Heat and Power Optimization in Ammonia Plant

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Abstract

Retrofit study of process industries, for improving energy efficiency, requires methods and tools to understand interactions between the core process and utility system. In this paper, Pinch and Exergy Analyses, as a well-established conceptual method, has been applied to an existing ammonia plant, in order to reduce energy consumption of the process and consequently improve its efficiency.

As a common practice, one can divide ammonia plant into two parts, the hot-end and the cold-end. In this paper, hot section of an existing ammonia plant has been studied in details, using Pinch Analysis, and the cold section has been rechecked by the application of Combined Pinch & Exergy Analysis.

In hot section, two different options are investigated that both lead to a threshold condition and achieve maximum energy saving. The first option covers only process-to-process energy integration, while the second option considers some modification in the convection section of the primary reformer through a new arrangement of the heating coils. Thus, a considerable reduction in cooling water, HP steam and fuel gas consumption is achieved.

In cold section, retrofit study is dominated by reducing the amount of shaft work or power consumption in the refrigeration system. Exergy consumption of ammonia plant depends strongly on the design of Ammonia Synthesis Loop. Due to the thermodynamically limited degree of conversion of hydrogen-nitrogen mixture to ammonia, industrial practice for ammonia synthesis is to recycle significant quantity of reactants back to the reactor after the removal of ammonia at low temperature. This is called "Ammonia Synthesis Loop". Application of the Combined Pinch & Exergy Analysis revealed that part of the shaft work, which was originally being used, was inefficient and could have been avoided in a well integrated design. Therefore, by optimizing the refrigeration levels, reasonable saving (15%) in power consumption was observed without a need for new investment.

1 Introduction

Ammonia production is an energy intensive process, so the recovery of relatively small quantities of heat can accumulate to become sizeable energy savings .The energy intensive nature of the process is the key driving force for improving the technology and reducing the overall cost of manufacturing. Hence, any attempt for energy conservation in the process goes a long way in many aspects .In recent years, some potentially significant developments and concepts have been done that may impact the manner in which ammonia is produced. Some of these manufacturing routes are being tested or employed at a few plants around the world, but have yet to be fully developed into commercial processes. This includes reformer combustion air preheat, control of steam to carbon ratio [1], hydrogen recovery from purge gas, improved CO2 removal system [2, 3] and co-generation [4, 5]. Other attempts include optimization [6], advanced control [7], improved catalysts [8] and heat integration [9, 10].

The design and retrofit of energy efficient process plants require tools that enhance the engineers understanding of the complex interactions between process plants and utility systems and point to potential solutions. There are two schools of systematic design methods, one relying on graphical diagrams and thermodynamic concept; and another approach based on the use of mathematical modeling and subsequent optimization.

Pinch Technology [11, 12, 13] as an example of first school, is a methodology, comprising a set of structured techniques, for systematic application of the first and second laws of thermodynamics. The application of these techniques enables process engineers to gain fundamental insight into the thermal interactions between chemical processes and the utility systems that surround them. Such knowledge facilitates optimizing the overall utility consumption and setting process and utility system configurations prior to final detailed simulation and optimization.

Exergy analysis [14, 15] as another example of first school, helps us to identify the inefficiency in the processes, so the engineers can point out the cause and magnitude of exergy loss in each process unit. Exergy based methodologies, however, lack the simple representations have made Pinch Analysis well recognized and applied in the process industries.

Optimization methodologies enable the engineer to address the multiple and complex trade-offs that are an integral part of energy integration which would not be possible to solve manually.

The ammonia plant analyzed in this work can be divided into two parts, the hot-end and the cold-end. The hot-end consists of all plant sections that involve in preparing the gases needed for the ammonia reaction such as: Desulphurization, Primary Reforming, Secondary Reforming, Shift Conversion, Co2 Removal and Methanation. The cold-end section is mainly the Ammonia Synthesis and Refrigeration Cycles. Using Pinch Analysis for detail study of hot section and the cold section has been rechecked by the application of Combined Pinch & Exergy Analysis.

2 Threshold Problems

As mentioned previously, Pinch Analysis is a thermodynamic approach to energy integration based on simple, powerful, graphical representations; several tools including, Driving Force plot (DFP), Composite Curve (CC), Grand Composite Curve (GCC) were adapted in the diagnosis of process energy-utilizing. In Composite Curve, the minimum vertical distance between hot and cold curves represents the minimum approach temperature for thermal exchanges, $\Delta T_{\min}$.This point of minimum temperature difference, for heat exchanges in the process, represents the critical point of the heat recovery and is called pinch point. The pinch point divides the process in two different thermodynamic regions, above and below the pinch point. Nevertheless, not all thermal systems have these properties. There are thermal systems that reach a point in which one of the thermal utilities reduces to zero when the $\Delta T_{\min}$ value diminishes by moving the hot and cold composite curves on the horizontal axis. The $\Delta T_{\min}$ value at which this happens is known as the ''$\Delta T_{Threshold}$''.

2.1 Definition of Cold P.H. & Hot P.H.

It can be seen that in the composite curves of Fig. 1 that three zones exist: the heating zone in the extreme right of the curves, the exchange zone, where they overlap, and the cooling zone in the extreme left of the curves. In the threshold problems, the hot composite curve, for example, has such a thermal load that from $\Delta T_{Threshold}$ approach value it stays completely inside the cold composite curve, resulting with only two zones, one of heating and one of overlap, the point that divides the composite curve in two zones is called Hot P.H. (Fig. 2). The same thing can happen when the cold curve is inside the hot curve resulting only in one zone of cooling and one of overlap. So the point that divides the composite curve into these two zones is called Cold P.H. (Fig. 3).

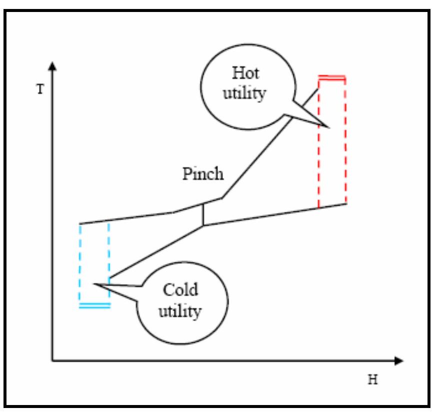


Fig.1: Composite curve

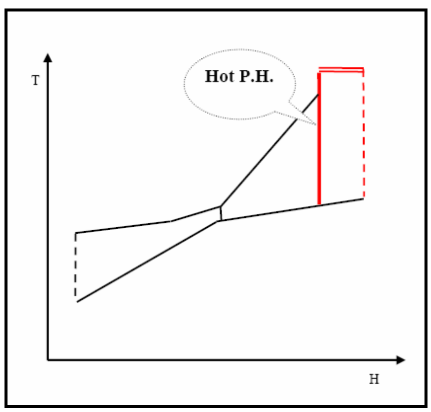


Fig.2: Hot P.H.

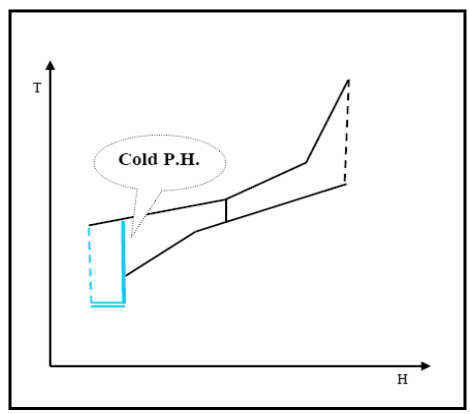


Fig.3: Cold P.H.

