Design of Crude Distillation Plants with Vacuum Units. II. Heat Exchanger Network Design

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This is the second part of a two-part paper. In this part, a multiperiod heat exchanger network design model is proposed to handle two different crudes, a light crude and a heavy crude, and the results are presented. This model considers the existence of a preflash drum, which is used only in the light crude period. The model contains a topological constraint so that all periods share the same heat exchange network but not necessarily at the same temperature levels.

Introduction

In part I of this work,[1] rigorous targeting procedures were developed for three types of complete crude distillation plants. It was found that the introduction of a vacuum tower changes the heat distribution among the pump-around circuits. Comparisons showed that the energy consumption for the preflash vacuum design is slightly smaller than that for the conventional vacuum design. Finally, it was concluded that the stripping-type design cannot compete with the conventional design. Thus, the energy targets obtained are used in this part to develop a heat exchanger network for a complete crude distillation plant.

Bagajewicz and Soto[2] presented heat exchanger networks (HENs) for atmospheric distillation featuring maximum energy efficiency. The problem with such a design is that it requires extensive splitting of the crude stream. Such high splitting reduces the controllability of the preheat train. In another paper by the same authors,[3] heat exchanger networks for atmospheric distillation using two, three, and four branches were studied, and it was found that the total cost is not sensitive to the number of branches. This is because HENs with fewer matches include fewer exchanger shells and, therefore, lower investment costs. It was concluded that, when branching is reduced, the tradeoff between heat utility and capital cost breaks even.

The model proposed in the above paper[3] uses binary variables to count heat exchangers, and these binary variables are shared by both operation periods. The sharing of binary variables forces the same matches for a given pair of streams in the same intervals. This paper extends the model to cases where a match between a given pair can take place in different intervals in different periods. The heat exchanger network also takes into account the flexibility of using preflashing units for light crude processing.

In addition to the main objective of maximum heat utilization, the HEN should also have the flexibility to accommodate varying operating conditions.[4] The problem of the multiperiod HEN has been addressed by several authors. For example, Floudas and Grossmann[5,6] proposed a procedure based on a superstructure representation that embeds all possible structural options for different time periods. Papalexandri and Pistikopoulos[4,7] proposed a unified hyperstructure representation of mass and heat exchange alternatives to account for all mass and heat integration possibilities.

The new concept of a “matching pattern” is presented to handle the same network for the different uses, and its mathematical representation is given. This representation is based on the same interval transshipment model as in Bagajewicz and Soto,[3] extending this model to allow the crude to match the same set of hot streams in different intervals. The final model is MILP.

Energy Targets

Figure 1 shows the diagram for a complete crude distillation plant. Note that the preflash drum is bypassed in the heavy crude period. The energy target used to design the heat exchanger network is determined by the procedure proposed in part I.[1] The data that constitute the starting point of the design are given in Tables 1 and 2.

The heat demand−supply diagrams presented in part I[1] reveal that a heat exchanger network featuring the minimum utility should be complex. For example, the pinch point for the light crude is 254 °C. Above the pinch, five hot streams are found in the region between 254 and 310 °C. To use the heat from all five streams completely, the crude stream has to be split into five branches. Bagajewicz and Soto[3] studied the effect of branches of the crude stream of an atmospheric column on the total annual cost. They found that the extra energy required for HENs with fewer branches could be offset in a large part by the savings in capital costs and showed that the annual cost of an HEN with two branches is similar to that of an HEN with four branches. In this paper, it is assumed that the same tradeoff takes place, and consequently, only two-branch models are used for the HEN design.

