NEW METHOD FOR THE COST ASSESSMENT ANALYSIS OF SHELL-AND-TUBE HEAT EXCHANGERS

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***Abstract*— A new simplified method for the cost assessment analysis of shell-and-tube heat exchangers (STHE) is presented in this paper. A comparison was carried out between the values obtained by the proposed method with the FOB average real cost for a total of 410 heat exchangers, with heat transfer surfaces (S_{HT}) ranging between 5 to 1150 m². It was found that the proposed method correlates well with an average error of $\pm 10.1\%$, for 84.15% of the available data. The method presents a lower adjustment in the range $300\ m^2 < S_{HT} \leq 450\ m^2$, with an average error of $\pm 12.9\%$, for 82.97 % of the available data. The best adjustments are located in the range $5\ m^2 < S_{HT} \leq 25\ m^2$, with an average error of only $\pm 8.0\%$, for 80.95 % of the available data. In all cases, the agreement of the proposed method is good enough to be considered satisfactory for practical design.**

***Keywords*— Shell-and-tube heat exchangers, cost, assessment analysis, heat transfer surface, index cost.**

I. INTRODUCTION

Every day in engineering processes, many physical situations are found in which it is necessary to transfer heat from a hot fluid to a cold fluid. For this purpose, there is a wide variety of heat transfer equipment and industrial installations, with the shell-and-tube heat exchangers being some of the most used equipment (Ling and Zhang, 2016; Zheng and Wang, 2019; Yang *et al.*, 2018).

In the design of the heat exchangers, a wide variety of aspects have to be considered that have direct influence in the design and the final purchase costs. A heat exchanger is integrated mainly for the front and rear head, shell, tubes, joints and tubesheets. However, in spite of the reduced number of basics elements of the shell-and-tube heat exchanger, it is a difficult and complex task to make a rapid assessment of the shell-and-tube heat exchangers cost (Camaraza-Medina *et al.*, 2020; Mukherjee, 2014; Roy and Majumder, 2018).

At the present time there is a wide variety of configurations in the shell-and-tubes heat exchangers, depending on the desired heat transfer requirements, the maximum pressure drop allowed, the methods used to reduce the thermal strains, the prevention of fluids leakages, easy maintenance, maximum tolerated pressures, ranges of process operation temperatures, and corrosion. Therefore, it is very difficult to have a reliable cost value of the shell-and-tube heat exchanger, in order to accomplish a feasibility analysis (Salahuddin *et al.*, 2015; Nitsche and Gbadamosi, 2016).

While it is possible that a heat exchanger fulfills the thermal requirements, and the admissible pressure drops and fouling factors, however, when a cost analysis is made, it could be found that the available exchanger is not a convenient option because it raises the initial investment requests and influences in a negative way the horizon expected by the investors (Hesselgreaves *et al.*, 2017; Wang *et al.*, 2010).

However, in many instances, when this type of analysis takes effect, in the search of similar situations in the technical literature on the subject, it is confirmed that data of similar and current events are found only in few occasions, due to the ample options offered by the shell-and-tube heat exchangers and to the rates of updating. When the access to values of updated costs is not possible, then, it is necessary to consult suppliers and manufacturers, which in many instances do not provide an effective or affirmative response or impose extra costs for the information provided (Camaraza, 2017; Caputo *et al.*, 2008).

Therefore, it would be very useful to have a method to assess the prices of any shell-and-tubes heat exchanger, allowing in a fast way, and with an acceptable precision, to obtain an updated cost of a heat exchanger. This method thus will permit an evaluation and selection of the most feasible choice, from a cost-reducing optics.

In the present paper, the main objective is providing an easy-to-follow and updated method to make a rapid assessment of the shell-and-tube heat exchangers cost.

II. METHODS AND VALIDATION

A. Analysis of the primary cost estimation for shell-and-tube heat exchangers

The proposed methodology is defined from a basic model of heat exchanger, which defines the cost of any selected heat exchanger. That way it is possible to get from simple way the approximate cost of a shell-and-tube heat exchanger (STHE), and the indicators required for the analysis. The basic model of the heat exchanger is given in Table 1.

