PROCESS DESIGN AND CONTROL

# Rigorous Procedure for the Design of Conventional Atmospheric Crude Fractionation Units. Part III: Trade-off between Complexity and Energy Savings†

**M. Bagajewicz* and J. Soto**

*School of Chemical Engineering and Materials Science, University of Oklahoma, Norman, Oklahoma 73019-1004*

This paper is a follow-up to a two-part paper on the design of atmospheric crude units. In the first part [Bagajewicz, M.; Ji, S. *Ind. Eng. Chem. Res.* **2001**, *40* (2), 617−626], heat duty targets were determined, which were used in the second part [Bagajewicz, M.; Soto, J. *Ind. Eng. Chem. Res.* **2001**, *40* (2), 627−634] for the design of a multipurpose heat exchanger network. The designs shown in this second part featured maximum energy efficiency and required the splitting of the crude into three or four branches, either above or below the desalter. This article explores the trade-off between the complexity stemming from increased branching and the energy recovery. Therefore, the total annualized costs (operating cost and depreciation of capital) of solutions limited to one or two branches are compared with results of previous work.

## Introduction

In previous work,[1,2] a systematic procedure for the design of conventional crude fractionation units (Figure 1) was presented. This procedure is based on a step-by-step combination of rigorous simulation and heat integration. The procedure starts with a column without pump-around circuits, and as heat is transferred from the condenser to the pump-around circuits at higher temperature, a trade-off between steam usage and furnace savings is established. This transfer of heat is possible because of the well-known operating and design flexibility that crude fractionation installations exhibit. Such design flexibility was studied in detail by Bagajewicz.[3] The procedure makes use of rigorous simulations and heat supply−demand diagrams.[4,5] On the basis of these targets, a heat exchanger network design procedure for handling crudes of different densities at maximum efficiency was developed.

Bagajewicz and Ji[1] obtained operating conditions for light and heavy crudes, and Bagajewicz and Soto[2] showed the associated heat exchanger networks that can handle maximum energy recovery in all scenarios. Such a heat exchanger network is shown in Figure 2. The figure also illustrates which heat exchangers are being used in each case. Above the desalter, very few heat exchangers are used by the light crude. The reverse is true below the desalter. This particular result was obtained using a transshipment model together with vertical heat transfer, much in the same way as the method proposed by Gundersen and Grossmann.[6] The conjecture that has been established[2] is that, by designing for these two extremes (light and heavy), the structure will also be able to handle all crudes with intermediate densities at the maximum efficiency with the same throughput.

As one can see in Figure 2, the level of branching in these two cases is large. Four branches are needed above and below the desalter. The figure was obtained using a heat recovery minimum approximation temperature (HRAT) of 22.22 °C and an exchanger minimum approach temperature (EMAT) of 16.66 °C. Straight pinch designs provide structures that require mixing and redistributing at the pinch, which is located above the desalter for the light crude (the heavy crude is unpinched). Bagajewicz and Soto[2] showed that the structure is even more complex if a smaller HRAT is used. Another reason to use an HRAT of 22.22 °C is that the area becomes more reasonable. It was also shown that, when an HRAT of 44.44 °C is used, the number of shells and the area needed drops somehow compensating in cost for the larger energy consumption.[2] Indeed, the costs are all similar.

There is one feature, however, that is common to all the energy-efficient designs, which is the high level of branching. Such high-branching designs might not be desired in practice for a variety of reasons. Therefore, the goal of this study is to determine the loss of energy savings if this branching is reduced and a more simple structure is used. This study also has the practical value of being a good horizon for retrofit studies. The reason for this is that many existing preheating trains have two branches and the most inefficient ones have one. Thus, a structure with four branches represents a horizon that is too costly to achieve and probably not worthwhile because of the high level of repiping in-

† First presented at ESCAPE 10, Florence, Italy, May 7−10, 2000.

* To whom all correspondence should be sent. Address: 100 E. Boyd St., T-335, Norman, OK 73019. E-mail: bagajewicz@ou.edu.

