Generalization of Decomposed Integration Methods for Cost Effective Heat Exchanger Networks with Multiple Cost Laws

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ABSTRACT: *At many circumstances, in heat exchange processes several exchangers were used with different cost laws due to their pressure ratings, materials of construction and exchange3r types. In such circumstances traditional methods of pinch technology can not be led to minimum total annual cost may cause some other disadvantages like more complexity or higher maintenance. In this research work a new approach based on decomposition has been used to achieve the cost-effective networks with multiple cost laws. The cost laws multiplicity can has several reasons. The most common cases are; mixed pressure ratings, mixed types and mixed materials of construction however many other factors such as purchasing exchangers from different vendors or purchasing exchangers in different times can also cause multiplicity cost laws.The present paper demonstrates application of two decomposition methodologies (Total decomposition and Partial decomposition) for a few sample conditions with typical cost laws. The outcomes of this study indicate effectiveness and potentiality of the methods.*

KEY WORDS: *Pinch technology, Mixed materials, Decomposition, Grass root design, Heat exchanger network, Partial decomposition, Process integration, Cost reduction, Energy saving.*

INTRODUCTION

In the recent years, process integration has been played a valuable position between other process main roles in the prosperity. One of these correlations is optimization methods. Some important parameters have the cost law of exchangers. For first time Kumana [1] suggested a simple equation to estimate the heat

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exchange capital costs as follow:

$$\text{Cost of exchanger} = a + b\,A^c \qquad (1)$$

a = Installation factor
b = Material factor
c = An exponent
A = Area of exchanger

In this equation "a" factor is very numerous and depends to social and economic conditions of any country. But "b" and "c" factors, which vary due to materials of construction, pressure rating and type of exchanger. Many parameters like size of exchangers, various vendors, and different times of purchasing, can also vary the factors. Traditional methods of pinch technology often assume only one cost law for all of the network exchangers.

In the methods minimum heat transfer area of network is predicted by Bath formula presented by Linnhoff and Townsend [2] as follows:

$$A\min = \sum_{i}^{\text{Intervals}} \frac{1}{\Delta T_{LM\ i}} \left[\sum_{j}^{\text{Streams}} \left(\frac{q_j}{h_j} \right) \right]_i \qquad (2)$$

$T_{LM\ i}$ = the logarithmic mean temperature difference of enthalpy interval i.
$(q_j)_i$ = enthalpy change of stream j in interval i.
$(h_j)_i$ = heat transfer coefficient (including film, wall and fouling contributions) of stream j in interval i.

By assuming equal area for all of heat exchangers the capital cost of network can be obtained by:

$$\text{Network capital cost} = N_{min}[a + b\,(\frac{A_{min}}{N_{min}})^c] \qquad (3)$$

N_{min} = Minimum number of heat transfer units

It should be noted that the major parameter in optimization of heat exchanger networks is total annual cost (T.A.C.). This value is computed by summation of energy cost and capital cost. Since these values have not same units, capital cost converts to annual capital cost by multiplying a factor called annualization factor. Then the new capital cost (annual capital cost) can be added to energy cost and total annual cost.

In the multiple cost law cases, S.G.Hall et. al [3] presents a simple method that uses Φ factors in bath formula.

$$\Phi_j = (b_1/b_2)^{1/c1}\ (A_{min}/N_{min})^{1-c2/c1} \qquad (4)$$

b_1 , c_1 : Reference cost law
b_2 , c_2 : Special cost law

$$\sum_{i}^{\text{Intervals}} \frac{1}{\Delta T_{LM\ i}} \left[\sum_{j}^{\text{Streams}} \left(\frac{q_j}{\Phi_j h_j} \right) \right]_i \qquad (5)$$

The A^*_{min} called weighted area and using this value in the equation (3) can produce accurate capital cost of a network which uses two or more types of heat exchangers with different cost laws.

The authors shown in their previous work [4] such networks may not be optimum sometimes. This is due to multiplicity of mixed or expensive exchangers.

If whole streams in a network were integrated entirely, it can create many conditions that should be use a mixed or expensive exchangers. This is called full integration method. If the network exchangers is of different material of construction or pressure rating, the networks can be categorized as mixed exchangers.

What is mixed exchanger? A mixed exchanger is an exchanger which is used to transfer heat between an ordinary and a special stream. The mixed exchangers are divided in as 1: mixed material exchangers, 2: mixed pressure rating exchangers. The mixed material exchangers have tubes made of special materials such as stainless steel or titanium and other parts made by carbon steel. Such exchangers are used for heat transferring between a corrosive stream and an ordinary one. The mixed pressure rating exchangers have more strengthened tubes to resist the pressure of passing stream and use for heat transferring between a high pressure and an ordinary stream. Likewise in an expensive high-pressure exchanger, all main parts are made by more strengthened materials and such exchangers are used for heat transferring between two high-pressure stream. Investigations show that price of a mixed exchanger is not equal to average price of an expensive or a cheap one, and approximately is near to the price of the expensive exchanger. This is because of great portion of tubes mass in weight mass of an exchanger and some other technical considerations. Since in a full-integrated network there are many mixed exchangers,