The costs of a shell-and-tube heat exchanger depend on several parameters: TEMA classification (front and rear head, shell), shell inner diameter, tube length, inner diameter and wall thickness of the tubes, tubes layout,

Table 1. Prototype model of the heat exchanger for cost estimation.

Parameter	Description
Tube wall thickness	14 BWG
Tube length	20' (6.096 m)
Number of tubeside passes	1 or 2
Design pressure, shellside	<150 psi (1.034 MPa)
Design pressure, tubeside	<150 psi (1.034 MPa)
Tube and shell material	Carbon steel (AISI-1030)

Table 2 Correction factor f used in Eq. (1).

TEMA's front head	f
A	1.02 – 1.03
B	1.0
C	1.06 – 1.07
D	1.5 – 1.7
N	1.05

Table 3. Correction factor r used in Eq. (1).

TEMA's rear head	r	TEMA's rear head	r
S	1.0	U	0.9
M	0.8	T	1.05
L	0.83	P	1.04
N	0.85	W	1.02

tube pitch, number of tubeside passes, materials used in the STHE, design conditions and risk potential.

The STHE with tubes of small diameters is the most common (3/4" or 1") and is generally more economical. Whereas the pitch is at least $1.25 \times d_e$, the pipes of large diameters provide a smaller heat transfer surface for a similar shell diameter. The triangular pitch is more economical that the square pitch because it generally leads to larger heat transfer surfaces for a given shell size. With an increment of the shell diameter the cost of the material increases, but the unit cost of the work force decreases by surface area (Camaraza, 2017).

In the method proposed in this paper, the cost per square meter of the heat transfer surface of the heat exchanger used as prototype should be first determined. For this purpose, the following equation is used, (Patel and Rao, 2010):

$$b = p \cdot r \cdot f \cdot \left(\frac{17.76}{1-e^{\left(\frac{0.178-D}{0.686}\right)}} \right) \tag{1}$$

In Eq. (1), D is the shell inner diameter, f is a cost correction factor (see Table 2) that depends on the TEMA's front head used in the heat exchanger, r is a cost correction factor (see Table 3) that depends on the TEMA's rear head used in the heat exchanger; p is a cost correction factor that depends on the outer diameter, pitch and layout of the tubes. The correction factor p is obtained as (Hadidi *et al*., 2013):

$$p = \frac{a \cdot (P_I)^2}{35 \cdot d_e} \tag{2}$$

In Eq. (2), a is a constant with values 0.85 and 1 for triangular and square pitch respectively, d_e is the outer diameter of the tubes and P_I is the tubes pitch. All dimensions are given in mm.

B. Modification to the cost for a heat exchanger different to the prototype.

If the analyzed heat exchanger is different to the prototype given in Table 1, then, it is required to make corrections to obtain a representative price considering a group of adjustment factors, that modify the cost per square meter of surface, obtained early in Eq. (1) by means of the following equation:

$$C = b \cdot \left(1 + C_S + C_X + C_L + C_{Ntp} + C_{PS} + C_{PT} + C_M + C_G\right). \tag{3}$$

In Eq. (3), the obtained cost is called FOB (*free on board).* The costs of delivery should be valued in terms of the existing distance between the manufacturer and the final customer. A simple estimate in these cases is obtained by increasing the FOB cost by 5 %.

The terms given in Eq. (3) are defined as follows:

- C_S is a correction factor that considers the shell types.
- C_X is a correction factor that considers the influence of the expansion joint.
- C_L is a correction factor that considers the influence of the tube length.
- C_{Ntp} is a correction factor that considers the influence of the tube side passes.
- C_{PS} is a correction factor that considers the influence of the fluid pressure on the shellside.
- C_{PT} is a correction factor that considers the influence of the fluid pressure on the tubeside.
- C_M is a correction factor that considers the influence of the materials used in each element of the STHE.
- C_G is a correction factor that considers the influence of the wall thickness of the tubes.

Table 4. Summary of the correction factor C_S.

