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A COMPARATIVE ANALYSIS METHODOLOGY OF CALCULATION OF STRENGTH TUBESHEETS BY EUROPEAN STANDARDS AND GUIDELINES FOR UDT

ANALIZA PORÓWNAWCZA METODYKI OBLICZEŃ WYTRZYMAŁOŚCIOWYCH ŚCIAN SITOWYCH WEDŁUG NORM EUROPEJSKICH I WYTYCZNYCH UDT

Abstract

This paper presents comparison of calculation methods of the required thickness of the tube sheet in the shell and tube heat exchanger compatible with the standards of the European standard PN - EN 13445-3, and the guidelines of the Polish Office of Technical Inspection (UDT). Details of the methods are illustrated by numerical examples – (calculations) for the selected design of the tubesheet.

Keywords: heat exchangers, tubes, tubesheets

Streszczenie

W artykule przedstawiono porównanie metod obliczeniowych wymaganej grubości ściany sitowej w płaszczowo-rurkowym wymienniku ciepła zgodnych ze standardami normy europejskiej PN-EN 13445-3 i wytycznymi polskiego Urzędu Dozoru Technicznego. Szczegóły metod zilustrowano przykładami liczbowymi dla wybranych konstrukcji dna sitowego.

Słowa kluczowe: wymienniki ciepła, rurki, dna sitowe

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1. Introduction

The European standard PN-EN 13445-3 shows three primary distinctions in terms of shell and tube heat exchangers. In addition to the above standard PN-EN 13445-3 is Index I, wherein it shows another design solution of a tubesheet. The analysis of strength calculations for the same configurations of tubesheet differs from those described in the Polish guidelines WUDT-UC. Polish guidelines WUDT-UC are treated as mandatory during the design of pressure equipment.

In the norm PN-EN 13445-3: 2002, rules for different types of heat exchangers were shown. According to the norm:

- U-tube heat exchanger (Figure 1);
- Fixed tubesheet heat exchanger (Figure 2);
- Floating head heat exchanger (Figure 3).

Floating head heat exchanger has three different configurations:

a) with an immersed floating head;
b) with an externally sealed floating head;
c) with an internally sealed floating tubesheet [3].

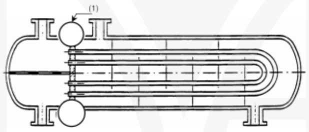

Fig. 1. U-tube heat exchanger [3]

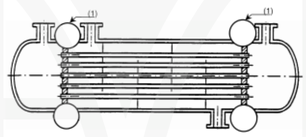

Fig. 2. Fixed tube sheet heat exchanger [3]

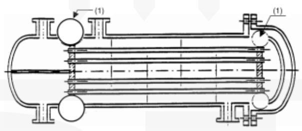

Fig. 3. Floating head heat exchange [3]

Table 1

The characteristic elements in the various types of heat exchangers

Characteristic	U-tube tubesheet heat exchanger	Fixed tubesheet heat exchanger	Floating head heat exchanger
Amount and shape tubesheet	One –flat, circular, uniform thickness	Two – flat, circular and identical (same materials, same connection with shell and channel)	Two – flat, circular, and identical connected by a bundle of straight tubes
Type of tubesheet (moving)	Stationary	Stationary	Stationary attached to the shell and channel Floating
Amount using configurations	6 (see Fig. 4)	6 (see Fig. 4)	6 stationary (Fig. 4) +3 floating (Fig. 5)
Loading conditions	3 cases	7 cases	3 cases
Tubesheet thickness	$e = \frac{D_0}{4\mu(0.8f)}\lvert P_s - P_t\rvert$	$e = \frac{D_0}{4\mu(0.8f)}\lvert P_s - P_t\rvert$	$e = \frac{D_0}{4\mu(0.85f)}\lvert P_e\rvert$

Tab. 1 shows a comparison of the information and characteristics among the types of heat exchangers which are shown in European standards. Tab. 1 also groups the equation on how to calculate the tubesheet thickness and which pressure we have to use in each heat exchanger.

This article shows one of this type – U-tube heat exchanger and different uses of the configurations of tubesheets. According the norm PN-EN 13445-3, the tubesheet may have one of the six configurations (design solutions) shown in Fig 4.