3 Ammonia Plant

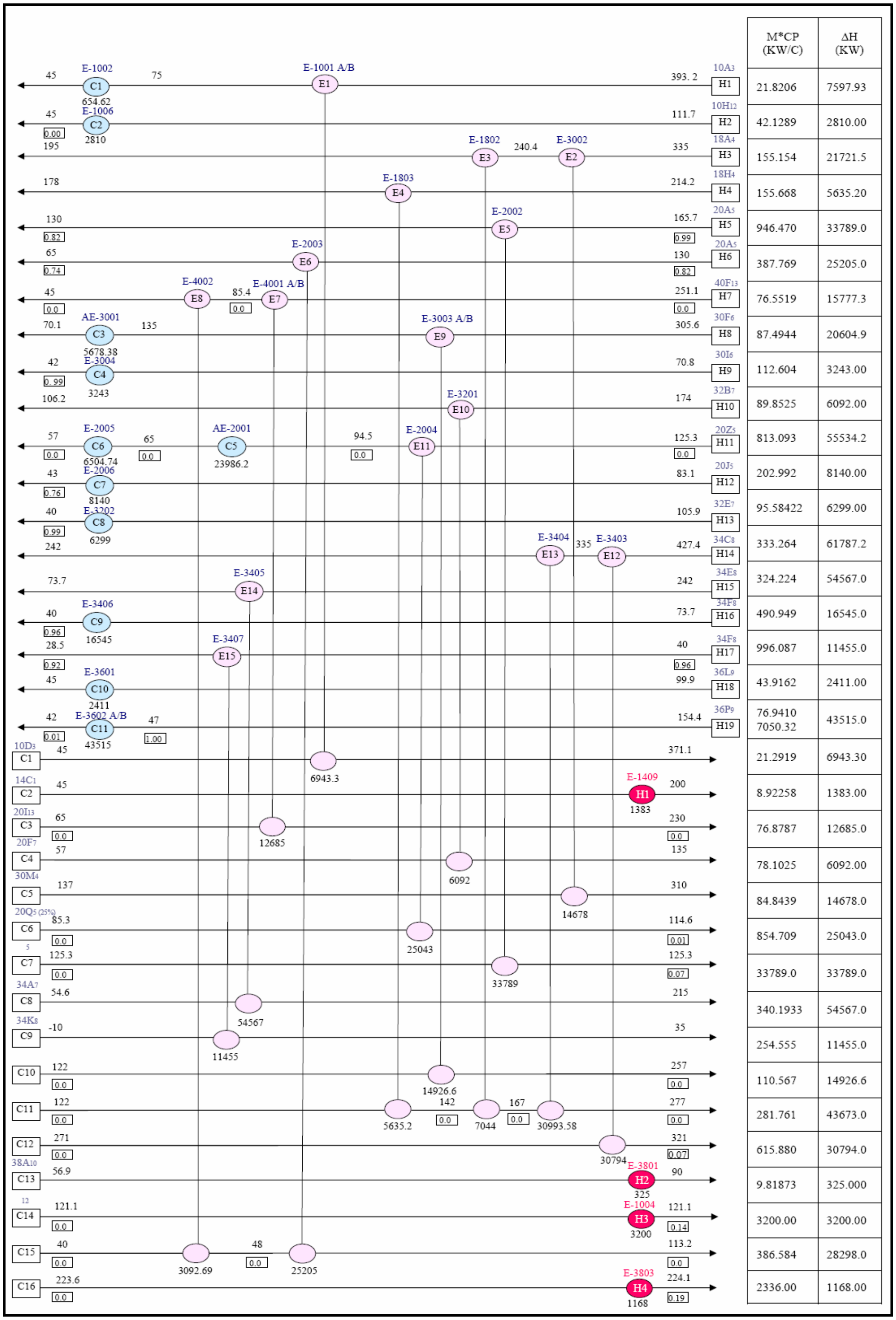
The Ammonia process scheme is a convectional arrangement of desulfurization, primary and secondary reforming, two stage CO shift, CO2 removal, methanation, NH3 synthesis and refrigeration cycle. The feedstocks for ammonia production are natural gas, steam and air and the major process waste stream is carbon dioxide.

4 Hot section

4.1 Data extraction

The process requires close attention to obtain proper data for analysis. The required data consists of physical properties, source and target temperatures, heat transfer coefficient, pressure drops, fouling coefficient, flowrates and enthalpies of cold and hot process streams. These data are taken from the process flowsheet except heat transfer coefficient for the two phase streams which has been obtained from the process flowsheet simulated using HTFS software.

Fig. 4 shows a grid representation of the existing HEN proposed for the hot section of ammonia plant and their thermodynamic data consist of thermal load (ΔH) and $m \times c_p$ (kW/°C). Stream data extracted for the current case study consists of 19 hot streams that require cooling and 16 cold streams to be heated. The grid diagram includes 15 heat exchangers, 11 coolers using cooling water, sea water, air coolers and 4 heaters using H.P. and L.P. steam. The existing process requires a total hot utility load of 6076 kW, and a total cold utility of 119786.2 kW.



	M*CP (KW/C)	ΔH (KW)
H1	21.8206	7597.93
H2	42.1289	2810.00
H3	155.154	21721.5
H4	155.668	5635.20
H5	946.470	33789.0
H6	387.769	25205.0
H7	76.5519	15777.3
H8	87.4944	20604.9
H9	112.604	3243.00
H10	89.8525	6092.00
H11	813.093	55534.2
H12	202.992	8140.00
H13	95.58422	6299.00
H14	333.264	61787.2
H15	324.224	54567.0
H16	490.949	16545.0
H17	996.087	11455.0
H18	43.9162	2411.00
H19	76.9410 7050.32	43515.0
C1	21.2919	6943.30
C2	8.92258	1383.00
C3	76.8787	12685.0
C4	78.1025	6092.00
C5	84.8439	14678.0
C6	854.709	25043.0
C7	33789.0	33789.0
C8	340.1933	54567.0
C9	254.555	11455.0
C10	110.567	14926.6
C11	281.761	43673.0
C12	615.880	30794.0
C13	9.81873	325.000
C14	3200.00	3200.00
C15	386.584	28298.0
C16	2336.00	1168.00

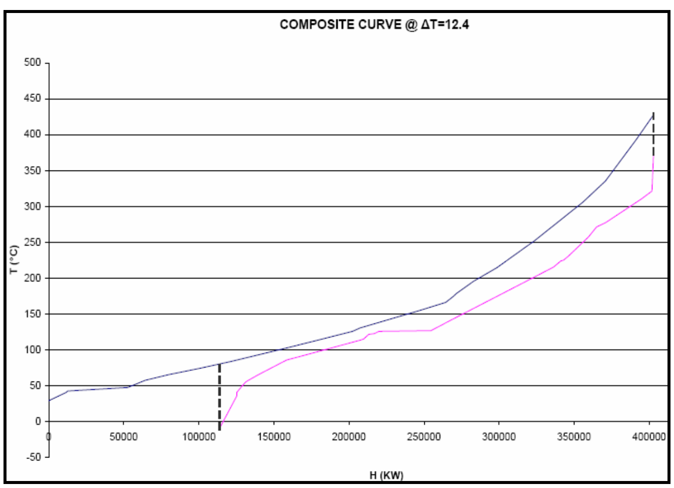
Fig.4: Grid diagram of the existing HEN proposed for the hot section

4.2 First retrofitted proposal for the HEN of the hot section

4.2.1 Minimum utility requirement

By considering the Range Targeting result, the minimum temperature approach used in this analysis is 12.4 °C which leads to a threshold condition and achieves maximum energy saving. Accordingly, the Composite Curve and Grand Composite Curve of the process are obtained, as shown in Figs. 5 and 6. Minimum hot and cold utility requirements (ΔH_h and ΔH_c) are found to be 0 and 113710.2 kW respectively.

Inasmuch as hot utility equals zero, Cold P.H. divides the composite curve into two zones, one zone of cooling and one of overlap. The Cold P.H. position which corresponds to $\Delta T_{Threshold} = 12.4$ is found at 79.75 °C on the hot composite curve and at -10 °C on the cold composite curve. Fig. 7 shows the heat exchangers that transfer heat across Cold P.H. . The grid diagram confirms that exchangers E1, E6, E8, E14 and E15 transfer heat from below Cold P.H. to above of this point; while, coolers C2, C3, C5, C7, C8, C10 and C11 are settle in the overlap zone (above the Cold P.H.). Table 1 proposed net heat transfers across Cold P.H. which the result is the same as the existing hot utility or in other words, the same as proposed target for reducing energy utilization.



