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Experiences from Using Heat Integration Software to Determine Retrofit Opportunities within a Refinery Process

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Abstract−Heat integration techniques can be used to optimize the energy requirement for both new and retrofit plant designs. Software tools for identifying retrofit options are becoming available. This paper reports our experiences from using heat exchanger network (HEN) optimization software for a retrofit case study of an oil refinery process. The HEN optimization software was used to automate the search for the most beneficial retrofit designs following the two-stage process proposed by Asante and Zhu. The software provided three potential retrofit designs. Results from this analysis were used as the basis of a rigorous mass and energy balance simulation of the plant. The simulation corroborated the energy savings, but there were some important differences. The simulation required 20% more heat exchange area. Furthermore, the retrofit design involving one topology change was shown to be less economic than an alternative design. These differences are discussed and a revised methodology is proposed.

Key words: Heat Integration, Retrofit Design, Heat Exchanger Networks, Dewaxing, Energy Recovery

INTRODUCTION

Pinch analysis of Heat Exchanger Networks (HENs) is a well-known technology that is now universally applied to the design of continuous processing plant and is also widely taught to undergraduate students of Chemical Engineering [Linnhoff et al., 1982]. Process simulation packages which carry out steady-state mass and energy balances have for some years provided pinch analysis tools to assist the process designer [Aspentech, 2002; Hyprotech, 2002; Simsci, 2002].

More recent advances by Zhu et al. [1995] have concentrated on the design of HENs as a mathematical optimization problem rather than the classical thermodynamic approach. This approach is more able to take into account the capital cost of the heat exchangers and issues associated with individual stream matches. Greenfield designs can begin with a superstructure, where every hot stream is linked by heat exchangers to every cold stream. Mathematical optimization based on an economic objective function is used to reduce the structure by determining which of the links are redundant. These techniques are also beginning to become available as additional features of the commercial simulation packages.

It can be argued that the retrofit design of existing HENs is an even more difficult mathematical problem than the design of new (or greenfield) HENs, as new links within the existing structure or network topology must be found. For a given topology, the overall heat exchange area can be increased (and the network ΔT_{min} decreased) to reduce energy consumption. This becomes a capital versus energy cost reduction trade-off, since as the area is increased, so too will the capital costs. For each network, there will be an optimal ΔT_{min} such that the overall cost is lowest.

In some cases, the maximum heat recovery condition cannot be obtained due to a match in the network that violates the minimum approach temperature value, which has been set by the designer. Asante and Zhu [1997] define the approach temperature difference at which this occurs as the network pinch. The pinching matches at the network pinch highlight the bottleneck in the network. This can be observed in Fig. 1. As the heat duty is reduced, the slope of each topology curve increases, as the ΔT_{min} for the pinching exchangers approaches zero.

Asante and Zhu [1997] developed a two-stage retrofit design methodology. In the first stage, the existing topology is modified in order to move heat from below to above the network pinch point, thereby reducing the utility requirements. This is illustrated by the topology modification curves in Fig. 1.

The topology changes suitable for retrofit design are:

• Resequencing heat exchangers in the system, i.e., by putting the same exchanger and associated piping in a different position within the network.

• Creating a new exchanger match, i.e., installing a new exchanger

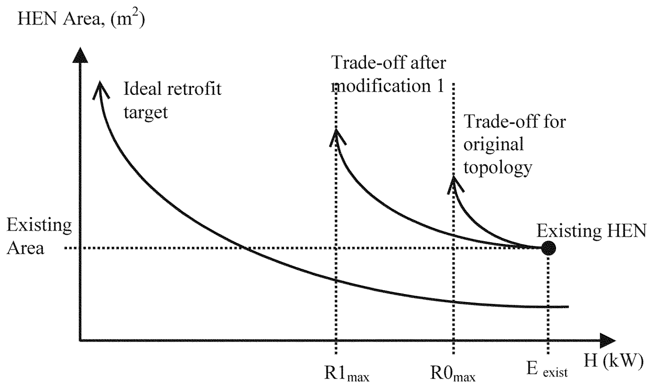

Fig. 1. Curves of heat exchange area versus heat load show how network topology changes are used to overcome the network pinch and approach the retrofit target.