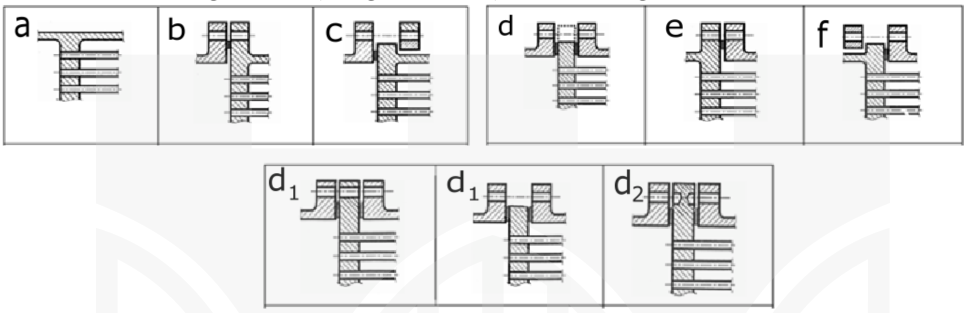

Fig. 4. Various types of configuration tubesheets [3]
a) integral with shell and channel; b) integral with shell and gasketed with channel, extended as a flange; c) integral with shell and gasketed with channel, not extended as a flange; d) gasketed with shell and channel, extended as a flange or not; e) gasketed with shell and integral with channel, extended as a flange; f) gasketed with shell and integral with channel, not extended as a flange

Configuration d covers the cases where the tubesheet is: extended as (d_1 as flange or not d_2)

In the floating tubesheet heat exchangers the floating tubesheet may have one of the 3 configurations shown in Fig 5.

- tubesheet integral (Fig. 5a),
- tubesheet gasketed, extended as a flange (Fig. 5b),
- tubesheet gasketed, not extended as a flange (Fig 5c).

Fig. 5. Various types of configuration floating tubesheets [3]

For each of these types configuration of tubesheet a different method of calculation is used. All of the methods were shown in European standards PE-EN 13445-3.

2. Examples of calculations for U-tube heat exchangers

Below is a numerical example (examples of calculations) of the method of strength calculations for tubesheet contained in European standards PN-EN 13445-3. The calculations were carried out for the tubesheet of configuration b shown in Fig. 6. Tab. 2

presents the type of material and properties which were selected in calculations. The assumed values of tubesheet were shown in Tab. 3 [7, 3].

Table 2

Properties of used material

Tubesheet - material	R_m [MPa]	R_p [MPa]	R_{pt} [MPa]	f [MPa]	f_{20} [MPa]	f_{test} [MPa]	E [MPa]
P280GH (1.0426)	460	280	225	150	186.67	266.67	198610

Table 3

Input date of tubesheet

Input date	Value	Units	Description
e_n	100	mm	Nominal thickness of tubesheet (assume)
c_t	3	mm	Tubesheet corrosion allowance on the tube -side
c_s	3	mm	Tubesheet corrosion allowance on the shell - side
p	34	mm	Tube pitch
d_t	25	mm	Nominal outside diameter of tubes
$l_{t,x}$	80	mm	Expanded length of tube in tubesheet
e_a	94	mm	Analysis thickness
e_t	2.3	mm	Nominal tube wall thickness
E_t	$1.9861 \cdot 10^5$	MPa	Elastic modulus of tube material at design temperature
E	198610	MPa	Elastic modulus of tubesheet material at design temperature
f_t	111.33	MPa	Nominal design stress of tube material at design temperature
f	150	MPa	Nominal design stress of tubesheet material at design temperature
S	178000	mm^2	Total unperforated area of tubesheet
D_0	1163.4	mm	Equivalent diameter of outer tube limit circle
G_S	1255	mm	Diameter of shell gasket load reaction
G_c	1255	mm	Diameter of channel gasket load reaction
W_S	181026	kN	Shell flange design bolt load for the assembly condition
W_c	1097.94	kN	Channel flange design bolt load for the assembly condition

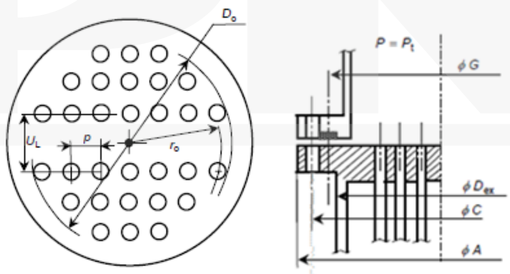

Fig. 6. Tubesheet design for b configuration [3]

The results of calculations on the thickness of the tubesheet are shown in Tab. 4. At this state of calculations, there are no differences in the method of calculation. Despite the following example of the various assumed operating pressures of the tubesheet, the calculation is carried out in the same way [3].