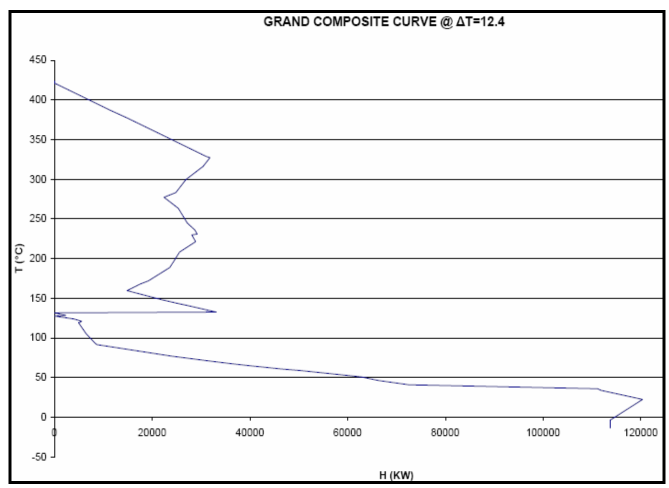
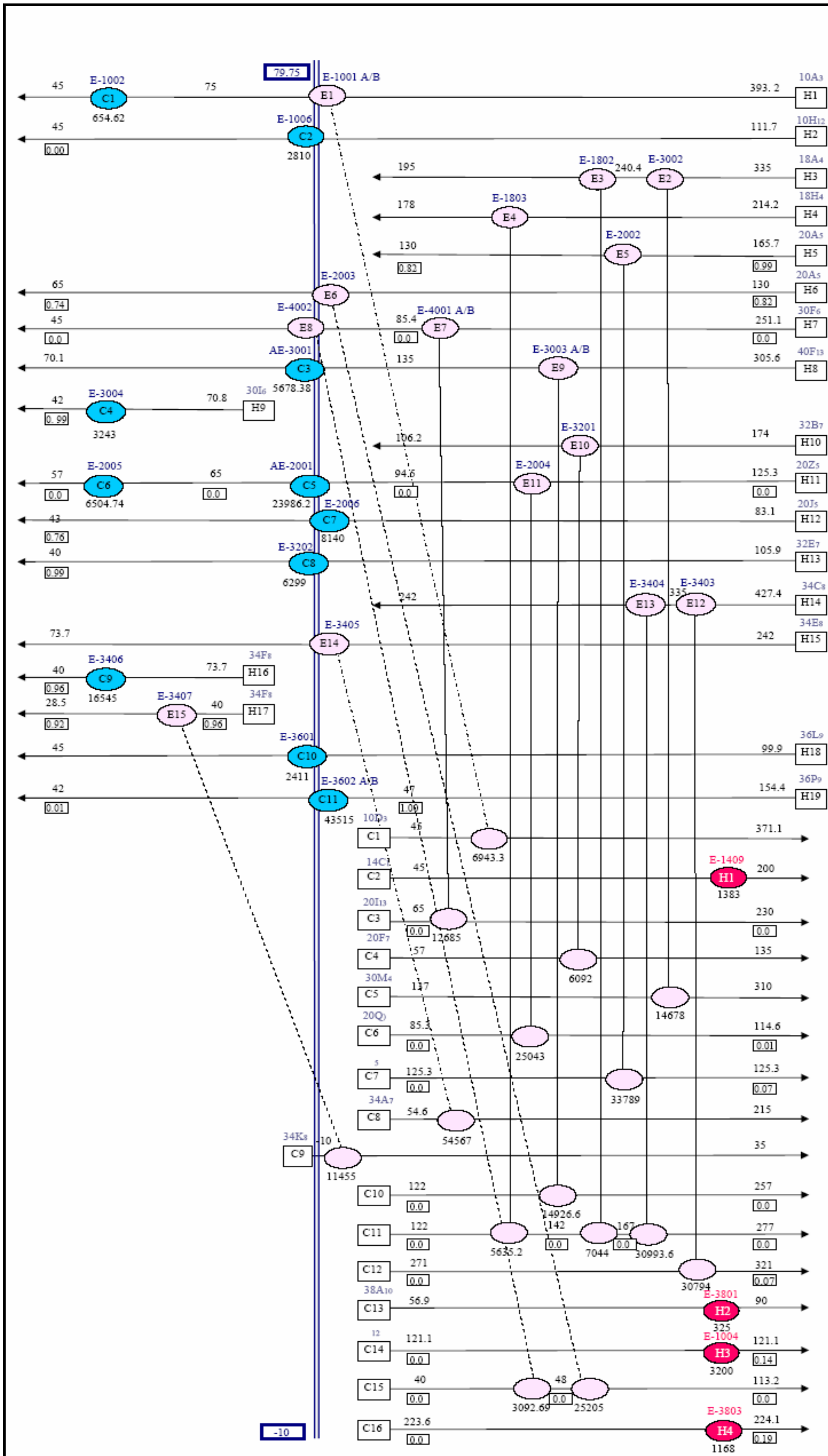


Fig.5: CC of the first retrofitted proposal

Fig. 6: GCC of the first retrofitted proposal



M*CP (KW/C)	ΔH (KW)
21.8206	7597.93
42.1289	2810.00
155.154	21721.5
155.668	5635.20
946.470	33789.0
387.769	25205.0
76.5519	15777.3
87.4944	20604.9
112.604	3243.00
89.8525	6092.00
813.093	55534.2
202.992	8140.00
95.58422	6299.00
333.264	61787.2
324.224	54567.0
490.949	16545.0
996.087	11455.0
43.9162	2411.00
76.9410 7050.32	43515.0
21.2919	6943.30
8.92258	1383.00
76.8787	12685.0
78.1025	6092.00
84.8439	14678.0
854.709	25043.0
33789.0	33789.0
340.1933	54567.0
254.555	11455.0
110.567	14926.6
281.761	43673.0
615.880	30794.0
9.81873	325.000
3200.00	3200.00
386.584	28298.0
2336.00	1168.00

Fig. 7: Grid diagram of existing HEN corresponds to Cold P.H.

Table 1: Summery of Cold P.H. violation at $\Delta T_{Threshold} = 12.4$

Heat exchanger	Heat flow across Cold P.H.(kw)	Result (kw)
E1	21.820 × (79.75 - 75)	-103.7014
E6	387.76 × (79.75 - 65)	-5720.548
E8	76.551 × (79.75 - 45)	-2660.366
E14	324.22 × (79.75 - 73.7)	-1962.354
E15	996.08 × (28.5 - 40)	-11455.00
C2	42.128 × (111.7 - 79.75)	1345.915
C3	87.494 × (135 - 79.75)	4833.850
C5	813.09 × (94.5 - 79.75)	11991.12
C7	202.99 × (83.1 - 79.75)	679.5265
C8	95.584 × (105.9 - 79.75)	2499.2926
C10	43.916 × (99.9 - 79.75)	884.8038
C11	76.941 × (154.4 - 79.75)	5743.456
TOTAL		6076.0

The reduction of the hot utility is equivalent to 4460 kg/h of HP steam which decreased the fuel gas consumption in the boiler and also 5910 kg/h reduction of LP steam has been reached, that indirectly effects the fuel gas consumption by increasing the enthalpy of BFW in the cycle. On the other hand reduction of 446.319 T/h of cooling water and 562.222 T/h of sea water of cold utility has been reported. The remaining questions are whether this claimed benefit is practically applicable and which streams should be modified. To answer these questions we should follow the threshold problem's steps

4.2.2 Diagnosis stage

In the diagnosis stage, searches for topology changes, which increase energy saving ,are carried out. The searches for potential topology changes are sequential, and require user interaction to asses the modification. At each step resequencing is considered first, followed by the additional of a new heat exchanger.

1. By moving E14 to the left, the heat interval on the hot stream H15 is released before getting imported into the heat exchanger. It cause considerable heat recovery by reasonable matches between the hot stream (H15) and cold streams (C2, C16 and split of C14) , thus 4141 kW reduction in duty of cooler C9 is obtained.
    - ✓ To eliminate the heater H4 from cold stream C16, exchanger D have been proposed which reduce the temperature of hot stream H15 down to 238.4 °C.
    - ✓ Hot stream H15 is cooled from 238.4 °C to 233.4 °C through heat exchanger C2.
    - ✓ Cold stream C2 is completely heated by a thin split of hot stream H15 via exchanger A.

By analyzing and rating the shifted heat exchanger E14, it is noticed that its heat transfer area should be increased to accommodate new thermal position, this results adding new shell to it, called E14A.

Here we should mention that one stream passes through E14 and Cooler C9, but because the stream phase changes in cooler C9 and large difference in $m.c_p$ have been reported; we separate H15 and H16 in grid diagram

2. By decreasing 1934 kW from the load of cooler C11, makes it possible to omit remained heaters from two cold streams C13, a split of C14 and replace them by new process heat exchangers, B and C1.