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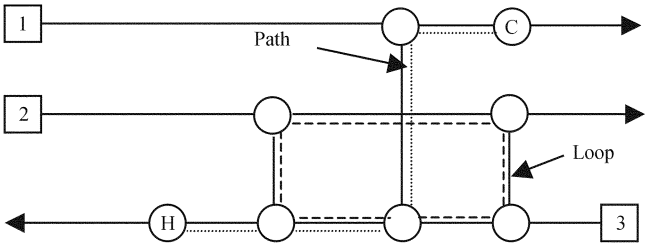

Fig. 2. Example of loop and utility path in network grid.

in the system.

• Stream splitting, e.g., installing new piping to partially bypass one or more exchangers.

The second stage in the retrofit methodology is to re-optimize the area-energy trade-off, i.e., to find the new optimal ΔT_{min}. This is achieved by identifying the loops and utility paths in the heat exchanger network, and then shifting the heat loads through each, respectively, until the minimum approach temperature for the network is reached. An example of a loop within a network grid is shown in Fig. 2. Heat loads can be shifted from one exchanger to another on the same stream, so that there is no net change in heating/cooling duty of each stream. A utility path occurs when hot and cold utility exchangers on different streams are linked by process exchangers. As depicted in Fig. 2, increasing the heat transfer in the process exchanger reduces both the hot and cold utilities for the utility path.

RETROFIT CASE STUDY

1. Dewaxed Oil Solvent Recovery Plant

At the Mobil Adelaide Lubricating Oil refinery, the main hot utility is steam generated by on-site boilers. A shortage of steam causes the lubricating oil production rate to be decreased. The largest user of steam in the Lubricating Oil refinery is the solvent dewaxing plant, known as the MEK (methyl ethyl ketone) unit. The purpose of the MEK unit is to remove the waxy components from the lubricating oil to improve its low temperature performance. After the separation of wax from the feed oil, the dewaxed oil (DWO) is sent to the solvent recovery section of the plant. In this section of the plant, high temperatures are used to remove the solvent from the final product. In a similar fashion, the wax and solvent is also separated in the slack wax (SW) recovery section.

Both medium pressure (MP) and high pressure (HP) steam are used in the MEK recovery sections as hot utilities to heat the wax or oil and solvent streams. During periods of limited steam availability, the MEK charge rate will be reduced. The objective of the case study was to save steam through better heat integration. In addition to the energy savings, a steam reduction would assist the plant to operate at higher throughput, during periods when its availability was limited.

The case study was conducted in two phases. In the first phase UMIST Centre for Process Integration [2002] software, ***Sprint*** (v1.5) was used to obtain a number of retrofit designs. In the second phase, a process simulation was used to confirm the retrofit analysis results.

2. The Existing Heat Exchanger Network

The MEK unit consisted of two solvent recovery processes, the

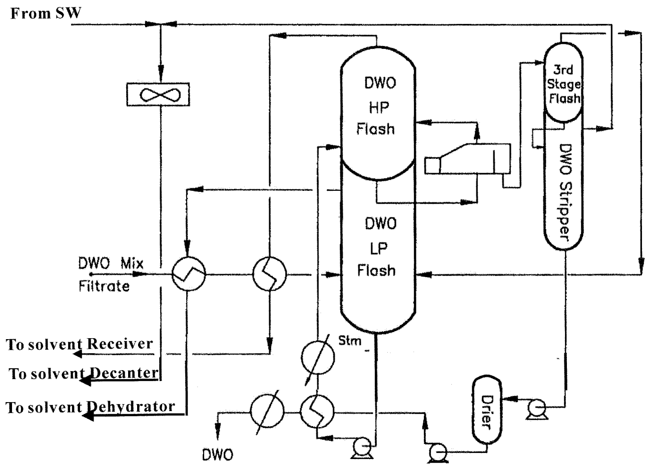

Fig. 3. Simplified process flow diagram for the Dewaxed Oil (DWO) section of the solvent recovery plant.

dewaxed oil (DWO) solvent recovery section and the slack wax (SW) solvent recovery section. The initial aim was to investigate both processes together. However, this proved to be too complex. As the DWO and SW sections are not presently integrated, it was decided to simplify the analysis to search for heat recovery within each system separately. This meant that energy saving which may result from the integration of the two systems would not be discovered. However, the simplicity of the existing arrangement from an operational viewpoint would be retained. The case study concentrates on the larger of the two solvent recovery sections, the DWO recovery section. However, due to the similarity of the two processes, similar opportunities for energy savings may be obtained from the SW system.