Heat Exchanger Network

The objective is to design a multiperiod HEN with a limited number of branches. As mentioned before, the

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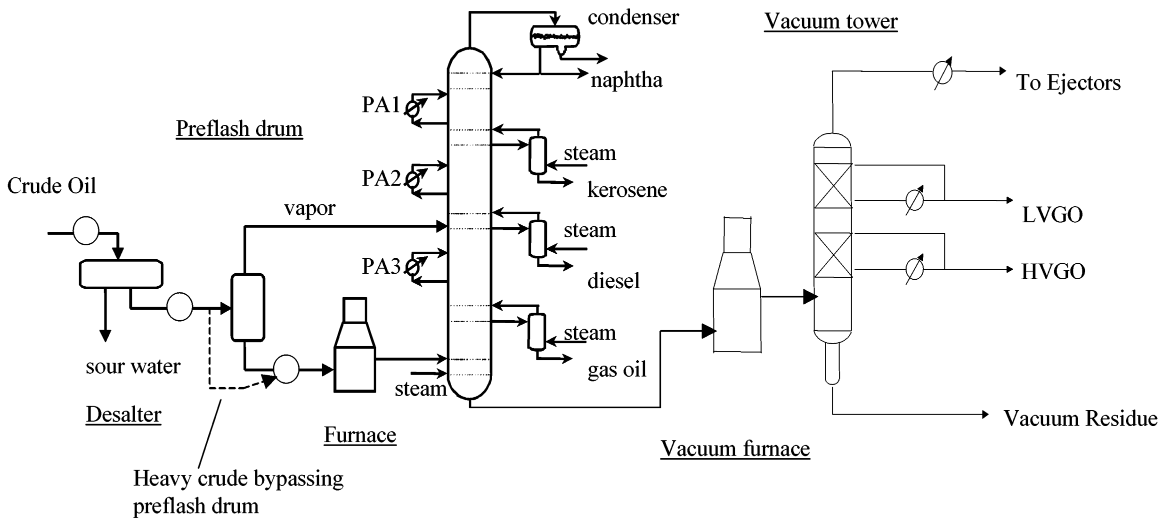

Figure 1. Complete crude distillation plant.

Table 1. Stream Data for Light Crude Distillation with Preflashing

stream	description	T_s (°C)	T_t (°C)	Q (MW)	MCP (MW/°C)
J1	crude before desalter	21.1	104.4	−38.83	−0.4658
J2	crude between desalter and preflash drum	162.8	383.4	−111.58	variable
J3	topped crude	348.9	413.4	−11.56	−0.1793
J4	crude between desalter and preflash drum	104.4	162.8	−26.61	−0.4560
I1	saline water	104.4	43.3	5.73	0.0938
I2	atmospheric condenser	144.8	43.3	53.71	0.5290
I3	atmospheric PA1	176.7	104.4	17.59	0.2434
I4	atmospheric PA2	246.9	176.7	11.72	0.1670
I5	atmospheric PA3	306.1	232.2	20.52	0.2775
I6	kerosene	185.0	43.3	10.52	0.0742
I7	diesel	232.2	43.3	7.19	0.0380
I8	atmospheric gas oil	312.8	60.0	17.34	0.0686
I9	vacuum PA1	232.2	93.3	7.20	0.0518
I10	vacuum PA2	312.8	176.7	7.33	0.0538
I11	LVGO	232.2	60.0	3.21	0.0186
I12	HVGO	312.8	82.2	12.56	0.0545
I13	vacuum residue	371.1	176.7	15.20	0.0781

Table 2. Stream Data for Heavy Crude Distillation

stream	description	T_s (°C)	T_t (°C)	Q (MW)	MCP (MW/°C)
J1	crude before desalter	21.1	137.8	−68.99	−0.5912
J2	crude between desalter and preflash drum	137.8	363.1	−123.51	variable
J3	topped crude	354.4	399.7	−22.06	−0.4872
I1	saline water	137.8	43.3	8.74	0.0925
I2	atmospheric condenser	119.1	43.3	12.83	0.1693
I3	atmospheric PA1	160.0	104.4	7.33	0.1319
I4	atmospheric PA2	256.5	176.7	10.26	0.1285
I5	atmospheric PA3	312.8	225.6	2.93	0.0336
I6	kerosene	214.2	43.3	3.91	0.0214
I7	diesel	288.6	43.3	10.00	0.0407
I8	atmospheric gas oil	278.8	60.0	3.23	0.0148
I9	vacuum PA1	225.6	93.3	19.69	0.1489
I10	vacuum PA2	312.8	176.7	7.33	0.0538
I11	LVGO	225.6	60.0	10.93	0.0660
I12	HVGO	312.8	82.2	10.29	0.0446
I13	vacuum residue	376.7	176.7	61.39	0.3069

penalty for the limited number of branches is that the HEN requires higher utilities. The requirements and assumptions are as follows: (1) Each cold stream can be split into at most two branches. (2) Each heat exchanger can handle variable heat loads. (3) Each cold stream exchanges heat with a fixed set of hot streams in the same order in all operation periods. (4) The HEN should have the ability to handle different numbers of process streams in different periods.