Driving Force Plot of new exchangers is illustrated in Fig. 8. Respect to the fact that cold streams C14 and C16 just had phase change in heat exchangers C1, C2 and D (without changes in their temperatures), therefore driving force plot is not an appropriate tool to evaluate these heat exchangers. Hence new matches have been checked by remaining problem analysis, and the results are shown in table 2. Fig. 9 clarifies the representation of retrofitted proposal in grid diagram.

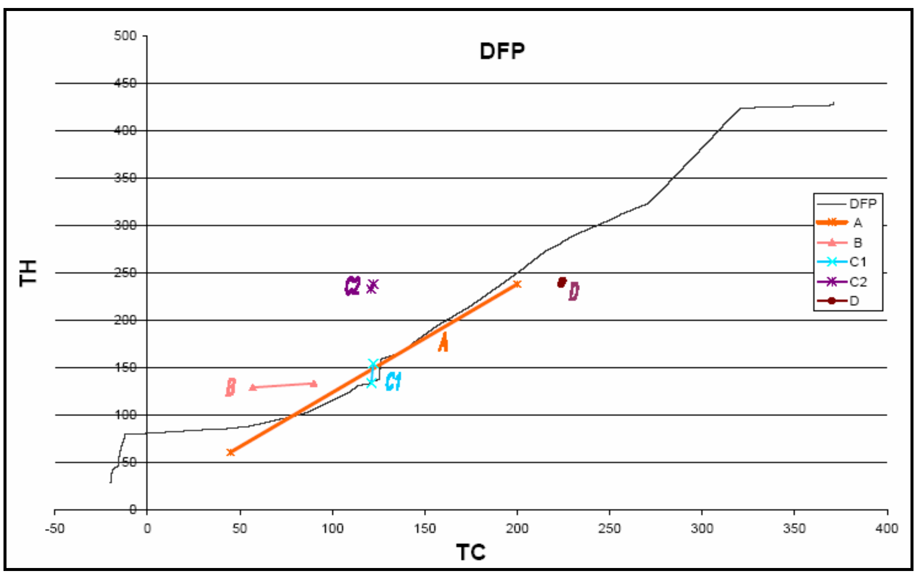
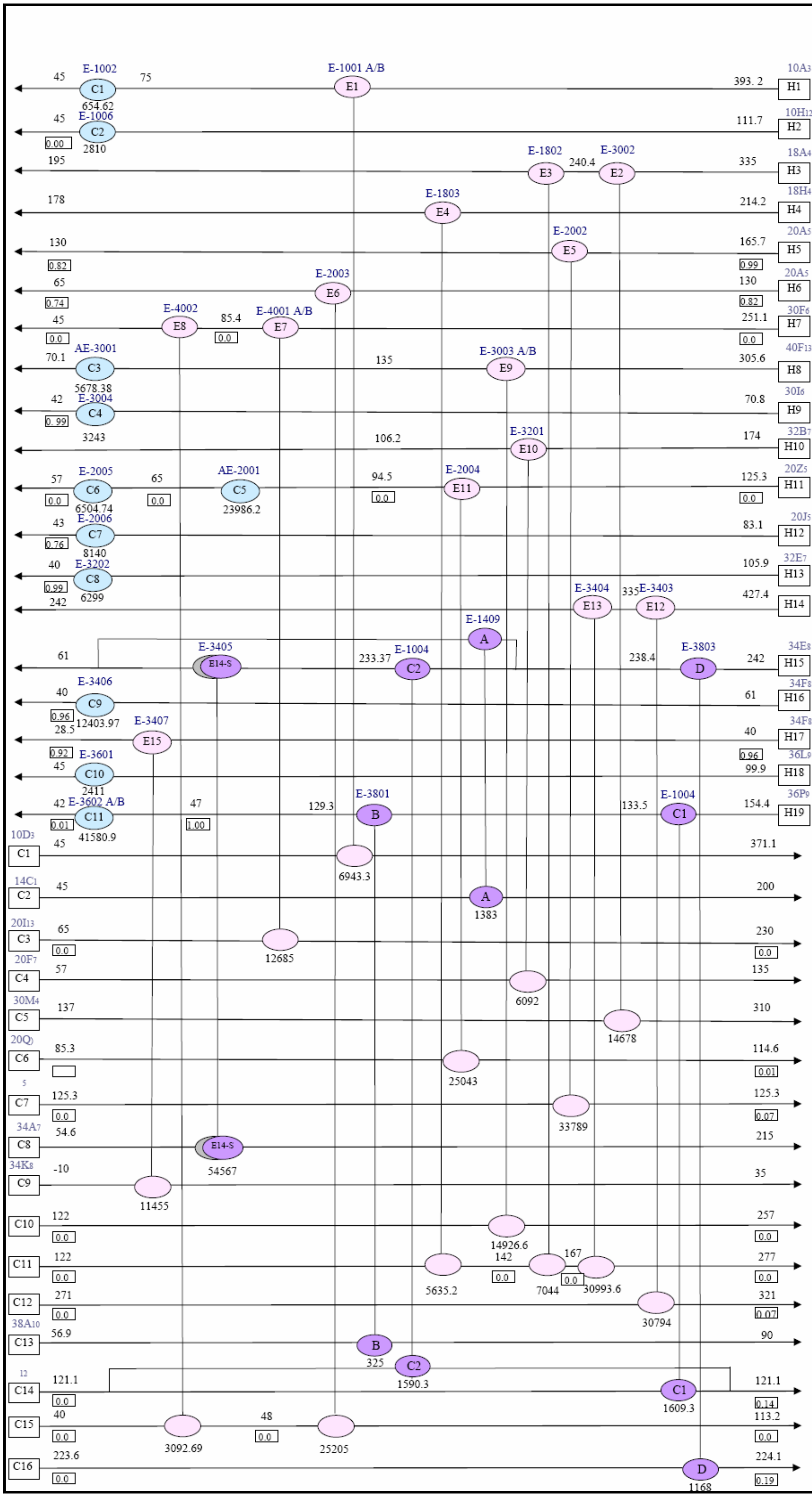


Fig. 8: DFP of new heat exchanger A, B, C1, C2, D

Table 2: Remaining problem analysis for the new heat exchangers

$\Delta T_{Threshold} = 12.4$ $\Delta H_h = 0$		Constant Coefficient $A_{1-1min} = 11539.67$			Fixed Pressure Drop $A_{1-2min} = 11762.5$		
Exchanger Name	$\Delta T_{Threshold,r}$	A_{1-1}	$A_{1-1min,r}$	$\alpha_{max,h}$	A_{1-2}	$A_{1-2min,r}$	$\alpha_{max,\Delta P}$
A	12.33	56.325	11495.19	0.999	96.5500	11615.2	1.000
B	12.40	6.6419	11513.11	1.000	73.1400	11735.61	0.996
C 1	11.57	89.733	11456.89	0.999	149.990	11689.56	0.993
C 2	11.42	15.899	11588.82	0.994	49.7700	11742.67	0.997
D	12.40	66.987	11504.95	0.997	158.810	11713.53	0.991
E14A	12.40	1659.6	10420.67	0.956	1701.98	10406.57	0.971

$\Delta T_{Threshold} = 12.4$ $\Delta H_h = 0$		Constant Coefficient $A_{1-1min} = 11539.67$			Fixed Pressure Drop $A_{1-2min} = 11762.5$		
Exchanger Name	$\Delta T_{Threshold,r}$	A_{1-1}	$A_{1-1min,r}$	$\alpha_{max,h}$	A_{1-2}	$A_{1-2min,r}$	$\alpha_{max,\Delta P}$
A + B	12.33	62.966	11536.47	0.995	169.69	11674.51	0.993
A + B + D	12.33	129.95	11502.09	0.992	328.50	11643.94	0.983
A + B + D + C1	11.49	219.68	11420.33	0.991	478.49	11572.25	0.976
A + B + D + C1 +C2	10.45	236.21	11473.08	0.986	528.26	11651.71	0.966
A + B + D + C1+C2+E14A	10.45	1895.8	10350.64	0.942	2230.2	10453.24	0.927



M*CP (KW/C)	ΔH (KW)
21.8206	7597.93
42.1289	2810.00
155.154	21721.5
155.668	5635.20
946.470	33789.0
387.769	25205.0
76.5519	15777.3
87.4944	20604.9
112.604	3243.00
89.8525	6092.00
813.093	55534.2
202.992	8140.00
95.58422	6299.00
333.264	61787.2
324.224	58708.3
590.665	12403.97
996.087	11455.0
43.9162	2411.00
76.9410 7050.32	43515.0
21.2919	6943.30
8.92258	1383.00
76.8787	12685.0
78.1025	6092.00
84.8439	14678.0
854.709	25043.0
33789.0	33789.0
340.1933	54567.0
254.555	11455.0
110.567	14926.6
281.761	43673.0
615.880	30794.0
9.81873	325.000
3200.00	3200.00
386.584	28298.0
2336.00	1168.00