10.1021/ie0106837 CCC: $25.00 
Published on Web 02/25/2003

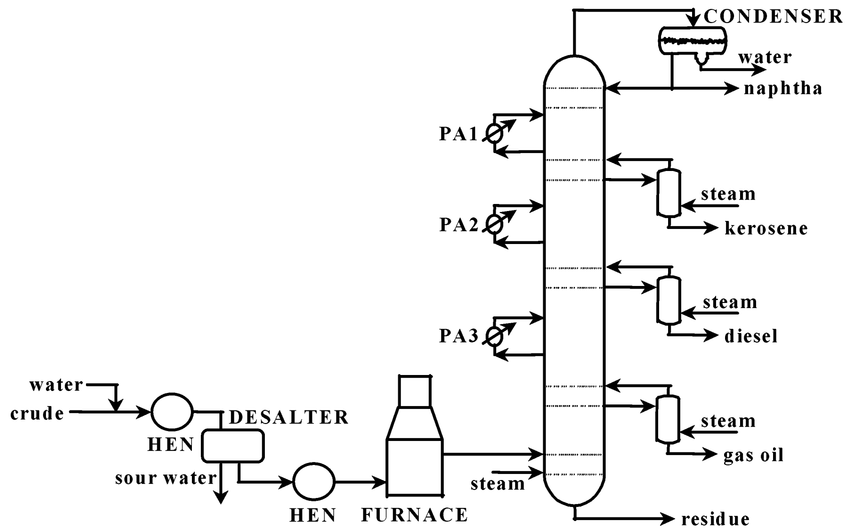


**Figure 1.** Conventional crude distillation.

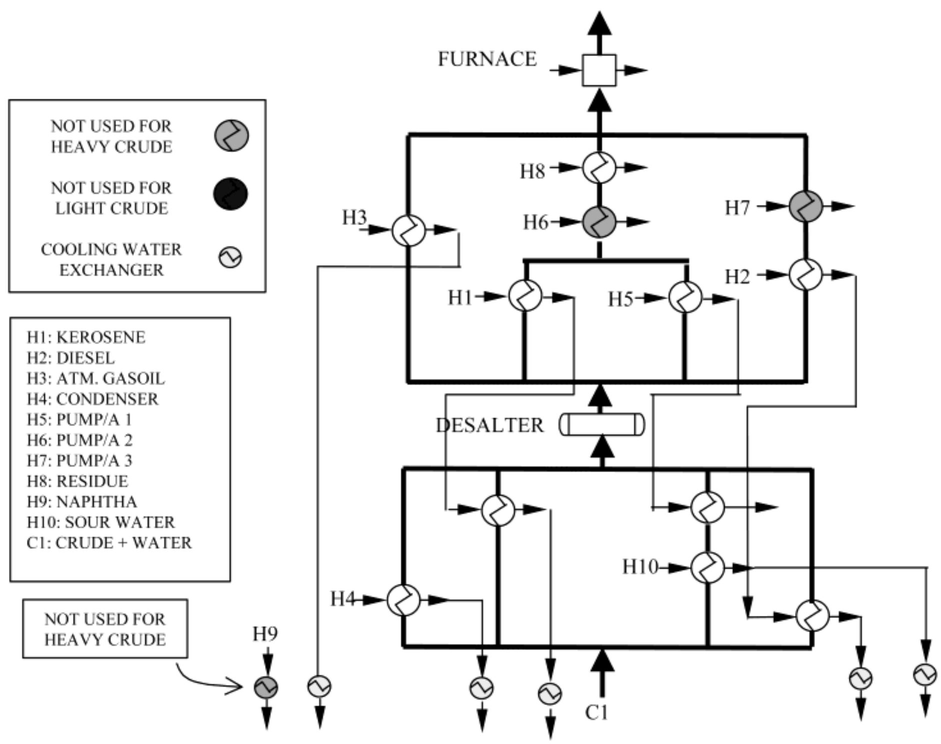


**Figure 2.** Multipurpose energy efficient network (HRAT = 22.22 °C, EMAT = 16.66 °C).

volved. A horizon of two branches can provide better clues for profitable energy retrofits.

In this paper, we propose a model for determining a heat exchanger network with only two branches above and below the desalter. Such a network has a higher energy consumption, but the assumption is that the penalty paid in energy might again be similar to the savings one might obtain because of the reduction in the number of shells and, consequently, in the investment cost.

## Mathematical Model

The present model is based on a transshipment paradigm. The major problem with the transshipment model[7] is that it uses one integer per pair of streams to determine the existence of a match. This approach can lead to many streams transferring heat in the same interval, and as a result, one cannot control splitting

Cold streams

$C = \mathrm{C1} \cup \mathrm{C2} \cup \{\mathrm{C3}\} \cup \{\mathrm{CW}\}$

C1 = {C11, C12} (branches below the desalter)

C2 = {C21, C22} (branches above the desalter)

{C3} (one branch below the furnace, if needed)

Hot streams

$\mathrm{H} = \mathrm{H1} \cup \{\mathrm{F}\}$

H1 = {kerosene, diesel, AGO, condenser, pump1, pump2, pump3, residue, naphtha, sour water}(where pump*i* stands for pump-around circuit *i*) with the transshipment model. The model used here is a small modification of the model presented by Bagajewicz and Soto.[2] Although integers are used, as in the original transshipment model, they are defined in each interval, and a special set of constraints that can count heat exchangers is added.[8] The model also builds on the vertical MILP model proposed by Gundersen and Grossmann.[6] The incorporation of these vertical constraints allows the proper balance between area and energy. The model without limitations on branching[2] also uses the vertical exchange constraints and a combination of HRAT/EMAT to obtain different networks. Thus, the same values of EMAT are here used for comparison. We now present the model.