Shell (TEMA standard)	r
E	0
J	0
X	0
G	0.05 – 0.1
H	0.1 – 0.15
F	0.15 – 0.2
K	0.25 – 0.35

The correction factor C_S depends on the shell type, according to the TEMA standard. Values of this correction factor are summarized in Table 4.

The correction factor C_X considers the influence of the expansion joint on the modified cost of the heat exchanger. This correction factor is described by a logarithmic relation of the inner shell diameter and is given by:

$$C_X = -0.113 \ln(D) + 0.176 \tag{4}$$

When $D \geq 3.048\, m$, then the correction factor is $C_X = 0.05$.

The correction factor C_L considers the influence of the tubes length on the STHE cost. When $L < 6.096\, m$, then the value of the correction factor C_L is given by:

$$C_L = \left(1 - \frac{L}{6.091}\right) \cdot \left[1.5 - \left(\frac{0.002083 \cdot d_i}{1-L/6.091}\right)\right]. \tag{5}$$

In Eq. (5), d_i and L are the inner diameter and the length of the tubes, respectively. If the tube length is $L \geq 6.096\, m$, then $C_L = 0$.

The correction factor C_{Ntp} considers the influence of the tubeside passes on the modified cost of the heat exchanger. When the number of the tubeside passes is $N \leq 2$ then $C_{Ntp} = 0$, however, if the number of the tubeside passes is $N > 2$, then the correction factor is obtained as (Asadi *et al.*, 2014):

$$C_{Ntp} = 0.01 \cdot (N - 1). \quad (6)$$

The correction factor C_{PS} considers the influence of the fluid pressure on the shellside. If $p_S \leq 10.342\ bar$, then $C_{PS} = 0$, but if $p_S > 10.342\ bar$, then the value of the correction factor C_{PS} is given by:

$$C_{PS} = \left[\frac{p_S}{10.342} - 1\right][0.07 - 0.063(D - 0.3048)] + \psi. \quad (7)$$

In Eq.(7) p_S is the fluid pressure on the shellside, ψ is a coefficient that depends on the fluid pressure in the shellside and inner shell diameter. If $p_S \leq 137.9$ bar, then $\psi = 0$, when $p_S > 137.9\ bar$, then the value of the coefficient ψ is given by:

$$\psi = 0.176 \ln(D) + 0.444. \quad (8)$$

In Eq. (8) when $D \geq 1.5\ m$, then $\psi = 0.52$.

The correction factor C_{PT} considers the influence of the fluid pressure on the tubeside. If $p_T \leq 10.342\ bar$, then $C_{PT} = 0$, when $p_T > 10.342\ bar$, then the value of the correction factor C_{PT} is given by (p_T is the fluid pressure):

$$C_{PT} = \left[\frac{p_T}{10.342} - 1\right] \cdot [0.0035 - 0.022(D - 0.3048)]. \quad (9)$$

In Eq. (7) and Eq. (9), the inner shell diameter D must be provided in m.

The correction factor C_M considers the influence of the materials used in each element of the heat exchanger. The cost correction for the materials is divided into several components, detailed below.

The fraction that corresponds to the cost of the tubes material can be determined as:

$$C_{MT} = 0.129 + 0.0016\left(\frac{d_i}{0.0254} - 12\right) \cdot \left(\frac{d_e}{29.53 a P_I^2}\right). \quad (10)$$

In Eq. (10) all dimensions are given in m. P_I is the tubes pitch, d_i and d_e are the inner and outer diameters of the tubes, a is a constant with values 0.85 and 1, for triangular and square pitch respectively.

The fraction that corresponds to the labor costs is determined by means of the following expression:

$$C_{MO} = -0.125 \ln\left(\frac{D}{0.0254}\right) + 0.843. \quad (11)$$

The fraction that corresponds to the cost of the shell material is determined as:

$$C_{MC} = -0.0029 \ln\left(\frac{D}{0.0254}\right) + 0.0568. \quad (12)$$

The fraction that corresponds to the cost of the material used in the front and rear head is determined as:

$$C_{MCA} = -0.003 \ln\left(\frac{D}{0.0254}\right) + 0.044. \quad (13)$$

The fraction that corresponds to the cost of the tubesheet material is determined as:

$$C_{MPT} = -0.002 \ln\left(\frac{D}{0.0254}\right) + 0.0299. \quad (14)$$

The fraction that corresponds to the cost of the material used in expansion joint and pins is determined as:

$$C_{MJ} = -0.001 \ln\left(\frac{D}{0.0254}\right) + 0.0198. \quad (15)$$

In Eq. (11) to Eq. (15), D is the shell inner diameter, in m.

