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ON THE DESIGN FLEXIBILITY OF ATMOSPHERIC CRUDE FRACTIONATION UNITS*

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This paper is devoted to study the effect of the design parameters on atmospheric crude distillation units. The following conclusions are obtained: Pump-around circuits play only a role in energy integration, but they have imperceptible effects on the separation goals. Column separation performance is not affected by side-stripper steam rates above a certain threshold, whilst condenser duty is increased unnecessarily. Main steam injection and overflash have important effects on the quality of gas oil. However when the overflash is reduced, the impact on the flowrate of gas-oil produced can be compensated by increasing main column steam injection. In this way, as the furnace duty is lowered, air emissions can be reduced without altering the column performance. Finally, the usage of reboilers is quantified confirming the recommendations that they should not be used in the design of these systems.

Keywords: Petroleum fractionation; Design flexibility

INTRODUCTION

The design of crude units is reviewed by Watkins (1979), where different design alternatives are presented and a method to design atmospheric and vacuum columns is suggested. Watkins' book is still the main reference for crude unit design and no other comprehensive attempt has been presented since. Crude fractionation columns, according to Watkins are classified into three types: U, A and R. Essentially, these three types correspond to three different types of cooling arrangements: top reflux, pump-around reflux and

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pump-back reflux, in Watkins' nomenclature. A top reflux corresponds to the conventional top condenser of distillation columns. In a pump-around reflux, liquid is drawn from a plate and after being cooled down it is returned to a few plates above. Finally in a pump-back reflux, liquid in equilibrium is sub-cooled and sent to the tray immediately below.

Figure 1 depicts an atmospheric crude fractionation unit containing all the features that characterize types U, A and R. In this figure the heat exchanger network is omitted to highlight design parameters unrelated to heat integration.

Crude is preheated to a certain temperature typically 260 °F, for desalting purposes. The column has typically three (sometimes four) side draws to produce kerosene, diesel oil and atmospheric gas oil(s). To produce a

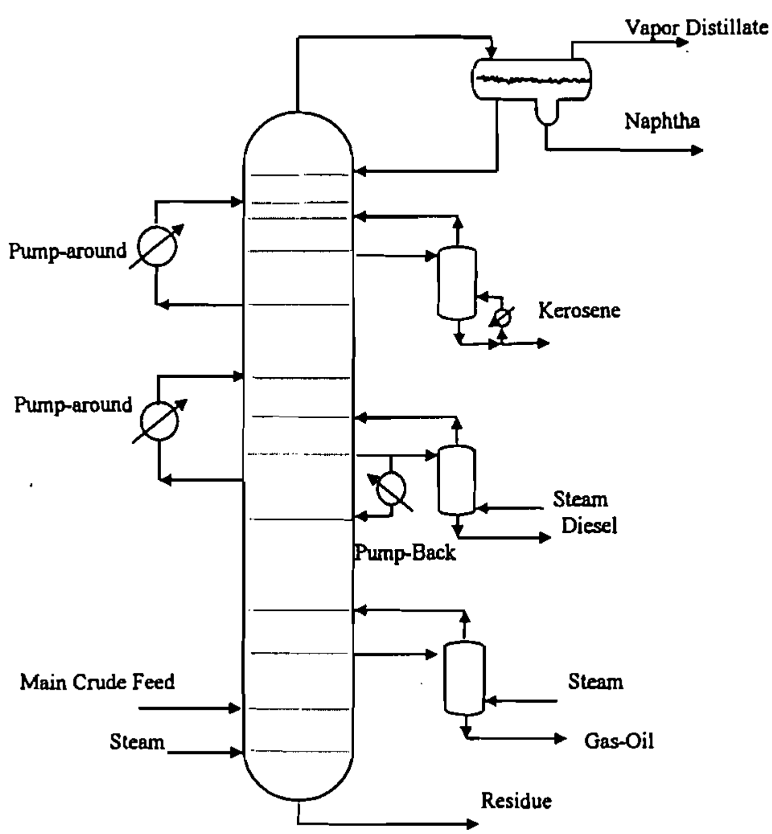

FIGURE 1 Atmospheric crude unit. Sketch of three reflux methods.