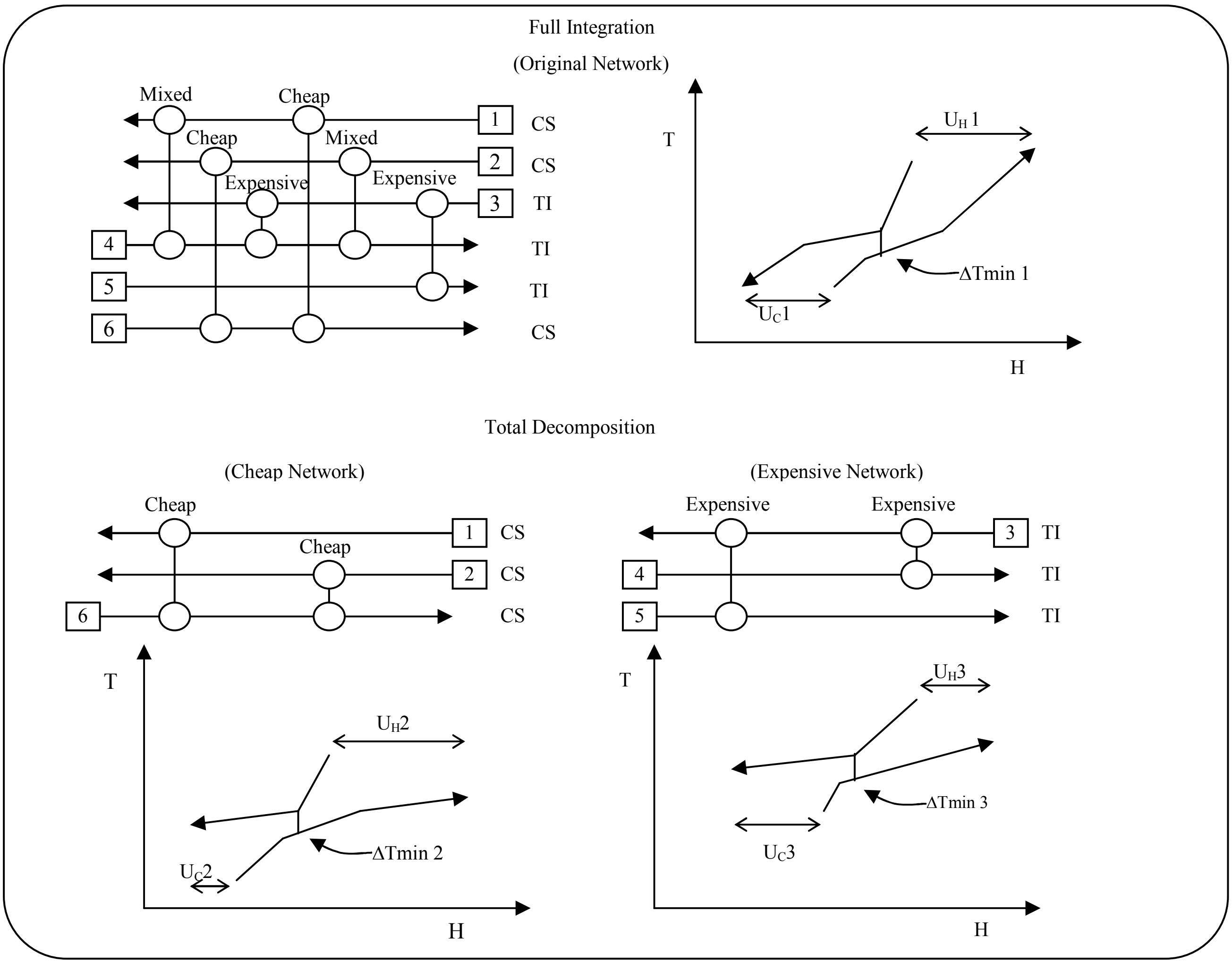

Fig. 1: Total decomposition using for preventing from mixed materials heat exchangers.

used so capital cost of such networks is raised.

In the other circumstances of exchangers variety like types of exchangers, the mixed exchangers can not be exist and expensive exchangers should be used instead of mixed ones and therefore capital cost of such networks will increase.

By decomposition methods [4], it is prevented from mixed exchangers in networks. These methods can be classified into two ways: total and partial decomposition and will more explain in the following section.

TOTAL DECOMPOSITION

By this method an original system divides in two ore more subsystems and each of them is fully independent of others. This means that there are no any heat exchanging relation between subsystems.

