Design of Crude Distillation Plants with Vacuum Units. I. Targeting

Shuncheng Ji† **and Miguel Bagajewicz***

School of Chemical Engineering and Materials Science, University of Oklahoma, 100 East Boyd St, T-335, Norman, Oklahoma 73019

In previous work (Ji, S.; Bagajewicz, M. *Ind. Eng. Chem. Res.* **2002**, *41*, 3003), it was shown that the preflash/prefractionation arrangement of distillation units is not as energy efficient as the conventional design in the absence of a vacuum unit. The same was found for a newly proposed stripping-type design. The use of a vacuum column, however, has many implications on energy consumption, which alters these conclusions. Three atmospheric vacuum distillation arrangement combinations are therefore studied in this paper, revealing that the addition of a vacuum column favors the preflashing distillation arrangement.

Introduction

This paper is a follow-up to a series of papers where the energy targeting of atmospheric units of different types was performed. The study was prompted by the scarce literature on design procedures for these systems, which do not employ modern and rigorous tools but rather rely on hand calculations and diagrams.[1−3] To ameliorate this difficulty, Liebmann and co-workers[4] proposed an integrated design procedure that takes into account distillation sequencing and pinch technology. Finally, Sharma et al.[5] proposed a more systematic method, but their approach still relies on Packie's diagrams.

Our earlier work started with a study of the flexibility aspects for the design of atmospheric columns using rigorous simulators.[6] From the results, Bagajewicz and Ji[7] proposed a rigorous targeting design procedure for the design of conventional crude distillation units. This procedure aims at finding the best scheme for a multipurpose crude distillation unit that processes a variety of crudes, which is an issue that had been overlooked by previous design procedures. Heat demand−supply diagrams, rather than grand composite curves, are used as guidance in the search for optimal schemes. Using energy targets for different crudes, a method for designing multipurpose heat exchanger networks was developed.[8] In the same work, the conjecture that a design for extreme crudes would be able to accommodate the processing of intermediate crudes was posed and partially confirmed. Ji and Bagajewicz[9,10] analyzed conventional crude fractionation units that use prefractionation columns or preflash drums and stripping-type columns. They concluded that, under the same high-product-yield conditions, prefractionation or preflashing and stripping-type designs without a follow-up vacuum columns are not advantageous in terms of energy efficiency. Finally, Bagajewicz and Soto[11] proposed a methodology for the design of heat exchanger networks corresponding to energy targets.

* To whom correspondence should be addressed. Phone: +01-(405)325-5458. Fax: +01-(405)325-5813. E-mail: bagajewicz@ou.edu.

† Current address: Conoco Inc., RW 6691, 1000 South Pine, Ponca City, OK 74601.

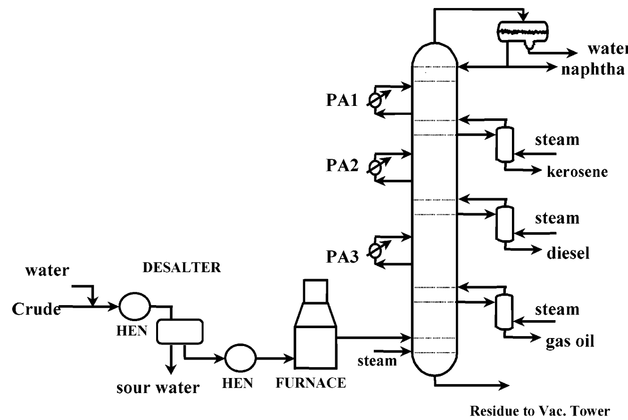

Figure 1. Conventional design.

In first part of this work, the energy targeting for combined atmospheric distillation and vacuum distillation is obtained, and the merits of using these designs is discussed. In the second part of this article,[12] the design of the heat exchanger network is undertaken.

Alternatives for Combined Atmospheric−Vacuum Distillation

Figure 1 shows the conventional design of an atmospheric unit. A detailed description of this design can be found elsewhere.[7]

The preflash design (Figure 2) is a variation of the conventional design that consists of introducing a flash unit to separate light components, in many cases for the specific purpose of reducing the load on the furnace and, hence, enhancing throughput. In the prefractionation design (Figure 3), the light components are separated in the prefractionation column and not sent to the column.