Fig. 9: Grid diagram of first retrofitted proposal

4.3 Second retrofitted proposal for the HEN of the hot section

In the production process, natural gas is mixed with steam and charged to the primary reformer. The function of reforming is to produce hydrogen by reacting the natural feed gas with steam over a nickel catalyst. The reaction products are H_2, CO and CO_2. The reformer configuration shall be on the basis of plant experience to maximize the overall efficiency of the equipment. The primary reformer shell consists of radiant box and convection section for heating coils. In the existing process the flue gas leaves the convection section of the primary reformer at 185 °C (Fig. 10). Whereas the lowest temperature the flue gas can be taken to is the acid dew point (140 °C in this case). In the current study as illustrated in Fig.11, the stack flue gas temperature has been lowered to 153 °C. As a result, heater H3 in the grid diagram might be canceled in case, coil C can satisfy the target temperature.

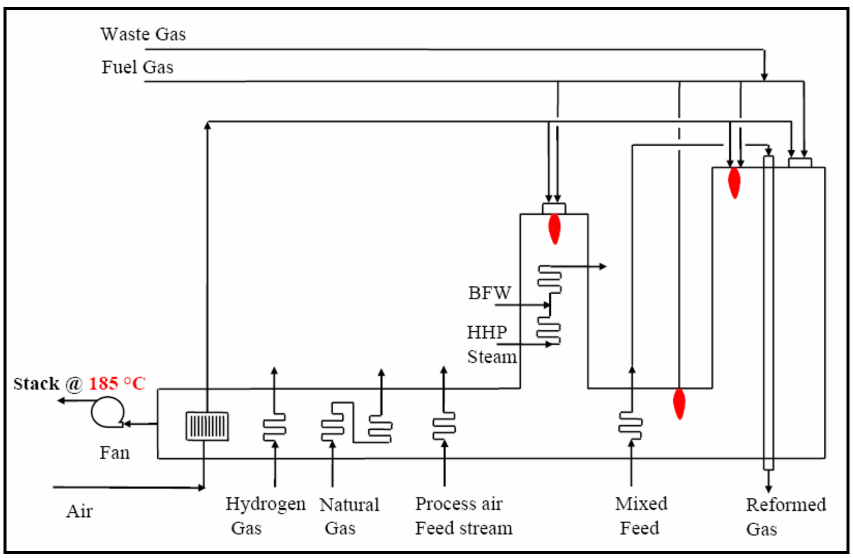


Fig. 10: The coil arrangement of the existing plant

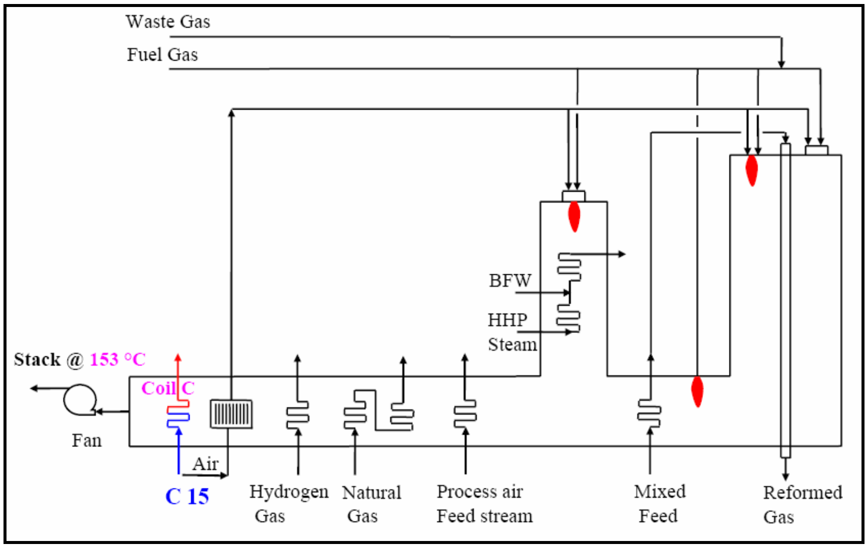


Fig. 11: The proposal coil arrangement

Accordingly, rest of the network is targeted and retrofitted using the network Pinch method. Nevertheless, before reducing ΔT_{min}, and getting the hot and cold curves in the composite curve closer to each other by means of reducing energy consumption, we should remove the cold stream C14 from grid diagram. There are two points of concern for omitting cold stream C14 from grid diagram: first, flue gas flowing into the primary reformer is not considered to be part of the process stream so as to let it enter the grid diagram as hot stream. Second point, the flue gas resulted from combustion is not considered to be hot utility as well. Further more, no extra expense is paid for obtainment of this energy and by not making use of it there will be no cost reduction. In other words it is like disposal.

The minimum temperature approach used for HEN in this case is 12.4 °C ,which leads to a threshold condition, similar to the first retrofitted option. The Cold P.H. position which corresponds to $\Delta T_{Threshold} = 12.4$ is found at 81.23 °C on the hot composite curve and at -10 °C on the cold composite curve. Accordingly, Minimum hot and cold utility requirements are found to be 0 and 116910.3 kW respectively. Here we follow the same steps as first option; hence, the summery of Cold P.H. violation at $\Delta T_{Threshold} = 12.4$ is illustrated in table 3.

The hot utility reduction is the same as the first retrofit but the reduction in the cold utility is equivalent to 309.976 T/h of cooling water.

Table 3: summery of Cold P.H. violation at $\Delta T_{Threshold} = 12.4$

Heat exchanger	Heat flow across Cold P.H.(kw)	Result (kw)
E1	21.820 × (81.23 - 75)	-135.942
E6	387.76 × (81.23 - 65)	-6293.49
E8	76.551 × (81.23 - 45)	-2773.48
E14	324.22 × (81.23 - 73.7)	-2441.41
E15	996.08 × (28.5 - 40)	11455
C2	42.128 × (111.7 - 81.23)	1283.668
C3	87.494 × (135 - 81.23)	4704.57
C5	813.09 × (94.5 - 81.23)	10789.7
C7	202.99 × (83.1 - 81.23)	379.596
C8	95.584 × (105.9 - 81.23)	2358.06
C10	43.916 × (99.9 - 81.23)	819.915
C11	76.941 × (154.4 - 81.23)	5629.77
TOTAL		2876

4.3.1 Diagnosis stage

1. By moving E14 to the left, the heat interval on the hot stream H15 is released before getting imported into the heat exchanger. This rearrangement offers two new matches (A, D) between cold streams C2 and C15 and hot stream H15 by removing heaters H1 and H4.
2. By reducing the load of cooler C8, makes a possibility of designing new exchanger called B, which transfers heat between cold stream C13 and hot stream H13, respectively heater H2 can be omitted.

Fig.12 is the representation of retrofitted proposal in grid diagram. Driving Force Plot of new exchangers is illustrated in Fig. 13. Also the new matches have been checked by remaining problem analysis, and the results are shown in table 4.