The essential of division can be based on different principles. The main principle is nature of streams. If in original system involves two kinds of streams, for example corrosive and ordinary (non-corrosive) streams, in such circumstance one subsystem involve for corrosive stream with expensive exchangers and other subsystem involves ordinary stream with cheap exchangers. So there is not any necessity to mix exchangers but the numbers of cheap and expensive exchangers may be increase. Since price of a mixed exchanger is larger than the average of prices of a cheap and an expensive exchanger, the cost of two mixed exchangers is larger than the cost of a cheap and an expensive exchangers. Therefore total decomposition can reduce the capital cost of heat exchanger networks with multiple kinds of exchangers (Fig. 1).

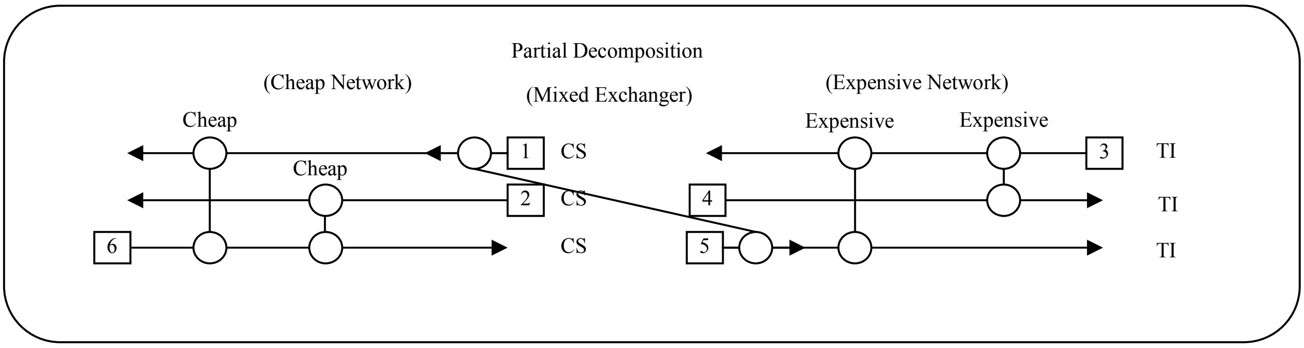

Fig. 2: Partial decomposition.

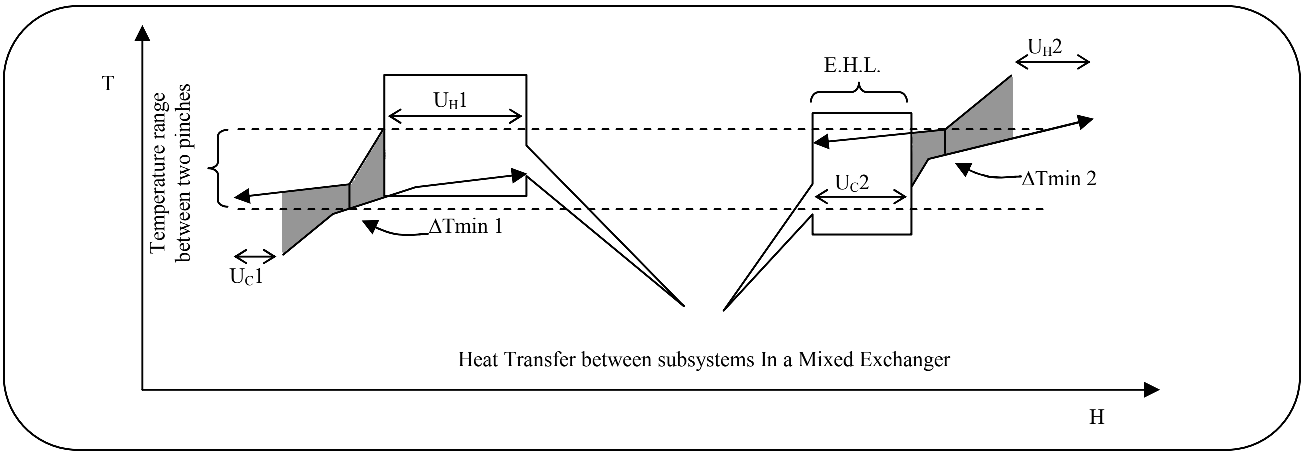

Fig. 3: Determination of exchangeable heat load – E.H.L.

In spite of this, total decomposition has an undesirable effect. It causes reduction of heat integration in subsystems. In another word summation of utility consumption in all of subsystems is often greater than the utility required for fully integrated original system. Therefore in many cases this deficiency can be modified by another method called partial decomposition.

PARTIAL DECOMPOSITION

The authors have been shown in their previous papers [4], in some cases, subsystems, many limits the amount of heat transfer between streams so that the total utility consumption is reduced.

In this manner one mixed exchanger is used for heat transferring between two subsystems. For the circumstance that there is not any possibility for mixed exchangers like mixed type, an expensive exchanger will use for heat transferring between subsystems. In spite of this, the total number of expensive exchangers in partial decomposition method is less than the fully integrated method for many resoan.

The streams which exchanges heat in the mixed exchanger called candidate streams . a candidate stream can be a part or whole of one stream in a subsystem. A subsystem without candidate stream called as remained subsystem and must be reintegrate again by ignoring candidate streams.