The prefractionation design, however, is considered to be similar to the preflash design when energy consumption is considered,[9] and for this reason, it is not included in this study. Because the condensation heat for naphtha (or light naphtha plus heavy naphtha) is constant, the only difference is that the prefractionation design provides this heat in two condensers with dif-

10.1021/ie011040u CCC: $22.00
Published on Web 10/26/2002

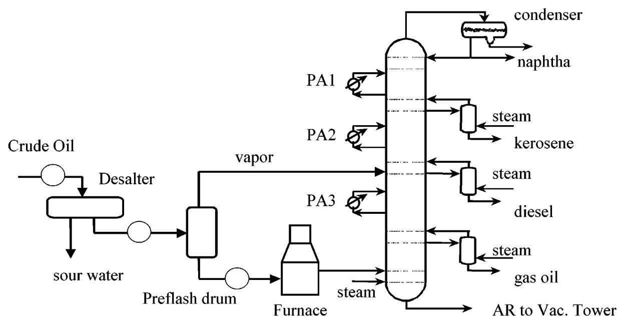

Figure 2. Preflash design.

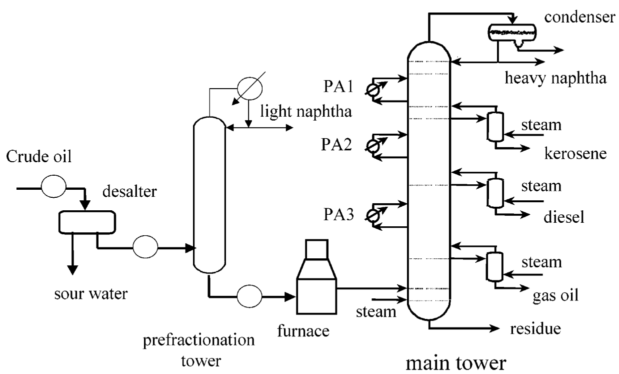

Figure 3. Prefractionation design.

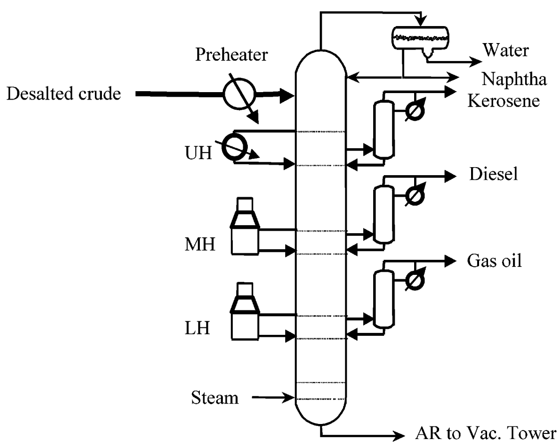

Figure 4. Stripping-type design.

ferent temperatures. When there is significant heat surplus in the temperature range of the condensers, the difference does not affect energy consumption.

In the stripping-type design (Figure 4), the crude is heated to a relative low temperature (about 150 °C) and fed at the top of the column. The crude goes down the column and is heated consecutively in three heaters (the upper heater, middle heater, and lower heater). Side products are withdrawn from the vapor phases and rectified in side rectifiers. This design has been analyzed in detail by Ji and Bagajewicz.[10]

Thus, the conventional and stripping-type designs are located at the two ends (completely direct and completely indirect sequences) of the spectrum of distillation sequences. The prefractionation design is a sequence somewhere between these two extremes. Indeed, in the prefractionation design, the lightest component is separated first, and an indirect sequence follows. The preflash design does not fall exactly into regular sharp split distillation theory, but it can be considered somewhat similar to the prefractionation design.

