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Identification of Heat Integration Retrofit Opportunities for Crude Distillation and Residue Cracking Units

Adrian L. Querzoli, Andrew F. A. Hoadley† and Tony E. S. Dyson

The Department of Chemical Engineering, P.O. Box 36, Monash University, Vic. 3800, Australia
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Abstract−This study investigates improving the energy efficiency of two key refining processes: the Crude Distillation Unit (CDU) and the Residue Cracking Unit (RCU). The research methodology followed the 'targeting before design' approach. The CDU is a 'tightly pinched' system, with limited opportunities for further energy savings. The RCU actual ΔT_{min} is around 55 °C indicating a low level of current heat recovery. The Total-Site analysis shows that theoretically 18 MW of heat could be transferred from the RCU to the CDU, reducing CDU requirements by 40% for a new or grass roots design. RCU retrofit designs were developed to increase steam generation by up to 35% and in line with targeting estimates would appear to have economic potential. The alternative CDU-RCU retrofit design was developed to decrease CDU hot utility use. Although the Total-Site profile demonstrated strong potential for heat integration, this retrofit design is not commercially attractive, as the decrease in CDU fuel does not offset the cost of reduced steam generation. This demonstrates the need to consider the different fuel and steam costs in the Total-Site analysis.

Key words: Heat Integration, Retrofit Design, Heat Exchanger Networks, Pinch Analysis, Crude Distillation, Residue Catalytic Cracking, Energy Recovery

INTRODUCTION

There are numerous drivers for oil refiners to continue to improve energy efficiency and reduce emissions. This work investigates the potential to improve heat integration in two key refining processes, the Crude Distillation Unit (CDU) and the Residue Cracking Unit (RCU), using BP Kwinana Refinery as a case study. The problem will be considered from a retrofit perspective, with the aim of providing conceptual retrofit designs for the refinery to progress further.

In oil refining, retrofit designs are far more common than grass roots applications. The retrofit problem generally aims to achieve one or more of the following objectives:

- Debottleneck throughput.
- Decrease energy use.
- Compensate for changes in feedstock, product or other process specifications.

The specific objectives of this research were to:

1. Review the actual heat integration performance of the existing CDU and RCU processes and identify potential areas for improvement.
2. Develop retrofit designs and operating strategies to increase heat integration in the CDU, RCU and combined systems.
3. Determine the economics of the retrofit designs to assess if any of the options are commercially attractive.

†To whom correspondence should be addressed.
E-mail: andrew.hoadley@eng.monash.edu.au

LITERATURE

1. Previous Refinery Studies

The pioneering work of Linhoff [1984] and later Smith [1995] at UMIST has enabled Process Integration to evolve as a new field in chemical engineering. There are numerous successful industrial applications, typically decreasing energy costs by 30%. The original development of pinch analysis for Heat Exchanger Network (HEN) optimization has been broadened substantially to encompass advanced distillation design, aqueous and gaseous emissions, refinery hydrogen management and cleaner production. Linhoff [1993] has compiled a comprehensive state of the art overview that discusses these applications.

Liebmann et al. [1998], Papalexandri et al. [1998], Bagajewicz [1998] and Briones et al. [1999] have all recently investigated the heat integration of Crude Distillation Units. However, Fraser and Gillespie [1992] in their comprehensive energy study of an existing oil refinery in South Africa recommended that refinery pinch analysis studies should not concentrate exclusively on crude unit preheat trains. The crude and vacuum units accounted for 60% of the total refinery energy use, but only 30% of the potential energy savings. Crude units have a single dominant cold stream and many hot streams at different temperature levels, which makes it relatively easy to match properly streams without pinch technology. They identified the causes of surplus energy use as process to process cross pinch exchange (72%), unnecessary heating in unpinched systems (17%), and process to cold utility cross pinch exchange (11%).

Hassan [1997] and later Al-Riyami [1999] used pinch analysis for the retrofit design of a Fluidized Catalytic Cracking plant (RCU). The retrofit objective was to improve energy recovery and performance of the existing network. Al-Riyami used the incremental area efficiency method for targeting and the network pinch method for retrofit design. The existing network had a ΔT_{min} of 24 °C and an area efficiency of 81%. The incremental area efficiency method produced a target ΔT_{min} of 12 °C.

