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Full Length Research Paper

Application of combined pinch and exergy analysis in retrofit of an olefin plant for energy conservation

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In this paper, the modification of an olefin plant was performed and its refrigeration cycles were optimized using the exergy concept combined with a pinch-based approach. By the combined pinch and exergy analysis (CPEA), the present research corrected the temperature levels of the refrigeration cycles of an olefin plant to minimize exergy loss in the network and to economically and efficiently reduce shaft work demand and energy consumption in these cycles.The application results of CPEA in the olefin plant showed that its power consumption could be reduced by 2553 kW with a reasonable investment and payback period time.

Key words: Refrigeration cycle, temperature levels, exergy loss, energy conservation.

INTRODUCTION

Among the variety of methods used to optimize the energy consumption in process industries, pinch technology is known as a powerful methodology for thermodynamic analysis of chemical processes and their related energy sources (Ataei et al., 2009; 2010; Linnhoff, 1993; Linnhoff and Flower, 1978; Panjeshahi and Ataei, 2008; Yoo et al., 2010). An advantage of this technology is its ability to target shaft work, the power of systems that deal with heat energy and shaft power/work (e.g., refrigeration cycles or steam/gas turbine cycles) (Ataei and Yoo, 2010; Feng and Zhu, 1997). In addition to determination of the duty of the heat exchangers network in such systems, shaft work should be determined for refrigeration cycles as input or in steam/gas turbine cycles as output (Tahouni et al., 2010).

Developments in heat exchanger network design reached the highest peak when heat recovery determination using Pinch technology was discovered by Haung and Elshout (1976) and Umeda et al. (1978). However, pinch analysis foresees only the targets of the heat loads of heat exchanger networks through balancing mass and energy of central process in systems such as refrigeration cycles and gas/steam turbines. Exergy analysis is a very effective method for measuring the shaft work or power that is used (Kotas, 1995; Kwak, 2003). Thus a proper combination of pinch analysis and exergy analysis could be a practical and valuable solution to the problem of simultaneously measuring heat energy and shaft work in these systems; This technique is also known as combined pinch and exergy analysis (CPEA) (Ataei and Yoo, 2010).

Therefore, it is possible to determine the ideal targets of shaft works in refrigeration systems through balancing the mass and energy of the central process in a low-temperature process (Ataei et al., 2010, Tahouni et al., 2010; Smith, 2005).

This research intends mainly to present a solution to reduce energy and power consumption in olefin units of petrochemical industries in a manner that can correct temperature cycles of refrigeration in heat exchanger networks using CPEA to reduce the shaft work that is needed by these cycles. This reduction causes a decrease in steam consumption of the compressors, which results in a reduction in fuel consumption in these units' boilers.

CURRENT CONDITION

Refrigeration cycles have been devised to provide enough cold for cool units of olefin units. In these cool units, the compressors consume a considerable amount