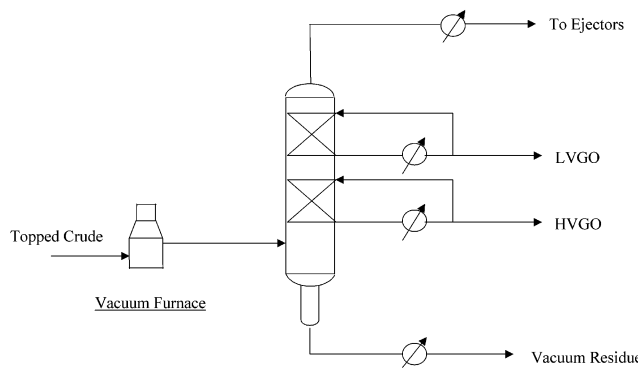

Figure 5. Vacuum distillation.[3]

A systematic procedure for obtaining design targets for heat integration in conventional crude fractionation units that use prefractionation columns or preflash drums was recently presented.[7,9] It shows that, under the usual temperature limits for the prevention of thermal cracking, the preflash design generates more atmospheric residue and less gas oil and consumes less energy.

Liebmann et al.[4] and Liebmann[13] reported that, for atmospheric distillation, the stripping-type design could feature a 5% lower utility cost than the optimized conventional design. However, the comparison is not appropriate because, in the stripping-type design, the crude oil was assumed to be heated to a much higher temperature than in the conventional design. Ji and Bagajewicz[10] took the temperature limit of thermal cracking into account and revealed that this stripping design is not competitive.

In the case of a system with a vacuum column, the atmospheric gas oil lost in the preflash or stripping-type designs is picked up in the vacuum column at the expense of extra vacuum jet steam consumption. This then raises the question of whether the total energy consumption is lower than in the conventional design. This is the main issue addressed in this paper.

Vacuum Oil Distillation

Figure 5 presents a schematic diagram for the production of light vacuum gas oil (LVGO) and heavy vacuum gas oil (HVGO). The HVGO section is the main heat removal zone. HVGO is withdrawn and cooled in the heat exchanger network, and then, a portion of the HVGO is returned to the top of the packing. The temperature of the steam and noncondensable materials leaving the top of the vacuum tower is determined by setting a 10−25 °C approach to the minimum practical cool oil temperature in the top pump-around circuit (usually 65−95 °C).

The residue section serves two purposes: One is to remove relatively light components, and the other is to reduce coke formation. The former is achieved by steam stripping using a steam to net residue ratio of 4−6 lb/bbl. The latter is realized by circulating the partially cooled bottoms to quench the liquid to 365 °C.

The absolute pressure in the vacuum tower flash zone is controlled between 25 and 100 mmHg. The effective pressure can be reduced to about 10 mmHg by injecting

Table 1. Vacuum Tower Specifications

total number of trays	7
flash zone pressure, psia	1.90
LVGO D86 95% temperature, °C	410[a]
flash zone temperature, °C	382
overflash ratio	0.02
overhead temperature, °C	127
bottom steam/vacuum residue, lb/bbl	2−3 (2.74)

[a] Equivalent to 30 vol % of total vacuum gas oil.

Table 2. Vacuum Tower Product Temperatures

product	temperature, °C	viscosity, CP
LVGO	104	3.9
	60	14.2
HVGO	104	10.2
	82	20.6
vacuum residue	104	1127
	160	60.3
	177	33.8

steam to the furnace and at the bottom of the vacuum tower. The amount of stripping steam used is a function of the boiling range of the feedstock and the fraction vaporized, and generally, it is in the range of 10−50 lb/bbl.

Vacuum Tower Specifications

Table 1 shows the specifications that were used in this study. Usually, the specification for the LVGO is its flow rate, typically defined to be one-third of the total distillate flow rate. In this study, however, the same flow rate for LVGO cannot be specified in the three complete plants because the residue from the atmospheric towers varies. Instead, a D86 95% temperature was used to specify LVGO for all three designs. The flash zone temperature was specified, and the flow rate of the HVGO as well as the overflash ratio were allowed to vary. Alternatively, one can specify the D86 90% temperature of the HVGO.

Products from the vacuum tower were cooled to recover heat before being sent for further processing. Naturally, one would like to recover as much heat as possible. However, the final temperatures of these products should not be too low because they become too viscous to be pumped efficiently. Table 2 shows the viscosities of the LVGO, HVGO, and vacuum residue at several temperatures. The final temperatures for the LVGO, HVGO, and vacuum residue were specified as 60, 82, and 177 °C, respectively.