Table 4

The method of calculations concerning size of tubesheet

Equation	Results/ value	Units	Description
$e_a = e_n - c_t - c_s$	94	mm	Analyses thickness tubesheet (initial)
$\mu = \frac{p^* - d^*}{p^*}$	0.2647	–	The basic ligament efficiency for shear
$\rho = \frac{l_{t,x}}{e}$	0.8511	–	The tube expansion depth ratio (0 ≤ ρ ≤ 1)
$d^* = \max\left\{\left[d_t - 2 \cdot e_t \cdot \left(\frac{E_t}{E}\right) \cdot \left(\frac{f_t}{f}\right) \cdot \rho;\right] \left[d_t - 2 \cdot e_t\right]\right\}$	22.09	mm	The effective tube hole diameter
$p^* = \frac{p}{\sqrt{1 - 4\frac{\min\left[(S);\,(4 \cdot D_0 \cdot p)\right]}{\pi \cdot D_0^2}}}$	36.85	mm	The effective tube pitch
$\mu^* = \frac{p^* - d^*}{p^*}$	0.4005	–	The effective ligament efficiency of perforated tubesheet for bending
$\frac{E^*}{E} = \alpha_0 + \alpha_1 \cdot \mu^* + \alpha_2 \cdot \mu^{*2} + \alpha_3 \cdot \mu^{*3} + \alpha_4 \cdot \mu^{*4}$	0.414	–	Determination of the graph
$E^* = E \cdot 0414$	82227.64	MPa	The effective elastic modulus of the tubesheet at design temperature
$\vartheta^* = \beta_0 + \beta_1 \cdot \mu^* + \beta_2 \cdot \mu^{*2} + \beta_3 \cdot \mu^{*3} + \beta_4 \cdot \mu^{*4}$	0.3106	–	The effective Poisson's ratio of tubesheet (Determination of the graph)
$D^* = \frac{E^* \cdot e^3}{12 \cdot (1 - \vartheta^{*2})}$	$6.2993 \cdot 10^9$	Nmm	The equivalent bending rigidity of tubesheet
$\rho_s = \frac{G_s}{D_0}$	1.0787	–	The shell diameter ratio
$\rho_c = \frac{G_c}{D_0}$	1.0787	–	The channel diameter ratio
$K = \frac{A}{D_0}$	1.1174	–	The tubesheet diameter ratio
$F = \frac{1 - \vartheta^*}{E^*} \cdot (E \cdot \ln K)$	0.1848	–	The coefficient
$W_{\max} = \max\left[W_s; W_c\right]$	181026	kN	The maximum flange design bolt load for the assembly condition

After this stage, for future calculations, pressures operating at the side shell and tube should be selected. In this example, calculations of three types of pressures were carried out. Values of the operating pressure were assumed.

In first load case, the analysed negative pressure operated on the shell – side. In the second load case, the analysed negative pressure operated on the tube – side. In the third case, the negative pressure operating on the shell or the tube side was not taken into consideration.

Table 5

Load cases used in design

ID	Load Case 1	LC2	LC3	Units	Description
P_s	-0.1	1	1	MPa	Shell – Side Pressure
P_t	0.6	-1	0.6	MPa	Tube – Side Pressure

Below, Tab. 6 shows the procedure and the results of calculations carried out of the different load cases described in Tab. 5.

Table 6

Calculation the moment acting at different part of tubesheet [3]

Equation	LC 1	LC 2	LC 3	Units	Description
$M_{TS} = \frac{D_0^2}{16} \cdot [(\rho_s - 1) \cdot (\rho_s^2 + 1) \cdot P_s - (\rho_c - 1) \cdot (\rho_c^2 + 1) \cdot P_c]$	-10087.73	28822.08	5764.42	Nmm	The moment due to pressures P_s and P_t acting on the unperforated tubesheet rim
$M^* = M_{TS} + \frac{W_{max}(G_c - G_s)}{2 \cdot \pi \cdot D_0}$	-10087.73	28822.08	5764.42	Nmm	The moment acting on the unperforated tubesheet rim
$M_P = \frac{M^* - \frac{D_0^2}{32} \cdot F \cdot (P_s - P_t)}{1 + F}$	-3894.83	11128.08	2225.62	Nmm	the moment acting at periphery of tubesheet
$M_0 = M_P + \frac{D_0^2}{64} \cdot (3 + \vartheta^*) \cdot (P_s - P_t)$	-52905.35	151160	30231.63	Nmm	The moment acting at centre of tubesheet
$M = \max[\lvert M_P \rvert ; \lvert M_0 \rvert]$	52905.35	151160	30231.63	Nmm	The maximum moment acting of tubesheet
$\sigma = \frac{6 \cdot M}{\mu^* \cdot (e_a - h_g')^2}$	97.86	279.59	55.92	MPa	The calculated stress in a component
$\tau = \left(\frac{1}{4 \cdot \mu}\right) \cdot \left(\frac{D_0}{e}\right) \cdot \lvert P_s - P_t \rvert$	-8.18	23.28	4.6756	MPa	The calculated shear stress in a component