In the case of light crude processing, a preflash drum is used to flash off light ends to avoid two-phase flow in the preheat heat exchanger train. The preflash drum is bypassed in the case of heavy crude processing. Therefore, the light crude oil period has one more cold stream.

The classical transshipment model[8] uses one integer per pair of streams to determine the existence of a match. This leads to many streams transferring heat in the same interval, and as a result, one cannot control splitting. Bagajewicz and Soto[3] used integers as in the original transshipment model, but they defined these integers in each interval. To count exchangers, they used a special set of constraints.[9]

Although the model presented by Bagajewicz and Soto[3] renders good control of branching, the model forces the two periods to share the same matches *in the same intervals*. Figure 2 illustrates a cold stream C_1 matching with hot streams H_1 and H_2 in two periods. The two topologies are apparently the same, that is, C_1 receives heat first from H_2 and then from H_1. Only two heat

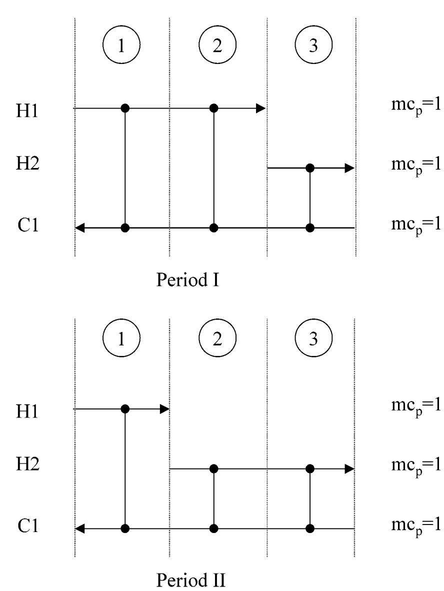

Figure 2. Two representations of the same matching sequence between C1 and hot streams H1 and H2.

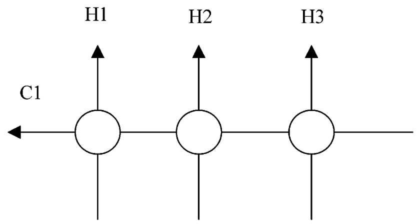

Figure 3. Cold stream matching with three hot streams.

exchangers are needed. However, the above model is unable to handle this situation because, in the second interval, the constraint of a single match in each interval is violated, even though that model allows cold streams to take heat from intervals of higher temperatures.

This paper uses two independent sets of binary variables to count matches in each period separately. A constraint is then applied that requires both periods to share the same topology. The topology is expressed in terms of matching patterns, which are defined in the following section.

Stream Matching Pattern

Each cold stream is required to exchange heat with the same hot streams and in the same order in all operation periods. An algorithm to represent the matching pattern for each cold stream in each period is needed. Such a representation should be unique for each match pattern and *independent of the intervals*.

Bagajewicz and Rodera[9] proposed to count heat exchangers using the constraint

$$K_{i,j,T} = \max(y_{i,j,T} - y_{i,j,iT-1}, 0) \tag{1}$$

In this constraint, $y_{i,j,iT}$ represents a match between hot stream i and cold stream j in interval T. This model counts continuous matches as a single exchanger.

Now, consider three hot streams H_1, H_2, and H_3 matching with cold stream J_1 as shown in Figure 3. A parameter a_i is associated with each hot stream.