Targeting Procedure

The energy targeting technique for designing complete distillation plants used here is an extension of the procedure developed for conventional units.[7] For the conventional vacuum design, the Watkins[3] design method is used to obtain an initial scheme without pump-around circuits. Then, a heat demand−supply diagram is constructed, and the direction of heat shifting needed for maximum energy efficiency is determined. This procedure can be repeated for other crudes.

Following, the procedure, as it applies to a system composed of a conventional atmospheric column followed by a vacuum column, is summarized (details are discussed in previous work[7]).

Step 1. Begin by setting up an atmospheric tower with no pump-around circuits.

Step 2. Perform a simulation. (Pro II from Simulation Sciences was used here.)

Step 3. Construct the heat demand−supply diagram.

Step 4. Transfer heat from the condenser of the atmospheric tower to the top atmospheric pump-around.

Step 5. If product gaps limits are violated, increase the stripping steam flow rate.

Step 6. If there is a heat surplus from the pump-around circuit just added, transfer the heat to the next pump-around circuit between draws in the same way as in step 4. If not, stop.

Step 7. For the vacuum tower, shift heat from the top pump-around to the low pump-around. The heat shifting should stop when either the energy consumption does not decrease or the minimum allowed gap bound is reached. Recall that the energy consumption is calculated by adding the minimum utility (obtained using pinch analysis) and the enthalpy of the steam added multiplied by a cost factor (0.7 in this case).[7]

The presence of the vacuum distillation affects the optimal heat load distribution in the atmospheric tower. With the variation of heat distribution in the vacuum tower, the pinch location might change. When step 7 is completed, one should check the heat demand−supply diagram and determine whether the heat distribution in the atmospheric tower is optimal. If not, one has to adjust the heat distribution and return to step 5.

Preflash/Prefractionation Case. A special feature of the preflash design is that the heat demand for the crude can be adjusted by changing the temperature of the preflash drum. The total heat load in the atmospheric tower depends on the duty of the furnace, which decreases with increasing preflash temperature (because more light components bypass it). On the other hand, the steam consumption increases rapidly to both maintain the gas oil yield and fix the product gaps. In the case of an atmospheric column with preflash, the total energy consumption reaches a minimum at around 177 °C.[9] However, the differences in energy consumption at other temperatures are relatively small. Finally, if steam is in surplus in the refinery, only the heating utility counts, and lower temperatures should be used. Therefore, in the case of the preflash design, the whole procedure is repeated at increasing temperature of the preflash drum until the total energy consumption starts to increase. During this procedure, product gaps are maintained by adjusting the stripping steam rates.

Stripping-Type Atmospheric and Vacuum Cases. With the knowledge that the conventional design starts with no pump-around circuits, one can propose a stripping-type design to start with only one heater. However, this is not feasible because one would have to use temperatures higher than the maximum limits imposed to prevent cracking. To overcome this problem, an initial heat distribution among the three heaters is chosen. Because all heaters are above the pinch temperature,[10] a redistribution of the heat supply in these heaters does not affect the energy consumption. Thus, steps 4−7 are replaced by the following steps:

Modified Step 4. Increase the temperature of the feed until the total energy consumption starts to increase.

Modified Step 5. To adjust gaps, modify the reflux ratio in side condensers.

Table 3. Variation of Energy Consumption with the Addition of Each Pump-Around Circuit in the Case of the Conventional Vacuum Design[a]

	energy consumption (MW)
no pump-around circuit (step 3)	97.29
with PA1 (step 4)	95.33
with PA1 and PA2 (step 6)	86.46
with PA1, PA2, and PA3 (step 6)	76.94
with VPA2 optimized (step 7)	75.13

[a] $\Delta T_{\min}$ = 22.2 °C. (Vacuum jet steam consumption not included.)