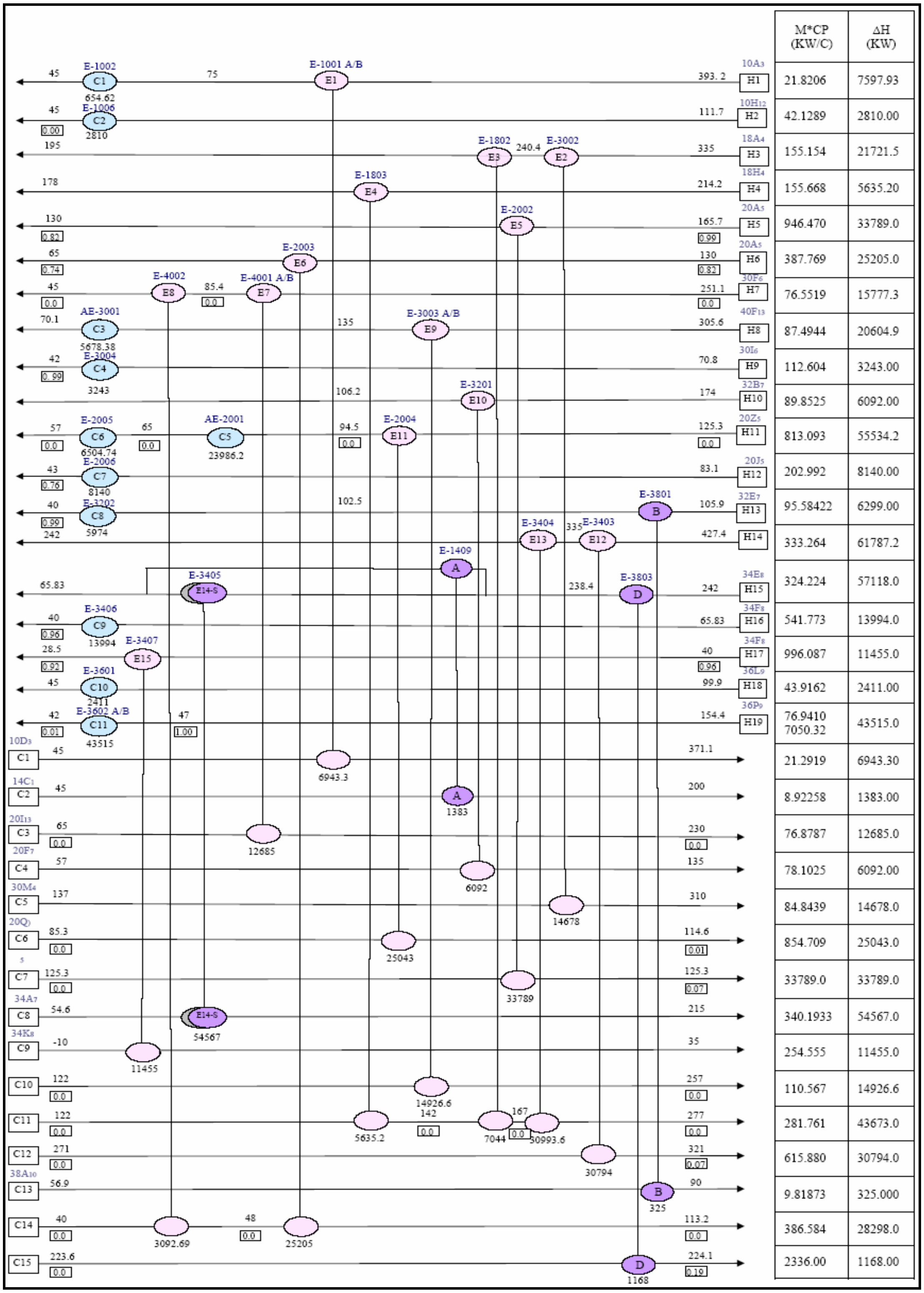


Fig. 12: Grid diagram of second retrofitted proposal

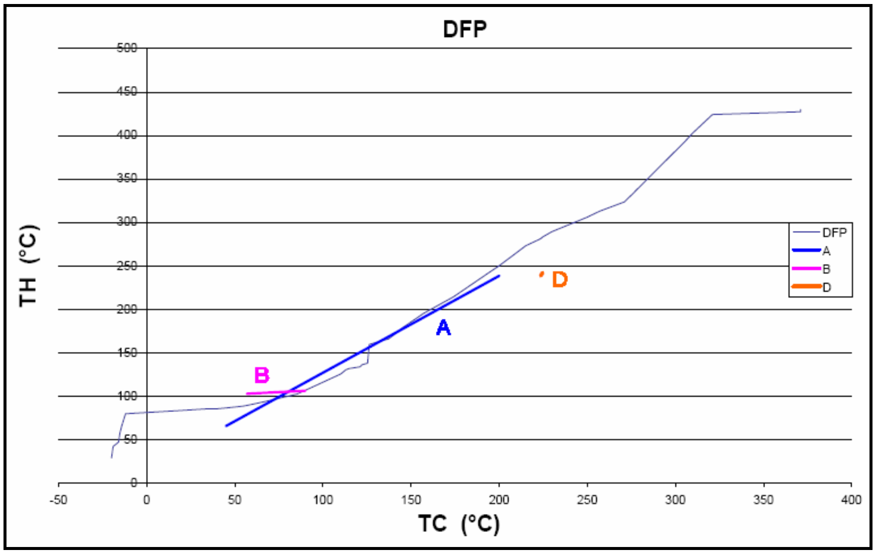


Fig. 13: DFP of new heat exchanger A, B, D

Table 4: Remaining problem analysis for the new heat exchangers

$\Delta T_{Threshold} = 12.4$ $\Delta H_h = 0$		Constant Coefficient $A_{1-1min} = 10474.46$			Fixed Pressure Drop $A_{1-2min} = 10914.38$			$\Delta T_{Threshold} = 12.4$ $\Delta H_h = 0$		Constant Coefficient $A_{1-1min} = 10474.46$			Fixed Pressure Drop $A_{1-2min} = 10914.38$		
Exchanger Name	$\Delta T_{Threshold,r}$	A_{1-1}	$A_{1-1min,r}$	$\alpha_{max,h}$	A_{1-2}	$A_{1-2min,r}$	$\alpha_{max,\Delta P}$	Exchanger Name	$\Delta T_{Threshold,r}$	A_{1-1}	$A_{1-1min,r}$	$\alpha_{max,h}$	A_{1-2}	$A_{1-2min,r}$	$\alpha_{max,\Delta P}$
A	12.31	49.67677	10434.00	0.999	257.220	10805.86	0.987	A +B	12.31	64.176	10421.44	0.999	376.82	10802.43	0.976
B	12.40	14.50015	10461.91	1.000	119.600	10910.97	0.990	A +B +D	12.31	130.58	10387.52	0.996	602.33	10771.88	0.960
D	12.40	66.41170	10440.30	0.996	225.510	10815.82	0.989	A +B +D +E14A	12.31	621.66	10050.25	0.982	1163.7	10521.08	0.934
E14A	12.40	491.080	10136.76	0.985	561.46	10623.19	0.976								

5 Cold section

5.1 Combined of Pinch and Exergy analysis

The first law analysis method is widely used to evaluate thermodynamic systems; however, this method is concerned only with energy conservation, and therefore it cannot show how or where irreversibilities occur in a system or process. To determine the irreversibilities, the exergy analysis method is applicable; Exergy is defined as maximum amount of work which can be produced by a system when it comes to equilibrium with a reference environment. The standard conditions of the earth atmosphere are considered as the thermodynamic state of the environment .Particularly in subambient systems, where in general all cooling and heating requirements have a direct shaftwork implication. Therefore combination of pinch and exergy analysis could be an appropriate tool for contemporaneous study of heat and power. As the most important application of combined pinch and exergy analysis is retrofit study of low temperature processes and refrigerant cycle, thus in this research we put into practice its conceptual to reduce the exergy loss of refrigeration cycle of the ammonia plant.

5.2 Ammonia refrigeration cycle

Refrigeration systems are cyclic processes that employ refrigerants to absorb heat from one place and move it to another. Mainly, a refrigeration system consists of a condenser, an evaporator, a compressor, and an expansion valve. Fig.14 shows the schematic of ammonia refrigeration cycle in which uses three ammonia levels -18.3, 2.1, and 9.3.