The model contains the following sets:

Intervals

$N = \{T_1, T_2, ..., T_N\}$ (intervals)

Crudes

P = {light crude, heavy crude}

The objective function is the total energy expenditure per year, including a penalty term for the vertical heat transfer. Previously,[2] only the vertical heat transfer was minimized, whereas the energy expenditure was limited by values obtained in targeting.

$$\min \left\{\alpha_L(Q_F^L + 0.7H_S^L) + \alpha_H(Q_F^H + 0.7H_S^H) + \gamma \sum_{i\in H}\sum_{j\in C}\sum_{k\in P} S_{i,j}^k \right\} \quad (1)$$

**Constraints.** *Heat Balances for Hot Streams.* These are transshipment constraints and are also the same as those previously published.[2]

$$R_{i,\mathrm{THs}_i}^k + \gamma\sum_{j\in C} V_{i,j,\mathrm{THs}_i}^k = \mathrm{WH}_{i,\mathrm{THs}_i}^k \qquad i \in \mathrm{H1},\ k \in P \quad (2)$$

$$R_{i,T}^k - R_{i,T-1}^k + \sum_{j\in C} V_{i,j,T}^k = \mathrm{WH}_{i,T}^k \qquad i \in \mathrm{H1},\ T \in N,\ k \in P,\ T \neq \mathrm{THs}_i \quad (3)$$

$$R_{\mathrm{F},\mathrm{THs_F}}^k + \sum_{j\in C} V_{\mathrm{F},j,\mathrm{THs_F}}^k = \theta_{\mathrm{F},\mathrm{THs_F}}^k \qquad k \in P \quad (4)$$

$$R_{\mathrm{F},T}^k - R_{\mathrm{F},T-1}^k + \sum_{j\in C} V_{\mathrm{F},j,T}^k = \theta_{\mathrm{F},T}^k \qquad T \in N,\ k \in P,\ T \neq \mathrm{THs_F},\ T \neq \mathrm{THe_F} \quad (5)$$

$$-R_{\mathrm{F},\mathrm{THe_F}-1}^k + \sum_{j\in C} V_{\mathrm{F},j,\mathrm{THe_F}}^k = \theta_{\mathrm{F},\mathrm{THe_F}}^k \qquad k \in P \quad (6)$$

$$\sum_{T\in N} \theta_{\mathrm{F},T}^k = Q_\mathrm{F}^k \qquad k \in P \quad (7)$$

*Heat Balances in Cold Streams.* These constraints are also the same as the transshipment constraints. However, a new feature is introduced: heat transfer from the set C2 to stream C3 is allowed, so that demand can be transferred to higher-temperature intervals, much in the same way that it is transferred down in hot streams. The total heat that can be transferred to each branch of the cold stream (there is only one cold stream in each interval) is a variable. Later, a constraint is introduced to limit the values of these variables.

$$D_{\mathrm{CW},\mathrm{TCs}_j}^k + \sum_{i\in H} V_{i,\mathrm{CS},\mathrm{TCs}_j}^k = \delta_{\mathrm{CW},\mathrm{TCs}_j}^k \qquad k \in P \quad (8)$$

$$D_{\mathrm{CW},T}^k - D_{\mathrm{CW},T+1}^k + \sum_{i\in H} V_{i,\mathrm{CW},T}^k = 0 \qquad T \in N,\ k \in P,\ T \neq \mathrm{TCs}_j \quad (9)$$

$$D_{j,\mathrm{TCs}_j}^k + \sum_{i\in H} V_{i,j,\mathrm{TCs}_j}^k = \delta_{j,\mathrm{TCs}_j}^k \qquad j \in \{\mathrm{C1, C2}\},\ k \in P \quad (10)$$

$$D_{j,T}^k - D_{j,T+1}^k + \sum_{i\in H} V_{i,j,T}^k = \delta_{j,T}^k \qquad j \in \{\mathrm{C1, C2}\},\ T \in N,\ k \in P \quad (11)$$

$$D_{\mathrm{C3},T}^k - D_{\mathrm{C3},T+1}^k + \sum_{i\in H} V_{i,\mathrm{C3},T}^k = \mathrm{WC}_{\mathrm{C3},T}^k \qquad T \in N,\ k \in P \quad (12)$$

$$D_{\mathrm{C3},\mathrm{TCs_{C3}}+1}^k = \sum_{j\in \mathrm{C2}} D_{j,\mathrm{TCe}_j}^k \qquad k \in P \quad (13)$$

*Split of Cold Streams.* As decribed above, the flow rate of each branch is variable, and therefore, the sum of the heat delivered to the branches is equal to the total heat demand of the cold stream in that interval.

$$\sum_{j\in \mathrm{C2}} \delta_{j,T}^k = W_{\mathrm{C2},T}^k \qquad k \in P \quad (14)$$

$$\sum_{j\in \mathrm{C1}} \delta_{j,T}^k = W_{\mathrm{C1},T}^k \qquad k \in P \quad (15)$$

$$\mathrm{FC}_j^k\, Cpc_{j,T}^k \Delta T_T = \delta_{j,T}^k \qquad j \in \{\mathrm{C1, C2}\},\ T \in N,\ k \in P \quad (16)$$

$$\sum_{j\in \mathrm{C2}} \mathrm{FC}_j^k = \mathrm{TF}_{\mathrm{C2}}^k \qquad k \in P \quad (17)$$

$$\sum_{j\in \mathrm{C1}} \mathrm{FC}_j^k = \mathrm{TF}_{\mathrm{C1}}^k \qquad k \in P \quad (18)$$

*Match Definitions.* These constraints are well-known. Notice that the number of matches for each branch is limited to one.