Next, another parameter, $PA_{j,T}$, is used to capture the information as to which hot stream matches with cold stream j in interval T

$$PA_{j,T} = \sum_i K_{i,j,T} a_i \tag{2}$$

If there is no match in interval T, then $PA_{j,T}$ equals 0. Next, the auxiliary variable $PB_{j,T}$ is defined as

$$PB_{j,T} = \max[(PA_{j,T}C - \sum_{k \le T-1} PA_{j,k}), 0] \tag{3}$$

where C is a number large enough to ensure that $PB_{j,T}$ is nonnegative. Further, define a matching pattern identification number (MPI_j) for a specific sequence of hot streams as follows

$$MPI_j = \sum_T PB_{j,T} \tag{4}$$

Under certain choices of a_i, MPI_j is unique for each matching sequence. Table 3 shows the details corresponding to an example where J_1 matches with three hot streams H_1, H_2, and H_3.

Table 3. Parameters Representing a Matching Pattern

	T1	T2	T3	T4	T5
$K_{H_1,J_1,T}$	0	1	0	0	0
$K_{H_2,J_1,T}$	0	0	0	1	0
$K_{H_3,J_1,T}$	0	0	0	0	1
$PA_{J_1,T}$	0	a_{H_1}	0	a_{H_2}	a_{H_3}
$PB_{J_1,T}$	0	$a_{H_1}C$	0	$a_{H_2}C - a_{H_1}$	$a_{H_3}C - a_{H_2} - a_{H_1}$
MPI_j	$C(a_{H_1} + a_{H_2} + a_{H_3}) - 2a_{H_1} - a_{H_2} = C' - 2a_{H_1} - a_{H_2}$				

The maximum operator in eq 3 can be represented in a linear form by using the following equivalent constraints[10]

$$B = \max(A_1, A_2) \leftrightarrow \begin{cases} A_1 + \lambda\,\Omega \ge B \\ B \ge A_1 \\ A_2 + (1-\lambda)\Omega \ge B \\ B \ge A_2 \end{cases} \tag{5}$$

where λ is binary and Ω is a sufficiently large number.

Parent and Child Matching Patterns

Suppose a matching pattern for a cold stream involves K hot streams in sequence. If a matching pattern is obtained by removing one or more hot streams without changing the order of the remaining hot streams, then the resulting pattern is called a child pattern. Figure 4 shows an example of a parent matching pattern and its six child patterns.

Thus, for any given cold stream, the matching pattern for one period has to be either identical to or a parent pattern of the other period.

Let $MP(N,m)$ represent the number of matching patterns for a cold stream to match with m hot streams that are picked from a hot stream pool of N hot streams. Thus

$$MP(N,m) = \frac{N!}{m!} \tag{6}$$

Let $CP(K,i)$ be the number of child patterns generated by removing i streams from a parent pattern with K hot streams. $CP(K,i)$ is given by

$$CP(K,i) = \binom{K}{i} \tag{7}$$

Then, the total number of child patterns, CP, is

$$CP = \sum_{i=1}^{K-1} \binom{K}{i} \tag{8}$$

Conditions for a Unique MPI. Consider a cold stream j matching sequentially with N hot streams I_1, I_2, I_3, ..., I_{N-1}, I_N, from high temperature to low temperature. According to Table 3, the expression for the matching pattern identification number is

$$MPI_j = C\sum_{i=1}^{N} a_i - \sum_{j=1}^{N-1} (N-j)a_j \tag{9}$$

Different cases are now considered to infer the values of parameters a_i to make the sequence unique. Consider switching streams I_k and I_m ($k < m$); then

