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Debottlenecking and Retrofitting by Pinch Analysis in a Chemical Plant

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Abstract: Energy saving, global warming and greenhouse gas emissions have become major technological, social and political issues. Being closely related to energy supply, they are of a strategic significance. Today, especially energy-sensitive industries such as refining and petrochemical are targeting to recover maximum amount of energy by applying Process Integration (PI) that deals with the energy efficiency, waste minimization and effective use of raw materials. Pinch Analysis is a structured approach and a systematic tool of PI. The prime objective of Pinch Analysis is to achieve financial savings by better process heat integration and reduce the externally provided energy requirements by recovering the maximum amount of energy within the system. It is also employed to improve effluent quality, reduce emissions, increase product yield and improve the flexibility and safety of the process. Properly calculated pinch targets have economic implications such as reduction of operating cost and capital investment. This study deals with energy saving strategies in a real VCM (Vinyl-Chloride-Monomer) plant by applying pinch method. The prime objective of this work is to achieve financial savings by better process heat integration (maximizing process-to-process heat recovery and reducing the external utility loads). It examines the existing process and introduces two alternative retrofit cases. Targets for heat recovery and utilities have been calculated (taking ΔT_{min}=10°C). Existing process and alternative cases have been compared. According to Retrofit 1, energy recovery reaches up to 12.51% whereas utility reduction is 57.24%. Retrofit 2 states that the recovered energy is 10.45% while the utility reduction is 47.83%. The results obtained indicate that there is a remarkable improvement in energy recovery and utility saving.

Keywords: Process Integration, Pinch Analysis, Heat Recovery, Energy Saving

1. Introduction

The past decade has seen significant industrial and academic efforts devoted to the development of process design methodologies that target energy conservation for a large variety of chemical process industries [1]. Especially energy saving is the most important issue in the petrochemical industry associated with cost. The petrochemical industry is a capital intensive industry consuming much energy and the energy cost contributes significantly to the total cost [2].

The majority of energy consumed in industry is typically used mainly for heating and cooling purposes. Efficient design of heating and cooling systems in industry is therefore vital and can be accomplished through design optimal heat recovery network using tools such as Pinch Analysis (PA). PA is a systematic technique for the design of thermally efficient systems. It allows the designer to identify the minimum heating and cooling requirements and maximum energy recovery potential by identifying a thermodynamic bottleneck or the pinch point for heat recovery [3].

The development of PA started in the late 1970s and still continues. Besides the applications in energy conservation, new developments are being made in the areas of water use minimization, waste minimization, hydrogen management and so on. The application of Pinch Technology has resulted in significant improvements in the energy and capital efficiency of industrial facilities worldwide. It has been successfully applied in many different industries from petroleum and base chemicals to food and paper. This study is an example on the application of Pinch Analysis to save energy in VCM Plant of Petkim Petrochemical Industy. Although it won't provide something new to the field, this work will contribute to the current literature by improving the existing knowledge about Pinch Technology on a real large scale process.

2. Methodology

Methods of energy saving in petrochemical processes are various. Renowned methods are optimization of operating conditions and retrofit of Heat Exchange Network (HEN) [2]. One of the most extensively studied and single most important industrial application area for Process Integration (PI) is Heat Exchange Network Synthesis (HENS). The principal aspects of HENS can be found in the fact that most industrial processes involve the transfer of heat from one process stream to another process stream (interchanging) or from a utility stream to a process stream. Consequently, the target in any industrial process design is to maximize the process-to-process heat recovery and to minimize the utility requirements. To meet this goal, industrial cost effective HEN (consisting of one or more heat exchangers that collectively satisfy the energy conservation tasks) is of particular importance [1].

Pinch Technology provides a systematic methodology for energy saving in processes and total sites. The methodology is based on thermodynamic principles. Pinch Analysis starts with the heat and material balance for the process. Thus, in order to start the PA, the necessary thermal data must be extracted from the process [4]. This involves inlet and outlet temperatures, heat capacities and heat duties of process streams requiring energy transfer [2].

The starting point for an energy integration analysis is the calculation of the minimum heating and cooling requirements for a HEN. Cascade Diagram is a visual representation that shows the net heating and cooling requirements in each temperature interval [5]. Also Composite Curves (CCs) and Grand Composite Curve (GCC) have been among the most popular graphical tools for describing optimal Heat Exchanger Networks [3].

To handle multiple streams, the heat loads or heat capacity flow rates of all streams existing over any given temperature range can be added. Thus, a single composite for all hot streams and a single composite curve for all cold streams can be produced by plotting temperature versus enthalpy diagram. The overlap between the composite curves represents the maximum amount of heat recovery possible within the process. The overshoot at the bottom of the hot composite represents the minimum amount of external cooling required and the overshoot at the top of the cold composite represents the minimum amount of external heating [6].

A further development for heat integration targeting has been the Grand Composite Curve (GCC). The GCC shows a clearer view of the areas of internal process heat self sufficiency as well as the demand for external heating and cooling, all in the context of the corresponding temperature levels [7].

In Pinch Technology, choosing a suitable minimum allowable temperature (ΔT_{min}) has significance. Since higher values of ΔT_{min} give higher hot and cold utility requirements, it therefore seems that ΔT_{min} should be as low as possible to give maximum energy efficiency. However, there is a drawback; lower ΔT_{min} values give larger and more costly heat exchangers [7]. Thus an optimal allowable temperature should be chosen. The temperature level at which ΔT_{min} is observed in the process is referred to as 'Pinch Point'. The pinch defines the minimum driving force (ΔT_{min}) allowed in the exchanger unit.

To design a heat exchange network, the most helpful representation is the Grid Diagram. It is much easier to draw than a flowsheet, especially as heat exchangers can be placed in any order without redrawing the stream system. Also, the grid represents the counter current nature of the heat exchange, making it easier to check exchanger temperature feasibility. The pinch is easily represented in the grid [6].