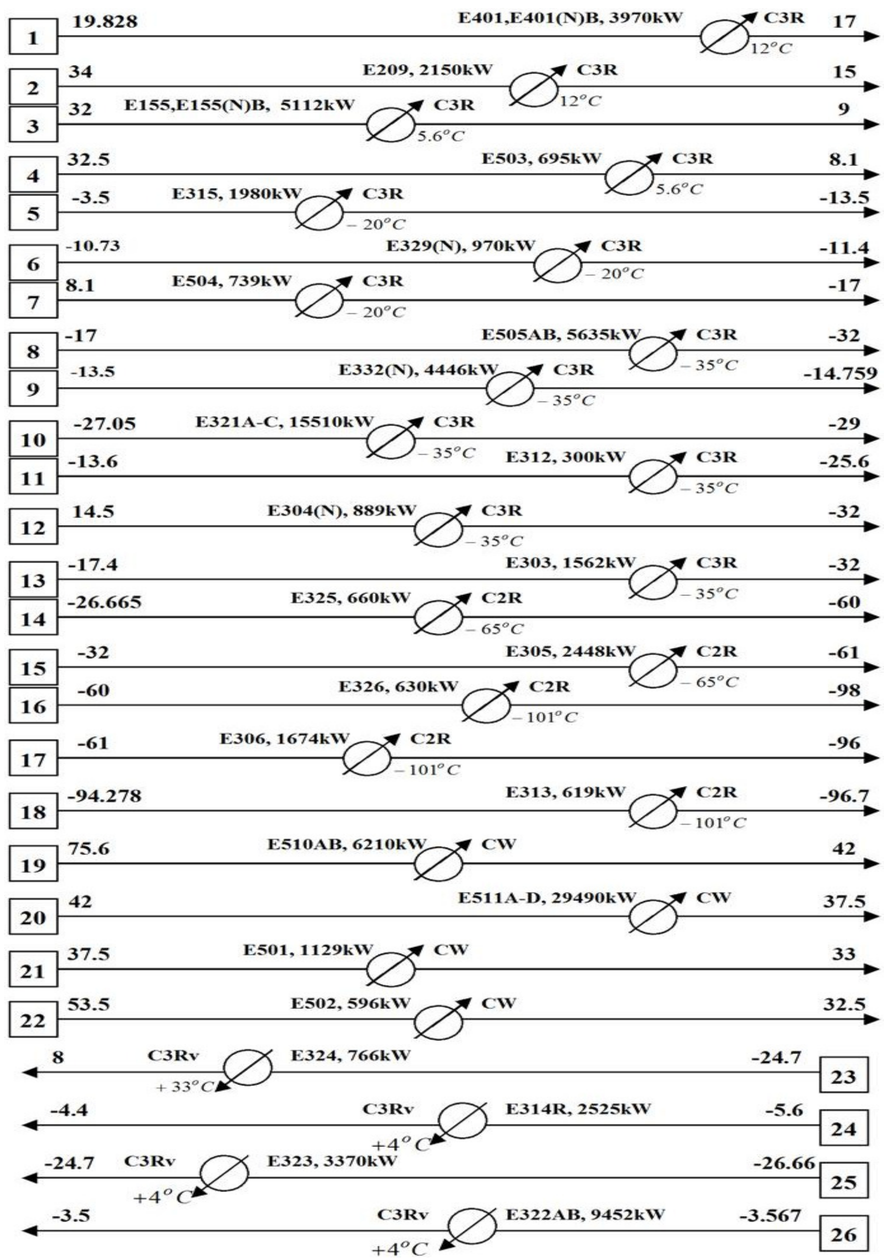

Figure 1. Diagram of the heat exchangers network of refrigeration cycles in the olefin plant.

of steam produced in these unit's boilers (Enweremadu et al., 2008). In a sample olefin plant used in this study, there are currently two refrigeration cycles of propylene and ethylene. The refrigeration cycle of propylene comprises three main temperature levels: 12, -20 and -35℃. There is also a secondary temperature level of 5.6℃. These four temperature levels cause cooling of the hot streams in 13 exchangers. In addition, the propylene steams in four heat exchangers heat the cold streams. After the compressor in the network, three other exchangers are operated to cool the propylene initially with cold water.

There are two temperature levels in the ethylene cycle: -65 and -110℃, which provide the cold needed for the hot streams in five exchangers. There are four exchangers on the path of ethylene coming out of the compressor that are used to reduce its temperature before transferring to the consumers. The ethylene is cooled by cold water in the first exchanger and by cold propylene in other three exchangers**.**

Figure 1 is a diagram of the system with the names of exchangers and temperatures in degree of Celsius. The figure also presents the streams with their numbers that have been described in Table 1.

Table 1. Stream data of the cooling network streams in the olefin p

No.	Stream name	Ts	Tt	ΔH (KW)	CP (KW/°C)	HTC(W/m^2°C)	ΔP (Bar)
1	Inlet to E401,E401(N)B	19.83	17.00	3970.00	1403.82	3087.13	0.60
2	Inlet to E209	34.00	15.00	2150.00	113.16	991.62	0.28
3	Inlet to E155,E155(N)B	32.00	9.00	5112.00	222.26	2156.63	0.50
4	Inlet to E503	32.50	8.10	695.00	28.48	1551.21	0.20
5	Inlet to E315	-3.50	-13.50	1980.00	198.00	1073.41	0.15
6	Inlet to E329(N)	10.73	-11.40	970.00	1447.76	1971.34	0.15
7	Inlet to E504	8.10	-17.00	739.00	29.44	1551.21	0.20
8	Inlet to E505A.B	-17.00	-32.00	5635.00	375.67	3631.63	0.20
9	Inlet to E332(N)	-13.50	-14.75	4446.00	3556.80	1021.39	0.15
10	Inlet to E321A-C	-27.05	-29.00	15510.00	7953.85	2912.05	0.20
11	Inlet to E312	-13.60	-25.60	300.00	25.00	1056.43	0.10
12	Inlet to E304(N)	14.50	-32.00	889.00	19.12	808.92	0.15
13	Inlet to E303	-17.40	-32.00	1562.00	106.99	1714.61	0.15
14	Inlet to E325	-26.67	-60.00	660.00	19.80	4387.81	0.70
15	Inlet to E305	-32.00	-61.00	2448.00	84.41	2176.03	0.15
16	Inlet to E326	-60.00	-98.00	630.00	16.58	3321.16	0.70
17	Inlet to E306	-61.00	-96.00	1674.00	47.83	1807.37	0.15
18	Inlet to E313	-94.28	-96.70	619.00	255.57	3280.64	0.20
19	Inlet to E510A.B	75.60	42.00	6210.00	184.82	1644.21	0.35
20	Inlet to E511A-D	42.00	37.50	29490.00	6553.33	2073.17	0.35
21	Inlet to E501	37.50	33.00	1129.00	3495.53	250.89	0.20
22	Inlet to E502	53.50	32.50	596.00	28.38	1551.21	0.50
23	Inlet to E324	-24.70	8.00	766.00	23.43	3495.53	0.60
24	Inlet to E314R	-5.60	-4.40	2525.00	2104.17	2066.24	0.10
25	Inlet to E323	-26.66	-24.70	3370.00	1719.39	1056.43	0.10
26	Inlet to E322A.B	-3.57	-3.50	9452.00	141074.63	1855.64	0.10

CORRECTING THE TEMPERATURE LEVELS

Since a refrigeration cycle is used to produce the coolness of shaft work, an ideal cycle is the one that has the least amount of shaft work consumption in the compressors (Enweremadu et al., 2008). However, because the correction of a system for energy recovery involves additional levels of heat network, the target comprises the following two steps: (a) For energy recovery and (b) For additional levels that could be installed in the network (Tahouni et al., 2010).

