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Heat transfer enhancement to decrease the energy consumption of a Light Naphtha Isomerization unit by means of heat exchanger network retrofitting

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Abstract. The Light Naphtha Isomerization (LNI) process increases the quality of gasoline, and the Pinch Design Method (PDM) is a novel method in the field of heat transfer that implements the design of Heat Exchanger Network (HEN) to improve energy efficiency. In this research, the HEN of an LNI unit was retrofitted using PDM to determine the best design to decrease hot and cold utility consumption. Stream selection and data extraction were necessary for PDM, and graphical tools in the form of Composite Curves (CC) and a Grand Composite Curve (GCC) were presented to calculate the minimum and actual hot and cold targets. The base-case results showed minimum hot and cold targets of 37 and 42 MW for ΔT_{min} = 10 °C, respectively and an energy pocket above the pinch in the interval of between 120 and 180 °C. The pocket enhanced heat recovery because of the large driving forces, decreasing MP steam consumption. Scenarios were suggested for the retrofitting of the LNI unit to enhance heat transfer to decrease energy consumption. In particular, the heat pump intensified heat transfer from the Cooling Water cold utility at 29.5 °C to the MP Steam hot utility at 150 °C.

1. Introduction

Recently, energy costs have increased as studies have confirmed a decrease in non-renewable energy resources all over the world. Energy optimisation and emission reduction is thus more necessary than ever in chemical processes due to issues relating to energy consumption, as well as more stringent environmental quality specifications [1,2]. The isomerization process is a chemical process that changes the chemical and physical properties of materials without changing their structural formulae. Light naphtha (C_5-C_6 fraction) isomerization mainly focuses on increasing the gasoline octane number at petroleum refineries to eliminate aromatics and toxic materials [2-4].

Studying heat transfer improvement is generally referred to as heat transfer enhancement. Different methods of heat transfer enhancement have been developed to decrease energy consumption in most major chemical units, such as petroleum refineries. Most of these methods make reductions in the weight and size or enhance the performance of heat exchangers; the other techniques try to improve heat recovery. Retrofitting the Heat Exchanger Network (HEN) is a new method for modifying an existing process to gain improved heat recovery to increase heat transfer. HEN designers usually evaluate the optimal HEN under multiple parameters based on different temperature approaches. Pinch Technology is entirely based on HEN design being successfully applied to minimise the energy consumption of various processes. This methodology, which is based upon thermodynamic analysis, represents a new set of methods for increasing heat transfer, which satisfies the stipulation of minimum cost of HEN design to obtain minimum energy consumption. The pinch design method approach is used to maximise heat transfer between all hot and cold process streams. It introduces the idea of the pinch point, which acts as a heat transfer “bottleneck”. This bottleneck is defined by a hot pinch temperature and a cold pinch temperature. Pinch Technology analysis thus begins by identifying all process streams to be heated and cooled [5,6].

Adequate changes can be identified in the base-case process conditions in Pinch Technology by drawing an enthalpy-temperature composite curve diagram that illustrates hot and cold streams that supply heat to and gain heat from each other [7,8]. A retrofit design can then be suggested to revise these hot and cold utilities using Pinch Technology [9].

Isomerization is an important process, as it decreases the aromatics and olefin content of gasolines [10]. The isomerization process generates fuels with high octane numbers and quality, low energy consumption, and low environmental pollution [1,11]. Javed et al. [12] studied ignition delay times of two low-octane gasolines used in an isomerization unit to produce high-octane gasolines without any energy considerations. Pinch Technology studies of Brazilian isomerization processes along with other saving methods predicted 35 PJ energy reductions along with decreases in sulphur content in diesel and gasoline between 2002 and 2009. In this paper, the authors claimed reductions in energy consumption of around 20% using Pinch Technology [13]. Feng et al. [14] used Pinch Technology to decrease the energy consumption in an isomerization unit; they stated that they reduced hot utility use from 66,900 kW to 44030.5 kW (34.2% saving) and cold utility use from 87450 kW to 64580 kW (26.2% reduction). They did not consider any utility placement in order to generate hot utilities using excess heat in the process, however.

This research aims to create base-case and retrofit studies of an industrial Light Naphtha Isomerization unit using the Pinch Design Method. The Heat Exchanger Network of the unit is investigated to determine the pinch points, utility targets, CC, and GCC. Then, the best utility placement considerations are applied to minimise LP Steam consumption to minimise utility costs. A retrofit design using a heat pump is also considered.

