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Energy savings horizons for the retrofit of chemical processes. Application to crude fractionation units[1]

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Abstract

This paper focuses on presenting a technique to calculate energy retrofit horizons in process plants. In particular, it focuses on crude fractionation units. The methodology takes advantage of two facts: (a) Pinch-type calculations can be performed using operator type representations and (b) Processes like crude fractionation offer large flexibility in the operating/design parameters. This paper builds on the well-known sequential technique of performing pinch analysis after fixing operating conditions, particularly including heating and cooling targets. The paper analyzes the mathematical properties of the newly introduced implicit pinch operator. © 1998 Elsevier Science Ltd. All rights reserved.

1. Introduction

Pinch technology has been extensively used to identify energy saving opportunities in the process industry. A thorough review of the principles and applications of this technology was published recently (Linnhoff, 1993). All these grassroots and retrofit design techniques have been applied assuming that the operating conditions of the process are fixed. In the case of grass root designs as well as in retrofit applications the Plus/Minus principle based on the Onion Diagram was proposed (Linnhoff et al., 1982, Linnhoff and Parker, 1984). The procedure suggests identifying energy saving opportunities by analyzing the grand composite curve of a particular design. The procedure works well when the changes have no other effect than the identified. Linnhoff (1993) cites the example where a pressure decrease in a distillation column decreases the temperature of both the condenser and the reboiler leading to energy saving opportunities under the assumption that the product temperatures have little or no effect on the rest of the flow sheet. Thus, in the presence of strong interactions, the procedure can be very difficult to implement as described.

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Several papers have been devoted to the discussion of procedures to perform the simultaneous design of separation and energy integration. Bagajewicz and Manousiouthakis (1992) highlight most of the milestones. Among the many papers devoted to the heat integration of a process, Duran and Grossmann (1986) presented a procedure that performs this heat integration simultaneously with the optimization of other parameters. Non-differentiable functions arise in the formulation, which are later smoothed. The interaction between pinch analysis and the separation system has been reintroduced in recent papers by means of the State Space Approach (Bagajewicz and Manousiouthakis, 1992; Bagajewicz et al., 1998). The interaction between the process (reactors and separation system), the heat exchanger network (HEN) and the utility system has also been the object of intense analysis based on pinch technology (Linnhoff et al., 1990, Hall and Linnhoff, 1994). The present paper focuses on this type of interactions to establish retrofit targets in crude fractionation units.

Since crude fractionation units are energy-intensive processes, they have been the target of pinch technology based retrofits. In a recent paper, grassroots design opportunities have been explored using a two-step procedure of designing several separation sequences followed by pinch analysis (Liebmann and Dhole, 1995). This paper proved that in the case of grassroot designs there exists potential savings. These new designs are however

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radically different from the current existing fractionation scheme rooted on crude preheating and the use of side strippers and pump-around circuits. Nevertheless, their results suggest that retrofits of current existing systems can lead to additional savings. Other work aimed for example at capacity or simply at fractionation efficiency increase (Lin et al., 1996). Snell and Juno (1996) have shown for example that additions of side strippers to vacuum columns, as well as modification of internal packing has produced savings of up to 30%.

This paper proposes an interactive process/pinch analysis scheme to determine energy retrofit horizons. The term "*horizon*" is used here to indicate the maximum amount of energy of a pre-established temperature level that one can recover by varying operating conditions on a fixed flowsheet. Thus for example, if one desires to determine an overall energy efficiency horizon, the procedure consists on varying all operating conditions, so that the minimum energy consumption is achieved. One can target parts of the energy consumption, like for example, the furnace consumption with the same procedure. Thus, the horizons can be used as reference targets for a retrofit of the heat exchanger network corresponding to a flowsheet. Structural changes in other equipment, (feed tray locations, new additional columns, reactors, etc.) are not considered in this paper.