During the construction of grid diagram, stream splitting or cycling matching can be done. Stream splitting is dividing a stream to satisfy the CP criteria. Cyclic matching is adding a series of smaller heat exchangers on a stream. After construction of grid diagram, relaxation paths and loops are found. The heat exchangers on the paths and loops are removed and their loads are added to hot and cold utilities.

3. Results and Discussion

In this study, an existing VCM plant was taken into consideration and retrofit was made by using pinch analysis. In the process 28 hot and 17 cold steams exist. By making heat and material balances according to the stream data taken from the process, the heat capacities and heat loads of each stream were calculated by using ASPEN Plus and ASPEN HYSYS (Table 1 and Table 2).

Then the adjusted supply and target temperatures are obtained by considering the minimum approach temperature to be 10˚C. These temperatures are shown from the highest value to the smallest in cascade design. The heat capacity flow rates and heat loads for each interval are calculated. Then the pinch temperature and minimum requirement of hot and cold utilities are obtained. The pinch temperature is found to be 102.5°C; hence the pinch temperatures for hot and cold streams are calculated as 107.5°C and 97.5°C, respectively. Also the minimum hot and cold utilities required are found to be 12288 kW and 41344 kW, respectively (Table 3).

Table 1. *Data of cold process streams.*

Stream Number	T_{in} (°C)	T_{out} (°C)	CP (kW/°C)	$\dot{Q}$ (kW)
C1	40	140	0.70	69.8
C2	-28	145	2.87	497.1
C3	60	150	4.05	364.2
C4	11	150	2.33	323.8

Stream Number	T_{in} (°C)	T_{out} (°C)	CP (kW/°C)	$\dot{Q}$ (kW)
C5	42	71	5.27	152.9
C6	97.5	98.5	857.5	857.5
C7	62	78	6.98	111.7
C8	100	101	526.7	526.7
C9	60	103	20.48	880.7
C10	103	160	22.45	1279.4
C11	160	203.7	115.77	5059.1
C12	102	103	1699	1699
C13	159	160	3925.4	3925.4
C14	75.3	76.3	691.5	691.5
C15	110	111	5061.4	5061.4
C16	130	131	3479.9	3479.9
C17	79.9	80.9	507	507

After plotting the hot and cold composite curves by using actual temperatures, the pinch temperature is also found to be 102.5°C. The composite curve is a graphical approach to the process while the cascade design is a mathematical approach. It can be seen from Table 3 and Figure 1, both cascade algorithm and composite curve give the approximate results. Then by using shifted temperatures, the grand composite curve is plotted (Figure 2). It is seen that the minimum hot and cold utilities are the same with the ones calculated from cascade diagram and composite curves. Also it is seen that at 102.5°C, no heat is transferred between streams. Hence the pinch point is found to be again 102.5°C [11].

Table 2. *Data of hot process streams.*

Stream Number	T_{in} (°C)	T_{out} (°C)	CP (kW/°C)	$\dot{Q}$ (kW)
H1	102	40	87.82	5138
H2	40	10	6.51	195.4
H3	95	65	5.31	159.4
H4	73	44	11.38	330
H5	45	5	0.98	39.3
H6	92.5	81.5	803.47	8838
H7	81	56	62.39	1559.7
H8	88.8	40	1.96	95.7
H9	56	10	6.99	321.7
H10	100	80.5	5.67	110.6
H11	148	80	147.98	10062.6
H12	80	40	49.82	1993
H13	85.4	-10.3	0.48	45.9
H14	-28	-32	284.48	1137.9
H15	102	65	17.47	646.6
H16	156.4	60	9.62	927.6
H17	40	39	2937.7	2937.7
H18	40	35	7.44	37.2
H19	75.4	35	8.57	346.2
H20	81	60	187.24	3932.1
H21	90	65	297.49	7437.2
H22	44.5	37	98.73	740.5
H23	37	10	2.86	77.3
H24	1250	300	3.58	3403.4
H25	68	43	45.08	1127.1
H26	68	45	21.03	483.7
H27	45	40	5.2	26
H28	116.9	50	34.8	2328.3

By using the pinch temperatures obtained in three different ways, the grid diagram is plotted. While composing the grid diagram, process is divided into two parts according to supply and target temperatures of the streams where one side is the cold utility which is used to cool the hot streams and the other side is the hot utility which is used to heat the cold streams. The streams are matched by making some assumptions, such as:

i. Heat should not be transferred across the pinch.
ii. Above pinch, heat capacity of the cold streams should be greater than hot streams' and vice versa.
iii. Minimum temperature approach should be satisfied between the hot and cold streams at each side of the heat exchanger.
iv. In each match, outlet temperature of the hot stream could not be smaller than the inlet temperature of the cold stream and outlet temperature of the cold stream could not be greater than the inlet temperature of the hot stream. This thermodynamic property should be checked in each heat exchanger.

Table 3. *Calculations of the cascade algorithm @ ΔT_{min} =10°C.*

T shifted	Interval	ΔT(°C)	CP_{cold}(kW/C)	CP_{hot}(kW/C)	ΔHCFR(kW/C)	ΔH(kW)			
1245							0,000	12287,986	$Q_{H,min}$
295	1	950!	0	3,58	-3,58	-3401	3401,000	15688,986	
208,7	2	86,3	0	0	0	0	3401,000	15688,986	
165	3	43,7	115,77	0	115,77	5059,149	-1658,149	10629,837	
164	4	1	3947,85	22,45	3925,4	3925,4	-5583,549	6704,437	
155	5	9	22,45	0	22,45	202,05	-5785,599	6502,387	
151,4	6	3,6	28,83	0	28,83	103,788	-5889,387	6398,599	
150	7	*1,4*	28,83	9,62	19,21	26,894	-5916,281	6371,705	
145	8	5	31,7	9,62	22,08	110,4	-6026,681	6261,305	
143	9	2	32,4	9,62	22,78	45,56	-6072,241	6215,745	
136	10	7	32,4	157,6	-125,2	-876,4	-5195,841	7092,145	
135	11	1	3512,1	157,6	3354,5	3354,5	-8550,341	3737,645	
116	12	19	32,4	157,6	-125,2	-2378,8	-6171,541	6116,445	