$$V_{i,j,T}^k - UY_{i,j,T} < 0 \qquad i \in H,\ j \in C,\ T \in N,\ k \in P \quad (19)$$

$$\sum_{i\in H} Y_{i,j,T} < 1 \qquad i \in H,\ j \in C,\ T \in N \quad (20)$$

*Counting Exchangers.* These constraints are such that, given a set of successive intervals in which there is a match, for example, $Y_{i,j,\mathrm{T1}} = Y_{i,j,\mathrm{T2}} = ... = Y_{i,j,\mathrm{T}n} = 1$, a variable $K_{i,j,T}$ will exist such that it will take the value of 1 for the first interval and 0 for the rest. (Note that the variable $K$ is not an integer.) The constraint that limits the summation of all of the values of $K$ forces these values to be 0 whenever possible, thus allowing the exchangers to be counted.

$$K_{i,j,T^*} = Y_{i,j,T^*} \qquad i \in H,\ j \in C,\ T^* = \mathrm{Max}\{\mathrm{THs}_i, \mathrm{TCe}_j\} \quad (21)$$

$$K_{i,j,T} \geq Y_{i,j,T} - Y_{i,j,T-1} \qquad i \in H, j \in C, T \in N \quad (22)$$

$$\boldsymbol{K}_{i,j,T} \leq 1 \qquad i \in H, j \in C, T \in N \quad (23)$$

$$\sum_{i \in H} \sum_{T \in N} K_{i,j,T} \leq 1 \qquad j \in C, T \in N \quad (24)$$

$$\sum_{j \in C} \sum_{T \in N} K_{i,j,T} \leq 1 \qquad i \in H, T \in N \quad (25)$$

$$\sum_{i \in H} \sum_{j \in C} \sum_{T \in N} K_{i,j,T} \leq N^* \qquad i \in H, j \in C, T \in N \quad (26)$$

*Vertical Heat Transfer (Gundersen and Grossmann[6]).*

$$\sum_{T \in N} V^{k}_{i,j,T} - S^{k}_{i,j} = Qv^{k}_{i,j} \qquad i \in H, j \in C, T \in N, k \in P \quad (27)$$

*Constraints in the Residuals.* These constraints are well-known.

$$R^{k}_{i,T} = 0 \qquad i \in H, T = T_N \quad (28)$$

$$D^{k}_{j,T} = 0 \qquad j \in \mathrm{C2} \cup \{\mathrm{C3}\}, T = \mathrm{TCe}_j \quad (29)$$

$$V^{k}_{i,j,T} \geq 0, \quad R^{k}_{i,T} \geq 0, \quad D^{k}_{i,T} \geq 0, \quad \delta^{k}_{j,T} \geq 0, \quad K_{i,j,T} \geq 0, \quad Y_{i,j,T} = \{0, 1\} \qquad i \in H, j \in C, T \in N \quad (30)$$

$$\theta^{k}_{\mathrm{F},T} \geq 0, \quad \theta^{k}_{\mathrm{CW},T} \geq 0 \quad (31)$$

The model is linear and was solved using GAMS-CPLEX. In addition, some of the deficiencies of the vertical model, which were originally pointed out by Gundersen and Grossmann,[6] namely, that "multiple matches can be required when a match expands across an enthalpy interval", that this global model "cheats", because "the same amount of heat may be assumed transferred vertically to more than one cold stream", and finally that the model works well when the same heat-transfer coefficient can be assumed for all streams, were analyzed in more detail in part II[2] and found not to be an issue in this case.

In addition, the model does not directly control the investment cost. Rather, this cost was indirectly controlled by limiting the number of units to the absolute minimum needed. If the number of units is reduced, then the penalty should be paid in terms of energy. In observing the demand−supply diagrams (Figure 3), one can notice that the amount of supply that each of the products and the third pump-around duty (PA3) offer is relatively much smaller than that of the rest of the pump-around circuits or the condenser duties. In addition, a good portion of the supply is already matched with cooling water for the light crude. For the case of the heavy crude, the number of exchangers is not binding, and the only reason that the solution of Figure 2 uses exchangers to match these products with the heavy crude is to save some area, but not to achieve energy savings, as Figure 3b suggests. If the number of units is forced to be smaller, then it is likely that the optimal constrained solution can avoid the use of exchangers between some of these products and the crude (using only cooling water), thus reducing the capital cost and not increasing the energy consumption substantially.

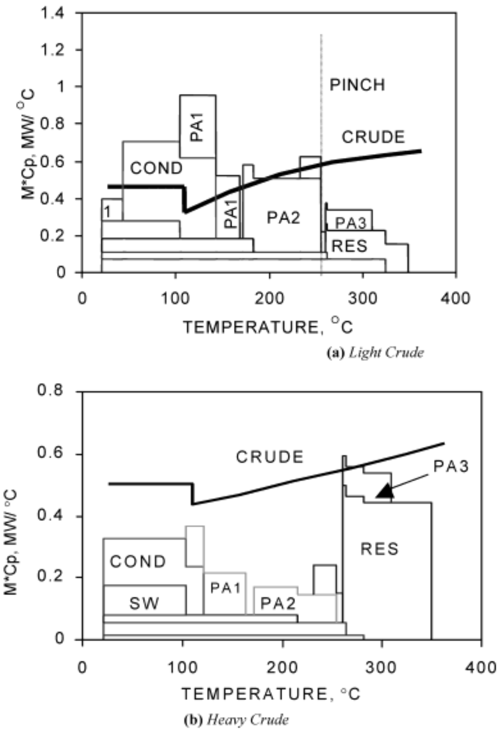


**Figure 3.** Heat demand−supply diagrams. 1. Naphtha and condensed water. 2. Sour water from the desalter. 3. Pump-around 1. COND: condenser. PA: pump-around. RES: residue. Products (from top to bottom): kerosene, diesel and gas oil.

