TOTAL COSTS OF SHELL AND TUBE HEAT EXCHANGERS WITH CONCENTRIC HELICAL TUBE COILS

by

Marko S. JARIĆ , Igor I. MARTIĆ, Nikola J. BUDIMIR, Igor D. SVETEL, and Mihailo P. MILANOVIĆ*

Innovation Center of the Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia

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The paper deals with the manufacturing costs of shell and tube heat exchangers with concentric helical tube coils. The most common correlations for calculating prices of shell and tube heat exchangers found in accessible literature were tested using the market data for a comparison and they have shown significant deviations. A new correlation for estimating prices of heat exchangers with concentric helical tubes (when the shell is made of carbon steel and the helical tube of copper) was determined in the following form:

$$C_{in} = 614 \cdot S_{hts}^{0.627}$$

Key words: *heat exchanger, correlation, manufacturing costs, helical tube*

Introduction

Heat exchangers with helical tubes are often encountered in chemical and petrochemical industries, HVAC systems, thermal, environmental, and many other engineering applications. They can be used as heaters, coolers, condensers and evaporators, and their design is largely restricted to non-fouling fluids [1, 2]. In comparison with straight-tube heat exchangers, heat transfer rate of helically coiled heat exchangers is significantly greater because of the secondary flow pattern in planes normal to the main flow [3, 4]. Basically, helical coil heat exchangers are a compact shell and tube apparatuses, consisting of several layers of coiled tubes within a closed shell. There is a number of types of these apparatuses and in the present study heat exchangers with concentric helical tubes (HECHT) are to be investigated. Tube bundle of HECHT consist of a number of tubes wound helically around a central supporting tube and placed in a cylindrical shell. Rows of tubes can be wound in the same direction, fig. 1, or in the opposite directions, fig. 2.

Between the tube coils the wire inserts are placed in order to prevent the collision of tubes [1, 5, 6]. Despite the decades of application of the HECHT coils in the industry, the problems related to their economic costs have not been fully explored.

Taking this into consideration, the primary objective of this paper was to determine the manufacturing costs of shell and tube HECHT. These costs in general case include the costs of materials for apparatus, energy, labor, and other costs.

* Corresponding author, e-mail: mihailo988@gmail.com

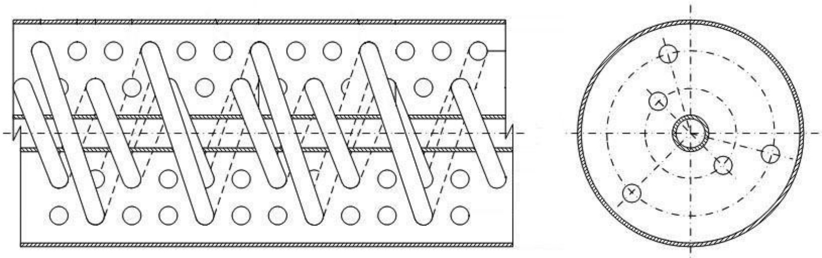

Figure 1. The HECHT with tubes wound in the same direction

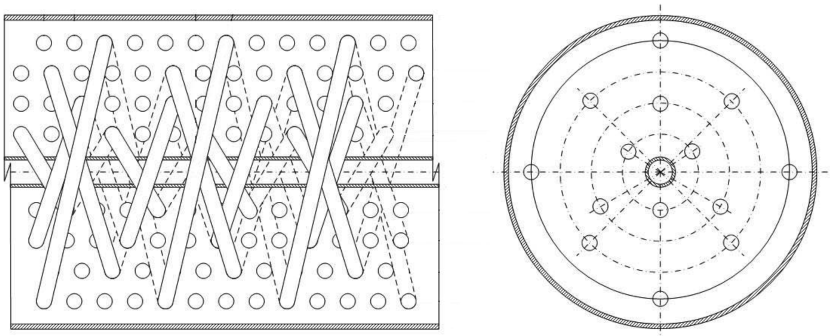

Figure 2. The HECHT with tubes wound in the opposite direction

Total costs at heat exchangers

The total cost resulting from the exploitation of the apparatus, C_{tot} [€ year^{-1}], in the general case can be expressed [5]:

$$C_{tot} = aC_{in} + C_{op} \tag{1}$$

where a [year^{-1}] is the annual discount rate, C_{in} [€] – the total investment cost, and C_{op} [€ year^{-1}] – the 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:

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

where p annual value of the interest rate on the loan for the purchase of equipment and n [year] – the 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 of the apparatus [5, 7].