T shifted	**Interval**	**ΔT(°C)**	**CP_{cold}(kW/C)**	**CP_{hot}(kW/C)**	**ΔHCFR(kW/C)**	**ΔH(kW)**			
115	13	1	5093,8	157,6	4936,2	4936,2	-11107,741	1180,245	
111,9	14	3,1	32,4	157,6	-125,2	-388,12	-10719,621	1568,365	
108	15	3,9	32,4	192,4	-160	-624	-10095,621	2192,365	
107	16	1	1729,43	192,4	1537,03	1537,03	-11632,651	655,335	
106	17	1	30,43	192,4	-161,97	-161,97	-11470,681	817,305	
105	18	1	557,13	192,4	364,73	364,73	-11835,411	452,575	
103,5	19	1,5	30,43	192,4	-161,97	-242,955	-11592,456	695,530	
102,5	20	1	887,93	192,4	695,53	695,53	-12287,986	0,000	PINCH
97	21	5,5	30,43	192,4	-161,97	-890,835	-11397,151	890,835	
95	22	2	30,43	292,74	-262,31	-524,62	-10872,531	1415,455	
90	23	5	30,43	298,41	-267,98	-1339,9	-9532,631	2755,355	
87,5	24	2,5	30,43	303,72	-273,29	-683,225	-8849,406	3438,580	
85,9	25	1,6	30,431	1107,19	-1076,76	-1722,816	-7126,590	5161,396	
85	26	0,9	537,43	1107,19	-569,76	-512,784	-6613,806	5674,180	
84,9	27	0,1	537,43	1404,68	-867,25	-86,725	-6527,081	5760,905	
83,8	28	1,1	30,43	1404,68	-1374,25	-1511,675	-5015,406	7272,580	
83	29	0,8	30,43	1406,64	-1376,21	-1100,968	-3914,438	8373,548	
81,3	30	1,7	37,41	1406,64	-1369,23	-2327,691	-1586,747	10701,239	
80,4	31	0,9	728,91	1406,64	-677,73	-609,957	-976,790	11311,196	
80,3	32	0,1	728,91	1407,12	-678,21	-67,821	-908,969	11379,017	
76,5	33	3,8	37,41	1407,12	-1369,71	-5204,898	4295,929	16583,915	
76	34	0,5	37,41	603,65	-566,24	-283,12	4579,049	16867,035	
75,5	35	0,5	42,68	853,28	-810,6	-405,3	4984,349	17272,335	
75	36	0,5	42,68	847,61	-804,93	-402,465	5386,814	17674,800	
70,4	37	4,6	45,7365	749,45	-703,7135	-3237,0821	8623,896	20911,882	
68	38	2,4	45,7365	758,02	-712,2835	-1709,4804	10333,377	22621,363	
67	39	1	45,7365	769,4	-723,6635	-723,6635	11057,040	23345,026	
65	40	2	38,7565	769,4	-730,6435	-1461,287	12518,327	24806,313	
63	41	2	11,17	769,4	-758,23	-1516,46	14034,787	26322,773	
60	42	3	11,17	835,51	-824,34	-2473,02	16507,807	28795,793	
55	43	5	11,17	515,24	-504,07	-2520,35	19028,157	31316,143	
51	44	4	11,17	318,38	-307,21	-1228,84	20256,997	32544,983	
47	45	4	11,7	262,98	-251,28	-1005,12	21262,117	33550,103	
45	46	2	5,9	262,98	-257,08	-514,16	21776,277	34064,263	
40	47	5	5,2	228,18	-222,98	-1114,9	22891,177	35179,163	
39,5	48	0,5	5,2	*229,16*	-223,96	-111,98	23003,157	35291,143	
39	49	0,5	5,2	327,89	-322,69	-161,345	23164,502	35452,488	
38	50	1	5,2	316,51	-311,31	-311,31	23475,812	35763,798	
35	51	3	5,2	271,43	-266,23	-798,69	24274,502	36562,488	
34	52	1	5,2	3067,4	-3062,2	-3062,2	27336,702	39624,688	
32	53	2	5,2	129,7	-124,5	-249	27585,702	39873,688	
30	54	2	5,2	33,83	-28,63	-57,26	27642,962	39930,948	
16	55	14	5,2	17,82	-12,62	-176,68	27819,642	40107,628	
5	56	11	2,87	17,82	-14,95	-164,45	27984,092	40272,078	
0	57	5	2,87	1,46	1,41	7,05	27977,042	40265,028	
-15,3	58	15,3	2,87	0,48	2,39	36,567	27940,475	40228,461	
-23	59	7,7	2,87	0	2,87	22,099	27918,376	40206,362	
-33	60	10	0	0	0	0	27918,376	40206,362	
-37	61	4	0	284,48	-284,48	-1137,92	29056,296	41344,282	$Q_{C,min}$