The fraction that corresponds to the cost of others element not considered already can be obtained as:

$$C_{others} = 1 - C_{MO} - C_{MT} - C_{MC} - C_{MCA} - C_{MPT} - C_{MJ}. \quad (16)$$

Table 5. Correction factors for cost estimation of the material.

Material	***A***		***B***
	Welded	**Seamless**	
Steel AISI -1045	1.0	2.5	1.0
Carbon steel - alloy			
0.5 Mo	1.04	2.6	1.04
1 Mo	1.05	2.7	1.05
2.5 Ni	1.15	2.9	1.15
3.5 Ni	1.2	3.1	1.2
2 Ni – 1 Co	Nonstandard	3.3	1.3
Carbon Steel - Alloys Cr - Mo			
1 Cr - 0.5 Mo	Nonstandard	2.6	2.0
3 Cr - 1 Mo	Nonstandard	3.2	2.5
9 Cr - 1 Mo	Nonstandard	6.1	Nonstandard
Stainless steel			
304	2.8	6.5	3.7
304L	3.0	7.5	4.7
310	7.4	12.0	9.8
310L	7.6	12.4	10.1
316	4.7	10.1	6.2
316L	4.8	11	6.4
410	6.9	17.2	7.9
Nickel 200	---	20.9	18.4
Monel 400	---	15.5	14.5
Inconel 600	19.4	---	15.3
Incoloy 800	11.0	21.8	9.0
Hastelloy B-2	34.9	48.6	38.4
Titanium grade 2	11.0	22.0	11.0
Zirconium 702	35.0	43.7	36.8
Non-ferrous alloys			
Copper	3.5	7.2	4.4
Aluminum	0.9	1.8	0.8
Aluminum-bronze	2.2	4.5	2.6
Aluminum-brass	2.3	4.4	2.5
Nickel-cooper	2.8	5.0	2.8

If the elements of the heat exchanger (tubes, shell, tubesheet, front and rear head) are not constructed with carbon steel AISI-1030, then the values obtained in Eq. (10) and Eq.(12) to Eq. (14) have to be modified. The required correction is given by:

Cost correction for the tubes material:

$$C''_{MT} = C_{MT} + C_{MT}\left(\frac{A-1}{0.29 \cdot A + 0.81}\right). \quad (17)$$

In Eq. (17) C_{MT} is obtained from Eq. (10) and A is a constant that depends on the material type and the construction technology (see Table 5).

Cost correction for the shell material:

$$C''_{MC} = C_{MC} + C_{MC}(B - 1)/10. \quad (18)$$

In Eq. (18) C_{MC} is obtained from Eq. (12).

Cost correction of the front and rear head material:

$$C''_{MCA} = C_{MCA} + C_{MCA}(B - 1)/16.66. \quad (19)$$

In Eq. (19) C_{MCA} is obtained from Eq. (13).

Cost correction of the tubesheet material:

$$C''_{MPT} = C_{MPT} + C_{MPT}(B - 1)/25. \quad (20)$$

In Eq. (20) C_{MPT} is obtained from Eq. (14). In Eq. (18) to Eq. (20), B is a constant that depends on the material type (see Table 5).

Finally, the correction factor C_M is obtained as:

$$C_M = C"_{MT} + C"_{MC} + C"_{MCA} + C"_{MPT}. \quad (21)$$

The correction factor C_G considers the influence of the tube wall thickness on the equipment cost. This correction factor was developed for a BWG 14 gauge, and is obtained as:

Table 6. Values of correction factor G".