Little research seems to have been published on the integration of major refinery units such as the CDUs and RCUs. Lee et al. [1989] compared direct and indirect thermal integration to assess the integration of Fluid Catalytic Cracking and Crude Distillation Units. Indirect thermal integration, via heat transfer media such as steam, is often used to minimize disturbances and control problems. However, the disadvantages include the need to transfer heat twice and the lower exergy of the hot stream. Lee et al. reported that direct thermal integration halved the additional exchanger area requirements in comparison with indirect integration.

2. Process Integration Retrofit Methodology

Linhoff [1993] discusses the use of pinch technology to calculate energy "targets," such as the minimum required Hot and Cold utilities. This 'shortcut' approach enables many alternatives to be efficiently screened without actually carrying out the design. The Pinch Design Methodology to achieve the maximum heat recovery target assumes that no individual heat exchanger should have a ΔT smaller than ΔT_{min}. Once this assumption has been made, the Actual performance (A) will only meet the Targets (T) if there is no heat transfer across the pinch (XP). The basic pinch equation summarizes this relationship:

$$A=T+XP \tag{1}$$

ΔT_{min} is defined as the ΔT between Hot and Cold composite curves at the pinch point. This is a key design parameter in assessing the trade off between capital and energy costs. A HEN with a smaller ΔT_{min} will require greater exchanger area to compensate for less temperature driving force, and this results in higher capital cost. However, this is offset by lower energy costs due to improved process heat recovery and decreased hot and cold utility requirements. The HEN capital cost can be calculated by using the cost of capital as the discount rate. The capital and energy costs can then be added to calculate the total cost of the HEN.

Tjoe and Linhoff [1986] introduced the concept of area efficiency (α) to measure how efficiently the design utilizes the existing area. Area efficiency is defined as the ratio of minimum area required (target) to the area actually used (existing) for the existing energy recovery.

$$\alpha=\{A_{target}/A_{existing}\}_{existing\ energy} \tag{2}$$

Energy efficiency (β) is defined as the ratio of target energy usage to the actual energy usage at the existing area.

$$\beta=\{Q_{target}/Q_{existing}\}_{existing\ area} \tag{3}$$

In the case of both the area and energy efficiencies α and β, the target values correspond to a grass roots or new design. This results in retrofit designs with an excessive number of modifications, and failure to extract value from the existing HEN. Pinching matches within the existing HEN determine the location of the network pinch. A pinching match is an exchanger where the approach temperature unavoidably tends towards a limiting value as HEN heat recovery is increased (see Fig. 1).

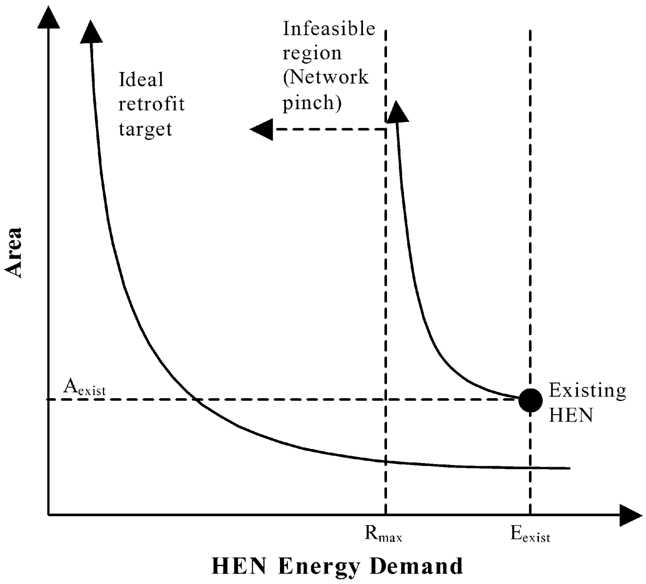

Fig. 1. The Network Pinch as a limit to heat recovery for the existing network.