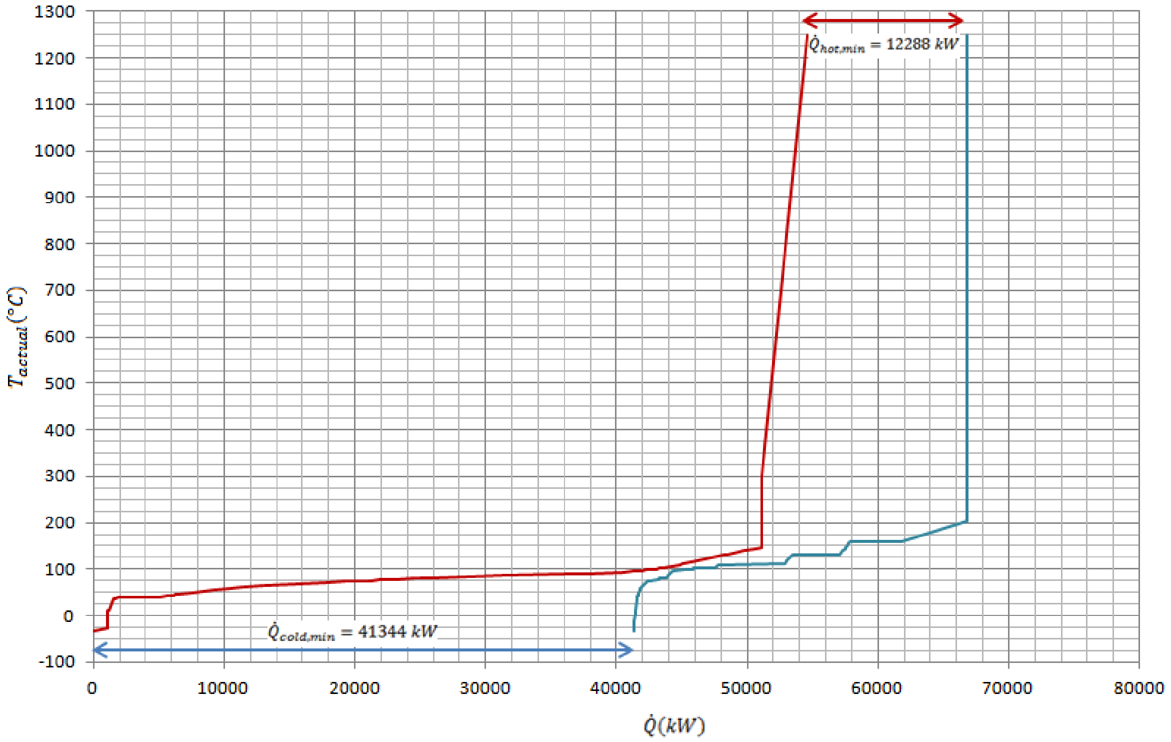

Figure 1. *Hot and cold composite curves.*

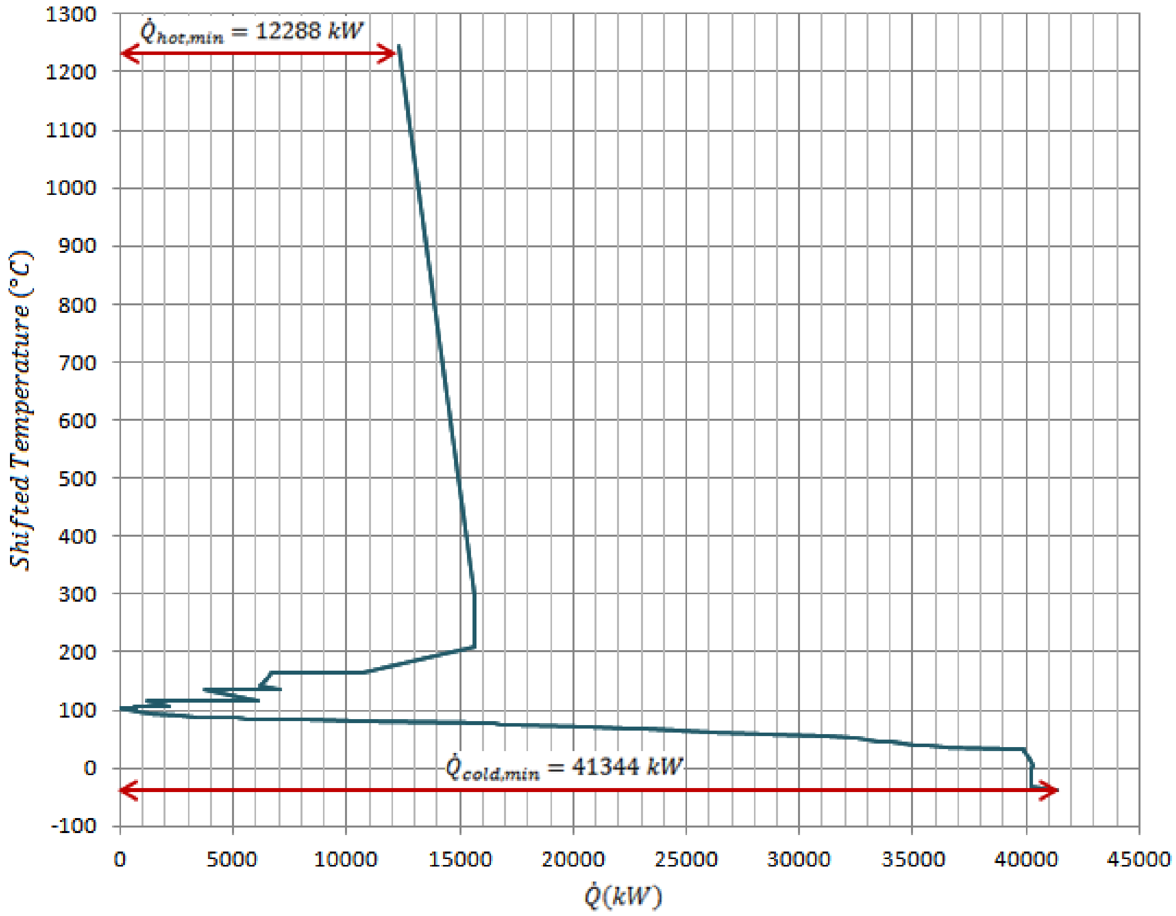

Figure 2. *Grand Composite Curve.*