2. Concepts and Methodology

2.1. Process Description

Isomerization of light fractions (C_5 and C_6) is one of the best methods of producing high-octane gasoline with high branching of light naphtha components to reduce environmental pollutions. In fact, branched light naphtha hydrocarbons have higher octane numbers than straight-run naphtha. Figure 1 shows the typical process flow diagram of a C_5-C_6 isomerization unit.

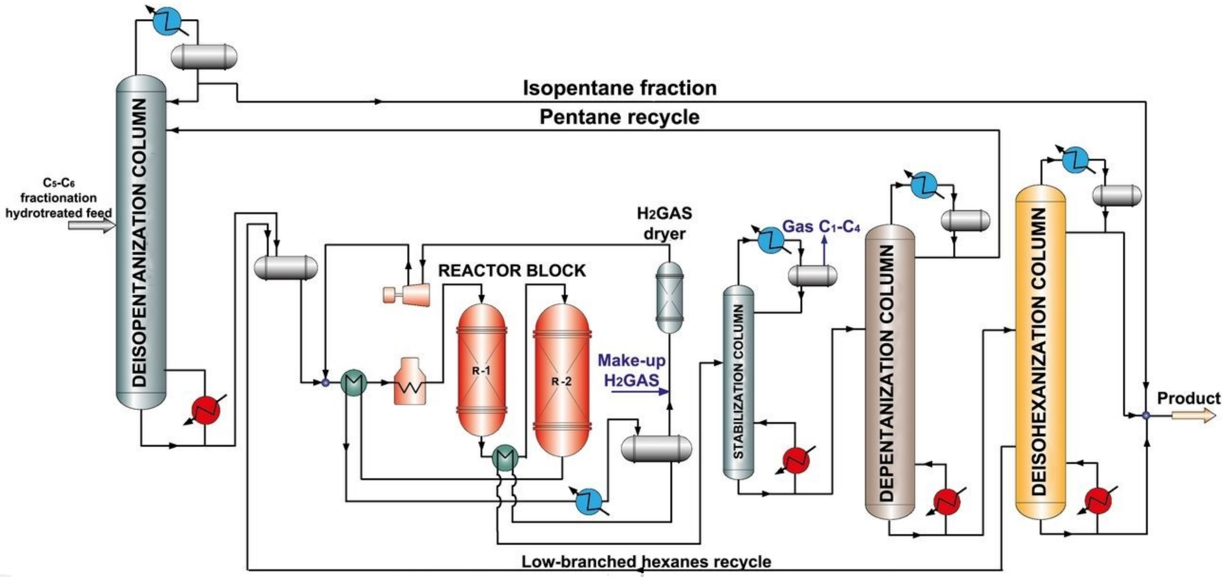

Figure 1. Typical process flow diagram of C_5-C_6 isomerization unit (adapted from [1]).

Some of the main sections of the isomerization unit are [1,3]:

2.1.1. Deisopentanizer (DIP)

To concentrate i-pentane (iso-pentane) and improve the gasoline octane number, a DIP distillation column is used to recycle n-C_5 (normal-C_5) to increase its concentration. The increase in n-C_5 concentration leads to a shift in the equilibrium reaction (n-C_5↔i-C_5) to produce gasoline richer in i-paraffins [11,15].

2.1.2. Isomerization Reactors

The exothermic reactions of aromatics saturation take place in the first fixed bed reactor (R-1) in the presence of hydrogen; the C_5-C_6 isomerization reactions continue and are completed in the second fixed bed reactor (R-2) [11,15].

2.1.3. IPSORB section

Isomerate products enter the IPSORB section (not shown in figure 1) after passing through the isomerization reactor. They thus pass through several consequential steps that separate unconverted n-paraffins from i-paraffins to improve the quality of gasoline products obtained from the isomerization unit using a molecular sieve. The n-C_6/n-C_5 is recycled into the DIP column by means of a circulating pump.

2.2. Pinch Technology

Pinch Technology is a method to enhance heat transfer in a unit; many such methods have been employed to decrease the energy consumption in chemical units such as the refineries, but one of the best regenerative energy-saving techniques is based on mathematical programming methods. Pinch analysis offers reliable, useful, and convenient thermodynamic information that allows the optimisation of energy consumption [5,7] and reduces resource utilisation effectively, causing a reduction in production costs [16].