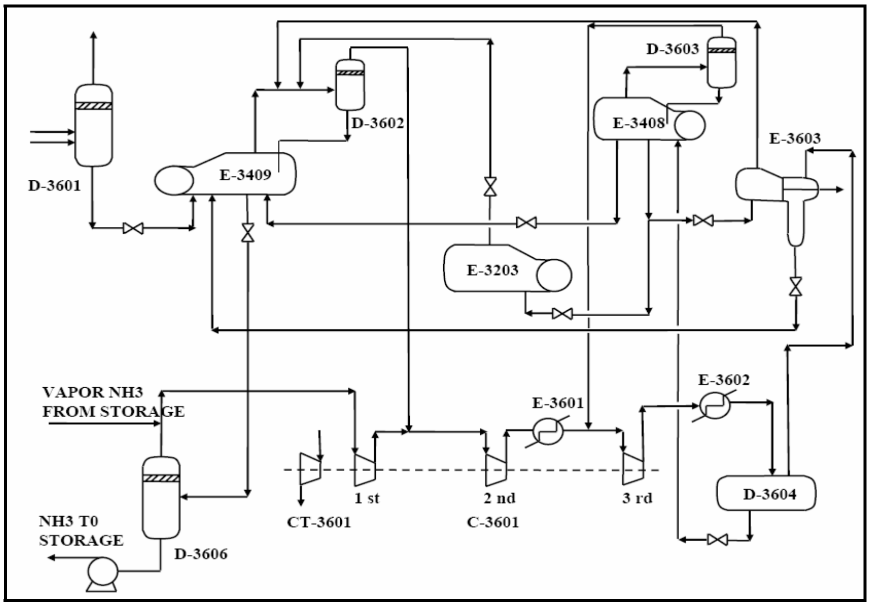


Fig 14: Schematic of ammonia refrigeration cycle

5.3 Data extraction

As shown in Fig. 15, stream data extracted for the current ammonia refrigeration cycle consists of 5 hot streams and 1 cold streams. The grid diagram includes 1 heat exchanger, 4 chillers using ammonia as a refrigerant and 2 water coolers. While analyzing the existing heat exchanger network, it is noticed that there is no hot utility and the refrigeration cycle is in threshold condition. This derives our first conclusion that the ammonia refrigeration cycle we selected for the case study is well integrated. Hence, saving in total utility consumption through process-to-process heat integration is not a promising option. Alternatively, savings are expected to be in optimizing the refrigeration levels. In the cold section, without changing the configuration of compressors and chillers, the refrigeration cycle is retrofitted by application of the Combined Pinch & Exergy Analysis; thus 15% of the compressor's shaft work could have been avoided in a well integrated design. The remaining questions are whether this claimed benefit is practically applicable and which refrigeration levels should be modified.

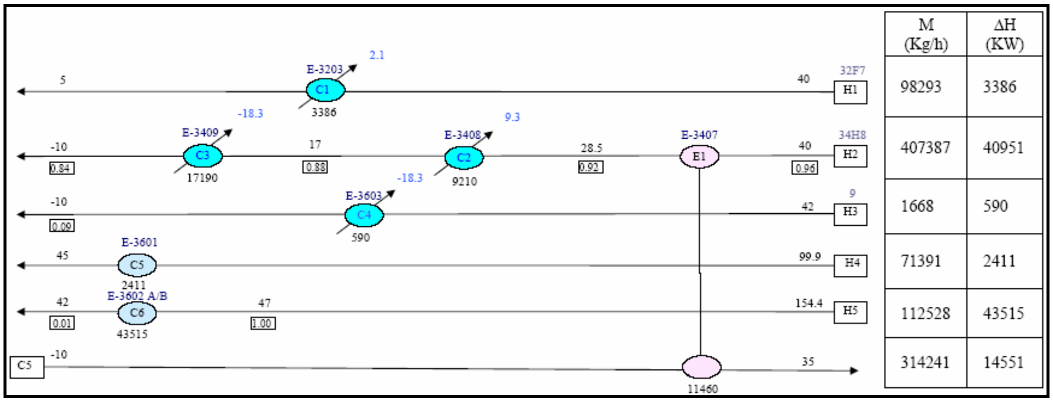


Fig. 15: Grid diagram of the existing HEN of cold section

5.4 Analysis of refrigeration levels in the existing ammonia cycle

Exergy losses are inevitable because all natural processes are irreversible. Technically and economically speaking, exergy is valuable, and as a consequence, whenever we try to solve a problem through the scope of exergy analysis, we try to find a specific exergy loss, which minimizes operational costs. Several tools, including Composite Curve (CC), Exergy Composite Curve (ECC), Exergy Grand Composite Curve (EGCC), were adapted in the diagnosis of process exergy-utilizing. The composite curve (Fig.16) can be redrawn by replacing the temperature axis with the Carnot factor $\eta_c = (1 - T_0 / T)$, resulting in the ECC (Fig.17). The area between the hot and cold composite curves is proportional to the exergy loss which is denoted $(\sigma T_\circ)_{HEN}$. Thus $(\sigma T_\circ)_{HEN}$ is proportional to the amount of ideal work equivalent lost in heat transfer. The analogous concept applies for the Grand composite curve.

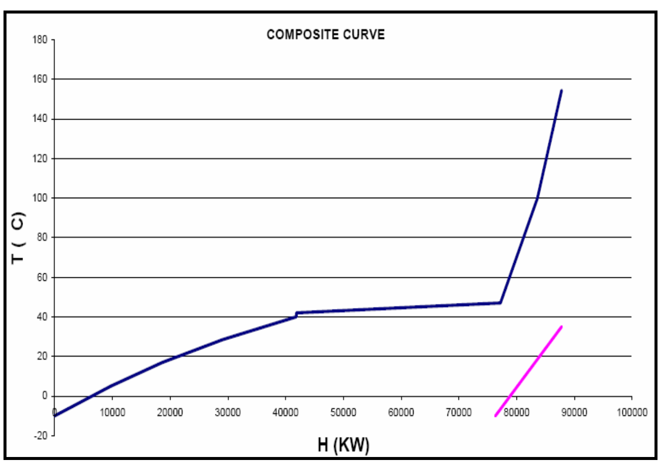


Fig 16: Composite Curve of cold section

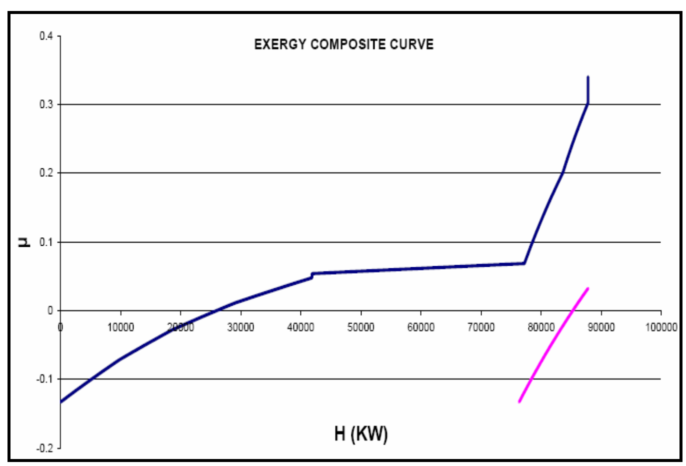


Fig 17: Exergy Composite Curve of cold section

Fig.18 shows the utility and refrigeration level placements in the EGCC. The ammonia cycle uses three ammonia levels -18.3, 2.1, 9.3.. The utility system provides exergy, part of which is lost in heat exchange (area between EGCC and utility levels, $(\sigma T_{\circ})_{HEN}$) whilst the remainder is supplied to the process (area inside EGCC, $\Delta EX_{process}$). For subambient process the refrigeration system is the utility system. Linnhoff and Dhole [14] have shown that changes in the area representing $(\sigma T_{\circ})_{HEN}$ are proportional to the changes in refrigeration shaftwork requirement.

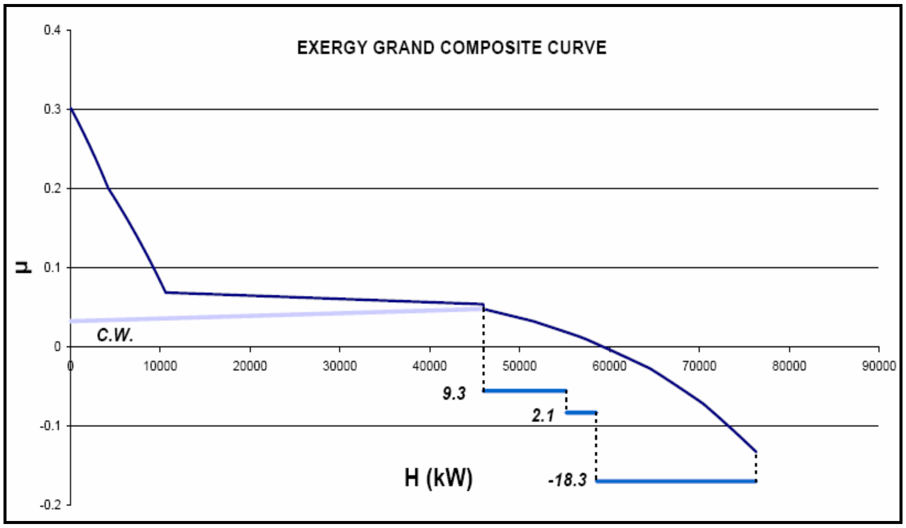


Fig 18: The refrigeration level placements on the Exergy Grand Composite Curve for existing refrigeration cycle

5.4.1 Simulation of the refrigeration cycle

HYSYS was used to simulate the cycle and the Soave &Redlich—Kwong–(SRK) equation of state was selected to calculate the thermodynamic properties of ammonia–water mixture because it shows good agreement with the plant data.