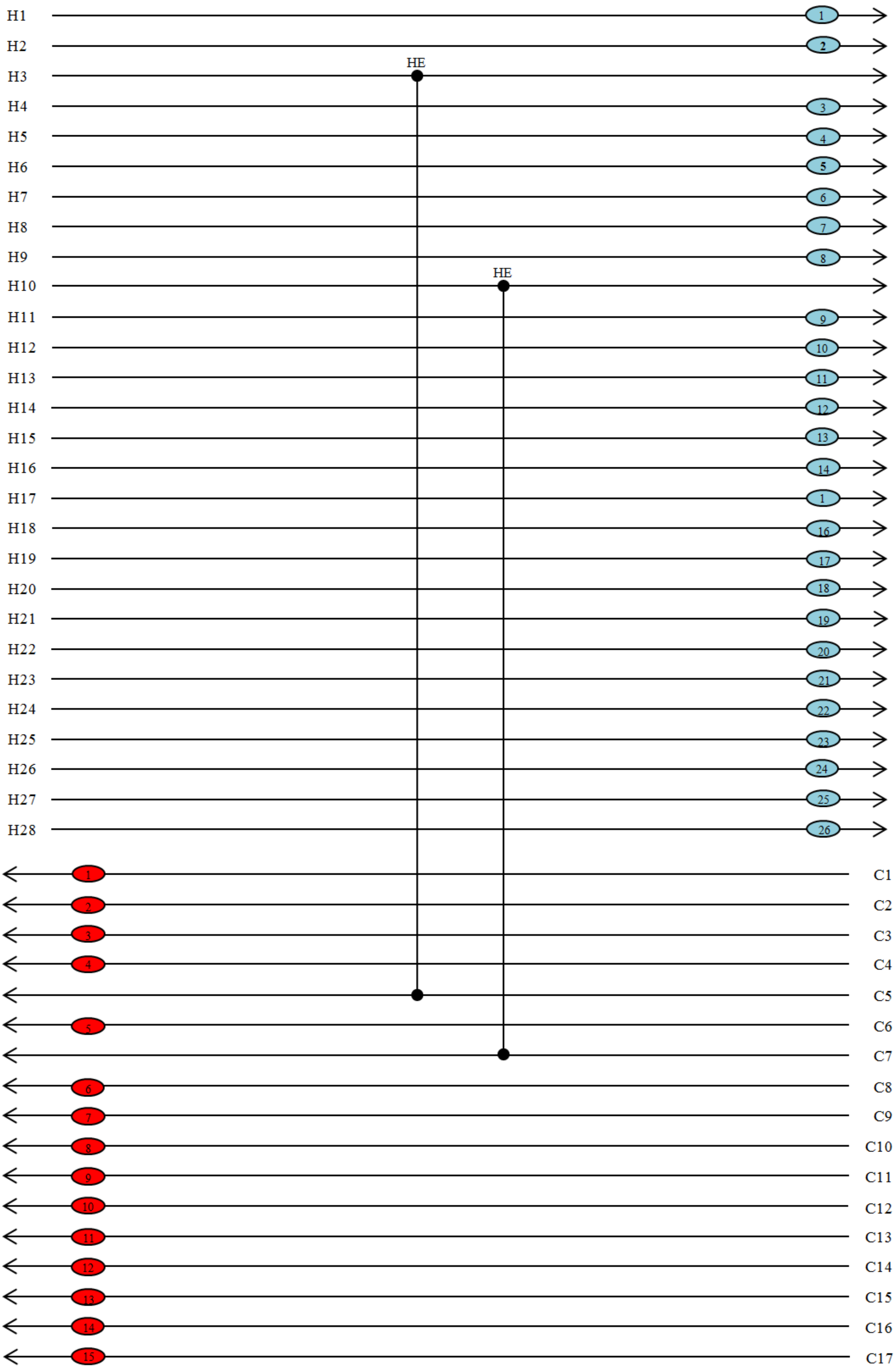

Figure 3. *Grid diagram of the existing process.*

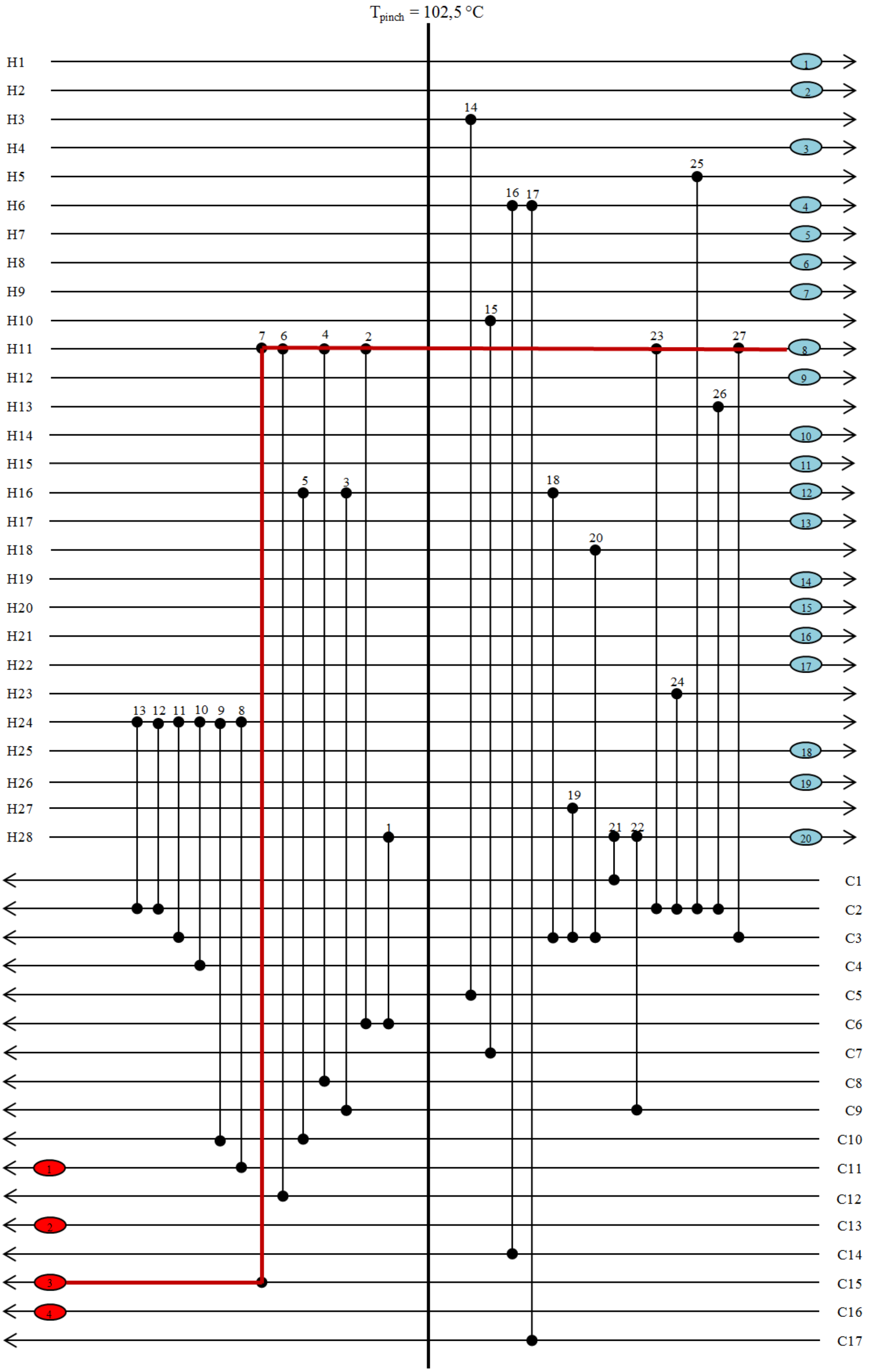

Figure 4. Grid diagram of Retrofit 1.