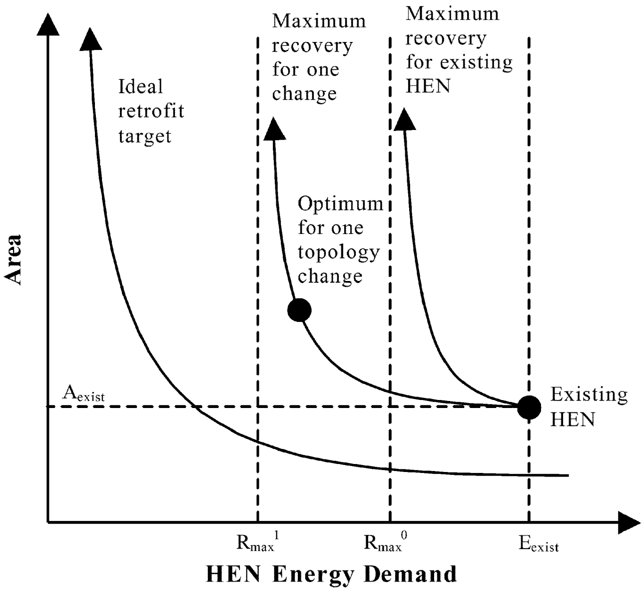

Fig. 2. HEN retrofit using topology changes to maximize heat recovery, followed by an optimization stage.

Asante and Zhu [1997] developed a two-stage methodology for HEN retrofit design using the Network Pinch. The first stage is a search for topology changes to maximize heat recovery and the second stage is the optimization of the fixed topology to evaluate the Capital-Energy trade off. The only way to overcome the network pinch is by changing the topology to shift heat from BELOW to ABOVE the network pinch (see Fig. 2). Each topology change creates a new network pinch and an optimal retrofit curve. Possible topology modifications include resequencing or repiping exchangers, adding a new exchanger and stream splitting. Resequencing involves changing the location of an existing exchanger, but maintaining the same hot and cold streams. Repiping involves changing

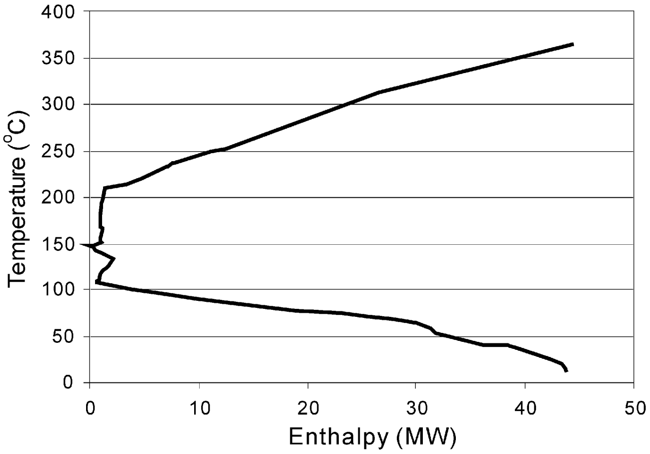

Fig. 3. Grand composite curve for the CDU average feed case, ΔT_{min}=30 °C.

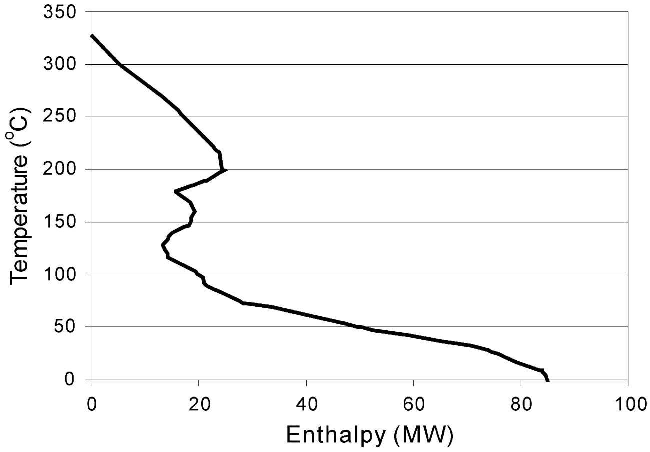

Fig. 4. Grand composite curve for the RCU, ΔT_{min}=45 °C.