The basic concepts of the Pinch Design Method (PDM) are shown in figure 2(a). The enthalpy-temperature diagram of Composite Curves (CC) illustrates hot (which are supplying heat) and cold (which are gaining heat) streams side-by-side [7]. The ΔT_{min} (minimum approach temperature difference) is the minimum vertical distance between hot and cold streams in CC, and those are above and below the pinch point as a sink and source of energy, respectively.

The Grand Composite Curve (GCC) is an ingenious diagram created from the CC. First, the hot composite is shifted down by ½ΔT_{min} and the cold composite curve is shifted up by ½ΔT_{min}. This causes the CCs to touch at the pinch. The process streams are no longer shown on the shifted composites at their actual temperatures, but rather at interval temperatures; thus, hot streams are represented ½ΔT_{min} colder and cold streams ½ΔT_{min} hotter than they are in practice. Figure 2(b) illustrates the sink of energy (above the pinch point, also known as the heat sink), the source of the energy (below the pinch point, also known as the heat source) and heat recovery pockets [17]. Heat recovery pockets occur when a utility level is available in a suitable range of temperatures to produce energy or another utility [18]. GCC allows the recognition of targets for several energy recovery potentials. Pinch Technology allows investigation of retrofit designs to revise hot and cold energy targets in the region of net heat availability or above the region of net heat requirements or the bottom of the composite curve (or GCC) to obtain the minimum energy targets Q_{Hmin} and Q_{Cmin} [9].

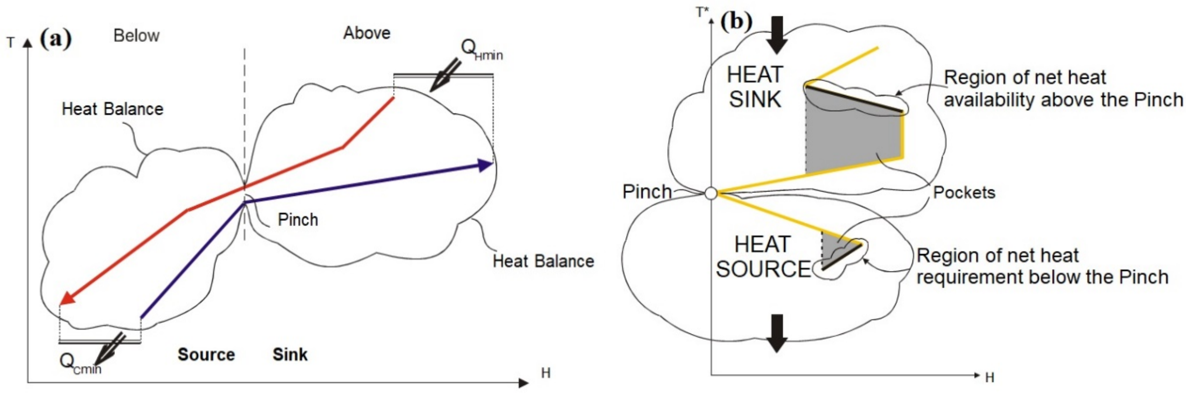

Figure 2. (a) Composite Curves (CC), pinch points, and energy targets and (b) Grand composite curve (GCC), Heat Sink, and Heat Source [8].

3. Results

3.1. Data Extraction

The design of HEN is the first step for energy integration of an LNI unit. Figure 3 shows the HEN design of the existing unit developed using the Aspen Energy Analyzer V10-aspen ONE. The cold and hot streams are represented by blue and red horizontal lines. The circles connected with vertical lines show heat exchangers. The grid diagram shows 21 exchanger units, including 6 process-to-process heat exchangers, 6 heaters (4 steam and 2 fired heaters), and 9 coolers (4 trim water and 5 air coolers). Figure 4 illustrates the inlet and the outlet streams, their supply and target temperatures of hot and cold streams, and the heat duty of each heat exchanger (Data Extraction table). The number of hot and cold process streams are 10 and 8, respectively.