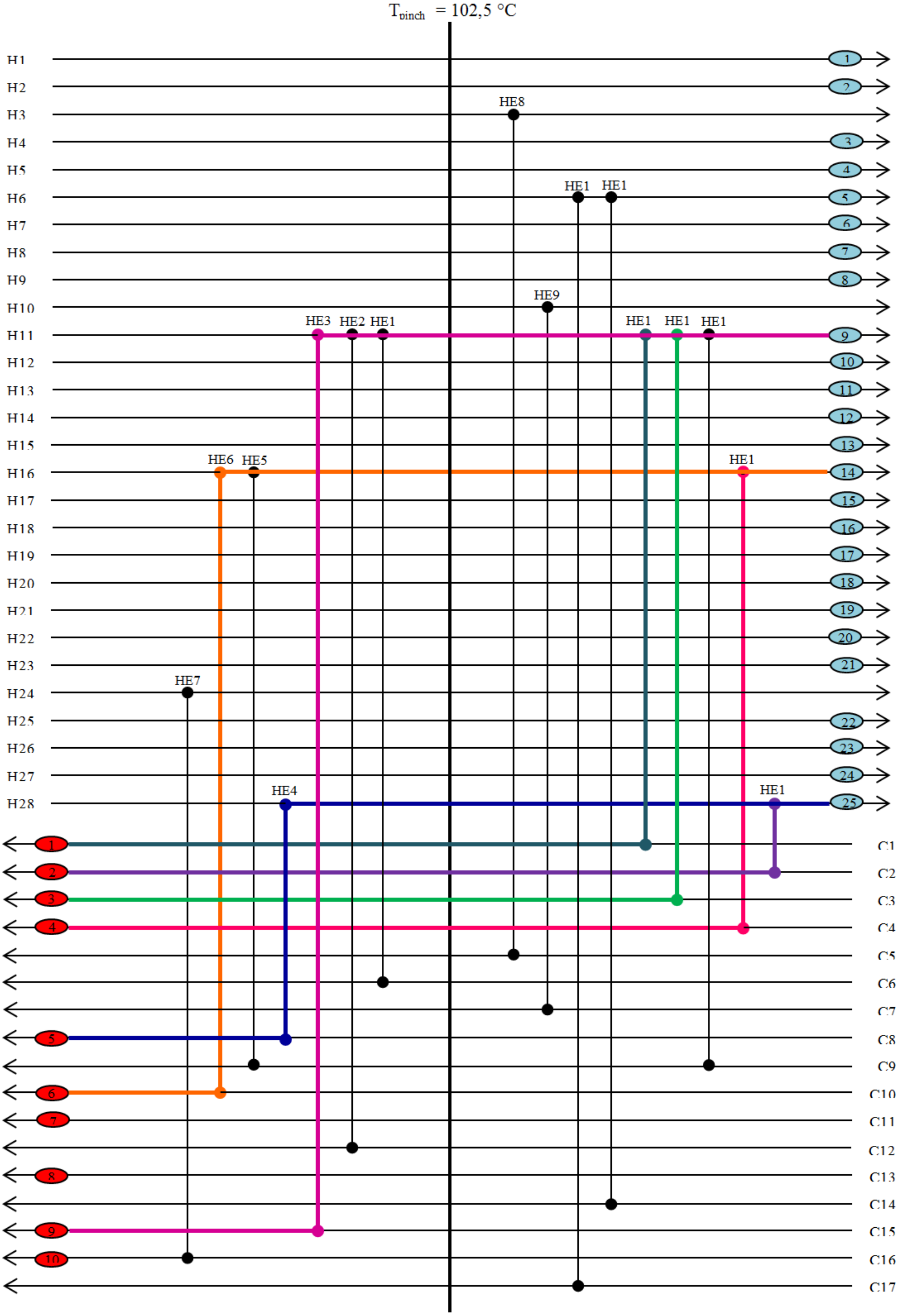

Figure 5. *Grid diagram of Retrofit 2.*

Table 4. *Temperature and heat load calculations of exchangers for Retrofit 1.*

	Heat Ex	**HOT**		**COLD**		**$\dot{Q}$(kW)**
		T_{in} (°C)	**T_{out} (°C)**	**T_{in} (°C)**	**T_{out} (°C)**	
ABOVE PINCH	1 [H28-C6]	116.9	107.5	97.5	97.88	327.3
	2 [H11-C6]	111.08	107.5	97.88	98.5	530.2
	3 [H16-C9]	119.22	107.5	97.5	103	112.7
	4 [H11-C8]	114.64	111.08	100	101	526.7
	5 [H16-C10]	156.4	119.22	103	118.94	357.9
	6 [H11-C12]	126.12	114.64	102	103	1699
	7 [H11-C15]	148	126.12	110	110.64	3237.3
	8 [H24-C11]	850.67	300	160	177.05	1973.68
	9 [H24-C10]	1109.9	850.67	118.94	160	921.5
	10 [H24-C4]	1144.07	1109.9	97.5	150	122.3
	11 [H24-C3]	1203.46	1144.07	97.5	150	212.6
	12 [H24-C2]	1241.7	1203.46	97.5	145	136.9
	13 [H24-C1]	1250	1241.7	97.5	140	29.7
BELOW PINCH	14 [H3-C5]	95	65	42	71	152.9
	15 [H10-C7]	100	80.5	62	78	110.6
	16 [H6-C14]	92.5	91.64	75.3	76.3	691.5
	17 [H6-C17]	91.64	91	79.9	80.9	507
	18 [H16-C3]	107.5	93.2	38.12	97.5	138.3
	19 [H27-C3]	45	40	26.96	38.12	26
	20 [H18-C3]	40	35	11	26.96	37.2
	21 [H28-C1]	107.5	106.35	40	97.5	40.1
	22 [H28-C9]	106.35	82.28	60	97.5	768
	23 [H11-C2]	107.5	106.16	28.62	97.5	197.7
	24 [H23-C2]	37	10	1.69	28.62	77.3
	25 [H5-C2]	45	5	-12	1.69	39.3
	26 [H13-C2]	85.4	-10.3	-28	-12	45.9
	27 [H11-C3]	106.16	105.13	60	97.5	151.6
					Q-recovered = 9934.1 kW	