The exergy composite curves (ECC) and the exergy grand composite curves (EGCC) constitute the key instruments of coupling processes in the equatorial atmosphere (CPEA) (Ataei and Yoo, 2010). These curves can be drawn because the statistics determine 25°C as the ambient temperature. The composite curves (CC) (Linnhoff, 1993; Polley and Panjeshahi, 1991; Smith, 2005) of heat exchangers, the ECC and the EGCC are shown in Figures 2, 3 and 4, respectively. The positions of the cooling levels of the refrigeration cycles are also represented in Figure 4. It should be noted that cold water is here considered a cooling network whose temperature change is 25 to 30°C

In diagrams CC or ECC, it can be seen that there is no process-process exchanger in the existing network; so all the hot streams in the process are cooled only through cooling accessories, that is, ethylene and propylene coolers. In addition, the cold streams are heated by heating accessories including hot steams of propylene. The heat load relating to cold utility is totally equal to 87414 kW, from which 37425 kW are cooled by cold water, 43958 kW are cooled by propylene refrigeration cycle, and 6031 kW by ethylene refrigeration cycle.

In addition, the duty of heating accessories provided by propylene steams is equal to 16113 kW. It is noteworthy that, as it is shown in the diagram EGCC, the network needs only the cold utility; therefore, the corrected network does not need heating energy. Thus we can conclude that this network is a threshold problem from the top side of the composite curves.

As shown in Figures 4 and 5, it is evident that the curve that is related to 16113 kW is away from perpendicular axis (Carnot coefficient). This amount of load is the one that has been determined on the left side of the diagram. It can be transferred to the process streams and put in process-process exchangers. Also, this amount of curve distance to the Carnot coefficient is quite equal to the

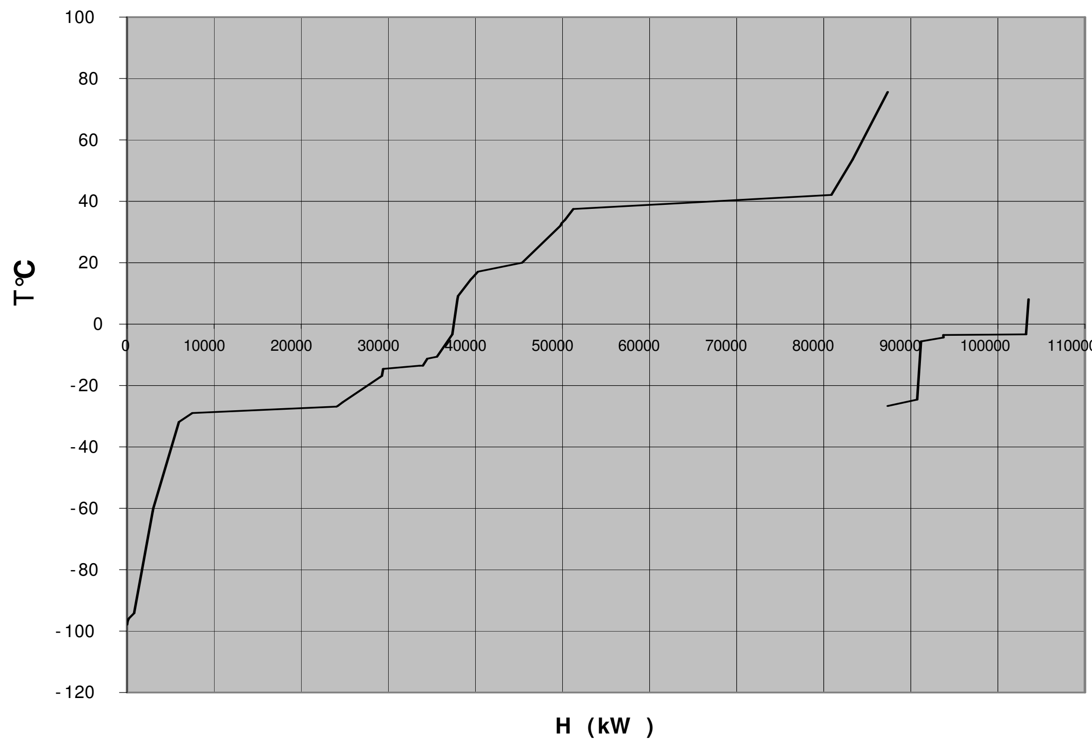

Figure 2. Composite curves (CC); the streams related to refrigeration cycles in the olefin plant.