Calculation price of heat exchangers

Only several correlations for estimating the cost of shell and tube heat exchangers can be found in the accessible literature. They are based on knowledge of the design of the apparatus, the operating pressure, the heat transfer surface, the material the apparatus is made of, *etc*. The most often cited correlations are listed in tab. 1, where they are not given in its original form, but are adjusted in order for the price to be expressed in an appropriate manner (in this case EUR2014 month September).

Prices of apparatuses have to be adjusted taking into account the year in which they were manufactured, tab. 2, and the year in which the analysis is done. The simplest method, which is used to correct the prices, takes into account the increasing costs due to market trends and the costs is given by next equation:

$$\frac{C_A}{I_A} = \frac{C_B}{I_B} \tag{3}$$

where C_A [€] is the price of apparatus at the moment A, C_B [€] – the price of apparatus at the moment B, I_A – the index of price at the moment A, and I_B – the index of price at the moment B [5, 8, 9].

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

Year	Material (Shell-Tube)	Temperature range [°C]	Pressure range, [bar]	S_{hts} range, [m^2]	Correlation	Ref.	Eq.
1990	Carbon steel-Carbon steel	–	–	–	$C_{in} = 6325 + 326S_{hts}^{0.8}$	[10]	(4)
1990	Carbon steel-Stainless steel	–	–	–	$C_{in} = 7695 + 370S_{hts}^{0.8}$	[10]	(5)
1990	Stainless steel-Stainless steel	–	–	–	$C_{in} = 9035 + 293S_{hts}^{0.91}$	[10]	(6)
1990	Carbon steel-Titanium	–	–	–	$C_{in} = 12649 + 623S_{hts}^{0.92}$	[10]	(7)
1990	Titanium-Titanium	–	–	–	$C_{in} = 15811 + 632S_{hts}^{0,93}$	[10]	(8)
1995	–	–	–	0.5-0.27	$C_{in} = 970S_{hts}^{0.432}$	[11]	(9)
1998	Carbon steel-Carbon steel	–	20-30	10-600	$C_{in} = 1499S_{hts}^{0.64}$	[12]	(10)
1998	Carbon steel-Brass	–	20-30	10-600	$C_{in} = 1368S_{hts}^{0.71}$	[12]	(11)
1998	Carbon steel-Stainless steel	–	20-30	10-600	$C_{in} = 1394S_{hts}^{0.86}$	[12]	(12)
1998	Stainless steel-Stainless steel	–	20-30	10-600	$C_{in} = 2006S_{hts}^{0.82}$	[12]	(13)
2001	Carbon steel-Carbon steel	≤ 350	≤ 10.5	9-6500	$C_{in} = 9096 + 120S_{hts}$	[13]	(14)
2004	Stainless steel-Titanium	–	–	–	$C_{in} = 32956 + 4011S_{hts}^{0.81}$	[14]	(15)
2007	Carbon steel-Carbon steel	≤ 300	≤ 50	–	$C_{in} = 3406S_{hts}^{0.68}$	[15]	(16)
2007	Carbon steel-Aluminum	≤ 300	≤ 50	–	$C_{in} = 4428S_{hts}^{0.68}$	[15]	(17)
2007	Carbon steel-Monel	≤ 300	≤ 50	–	$C_{in} = 7115S_{hts}^{0.68}$	[15]	(18)

→

Table 1. (Continuation)

Year	Material (Shell-Tube)	Temperature range [°C]	Pressure range, [bar]	S_{hts} range, [m^2]	Correlation	Ref.	Eq.
2007	Carbon steel-Stainless steel	≤ 300	≤ 50	–	$C_{in} = 5791 S_{hts}^{0.68}$	[15]	(19)
2007	Stainless steel-Stainless steel	≤ 300	≤ 50	–	$C_{in} = 9878 S_{hts}^{0.68}$	[15]	(20)
2009	Carbon steel-Carbon steel	–	–	9-90	$C_{in} = 2095 S_{hts}^{0.551}$	[16]	(21)
2009	Admiralty	–	–	9-90	$C_{in} = 1522 S_{hts}^{0.679}$	[16]	(22)
2009	Copper–brass	–	–	9-90	$C_{in} = 1844 S_{hts}^{0.679}$	[16]	(23)
2014	Carbon steel-Copper	0-200	2-30	2.5-38	$C_{in} = 749 + 332 S_{hts}$	[17]	(24)