$$MPI_j' - MPI_j = -(N-k)a_m - (N-m)a_k + (N-k)a_k + (N-m)a_m \tag{10}$$

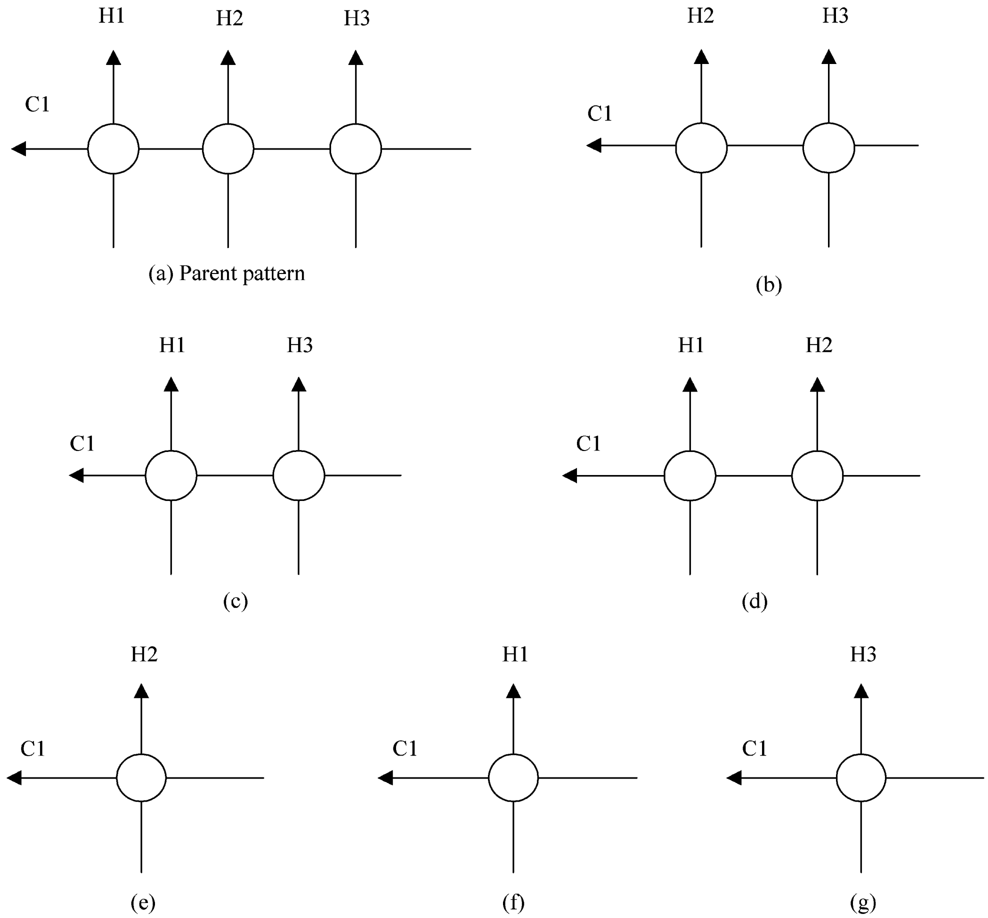

Figure 4. Parent pattern and its child patterns.

where MPI'_j is the new pattern. After some manipulation, one obtains

$$MPI'_j - MPI_j = (m - k)(a_k - a_m) \quad (11)$$

Thus, the condition for $MPI'_j = MPI_j$ is $a_k = a_m$.

Now consider altering the order of three arbitrary hot streams I_k, I_l, and I_m ($k < l < m$) to a new order, say, I_m, I_k, I_l, keeping the positions of the other matches unchanged. Then

$$MPI'_j - MPI = -(N - k)a_m - (N - l)a_k - (N - m)a_l + (N - k)a_k + (N - l)a_l + (N - m)a_m \quad (12)$$

Thus, the condition for $MPI'_j = MPI_j$ is

$$a_m = \frac{(l - k)a_k + (m - l)a_l}{m - k} \quad (13)$$

In a similar fashion, one can obtain the condition for $MPI'_j = MPI_j$ when four hot streams (I_x, I_y, I_z, I_u) are exchanged as

$$a_m = \frac{ia_x + ja_y + ka_z + la_u}{i + j + k + l} \quad (14)$$

where i, j, k, and l are positive integers that represent differences between the exchanged positions. In view of the above, to make the value of MPI_j unique, parameters a_i should satisfy the following conditions: (1) Each parameter is positive. (2) Each parameter is different. (3) No parameter can be equal to the average of any other numbers of parameters.