The DWO solvent recovery plant consists of a three-stage flash separation process, as depicted in Fig. 3. It is dominated by two cold streams. Cold stream 1 is the feed to the low pressure vessel and cold stream 2 takes the low pressure flash bottoms and passes these to the high pressure flash vessel. There are three dominant hot streams consisting of the two solvent vapor streams and the final dewaxed oil product rundown.

The grid diagram for the simplified network is shown in Fig. 4, with heat exchangers shown linking the hot streams (lines drawn from left to right) with the cold streams (lines drawn from right to left). Exchanger data including F_t factors and overall heat transfer coefficients, U, were required for all the existing exchangers in the DWO recovery sections. Economic data for equipment capital and energy costs were included so that a full retrofit analysis could be carried out and the different options could be compared. Details of both the stream and cost data are provided by Phipps [2002].

With the exception of exchanger 1 (E1), which had an approach temperature of 29 °C, the network had a minimum approach temperature ΔT_{min}=43 °C. The hot utility usage (MP and HP) was 10.13 MW compared with a theoretical or target of 9.17 MW. The difference of 0.96 MW was cross-pinch heat transfer that occurs in the air coolers. The high network ΔT_{min} indicates that increased heat recovery should be economic.

From the existing grid, three retrofit designs were sought involving using the ***Sprint*** software:

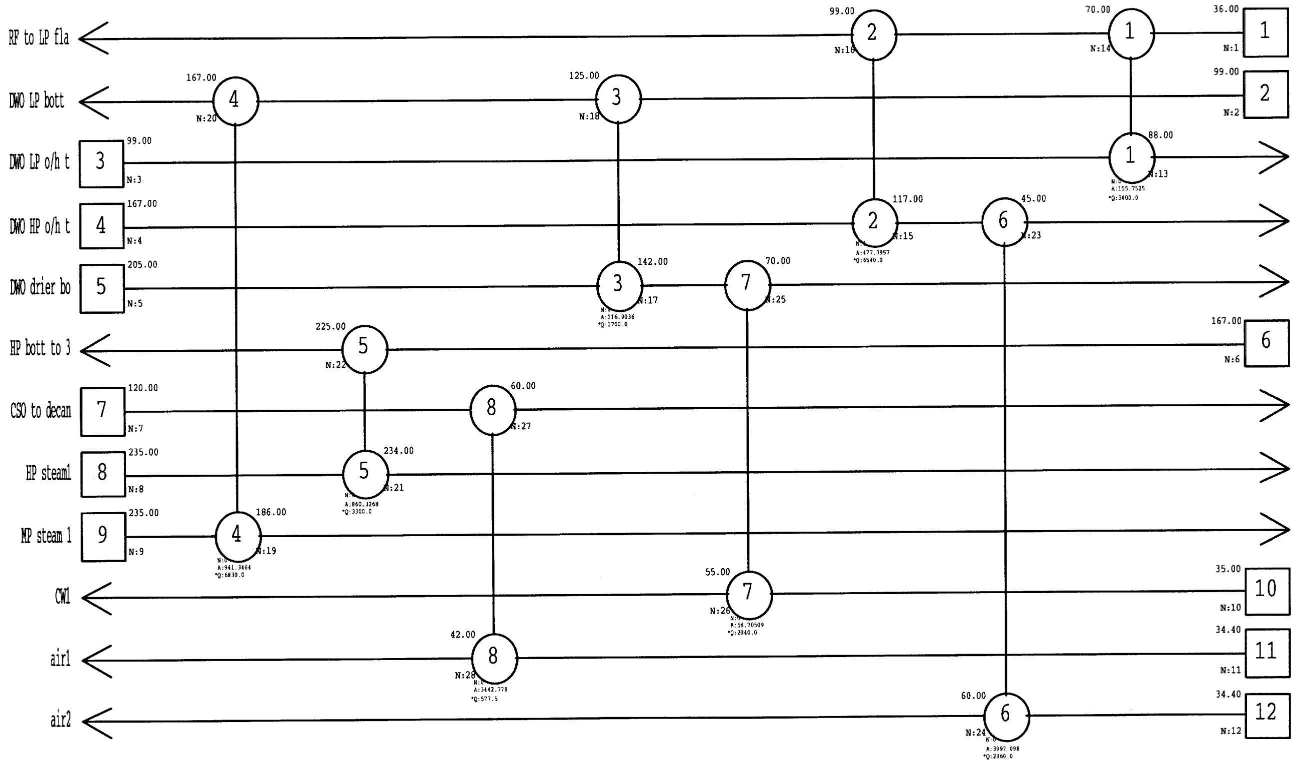

Fig. 4. Network grid diagram for DWO recovery section.

a) The heat exchange area optimisation of the existing HEN
b) One HEN topology change and area optimization
c) Two HEN topology changes and area optimization.