Table 2. Year built of apparatus

No.	S_{hts} [m^2]	Year built	Cost of apparatus in year built	Cost of apparatus [€$_{2014}$]
1	0.5	2013	500	525
2	1	2014	600	614
3	1.5	2011	850	823
4	2	2012	1100	1083
5	2.5	2009	1190	1381
6	3	2010	1275	1221
7	4	2011	1360	1316
8	5	2012	1550	1526
9	6	2013	1650	1731
10	7	2012	1750	1723
11	8	2010	1880	1800
12	9	2012	2180	2146
13	10	2011	2150	2080
14	12	2010	2520	2413
15	15	2013	2850	2989
16	18	2011	3420	3308
17	20	2011	3800	3676
18	22	2010	4180	4002
19	25	2010	4750	4548
20	30	2012	5700	5610
21	35	2010	6650	6367
22	40	2012	7600	7480
23	44	2013	8250	8652
24	47	2013	9030	9470

Analysis of manufacturing costs of heat exchangers with concentric helical tube coils

For the heat exchangers with a concentric helical tube coils, the correlation for the assessment of investment costs is not encountered in the literature. Therefore, the goal of this analysis was to determine the deviations appearing during the use of the existing correlations (4)-(24). Deviation in prices calculated using the correlations (2)-(24) and the actual prices of apparatuses (data obtained from the manufacturer on territory Bosnia and Hercegovina, Serbia, and Croatia) is expressed using statistical indicators: correlation ratio (CR) and the root-mean square deviation (RMSD), which are also shown in tab. 3.

Table 3. Statistical parameters of the literature correlations

No.	Year	Material (Shell-tube)	Temperature range [°C]	Pressure range [bar]	S_{hts} range [m^2]	Correlation	Ref.	CR	RMSD	Eq.
1	1990	Carbon steel-Carbon steel	–	–	–	$C_{in} = 6325 + 326S_{hts}^{0.8}$	[10]	0	438.76	(4)
2	1990	Carbon steel –Stainless steel	–	–	–	$C_{in} = 7695 + 370S_{hts}^{0.85}$	[10]	0	551.75	(5)
3	1990	Stainless steel – Stainless steel	–	–	–	$C_{in} = 9035 + 293S_{hts}^{0.91}$	[10]	0	641.66	(6)
4	1990	Carbon steel –Titanium	–	–	–	$C_{in} = 12649 + 623S_{hts}^{0,92}$	[10]	0	979.37	(7)
5	1990	Titanium – Titanium	–	–	–	$C_{in} = 15811 + 632S_{hts}^{0,93}$	[10]	0	1214.69	(8)
6	1995	-	–	–	0.05-0.27	$C_{in} = 970S_{hts}^{0.432}$	[11]	0.8284	29.02	(9)
7	1998	Carbon steel – Carbon steel	–	20-30	10-600	$C_{in} = 1499S_{hts}^{0.64}$	[12]	0	159.53	(10)
8	1998	Carbon steel – Brass	–	20-30	10-600	$C_{in} = 1368S_{hts}^{0.71}$	[12]	0	177.64	(11)
9	1998	Carbon steel – Stainless steel	–	20-30	10-600	$C_{in} = 1394S_{hts}^{0.86}$	[12]	0	310.93	(12)
10	1998	Stainless steel –Stainless steel	–	20-30	10-600	$C_{in} = 2006S_{hts}^{0.82}$	[12]	0	431.06	(13)
11	2001	Carbon steel– Carbon steel	≤ 350	≤ 10.5	9-6500	$C_{in} = 9096 + 120S_{hts}$	[13]	0	616.41	(14)
12	2004	Stainless steel – Titanium	–	–	–	$C_{in} = 32956 + 4011S_{hts}^{0.81}$	[14]	0	3088.83	(15)
13	2007	Carbon steel – Carbon steel	≤ 300	≤ 50	–	$C_{in} = 3406S_{hts}^{0.68}$	[15]	0	541.19	(16)
14	2007	Carbon steel – Aluminium	≤ 300	≤ 50	–	$C_{in} = 4428S_{hts}^{0.68}$	[15]	0	733.03	(17)
15	2007	Carbon steel –Monel	≤ 300	≤ 50	–	$C_{in} = 7115S_{hts}^{0.68}$	[15]	0	1237.52	(18)
16	2007	Carbon steel – Stainless steel	≤ 300	≤ 50	–	$C_{in} = 5791S_{hts}^{0.68}$	[15]	0	988.93	(19)
17	2007	Stainless steel – Stainless steel	≤ 300	≤ 50	–	$C_{in} = 9878S_{hts}^{0.68}$	[15]	0	1756.32	(20)
18	2009	Carbon steel – Carbon steel	–	–	9-90	$C_{in} = 2095S_{hts}^{0.551}$	[16]	0	201.48	(21)
19	2009	Admiralty	–	–	9-90	$C_{in} = 1522S_{hts}^{0.679}$	[16]	0	187.23	(22)
20	2009	Copper–brass	–	–	9-90	$C_{in} = 1844S_{hts}^{0.679}$	[16]	0	247.38	(23)
21	2014	Carbon steel-Copper	0-200	2-30	2.5-38	$C_{in} = 749 + 332S_{hts}$	[17]	0	79.17	(24)