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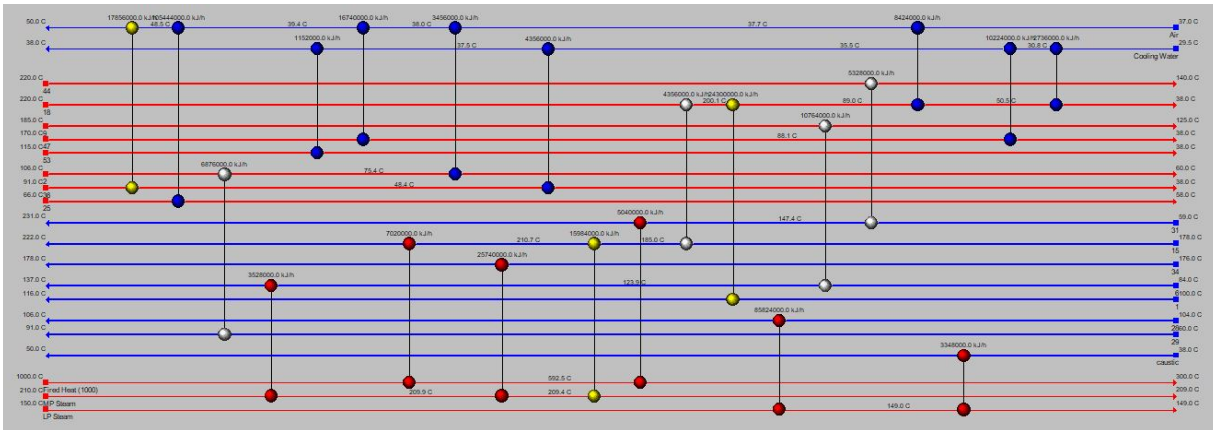

Figure 3. Heat Exchanger Network (HEN) of the existing design.

Heat Exchanger		Cold Stream	Cold T in [C]	Tied	Cold Tout [C]	Tied	Hot Stream	Hot T in [C]	Tied	Hot T out [C]	Tied	Load [kJ/h]	Area [m2]		Fouling [C-h-m2/kJ]	dT Min Hot [C]	dT Min Cold [C]
E-1851		28	104.0	☑	106.0	☐	LP Steam	150.0	■	149.0	■	8.582e+007	2766.9		0.0000	44.00	45.04
E-1855		6	84.0	☑	123.9	☑	9	185.0	☑	125.0	☐	1.076e+007	593.5		0.0000	61.08	41.00
E-1875		Cooling Water	37.5	■	38.0	■	53	115.0	☑	38.0	☐	1.152e+006	109.7		0.0000	77.00	0.5302
E-1863		31	59.0	☑	147.4	☑	44	220.0	☑	140.0	☐	5.328e+006	192.9		0.0000	72.61	81.00
E-1865		Air	37.0	■	37.7	■	18	89.0	☑	50.5	☑	8.424e+006	1157.6		0.0000	51.29	13.51
E-1861		Air	38.0	■	39.4	■	47	170.0	☑	88.1	☑	1.674e+007	775.9		0.0000	130.6	50.03
E-1858		Air	48.5	■	50.0	■	36	91.0	☑	48.4	☑	1.786e+007	---		0.0000	41.00	-7.820e-00
E-1860		caustic	38.0	☑	50.0	☐	LP Steam	149.0	■	149.0	■	3.348e+006	45.8		0.0000	99.04	111.0
H-1851		15	210.7	☑	222.0	☐	Fired Heat (1000)	1000.0	■	592.5	■	7.020e+006	49.1		0.0000	778.0	381.8
E-1862		Cooling Water	30.8	■	35.5	■	47	88.1	☑	38.0	☐	1.022e+007	654.0		0.0000	52.59	7.241
E-1853		Air	37.7	■	38.0	■	2	75.4	☑	60.0	☐	3.456e+006	460.9		0.0000	37.37	22.28
E-1857		34	176.0	☑	178.0	☐	MP Steam	209.9	■	209.4	■	2.574e+007	1132.1		0.0000	31.92	33.35
E-1859		Cooling Water	35.5	■	37.5	■	36	48.4	☑	38.0	☐	4.356e+006	1109.6		0.0000	10.92	2.535
E-1873		15	185.0	☑	210.7	☑	MP Steam	209.4	■	209.0	■	1.598e+007	---		0.0000	-1.357	23.99
H-1852		31	147.4	☑	231.0	☐	Fired Heat (1000)	592.5	■	300.0	■	5.040e+006	81.0		0.0000	361.5	152.6
E-1854		Air	39.4	■	48.5	■	25	66.0	☑	58.0	☐	1.054e+008	2.2752e+04		0.0000	17.53	18.55
E-1852		29	60.0	☑	91.0	☐	2	106.0	☑	75.4	☑	6.876e+006	1257.2		0.0000	15.00	15.39
E-1856		6	123.9	☑	137.0	☐	MP Steam	210.0	■	209.9	■	3.528e+006	63.8		0.0000	73.00	86.01
E-1864		15	178.0	☑	185.0	☑	18	220.0	☑	200.1	☑	4.356e+006	431.4		0.0000	34.99	22.09
E-1874		1	100.0	☑	116.0	☐	18	200.1	☑	89.0	☑	2.430e+007	---		0.0000	84.09	-10.99
E-1866		Cooling Water	29.5	■	30.8	■	18	50.5	☑	38.0	☐	2.736e+006	300.0		0.0000	19.75	8.500