Depending on the applied pressure, different torques were obtained. In any case, the strength conditions of the maximum radial bending stress in the tubesheet and the maximum shear stress in the tubesheet have been fulfilled. The designed tubesheet fulfilled strength conditions for pressures assumed in Tab. 5. The material and size of the tubesheet were well selected.

3. Example of calculation for U-tube heat exchanger tubesheet extended as a flange

This section shows a comparison of the results of calculations performed in accordance with the WUDT-UC [2, 4, 8] and European standards. Tab. 7. shows input dates of strength parameters for the material used in the calculations [7, 6]. Tables 9, 10 and 11 were shown the selected results of these calculations. The calculations were carried out for tubesheet extended as a flange [4, 8].

Table 7

Properties of used material

Tubesheet – material	R_m [MPa]	R_p [MPa]	R_{pt} [MPa]	E [MPa]
S235JRG2 (1.0038)	410	235	210	205000

Tab. 8 contains basic information about the value assumed during the design of tubesheet. The input dates of tubesheet were selected from the Polish standards for this project [1, 5].

Table 8

The dimensions and the results of the calculated thickness of the tubesheets depending on the area

WUDT-UC	PN-EN 13445-3	Units	Description
$d_z = 25$	$d_t = 25$	mm	The nominal outer diameter of the pipe
$t = 32$	$p = 32$	mm	The tube pitch
$g = 12$	–	mm	Initial thickness
$l_0 = 12$	$l_{t,x} = 12$	mm	The expanded length of tube in tubesheet
–	$U_L = 32$	mm	The large centre- to- centre distance between adjust tube rows
$f = 533.126$	$S = 533.126$	mm^2	The total unperforated area of tubesheet

Tab. 9 and 10 show the results of calculating assembly and operating the bolts loads, necessary for the appropriate operation of the flange connection.

Table 9

The results of calculations for the assembly in the event of a tubesheet used in connection flange -screw

WUDT-UC	PN-EN 13445-3	Units	Description
D_1 = 1400	d_1 = 1400	mm	The nominal diameter of the tubesheet
D_w = 1426	B = 1426	mm	The inside diameter of the contact face between loose and stub flanges in a lap joint
D_u = 1481	G = 1504.3	mm	The diameter of gasket load reaction
–	b_0 = 26	mm	The basic gasket or joint seating width
U = 54.5	w = 52	mm	The contact width of gasket or joint seating pressure
U_{cz}= 25.61	b = 12.85	mm	The effective gasket or joint seating width
σ_m = 18.3	y = 26.20	MPa	The minimum required gasket or joint seating pressure
N_{m1} = 2502000	W_A = 104694	**N**	The minimum required bolt load for assembly condition
C = 1.4	–	–	The correction coefficient use in WUDT-UC
N_{m2} = 5618000	–	N	The minimum required bolt load for assembly condition – used correction coefficient

Table 10

The results of calculations for operating in the event of a tubesheet used in connection flange – screw

WUDT-UC	PN-EN 13445-3	Units	Description
D_u = 1481	G = 1504.3	mm	The inside diameter of the contact face between loose and stub flanges in a lap joint
p_0 = 1.6	P = 1.6	MPa	Design pressure
b = 1.5	–	–	The coefficient of hedging against a decline in the strength S as a result of creep
σ_r = 4.8	mP = 2.4	MPa	The pressure on the gasket to guarantee tightness of the joint in the operating conditions
U_{cz} = 26.61	b = 12.85	mm	The effective gasket or joint seating width
P = 2754000	H = 2843667	N	The total hydrostatic end force
S = 953200	H_G = 22684	N	The compression load on gasket to ensure tight joint
N_r = 4013000	W_{op} = 2866351	N	The minimum required bolt load for operating condition

Tab. 11 shows the final results for the calculation of the bottom sieve according to WUDT-UC and European standards.

