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TECHNO-ECONOMIC ANALYSIS OF HEAT EXCHANGERS WITH PARALLEL HELICAL TUBE COILS

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Preliminary notes
The paper deals with the investment and exploitation costs for shell and tube heat exchangers with parallel helical tube coils. The most common correlations for estimating prices of shell and tube heat exchangers found in open literature were tested using the market data for a comparison and they have shown significant deviations. A new correlation for calculating prices of heat exchangers with helical tubes (when the shell is made of carbon steel and the helical tube of copper) was determined. In addition, the costs of electricity needed to drive pumps, as well as the costs of chemical cleaning of the apparatuses with inhibited mineral acids were estimated.

Keywords: *chemical cleaning, heat exchanger, investment costs, operating costs*

Tehno-ekonomska analiza bubnjastih izmjenjivača topline s paralelnim zavojnim cijevima

Prethodno priopćenje
U radu su prikazani investicijski i eksploatacijski troškovi kod bubnjastih izmjenjivača topline s paralelnim zavojnim cijevima. Provedena je statistička analiza najčešće rabljenih korelacija iz otvorenih literaturnih izvora za određivanje cijena bubnjastih izmjenjivača topline s tržišnim podacima aparata s kojom je utvrđeno da pokazuju značajna odstupanja i da se ne mogu s dovoljnom pouzdanošću koristiti za navedeni tip aparata. Uspostavljena je nova korelacija za procjenu cijena aparata sa zavojnim cijevima (za slučaj kada je omotač aparata izrađen od ugljičnog čelika, a cijevni snop od bakra). Procijenjeni su troškovi električne energije za pogon pumpi kao i troškovi kemijskog čišćenja aparata inhibiranom klorovodičnom i sumpornom kiselinom.

Ključne riječi: *investicijski troškovi, izmjenjivač topline, kemijsko čišćenje, pogonski troškovi*

1 Introduction

Shell and tube heat exchangers with parallel helical tube coils (HEHTC) consist of a large number of helical tube coils which are placed within a cylindrical shell in the form of a tube bundle. The number of passes of fluid at the tube-side and at the shell-side is usually one or two. The number of passes of fluid at the tube-side is provided by means of baffles allocated in the stationary head-channel, whereas the number of passes of fluid at the shell-side is provided by longitudinal baffles allocated in the cylindrical shell [1, 2]. The main types of shell and tube heat exchangers with parallel helical tubes are with fixed tube sheets (Fig. 1) and with internal/external floating head (Fig. 2 and Fig. 3) [2, 3].

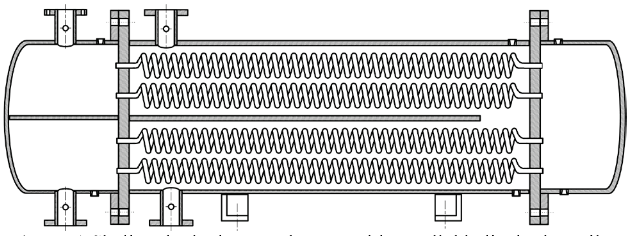

Figure 1 Shell and tube heat exchanger with parallel helical tube coils - fixed tube sheet type

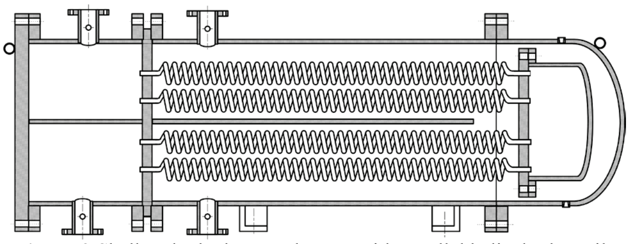

Figure 2 Shell and tube heat exchanger with parallel helical tube coils with internal floating head

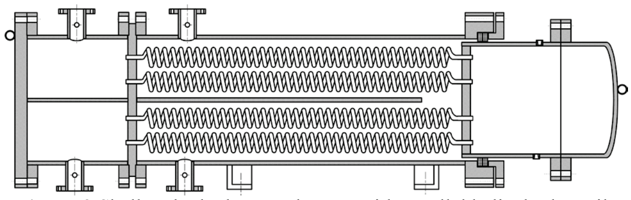

Figure 3 Shell and tube heat exchanger with parallel helical tube coils with external floating head

Although used in thermal engineering and process industries for almost half a century, problems related to HEHTC economic costs have not been fully explored. Thus, the primary objective of this paper was to determine the costs resulting from the exploitation of HEHTC.