The procedure takes advantage of the fact that crude units are very flexible, allowing for multiplicity of steady states producing essentially similar quality of products. This flexibility is addressed in a separate paper, but a brief summary is offered here. The foundation of the interactive scheme is proposed next. The basic idea of this scheme was first presented by Duran and Grossmann (1986) and it states that for each process state there exist a unique minimum utility value, for which, as it is well known, there exist at least one heat exchanger network. The optimization procedure is proposed next. One of the constraints of this optimization procedure is the minimum utility calculation. The pinch operator, introduced in a previous work (Bagajewicz and Manousiouthakis, 1992) is reformulated in an implicit form. To validate the optimization procedure the continuity properties of the implicit pinch operator are discussed. Finally a small example is presented and the results of a case study are shown. The case study corresponds to an existing mid-continent Crude Plant of 78,000 barrels per day of capacity.

2. Crude plant flexibility

In analyzing crude fractionation units, the following observations have been made (Bagajewicz, 1998) :

- Pump-around duties have minimal effect on separation, but rather they are effective means of cooling the reflux at high temperatures.
- Variations of steam injection in side-strippers have little effect on separation.
- Variations of Main Steam injection together with a reduction of the over-flash can reduce furnace outlet temperatures, which in turn can realize energy savings.

3. Minimum utility distribution

As it was briefly explained in the introduction, most energy retrofit calculations have been conducted using pinch calculations after process conditions have been fixed. However, crude plants have a large degree of flexibility. As several parameters can be varied these different sets of process conditions can give raise to different values of minimum utility usage. From all these different process conditions one is particularly interested in the set that will produce the smallest value of utility usage. To calculate the minimum utility one can use the graphical method of measuring the non-overlapping region on the high-temperature end of the pinch diagram, or look for the minimum (negative) value in the cascade temperature intervals table calculations (Linnhoff et al., 1982) or simply solving a linear optimization problem (Cerda et al., 1983; Papoulias and Grossmann, 1983).

3.1. Minimum overall heating utility usage

Minimum utility calculations are performed by establishing several intervals of temperatures. Typically, these intervals are created by listing all inlet and outlet hot stream temperatures and shifted inlet and outlet cold stream temperatures. The shift is given by the minimum approach. Assume a set of m_I intervals has been found. Let Γ_l^H be the set of hot streams that exist in interval i and Γ_i^C the set of cold streams that exist in interval i. The minimum heating utility $S_{\min}$ is obtained by solving the following LP problem: (Cerda et al., 1983)

$$S_{\min} = \text{Min}\ \delta_0,$$

s.t

$$\delta_i = \delta_{i-1} + q_i, \forall i = 1, \dots m_1, \tag{1}$$

$$\delta_i \geqslant 0,$$

where q_i is the heat surplus or demand of heat in interval i and is given by

$$q_i = \sum_{k \in \Gamma_i^H} F_k^H cp_k^H (T_{i-1} - T_i) - \sum_{s \in \Gamma_i^C} F_s^C cp_s^C (T_{i-1} - T_i). \tag{2}$$

The solution to problem (1) can be obtained as follows:

$$S_{\min} = -\underset{\forall i}{\text{Min}}\,\{\theta_i\}, \tag{3}$$

$$\theta_i = \theta_{i-1} + q_i, \forall i = 1, \dots m_1,$$

$$\theta_0 = 0. \tag{4}$$

3.2. Utility demand distribution

It is customary to assume that $S_{\min}$ is delivered at the highest temperature and cascaded through all the temperature intervals above the pinch. However, one can construct a profile of utility demand. Such a profile can be constructed by attempting to deliver as much heating utility as possible at the lowest temperature possible. This can be obtained by solving the following LP problem:

$$\text{Min} \sum_{i=0}^{m_I - 1} (m_I - i) S_i,$$

s.t

$$\theta_i = \theta_{i-1} + q_i + S_{i-1}, \forall i = 1, \dots m_i,$$

$$\theta_i \geqslant 0, \quad \theta_0 = 0. \tag{5}$$

The objective function of this problem prices utility demand with higher prices as the temperature increases. It is not difficult to show that the solutions of problems (1) and (5) are related by the following equality:

$$S_{\min} = \sum_{i=0}^{m_I - 1} S_i. \tag{6}$$

Additionally, the solution to problem (5) can be obtained in terms of the solutions to problem (1) using the following recursive formula:

$$S_{m_p} = 0, \tag{7}$$

$$S_i = \underset{\forall j = 0, i}{\text{Min}} \left\{ \delta_j - \sum_{k=i+1}^{m_p} S_k \right\}, \tag{8}$$

where m_p is the interval at which the pinch takes place.