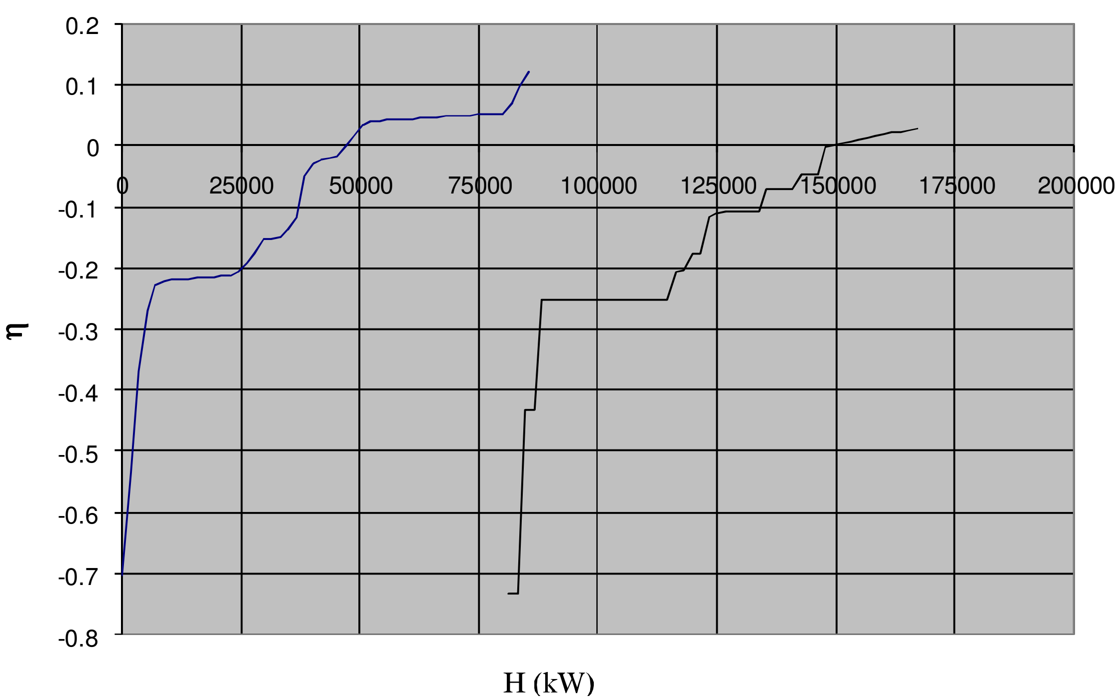

Figure 3. Exergy composite curves (ECC); the streams related to refrigeration cycles in the olefin plant.

total amount of heat load of cold streams.

After determining the temperature levels related to the utility services on the EGCC in Figure 4, and estimating of the amount of needed heat load, it is clear that the utility services needed by the system are equal to 71301 kW. This amount is related to the cold utility services,

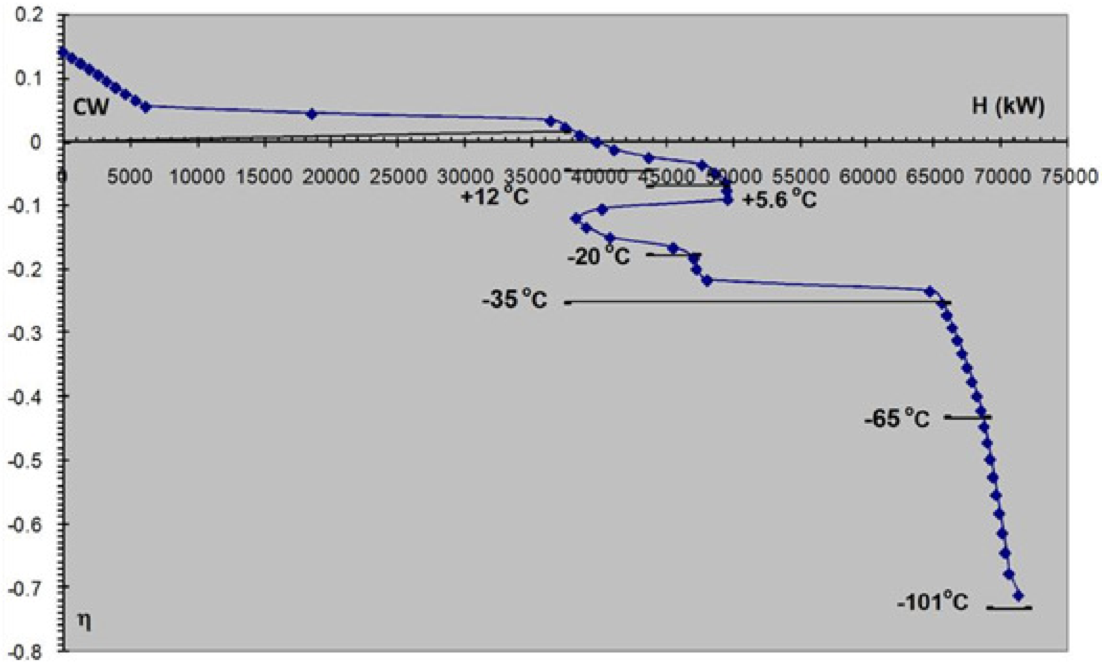

Figure 4. Exergy grand composite curves (EGCC) of refrigeration cycles in the olefin plant and representation of cooling levels in it