Table 1. CDU utility summary for light, average and heavy feed cases (ΔT_{min}=30 °C)

Utility (MW)	Light		Average		Heavy	
	Target	Actual	Target	Actual	Target	Actual
Fired heat	41.8	42.4	43.4	45.0	40.4	45.1
MPS	1.7	0.0	1.0	0.0	0.0	0.0
Cooling water	46.4	46.7	42.5	45.4	33.2	38.9

Table 2. RCU utility summary for ΔT_{min} of 15, 30 and 45 °C

Utility (MW)	ΔT_{min} (°C)				
	15	30	45	60	Actual
Fired heat/MPS	0.0	0.0	0.0	0.0	2.4
MPS generation	20.6	18.8	13.5	8.1	10.0
Cooling water	64.4	66.2	71.5	76.9	77.4

the location of an existing exchanger and changing either the hot or cold stream. Adding a new exchanger involves creating a new match between hot and cold streams. Stream splitting involves rearranging exchangers in parallel.

RESULTS

1. CDU Case

Fig. 3 shows the Grand Composite Curve (GCC) for the CDU, assuming a ΔT_{min} of 30 °C. The CDU is 'tightly pinched' over the temperature range from 100 °C to 210 °C. Effectively, the process can be divided into an 'heat sink' above 210 °C, an 'heat source' below 100 °C, and 'heat balanced' from 100 °C to 210 °C.

Table 1 summarizes the utility requirements for the light, average and heavy feed cases and also the targets for these cases for a ΔT_{min}=30 °C. By combining both fired heat and MPS it is possible to calculate the energy recovery efficiency, β values, for the different CDU feed cases. $\beta_{heating}$ values of 102.6%, 98.7% and 89.6% for the light, average and heavy feed cases, respectively, show that the CDU becomes less energy efficient as the feed composition becomes heavier. Note that these energy efficiencies are taken relative to the target requirements set by the ΔT_{min} of 30 °C. The efficiency for the light feed of greater than 100% indicates that the ΔT_{min} is too high for this case.

The heat rejected to cooling water shows the same trend with the energy efficiency $\beta_{cooling}$ of 99.4%, 93.6% and 85.3%, respectively. However, the absolute cooling water requirement reduces with heavier feeds reflecting the change in the product mix from the column and the need to retain temperature in the heavier products.

The high β values and the tightly pinched GCC indicate that additional heat recovery within the CDU was likely to be difficult to achieve and therefore uneconomic. A retrofit analysis was performed by Querzoli [2002], which confirmed that the minimum payback for energy savings of 2 MW or greater was in excess of 6 years.

2. RCU Case

Fig. 4 shows the GCC for the RCU process with a ΔT_{min} of 45 °C. This is an example of a 'threshold problem', with surplus heat available at all temperature levels and zero hot utility required during steady state operation.

Table 2 summarizes the RCU utility targets for a range of ΔT_{min} and compares them with the actual utility use. Although the RCU does not require any hot utility, this does not mean the GCC and utility targets are meaningless. On the contrary, the availability of high level surplus heat creates opportunities for direct or indirect heat integration with other processes. In the first instance, we can measure this potential via the MPS generation target. The RCU energy efficiency can be defined as the actual MPS generation as a percentage of the target. As expected, higher values of ΔT_{min} cause a reduction in heat recovery potential, which in turn decreases the MPS generation target.

Comparison of the actual utility use against targets indicates the RCU is designed for a ΔT_{min} of around 55 °C. This is significantly higher than the CDU actual ΔT_{min} of 35 °C. It is not clear why the RCU was designed with such a large ΔT_{min}, which is likely to be outside the optimum 'capital-energy' range. One possible explanation is that the focus on heat recovery in the RCU design was poor, because the unit has so much surplus heat available and is a net heat supplier, i.e., MPS export to the refinery.