Figure 4. Data Extraction form.

Three types of hot and two types of cold utilities are available in the LNI unit. The hot utilities are LP Stream (at 150 °C), MP Stream (at 210 °C), and Fired Heater flue gas (1000 to 300 °C) and the cold utilities are Cooling Water (29.5 to 38 °C) and Air (37 to 50 °C). The order of Target Load (KJ/h) for these utilities is Air > LP Steam > MP Steam > Fired Heat > Cooling Water. Therefore, the largest amount of cold utility of the plant belongs to cooling water. Load, Cost Index, and hot and cold utility targets are reported in Table 1.

Table 1. Hot and cold utility data.

Utility	Load (KJ/h)	Cost Index (Cost/s)	Total Targets (KJ/h)	Total Costs (Cost/s)
LP Steam	8.190e+007	4.322e-002	Heating Target	Heating
MP Steam	3.402e+007	2.079e-002	1.286e+008	7.900e-002
Fired Heat (1000)	1.269e+007	1.498e-002		
Cooling Water	7.285e+006	4.299 e-004	Cooling Target	Cooling
Air	1.439e+008	3.998 e-005	1.525e+008	4.699e-004

3.2. HEN Analysis

Figure 5(a) shows the Composite Curves (CC) of the unit, including the minimum approach temperature (ΔT_{min} = 10 °C), and hot (110 °C) and cold (100 °C) pinch temperatures. The total network cross pinch load is 22.47 GJ/h. The cross-pinch heat exchangers above the pinch are E-1861, E-1855 and E-1863 and those below the pinch are E-1860 and E-1875. The amount of cross heat flow above the pinch is 19.04 6 GJ/h. The cross-pinch heat flow must be minimised to increase energy recovery targets in a retrofit design, which is out of the scope of the current study. The Grand Composite Curve is shown in figure 5(b). The GCC shows a heat recovery pocket in the interval between 120 and 180 °C, with only LP Steam (hot utility) used in this interval at 150 °C.

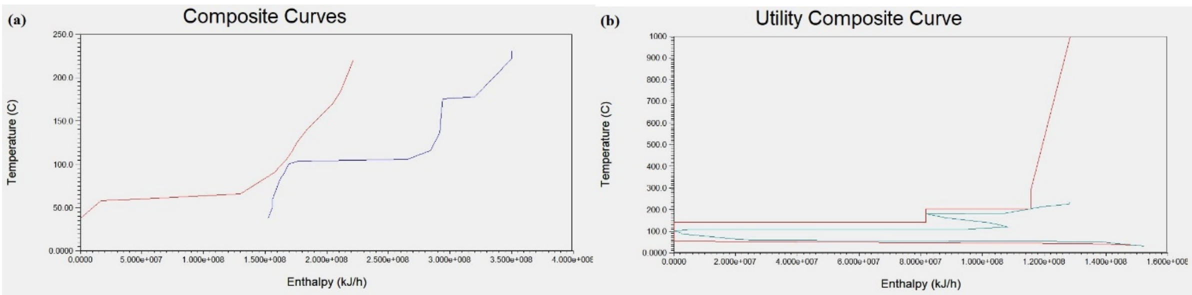

Figure 5. (a) Composite Curve and (b) Grand Composite Curve with utility placement.