3.3. Utility supply distribution

Consider now a set of n_u hot utilities available at different temperature levels $T_j^U (T_j^U > T_{j+1}^U)$ and assume that U_j is the amount of heat supplied by each utility. If one wants to satisfy the minimum utility profile with this small number of utilities, then the following holds:

$$S_{\min} = \sum_{i=1}^{n_U} U_i, \tag{9}$$

$$U_j \leqslant \sum_{k=j}^{m_p} S_k, \quad j = 1, \dots, n_{\underline{U}}. \tag{10}$$

When Eq. (10) becomes an equality, the utility usage at each temperature level is maximized. Marechal (1995) has proposed an MINLP problem to address a more general situation where utilities are priced with real costs, including fixed costs. Furthermore, Marechal and Kalitventzeff (1996) proposed new composite curves called integrated composite curves that help visualize the optimum utility usage. As it is well known, the introduction of these multiple level utilities introduces additional pinches in the system. These pinch points have impact in the overall number of heat exchangers, but do not alter the overall energy consumption. Solutions to the multiple utility problem can also be found by solving the following problem:

$$\text{Min} \sum_{i=0}^{n_U} \omega_i U_1$$

s.t

$$S_{\min} = \sum_{i=1}^{n_U} U_1 \tag{11}$$

$$U_j \leqslant \sum_{k=K(j)}^{m_p} S_k, \quad j = 1, \dots, n_U,$$

where ω_i are the utility costs and $K(i)$ is the interval that corresponds to the temperature at which utility i is available. When the cost of utility is increasing with temperature level, the solution $(\hat{U}_j, j = I, \dots n_{\underline{U}})$ to the above problem is given by the following recursive formula:

$$\hat{U}_j = \sum_{k=K(j)}^{m_p} S_k - \sum_{k=i+1}^{n} \hat{U}_k. \tag{12}$$

Note first that problem (11) will always give a solution where the minimum overall utility is delivered, in contrast to the model presented by Marechal (1995) where minimum utility usage is not guaranteed, but rather minimum utility cost is, which may not guarantee overall minimum utility.

4. Optimization procedure

As a motivation for this section we will consider minimizing the overall energy consumption as the retrofit objective. Other objectives, such as minimizing air emissions can be posed by minimizing the highest temperature level utility.

As explained, in a retrofit that addresses these goals, it is desired to modify the process conditions and the heat exchanger network so that these goals are accomplished. The minimization of overall energy consumption can be obtained by modifying the process conditions so that the minimum possible value of $S_{\min}$

is obtained. A retrofit horizon, that is, that maximum achievable energy efficiency can be obtained by solving

$$\min_{\forall x, p} S_{\min}$$
$$\text{s.t} \qquad (13)$$
$$F(x,p)=0,$$
$$S_{\min}=H_{\min}(x),$$

where x denotes the flowrates, heat capacities and supply and target temperatures of streams hot and cold streams, p are the plant parameters and $F(x,p)$ is the plant model. In turn, $H_{\min}(x)$ is the function that provides the minimum utility. This function is given by Eqs. (3) and (4) which is the mathematical realization of the Implicit Pinch Operator. Similarly, if air pollution reductions are sought, then the following problem can be solved:

$$\min_{\forall x, p} \hat{U}_1$$
$$\text{s.t} \quad F(x,p)=0, \qquad (14)$$
$$S_i=H_i(x)\ i=1,\ldots,m_p,$$
$$\hat{U}_1=S_{\min}-\sum_{k=K(1)}^{m_p} S_k.$$

The function $H_i(x)$ provide the minimum utility profile. These functions are given by Eqs. (7) and (8) which constitute the mathematical realization of the Implicit Minimum Heat Demand Operator.

Problems (13) and (14) require varying the process conditions x as well as some selected process parameters p. The process is illustrated in Fig. 1.