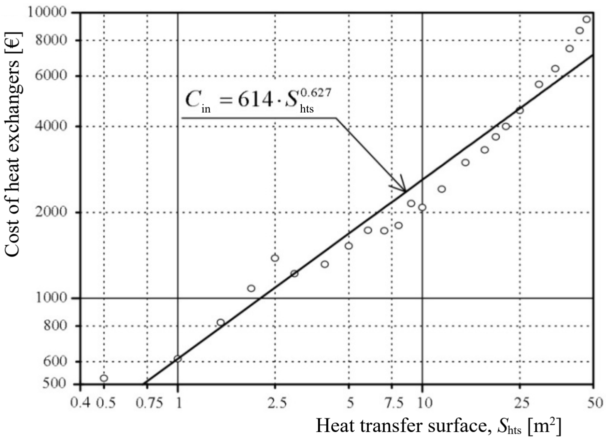

Figure 3. Manufacturing costs for apparatus *vs.* to heat transfer surface

The analysis using these correlations shows significant deviations and they cannot be successfully used to describe the manufacturing costs for the mentioned type of shell and tube heat exchangers (a heat exchanger with concentric helical tubes, where the apparatus shell is made of carbon steel and the heat exchanger's tubes are made of copper). Therefore, on the basis of the data given in tab. 2 (for 2014 year price), a new correlation was found in form, fig. 3:

$$C_{in} = 614 S_{hts}^{0.627} \tag{25}$$

for range 0.5 m^2 < S_{hts} < 47 m^2, 4 < p < 25 bar, 10 < T < 180 ºC. Its statistical parameters are CR = 0.9497 and RMSD = 15.94%. In the eqs. (4)-(24) the value of heat transfer surface, S_{hts}, was expressed taking into account the outside of the tube.

Operating costs

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

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 [7, 17]:

$$P = \frac{1}{\eta}\left(\frac{\dot{m}_{ts}}{\rho_{ts}}\Delta p_{ts} + \frac{\dot{m}_{ss}}{\rho_{ss}}\Delta p_{ss}\right) \tag{26}$$

where P [W] is the pumping power, η – the pump efficiency (this value is commonly 0,6-0,7), $\dot{m}_{ts}$ [kgs^{-1}] – the tube-side flow rate, $\dot{m}_{ss}$ [kgs^{-1}] – the shell-side flow rate, ρ_{ts} [kgm^{-3}] – the tube-side fluid density for average fluid temperature, ρ_{ss} [kgm^{-3}] – the shell-side fluid density for average fluid temperature, Δp_{ts} [Pa] – the total pressure drop for tube-side, and Δp_{ss} [Pa] – the total pressure drop for shell-side.

Costs incurred by using electricity C_{El} [€ year^{-1}] are defined by the equation:

$$C_{El} = PK_{El}\tau \tag{27}$$

where K_{E1} [€(Wh)$^{-1}$] is the price of electrical energy and τ [hyear^{-1}] – the hours of operation per 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 for 2014 year is taken to be 0,013 €/(kWh) [18].