Generally there are some conditions for partial decomposition:

1- Temperature positions of pinches in subsystems should have considerable difference.

2- Composite curves of subsystems would have overshoots in temperature range between pinches. The smaller overshoot called exchangeable heat load (E.H.L.).

3- After selecting of candidate streams and reintegration of remained subsystems, utility consumption of remained subsystems reduces than the utility consumption of subsystems before selecting of candidate streams and reintegration (Figs. 2 , 3).

QUANTITATIVE INVESTIGATIONS

The cost laws of exchangers have a wide tolerance. Even an exchanger may have different cost laws in various local and temporal conditions. It is clear that investigation of all of them is impossible. But it is tried that any sample from various cost laws of different materials, pressure ratings and types were used. As shown above, cost laws are the important point to get desired results from decomposition methods.

Certainly traditional pinch technology which is a full integrated method can be as a powerful tool so it has a matchless effect in reduction of T.A.C. and challenging it, is very difficult and by the other methods rarely can achieved the T.A.C. less than the T.A.C. of full integration method. Therefore some other advantages like simplicity, less number of mixed or expensive exchangers, less number of stream splitting, etc should be considered.

Table 1 shows stream data and table 2 shows economic data including cost laws of different heat exchangers, utility prices, plant life time and interest rate used by hall et al [3]. Here this case study will be used as different examples with different combinations for special streams and various cost laws. Targeting calculations are done by pilot software ver. 2.00 under licensed by Dr. M.H. Panjeh Shahi.

EXAMPLE 1: MIXED MATERIALS OF CONSTRUCTION

In the first case Hall [3] supposed that streams 3,4,6,9 required stainless steel (SS) and others required carbon steel (CS). As that shown in table 3, in full integration method a network with 13 units and 3,118,793 $/Yr T.A.C. will be suggested. In total decomposition method streams 3,4,6,9 form the expensive subsystem and others form cheap subsystems. The summation of T.A.C. of two subsystems, is 6.11% higher than the full integration but total numbers of units is one less than the full integration method. In this case the pinch of expensive subsystem is upper than the cheap subsystem, so 2000 kW of cold utility consumption of the expensive subsystem can recover by hot utility consumption in cheap one. Therefore by applying partial decomposition for this case, increasing of T.A.C. becomes 1.1% and the number of units is the same 11 units.

Table 1: Stream and utility data.

Stream	Temperature (°C) Supply	Temperature (°C) Target	Heat Capacity Flow Rate (kW/°C)	h-value KW/m^2 °C
1- Hot	120	65	50	0.5
2- Hot	80	50	300	0.25
3- Hot	135	110	290	0.3
4- Hot	220	95	20	0.18
5- Hot	135	105	260	0.25
6- Cold	65	90	150	0.27
7- Cold	75	200	140	0.25
8- Cold	30	210	100	0.15
9- Cold	60	140	50	0.45
Steam	250	—	—	0.35
Cooling water	15	—	—	0.2

Table 2: Economic data used by Hall.

Type of exchanger	Pressure rating (bar)	Materials of construction	Cost law ($)
Shell / Tube	10	Carbon Steel (CS)	30800 + 750 A0.81
Shell / Tube	10	Stain less Steel (SS)	30800 + 1644 A0.81
Shell / Tube (Mixed)	10	CS / SS	30800 + 1339 A0.81
Shell / Tube	10	Titanium (TI)	30800 + 4407 A0.81
Shell / Tube (Mixed)	10	CS / TI	30800 + 3349 A0.81
Shell / Tube	35	CS	30800 + 1089 A0.81
Shell / Tube (Mixed)	10/ 35	CS	30800 + 890 A0.81
Shell / Tube	60	CS	30800 + 1438 A0.81
Shell / Tube (Mixed)	10/ 60	CS	30800 + 983 A0.81

Cost of hot utility 120 $ / kW Year
Cost of cold utility 10 $ / kW Year
Plant life = 6 Year Interest rate = 10 %
Annualization factor = 0.2296074
A = shell / tube exchanger area (m2)

Table 3: Decomposition using for mixed materials of construction (CS/SS) – 1st case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		10	70, 80	18450	4500	17536[a]	13	3118793	
Total Decomposition	CS	5	75 , 80	21200	5250	10437	7	3094403	- 6.11 %
	SS	29	Threshold	0	2000[b]	1331	4	21503	
Partial Decomposition	CS	8	72 , 80	19500	5550	11691	7	2936575	- 1.1 %
	SS	24	Threshold	0	0	1327	3	178685	
	CS/SS	45	Threshold	0	0	297	1	38057	

Streams 3,4,6,9 require Stainless Steel exchangers a : weighted Area b: E.H.L.