In the case of problem (14) the overall minimum utility consumption for any feasible solution is guaranteed but it is not necessarily equal to the solution obtained in (13). There are of course other operating conditions where that same or even smaller high temperature utility consumption is obtained, if one is willing to give up the restriction of minimum overall utility consumption. The trade off in these cases can be resolved by solving the following problem:

$$\min \sum_{i=0}^{m_t-1} \omega_i U_i$$
$$\text{s.t} \quad F(x,p)=0, \qquad (15)$$
$$S_i=H_i(x),\ \forall i,$$
$$U_j \geqslant \hat{U}_j, \quad j=1,\ldots,n_u.$$

In this paper, only problems (13) and (14) are analyzed. In the next section we will show that $H_i(x)$ is a continuous smooth function for certain set of values of x. It is a well-known fact that for fixed x and p, utilities create pinches. Thus the continuity of $\hat{U}_j$ is also discussed. The use of implict representations of pinch operators presents the advantage of considerably reducing the number of variables and constraints. In addition, it makes the problem easily usable in commercial simulators. Both issues are illustrated by the Case Study presented in this paper.

5. Implicit pinch operator

The introduction of pinch calculations in the context of an optimization problem was first proposed by Duran and Grossman (1986). Arguing that the incorporation of an implicit procedure, like the one suggested by (3) would give rise to non-differentiabilities in the problem, they introduce an explicit procedure that contains non-differentiable functions which are later replaced by smooth approximations. El Halwagi and Manousiouthakis (1990) proposed a mixed integer alternative to represent pinch calculations, which was later applied by

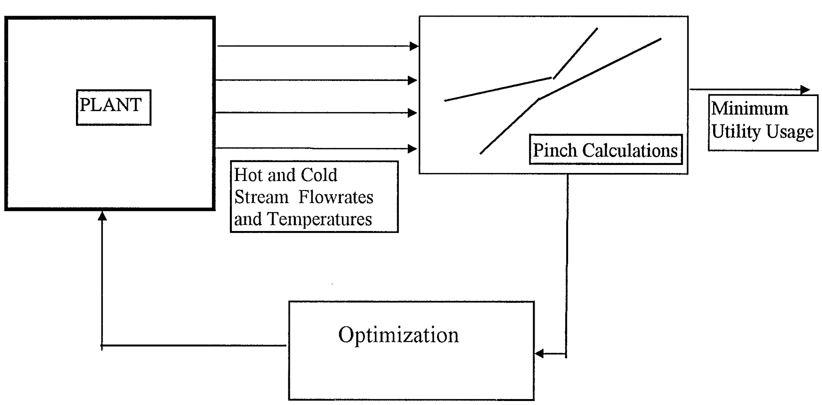

Fig. 1. Retrofit horizons: optimization based procedure.

Bagajewicz and Manousiouthakis (1992) to the design of distillation networks. Both approaches rely on creating a constraint for each pinch point candidate. All the aforementioned papers illustrate their technique with small examples. There is no reported performance for large systems, where several streams are considered at the same time. In this paper, we consider the use of these previously dismissed implicit procedure. We therefore show in this section that $H_{\min}(x)$ is a continuous function with certain needed smooth properties that can be exploited to solve large problems in a compact manner.

Assume first that a pinch exists, i.e., $S_{\min} = -\theta_{m_p} > 0$. It is desired to prove that the first and second derivatives of $S_{\min}$ with respect to the flowrates of hot and cold stream as well as the inlet and outlet temperatures of the hot and cold stream exist. For the proof we will assume that only one pinch point exists.