The RCU retrofit analysis assumes a ΔT_{min} of 45 °C. The pseudo grass roots methodology involves developing topology modifications to eliminate cross pinch heat transfer. In the case of the RCU, this refers to heat transfer across the utility pinch at 215 °C, which is created when MPS generation is maximized. Fig. 5 shows a grid diagram. It has been simplified to show only the main cross pinch

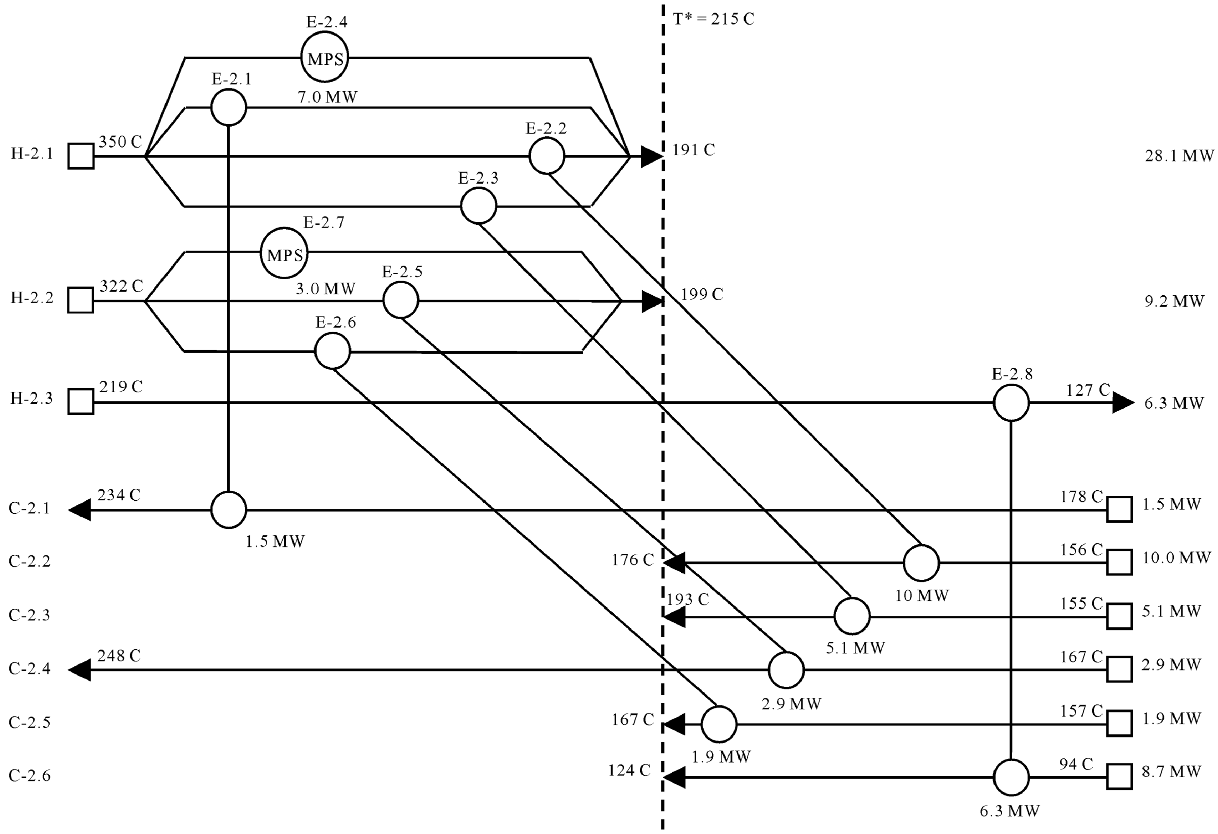

Fig. 5. RCU grid diagram, key streams and exchangers only.