Table 4. Cost incurred by using electricity [€ year^{-1}]

No.	Year of manufacturing	Heat transfer surface S_{hts}, [m^2]	Industrial plant	District heating system
1	2013	0.5	31	11
2	2014	1	64	23
3	2011	1.5	95	35
4	2012	2	129	47
5	2009	2.5	159	58
6	2010	3	192	70
7	2011	4	256	93
8	2012	5	320	116
9	2013	6	384	140
10	2012	7	449	163
11	2010	8	512	186
12	2012	9	577	210
13	2011	10	641	233
14	2010	12	789	287
15	2013	15	962	350
16	2011	18	1122	408
17	2011	20	1282	466
18	2010	22	1444	525
19	2010	25	1602	583
20	2012	30	1923	699
21	2010	35	2237	813
22	2012	40	2574	936
23	2013	44	2832	1030
24	2013	47	3025	1100

Costs of cleaning of apparatus

An 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 a smaller diameter pipes [19, 20].

Heat exchangers may be cleaned by:
- mechanical methods,
- chemical methods or
- combination of both [20, 21].

In consideration of the costs incurred by cleaning of a heat exchanger it is regarded 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,
- chemical solutions reach normally inaccessible areas,

– they are less labor intensive than mechanical cleaning,
– cleaning can, almost always, be performed *in situ* [22].

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) [21].

A review of most 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	Mineral acids		
Citric acid ($C_6H_8O_7$)	Hydrochloric acid (HCl)	Sodium ash (Na_2CO_3)	Kerosene
Formic acid (CH_2O_2)	Sulfuric acid (H_2SO_4)	Sodium silicate (Na_2SiO_3)	Naphta
Gluconicacid ($C_6H_{12}O_7$)	Sulfamic acid (H_3NSO_3)	Sodiumhydroxide (NaOH)	Naphta derivatives
	Nitric acid (HNO_3)	Trisodium phosphate (Na_3PO_4)	Trichloroethane

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 the deposit, but also on the exchanger material and the cleaning conditions. Incorrect use of acid or for chemical cleaning of the apparatus can lead to corrosion. It is necessary to avoid this negative side-effect and substances which used for this purpose are called 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 re-circulated systems and are selected for their effectiveness in protecting the specific metal or combination of metals in a given system [23]. 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 HCl solutions [24].

The most common used 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. [25]. All heat exchangers that were analyzed were apparatuses with concentric helical tube coils, 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.

Among the previously listed substances the most widely used cleaning agents primarily due to their price are:
– hydrochloric acid and,
– sulfuric acid.

Hydrochloric acid is the most common and most versatile mineral acid. This acid is a solution of the gas hydrogen chloride which is a poisonous, highly corrosive, hazardous liquid that reacts with most metals to form explosive hydrogen gas. Its appearance varies from pale yellow to colorless, according to purity. The HCl acid has many applications in the production of organic and inorganic compounds such as fertilizers, chlorides, dyes and more. The HCl plays an important role in pickling of steel, acid treatment of oil wells, chemical cleaning and processing, and ore reduction among others. When boiling all aqueous solutions, HCl forms an azeotropic constant boiling mixture that contains 20.24% HCl and boils at 110 °C. [26] It is used on virtually all types of industrial process equipment at strengths from 2-28% mass (whereby the 5-10% mass is the most usual range). The HCl is very aggressive and corrosive mineral acid so it is necessary to add inhibitor to prevent corrosion. It can be inhibited at temperatures up to about 80 °C [27].

The solution of this HCl will dissolve and remove rust, scale, carbonates, phosphates, most sulphates, ferrous sulfide, oxide coatings and will strip chromium, zinc and cadmium plating. Inhibited HCl can be used for cleaning carbon steels, cast iron, brasses, bronzes, copper-nickels, and Monel 400. This acid is not recommended for cleaning austenitic stainless steel (series 300), free-machining alloys, magnesium, zinc, aluminium, cadmium, or galvanised steel, Inconel 600, Incoloy 800 and brass [21, 27, 28].