BWG Gauge	G" values
$BWG < 14$	$-1.188\ln(\text{BWG}) + 4.136$
$BWG = 14$	1
$BWG > 14$	$271.24/(\text{BWG})^{2.1}$

Table 7 Fluid classification according to the mass flux.

Group	Points (x)	$m(kg/s)$
I	1	$m > 65$
II	2	$35 < m \leq 65$
III	3	$5 < m \leq 35$
IV	4	$m \leq 5$

Table 8. Classification according to fluids characteristics.

Group	Points (y)	Fluid description
V	0	Liquids and toxic gasses, acids, caustics, oils and inflammables
VI	1	Steam
VII	2	Water and other fluids not considered in groups V and VI (with temperatures of the fluid over 90ºC)
VIII	3	Water and other fluids not considered in groups V and VI (with temperatures of the fluid under 90ºC)

$$C_G = G"C_{MT}. \quad (22)$$

In Eq. (22) C_{CM} is obtained from Eq. (12), while G" depends on the BWG gauge (see Table 6).

C. Selection criteria for the operational risk in shell-and-tube heat exchangers.

Shell-and-tube heat exchangers are classified in eight different categories, according to a selection criterion that considers the operational risk, which depends directly on the mass flux and the fluids characteristics, its rating of corrosion, and dangerousness or toxicity.

The fluids used in the analysis of shell-and-tube heat exchangers are classified in four categories according to the mass flux of each fluid (see Table 7). For the operational risk study, the points obtained for each fluid are compared and the minor value will be used.

The fluids used in the analysis of shell-and-tube heat exchangers are classified in four categories according to the characteristics of each fluid (see Table 8). For the operational risk study, the points obtained for each fluid are compared and the minor value will be used.

Points x and y obtained from Tables 7 and 8 are added, obtaining:

$$Z = x + y. \quad (23)$$

Then, the increase of cost required to consider the effects of the operational risk is:

$$E = 1.143 \cdot e^{-0.019Z}. \quad (24)$$

The effects of the operational risk have influence on the modified cost per square meter of surface. Thus, the cost obtained in Eq. (3) is now modified, taking into account the effect of operational risk on the final cost per square meter of surface (Mohanty *et al.*, 2016):

$$C" = E \cdot b \cdot (1 + C_S + C_X + C_L + C_{Ntp} \quad (25)$$
$$+ C_{PS} + C_{PT} + C_M + C_G).$$

D. Costs updates for future estimates.

The data used in the development of the proposed method belong to the second quarter of 2019. The cost of a heat exchanger valued with this method can be updated to the cost of another later date by means of indexes. For heat exchangers the use of the term heat exchangers & tanks, given in the Chemical Engineering Plant Cost Index (CEPCI) is recommended. The future cost of a shell-and-tube heat exchanger can be updated by means of the following equation (Medina *et al.*, 2018):

$$V_{MS} = C" \cdot (CEPCI_n / CEPCI_x). \quad (26)$$

In Eq. (26), $C"$ is obtained from Eq. (3), while $CEPCI_n$ and $CEPCI_x$ are the Chemical Engineering Plant Cost Index for a future date and for the second quarter of 2019, respectively.

III. VALIDATION AND ADJUSTMENTS OF THE PROPOSED METHOD.

A. Comparison of real costs with the values obtained with the use of the proposed method.

In order to accomplish the verification of the developed method, a compilation of data of costs of shell-and-tubes heat exchangers was put together. The available costs in the compilation are correlated with the values of costs obtained with the use of the method developed in the present paper, therefore, is required that the data of available costs are in FOB values and updated to the first or second quarter of 2019. The obtained values that do not fulfill this requirement are discarded.