2 Exploitation costs for heat exchangers

The total cost resulting from the exploitation of apparatus (C_{tot}, EUR/year) can be expressed as follows [4]:

$$C_{tot} = a \cdot C_{in} + C_{op}, \tag{1}$$

where a (year^{-1}) is annual discount rate, C_{in} (EUR) is investment cost, and C_{op} (EUR/year) is annual operating cost.

The depreciation rate is a decrease in the value of the apparatus (plant) in the course of its operation due to wear and tear of equipment. Its compensation provides a simple or extended reproduction of the work process.

It depends on the equipment life and on the banking interest [5] and is calculated using the next equation

$$a = \frac{p \cdot (1+p)^n}{(1+p)^n - 1}, \tag{2}$$

where p is annual value of the interest rate on the loan for the purchase of equipment, and n (year) is equipment life. If the company does not use bank loans to buy equipment, then $a = 1/n$. Economic analyses usually consider this second case, where a period of 10 years is most often adopted for the equipment life [6, 7, 8].

3 Investment costs

One can find several correlations for estimating investment cost of shell and tube heat exchangers in open literature. They are based on knowledge of the design of apparatus, the operating pressure, the heat transfer surface, and the material of apparatus. The most often cited correlations are listed in Tab. 1, adjusted so that price is expressed in an appropriate manner (EUR2011).

Prices of exchangers, obtained from the manufacturer, should be translated also from the year of manufacturing (Tab. 2) into the year for which the analysis is made. The simplest method takes into account the increasing costs due to market trends, given by the equation:

$$\frac{C_{\mathrm{A}}}{I_{\mathrm{A}}} = \frac{C_{\mathrm{B}}}{I_{\mathrm{B}}}, \tag{23}$$

where C_{A} is the price of apparatus at the moment A, EUR, C_{B} is the price of apparatus at the moment B, EUR, I_{A} is the index of price at the moment A, I_{B} is the index of price at the moment B [16].

For shell and tube heat exchangers with parallel helical tubes with a fixed tube sheet we encounter no correlation for the assessment of investment costs in the literature. Therefore, an analysis was performed with the goal to determine to what extent the discrepancies arose when using the existing equations (3 ÷ 22). Deviation in prices, calculated using the correlation (3 ÷ 22) and the actual price, is expressed using statistical indicators: correlation ratio (CR) and the root-mean square deviation (RMSD) as shown in Tab. 3. The analysis proved that these correlations show significant deviations and that they cannot be successfully used to describe the investment costs for the shell and tube heat exchangers with parallel helical tubes with a fixed tube sheet, where the apparatus shell is made of carbon steel and the heat exchanger's tubes made of copper. Therefore, on the basis of the data given in Tab. 2, a new correlation was found in the following form (Fig. 4):

$$C_{\mathrm{in}} = 700 + 310 \cdot S_{\mathrm{hts}}, \tag{24}$$

for the range 2,5 m^2 < S_{hts} < 38 m^2, 2 < p < 30 bar and 0 ≤ t ≤ 200 °C. Its statistical parameters are CR = 0,9068 and RMSD = 17,10 %. In the above equations (3 ÷ 22) the value of heat transfer surface (S_{hts}) was expressed taking into account the outside of the tube.

Table 1 Correlations from literature for estimation price of shell and tube heat exchangers by various authors