Sulfuric acid (H_2SO_4) is the single most important inorganic chemical in tonnage produced and in use. The H_2SO_4 can be described as a colorless, oily, hygroscopic liquid with no odor and it is the largest inorganic chemical manufactured and one of the most widely used inorganic chemical in the manufacture of many other products. It is manufactured by the combustion of sulfur with dry air to form SO_2, then SO_3 is produced through a catalytic conversion. Finally, H_2SO_4 is obtained after absorption of SO_3 in water. The H_2SO_4 is a strong acid and a strong oxidizing agent and therefore it reacts violently with bases, combustible, reducing materials, water and organic compounds with the evolution of heat. It is highly corrosive to most common metals and forms a flammable/explosive gas. The H_2SO_4 is mostly used in the manufacturing of fertilizers, organic pigments, explosives and more. As a strong electrolyte it is used in electroplating baths for pickling, and for operations in the production of iron and steel. Moreover, it is extensively used as a solvent for ores and as a catalyst in the petroleum industry. Except the aforementioned, H_2SO_4 is used for process of chemical cleaning heat exchangers.

Taking into account that H_2SO_4 is strong and highly corrosive acid it is necessary to add inhibitor for process of chemical cleaning heat exchangers. It is uses for chemical cleaning heat exchangers made of carbon steel, austenitic stainless steels, copper-nickels, admirality brass, aluminum bronze, and Monel 400. It should not be used on cleaning aluminum [21, 27, 28].

Chemical cleaning most frequently performed with chemical substances which were circulated through the apparatus at intervals of several hours (usually $\tau = 4\text{-}6$ hours) at the temperature $t = 20\text{-}70$ °C [25, 29, 30]. Since the working medium that passed through the apparatus was water, the main deposit on the heat transfer surface was calcium carbonate (limestone) and cost analysis of chemical cleaning was conducted for inhibited hydrochloric and sulfuric acid.

The concentration of acid in the solution is usually in the range of 2-10% [29, 31-34].

The costs of cleaning, C_{cl}, [€ year^{-1}] are defined:

$$C_{\mathrm{cl}} = m_{\mathrm{ac}} C_{\mathrm{ac}} + m_{\mathrm{ih}} C_{\mathrm{ih}} \tag{28}$$

where m_{ac} [kg year^{-1}] is the amount of cleaning agent, C_{ac} [€kg^{-1}] – the unit price of the cleaning agent, m_{ih} [kg year^{-1}] – the amount of corrosion inhibitor, C_{ih} – the unit price of corrosion inhibitor of HCl and H_2SO_4.

Where it was considered that the corrosion inhibitors are administered at a concentration of 3000 ppm.

The frequency of the 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 [25, 35]. Within the cost estimates of the apparatuses cleaning, it is considered 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.

Table 6. The cost of apparatus cleaning, once a year [€ year^{-1}]

No.	S_{hts}, [m^2]	Solution of inhibited, HCl			Solution of inhibited H_2SO_4		
		2%	5%	10%	2%	5%	10%
1	0.5	4	4	5	4	4	5
2	1	5	4	5	4	5	5
3	1.5	6	6	7	6	6	7
4	2	8	10	11	9	10	11
5	2.5	9	11	12	10	11	12
6	3	11	12	14	12	13	14
7	4	13	15	17	15	16	18
8	5	19	22	24	21	23	25
9	6	20	23	26	22	24	26
10	7	22	26	29	25	27	30
11	8	25	28	32	27	30	33
12	9	27	31	35	30	33	36
13	10	29	34	38	33	36	39
14	12	41	47	53	45	50	54
15	15	46	52	59	50	55	60
16	18	89	102	114	98	108	118
17	20	70	80	90	77	85	92
18	22	73	83	94	81	89	97
19	25	78	89	100	86	94	103
20	30	89	102	114	98	108	118
21	35	107	122	138	119	130	142
22	40	122	140	157	136	149	162
23	44	182	208	234	201	221	240
24	47	201	230	259	223	244	266

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 HCl three times a year. Balance of total cost in relation to the heat transfer surface is expressed in [€ year^{-1}] and is shown in tab. 7 and in fig. 4. It is necessary to emphasize that the total costs for heat exchangers here, unlike in [7], is calculated taking into account the costs of chemical cleaning appliances as well.

Conclusion

The paper presents the total costs for heat exchangers with parallel helical tube coils. The cost analysis was conducted for appliances that are found in industrial plants and for appliances in the district heating system in the Republic of Serbia.