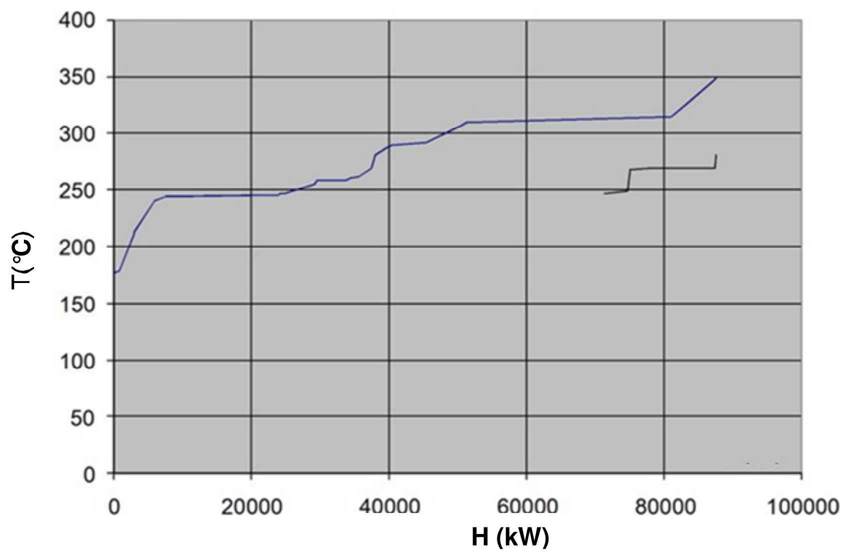

Figure 5. Corrected composite curves (CC) of streams in refrigeration cycles in the olefin plant.

which should be provided by cold water and refrigeration cycles of propylene and ethylene. Therefore, the amount of needed cold utility (87414 kW) is reduced by 16113 kW in the corrected system. In other words, we can say that all hot utilities can be eliminated, and the cold streams of the process together with the load of 16113 kW can form process-process exchangers with the hot process streams, and then start to exchange heat. This method, which is accompanied by a reduction in the cold utilities, results in a saving of 16113 kW in power consumption**.** EGCC shows that the shaft work needed by the system corresponds to the amount of recoverable heat, and therefore a considerable amount of shaft work will be saved in the system. The corrected CC is shown in Figure 5.

According to Figure 4, the primary refrigeration cooling level is +12°C and the secondary is +5.6°C. These two temperature levels are located on the EGCC where the

Table 2. Resuts obtained from computations of enthalpy changes and exergy loss in refrigeration cycles.'

Total hot utility consumption (kW)	16113
Total cold utility consumption (kW)	87414
Cooling by cooling water (kW)	37425
Cooling by propylene cycle (kW)	43958
Enthalpy change for level + 12°C (kW)	6120
Enthalpy change for level + 5.6°C (kW)	5807
Enthalpy change for level -20°C (kW)	3689
Enthalpy change for level -35°C (kW)	28342
Exergy change for level +12°C (kW)	279
Exergy change for level -20°C (kW)	656
Exergy change for level -35°C (kW)	7145
Total Exergy change in propylene cycle (kW)	8080
Exergy efficiency of Propylene cycle (%)	69.6
Cooling by ethylene cycle (kW)	6031
Enthalpy change for level -65°C (kW)	3108
Enthalpy change for level -101°C (kW)	2923
Exergy change for level -65°C (kW)	1345
Exergy change for level -101°C (kW)	2141
Total Exergy change in ethylene cycle (kW)	3486
Exergy efficiency of ethylene cycle (%)	93.6

cold and hot streams exchange heat using process-process heat exchangers. It is, therefore, essential to eliminate these two temperature levels to correct the refrigeration cycle of propylene.

Review of the existing temperature levels

Cooling streams undergo some changes in enthalpy and exergy in their relevant temperature levels of exchangers. These changes are due to heat exchange and change of phase indicating the reduced quality of energy or reduced energy potential. It is, therefore, essential first to determine the enthalpy change for each existing cooling level. It should be done for the exergy change as well.

Table 2 indicates the results of computations related to the exergy changes in each temperature level of the propylene and ethylene refrigeration cycles. It should be noted that the exergic efficiency of propylene and ethylene compressors of these two cycles, which are 11.6 and 72.3 MW, respectively, can be computed using Equation 1.

$$\eta_{ex} = \frac{\sum \Delta Ex}{W_{act}} \tag{1}$$

Setting targets of optimal cooling levels

Review of the cooling levels in the cycle easily shows that there are considerable temperature differences between processes, that is, between EGCC and temperature levels. This difference indicates σT_{oHEN} or exergy loss in the existing system. Therefore, the decreased amount of exergy loss or shaft work is directly proportional to the levels between cooling levels and EGCC. The most important correction is selecting an appropriate cooling level that has the least temperature difference in comparison with the central process.