5.1. Derivatives with respect of flowrates:

Rewrite θ_i as follows:

$$\theta_1 = \sum_{j=1}^{i} \sum_{k\in\Gamma_j^H} F_k^H cp_k^H (T_{j-1} - T_j) - \sum_{j=1}^{i} \sum_{s\in\Gamma_i^C} F_s^C cp_x^C (T_{j-1} - T_j). \tag{16}$$

To simplify notation, introduce the following binary functions:

$$y(k, i) = \begin{cases} 1 & \text{if } k \in \Gamma_i^H, \\ 0 & \text{otherwise,} \end{cases} \tag{17}$$

$$z(s, i) = \begin{cases} 1 & \text{if } s \in \Gamma_i^c, \\ 0 & \text{otherwise.} \end{cases} \tag{18}$$

Therefore,

$$\theta_i = \sum_{j=1}^{i} \sum_{\forall k} y(k,j) F_k^H cp_k^H (T_{j-1} - T_j) - \sum_{ji=1}^{i} \sum_{\forall s} z(s,j) F_s^C cp_s^C (T_{j-1} - T_j). \tag{19}$$

Differentiate this expression assuming that all temperatures and flowrates are fixed, except the flowrate of stream $k1$, F_{k1}^H.

$$\mathrm{d}\theta_i = \sum_{j=1}^{i} cp_{k1}^H (T_{j-1} - T_j) y(k1, j)\, \mathrm{d}F_{k1}^H. \tag{20}$$

Thus, infinitesimal changes in the surplus heat of each interval are proportional to infinitesimal changes in the flowrate. Since there is only one pinch, the minimum value will continue to occur for interval m_p, i.e

$$\mathrm{d}H(x) = \mathrm{d}S_{\min} = -\mathrm{d}\theta_{m_p} = -\sum_{j=1}^{i} cp_{k1}^H (T_{j-1} - T_j) y(k1, j) \mathrm{d}F_{k1}^H. \tag{21}$$

Notice that variations of the flowrate of streams that do not exist above the pinch temperature do not affect the minimum utility, as expected. Thus the first derivative with respect to any hot stream flow rate exists and does not depend on flowrate. A similar derivation for variations of flowrates of cold streams renders the following:

$$\mathrm{d}H(x) = \mathrm{d}S_{\min} = -\mathrm{d}\theta_{m_p} = \sum_{j=1}^{i} cp_{s1}^C (T_{j-1} - T_j) z(s1, j) \mathrm{d}F_{s1}^C. \tag{22}$$

Thus, when only one pinch exists and $S_{\min} > 0$, the minimum utility function is continuous and has continuous first and second derivatives with respect to flowrates.

5.2. Derivatives with respect to stream temperatures

Assume without loss of generality that no two temperatures are equal. This can be easily established by a one-to-one correspondence between stream inlet and outlet temperatures and intervals. Even though this might create intervals with zero heat content, the objective is accomplished. Thus if the inlet temperature of a hot stream is the only allowed to change, we differentiate Eq. (16) to obtain

$$\mathrm{d}S_{\min} = -\mathrm{d}\theta_{m_p} = \begin{cases} -F_{k1}^H cp_{k1}^H dT_{k1}^H & \text{if } y(k1,j) \neq 0 \text{ for some } j \geqslant m_p, \\ 0 & \text{otherwise.} \end{cases} \tag{23}$$

A similar result can be obtained for the case of outlet temperatures and for the inlet and outlet cold stream temperatures.

5.3. Conclusions

The Implicit Pinch Operator is a continuous function of temperature and flowrate at all values except when there is no utility consumption, i.e. $S_{\min} = 0$ and when there is more than one pinch. By extension, the implicit utility demand operator has the same properties. Thus, any point that satisfies the combined features that the energy consumption $S_{\min}$ (or U_1 in the case of air emission minimization) is strictly positive and contains only one pinch point, can be considered to be a Khun–Tucker point of problem (13) or (14) depending of the case.

The feasible region of the problem is depicted in Fig. 2.

Clearly, $H(x) = 0$ and continuous with continuous first derivative for all the points inside the region where $S_{\min} = 0$. As proved above the same is true for all the points lying in the region where $S_{\min} > 0$. Points inside the zero minimum utility region constitute alternative solutions and will also be Khun–Tucker points. Additional screening objective functions are therefore needed if only one is to be selected. At the boundary between the two regions, $H(x)$ does not have a continuous first derivative, as it is apparent from the analysis above. The detailed analysis of this case is left for future work, as crude systems always consume heating utility.

Feasible solutions with multiple pinches are another exception. In the appendix, it is shown why they present discontinuous first derivatives. Properties of such points have not been investigated. It is not clear for example, if they are isolated or there exist continuous surfaces containing them. The study of these properties remains the object of future work.