Table 5. *Temperature and heat load calculations of exchangers for Retrofit 2.*

	Heat Ex	**HOT**		**COLD**		**$\dot{Q}$(kW)**
		T_{in} (°C)	**T_{out} (°C)**	**T_{in} (°C)**	**T_{out} (°C)**	
ABOVE PINCH	1 [H11-C6]	113.3	107.5	97.5	98.5	857.5
	2 [H11-C12]	124.78	113.3	102	103	1699
	3 [H11-C15]	148	124.78	110	110.679	3436.7
	4 [H28-C8]	116.9	107.5	100	100.62	327.3
	5 [H16-C9]	119.215	107.5	97.5	103	112.7
	6 [H16-C10]	156.4	119.215	103	118.942	357.9
	7 [H24-C16]	1250	300	130	130.978	3403.4
BELOW PINCH	8 [H3-C5]	97	65	42	71	152.9
	9 [H10-C7]	100	80.5	62	78	110.6
	10 [H6-C17]	92.5	91.87	79.9	80.9	507
	11 [H6-C14]	91.87	91	75.3	76.3	691.5
	12 [H11-C1]	107.5	107.23	40	97.5	40.1
	13 [H11-C3]	107.23	106.2	60	97.5	151.6
	14 [H11-C9]	106.2	101	60	97.5	768
	15 [H16-C4]	107.5	91.74	11	97.5	151.6
	16 [H28-C2]	107.5	97.15	-28	97.5	360.2
					Q-recovered = 8302.6kW	

Table 6. *Heat loads of utilities (heaters and coolers).*

Utility	**Heat Load (kW)**				
		Retrofit 1		**Retrofit 2**	
	Existing Process	**Before Network Relaxation**	**After Network Relaxation**	**Before Network Relaxation**	**After Network Relaxation**
Cooler 1	5138	5138	5138	5138	5138
Cooler 2	195.4	195.4	195.4	195.4	195.4
Cooler 3	330	330	330	330	330
Cooler 4	39.3	7639.5	7639.5	39.3	39.3
Cooler 5	8838	1559.7	1559.7	7639.5	7639.5
Cooler 6	1559.7	95.7	95.7	1559.7	1559.7
Cooler 7	95.7	321.7	321.7	95.7	95.7
Cooler 8	921.7	3720.6	6957.9	321.7	321.7
Cooler 9	10062.6	1993	1993	3110.2	6738.6