No.	Year	Material (Shell-Tube)	Temp. range (°C)	Pressure range (bar)	S_{hts} range (m^2)	Correlation / EUR	Ref.	Eq.
1	1990	Carbon steel - Carbon steel	-	-	-	$C_{\mathrm{in}} = 5910{,}7 + 304 \cdot S_{\mathrm{hts}}^{0,8}$	[9]	(3)
2	1990	Carbon steel - Stainless steel	-	-	-	$C_{\mathrm{in}} = 7191{,}1 + 345{,}4 \cdot S_{\mathrm{hts}}^{0,85}$	[9]	(4)
3	1990	Stainless steel - Stainless steel	-	-	-	$C_{\mathrm{in}} = 8443{,}8 + 273{,}6 \cdot S_{\mathrm{hts}}^{0,91}$	[9]	(5)
4	1990	Carbon steel - Titanium	-	-	-	$C_{\mathrm{in}} = 11821{,}4 + 581{,}5 \cdot S_{\mathrm{hts}}^{0,92}$	[9]	(6)
5	1990	Titanium - Titanium	-	-	-	$C_{\mathrm{in}} = 14776{,}7 + 590{,}2 \cdot S_{\mathrm{hts}}^{0,93}$	[9]	(7)
6	1995	-	-	-	0,05÷0,27	$C_{\mathrm{in}} = 906{,}5 \cdot S_{\mathrm{hts}}^{0,432}$	[10]	(8)
7	1998	Carbon steel - Carbon steel	-	20÷30	10÷600	$C_{\mathrm{in}} = 1400{,}4 \cdot S_{\mathrm{hts}}^{0,64}$	[11]	(9)
8	1998	Carbon steel - Brass	-	20÷30	10÷600	$C_{\mathrm{in}} = 1278{,}2 \cdot S_{\mathrm{hts}}^{0,71}$	[11]	(10)
9	1998	Carbon steel - Stainless steel	-	20÷30	10÷600	$C_{\mathrm{in}} = 1302{,}7 \cdot S_{\mathrm{hts}}^{0,86}$	[11]	(11)
10	1998	Stainless steel -Stainless steel	-	20÷30	10÷600	$C_{\mathrm{in}} = 1874{,}4 \cdot S_{\mathrm{hts}}^{0,82}$	[11]	(12)
11	2001	Carbon steel - Carbon steel	≤350	≤10,5	9÷6500	$C_{\mathrm{in}} = 8500{,}7 + 111{,}4 \cdot S_{\mathrm{hts}}$	[12]	(13)
12	2004	Stainless steel - Titanium	-	-	-	$C_{\mathrm{in}} = 30800 + 3748 \cdot S_{\mathrm{hts}}^{0,81}$	[13]	(14)
13	2007	Carbon steel - Carbon steel	≤300	≤50	-	$C_{\mathrm{in}} = 3183{,}2 \cdot S_{\mathrm{hts}}^{0,68}$	[14]	(15)
14	2007	Carbon steel - Aluminium	≤300	≤50	-	$C_{\mathrm{in}} = 4138{,}1 \cdot S_{\mathrm{hts}}^{0,68}$	[14]	(16)
15	2007	Carbon steel - Monel	≤300	≤50	-	$C_{\mathrm{in}} = 6684{,}7 \cdot S_{\mathrm{hts}}^{0,68}$	[14]	(17)
16	2007	Carbon steel - Stainless steel	≤300	≤50	-	$C_{\mathrm{in}} = 5411{,}4 \cdot S_{\mathrm{hts}}^{0,68}$	[14]	(18)
17	2007	Stainless steel - Stainless steel	≤300	≤50	-	$C_{\mathrm{in}} = 9231{,}2 \cdot S_{\mathrm{hts}}^{0,68}$	[14]	(19)
18	2009	Carbon steel - Carbon steel		-	9÷90	$C_{\mathrm{in}} = 1957{,}8 \cdot S_{\mathrm{hts}}^{0,551}$	[15]	(20)
19	2009	Admiralty		-	9÷90	$C_{\mathrm{in}} = 1422{,}2 \cdot S_{\mathrm{hts}}^{0,679}$	[15]	(21)
20	2009	Copper–brass		-	9÷90	$C_{\mathrm{in}} = 1722{,}7 \cdot S_{\mathrm{hts}}^{0,679}$	[15]	(22)

Table 2 Year built of apparatus

No.	S_{hts}, m^2	Year built	Cost of apparatus in year built / EUR	Cost of apparatus (EUR_{2011})
1	2,51	2005	1200	1568
2	4,02	2010	1600	1760
3	8,55	2009	3900	4690
4	11,56	2009	3600	4329
5	11,56	2008	3600	3515
6	15,03	2010	4500	4950
7	18,60	2008	5800	5663
8	18,95	2009	6200	7456
9	22,11	2008	6600	6445
10	24,18	2010	5600	6160
11	26,24	2008	9300	9081
12	28,13	2009	7300	8779
13	28,75	2006	11900	14580
14	32,17	2008	9600	9374
15	35,94	2010	11000	12098
16	37,20	2008	11880	11600