In the work presented in this paper a sequential quadratic programming technique was used. The starting point of the optimization procedure had non-zero minimum utility and the optimization path is feasible.

Before proceeding to illustrate the technique with a Case Study, we briefly discuss the continuity of the utility distribution $\hat{U}_j$. The values of these functions are defined by Eq. (12). Thus, the smoothness and continuity of $\hat{U}_j$ should be discussed in the context of the smoothness and continuity of the utility distribution functions S_k. The continuity of these can be proved by examining: Eqs. (7) and (8). These equations represent a recursive formula that contains the heat surplus in each interval. In much the same way as in the case of $S_{\min}$, one can prove that the utility demand distribution is continuous. The first derivative is not continuous for the case where $S_k = 0$ and $S_k(x + \mathrm{d}x)$, that is when a small perturbation will make it positive. In addition, one must realize that, although these can be issues relevant to the numerical stability of the optimizers used, once a solution is found one can verify if the solution obtained is at these critical points.

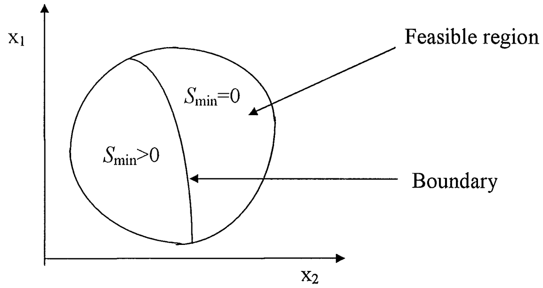

Fig. 2. Feasible region.

6. Illustrative example

To illustrate the above scheme a small example was built. The example was taken from the application libraries of the simulator PRO/II from Simulation Sciences (R3R). A few modifications were added to this example, which are depicted in Fig 3. (a desalter unit was added).

Two optimizations were performed. One to minimize the total utility usage (including direct steam) and one to minimize the furnace load. These correspond to Problems (13) and (14), respectively. The variables optimized are shown in Table 1.

The optimization took a few minutes in PRO/II. Table 2 shows the results of the optimization. First, an optimization shows that transferring cooling load from the condenser to the pump-around circuits is beneficial. In addition, the furnace inlet temperature is decreased by reducing the over-flash ratio and increasing the main steam injection. This effects were explained elsewhere (Bagajewicz, 1998). The results from the minimization of furnace load are quite different. First, the load is reduced from 63 to 59.9 MW by a combination of effects (reduction of two pump-around loads and the over-flash ratio).

Note however that the overall minimum utility increases to 134.9 MW. Although the result from the furnace load optimization seems unrealistic and probably would not be implemented in practice (unless there is a large surplus of steam in a plant), it illustrates the two extremes that this system can exhibit. There is however another angle of the problem that gives this option validity: when throughput wants to be increased and the furnace is incapable of handling a larger rate.

6.1. Case study

The method was also applied to an existing crude fractionation unit of 78,000 bbl/day capacity. The plant consists of an atmospheric column, a vacuum column, a rerun column and a stabilizer column. An optimization was set up in PRO/II to minimize $S_{\min}$, that is, solving problem (13). Several parameters were allowed to vary within pre-specified bounds: side-stripper steam rates, main column steam injection rates, columns reflux ratios, and most important, pump-around rates. The solution to this optimization was such that the product distribution is identical to the base case (differences are smaller than 0.5%). The overall minimum utility horizon is established at 42.4 MW, which represents a 16% reduction from the base case 50.4 MW reduction. The