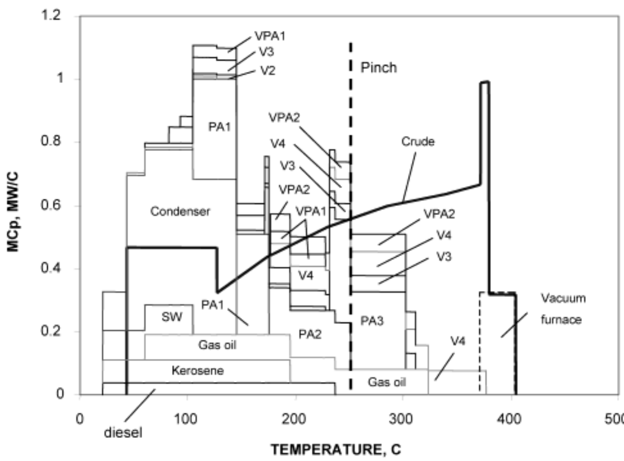

Figure 6. Heat demand−supply diagram for light crude (conventional atmospheric + vacuum column). V2, LVGO; V3, HVGO; V4, vacuum residue.

Results

It is shown in a previous work[7] that both the preflash and stripping-type designs produce more residue than the conventional design. The higher feed rate to the vacuum tower has two immediate effects. One is the requirement of a higher capacity in the vacuum tower, and the other is a higher suction load to the vacuum-producing system. From the viewpoint of energy consumption, both the preflash design and the stripping-type design have the advantage of reducing the direct heat demand of the crude oil by avoiding overheating of the light components. However, the corresponding vacuum system consumes more steam. The tradeoff between these two factors is investigated next. The feedstock used in this section is a light crude of API 36. The property data for this crude are reported in the Appendix.

Conventional Atmospheric−Vacuum Distillation Design. Basically, there are two rules to determine whether a new pump-around is needed (step 6). One is the existence of a heat surplus in the last pump-around added, and the other is that the addition of a new pump-around should reduce the total energy consumption. For the vacuum tower, the two pump-around circuits are already present at the beginning of the procedure. The problem is then to minimize the objective function without violating the product gap.

Table 3 shows the resulting energy consumption after the corresponding steps in the targeting procedure are implemented. The resulting heat demand−supply diagram is shown in Figure 6. The same diagram for the atmospheric column is shown elsewhere.[7]

The installation of PA1 or VPA2 results only in a small reduction of the energy consumption because the temperature of the heat provided by PA1 is still low and most of this heat is in the region where the heat supply is already in surplus. In the case of VPA2, its duty is comparatively small. Although smaller, the heat loads of the vacuum pump-around circuits and products affect the heat distribution in the atmospheric pump-around circuits. With additional heat sources available in the intermediate temperature region (PA2 region), it is beneficial for the complete design to shift more heat from PA2 to PA3. Table 4 compares the loads for the two cases.

Table 4. Comparison of Pump-Around Loads (in MW) in the Atmospheric Tower

pump-around circuit	conventional design[a]	atmospheric−vacuum design
PA1	22.28	23.07
PA2	33.71	12.87
PA3	8.79	22.69

[a] Taken from Bagajewicz and Ji.[7]

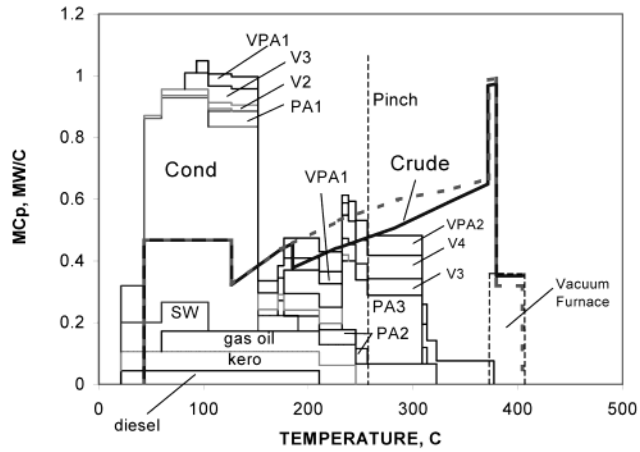

Figure 7. Heat demand−supply diagram for preflash type distillation (light crude).