RESULTS

1. Base Case Optimization for the DWO Network

Table 1 shows the results of the ΔT_{min} optimization for the case where there are no topology changes. Heat exchange area was added to E3 only, as a result of shifting heat loads through the utility path connecting exchangers E4, E3, and E7, until the specified minimum approach temperature for E3 was met. Note that some area had to be added to E3, just to bring the ΔT_{min} for this exchanger to the initial network ΔT_{min}=29 °C, set by E1.

2. Retrofit Design with One Topology Change

The three strategies of overcoming the network pinch were re-

Table 1. ΔT_{min} optimization for the base case retrofit design

ΔT_{min} (°C)	Area added to E3 (m^2)	Capital cost (A$)	Energy saved, (kW)	Q_H (kW)	Q_C (kW)	Savings (A$/yr)	Payback (years)
43	Base case	-	-	10130	4978	-	-
29	114.9	135766	623	9507	4355	87320	1.555
20	123.4	142930	652	9478	4326	91399	1.564
18	141.6	158180	708	9422	4269	99347	1.590
15	173.6	185071	793	9337	4185	111269	1.663
10	247.2	246828	935	9195	4043	131138	1.882
5	378.8	357290	1077	9053	3901	151007	2.366

Table 2. *Sprint* results for the first topology change

Trial	Exch.	Min hot utility (kW)	Hot utility change (kW)	Cost (A$/yr)	% Change
1	9	9143	590	0.1360E+07	6.06
2	9	9399	334.3	0.1396E+07	3.43
Trial	**Exch.**	**Hot stream**	**Outlet of unit**	**Cold stream**	**Outlet of unit**
1	9	4	Start of stream 4	2	Exchanger 3
2	9	4	Start of stream 4	2	Start of stream 2