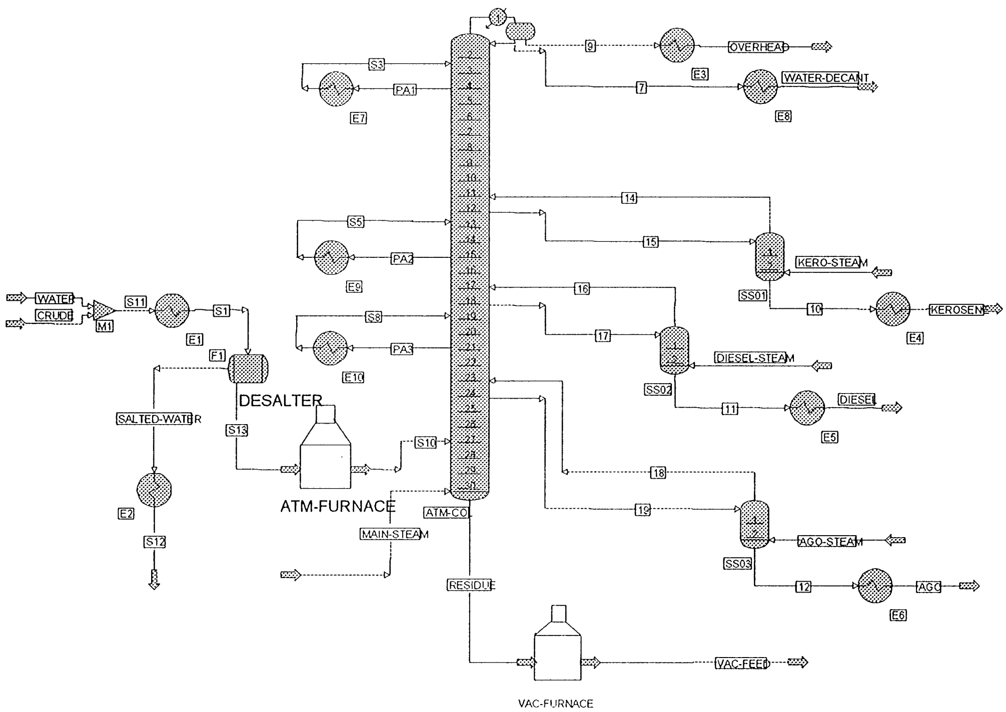

Fig. 3. Example R3R.

Table 1
R3R Optimization variables

Variable	Minimum value	Maximum Value
Kerosene side – stripper steam rate	1,470 kg/h	2,043 kg/h
Diesel side stripper steam rate	1,470 kg/h	2,043 kg/h
AGO side stripper steam rate	490 kg/h	735 kg/h
Atmospheric column main steam rate	4,086 kg/h	4,903 kg/h
Atmospheric column over-flash ratio	0.1%	3%
Kerosene pump – around circuit duty (PA1)	2.9 MW	16.1 MW
Diesel pump – around circuit duty (PA2)	2.9 MW	16.1 MW
Gas – oil pump – around circuit duty (PA3)	2.9 MW	16.1 MW
Pump – around circuit PA1 return temperature	77°C	82°C
Pump – around circuit PA2 return temperature	149°C	160°C
Pump – around circuit PA3 return temperature	221°C	243°C

optimization in PRO/II took around 15 minutes in a Pentium 133 machine.

7. Considerations for future work

Several parameters have been left unexplored in this case study. For example, one can include variations of tray efficiencies to consider retrofit horizons that include the replacement of trays by packing. The number of trays and the possible incorporation of additional columns, or in general, stacks of trays can also be considered. As this is performed one starts to exceed the capabilities of PRO/II, which cannot perform structural optimization. Strategies like the proposed by the State Space Approach (Bagajewicz and Manousiouthakis, 1992) are therefore more amenable to perform these studies.

8. Conclusions

It has been demonstrated in a separate study, that the design of crude fractionation units has several degrees of flexibility. Taking advantage of this flexibility, an interactive scheme is developed in which the design parameters are changed while minimum utility calculations

