis was performed and the exponential regression model was used due to its simplicity and reliability. This model has the following general form:

$$I=e^{a0}*(t/a)^{a1}*(s/a)^{a2}*(c/a)^{a3}*(P/Y_{st})^{a4}*(E_t/Y_{st})^{a5}*(E_s/E_t)^{a6}*(Y_{ss}/Y_{st})^{a7} \quad (1)$$

Table 6. Coefficients of Equation (1)

	(1) Sequential case P^*/Y_{st}	S^*_z/Y_{st}	S^*_h/Y_{st}	k	(2) Simultaneous case P^*/Y_{st}	S^*_z/Y_{st}	S^*_h/Y_{st}	k
a0	4.3701	−4.0000	−7.3460	3.5106	0.8785	3.3827	2.6047	7.2153
a1	−0.4991	0.1314	0.0670	0.3317	0.0576	0.0961	0.1507	0.0973
a2	−1.0204	−0.2342	−0.2953	0.0767	−0.5794	0.2436	0.3017	−0.1615
a3	0.0802	0.4538	0.3674	0.6622	0.1162	0.4416	0.3318	0.6021
a4	7.7860	0.2062	0.2658	−1.1764	4.9483	1.1023	0.7301	0.5927
a5	−0.9127	0.9625	1.3568	0.0916	−0.2471	−0.1592	−0.1578	−0.4926
a6	−4.2068	1.2846	1.2034	0.1509	−2.8423	0.0303	−0.2112	−0.6423
a7	0.8536	−0.8717	−1.1720	0.2467	0.6834	−0.0494	0.1600	0.1457
Model F value	21.95	82.76	39.78	79.38	36.62	51.18	56.4	80.41
PROB>F	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
R-SQUARE	0.83	0.95	0.90	0.95	0.89	0.92	0.93	0.95

Where "I" might be P^*/Y_{st}, S^*_z/Y_{st}, S^*_h/Y_{st} or k, for the simultaneous and sequential expansion processes; in other words, Eqn. (1) actually represents eight equations. The specific values of every coefficient in Equation (1) are given in Table 6. In addition,

Table 7. Comparison between the F.E.M. and the Reg. Equations for reference case

(1) Sequential Case

		Conditions				Results							
OBS	CASE (Table 2)	t/a	s/a	c/a	P/Y_{st}	P^*/Y_{st} FEM.	REG.	S^*_z/Y_{st} FEM.	REG.	S^*_h/Y_{st} FEM.	REG.	k § FEM.	REG.
1	T4	0.0980	1.6	0.032	0.750	0.044	0.038	2.189	2.026	2.383	1.888	4.540	4.101
2		0.0980	1.6	0.003	0.917	0.113	0.151	0.828	0.722	0.728	0.835	0.622	0.675
3		0.1300	1.6	0.032	0.917	0.103	0.158	2.217	2.192	2.383	2.030	5.240	3.557
4		0.1300	2.5	0.003	0.750	0.020	0.017	0.672	0.647	0.450	0.707	0.526	0.972
5	T5	0.0490	1.8	0.032	1.000	0.035	0.046	1.407	1.766	1.220	1.105	3.970	3.434
6		0.0490	2.8	0.003	1.100	0.047	0.051	0.720	0.555	0.460	0.417	0.507	0.662
7		0.1660	1.8	0.032	1.100	0.100	0.053	1.100	2.114	0.740	1.230	6.070	4.601
8		0.1660	2.8	0.001	1.000	0.008	0.012	0.547	0.388	0.187	0.295	0.261	0.536
9	T6	0.0653	1.4	0.032	0.485	0.027	0.014	1.112	0.938	0.709	0.873	4.150	4.689
10		0.0653	2.3	0.003	0.612	0.052	0.042	0.365	0.299	0.212	0.336	0.597	0.772
11		0.1106	1.4	0.032	0.612	0.040	0.064	0.913	1.055	0.819	0.962	4.810	4.243
12		0.1106	2.3	0.000	0.485	0.002	0.003	0.004	0.008	0.025	0.017	0.006	0.006