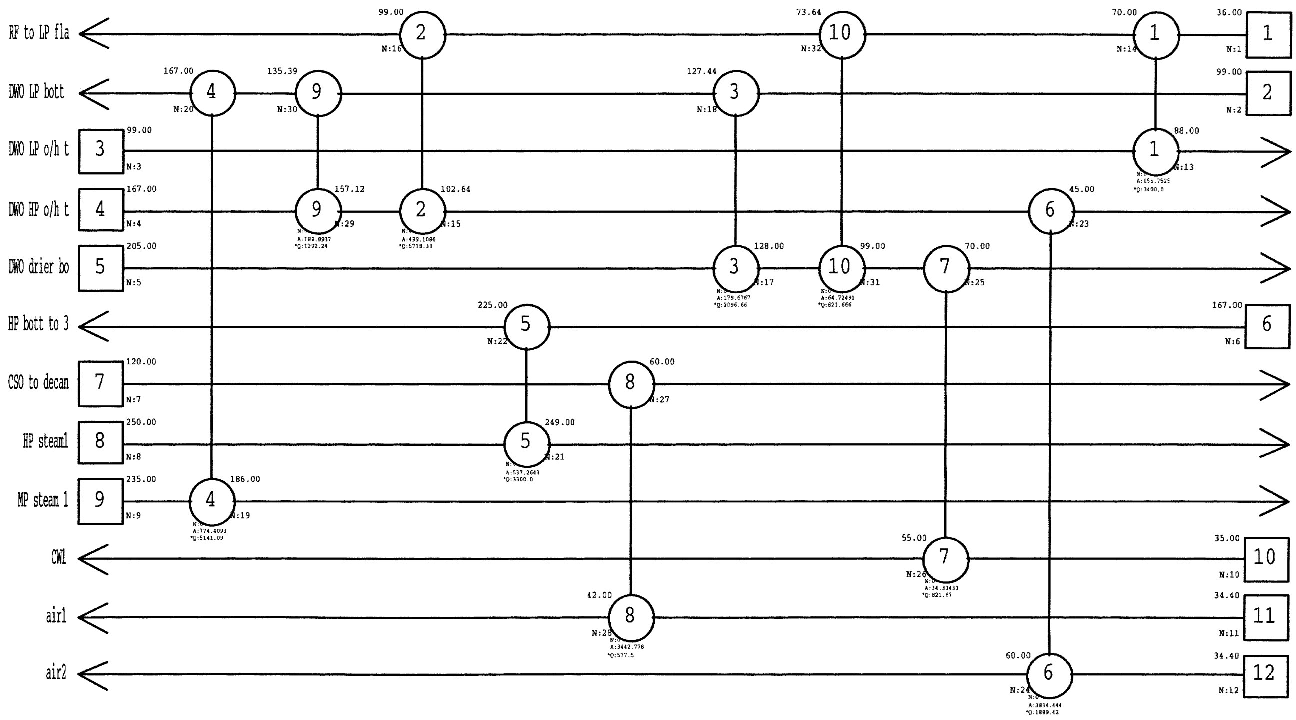

Fig. 5. Grid diagram for one (E9) and two topology changes, (E9 and E10) added.

Table 3. ΔT_{min} optimization for the HEN with E9 added

ΔT_{min} (°C)	Total area added (m^2)	Capital cost (kA$)	Utility duty change (kW)	Q_H (kW) 10130	Q_C (kW) 4977.5	Savings (kA$/yr)	Payback (years)
29 (not optimized)	191.95	279.2	987	9143	3991	145.0	1.93
18	402.5	455.9	1673	8457	3305	245.2	1.86
16	434.8	483.0	1752	8378	3226	256.8	1.88
15	460.5	504.6	1811	8319	3167	265.4	1.90
10	619	637.7	2107	8023	2870	308.7	2.07
5	913.1	884.4	2446	7684	2532	358.4	2.47

searched by using ***Sprint***. No beneficial options were obtained for using the existing heat exchange area with a different topology, through resequencing or repiping any of the exchangers. The Sprint output for adding a new exchanger, with a minimum exchanger approach temperature of 29 °C, is given in Table 2.

Table 2 shows that two options were obtained, with the first option having almost twice the energy recovery (6.1% reduction compared 3.4% reduction). Both options involved exchanging heat from the hot stream 4 (167 °C) with cold stream 2, either after E3 (125 °C) or at the start of the stream (99 °C). Note that both options are above the pinch. Although less heat is recovered by the second option, the higher temperature difference means that less new area is required.

Option 1 was selected as the most beneficial and the new exchanger was given the tag E9. The grid diagram is shown in Fig. 5. Following the methodology of Asante and Zhu, the second stage was to conduct an energy versus exchanger area optimization similar to the base case analysis, but with the new HEN topology. By adding E9, an additional utility path was created which links E4, E9 and E6. The amount of heat shifted through the paths was optimized such that the overall cost was lowest. However, locating E9 on stream 4 has the effect of pinching E2 and as a result, as the ΔT_{min} was re-

Table 4. *Sprint* results for two topology modifications

Trial	Exch.	Min Q_H (kW)	ΔQ_H (kW)	Cost (A$/yr)	% Change
1	10	8441	702	0.1263E+07	7.68
2	10	8746	398	0.1309E+07	4.35
3	10	8842	301	0.1318E+07	3.29
4	10	8842	301	0.1318E+07	3.29
5	10	8971	173	0.1334E+07	1.89

Trial	Exch.	Hot stream	Outlet of unit	Cold stream	Outlet of unit
1	10	5	Exch. 3	1	E1
2	10	5	Start of 5	1	E1
3	10	5	Start of 5	1	E2
4	10	5	Exch. 3	1	E2
5	10	7	Start of 7	1	E1

duced; the areas of the pinching exchangers, E2, E3, and E9 were all increased. Details of the optimization are shown in Table 3. Table 3 also shows that the financial payback is flat over a wide range of ΔT_{min}.

3. Retrofit Design with Two Topology Changes (E9 and E10)

The three options for topology changes were again evaluated for the retrofit HEN with E9. Once again, there were no beneficial results for re-sequencing or re-piping. The results for the option of adding a new exchanger, E10, are shown in Table 4. This time five options were obtained with the top four recovering some heat from hot stream 5 above the pinch. The first and most beneficial option was chosen, which created a new match, E10, between streams 1 and 5. This is shown in the network grid diagram in Fig. 5.

The addition of E10 created one new loop (E2-E9-E3-E10-E2) and two new utility paths that could be included in the optimization procedure. As for the addition of E9, the second step involving the economic optimization was carried out for reducing ΔT_{min}.