Finally, we point out that retrofit studies can benefit from the knowledge obtained about these less-complex grassroots designs. Indeed, most existing crude units contain at the most two branches above and below the desalter, branches that are sometimes matched with split hot streams in such a fashion that they are equivalent to no branching at all. Nevertheless, grassroots designs with only two branches might serve as useful horizon designs for retrofitting and even suggest a few changes directly.

## Results and Discussion

First, the model was run, and a structure was obtained that uses 23 heat exchangers. Many of these heat exchangers are matches between hot streams and single or double branches in such a way that many hot streams use two heat exchangers above the desalter. The network is shown in Figure 4. This model contains too many heat exchangers and is still excessively complicated. Thus, the number of matches was restricted so that each hot stream matches only once above the desalter and once below it. In both cases, an HRAT of 22.22 °C (40 °F) and an EMAT of 16.66 °C (30 °F) were used. Of these, only the EMAT is a constraint of importance in the model. Complexity pushes the HRAT to higher values (greater energy consumption). The result is shown in Figure 5. For comparison, the model was run with the branching restricted, giving the solution shown in Figure 6. When it was noticed that this model included one cooler with a relatively small load for cooling the residue, the model was run again, forbidding this match. As expected, the energy consumption increased slightly for the light crude in what can be now considered for all practical purposes an alternative one-branch solution (see Figure 7).