Table 4: Decomposition using for mixed materials of construction (CS/TI) – 1st case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		15	65, 80	19950	6000	26583[a]	12	3598176	
Total Decomposition	CS	5	75 , 80	21200	5250	10437	7	3094403	0.23 %
	TI	29	Threshold	0	2000[b]	1331	4	495276	
Partial Decomposition	CS	8	72 , 80	19500	5550	11691	7	2936575	3.7 %
	TI	24	Threshold	0	0	1327	3	443338	
	CS/TI	45	Threshold	0	0	297	1	84570	

Streams 3,4,6,9 require Titanium exchangers a : weighted Area b: E.H.L.

If the streams 3,4,6,9, use Titanium (TI) instead of Stainless steel (SS), better improvement in T.A.C. will obtained. As shown in table 4, 0.23% improvement in T.A.C. achieved by total decomposition and 3.7 % by partial decomposition.

The main reason to obtain better results when using Titanium is the difference of "b" factor in the cost laws of SS and TI. Here, "a" and "c" factors are equal and only "b" factors have differences. As it will be shown later, the differences in "a" and "c" factors can also be effective.

In the second case, Hall [3] supposed streams 4,5,6,7 were corrosive and required special materials. Tables 5 and 6 show the results. In this case partial decomposition is not possible because pinches of two subsystem have not considerable difference in their temperature positions. Similar to the last case, better results is obtained by using of Titanium. There is 0.24 % in T.A.C. increase with SS and 3.85 % reduction using with TI. Also the numbers of units are reduced to 11 units in both using of SS and TI.

Table 7 shows specification of some different exchangers and their cost laws. These informations are obtained from 3 references [3, 5, 6]. The plate & frame exchangers cost laws are used by polley et. al [5]. Such exchangers can not operate in high temperature and pressures. Their operational conditions are approximately up to 170°C and 150 psi. The spiral exchanger cost law were used by Hall et. al [3]. These exchangers often use for slurry streams. The other shell/tube exchangers including floating head and fixed or U types are adapted from references [5,6].

Table 5: Decomposition using for mixed materials of construction (CS/SS) – 2nd case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		10	70 , 80	18450	4500	20355[a]	13	3217367	
Total Decomposition	CS	5	130 , 135	8500	5500	9428	7	1537475	- 0.24 %
	SS	25	Threshold	10950	0	3273	4	168747	

Streams 4,5,6,7 require Stainless Steel exchangers a : weighted Area

Table 6: Decomposition using for mixed materials of construction (CS/TI) – 2nd case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		17	63 , 80	20250	6300	36865[a]	12	3958413	
Total Decomposition	CS	5	130 , 135	8500	5500	9428	7	1537475	3.85 %
	TI	25	Threshold	10950	0	3273	4	2268345	

Streams 4,5,6,7 require Titanium exchangers a : weighted Area

Table 7: Some different exchangers and their cost laws.

Type of exchanger	Pressure rating (psi)	Materials of construction	Cost law ($)
S/T(floating head)	150	CS	1297 A0.65
S/T(floating head)	150	TI	6267 A0.65
S/T(floating head)	150	CS / TI	3959 A0.65
S/T(floating head)	900	CS	2271 A0.65
S/T(floating head)	900	TI	10968 A0.65
S/T(floating head)	900	CS / TI	6929 A0.65
Plate & frame	150	SS	272 A0.6907
Plate & frame	150	TI	262 A0.7514
Spiral	10	CS	19687A0.59
S/T (Fixed / U)	150	CS	137 A1.36
S/T (Fixed / U)	150	TI	655 A1.36
S/T (Fixed / U)	150	CS / TI	414 A1.36
S/T (Fixed / U)	900	CS	237 A1.36

S/T : Shell & Tube Fixed / U : Fixed or U type

Table 8: Decomposition using for mixed materials of construction (CS/SS) – 3rd case.

Full Integration		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m2)	Nmin	T.A.C. ($/Yr.)	T.A.C. Improvement
		8	80 , 72	17850	3900	48384a	13	2991714	
Total Decomposition	CS	2	80 , 78	20530	3780	12756	7	2775832	- 7.8 %
	TI	6	135 , 129	550	3350b	1969	5	449402	
Partial Decomposition	CS	2	80 , 78	17601	4200	12463	6	2410270	1.09 %
	TI	7	122 , 115	1244	694	1810	5	487631	
	CS/TI	36	Threshold	0	0	647	1	61046	

Streams 1,5,6,9 require Titanium exchangers a : weighted Area b: E.H.L.

Table 9: Decomposition using for mixed pressure rating(10bar & 35bar) – 1st case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m²)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		8	72, 80	17850	3900	15638[a]	13	2972761	
Total Decomposition	10 bar	5	75 , 80	21200	5250	10437	7	3094403	- 9.43 %
	35 bar	29	106 , 135	0	2000[b]	1331	4	158741	
Partial Decomposition	10 bar	8	72 , 80	19500	5550	11691	7	2936575	- 3.9 %
	35 bar	24	Threshold	0	0	1327	3	125493	
	10 / 35	45	Threshold	0	0	297	1	27667	

Streams 3,4,6,9 require 35bar exchangers a: weighted Area b: E.H.L.