Table 4. Parameter a_i in This Work

stream	a_i	stream	a_i
I1	1.211	I8	8.051
I2	2.032	I9	9.132
I3	3.272	I10	10.332
I4	4.533	I11	11.161
I5	5.041	I12	12.243
I6	6.072	I13	13.412
I7	7.311	S1	20

Table 4 lists parameters a_i used in this study. To expedite data analysis, parameters a_i were defined as the summations of the hot stream numbers and a decimal number.

Multiperiod Model

In this paper, most of the constraints employed by Bagajewicz and Soto[2] are used. However, instead of requiring the same matches, interval-by-interval, for different periods, matching pattern constraints are used. The sets, variables, and constraints are listed here.

Sets

Cold streams before splitting: JO

Cold streams after splitting: J (including cooling water, which is placed last)

Subsets

JA = [J_1, J_2], where J_1 and J_2 are two branches of JO1(crude before the desalter)

JB = [J_3, J_4], where J_3 and J_4 are two branches of JO2 (crude after the desalter)

JC = [J_5, J_6], where J_5 and J_6 are two branches of JO3 (crude after the preflash drum)

Hot streams including furnace: H (the furnace appears last)

H1 = {kerosene, diesel, AGO, residue, naphtha, sour water, condenser, PA1, PA2, PA3}

Intervals $T = \{T_0, T_1, ..., T_N\}$

Variables

Let θ(J) be the split ratio of branch J. For each period, the following equations hold

$$\sum_{\mathrm{JA}} \theta(ja) = 1 \tag{15}$$

$$\sum_{\mathrm{JB}} \theta(jb) = 1 \tag{16}$$

$$\sum_{\mathrm{JC}} \theta(jc) = 1 \tag{17}$$

$$\mathrm{QC}_{ja,t} = \theta_{ja}\mathrm{QCO}_{jo1,t} \tag{18}$$

$$\mathrm{QC}_{jb,t} = \theta_{jb}\mathrm{QCO}_{jo2,t} \tag{19}$$

Heat balances for hot streams are

$$R_{S,T} - R_{S,T-1} + \sum_j Q_{S,jT} = \mathrm{HU}_T \tag{20}$$

$$R_{i,T} - R_{i,T-1} + \sum_j Q_{i,j,T} - \mathrm{QH}_{i,T} = 0 \tag{21}$$

The heat balance for each cold stream is

$$\sum_i Q_{i,j,T} - \mathrm{QC}_{j,T} = 0 \tag{22}$$

The upper bounds for heat exchange in interval T are

$$Q_{i,j,T} - y_{i,j,T}U_{i,j,T} \le 0 \tag{23}$$

$$Q_{i,j,T} - \epsilon_{i,j,T}y_{i,j,T} \le 0 \tag{24}$$

where $U_{i,j,T}$ and $\epsilon_{i,j,T}$ are positive constants. For simplicity, the same value can be used for all i, j, T.

A cold branch can match with only one hot stream (except the heating utility) in each interval

$$\sum_{i \ne S} y_{i,j,T} \le 1 \tag{25}$$

$$\begin{cases} K_{i,j,T} \ge y_{i,j,T} - y_{i,j,T-1} \\ K_{i,j,T_1} = y_{i,j,T_1} \end{cases} \quad T > T_1 \tag{26}$$

In this constraint, $K_{i,j,T}$ is a binary variable used to count heat exchangers. Note that $K_{i,j,T}$ can be 1 in a period even if the heat duty in that interval is 0. This represents a heat exchanger that is in use in one period and idle in the other period.

The bound on the number of heat exchangers is

$$\sum_{i,j,T} K_{i,j,T} \le N \tag{27}$$

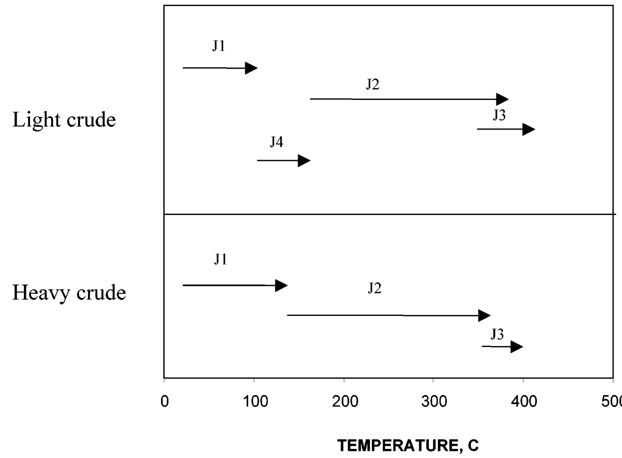

Figure 5. Starting and targeting temperatures of colds streams in two periods.