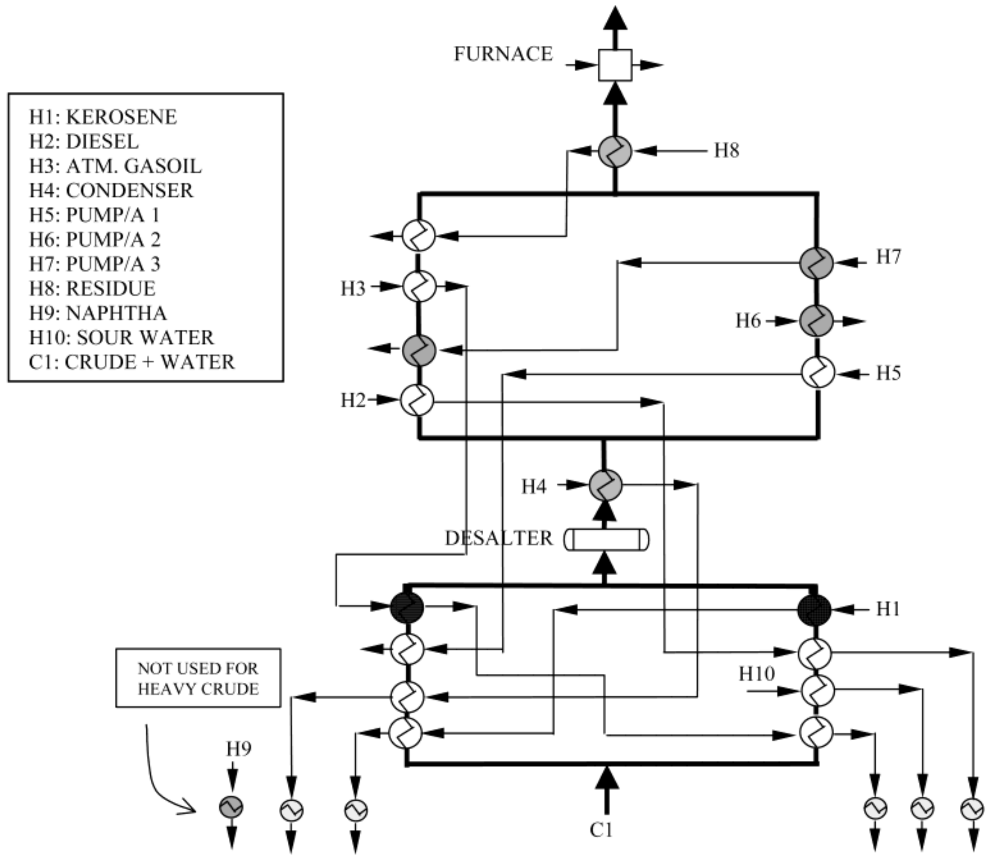


**Figure 4.** Two-branch (unrestricted) solution.

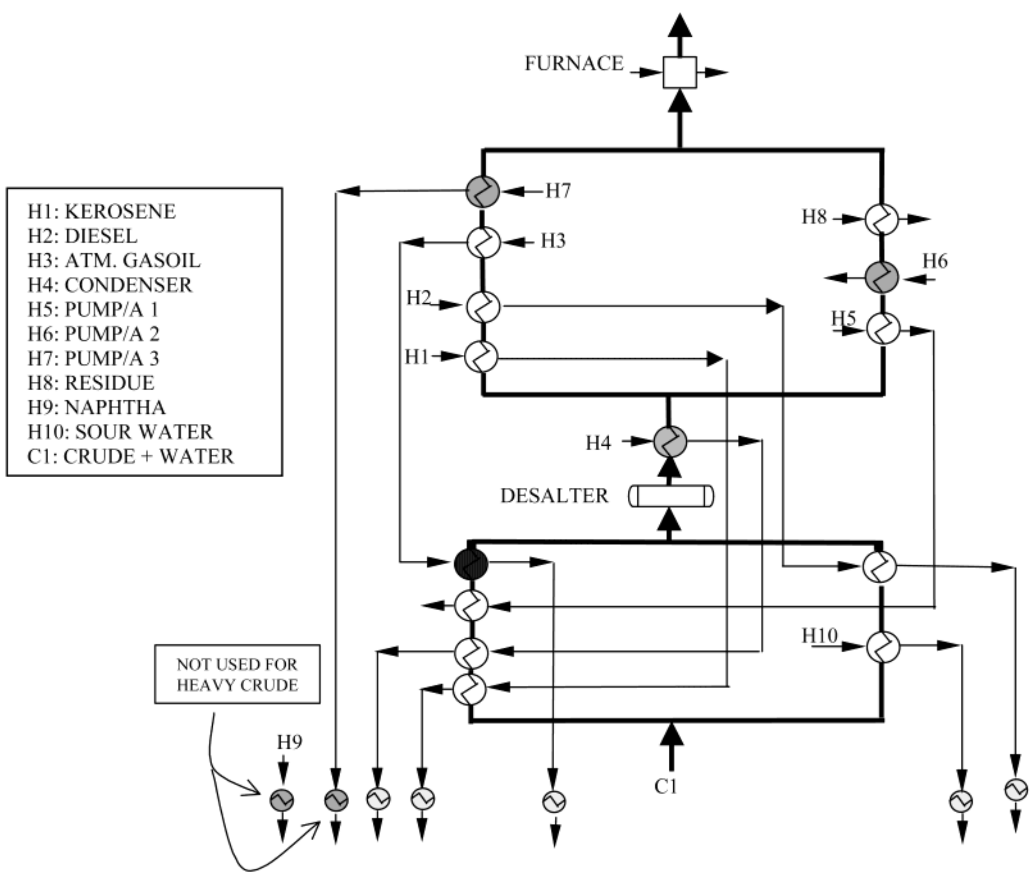


**Figure 5.** Two-branch (restricted) solution.

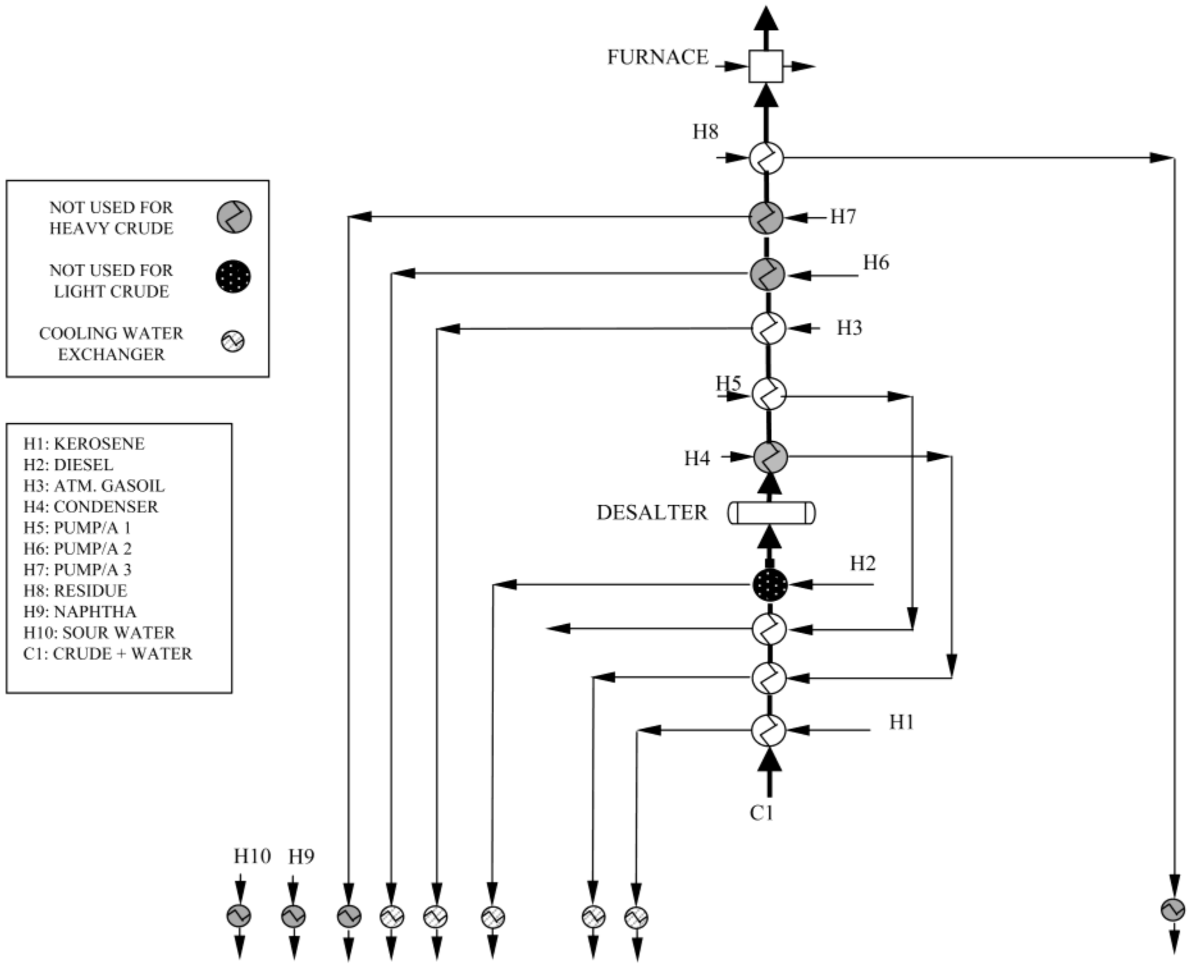


**Figure 6.** One-branch solution.

**Table 1. Comparison of Results**

| design | furnace load (light/heavy crude) (MW) | number of exchangers | number of shells | operating costs ($10^6$\$/year) | fixed costs ($10^6$\$/year) | total costs ($10^6$\$/year) |
|---|---|---|---|---|---|---|
| optimal (Figure 2) | 59.7/81.3 | 18 | 40 | 4.51 | 2.07 | 6.58 |
| two-branches (Figure 4, unrestricted) | 63.0/84.0 | 23 | 41 | 4.71 | 1.90 | 6.61 |
| two-branches (Figure 5, restricted) | 63.0/84.2 | 21 | 42 | 4.72 | 2.01 | 6.73 |
| one-branch (Figure 6) | 71.6/93.9 | 19 | 35 | 5.16 | 1.63 | 6.79 |
| one-branch (Figure 7) | 72.04/93.9 | 18 | 34 | 5.17 | 1.64 | 6.81 |

The energy consumption of the light and heavy crudes, the total numbers of exchangers for the different structures, and the annualized costs are shown in Table 1. In all of the above solutions, no energy penalty was paid for a reduction of the number of heat exchangers. In other words, the models were run with the number of exchangers being reduced until such a reduction triggered increased energy consumption, at which point the reduction was stopped.

The difference in energy expenditure between the unrestricted and restricted structures is small. Thus, from the point of view of reduced complexity as well as cost, the restricted design should be adopted. In addition, the energy penalty for the simplicity obtained from the restricted case as compared with the optimal design is around 3.3 MW, a small value. Comparatively, the one-branch solution has, as expected, a much higher energy consumption. However, it compensates with lower capital costs (smaller number of shells). A comparison of the total costs should not be used to make conclusions, because the costs might not reflect the right energy-to-capital ratios. Rather, the operating costs should be analyzed comparatively.

## Conclusion

The design of heat exchanger networks with limited branching and reduced numbers of exchangers/shells for crude units was discussed. A model was presented and used to obtain results that quantify the energy penalty