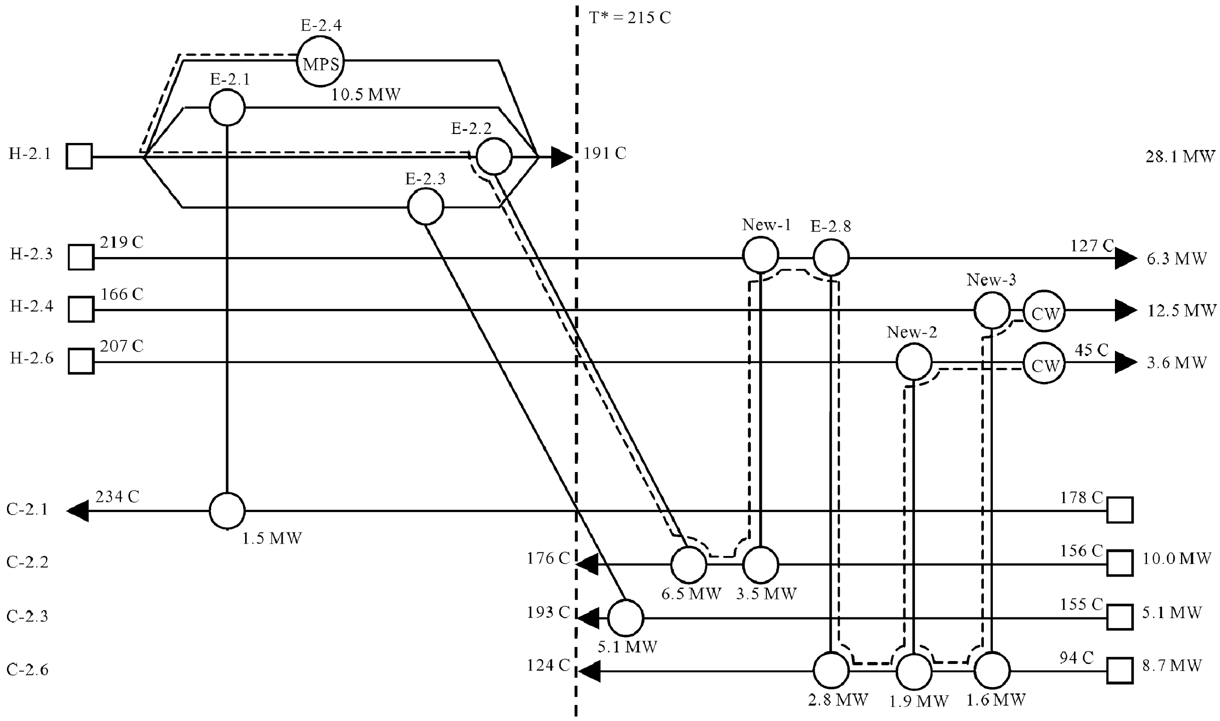

Fig. 6. RCU retrofit design 2-A, key streams and exchangers only. The utility paths are shown as dashed lines.

and utility heat exchangers. Querzoli [2002] gives further details of the stream conditions in his thesis.

Three different retrofit designs were developed, each one attempting to reduce the cross pinch heat transfer in either exchanger E-2.2 or E-2.3.

(1) Design 2-A generates additional MPS by installing an exchanger between H-2.3 and C-2.2. This modification decreases cross utility pinch heat transfer in E-2.2 by 3.5 MW, and therefore enables MPS generation (E-2.4) to be increased by 3.5 MW. This leaves C-2.6 in need of additional heat input, which is provided by H-2.6 and H-2.4 in two new exchangers. This design is demonstrated in Fig. 6.

(2) Design 2-B investigates decreasing E-2.3 duty instead of E-2.2. Stream C-2.3 must be heated to 193 °C, which results in a much lower New-1 hot-end approach temperature. The result is that New-1 requires twice as much area in this design compared with Design 2-A.

(3) Design 2-C shifts heat duty along the same utility path as Designs 2-A and 2-B, but only 1.9 MW additional MPS is generated versus 3.5 MW in the former two designs. This case was developed to test if an interim solution that recovers less MPS could in fact have better economics, due to a higher MPS recovery per unit of additional area required.

Area optimization was addressed as part of the retrofit design methodology. Designs 2-A and 2-C are sequential in the sense that as the duty of exchanger New-1 is increased, a point is reached where exchanger New-2 becomes pinched. At this point, if New-1 duty is to be increased further, additional heat must be provided to cold stream C-2.6 via exchanger New-3. Fig. 7 illustrates the area optimization of Designs 2-A and 2-C. This graph was used to determine additional MPS generation duty for each design, seeking to