The two operation periods under consideration should share the same matching patterns

$$\mathrm{MPI}_j^{\mathrm{I}} = \mathrm{MPI}_j^{\mathrm{II}} \tag{28}$$

Solution Procedure

To reduce computational time, this problem is decomposed into two subproblems: a design each above and below the preflash drum temperature level. The objective function for the subproblem above the preflash drum is minimization of the heating utility. The number of exchangers N is initially given a large value and reduced step-by-step until the utility consumption starts to increase. In addition, in this subproblem, the residual heats in the last interval can be nonzero, allowing heat to cascade down to the other subproblem. As no heating utility is required below the preflash drum, the number of heat exchangers below the preflash drum is minimized. Caution has to be taken when the model above the preflash drum is solved. More than one solution that has the same heating utilities and the same number of exchangers might exist. If this happens, one has to use each solution and solve the subproblem below the preflash drum to determine which solution yields lower capital costs below the preflash drum.

Results and Discussion

Because the heavy crude bypasses the preflash drum, there is one fewer cold stream in the heavy crude period than in the light crude period. To make the number of cold streams the same, the heavy crude is regarded as going through a dummy preflash drum. This dummy preflash drum has neither a temperature constraint nor a vapor effluent. In this way, the heavy crude (after the desalter and before the furnace) is divided into two segments: before and after the preflash drum (Figure 5).

For the case above the preflash drum, a solution was found by minimizing the total heating utilities. This solution was then excluded, and the model was run again to see whether an alternative solution with the same heating utility exists. No alternative with the same heating utility was found in this study.

Table 5 compares the targeted furnace duty and the actual duty. The duties for both the light crude and the heavy crude increase (as expected). Figure 6 shows the

Table 5. Comparison of Targeted Furnace Duty and Actual Furnace Duty[a]

	light crude	heavy crude
targeted furnace duty (MW)	68.02	57.26
actual furnace duty (MW)	71.55	61.92

[a] HRAT/EMAT = 33.3 °C/22.2 °C.

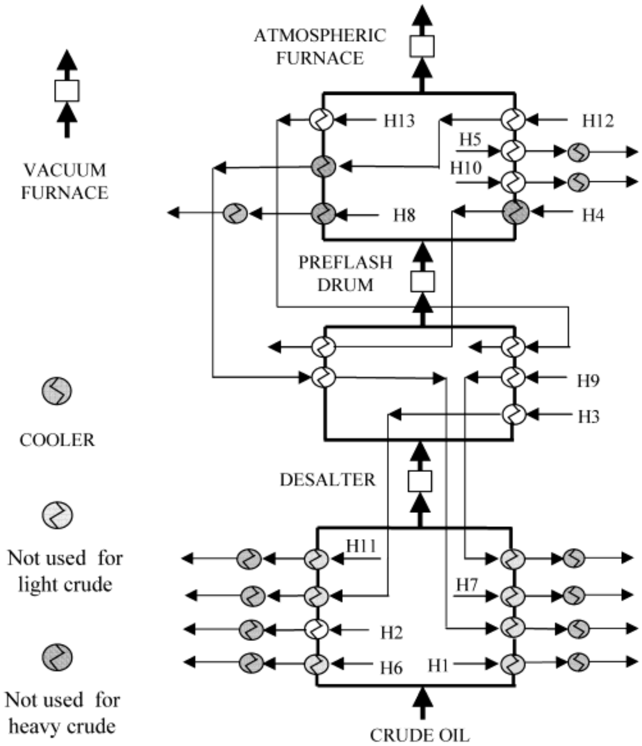

Figure 6. Two-branch heat exchanger network.

heat exchanger network. There are 9 exchangers (including the atmospheric furnace and the vacuum furnace) above the preflash drum, 13 exchangers below the preflash drum, and 11 coolers, totaling 33 exchangers. In the light crude period, five exchangers are not used below the desalter. In the heavy crude period, three exchangers are idle above the desalter.