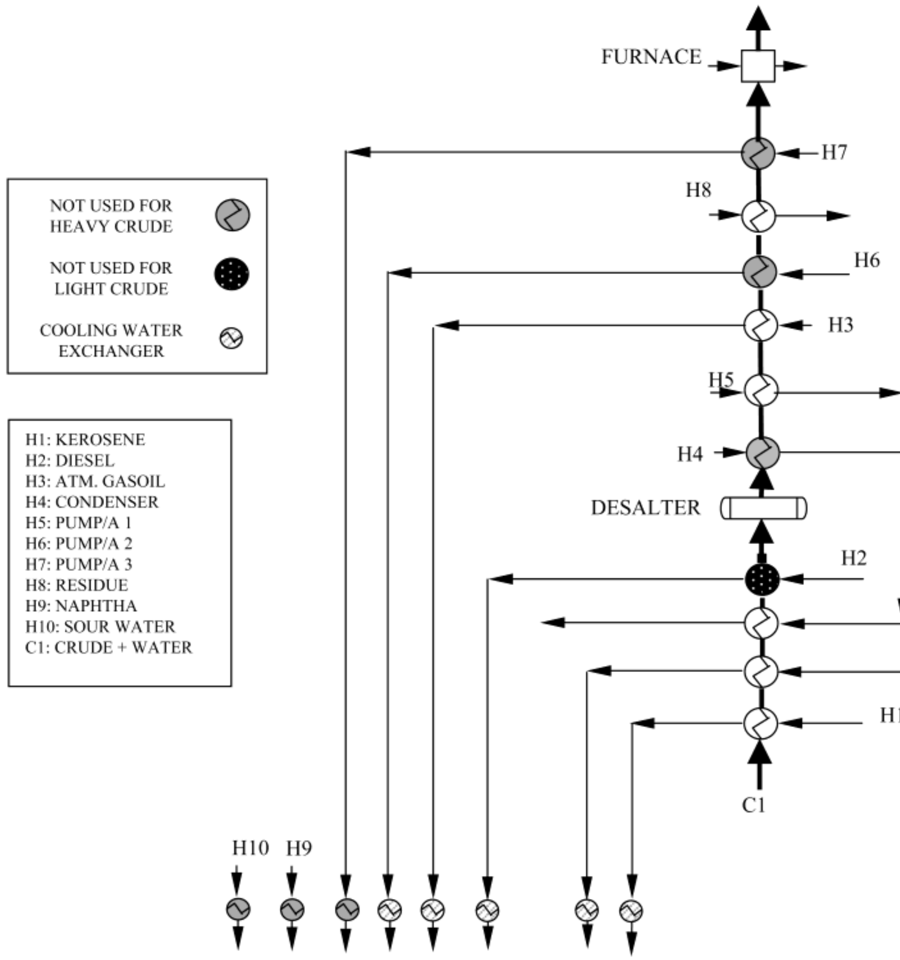


**Figure 7.** Alternative one-branch solution.

incurred by imposing such a level of simplicity. It was found that, for reduced branching, there is an energy penalty of a few megawatts. From these results and from observations of energy-efficient designs for other values of the HRAT/EMAT ratio,[2] one can conclude that several alternative designs with similar costs (in the range of 6.5−7 $10^6$\$/year) are available that can be used specifically as horizons for retrofit designs.

## Nomenclature

*Parameters*

$\alpha_L$, $\alpha_H$ = fraction of the year during which each crude is processed
$Cp^k_{j,T}$, $j \in C$ = heat capacity of cold stream $j$ in interval $T$ for crude $k$
$WH^k_{i,T}$, $i \in H1$ = heat load of hot stream $i$ in interval $T$
$TCs_j$, $j \in C$ = interval at which cold stream $j$ starts
$TCe_j$, $j \in C$ = interval at which cold stream $j$ ends
$THS_i$, $i \in H$ = interval at which hot stream $i$ starts
$THe_i$, $i \in H$ = interval at which hot stream $i$ ends
$N^*$ = maximum numberamount of heat exchangers
$Qv^k_{i,j}$ = maximum heat that can be transferred vertically between streams $i$ and $j$
$\Delta T_i$ = interval of temperature $i$
$U$ = large constant
$TF^k_j$ = total flow of cold streams $j$
$W^k_{C,T}$ = heat load of cold streams in interval $T$
$\gamma$ = weight factor for the vertical heat transfer
F = furnace
$H^k_S$ = enthalpy of the stripping steam as a function of pump-aroundPA heats

*Variables*

$R^k_{i,T}$ = heat surplus from hot stream $i$ cascaded *down* to the next interval
$D^k_{j,TCsj}$ = heat demand that is transferred up in the cascade of cold streams
$V^k_{i,j,T}$ = heat transferred from hot stream $i$ to cold stream $j$ in interval $T$
$K^k_{i,j,T}$ = counter of matches
$Y^k_{i,j,T}$ = match between $i$ and $j$ in interval $T$ in plant $k$
$S^k_{i,j}$ = vertical heat transfer from stream $i$ to stream $j$ for crude $k$
$\Delta T^k_T$ = temperature change of interval $T$ in plant $k$
$H^k_S$ = enthalpy of the stripping steam as a function of pump-aroundPA heats
$Q^k_F$ = furnace load for crude $k$
$Q^k_{CW}$ = heat removed by cooling water
$\theta^k_{F,T}$ = heat demand covered by the furnace in each interval
$\delta^k_{j,T}$ = portion of the total heat demand of the cold stream covered in each interval
$FC^k_{j,T}$, $j \in C$ = flow rate of crude streams $j$

## Literature Cited

(1) Bagajewicz, M.; Ji, S. Rigorous Procedure for the Design of Conventional Atmospheric Crude Fractionation Units. Part I: Targeting. *Ind. Eng. Chem. Res.* **2001**, *40* (2), 617−626.

(2) Bagajewicz, M.; Soto, J. Rigorous Procedure for the Design of Conventional Atmospheric Crude Fractionation Units. Part II: Heat Exchanger Networks. *Ind. Eng. Chem. Res.* **2001**, *40* (2), 627−634.

(3) Bagajewicz, M. On the Design Flexibility of Crude Atmospheric Plants. *Chem. Eng. Commun.* **1998**, *166*, 111−136.

(4) Andrecovich, M.; Westerberg, A. A Simple Synthesis Method Based on Utility Bounding for Heat-Integrated Distillation Sequences. *AIChE J.* **1985**, *31* (3), 363−375.

(5) Terranova, B.; Westerberg, A. Temperature−Heat Diagrams for Complex Columns. 1. Intercooled/Interheated Distillation Columns. *Ind. Eng. Chem. Res.* **1989**, *28*, 1374−1379.

(6) Gundersen, T.; Grossmann, I. E. Improved Optimization Strategies for Automated Heat Exchanger Network Synthesis through Physical Insights. *Comput. Chem. Eng.* **1990**, *14*, 9, 925−944.

(7) Papoulias, S.; Grossmann, I. E. A Structural Optimization Approach in Process Synthesis II: Heat Recovery Networks. *Comput. Chem. Eng.* **1983**, *7*, 707.

(8) Bagajewicz, M.; Rodera, H. A New MILP Model for Heat/Mass Exchanger Networks Featuring Minimum Number of Units. Presented at the AIChE Annual Meeting, Miami, FL, Nov 15−20, 1998.

*Received for review* August 16, 2001
*Revised manuscript received* November 26, 2002
*Accepted* December 19, 2002

IE0106837