Table 10: Decomposition using for mixed pressure rating (10bar & 60bar) – 1st case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m²)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		8	72, 80	17850	3900	17554[a]	13	3041440	
Total Decomposition	10 bar	5	75 , 80	21200	5250	10437	7	3094403	- 7.46 %
	60 bar	29	106 , 135	0	2000[b]	1331	4	174139	
Partial Decomposition	10 bar	8	72 , 80	19500	5550	11691	7	2936575	- 2.75 %
	60 bar	24	Threshold	0	0	1327	3	158912	
	10 / 60	45	Threshold	0	0	297	1	29820	

Streams 3,4,6,9 require 60 bar exchangers a: weighted Area b: E.H.L.

These are only a few samples and consideration of all type of exchangers is impossible. Here, with the purpose of showing the application of the methods for various exchangers and presented cost laws in table 7 the procedure can be replaced with any other cost laws.

As the third case it is supposed that streams 1,5,6,9 are corrosive and require special materials and the others need CS. Also the cost laws of floating head exchangers were used for this case. At this time, table 8 shows that –7.8 % improvement in T.A.C. were achieved by total decomposition (7.8 % raising in T.A.C.) but partial decomposition gives 1.09 % improvement (1.09 % reduction in T.A.C.). Both methods need to total number of units equal to 12 which is 1 unit less than the fully integration method.

In this circumstance, some parameters are varied in compare with the last circumstances. Here "a" factors are equal to zero, "b" factors raise and "c" factors are reduced. Also E.H.L. is raised from 2000kW to 3350 kW. However the achieved scopes do not have considerable difference with the last ones.

EXAMPLE 2: MIXED PRESSURE RATING

Now, it is assumed that streams are not corrosive however some of them have high operating pressure. Commonly operating pressure for ordinary streams is assumed 10 bar (150 psi). By increasing pressure, exchangers must be strengthening by materials and the other technical considerations. Similar to application of expensive exchangers for heat transfer between two corrosive streams in the mixed materials networks, to heat transfer between two streams with high operating pressure, an exchanger should be used that is strengthened in both shell and tube sides. But for heat transferring between one ordinary stream and a high pressure one, a mixed pressure rating exchanger can be use. It is evident that if such exchanger is unavailable, an exchanger with high-pressure resistance in both sides can be use instead of mixed pressure rating one.

Tables 9 and 10 show the results of total and partial decomposition using for 1st case of assumption for special streams (streams 3,4,6,9 are special and others are ordinary). By the 35 bar pressure rating, –9.43 %

Table 11: Decomposition using for mixed pressure rating (150psi & 900psi) – 3rd case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		5	80 , 75	16950	3000	25106[a]	13	2593259	
Total Decomposition	150psi	2	80 , 78	20530	3780	12756	7	2775832	- 15.39 %
	900psi	2	135 , 133	350	3150[b]	231	5	216579	
Partial Decomposition	150psi	2	80 , 78	17800	4200	12237	6	2431097	- 5.07 %
	900psi	2	122 , 120	955	605	2291	5	260677	
	900psi	37	Threshold	0	0	593	1	33096	

Streams 1,5,6,9 require 900 psi exchangers a : weighted Area b: E.H.L

Table 12: Decomposition using for combination of mixed pressure rating and mixed materials of construction – 3rd case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		15	80 , 65	19950	6000	64098[a]	12	3400429	
Total Decomposition	150psi(CS)	2	80 , 78	20530	3780	12756	7	2775832	- 2.26 %
	900psi(TI)	11	135 , 124	800	3600[b]	1761	5	701592	
Partial Decomposition	150psi(CS)	2	80 , 78	17350	4200	12786	6	2384483	5.05 %
	900psi (TI)	13	121 , 108	1592	792	1578	5	729511	
	900psi(TI)	34	Threshold	0	0	721	1	114634	

Streams 1,5,6,9 require 900 psi (TI) exchangers a : weighted Area b: E.H.L.

improvement in T.A.C. (9.43 % raising) is achieved in total decomposition and partial decomposition gives –3.9 % improvement (3.9% raising).

Better improvements were achieved by 60 bar mixed pressure ratings. –7.46 % for total decomposition and –2.75 % for partial decomposition. To achieve more confidence, the calculations are repeated with 150 psi and 900 psi data in 3rd case assumption of special streams in table 11. Improvement results are –15.39% for total decomposition and –5.07% for partial decomposition. In this circumstance there is not mixed pressure rating heat exchanger and a 900 psi pressure rating heat exchanger is used instead of mixed one. However these results may not seem very attractive but there is an encouragement. All obtained results have approximately same relative difference. Thus it can deduced that the methods have a logical manner and scopes of T.A.C. reduction are differing by any case study.