In summary, by optimizing the original HEN by adding area to E3, approximately 700 kW of MP steam may be saved. With a single topology change, adding E9 and increasing the existing area of E2 and E3, the reduction in steam is predicted by ***Sprint*** to be 1,750 kW. By adding both E9 and E10, a savings in MP steam of 2,460 kW is predicted.

4. Process Simulation of Retrofit Options

The flowsheet simulation software ***ProII*** with Provision, Simsci [2002] was used to validate the retrofit designs for the DWO recovery section. Initially, heat exchanger area was added according to the most beneficial trials obtained from the Sprint optimization work. Fig. 6 shows the results of the PFD ProII simulation optimization of energy versus area, and the comparison with the results obtained from Sprint. This figure shows that the Sprint output over-estimates the potential energy that can be saved by increasing exchanger area.

Accounting for about 40% of the error was the difference in the increased area required in the ***ProII*** simulation for E3, for a similar duty. This occurs because the LP flash vessel operates at a fixed pressure rather than a fixed temperature; therefore an increase in the feed temperature of stream 1 increases the starting temperature of stream 2 and with a greater LP flash the flowrate of both streams 2 and 4 are reduced.

Also ***Sprint*** under-predicted the area required for the new exchanger E9, due to the estimate used for the overall heat transfer coefficient. This accounted for the remainder of the error.

A retrofit design option not identified by ***Sprint*** was the addition of E10 (without E9). The optimization curve in Fig. 7 for the new

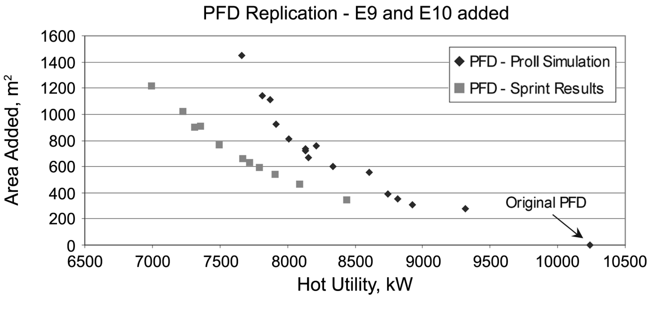

Fig. 6. Comparison of *Sprint* and *ProII* curves of heat recovery versus added area.

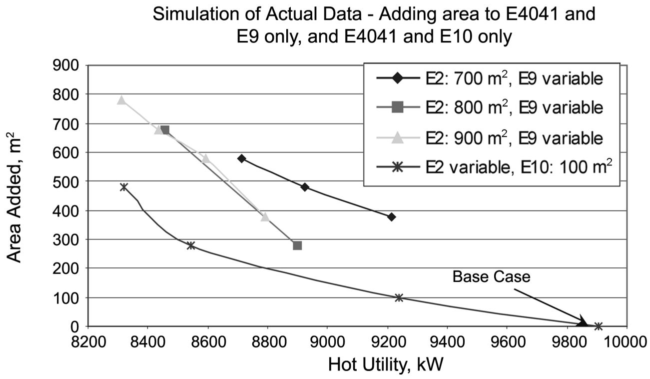

Fig. 7. *ProII* results showing additional area versus steam utility demand for one topology change.

exchanger E10 and additional area for E2 is considerably shallower than the curves for E2 and E9. This means that for adding a similar amount of total area, a greater steam saving can be achieved.

DISCUSSION

The first consideration is the size of the heat exchanger network that can be considered for retrofit analysis. When both sections of the solvent recovery plant were considered together, the software took a long time to reach a solution for each of the retrofit options tested. This is because the number of trials for a single topology change is related to the potential for creating loops and utility paths within the network. The number of topology changes to be tested is roughly equal to the product of the number segments (between existing exchangers) of hot and cold streams. Simplifying the network in order to consider just the DWO section reduced the number of trials for the first topology change from more than 100 to 21.

It was also difficult for the user to identify which exchangers were the pinching matches, and which loops and paths were being used to shift heat loads through the network. Identifying the loops and paths within the system is essential to understand the ΔT_{min} optimization and the outputs from the different trials. To avoid these problems it was essential to simplify the analysis. For this case study, this meant considering just one section of the solvent recovery plant and ignoring all the streams that were not critical, i.e., those that did not affect the pinch point. As a general rule, it is recommended that the network chosen for retrofit analysis be broken down into manageable areas, i.e., less than 15 streams in one area.