For this purpose, a total of 410 primary values of costs (see Table 9) were compiled from Camaraza (2020). The extensive range of implicated variables makes it very difficult to show a summary of all and their repercussion on the final cost of the shell-and-tube heat exchanger. However, to establish the correlation values, the proposed method is formulated in an application developed in the EES software. The errors are determined by the following expression (Camaraza-Medina *et al.*, 2019):

$$error = 100 \cdot (C" - C_{real})/C". \quad (27)$$

In Eq. (27) C_{real} is the average FOB cost per square meter of area. In Fig. 1 the adjustment between the obtained values with the proposed method and the average FOB cost per square meter of heat exchange surface is represented graphically in a 15 percent error band. In Table 9 the correlation between the obtained values with the proposed method and the average FOB cost per square meter of several shell-and-tube heat exchangers is summarized for ten validity intervals.

In the correlation and adjustment, a total of 410 exchangers, with heat transfer surfaces ranging between 4 to 1150 m^2 were compared. It was found that the proposed method correlates well with an average error of $\pm 10.1\%$, for 84.15% of the available data.

IV. CONCLUSIONS

A new simplified method for the cost assessment of shell-and-tube heat exchangers was presented in this paper. The developed method was verified by comparison with a total of 410 STHE available data on average FOB cost per square meter of heat exchange area.

In the correlation and validation of the proposed method, the STHE used in the calculations have a heat transfer area (S_{HT}) ranging between 5 to 1150 m^2.

Table 9. Correlation adjustments with the real cost available.

S_{HT} (m^2)	Number of STHE	Deviation percent	
$5 < S_{HT} \leq 25$	21	8.3 -7.5	80.95% data
$25 < S_{HT} \leq 90$	58	10.2 -10.5	84.48% data
$90 < S_{HT} \leq 150$	66	11.4 -12.1	81.81% data
$150 < S_{HT} \leq 300$	41	11.1 -10.3	87.80% data
$300 < S_{HT} \leq 450$	47	13.2 -12.6	82.97% data
$450 < S_{HT} \leq 600$	36	10.8 -9.9	83.33% data
$600 < S_{HT} \leq 720$	32	12.6 -11.8	84.37% data
$720 < S_{HT} \leq 850$	39	10.1 -12.6	87.17% data
$850 < S_{HT} \leq 1000$	41	13.1 -11.9	85.36% data
$1000 < S_{HT}$	29	10.6 -10.1	82.75% data
For all data above	410	10.2 -10.1	84.15% data

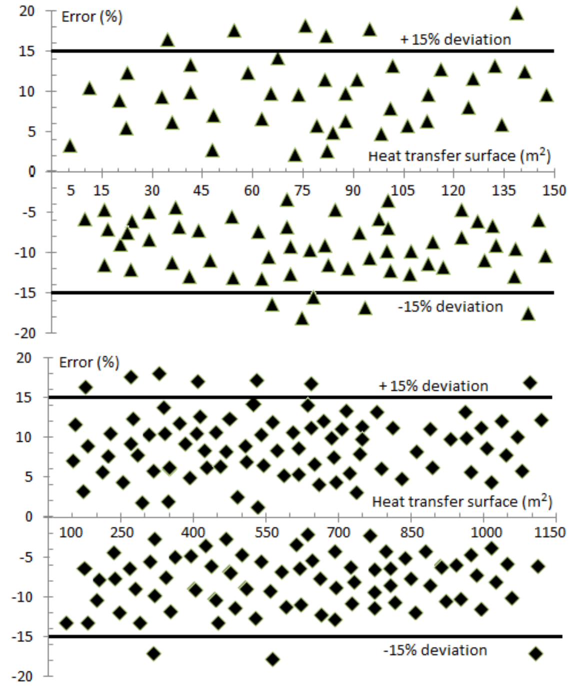

Figure 1. Correlation of the obtained values using the proposed method with real costs for a heat exchange area ranging between 4-1150 m^2.

It was found that the proposed method correlates well with an average error of $\pm 10.1\%$, for 84.15% of the available data. The method presents a lower adjustment in the range $300\ m^2 < S_{HT} \leq 450\ m^2$, with an average error of $\pm 12.9\%$, for 82.97 % of the available data. The best adjustments are located in the range $5\ m^2 < S_{HT} \leq 25\ m^2$, with an average error of only $\pm 8.0\%$, for 80.95 % of the available data. In all cases, the agreement of the proposed method is good enough to be considered satisfactory for practical design.

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