Table 7. Total annual operating costs of apparatus [€ year^{-1}]

No.	Year of manufacturing	S_{hts}, [m^2]	Operating costs, [€ year^{-1}]
1	2013	0.5	43
2	2014	1	77
3	2011	1.5	113
4	2012	2	158
5	2009	2.5	191
6	2010	3	228
7	2011	4	302
8	2012	5	385
9	2013	6	453
10	2012	7	526
11	2010	8	597
12	2012	9	670
13	2011	10	742
14	2010	12	929
15	2013	15	1118
16	2011	18	3427
17	2011	20	1522
18	2010	22	1694
19	2010	25	1869
20	2012	30	2228
21	2010	35	2604
22	2012	40	2994
23	2013	44	3455
24	2013	47	3715

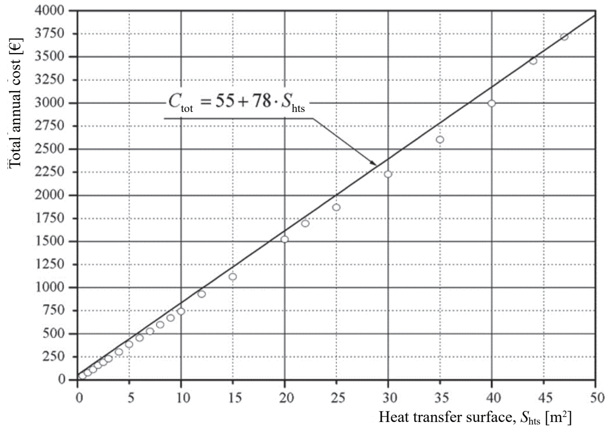

Figure 4. Total annual costs of shell and tube heat exchangers with parallel helical tube [€ year^{-1}]

After examining the correlations currently found in the accessible literature on investment costs of shell and tube heat exchangers, it was concluded that a new correlation needs to be found.

The new correlation, eq. (25), 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:

$$C_{\text{in}} = 614 S_{\text{hts}}^{0.627}$$

for range 0.5 m^2 < S_{hts} < 47 m^2, 4 < p < 25 bar, 10 < T < 180 ºC. Statistical parameters of the equation are CR = 0.9497 and RMSD = 15.94%.

The analysis of chemical cleaning of heat exchangers is also demonstrated in the paper. The analysis of the cost of chemical cleaning included the use of inhibited hydrochloric (2%, 5%, and 10%) and inhibited sulfuric acid (2%, 5%, and 10%) as of cleaning agents, whereas 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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Nomenclature

a – annual discount rate, [year^{-1}]
C_{ac} – unit price of the cleaning agent, [€kg^{-1}]
C_{cl} – cost of cleaning heat exchangers, [€ year^{-1}]
C_{ih} – unit price of the corrosion inhibitor, [€ kg^{-1}]
C_{in} – investment cost of heat exchanger (price of manufactured apparatus), [€]
C_{op} – operating cost of heat exchanger, [€ year^{-1}]
C_{tot} – total operating cost of heat exchanger, [€ year^{-1}]
K_{El} – price of electrical energy, [€ kWh^{-1}]
m_{ac} – amount of cleaning agent, [kg]
m_{ih} – amount of corrosion inhibitor, [kg]
$\dot{m}_{\text{ts}}$ – tube-side flow rate, [kgs^{-1}]
$\dot{m}_{\text{ss}}$ – shell-side flow rate, [kgs^{-1}]
n – equipment life, [year]
P – pumping power, [W]
p – operating pressure, [bar]
S_{hts} – heat transfer surface, [m^2]
T – temperature, [°C]

Greek symbols

Δp_{ts} – total pressure drop for tube-side flow, [Pa]
Δp_{ss} – total pressure drop for shell-side flow, [Pa]
ρ_{ts} – tube-side fluid density for average temperature at tube-side, [kgm^{-3}]
ρ_{ss} – shell-side fluid density for average temperature of shell-side, [kgm^{-3}]
η – pump efficiency
τ – hours of operation per year, [hours]

Subscripts

ac – acid
cl – cleaning
hts – heat transfer surface
ih – inhibitor
in – investment
op – operating
ts – tube side
ss – shell side
tot – total

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