sharper separation, specifically, to strip some of the lighter fraction of the draw, a stripper is set for each case. Steam is used to produce this additional separation, but reboilers have also been considered in the past. Figure 1 contains one such reboiler in the kerosene stripper. Type U column, corresponds to a column where no pump-around circuit or pump-back is present. Thus, all the cooling is performed at the top condenser. In type A columns, two to three pump-around circuits are typically used to cool down some of the liquid and they may still share the cooling duty with a top condenser. Finally, type R columns with pump-back reflux can also contain a top reflux. The reason for this intermediate cooling is explained by the desire to reduce flow variations between the top and the bottom trays. Watkins shows that these flowrate variations are typically reduced by 60%, avoiding therefore an over-sizing of the column diameter. One additional advantage is that heat is available at higher temperature level, so energy integration can be enhanced. The disadvantage of the pump-around circuits is however identified by Watkins as a loss of theoretical trays. On the other hand, also according to Watkins, although sub-cooling takes place in pump-back refluxes there is no loss of separation efficiency.

Overflash is a term coined for the ratio of the volumetric flowrates of liquid flowing from the tray above the feed and the feed. This value is set to 2–3%. The purpose is, according to Watkins, to guarantee that the plates between the flash zone and the first draw above it do not dry up.

Steam injection has been used for years as an alternative to reboilers. Nelson (1949) first pointed out that reboilers, usually run by hot oil as is still the practice in several rerun and stabilizing columns, "do increase the efficiency of fractionation, but a satisfactory degree of separation can usually be obtained more cheaply by the use of a (steam) stripping section". This type of analysis has been repeated in one way or another throughout the years. For example, Hsie and McAvoy (1990) state that "steam also reduces the partial pressure of the hydrocarbons and thus lowers the required vaporization partial pressure of the hydrocarbons and thus lowers the required vaporization temperature". The obvious implication of all these statements is that steam injection is better, because it lowers the temperature, and eventually by implication, lowers the energy requirements. These implications are yet to be completely proven.

Side-strippers have been used to improve the Gap, which is the difference between the 5% ASTM temperature of a fraction drawn from the column and the 95% ASTM temperature of the adjacent heavier fraction (Watkins, 1979). Steam stripping as well as reboilers have been used over the years to provide the necessary vaporization.

Over the years, these designs have been applied in a variety of combinations. They have all evolved to configurations containing type A (pump-around) reflux, with or without top reflux. When top reflux is not used, it is usual to have a pump-around discharging sub-cooled liquid on the top tray. Pump-back reflux (type R) seems to have been abandoned in practice. Similarly steam injection as opposed to the use of reboilers is the current practice. Industry has only in appearance settled with these designs. There is an active pursuit for de-bottlenecking to increase throughput and energy efficiency retrofits, especially in the last 15–20 years. One such recent study is offered by Lin *et al.* (1996).

Fractionation of crude is energy intensive, and the main driving force for better designs stems from the sizable savings that can be achieved with proper heat integration. Pinch Technology (Linnhoff, 1993) has contributed to a great extent to profound changes in the heat exchanger network configuration of crude units. When applied to the analysis of crude units, the first discovery of pinch technology was that a lot of heat was transferred across the pinch, due in great part to the fact that the preheating crude was not split but rather heated up in a series of heat exchangers one after the other, whereas pinch designs usually call for stream splitting. Linnhoff *et al.* (1982) proposed the concept of appropriate placement, in which process decisions are made in light of the impact on heat recovery through the pinch diagram. Linnhoff and Parker (1984) extended the idea to an iterative scheme be proposing the Plus/Minus approach, where pinch diagrams suggest process changes that would in turn improve the heat recovery. Unfortunately, this method was described in the context of case studies, but never generalized nor automated. Bagajewicz (1997) has proposed such automation and has studied energy emission saving horizons for entire crude units. In this study, several parameters, such as pump-around rates and return temperatures, as well as steam injection rates have been varied to achieve maximum savings. The study takes advantage of the findings about column flexibility that this paper presents.