Table 3 Correlations for price estimation of shell and tube heat exchangers with its statistical parameters

No.	Correlation / EUR	*CR*	*RMSD*	No.
1	$C_{in} = 5910{,}7 + 304 \cdot S_{hts}^{0{,}8}$	0,4345	119,58	(3)
2	$C_{in} = 7191{,}1 + 345{,}4 \cdot S_{hts}^{0{,}85}$	0	161,19	(4)
3	$C_{in} = 8443{,}8 + 273{,}6 \cdot S_{hts}^{0{,}91}$	0	189,57	(5)
4	$C_{in} = 11821{,}4 + 581{,}5 \cdot S_{hts}^{0{,}92}$	0	332,1	(6)
5	$C_{in} = 14776{,}7 + 590{,}2 \cdot S_{hts}^{0{,}93}$	0	413,71	(7)
6	$C_{in} = 906{,}5 \cdot S_{hts}^{0{,}432}$	0	49,47	(8)
7	$C_{in} = 1400{,}4 \cdot S_{hts}^{0{,}64}$	0,6391	53,11	(9)
8	$C_{in} = 1278{,}2 \cdot S_{hts}^{0{,}71}$	0	66,31	(10)
9	$C_{in} = 1302{,}7 \cdot S_{hts}^{0{,}86}$	0	154,62	(11)
10	$C_{in} = 1874{,}4 \cdot S_{hts}^{0{,}82}$	0	225,57	(12)
11	$C_{in} = 8500{,}7 + 111{,}4 \cdot S_{hts}$	0	171,42	(13)
12	$C_{in} = 30800 + 3748 \cdot S_{hts}^{0{,}81}$	0	1266,65	(14)
13	$C_{in} = 3183{,}2 \cdot S_{hts}^{0{,}68}$	0	275,04	(15)
14	$C_{in} = 4138{,}1 \cdot S_{hts}^{0{,}68}$	0	386,68	(16)
15	$C_{in} = 6684{,}7 \cdot S_{hts}^{0{,}68}$	0	684,66	(17)
16	$C_{in} = 5411{,}4 \cdot S_{hts}^{0{,}68}$	0	535,64	(18)
17	$C_{in} = 9231{,}2 \cdot S_{hts}^{0{,}68}$	0	982,76	(19)
18	$C_{in} = 1957{,}8 \cdot S_{hts}^{0{,}551}$	0,4072	70,7	(20)
19	$C_{in} = 1422{,}2 \cdot S_{hts}^{0{,}679}$	0	70,24	(21)
20	$C_{in} = 1722{,}7 \cdot S_{hts}^{0{,}679}$	0	104,51	(22)

4 Operating costs

Operating costs are calculated as the sum of costs incurred by using electricity needed to operate the pumps and costs incurred by cleaning the apparatus.

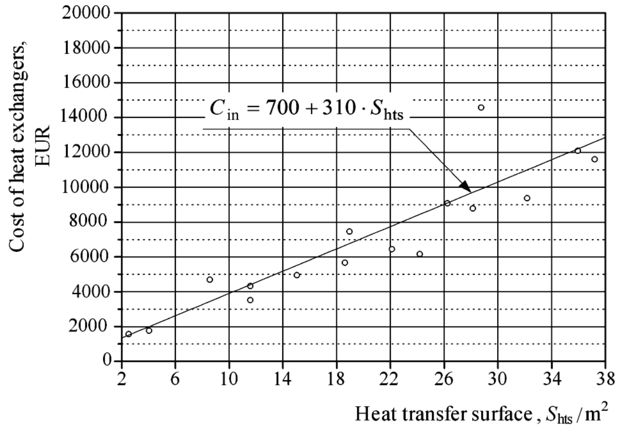

Figure 4 Investment costs of apparatus versus heat transfer surface

4.1 Costs of electricity

Consumption of electricity depends on the power required to drive the pumps which transport fluid through the tube-side and through the shell-side [6]