EXAMPLE 3: COMBINATION OF MIXED PRESSURE RATING AND MIXED MATERIALS OF CONSTRUCTION

In many circumstances special streams are both corrosive and high pressure. It is clear that such circumstances need more forecast exchangers. An example is studied in table 12. Here the 3rd case of assumption for special streams was used. The obtained results are more suitable than results in tables 8 and 11. Total decomposition gives –2.26 % improvement in T.A.C. and partial decomposition gives 5.05% improvement. Number of units had not any variation in this circumstance. The main reason of more suitable results is larger difference in "b" factors. In table 7 all S / T floating head exchangers have a same "a" and "c" factors (0 and 0.65) but "b" factors are different. By notice to "b" factors of exchangers used in table 12, it is cleared that the "b" factors have larger difference than the "b" factors of exchangers used in tables 11and 8 orderly. This is caused better results than previous circumstance.

EXAMPLE 4: NETWORKS WITH MULTIPLE TYPES EXCHANGERS

As that said, some special streams need to other type of exchangers. Two usual other types of exchangers are spiral exchangers and plate & frame exchangers. Spiral exchangers often use for slurry or dirty streams and plate & frame exchangers have a wide range of applications in food and drug industries. Also their applications in other industries are spreading day by day.

Tables 13,14 and 15 show the obtained results. The exchangers that used in these circumstances are one kind of spiral exchanger, a plate & frame exchanger made by SS and a plate & frame exchanger made by TI. Also 3rd assumption of special streams was used. Here, like the previous circumstance there is not any mixed type exchanger and expensive one is used instead of it. As that expect, the partial decomposition gives better results than the total decomposition but the results in compared to full integration results are not predictable. They may be less or little more than full integrated results. In table 13, -2.7 % improvement in T.A.C. is obtained by total decomposition and 1.6% improvement is obtained by partial decomposition.

Tables 14 and 15 have less improvement. The results of these tables are approximately similar. –17% improvement by total decomposition and –5 % improvement by partial decomposition. Here, an interested point is the similarity between results of Tables 14 and 15 despite of the multiplicity of materials of construction of plate & frame exchangers. By referring to table 7, it is observed that the "b" factor of SS plate & frame exchanger is higher than the "b" factor of TI plate & frame exchanger but its "c" factor is lower than the other one. Therefore the factors compensate each other and give similar results.

EXAMPLE 5: HIGH SCOPE CIRCUMSTANCES

Previous circumstances often had poor scopes for improvements of T.A.C. specially the circumstances, which had the T.A.C. of decomposed methods less than the T.A.C. of fully integrated method. Such conditions are not always. It can be circumstances that have T.A.C. considerably lower than the fully integrated method. Tables 16,17 and 18 present circumstances which all of their improvements are above 20% and even 44%. In these circumstances special streams are in arrangement of 1st case and use fixed S / T exchangers. In another word all streams of circumstances in this example use S / T exchangers, some of them using floating head S / T exchangers and others using fixed or U type S / T exchangers.

It is may be such conditions rarely happening in practice but the aim of these studies is showing of applicability and beneficially of the methods.

As it is shown in table 17, improvement obtain by partial decomposition is less than total decomposition but in tables 16 and 18 partial decomposition gives better results than the total decomposition. By notice to the cost laws of exchangers used in this example, it is cleared that the "c" factor of fixed/U type exchangers is considerably higher than the others. Although the "b" factors is higher too but such differences in "b" factors were exist in last examples and did not cause the considerable improvements. So, the most effective parameter is the larger relative difference in "c" factors of cost laws.

Furthermore, in a cost law of exchanger, "a" factor is a constant, "b" factor is a coefficient and "c" factor is an exponent for area. So effect of the factors is not equivalent and "c" factor has highest effect and "a" factor has lowest effect on the cost of an exchanger.

CONCLUSION

The paper shows that multiplicity of cost laws in heat exchanger networks generates an opportunity, which validate decomposed integration methods. In this method, achieved improvements are independent from cause of variety of cost laws. Quantitative investigations are showing that applications of the new methods can provide considerable scopes in reduction of T.A.C. The scopes include a wide tolerance of savings in T.A.C. even over 40%. In addition, other important advantage, which obtain by the methods is elimination of mixed exchangers or reduction of their numbers to only one unit.

Table 13: Decomposition using for networks with multiple types of exchangers (S / T and Spiral) – 3rd case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		15	80 , 65	19950	6000	78267[a]	12	3531623	
Total Decomposition	S / T (CS)	2	80 , 78	20530	3780	12756	7	2775832	- 2.7 %
	Spiral	12	135 , 123	850	3650[b]	1733	5	850765	
Partial Decomposition	S / T (CS)	2	78 , 80	17300	4200	12857	6	2379357	1.6 %
	Spiral	15	105 , 120	1702	851	1525	5	873356	
	Spiral	35	Threshold	0	0	736	1	222138	

Streams 1,5,6,9 require Spiral exchangers a : weighted Area b: E.H.L.