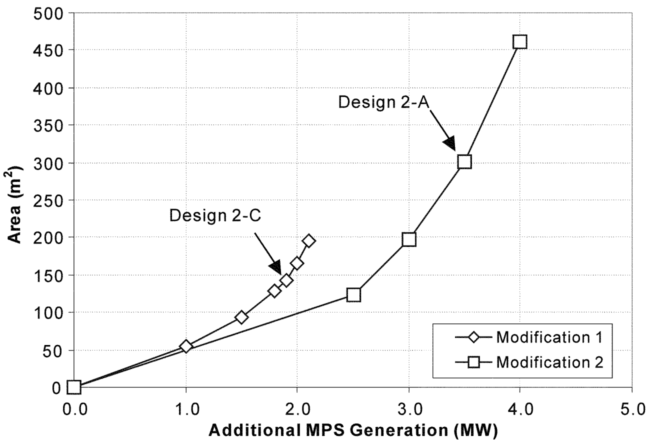

Fig. 7. Area optimization for RCU retrofit designs 2-A and 2-C.

Table 3. Summary of RCU retrofit design economics

Design	Cost (A$k)	Benefit (A$k)	Payback (yrs)
2-A	850	536	1.6
2-B	983	536	1.8
2-C	600	291	2.1

maximize MPS generation to the point at which the incremental area required per unit of additional MPS steam becomes excessive. One aim was to minimize the number of modifications with less than 50 m^2 additional area, as these relatively small modifications result in poor economies of scale.

The economics of the three RCU retrofit designs are summarized in Table 3. With a simple payback of 1.6 years, Design 2-A is commercially attractive and warrants further development. Design 2-C did prove to have a higher MPS recovery per unit of additional area with 75 kW MPS per m^2, compared with 80 and 140 kW MPS per m^2 for Designs 2-A and 2-B, respectively. However, the simple payback for Design 2-C was worse than Designs 2-A and 2-B. This reflects the poor scale of Design 2-C, which involves too many small modifications for too little MPS generation.

The RCU retrofit designs have substantially lower simple payback than the CDU retrofit designs, which ranged from 6 to 10 years. This is partly explained by the difference in ΔT_{min} for the two processes. The RCU has a significantly higher ΔT_{min}, which means energy efficiency can be improved with less additional area and therefore lower capital cost. A further reason for the superior RCU retrofit economics is the capability to generate MPS, since the refinery places a higher value on MPS than fired heat.

3. CDU-RCU Integration

After assessing the CDU and RCU systems separately, it is apparent that the processes are compatible and that the combined system has strong heat integration potential. In particular, the CDU process is heat deficient above 200 °C, whereas the RCU has a heat surplus above 200 °C. Fig. 8 shows the total site profile for the CDU-RCU combined system, indicating potential to integrate 18 MW at a temperature level of 260 °C, which would reduce the CDU fired heat duty by 40% (to 26.5 MW). This could be achieved via direct integration (eg., Slurry circuit) or indirect integration (eg., VHP steam main or hot oil circuit).

There is generally scope for heat integration between two processes when the pinch temperatures are significantly different. In this case, the CDU process pinch at 195 °C and the RCU utility pinch at 215 °C are quite close together, which minimizes heat integration potential. This means that if energy is transferred from the RCU to the CDU, then less MPS will be generated. Generally, the designer seeks to maximize the use of hot utilities at the lowest pos-

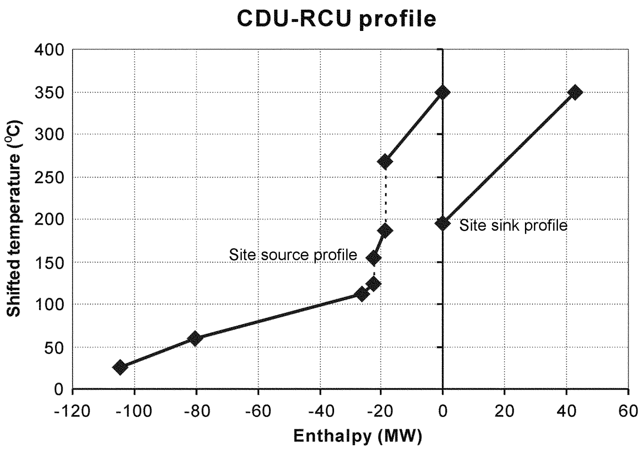

Fig. 8. CDU-RCU total site profile, ΔT_{min}=30 °C.

sible temperature level (eg., LPS 1st, MPS 2nd, Fired heat 3rd) and maximize the use of cold utilities at the highest possible temperature level (MPS generation 1st, LPS generation 2nd, cooling water 3rd, refrigeration 4th). This philosophy would encourage the integration of these units at the expense of MPS generation. However, the unusual utility economics in this study alters the normal strategy for utility placement. The cost of MPS is 1.6 times the cost of fired heat per MW absorbed. Therefore, fired heat should be used preferentially as hot utility rather than MPS.