The use of the automated heat exchanger network retrofit software significantly reduced the amount of time, which would otherwise have been spent carrying out "trial and error" simulations. These simulations would have needed to investigate the retrofit options involving the repiping of existing exchangers in different locations. The ***Sprint*** automated trials quickly determined that there were no beneficial retrofit changes available for these options in this case study. ***Sprint*** also determined good options for the location of new exchangers within the network, without the need for extensive simulation trials.

It is of some concern that ***Sprint*** missed the best option for the single topology change, selecting to install E9 rather than E10. Inspecting the grid diagram in Fig. 5, the only utility path created by

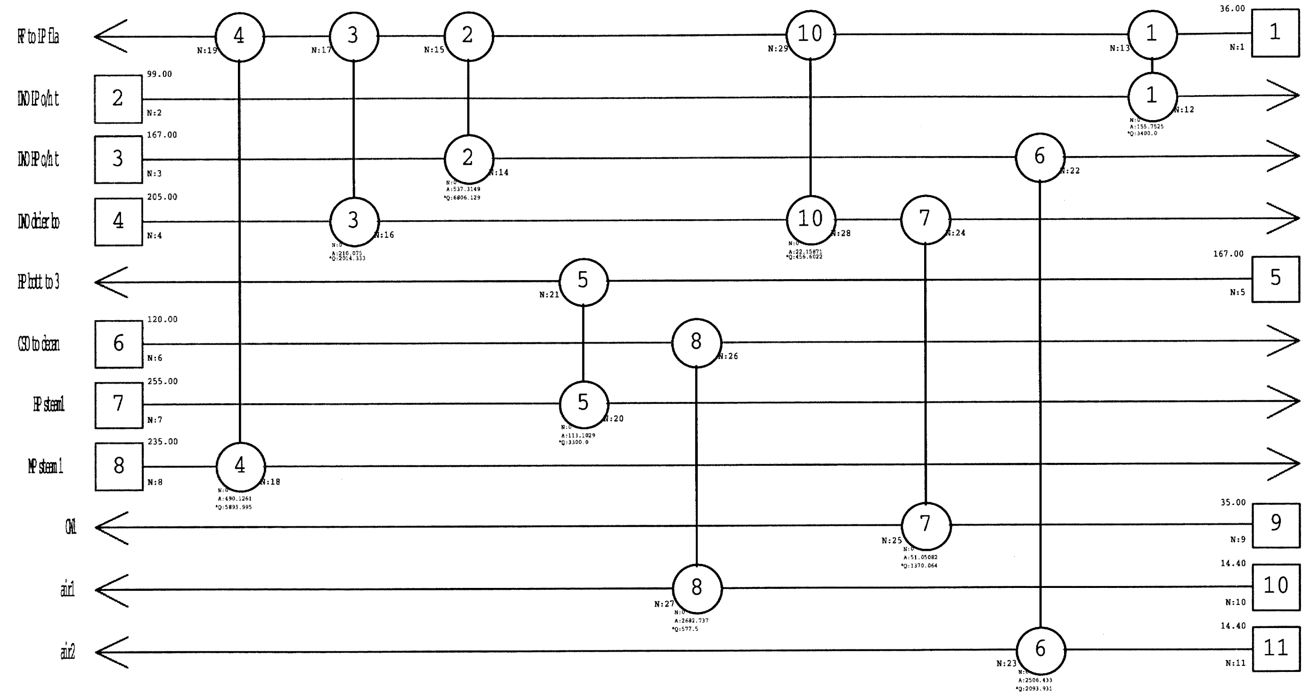

Fig. 8. Modified grid diagram, streams 1 and 2 combined and one topology changes.

E10 (without E9) involves the sequence (E4-E3-E10-E2-E6). Reducing hot utility (E4) along this path will involve increasing the duty of exchangers E3 and E2 and reducing the duty on E10 and E6, thus making E10 redundant. However, if we redraw the grid diagram combining streams 1 and 2 as a single stream (unbroken by the LP flash vessel), as depicted in Fig. 8, now the best option discovered by ***Sprint*** for the first topology change is the position occupied by E10 in Fig. 5. At a ΔT_{min}=21 °C, approximately 15% more energy is recovered using E10 for the same amount of additional area.