$$P = \frac{1}{\eta} \cdot \left(\frac{\dot{m}_{ts}}{\rho_{ts}} \cdot \Delta p_{ts} + \frac{\dot{m}_{ss}}{\rho_{ss}} \cdot \Delta p_{ss} \right), \tag{25}$$

where: P is the pumping power, W; η is the pump efficiency (commonly 0,6 ÷ 0,7); $\dot{m}_{ts}$ is the tube-side flow rate, kg/s; $\dot{m}_{ss}$ is the shell-side flow rate, kg/s; ρ_{ts} is the tube-side fluid density for average fluid temperature, kg/m^3; ρ_{ss} is shell-side fluid density for average fluid temperature, kg/m^3; Δp_{ts} is the total pressure drop for tube-side, Pa; Δp_{ss} is the total pressure drop for shell-side, Pa.

Costs incurred by using electricity (C_{El}, EUR/year) are defined by the equation

$$C_{El} = P \cdot K_{El} \cdot \tau, \tag{26}$$

where K_{El} is the price of electrical energy, EUR/(W·h), τ are hours of operation per year, h/year.

Operating costs of the actual heat exchangers (Tab. 4) were determined for the case when these apparatuses operate within the industrial plants (330 days or 7920 hours of operation) and within the district heating system (180 days or 2880 hours of operation). The average electricity price taken is 0,090 EUR/(kW·h) [17].

4.2 Costs of cleaning of apparatus

A marked increase in pressure drop and/or reduction in performance usually indicate that cleaning is necessary. Cleaning of the apparatus includes cleaning its tubes, shell sides, nozzle and end channels. If the pipes are not clean, there may be interruption of flow through a pipe, which leads to great temperature stresses and loosening at the connections. This is particularly the case when the tube bundle of shell and tube heat exchangers is formed from smaller diameter pipes [18].

Heat exchangers may be cleaned by mechanical methods, chemical methods or their combination [19]. In consideration of the costs incurred by cleaning of a heat exchanger it is assumed that it takes place by chemical methods. These methods have a number of advantages over the mechanical ones. Namely they are relatively quick, surfaces do not experience mechanical damage, they can reach inaccessible areas, they are less labour intensive, and they can, almost always, be performed *in situ* [20].

Table 4 Cost incurred by using electricity, EUR/year

No.	S_{hts}, m^2	Industrial plant	District heating system
1	2,51	258	94
2	28,75	818	297
3	32,17	1253	456
4	26,24	632	230
5	22,11	2838	1032
6	37,20	4619	1680
7	18,60	752	273
8	11,56	1559	567
9	18,95	520	189
10	8,55	1155	420
11	28,13	3466	1261
12	11,56	476	173
13	4,02	579	210
14	15,03	383	139
15	35,94	954	347
16	24,18	2426	882

When performing chemical cleaning, it is necessary to know the composition of the deposits formed in order to select the appropriate chemicals. Chemicals for cleaning heat exchangers in general may be classified into the following categories:

- organic acids,
- mineral acids,
- alkalis,
- organic compounds (solvents) [19].

A review of commonly used substances for chemical cleaning is listed in Tab. 5.

Table 5 The classification of substances for chemical cleaning of shell and tube heat exchangers

Acids	Alkalis	Organic solvents
Organic acids:	Na_2CO_3	Kerosene
$C_6H_8O_7$, HCOOH	NaOH	Naphta
Mineral acids:	Na_2SiO_3	Naphta derivatives
HCl, H_2SO_4, H_3NSO_3, HNO_3	Na_3PO_4	Trichloroethane

Among the above listed substances the most widely used cleaning agents are hydrochloric and sulphuric acid, primarily due to their price. However, these mineral acids are highly ionized and strong, which may cause rapid corrosion, if solution is insufficiently inhibited.

The type of cleaning agent which is chosen has a major effect on the cost-effectiveness of the cleaning job. The selection of cleaning chemicals does not only depend on the type of deposit, but also on the exchanger material and cleaning conditions. As stated previously, incorrect use of acid for chemical cleaning of the apparatus can lead to corrosion and it is necessary to avoid this negative side-effect by using corrosion inhibitors.