The complete plant has a lower duty in the middle pump-around (PA2) and a higher duty in the lower pump-around (PA3). This is because, in the atmospheric-only conventional distillation case, when the PA3 duty reaches 8.79 MW, the surplus in the PA2 region vanishes. Therefore, a further heat shift to PA3 does not reduce the net heat demand and worsens the separation between diesel and gas oil. In the complete atmospheric−vacuum plant, however, the vacuum products and pump-around circuits provide new heat sources in the PA2 region (Figure 6), which contributes to a larger heat surplus in the PA2 region and allows more heat to be shifted from PA2 to PA3. The duty of PA3 increases until the tradeoff between the reduced energy consumption and the increased steam consumption is not favorable.

Preflash Atmospheric Design with Vacuum Column. Figure 7 shows the final supply−demand diagram for the preflash atmospheric design with a vacuum column. The major difference from the conventional design is in the heat demand curve. The heat demand curve for the crude without preflashing is shown as the dashed curve. Note that the crude curve drops at the preflash temperature (162.8 °C).

With the separation of light components at the preflash drum, the heat demand for the crude after leaving the preflash drum and before entering the

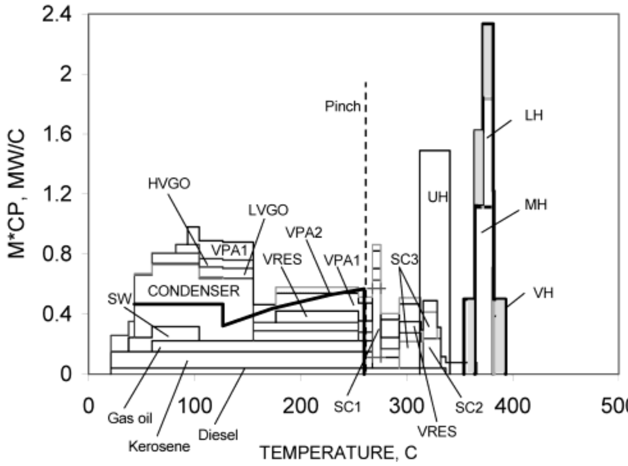

Figure 8. Stripping-type crude distillation (light crude). SC, side condenser; VRES, vacuum residue; SW, saline water; UH, MH, and LH, upper, middle and lower heaters, respectively, for the atmospheric tower; VH, vacuum heater.

atmospheric tower is lower than that for the conventional atmospheric–vacuum distillation design. As the preflash design produces more atmospheric residue, the duty of the vacuum furnace is higher. The vacuum jet steam consumption also increases with the increased feed load to the vacuum tower.

Stripping-Type Design with Vacuum Column. Figure 8 shows the heat demand–supply diagram for the stripping-type design with a vacuum tower. An important feature of this diagram is that the demand curve for the crude is not continuous. Between 237.8 °C (the temperature at which the crude enters the atmospheric tower) and 290.1 °C (the temperature at which the crude enters the upper heater), there is no heat demand.

Although the heat requirements for heating and vaporizing the crude are similar to those of the conventional-vacuum design, the stripping-type design requires a larger portion of heat at high temperatures. This is disadvantageous from the viewpoint of heat recovery. The stripping-type design also requires larger heat duty from the vacuum furnace because the atmospheric tower vaporizes less distillates and leaves more atmospheric residue for the vacuum tower to separate.

Comparison. A comparison among the three complete plants is shown in Table 5. In this table, from left to right, are the conventional design, the preflash design, and the stripping-type design.

The preflash design has the lowest energy consumption, but its difference from the conventional design is small. Note that the total yields of distillates are almost the same. The stripping-type design consumes 40% more energy than the conventional design. Both the steam consumption and the minimum heating utility are higher for the stripping-type design than for the conventional design. A larger vacuum steam consumption is incurred by the larger amount feed to the vacuum tower. The vacuum steam consumption of the stripping-type design is 48.5% higher than that of the conventional design. The large increase in the duty of the atmospheric tower is due to the requirement of heat at higher temperature levels where less recoverable heat is available. The requirement for heat at higher temperature makes a large part of the heat from the