Structural alternatives to current designs have been proposed as early as in 1929. Piromoov and Beiswenger (1929) proposed the Carrier Distillation process, which was implemented by Lummus and apparently later abandoned. The purpose is to take part of the topping column overhead and mix it with the feed crude, with the resulting effect of lowering the boiling point of the mixture. Radical departures from the current designs have been also proposed. For example Brugma (1941) proposed an arrangement that has startling resemblance to energy integrated (Petlyuk type) configurations. According to Nelson (1949), Brugma configurations have been abandoned because the entire length of the three towers is equal to the conventional configuration.These were the years where energy consumption was not of much concern, so revisiting these old ideas might produce some surprises. Also, crude pre-flash columns have been used to stabilize the crude (Nelson, 1949). After the fertile period of the forties, industry evolved implementing the three designs that Watkins (1979) explores in his book, to later abandon pump-back reflux and reboilers. Currently there are efforts to perform modifications of columns for debottlenecking studies. Mainly, these modifications have been related to plate efficiency enhancement and in the case of vacuum columns lower pressure drop (Snell and Juno, 1996). In a recent paper, Liebmann and Dhole (1995) have shown that radically different designs can realize substantially higher savings.

In view of these recent results, there is mounting consensus (still incipient in some cases and strong in others) that the whole design procedures of crude distillation units have to be revisited. To help in this effort there are available considerable different techniques than those available only 20 years ago. Four major milestones can be cited:

- *Accurate thermodynamic representations of petroleum mixtures were developed in terms of pseudo-components*. Pseudo-components are defined on the basis of TBP curves, average API gravity and average molecular weight. With these three properties, critical properties are calculated. This allows the calculation of enthalpies ans fugacities (Cavett, 1962; Lee and Kesler, 1975; Kesler and Lee, 1976; Twu, 1983, 1984). Thus, this discrete description of petroleum mixtures opened the door for the usage of rigorous plate by plate algorithms to model crude units.
- *Powerful methods to perform rigorous plate-by-plate calculations, such as the inside out algorithm (Russell, 1983) where developed.* This method is suitable for hydrocarbon systems and has the capability of merging the side-strippers and pump-around circuits with the main crude column in a single efficient iterating scheme.
- *Computer simulation is a mature field, with speed capabilities powerful enough to allow rigorous modeling of complex systems and results in reasonable time.*
- *New systematic design methodologies where developed that are based on mathematical modeling*. Pinch Technology was developed in the late seventies and is now a mature field (Linnhoff, 1993). Superstructure optimization was pioneered by Sargent and Gaminibandara (1976) and applied for the first time to heat exchanger networks by Grossmann and

Sargent (1978). The State Space approach (Bagajewicz and Manousiouthakis, 1992; Bagajewicz *et al.*, 1996) provides a suitable environment for the combined pinch analysis of heat and mass transfer networks, and makes use of a the concept of operators.

This paper is a first step to systematically address the design of crude units in the context of the aforementioned new tools. The purpose here is to analyze how current designs operate, and what is their flexibility. In concentrates on the design of atmospheric crude distillation columns, pinpointing some truths and half truths found in the literature.

A base case for comparison is first described and simulation results are presented where the influence of several variables is investigated. The following parameters are studied

- Pump-around circuits: Effect of the amount of heat removed
- Side Stripper Steam: Effect of Steam Rates
- Main Steam injection: Effect of Steam Rate
- Effect of Overflash
- Use of Reboilers.

The list of parameters is by no means exhaustive, but represents the most important design variables. The purpose is to prove that these variables can be used in several combinations of values, yet producing the same degree of separation, i.e., the same products. The optimal combination of these parameters is therefore a matter of an optimization procedure.

BASE CASE STUDY

A type A column was used as basis to study the effect of the design parameters. The column used is depicted in Figure 2 and its structural parameters, which will not be changed in this study are described in Table I.

Figure 3 depicts the TBP curve corresponding to the crude used. Its average API is 28.6.

Light-ends composition is described in Table II.

To perform these studies the PRO/II Simulator (Simsci) was used. Table III shows the set of independent design variables of the base case.

Once all these parameters are fixed the system can be completely determined. It is important to notice that the way PRO/II was run corresponds to a design type mode. For example, as an output of these