Corrosion inhibitors are substances added to a liquid (water or an aqueous solution of acid) to prevent corrosion or to reduce it to an acceptably low rate. They are used mainly in closed or recirculated systems and are selected for their effectiveness in protecting the specific metal or combination of metals in a given system [21]. Inhibitors are usually used at very low concentrations from 1000 to 3000 ppm and can give 99,8 % + inhibition on a metal surface, even in highly corrosive hydrochloric acid solutions [22].

The procedure of chemical cleaning involves circulating fluid through the tube and shell side until the apparatus is completely cleaned. After cleaning, it is necessary to wash out all the chemicals thoroughly before the heat exchanger is back in service [2]. Intervals between two successive instances of cleaning should not be long, since the difficulties in cleaning rapidly increase with the increase of thickness of plaque (deposits). Therefore, they range between 6 weeks and 6 months. [23]. All heat exchangers that were analyzed for apparatus with fixed tube sheets (Fig. 1), and thus the cleaning of the devices was carried out by chemical methods only. Water was the working fluid at both sides of heat exchangers.

Chemical cleaning was performed with chemical substances which were circulated through the apparatus at intervals of several hours (usually τ = 4 ÷ 6 h) at the temperature t = 20 ÷ 70 °C [23, 24, 25]. Since the working medium that passed through the apparatus was water, the main deposit on the heat transfer surface was calcium carbonate (limestone). In accordance with these facts, calculation of costs of chemical cleaning of heat exchangers was conducted. Hydrochloric and sulphuric acids, as noted above, are highly corrosive, therefore their diluted solution was taken into consideration in the analysis. The concentration of acid in the solution is usually in the range of 2 ÷ 10 % [24, 26, 27, 28, 29].

The costs of cleaning (C_{cl}, EUR/year) are:

$$C_{cl} = \mathrm{m}_{ac} \cdot C_{ac} + m_{ih} \cdot C_{ih} \, , \tag{26}$$

where m_{ac} is the amount of cleaning agent, kg/year, C_{ac} is the unit price of the cleaning agent, EUR/kg, m_{ih} is the amount of corrosion inhibitor, kg/year, C_{ih} is the unit price of corrosion inhibitor of HCl and H_2SO_4.

Table 6 The cost of apparatus cleaning, once a year, EUR/year

S_{hts}, m^2	Solution of inhibited HCL			Solution of inhibited H_2SO_4		
	2 %	5 %	10 %	2 %	5 %	10 %
2,51	3	5	7	3	4	6
28,75	24	35	53	22	30	43
32,17	26	39	59	25	33	48
26,24	20	30	45	19	26	36
22,11	19	28	42	18	24	34
37,20	31	45	69	29	39	56
18,60	16	24	36	15	21	29
11,56	11	16	24	10	14	20
18,95	16	24	36	15	20	29
8,55	8	12	18	7	10	14
28,13	23	34	52	22	29	42
11,56	11	16	24	10	14	20
4,02	4	6	9	4	5	8
15,03	13	20	30	13	17	24
35,94	28	42	64	27	36	51
24,18	20	30	45	19	26	36

It was assumed that corrosion inhibitors are administered at a concentration of 3000 ppm. The frequency of apparatus cleaning in general depends on the characteristics and purity of the fluid that flows through the device, as well as on the flow conditions. It is in the range of 1 to 3 times per year [23, 30].

Within the cost estimates of the apparatuses cleaning, it is assumed that the apparatuses located in a district heating system, for the conditions of the heating season in the Republic of Serbia, are usually cleaned once a year (Tab. 6), whereas the built-in appliances in industrial plants are usually cleaned two or three times per year (Tab. 7 and Tab. 8).