(2) Simultaneous Case

		Conditions				Results							
OBS	CASE (Table 2)	t/a	s/a	c/a	P/Y_{st}	P^*/Y_{st} FEM.	FEG.	S^*_z/Y_{st} FEM.	REG.	S^*_h/Y_{st} FEM.	REG.	k § FEM.	REG.
1	T4	0.0980	1.6	0.010	0.750	0.073	0.061	0.956	0.814	0.750	0.662	1.570	1.769
2		0.0980	1.6	0.003	0.917	0.147	0.143	0.944	0.597	0.672	0.514	0.903	0.965
3		0.1300	1.6	0.032	0.917	0.166	0.192	1.011	1.744	0.711	1.177	5.480	4.126
4		0.1300	2.5	0.003	0.750	0.034	0.042	0.739	0.548	0.589	0.569	0.535	0.819
5	T5	0.0490	1.8	0.032	1.000	0.043	0.060	1.387	1.782	1.253	1.168	3.960	2.924
6		0.0490	2.8	0.003	1.100	0.057	0.057	0.893	0.775	0.580	0.676	0.568	0.693
7		0.1660	1.8	0.010	1.100	0.112	0.090	0.953	1.332	0.687	1.023	2.050	1.729
8		0.1660	2.8	0.001	1.000	0.042	0.033	0.813	0.483	0.760	0.526	0.257	0.330
9	T6	0.0653	1.4	0.032	0.485	0.042	0.026	0.987	0.854	0.699	0.699	4.410	4.341
10		0.0653	2.3	0.003	0.612	0.062	0.048	0.852	0.438	0.579	0.457	0.989	1.106
11		0.1106	1.4	0.032	0.612	0.078	0.086	0.972	1.162	0.719	0.898	5.280	5.247
12		0.1106	2.3	0.000	0.485	0.004	0.006	0.004	0.010	0.027	0.029	0.011	0.008

Table 6 shows MODEL F and R-SQUARE for each equation. MODEL F indicates how well the model as a whole accounts for the dependent variable's behavior. If the significance probability, labelled PR>F, is small, it indicates significance R-SQUARE measures how much variation in the dependent variable can be accounted for by the model. R-SQUARE ranges from 0 to 1. For example, based on the results of S^{c}_{z}/Y_{st}, shown in Table 6, the R-SQUARE value is 0.95 indicating that we can account for over 95% of residual contact pressure by knowing the values of the parameters in Eqn.(1). In general, the larger the value of R-SQUARE, the better is the model fit. This indicates a good correlation between the empirical equations and the 27 observation points.

Several arbitrary cases were checked using Equation (1). Table 7 shows a comparison between the results obtained using the finite element method and the proposed empirical equations. They seem to indicate the same tendency for both sets of results.

REMARKS

The applicable range of Equation (1) should be considered carefully because this equation was developed based on a limited range of values for every parameter involved.

Upper and lower limits on the expansion pressure level must be imposed. First, the upper value of P/Y_{st} will be discussed. The simplest case would be the one where there is no clearance (c=0), and the tube and tubesheet are of the same material. In this particular case, the problem is simplified to that of an infinite plate with a hole of a diameter equal to the inner tube diameter, subjected to internal pressure. Plastic flow begins at the inside surface of the hole when the pressure reaches $Y_{st}/\sqrt{3}$. As the pressure is increased beyond this limit, the plastic zone spreads outward from the hole. Under the assumption of plane stress, this does not continue indefinitely: For a pressure value of $2*Y_{st}/\sqrt{3}$ or $1.15*Y_{st}$, the radius of the plastic zone reaches 1.75 times the radius of the hole. Further increase of the pressure has no further effect on plastic zone. So the maximum value of P/Y_{st} may be 1.15. For more details see Ref.[13]. The lower expansion pressure is the one at which the recovery of the tube and tubesheet are equal. It is dependent on both the tube's yield point and the geometries of tube $U_t=a/(a-2t)$ and tubesheet $U_s=a_s/a_o$; and can be expressed by the following equation[14]:

$$P/Y_{st} = [2*(U_s^2-1)]/[\sqrt{(3*U_t^4+1)}*(1.3*U_s^2+0.7)] + (U_t^2-1)/2 \qquad (2)$$