Table 14: Decomposition using for networks with multiple types of exchangers (S / T and Plate & frame (SS)) – 3rd case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		4	75 , 79	16600	2650	17466[a]	14	2447549	
Total Decomposition	S / T (CS)	2	80 , 78	20530	3780	12756	7	2775832	- 17.11 %
	Plt & frm (SS)	1	134 , 135	300	3100[b]	2632	5	90672	
Partial Decomposition	S / T (CS)	2	78 , 80	17849	4200	12148	6	2436378	-5.13 %
	Plt & frm (SS)	1	123 , 124	834	855	2535	5	131756	
	Plt & frm (SS)	37	Threshold	0	0	579	1	5055	

Streams 1,5,6,9 require Plate & frame (SS) exchangers a : weighted Area b: E.H.L.

Table 15: Decomposition using for networks with multiple types of exchangers (S / T and Plate & frame (TI)) – 3rd case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		5	75 , 80	16950	3000	15866[a]	13	2456758	
Total Decomposition	S / T (CS)	2	80 , 78	20530	3780	12756	7	2775832	- 17 %
	Plt & frm (TI)	1	134 , 135	300	3100[b]	2632	5	100356	
Partial Decomposition	S / T (CS)	2	78 , 80	17849	4200	12184	6	2436378	-5.2 %
	Plt & frm (TI)	1	123 , 124	834	855	2535	5	141117	
	Plt & frm (TI)	37	Threshold	0	0	579	1	7164	

Streams 1,5,6,9 require Plate & frame (TI) exchangers a : weighted Area b: E.H.L.

Table 16: Decomposition using with high improvements (mixed types of S / T exchangers – floating head and fixed / U) – 1st case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		18	62, 80	20400	6450	139099[a]	12	4078529	
Total Decomposition	Floating head	2	78, 80	20480	4530	14516	8	2815657	22.16 %
	Fixed / U	29	Threshold	0	2000[b]	1331	4	358975	
Partial Decomposition	Floating head	3	77, 80	18999	5050	14497	7	2628726	24%
	Fixed / U	24	Threshold	0	0	1327	3	374151	
	Fixed / U	45	Threshold	0	0	297	1	72552	

Streams 3,4,6,9 require fixed / U exchangers a : weighted Area b: E.H.L.

Table 17: Decomposition using with high improvements (mixed types and materials of S / T exchangers – floating head (CS) and fixed / U (TI)) – 1st case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A(m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		75	60, 135	38550	24600	407002[a]	11	7924471	
Total Decomposition	Floating head (CS)	2	78, 80	20480	4530	14516	8	2815657	43.76 %
	Fixed / U (TI)	29	Threshold	0	2000[b]	1331	4	1640650	
Partial Decomposition	Floating head (CS)	3	77, 80	18999	5050	14497	7	2628721	39.87 %
	Fixed / U (TI)	24	Threshold	0	0	1327	3	1788825	
	Fixed / U (TI)	45	Threshold	0	0	297	1	346877	

Streams 3,4,6,9 require fixed / U (TI) exchangers a : weighted Area b: E.H.L.

Table 18: Decomposition using with high improvements (mixed types and pressure rating of S / T exchangers – floating head (150 psi) and fixed / U (900 psi)) – 1st case.

		ΔTmin (°C)	Pinch Temp. (°C)	U_H (kW)	U_C (kW)	A (m^2)	N_{min}	T.A.C. ($/Yr.)	T.A.C. Improvement
Full Integration		18	62, 80	20400	6450	312480[a]	12	5162671	
Total Decomposition	Floating head (150psi)	2	78 , 80	20480	4530	14516	8	2815657	33.71 %
	Fixed / U (900 psi)	29	Threshold	0	2000b	1331	4	606403	
Partial Decomposition	Floating head (150psi)	3	77 , 80	18999	5050	14497	7	2628721	34.11 %
	Fixed / U (900 psi)	24	Threshold	0	0	1327	3	647254	
	Fixed / U (900 psi)	45	Threshold	0	0	297	1	125511	

Streams 3,4,6,9 require fixed / U (900 psi) exchangers a : weighted Area b: E.H.L.

This causes a simpler network with lower maintenance costs. Scope of improvement in T.A.C. depends in two important points:

1- Differences in factors (including “a”, ”b” and “c”) of several cost laws. Effect of each of them is not equal. Difference in “c” factors has highest and difference in 31 factor has lowest effect. As much as difference between various cost laws, provide higher scopes for T.A.C. improvements. Also in some circumstances difference of factors may be compensating each other and do not produce considerable improvement in T.A.C.

2- The shape of composite curves in a full integrated network and decomposed ones. This property indicates feasibility of partial decomposition and net improvement caused by it. Also the nature of composite curves and their kick points positions may be produce a condition which partial decomposition will be feasible but do not result reliable improvement due to unsuitable candidate streams. In such circumstances often fully integrated or total decomposed networks determine final option. In another word, total decomposition is always possible but desirability of its results may be less than the full integration method or not.

Partial decomposition is not always possible but usually gives a result better than total decomposition.

Finally the presented methods (total and partial decomposition) do not reduce reliability of traditional methods (i.e. full integration) and can be use to provide additional options in the designing procedure of a network with special streams

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