Utility	**Heat Load (kW)**				
		Retrofit 1		**Retrofit 2**	
	Existing Process	**Before Network Relaxation**	**After Network Relaxation**	**Before Network Relaxation**	**After Network Relaxation**
Cooler 10	1993	1137.9	1137.9	1993	1993
Cooler 11	45.9	646.6	646.6	45.9	45.9
Cooler 12	1137.9	318.7	318.7	1137.9	1137.9
Cooler 13	646.7	2937.7	2937.7	646.6	646.6
Cooler 14	927.6	346.2	346.2	255	814.4
Cooler 15	2937.7	3932.1	3932.1	2937.7	2937.7
Cooler 16	37.2	7437.2	7437.2	37.2	37.2
Cooler 17	346.2	740.5	740.	346.2	346.2
Cooler 18	3932.1	1127.1	1127.1	3932.1	3932.1
Cooler 19	7437.2	483.7	483.7	7437.2	7437.2
Cooler 20	740.5	1192.9	1192.9	740.5	740.5
Cooler 21	77.3			77.3	77.3
Cooler 22	3403.4			1127.1	1127.1
Cooler 23	1127.1			483.7	483.7
Cooler 24	483.7			26	26
Cooler 25	26			1640.8	2328.3
Cooler 26	2328.3				
$\dot{Q}_{cold,total}$ =	54208	41294	44531.3	41294	46169.3
Heater 1	69.8	3085.22	3085.22	29.7	69,8
Heater 2	497.1	3925.4	3925.4	136.9	497.1
Heater 3	364.2	1824.1	5061.4	212.6	364.2
Heater 4	323.8	3479.7	3479.7	122.3	323.8
Heater 5	857.5			199.4	526.7
Heater 6	526.7			921.5	1279.4
Heater 7	880.7			5059.1	5059.1
Heater 8	1279.4			3925.4	3925.4
Heater 9	5059.1			1624.7	5061.4
Heater 10	1699			76.3	76.3
Heater 11	3925.4				
Heater 12	691.5				
Heater 13	5061.4				
Heater 14	3479.7				
Heater 15	507				
$\dot{Q}_{hot,total}$ =	25217	12308	15551.7	12308	17183.3

First of all, the grid diagram of the existing process was drawn (Figure 3). In the existing process only two matching is done between the hot and cold process streams. So, only 270 kW heat is recovered. Then two alternative cases were presented. While composing the grid diagram, some rules were taken into consideration such as

Above pinch (hot end)	Below pinch (cold end)
$CP_{hot} \leq CP_{cold}$	$CP_{hot} \geq CP_{cold}$
$N_{hot} \leq N_{cold}$	$N_{hot} \geq N_{cold}$

During the construction of grid diagram, it is avoided using stream splitting. Because stream splitting requires extra pipework and valve, and the flow down each section of the split need to be controlled. Hence cyclic matching is preferred and a series of smaller heat exchangers are placed on a stream. In each match, temperatures around the exchangers are checked to see if they are thermodynamically feasible or not. Also violation of ΔT_{min} is avoided.

In the case of Retrofit 1, it is avoided using heaters and coolers with small heat loads. Instead, using more exchangers with smaller heat loads is preferred. The temperatures around exchangers and heat loads of heaters, coolers and exchanger are calculated. The minimum hot and cold utilities and loads of heat exchangers (hence the heat recovery) are found to be the same with the results obtained from cascade. Then Network Relaxation is done on VCM plant. One relaxation path is found on the grid diagram of Retrofit 1. One heat exchanger on the path is eliminated and its heat load is added to the heater and cooler at each side of the path. It is seen that the heat recovery is 9934.1 kW which is less than the value calculated from cascade algorithm (12288 kW).

In the case of Retrofit 2, it is tried to use heat exchangers with higher heat loads. Thus in Retrofit 2, the number of utilities (heaters and coolers) is increased while the number of exchangers is decreased. In this grid diagram, no loop exists but seven relaxation paths are found. This time seven heat exchangers on the paths are removed and their heat loads are added to the utilities. At the end, it is seen that the recovery of heat between process streams are 8302.6 kW which is smaller than the heat recovery calculated for the case of Retrofit 1.

The temperatures around exchangers and their heat loads are calculated both for Retrofit 1 and Retrofit 2 and the results are given in Table 4 and Table 5. The exchangers eliminated after network relaxation are shown in red color. So their heat loads are not taken into consideration in the calculation of heat recovery. Also the heat loads of utilities (coolers and heaters) for each cases are calculated and given in Table 6. The heat loads before and after network relaxation are given since after network relaxation the heat loads of some of the utilities are increased with the addition of heat loads of eliminated exchangers.

The comparison of existing process, Retrofit 1 and Retrofit 2 is given in Table 7. It seems that Retrofit 1 is better for higher energy recovery but there are more equipments. Since heat exchangers may cost so much, an optimization should be made between the cost of utilities (operating cost) and the cost of equipments (capital cost) in order to decide which case is better.

4. Conclusion

This study deals with the energy saving strategies in a real VCM plant by applying pinch method. It examines the existing process and introduces 2 alternative retrofit cases. Results obtained indicate that there is a remarkable improvement in energy usage:

According to the pinch analysis made before, the yield reduction is 0.5% for cold and 1.06% for hot utilities. Also the energy recovery is only 0.34%. But according to Retrofit 1, the reductions in cold and hot utilities are 18.26% and 38.98%, respectively. Also the energy recovery increases up to 12.51%. On the other hand, Retrofit 2 states that there is 15.25% saving of cold and 32.58% saving of hot utilities. Also, in Retrofit 2, the recovered energy is 10.45%.

If we compare the requirement for hot and cold utilities and recovered energy between the process streams, it seems that Retrofit 1 gives the best results. But as it seen from Table 7, the number of equipment in Retrofit 1 is 50 whereas it is 44 in Retrofit 2.

The best process can be chosen after making cost calculations since heat exchangers may cost so much. An optimization should be done between the cost of utilities (operating cost) and the cost of equipments (capital cost). Hence, as a further investigation the heat exchanger network can be optimized by comparing energy cost and the capital cost of the network so that the total annual cost is minimized.

Table 7. *Comparison of existing process and alternative cases.*

	Existing Process	Retrofit 1	Retrofit 2
Heat Loads			
$\dot{Q}_{c,min}(kW)$	54208	44531.3	46169.3
$\dot{Q}_{h,min}(kW)$	25217	15551.7	17183.3
$\dot{Q}_{recovered}(kW)$	270	9934.1	8302.6
Number of Equipments			
# Heat Exch.	2	26	9
# Heaters	15	4	10
# Coolers	26	20	25
U_{min}	43	50	44
Heat Loads			
Saving of Utilities (%)			
Cold	0.5	18.26	15.25
Hot	1.06	38.98	32.58
Total Heat Recovery (%)	0.34	12.51	10.45

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