As previously mentioned, the locations of the cooling levels, +12 and +5.6°C in the propylene cycle are precisely the same in the EGCC. Thus we can easily provide coolness and heat that are needed by process-process exchangers. In other words, by correcting the heat process-process exchanger network, there will be no need for these temperature levels in this refrigeration cycle. Therefore, these two temperature levels should be removed from the propylene refrigeration cycle. On the other hand, given the principle of reduction of σT_{oHEN} in the existing system, which is precisely proportional to the decreased levels of the EGCC and cooling levels, it seems that in the refrigeration cycle, the temperature levels of -35°C in the olefin unit should be changed to -34°C. Of course, the level of -20°C has an appropriate position and does not need to be changed.

It is noteworthy that the existing situation of streams that are still in the refrigeration cycles of the olefin unit is cooled by cooling water, and is maintained after correction of the network. For example, the streams that are in these networks are E502, E501, E511A-D, and E510A/B; they are cooled using cooling water. Regarding

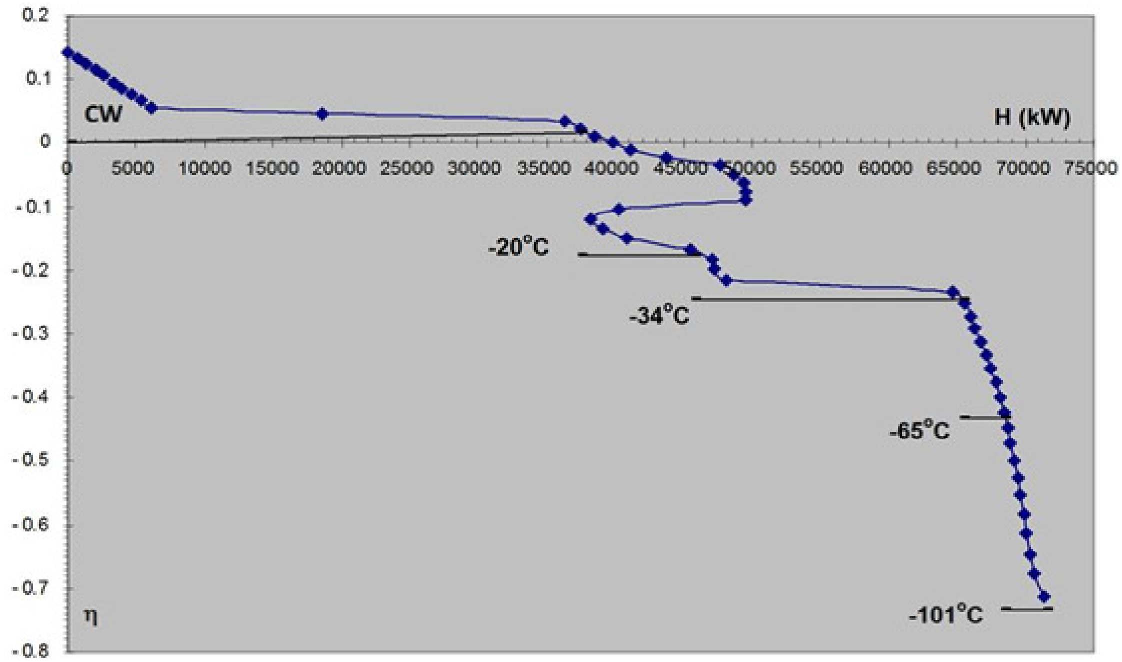

Figure 6. A representation of the optimal cooling level in EGCC diagram.

the ethylene cycle, we can observe that heat streams within the range of -26.665 to -98℃ are cooled by cooling levels of the cycle. This cycle has two cooling levels of -65 and -101℃ that are evident by observation. Considering the principle of reduction of σT_{oHEN}, they can access the minimal amount of loss, which makes shaft work possible. Therefore, the corrected network is suggested because no change will be made in the streams that are to be cooled by the cooling water. Figure 6 indicates corrected temperature levels on the EGCC.

According to Figure 6, temperature levels of the cooling water, of the ethylene cycle (-65 and -101℃), and the cooling amount do not change. In the propylene cycle, secondary level +5.6℃ and main level of +12℃ are eliminated; the level of -35℃ changes to -34℃, and the cooling level of -20℃ do not change. Thus, instead of temperature levels of +12, +5.6, -20 and -35℃ in the refrigeration cycle, we can suggest -20, and -34℃. Now we can estimate the amount of enthalpy change and exergy change at each suggested level.

Considering that the main objective here is to save shaft work that is needed by the system, first we must obtain $\Delta\sigma T_{oHEN}$ and then ΔW_{act}, which is the saving in shaft work that is needed by the propylene cycle.

$$\Delta(\sigma T_{oHEN}) = \sum \Delta Ex_1 - \sum \Delta Ex_2 \quad (2)$$

$$\Delta W_{act} = \frac{1}{\eta_{ex}}(\Delta(\sigma T_{oHEN})) \quad (3)$$

$\sum \Delta E\, x_1$ is the total exergy change in the existing propylene cycle and $\sum \Delta E\, x_2$ is the total exergy in the corrected propylene cycle.