Table 11

Comparison of the results of calculated thickness of the tubesheet

The calculated thickness of the tubesheet	WUDT-UC g_o mm	PN-EN 13445-3 e mm
1. Precinct flange connection	26	32
2. Precinct bundle of tubes	20	12
3. Outside the bundle of tubes	34	12
The thickness of whole tubesheet *	34	32

* Industry seeks to standardise the thickness of the tube sheet for each of its area

4. Conclusion

The European standard PN-EN 13445-3 has procedures for the calculation of tubesheet for more structural solutions than Polish guidelines WUDT-UC. The calculations are dependent on the heat exchanger and the type of tubesheets.

In the case of guidelines WUDT-UC, the amount of these solutions is very limited and reduced to a few cases. However, this greatly facilitates carrying out the calculations. All the values in the design are known.

Large difference were noted when comparing the two methods of calculating algorithms. For calculation algorithm strength WUDT-UC as the minimum thickness of the tube sheet assumes a value equal to 12 mm, regardless of the material from which the tube sheet and the diameter of the heat exchanger and the load applied pressure.

In the European standard PN-EN 13445-3, there is no requirement specifying the minimum size of the tubesheet. The calculation is carried out for the assumed thickness of the tubesheet. It is important only for the thickness to fulfil strength requirements. If these conditions are not fulfilled, the calculations must be repeated by increasing the thickness of the tubesheet.

When comparing the results of calculation for tubesheet extended as a flange, conducted for both of these documents, large differences are noted. The same situation occurs in the event of comparing the dimensions of sealing solutions for the flange connection. They relate to the average diameter of the seal D_u and the inside diameter of the contact face between loose and stub flanges in a lap joint G.

According to the algorithm calculations WUDT-UC thickness of the tubesheet meets the conditions adopted in the project in the precinct flange connection and it is 26 mm. However, according to European standard PN-EN 13445-3, this value is higher, at 32 mm. In the precinct bundle of tubes, higher values in the calculation were obtained for the guidance WUDT-UC equal 20 mm. In the case of the European standard, this value was 12 mm. For the region outside the bundle of tubes, a similar situation was noted. For the European standard PN-EN 13445-3 there was a higher value – 32 mm than for the guidelines WUDT-UC – 12 mm.

Finally, the thickness of tubesheet for European standard PN-EN 13345-3 was equal to 34 mm. The calculations that were carried out for guidelines WUDT-UC amounted to 32 mm.

It was found that the calculations performed according to the European standards PN-EN 13445-3 are more accurate and increase the strength of the structure. Due to the greater thickness of the tubesheet heat exchanger, it meets the requirements of safety and allows safe operation of the device.

In the analysed examples, an analogy on the section of the tubesheet into different areas was noted. Equation determination of tubesheet thickness have been summarised in below Tab. 12.

Table 12

Comparison of formulas used to determine the thickness of the tube sheet in each of its region

Region / Standards	Precinct flange connection	Outside the bundle of tubes	Precinct bundle of tubes
WUDT-UC	$D_z = D_w + 2 \cdot g_S$: - assembly conditions: $\sigma_{km} = 2 \cdot N_m \cdot \frac{D_0 - D_w - 2 \cdot g_s}{\pi \cdot (D_{zk} - 2 \cdot d_0) \cdot h^2}$ - operating conditions: $\sigma_{kr} = 2 \cdot N_r \cdot \frac{D_0 - D_w - 2 \cdot g_s}{\pi \cdot (D_{zk} - 2 \cdot d_0) \cdot h^2}$	$g_0 = 0.45 \cdot \delta \cdot \sqrt{\frac{p_0}{k}}$	$g = \frac{q_{\min}}{m}$
PN-EN 13445-3	- assembly conditions: $e_{fl,a} = \sqrt{\frac{12}{\pi \cdot D_{ex} \cdot \left[(1+\vartheta)+(1-\vartheta)\cdot\left(\frac{D_{ex}}{A}\right)^2\right]} \cdot \frac{M_A}{f_A}}$ - operating conditions: $e_{fl,op} = \sqrt{\frac{12}{\pi \cdot D_{ex} \cdot \left[(1+\vartheta)+(1-\vartheta)\cdot\left(\frac{D_{ex}}{A}\right)^2\right]} \cdot \frac{M_{op}}{f}}$	Assumed in the project, checked under the strength conditions and corrected when are not complied.	Assumed in the project, checked under the strength conditions and corrected when are not complied.

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