4. Discussion

Figure 5(b) shows that the GCC has a pocket above the pinch in the interval between 120 and 180 °C. Therefore, the profile of the GCC represents the residual heating demands after recovering the maximum heat within the shifted temperature intervals. Although the overall process above the pinch is a net heat sink, this interval has net heat availability. The process below the pinch is a net heat source, but the GCC has no pocket below the pinch and there is no net heat requirement below the pinch.

The options for placing utilities are thus in the pocket above the pinch, between 120 and 180 °C. This would allow process-to-process heat transfer at large driving forces, or exploitation of these large driving forces to generate a utility to be used at lower temperatures. Here, process-to-process heat transfer was chosen to utilise the large driving forces in the pocket located between 120 and 180 °C, as the Utility Unit in the refinery has only LP steam in this interval. The demand for LP steam consumption at 150 °C is thus decreased, as the heat recovery is enhanced by retrofitted process-to-process heat exchangers, E-

1855 (Hot Feed/Effluent Exchanger) and E-1863 (Desorbent/Recycle Exchanger). Retrofitting of the heat exchangers was necessary to intensify the heat transfer between the hot stream R1851A Outlet (Stream No. 9) and the cold stream E-1855 Cold Inlet (Stream No. 6) in E-1855 and between the hot stream Desorbent Out (Stream No. 44) and the cold stream Desorbent Gas (Stream No. 31) in E-1863 (figure 4). The grass-roots HEN design did not satisfy the energy targets based on the 22.47 GJ/h total cross pinch based on the amount of cross heat flow above the pinch (19.04 6 GJ/h) being higher than that below the pinch. Retrofitting of heat exchangers thermally or mechanically effects changes in process streams properties or geometry, respectively.

A heat pump is a device that absorbs heat at low temperatures in the evaporator, consumes shaft-work when the working fluid is compressed, and rejects heat at a higher temperature into the condenser. The suitability of a heat pump in the isomerization process can be easily assessed against the process GCC, with the appropriate heat pump location the determinant problem for heat recovery. If the heat pump is located above or below the pinch point, the consumption of energy will increase. The most suitable location for the heat pump is thus at the pinch point of the process. In this situation, the heat pump receives Q_C (in the evaporator) from below the pinch point and loses Q_H (in the condenser) above it by using the compressor shaft-work. An expanding valve can be used to complete the cycle. The use of a suitable thermodynamic cycle should thus be investigated. A heat pump across the process pinch is available in the Utility Composite Curve (figure 5b) and appears to reduce both Cooling Water and LP steam utility use. The evaporator and condenser temperatures can be 29.5 and 150 °C respectively, which are also the Cold Water and MP Steam supply temperatures. The savings can be compared to the power consumption of the heat pump, where the economics of the heat pump are improved if it operates across a small temperature difference. In this study, the temperature of saturated LP steam is fixed but the cold-water temperature can be increased to 38 °C to improve the economics of the heat pump. LP Steam stream is represented at $\frac{1}{2}\Delta T_{min}$ colder and Cooling Water stream at $\frac{1}{2}\Delta T_{min}$ hotter than in practice in the Curve.

5. Conclusion

Generally, high-temperature hot utilities such as MP Steam at 150 °C are more expensive than low-temperature hot utilities such as LP Steam. The cost of MP steam is higher than that of LP steam; however, the 3.402e+007 KJ/h MP steam consumption was lower than the 8.190e+007 KJ/h LP steam consumption, resulting in a lower net cost for MP steam consumption. It is therefore important to maximise the use of lower temperature hot utilities to keep the total hot utility cost to a minimum. The GCC was used to place multiple utilities, including MP Steam, LP Steam, air, and Cooling Water. The below of the pinch point acted as an important source of energy, but there were no energy pockets in this situation to use for energy generation. Two cases were studied to enhance heat transfer in the isomerization process: using the energy pocket (above the pinch point) and a heat pump. The results showed the infeasibility of generating new hot utilities using the energy pocket, as the driving forces in the pocket would have to be large enough to justify adding the new levels of hot utilities. A heat transfer process was then used inside the pocket to allow intensified heat transfer to examine how the process of GCC could be used to select and match appropriate heating and cooling utilities. Heat pump application was the second case, which absorbed heat at 29.5 to 38 °C, consumed shaft-work, and output heat at 150 °C. The heat pump across the process pinch reduced both Cooling Water and LP steam utility consumption, which resulted in both energy and cost savings.

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