Therefore, the amount of reduction in shaft work in the aforementioned system is equal to 2.553 MW. Given 140 $/kWyr as shaft work production price in the Olefin plant, by applying the aforementioned corrections in the propylene system, we can save 357420$ annually**.** Using Bath formula (Polley et al., 1990; Smith, 2005), we can find the minimal level (A_{min}) needed for correcting the propylene system.

$$A_{\min} = \sum_{i}^{\text{intervals}} \frac{1}{\Delta T_{lm,i}} \left[\sum_{j}^{\text{streams}} \left(\frac{Q}{h}\right)_j \right]_i = 1783 \ m^2 \quad (4)$$

Because there is no process heat exchanger in this network, at least 1783 m^2 is added to the heat levels. The amount of funds have been invested here are estimated to 349950$. Table 3 indicates the modification results of refrigeration cycles which are peculiar to the propylene cycle**.** New heat exchangers of the plant were design using the method presented by Cichelli and Brinn (1956) and the results are given in Table 4.

Network synthesis and applying corrected design

Using Pinch design method (PDM) (Polley et al., 1990; Smith, 2005), we can finally add 10 more heat exchangers that should be located in the plant as shown in Figure 7. It is noteworthy that Figure 7 includes only

Table 3. Modification results in refrigeration cycles of the olefin plant.

Total hot utility consumption (kW)	0
Total cold utility consumption (kW)	71301
Cooling by cooling water (kW)	37425
Cooling by ethylene cycle (kW)	6031
Enthalpy change for level -65°C (kW)	3108
Enthalpy change for level -101°C (kW)	2923
Exergy change for level -65°C (kW)	1345
Exergy change for level -101°C (kW)	2141
Total exergy change in ethylene cycle (kW)	3486
Exergy efficiency of ethylene cycle (%)	93.6
Exergy loss reduction in ethylene cycle (kW)	0
Shaft work saving in ethylene cycle (kW)	0
Cooling by propylene cycle (kW)	27845
Entalphy change for level -20°C (kW)	8285
Entalphy change for level -34°C (kW)	19560
Exergy change for level -20°C (kW)	1474
Exergy change for level -34°C (kW)	4829
Total Exergy change in propylene cycle (kW)	6303
Exergy efficiency of propylene cycle (%)	69.6
Exergy loss reduction in propylene cycle (kW)	1777
Shaft work saving in propylene cycle (kW)	2553
Total Saving ($/year)	357420
Additional heat exchanger area (m^2)	1783
Total investment ($)	349950
Simple payback time (year)	0.98

Table 4. Structure of new heat exchangers.

New heat exchanger	A	B	C	D	E	F	G	H	I	J
ΔP of tube (Bar)	2	55	27	50	20	2.807	10	1.01	10	2.168
ΔP of shell (Bar)	10	2	2	2	2	2.906	2	0.8855	57.69	18.73
Fluid quantity in shell (kg/h)	111770	360470	360470	360470	360470	38325	360470	38325	38325	38325
Fluid quantity in tube (kg/h)	40169	40169	104700	191110	55947	55947	55947	55947	13001	62651
Area (m^2)	117.8	55.66	119.9	210.1	21.55	109.3	10.77	122.6	858.2	157.5
Shells (ser.×par.)	1×1	1×1	1×1	1×1	1×1	1×1	1×1	1×1	1×1	1×1
Shell diameter (mm)	544.47	727.81	1056.49	703.64	462.42	737	334.42	838	1250	686
Total number of tubes	328	155	334	560	60	624	30	933	2390	635
Tube passes	1	1	2	4	2	1	1	1	1	1
Tube O.D. (mm)	19.05	19.05	19.05	19.05	19.05	19.05	19.05	19.05	19.05	19.05
Tube thickness (mm)	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11
Tube pitch (mm)	25.4	50	50	25.4	50	23.81	50	23.81	25.4	23.81
Tube length (mm)	6	6	6	6	6	2.926	6	2.195	6	4.145
Tube layout (DEG)	30	30	30	30	30	30	30	30	30	30
Baffle cut (%)	20	20	20	20	20	45	20	45	20	30
Nunber of baffles	7	7	7	7	7	3	7	3	7	17
Baffle spacing (mm)	800	800	800	800	800	736.6	800	623.2	800	240.3
Duty (KW)	2525	1445	2150	5112	636.8102	58.12	108.19	2599.7	707.88	770.299
Type	AEL	AEL	AEL	BEM	AEL	AEL	AEL	AEL	BEM	AEL