This highlights the need for the designer to take particular care with the initial selection of streams. The LP Flash vessel was an obvious breakpoint for the feed stream. However, as there was no hot utility used to heat stream 1, the effect of fixing the target temperature going into the LP flash vessel meant that this stream did not have a degree of freedom that could be exploited in the retrofit design, until a loop was created after the second topology change. By combining the two feed streams thereby permitting the LP flash vessel temperature to float, provided a degree of freedom through E4 to the whole stream including the feed to the LP flash vessel.

Care still needs to be taken to ensure that the flowrates of the overhead streams in particular are being correctly simulated as these flowrates will change with the flash conditions. The HEN software is not a process simulation and cannot predict how increased heat recovery will change the process. Ultimately, the process stream conditions need to be checked for the new heat exchanger topology. Therefore, there will always be a need to conduct a process simulation for the retrofit design to ensure that quality constraints are still being met. Similarly, hydraulic constraints (not a considered in this paper) would also need to be checked.

The other source of discrepancy between the process simulation and the retrofit analysis was the heat exchange area prediction for new exchangers. The default values to be used for new exchangers are not necessarily going to be accurate. An intermediate step in

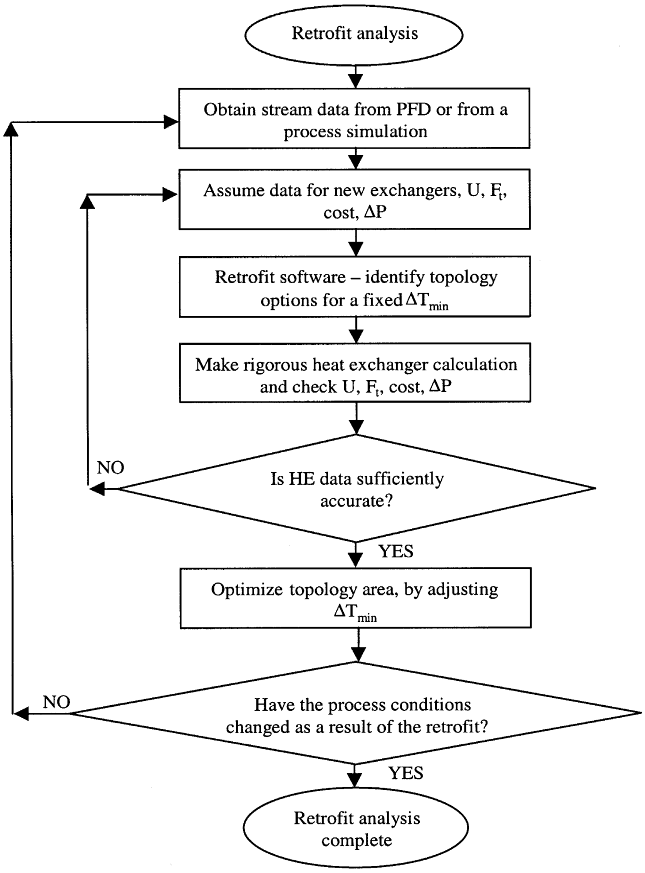

Fig. 9. Revised methodology for heat exchanger retrofit analysis.

the retrofit design methodology is warranted. This would involve using the output from the software to make a rigorous heat exchanger calculation to check that the assumptions made in regard to film heat transfer coefficients and F_t factors were at least conservative. After checking this data, it may be necessary to rerun the retrofit analysis.

Following this study, a revised flowsheet of the methodology for retrofit heat exchanger design has been developed in Fig. 9. This flowsheet shows two additional checks. The first is on the heat exchanger data used in the search for the best topology options. The second check is on the stream table data obtained from a process simulation.

CONCLUSIONS

The case study of the heat exchanger network retrofit for the MEK solvent recovery plant has demonstrated the value of using HEN optimization software. Good retrofit options were obtained efficiently.

However, from this study, it is suggested that the heat exchanger network being investigated should be simplified as much as possible, with an upper limit of 15 streams. This will enable the user to stay in control of the optimization, by being able to understand the results. Furthermore, this study has highlighted the care that must be taken in extracting stream data from the process flowsheet. Streams that do not use either hot or cold utility need particular attention in order to determine whether they are able to participate in the retrofit analysis.

It has also been shown that less efficient topology changes can be obtained from the software, if inaccurate heat exchanger data is assumed. Another source of error occurs if the process conditions are affected by additional heat recover. A revised retrofit methodology has been proposed with additional checks on both the heat exchanger data and the process stream data, in order to ensure that the retrofit analysis accurately represents the process and the process economics.

ACKNOWLEDGMENTS

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