To illustrate the impact of the relative utility costs, a retrofit design to achieve 7.0 MW reduction in the CDU furnace duty was identified. This option also incurred a 7.0 MW decrease in RCU MPS generation. This proposed retrofit results in a net increase in operating costs due solely to the difference in utility costs, without considering the cost of additional equipment.

DISCUSSION

This case study highlights two aspects of heat integration pertaining to the plant retrofit situation. The first aspect is the value of energy targeting together with an understanding of the Grand Composite Curve for identifying realistic opportunities for energy recovery.

In this study the CDU case gave a good example of a process where further energy recovery was likely to be difficult and therefore not economic. The energy recovery efficiency β values were high for a ΔT_{min} value, which was likely to be close to an economic optimum. Furthermore, the Grand Composite Curve shape showed a tightly pinched profile over a wide range of temperatures. This indicated that effort had already been expended in the original design to maximize heat recovery and further recovery would need to span this "pinched" range thus involving a large number of hot steams.

For the RCU, the β value was defined for a threshold situation on the basis of MPS generation compared with the target value. In contrast with the CDU, the RCU showed a significant inefficiency in the current design. Also, the GCC only became tightly pinched, below the MPS generation temperature and only when MPS generation had been maximized.

Commercial process simulators are now linked to process integration tools for automatically generating utility targets, composite and Grand Composite Curves. Therefore, if a reasonably accurate process model is available, the energy recovery efficiency can be obtained and an initial investigation of retrofit energy saving can be made with relative ease.

The second aspect of importance from this study is that energy savings do not necessarily equate to energy cost savings, even before the cost of capital is included. Makwana et al. [1998] provides a methodology for targeting utility energy savings called "Top Level Analysis," which can be used to determine the relative savings of low, medium and high pressure steam in $/t of steam saved. Top level analysis applied to this study would give a cost of MP steam in $/MW generated and a cost of refinery fuel gas also in $/MW saved. The calculation of these two costs would direct the designer to maximize MP steam generation, if necessary to the detriment of fuel gas usage, up until some limit on MPS or fuel gas is reached. A prior knowledge of these costs would have eliminated the CDU-RCU case, prior to making any integrated design.

The CDU-RCU case also highlights the significant difference between grass roots and retrofit problems. A significant portion of the benefit for CDU-RCU heat integration is the reduced CDU fired heater duty, but in the retrofit problem the heater capital cost has already been spent. In the grass roots problem, the size of the heater would be decreased substantially (by up to 40%), and this potentially creates significant capital cost savings.

CONCLUSIONS

A heat integration analysis was performed on two major refinery units. A two-stage method was used with initial targeting followed by a retrofit analysis. The latter focused on reducing the ΔT_{min} of the pinching network exchangers. The analysis, therefore, took into consideration the current network topology and attempted to minimize topology changes.

In the case of the CDU, preliminary targeting and energy recovery efficiencies indicated that further energy recovery was unlikely to be economic. A retrofit design was carried out and heat recovery of an additional 2 MW had a payback of around 6 years. This is not economic in the current refinery climate. In contrast with the case of the RCU, the preliminary targeting and energy recovery efficiencies indicated a significant opportunity for further energy recovery. A retrofit design was conducted, including the heat exchange area optimization of the pinching exchangers. The retrofit design for an additional 3.5 MW of MPS had a payback of 1.6 years and is likely to be economic.

The integration of the CDU and RCU was investigated, and from a Total Site Analysis it appeared to offer a large potential for hot utility savings (40% reduction). However, because these savings could only be achieved through a reduction in MPS generation, the integration of the two units had a negative economic return. This case illustrates the value of conducting a "Top level analysis" to determine relative utility costs prior to making any heat integration study.

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