Table 2
Optimization results for R3R

	Base case	Minimum overall utility	Minimum furnace utility
Overall minimum utility horizon	117.1 MW	108.8 MW	134.9 MW
Furnace load horizon	70.2 MW	63.0 MW	59.9 MW
Pinch point	22.9°C	22.9°C	22.9°C
Atmospheric furnace outlet temp.	382°C	377°C	348°C
Kerosene stripper steam rate	1,814 kg/h	1,793 kg/h	1,484 kg/h
Diesel stripper steam rate	2,041 kg/h	1,470 kg/h	1,470 kg/h[a]
AGO stripper steam rate	680 kg/h	502 kg/h	490 hg/h[a]
Atmospheric col. main steam rate	4,536 kg/h	4853 kg/h	4,698 kg/h
Atmospheric column over-flash	3%	2.3%	0.1%(a)
Pump-around PA1 duty	2.6 MW	2.9 MW[b]	2.9 MW[b]
Pump-around PA2 duty	2.6 MW	2.9 MW[b]	0.6 MW
Pump-around PA3 duty	2.1 MW	2.9 MW[b]	0.75 MW
Pump-around PA1 return temp.	79.5°C	78.6°C	77.0°C[a]
Pump-around PA2 return temp.	154.5°C	153°C	149°C[a]
Pump-around PA3 return temp.	232°C	243°C[b]	221°C[a]

[a]Indicates that the minimum bound has been reached.
[b]Indicates that the maximum bound has been reached.

are performed for each selection. An optimization is set, so that the maximum heat recovery is obtained. The theoretical basis for the usage of an implicit representation of the Pinch calculations is explored and continuity properties are discussed. The simulation package Pro/II (SimSci) has been used to perform these studies.

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Appendix

Let us analyze the case where two pinch points exist. Assume those pinch points take place at interval m_{p1} and m_{p2}, with $m_{p1} < m_{p2}$. Therefore the minimum utility is given by $S_{\min} = -\delta_{m_{p1}} = -\delta_{m_{p2}}$.

Let us first concentrate on hot stream $k1$ flowrate changes. Similarily to the derivation of Eq. (21) one obtains

$$\mathrm{d}\theta_{m_{p1}} = \sum_{j=1}^{K1} cp_{k1}^{H}(T_{j-1} - T_j)y(k1, j)\,\mathrm{d}F_{k1}^{H}, \tag{22}$$

$$\mathrm{d}\theta_{m_{p1}2} = \mathrm{d}\theta_{m2} + \sum_{j=K1+1}^{K2} cp_{k1}^{H}(T_{j-1} - T_j)y(k1, j)\mathrm{d}F_{k1}^{H}. \tag{23}$$

Therefore, if stream $k1$ only exists at temperatures above the first pinch m_{p_1}, then $\mathrm{d}\theta_{m_{p11}} = \mathrm{d}\theta_{m_{p2}}$ and therefore, the first and second derivative are continuous and the proof is complete. However if stream $k1$ exists between the two pinch temperatures, i.e., $y(k1, j)$ is different from zero for some $m_{p1} \leqslant j \leqslant m_{p2}$, then $\mathrm{d}\theta_{m_{p11}} \neq \mathrm{d}\theta_{m_{p2}}$. Specifically, an increase in flowrate of such hot stream will make $\theta_{m_{p1}} + \mathrm{d}\theta_{m_{p11}} < \theta_{m_{p2}} + \mathrm{d}\theta_{m_{p2}}$ and therefore the second pinch m_{p2} disappears and the first pinch remains. The inverse happens in the case of a decrease of flowrate. Thus

$$\mathrm{d}S_{\min} = \begin{cases} -\mathrm{d}\delta_{m_{p1}} = -\sum_{j=1}^{m_{p1}} cp_{k1}^{H}(T_{ji-1} - T_j)y(k1,j)\mathrm{d}F_{k1}^{H} \\ \text{for} \quad \mathrm{d}F_{k1}^{H} > 0, \\ -\mathrm{d}\delta_{m2} = -\sum_{j=1}^{m_{p2}} cp_{k1}^{H}(T_{ji-1} - T_j)y(k1,j)\mathrm{d}F_{k1}^{H} \\ \text{for} \quad \mathrm{d}F_{kl}^{H} < 0 \end{cases} \tag{24}$$

and the first derivative is not continuous.

Nomenclature

$S_{\min}$	minimum utility
δ	heat surplus
q	heat balance
F	flowrate
cp	heat capacity
T	temperature
S_i	utility demand profile
U_i	utility demand

Greek Letters

θ cumulative heat surplus
ω_i utility costs

Supra-indices

H hot stream
C cold stream
U utility

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