The reason for using more exchangers for the heavy crude below the desalter is that no hot streams with large capacities are available. Unlike the case with the light crude, where the condenser alone can provide enough heat for the light crude, the heavy crude has to pick up heat from several hot streams. The different heat supply scenarios below the desalter increase the complexity of the heat exchanger network.

The total area for the two-branch design is 56 576 m^2 (Table 6). The total area for the HEN without the restriction of splitting is 66 988 m^2. This estimate was obtained by calculating the area from the supply–demand diagram with the assumption of vertical heat transfer. Therefore, the restriction of splitting reduces the total area by 15%. This observation is consistent with that reported by Bagajewicz and Soto.[3]

Conclusions

This paper addresses the design of a heat exchanger network for complete crude distillation plants. A multiperiod heat exchanger network design model was proposed to handle two different crudes. To reduce the complexity of the heat exchanger network, an assumption was made that the crude streams can be split into no more than two branches. This model also takes into account the flexibility of using a preflash drum for the light crude only. This multiperiod model contains a topological constraint through which all periods share the same heat exchange matching pattern but not necessarily at the same temperature levels.

Table 6. Comparison of Areas[a–c]

	hot/cold streams	light crude (m^2)	heavy crude (m^2)	HX area (m^2)
1	I8/J1	1068		1068
2	I12/J1	310		310
3	I13/J1	1199	9285	9285
4	I4/J2	2456	0	2456
5	I10/J2	427	600	600
6	I5/J2	3578	240	3578
7	I12/J2	71	239	239
8	J41/I12	915	244	915
9	J41/I4	383	1905	1905
10	J42/I3	3484		3484
11	J42/I9	160	572	572
12	J42/I13	770	4058	4058
13	I6		401	401
14	I2	6879	5650	6879
15	I3		823	823
16	I11		2146	2146
17	I1		1436	1436
18	I12		600	600
19	I7		1803	1803
20	I9		3664	3664
	sum			46221
		coolers		
1	I1	1133	0	1133
2	I2	4319	140	4319
3	I3	503	244	503
4	I5	154	64	154
5	I6	1273	0	1273
6	I7	724	300	724
7	I8	866	233	866
8	I9	407	0	407
9	I10	161	185	185
10	I11	265	498	498
11	I12	291	0	291
	sum			10355
	total			56576

[a] Areas estimated from the heat demand–supply diagram. [b] $U = 125$ W/m^2·°C [c] Area for heat exchangers (m^2) = 58 903. Area for coolers (m^2) = 8085. Total area (m^2) = 66 988.

Nomenclature

$\epsilon_{i,j,T}$ = positive number used in the logical inequality
$\theta(J)$ = split ratio of branch J
CP(K,i) = the number of child patterns generated by removing i streams
E = total energy consumption
H_i^s = enthalpy of steam i
HU_T = heat from the hot utility in interval T
I = hot stream
J = cold stream
MP(N,m) = the number of matching patterns
$K_{i,j,T}$ = variable used to count heat exchangers
$PA_{j,T}$ = parameter representing a match between a cold stream j and hot stream i in interval T
$PB_{j,T}$ = auxiliary variable for representing a heat exchange match pattern
$Q_{i,j,T}$ = heat transfer between hot stream i and cold stream j in interval T
$QH_{i,T}$ = heat available from hot stream i in interval T
$QC_{j,T}$ = heat demand for cold stream j in interval T
$Q_{S,j,T}$ = heat transfer between hot utility S and cold stream j in interval T

$R_{S,T}$ = residue heat of hot utility in interval T
$R_{i,T}$ = residue heat of hot stream i in interval T
T = interval
U = minimum heating utility
$U_{i,j,T}$ = positive number used in the logical inequality
$y_{i,j,T}$ = binary variable for heat transfer between stream i and cold stream j in interval T

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