5.5 Retrofitted proposal for the refrigeration levels

We have improved on the temperature differences between process and the refrigeration levels to introduce the new refrigeration levels. The existing (9.3, 2.1,-18.3) and proposal (14, 2.1, -13) refrigeration level placements are shown in Fig.19. This figure clarifies that the area between EGCC and refrigeration levels, $(\sigma T_{\circ})_{HEN}$ decreased but there are no changes in chiller's duty.

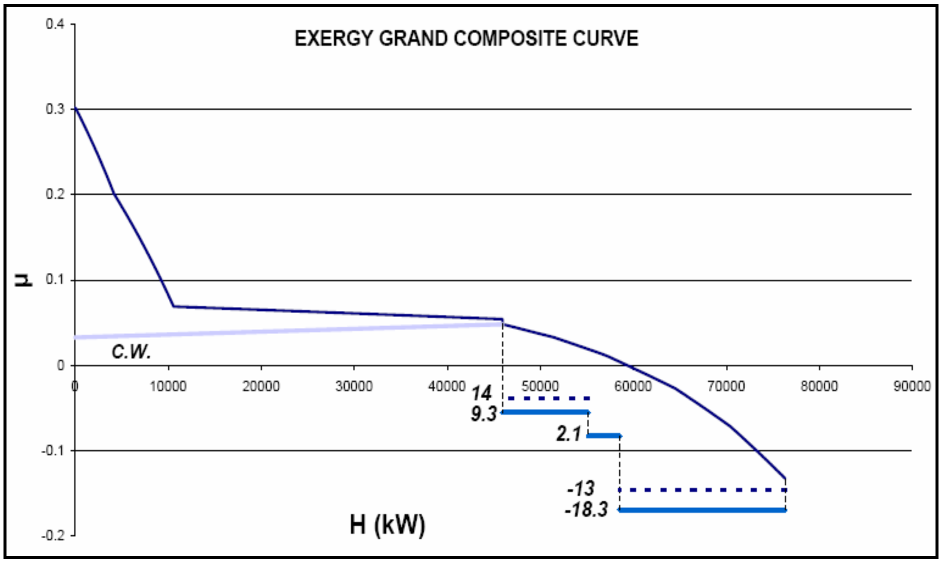


Fig 19: Exergy Grand Composite Curve with existing and proposal refrigeration levels

Here it should be noted that in the understudy ammonia cycle the chillers operating pressure will determine the refrigeration level. Therefore, by changing the chiller's operating pressure, the targeted refrigeration levels can be achieved. Thus, to access the required pressure and also by the aim of confirming the retrofitted result, the refrigeration cycle is simulated by HYSYS software before and after retrofit and pressure variation of chillers are recorded in table 5.

Table 5: Pressure variation of chillers after retrofit

Exchanger Name	Ref. Level Before Retrofit	Pressure Before Retrofit	Ref. Level After Retrofit	Pressure After Retrofit
E-3203	+ 2.1°C	4.6 bar	+ 2.1°C	4.6 bar
E-3408	+ 9.3°C	6 bar	+14°C	7.13 bar
E-3409	-18.3°C	2 bar	-13 °C	2.5 bar
E-3603	-18.3°C	2 bar	-13 °C	2.5 bar

To change the chiller's operating pressure in order to reach the target refrigeration levels we just set the outlet pressure of the valves that settles before and after each chiller.

In the ammonia refrigeration cycle, applying the proposal temperature levels will decrease the ΔT_{LM} of chillers, hence by increasing the normal levels in chillers, the heat transfer coefficient will be increased which leads to the chiller's heat load remaining constant. The retrofitting, taken regarding the temperature levels, cause just slight changes in chillers E-3408 & E-3409 flow rates. Since these changes are not of any significance and regarding the fact that the chiller's heat load are fixed after the retrofit, there is no need for making any changes or designing new chillers.

5.5.1 Exergy degradation calculation for existing and retrofitted cycle

The environment parameters are assumed as follows: $P_0 = 101325\,\text{Pa}$, $T_0 = 298.15\,\text{K}$. The exergy analysis of the existing chillers and the chillers with the proposal refrigeration levels are carried out using $\Delta \text{Ex} = \Delta \text{H}\left(1 - \frac{\text{T}_0}{\text{T}}\right)$.The results are summarized in Table 6.

Table 6: Exergy degradation of existing and proposal refrigeration levels

Exchanger	ΔH (kW)	Existing Refrigeration level	ΔEx (kW)	Proposal Refrigeration level	ΔEx (kW)
E-3408	9210	+9.3°C	-512.21	+14°C	-353
E-3203	3390	+2.1°C	-282.2	+2.1°C	-282.2
E-3409,E-3603	17780	-18.3°C	-2998.2	-13°C	-2598.6
Result		$\sum_{i=1}^{3} \lvert \Delta \text{Ex} \rvert_1 = 3793$		$\sum_{i=1}^{3} \lvert \Delta \text{Ex} \rvert_2 = 3234$	

Regarding the fact that the existing compressor's shaftwork is $W = 12780KW$ the exergy efficiency is found to be:

$$\eta_{ex} = \frac{\sum_{i=1}^{3} |\Delta Ex|}{W} = \frac{3793}{12780} = 0.3$$

$$\Delta\left(\sigma T_{o_{HEN}}\right) = \sum \Delta EX_1 - \sum \Delta EX_2 \qquad (5) \qquad \Longrightarrow \qquad \Delta\left(\sigma T_{o_{HEN}}\right) = 558KW$$

Hence, ΔW_{act} is found to be:

$$\Delta \text{W}_{\text{act}} = \frac{1}{\eta_{\text{ex}}} \Delta\left(\sigma \text{T}_{\text{o}_{\text{HEN}}}\right) \qquad (6) \qquad \Longrightarrow \qquad \Delta W_{act} = 1860KW$$

Note that the above equation assumes that η_{ex} remains constant.

6 Discussion and conclusion

Detailed energy conservation study of the hot-end of an existing ammonia plant has been performed and two promising retrofit options have been investigated to claim total energy reduction of 6076 Kw, which is equivalent to 4460 kg/h reduction of HP steam which decreased the fuel gas consumption in the boiler and also 5910 kg/h reduction of LP steam has been reached, that indirectly effects the fuel gas consumption by increasing the enthalpy of BFW in the cycle. Consequently, we reach satisfactory conformity between the result achieved from the design and the one obtained from target.

Retrofit study of low temperature processes is dominated by the shaft work or power consumption of the refrigeration system and it is important to determine optimum temperatures and pressures in a refrigeration system. In the cold section of ammonia plant, application of the Combined Pinch & Exergy Analysis revealed that part of the shaft work was inefficient. Therefore, by optimizing the refrigeration levels, reasonable shaft work have been saved ($\Delta W_{act} = 1860 KW$) without a need for new investment. Also to check the integrity of other part of process with the new refrigeration levels in the cycle, simulation was performed with good accuracy.

Nomenclature

$\Delta T_{\min}$	minimum temperature difference
$\Delta T_{Threshold}$	threshold temperature difference
$m.c_p$	heat capacity, kW/°C
ΔH_h	hot utility
ΔH_c	cold utility
$\Delta T_{\min, r}$	remaining minimum temperature difference
$\Delta T_{Threshold, r}$	remaining threshold temperature difference
$\alpha_{\max, \Delta P}$	area efficiency by assumption of fixed pressure drop
$\alpha_{\max, h}$	area efficiency by assumption of fixed heat transfer coefficient
A_{1-1}	area with 1-1 exchanger
A_{1-2}	area with 1-2 exchanger
$A_{1-1\min .r}$	remaiing area with 1-1 exchanger
$A_{1-2\min ,r}$	remaiing area with 1-2 exchanger
η_c	carnot factor
T_0	refrence temperature
$(\sigma T_{\circ})_{HEN}$	exergy loss in the HEN
$\Delta EX_{process}$	exergy supplied to the process
P_0	refrence pressure
W	compressor shaftwork
H	enthalpy
S	entropy
Ex	exergy
η_{ex}	exergetic efficiency of the refrigeration system

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