CONCLUSIONS

1. The finite element method, together, with a statistical analysis approach were used to perform a parametric study of the tube-tubesheet joint. Based on the results, it was possible to propose empirical equations for determining the residual contact pressure and residual stresses introduced by the expansion process.
2. The most important factors for determining residual contact

pressure seem to be the expansion pressure level (P/Y_{st}) and Young's modulus of the tubes material(E_t/Y_{st}). The ratio of yield stress of tubesheet and tube materials (Y_{ss}/Y_{st}) is relatively less significant. The expansion pressure level mostly influences the residual contact pressure, and has much less effect on residual stress levels in the transition zone.

3. Initial clearance between tube and tubesheet seems to have a very significant effect on residual stresses in the transition zone.

4. The one important factor affecting apparent tube wall reduction appears to be the initial clearance between tube and tubesheet.

REFERENCES

1. Ma,H., Chaaban,A. and Bazergui,A. (1990) "Tube-to-tubesheet joints analysis: a proposed method", ASME,PVP-Vol.194.
2. Chaaban,A., Ma,H. and Bazergui,A. (1991) "Tube-to-tubesheet Joint: a Propoposed equations for the Equivalent Sleeve Diameter Used in the Single Tube Model", will be presented in the ASME, PVP. Conference, June 1991, San Diego.
3. Chaaban,A., Morin,E., Ma,H. and Bazergui,A. (1989) "Finite Element Analysis of Hydraulically Expanded Tube-to-Tubesheet joints: A Parametric Study", ASME, PVP-Vol. 173, pp. 19-25.
4. Updike,D.P., Kalnins,A. and Caldwell,S.M. (1989) "Residual stress in Transition Zone of Heat Exchanger Tubes", ASME, PVP-Vol.175, pp. 39-44.
5. Updike,D.P., Kalnins,A. and Caldwell,S.M. (1988) "A Method foe Calculating Residual Stresses in the Transition Zones of Heat Exchanger Tubes", ASME, PVP-Vol. 139, pp. 113-118.
6. Soler,A.I. and Hong,X. (1984) "Analysis of Tube-Tubesheet Joint Loading Including Thermal Loading", Journal of Applied Mechanics, Vol.51, pp.339-344.
7. Kalnins,A. Updike,D.P. and Caldwell,S.M. (1989) "Contact Pressure in Rolled Tube-Tubesheet Joints", Transaction of the 10th International Conference on Structural Mechanics in Reactor Technology, Vol.L, pp.195-200.
8. Wang,Y. and Soler,A.I. (1988) "Effect of Boundary Conditions on the Tube-Tubesheet Joint Annulus Model - Finite Element Analysis", ASME, PVP, 139.
9. Fisher,F.F. and Brown,G.J. (1945) "Tube Expanding and Related Subjects", Transactions of the ASME, pp.563-575.
10. TUBULAR EXCHANGER MANUFACTURERS ASSOCIATION, INC. (1968) "Standards of Tubular Exchanger Manufacturers Association", Fifth Edition.
11. TAGUCHI,G. (1987) "System of Experimental Design", KRAUS INTERNATIONAL PUBLICATIONS.
12. SAS INSTITUTE, (1982) "SAS User's Guide: Statistics", U.S.A.
13. Yohell, S. (1982) "Heat-exchanger Tube-to-tubesheet Connections", Chemical Engineering, pp.78-94.
14. Krips,H. and Podhorsky,M.(1976) "Hydraulic Expansion - a new method for the anchoring of tubes", VGB KRAFT-WERKSTECHNIK No.7/1976,pp.456-464.