Table 5. Comparison of the Optimal Designs of Three Complete Plants

	conventional	preflash	stripping-type
	steam supply (MW)		
atmospheric	15.74	13.08	16.38
vacuum[a]	11.55	12.35	17.15
total steam	27.28	25.43	33.53
	product gap (°C)		
naphtha–kerosene	16.6	16.7	18.8
kerosene–diesel	0.0	0.0	0.7
diesel–gas oil	−4.0	−4.5	−25.8
LVGO–HVGO	−30.4	−29.7	−30.2
	yield (M^3/h)		
naphtha	244.39	244.92	244.81
kerosene	144.76	145.15	141.03
diesel	71.82	69.95	51.84
gas oil	124.25	110.40	45.44
LVGO	22.92	34.92	115.09
HVGO	81.43	86.09	92.24
total distillates	689.57	691.43	690.45
vacuum residue	105.53	103.58	104.37
vacuum overhead	0.202	0.258	0.108
HDBR[b] (MW)	195.81	191.58	
HU (MW)	62.57	62.10	80.48
energy (MW)	81.67	79.90	114.01

[a] Steam consumption = 23.28 lb per bbl feed. [b] Total heat demand before recovery.

products and pump-around circuits unusable, and more cooling water has to be used to remove the unusable heat.

It is also seen that both the stripping-type design and the preflash design produce less atmospheric gas oil, but the loss is picked up by the vacuum tower in terms of more LVGO. The product gaps are similar among the three designs except for the diesel–gas oil gap in the stripping-type design, where some diesel is not vaporized in the middle heater and is carried out in the gas oil stream.

For the stripping-type crude distillation, the addition of the vacuum tower does not have a significant effect on the topology of the heat demand–supply diagram (the heat demand takes place at high temperatures). The heat from the vacuum products and vacuum pump-around circuits appears on the left of these heaters. This explains why the energy efficiency for the stripping-type design in a complete plant is even worse than that in the stripping-type atmospheric distillation plant.

Results for a Heavy Crude

As mentioned previously, both the preflash design and the stripping-type design aim at light crudes. In terms of energy efficiency, the possible gain from both designs is that the heat demand for the light components can be lowered.[9,10] In addition, the early separation of light components reduces the yield of gas oil and increases the feed load to the vacuum tower.[9] For heavy crude, the increased feed load is even worse than in the light-crude case because the heavy crude contains much more atmospheric residue. If the preflash design or the stripping-type design is used, the capacity of the vacuum tower has to increase. Therefore, there is no advantage to using the preflash design or the stripping-type design for a heavy crude. For this reason, we illustrate only the conventional vacuum design for the heavy crude. The property data of this crude are reported in the Appendix.

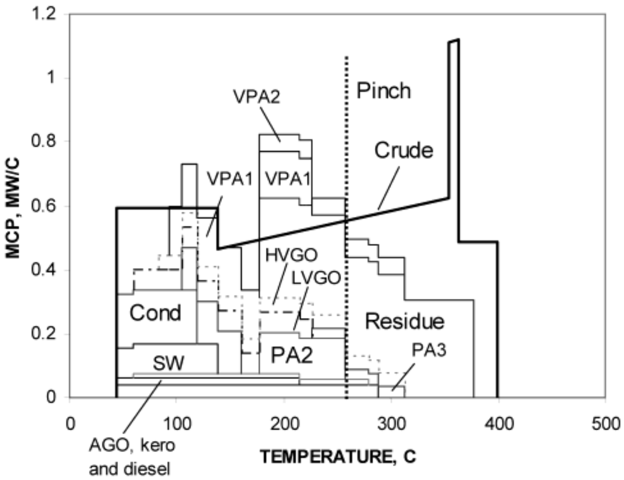

Figure 9. Conventional vacuum crude distillation (heavy crude). VPA, vacuum pump-around; SW, saline water; Cond, condenser of the atmospheric tower.

The heating utility for a complete conventional plant processing a heavy crude is 51.35 MW. The heat demand−supply diagram and the operation variables for a scheme with three pump-around circuits are shown in Figure 9. The pinch point is at 256.5 °C/234.3 °C. Compared with the conventional design without vacuum distillation,[7] the heat deficit in the low to medium temperature range is improved but still prevails. The heat surplus in the PA2 region can be used to cover the heat deficit in the condenser region. Similarly to the atmospheric design, the total energy consumption is not sensitive to the atmospheric tower heat distribution. This allows added flexibility for the heat exchanger network design.