Table 7 The cost of apparatus cleaning, twice a year, EUR/year

S_{hts}, m^2	Solution of inhibited HCL			Solution of inhibited H_2SO_4		
	2 %	5 %	10 %	2 %	5 %	10 %
2,51	6	9	14	6	8	11
28,75	47	69	106	45	60	85
32,17	53	77	118	50	67	95
26,24	40	59	90	38	51	73
22,11	38	55	84	36	48	68
37,20	62	91	139	59	79	112
18,60	33	48	73	31	41	59
11,56	22	32	49	21	28	39
18,95	32	47	72	31	41	58
8,55	16	23	35	15	20	29
28,13	46	67	103	44	58	83
11,56	22	32	49	21	28	39
4,02	8	12	19	8	11	15
15,03	27	39	60	26	34	48
35,94	57	83	128	54	72	103
24,18	40	59	90	38	51	73

Table 8 The cost of apparatus cleaning, three times a year, EUR/year

S_{hts}, m^2	Solution of inhibited HCL			Solution of inhibited H_2SO_4		
	2 %	5 %	10 %	2 %	5 %	10 %
2,51	9	14	21	9	12	17
28,75	71	104	159	67	90	128
32,17	79	116	177	75	100	143
26,24	60	89	135	57	77	109
22,11	56	83	126	54	72	102
37,20	93	136	208	88	118	168
18,60	49	71	109	46	62	88
11,56	32	48	73	31	41	59
18,95	48	71	108	46	61	87
8,55	24	35	53	22	30	43
28,13	69	101	155	66	88	125
11,56	32	48	73	31	41	59
4,02	13	18	28	12	16	23
15,03	40	59	90	38	51	73
35,94	85	125	191	81	109	154
24,18	60	89	135	57	77	109

In addition to the previous analysis, the balance of the total cost per year for the analyzed heat exchangers is also shown. In this case, it is considered that the devices are installed in industrial plants and that the chemical cleaning is performed with a 5 % inhibited hydrochloric acid twice a year. Balance of total cost in relation to the heat transfer surface is expressed in EUR/year and is shown in Tab. 9 and in Fig. 5.

It is necessary to emphasize that the total cost for heat exchangers here, unlike in [6] and [7], is calculated taking into account the costs of chemical cleaning appliances.

Table 9 Total annual operating costs of apparatus, EUR/year

No.	S_{hts}, m^2	Operating costs
1	2,51	424
2	28,75	2345
3	32,17	2267
4	26,24	1599
5	22,11	3537
6	37,20	5870
7	18,60	1366
8	11,56	1943
9	18,95	1313
10	8,55	1647
11	28,13	4411
12	11,56	941
13	4,02	767
14	15,03	917
15	35,94	2247
16	24,18	3101

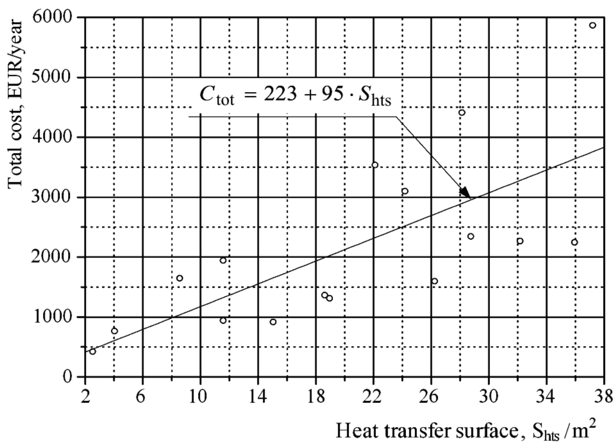

Figure 5 Total annual costs of shell and tube heat exchangers with parallel helical tube, EUR/year

5 Conclusion

After examining correlations from the open literature on investment costs of shell and tube heat exchangers, it was concluded that the new correlation needed to be found.

The new correlation for determining the price of shell and tube heat exchangers with parallel helical tube coils (when the shell is made of carbon steel and the tube is made of copper) has the following form:

$$C_{in} = 700 + 310 \cdot S_{hts}, \qquad (24)$$

for the range $2,5 < S_{hts} < 38$ m^2, $2 \leq p \leq 30$ bar, and $0 \leq t \leq 200$ °C. Statistical parameters of the equation are CR = 0,907, and $RMSD$ = 17,10 %.

The analysis of chemical cleaning of heat exchangers was also made, including the use of inhibited hydrochloric (2 %, 5 % and 10 %) and inhibited sulfuric acid (2 %, 5 % and 10 %) as cleaning agents. It was determined that the costs when using hydrochloric acid were about 5,9 % higher than the costs of cleaning with sulfuric acid.

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