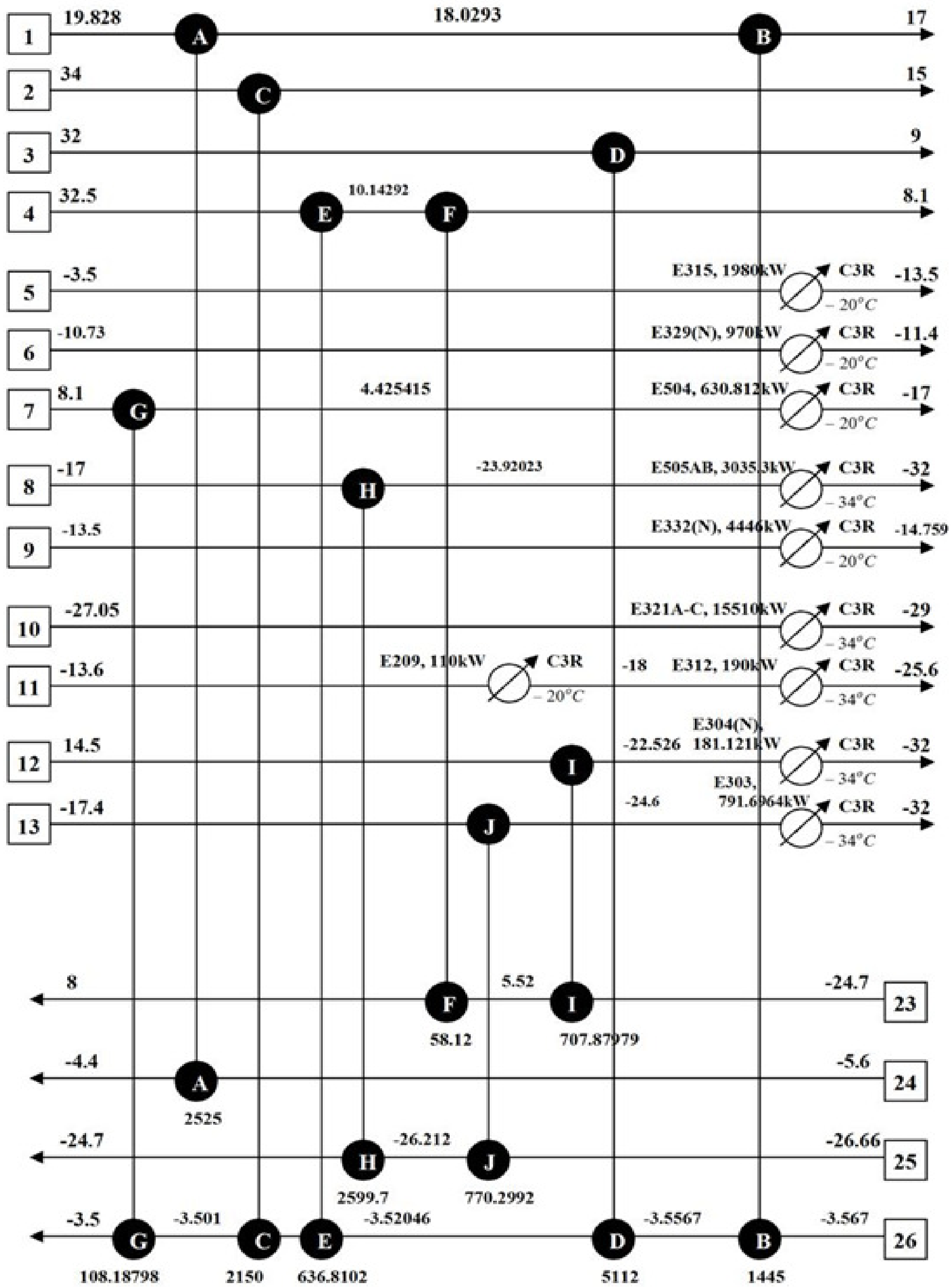

Figure 7. Diagram of the propylene cooling network after correction.

streams of propylene cycle, because only that refrigeration cycle was modified and the other streams that are cooled by the cooling water and ethylene cycle were not changed.

CONCLUSION

In project, the combined exergy and pinch analysis was used in a sample olefin plant to optimize cooling systems in a low temperature process. In order to minimize the amount of exergy loss in the process, we made some corrections to the refrigeration system.

The results showed that by application of CPEA in the illustrative olefin plant and changing the three temperature levels of only one of its refrigeration cycle, more than 2.5 MW power, equal to 357420$/year, can be saved. The total investment of the project to add 10 new heat exchangers was estimated by 350000$. Accordingly, the simple back time in this project is less than one year.

Nomenclature: **A_{min},** Minimum heat transfer area, m^2; **C2R,** cooling by ethylene refrigeration cycle; **C3R,** cooling by propylene refrigeration cycle; **CP,** heat capacity, kW/°C; **CW,** cooling by cooling water; **h,** heat transfer coefficient, $W/m^2°C$; **H,** enthalpy, kW; **HTC,** dirty heat transfer coefficient, $W/m^2°C$; Q, heat load, kW; T, temperature, °C; **T_s,** supply temperature, °C; **T_t,** target temperature, °C; **W_{act},** actual shaft work, kW;

Greek letters: **ΔH,** Enthalpy change, kW; **ΔP,** pressure drop, bar; **ΔT_{lm},** logarithmic temperature difference, °C; **$\Delta\sigma T_{oHEN}$,** change in exergy loss, kW; $\sum \Delta Ex$, total exergy change, kW; **σT_{oHEN},** exergy loss, kW; **η,** Carnot factor; **η_{ex},** exergetic efficiency, %.

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