Conclusions

Rigorous targeting procedures have been performed for three types of complete crude distillation plants. It was found that the introduction of a vacuum tower changes the topologies for both the conventional design and the preflash design, thereby changing the heat distribution among the pump-around circuits. In the stripping-type design, however, the heat provided by the vacuum products cannot be utilized. The energy consumption for the preflash vacuum design is slightly smaller than the conventional vacuum design, and therefore, these two can be considered equivalent.

A target for the conventional vacuum design with the heavy crude reveals that there is still a large heat deficit in the atmospheric condenser region and the total energy consumption is not sensitive to the atmospheric tower heat distribution. The energy targets obtained above are used in part II of this work[12] to develop a heat exchanger network for a complete distillation plant.

Appendix

The properties of the crude oils used are summarized in Table A.1. The process rate is 5000 bbl/h. The TBP data and light ends composition are given in Tables A.2 and A.3, respectively.

Table A.1. Feedstock Used for the Design

crude	density (kg/m^3)	throughput (m^3/h)
light crude	845 (36.0 API)	795
heavy crude	934 (20.0 API)	795

Table A.2. TBP Data (°C)

vol %	light crude	heavy crude
5	45	133
10	82	237
30	186	344
50	281	482
70	382	640
90	552	N/A

Table A.3. Light-Ends Composition of Crude

compound	light crude (vol %)	heavy crude (vol %)
propane	0.78	0.04
isobutane	0.49	0.04
n-butane	1.36	0.11
isopentane	1.05	0.14
n-pentane	1.30	0.16
total	5.11	0.48

Literature Cited

(1) Nelson, W. L. *Petroleum Refinery Engineering*, 4th ed.; McGraw-Hill: New York, 1958.

(2) Packie, J. W. Distillation Equipment in the Oil Refining Industry. *AIChE Trans.* **1941**, *37*, 51.

(3) Watkins, R. N. *Petroleum Refinery Distillation*; Gulf Publishing Co.: Houston, TX, 1979.

(4) Liebmann, K.; Dhole, V.; Jobson, M. Integration Design of a Conventional Crude Oil Distillation Tower Using Pinch Analysis. *Inst. Chem. Eng. A* **1998**, *76*, 335.

(5) Sharma, R.; Jindal, A.; Mandawala, D.; Jana, S. Design/Retrofit Targets of Pump-Around Reflexes for Better Energy Integration of a Crude Distillation Column. *Ind. Eng. Chem. Res.* **1999**, *38*, 2411.

(6) Bagajewicz, M. On the Design Flexibility of Atmospheric Crude Fractionation Units. *Chem. Eng. Commun.* **1998**, *166*, 111.

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

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

(9) Ji, S.; Bagajewicz, M. Design of Crude Fractionation Units with Preflashing or Prefractionation: Energy Targeting. *Ind. Eng. Chem. Res.* **2002**, *41*, 3003.

(10) Ji, S.; Bagajewicz, M. On the Energy Efficiency of Stripping-Type Crude Distillation. *Ind. Eng. Chem. Res.*, in press.

(11) Bagajewicz, M.; Soto, J. Rigorous Procedure for the Design of Conventional Atmospheric Crude Fractionation Units. 3. Trade-Off between Complexity and Energy Savings. *Ind. Eng. Chem. Res.*, manuscript submitted.

(12) Ji, S.; Bagajewicz, M. Design of Crude Distillation Plants with Vacuum Units. II. Heat Exchanger Network Design. *Ind. Eng. Chem. Res.* **2002**, *41*, 6100−6106.

(13) Liebmann, K. Integrated Crude Oil Distillation Design. Ph.D. Dissertation, University of Manchester Institute of Science & Technology, Manchester, U.K., 1996.

Received for review December 30, 2001
Revised manuscript received August 28, 2002
Accepted August 28, 2002

IE011040U