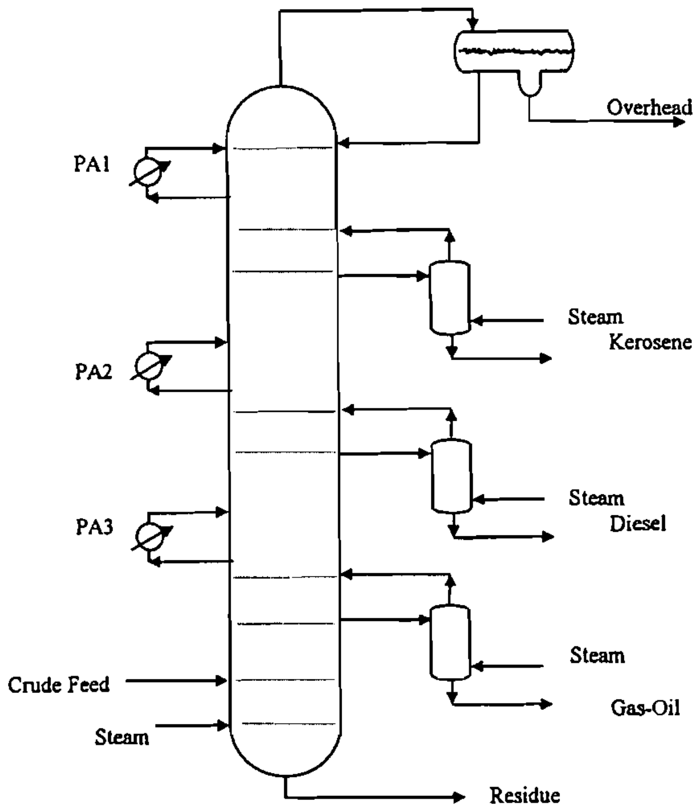

FIGURE 2 Base case. Type A crude unit.

TABLE I Base case column characteristics

Variable	*Value*
Number of Plates	30
Number of trays (Side Strippers)	2
Pump-around 1 (PA 1) Draw Tray	4
Pump-around 1 (PA 1) return Tray	2
Pump-around 2 (PA 2) Draw Tray	15
Pump-around 2 (PA 2) return Tray	13
Pump-around 3 (PA 3) Draw Tray	21
Pump-around 3 (PA 3) return Tray	19
Kerosene Draw Tray	12
Kerosene Side-Stripper return Tray	11
Diesel Draw Tray	18
Diesel Side-Stripper return Tray	17
Gas-Oil Draw Tray	24
Gas-Oil Side-Stripper return Tray	23
Crude Feed Tray	27

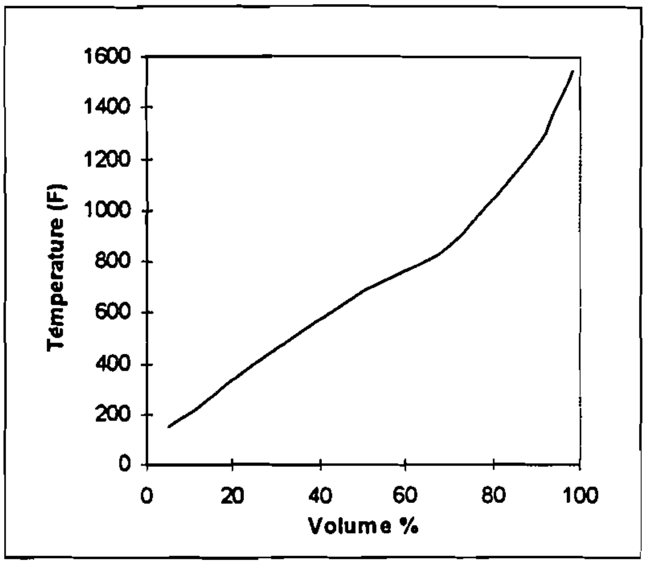

FIGURE 3 Crude TBP curve.

TABLE II Light-ends composition of crude

Compound	*Vol %*
Ethane	0.1
Propane	0.2
Isobutane	0.3
n-Butane	0.7
Isopentane	0.5
n-Pentane	1.2

TABLE III Design variables for the base case

Variable	*Value*
Overflash	3%
Main Steam (60 psig, 600 °F)	10000 lb/hr
Kerosene Stripper Steam (60 psig, 600 °F)	2000 lb/hr
Diesel Stripper Steam (60 psig, 600 °F)	4500 lb/hr
AGO Stripper Steam (60 psig, 600 °F)	4000 lb/hr
Condenser Temperature	110 °F
Kerosene D86 95% Temperature	520 °F
Diesel D86 95% Temperature	665 °F
AGO TBP 95% Temperature	885 °F
Pump-around 1 (PA 1) Return Temperature	175 °F
Pump-around 2 (PA 2) Return Temperature	310 °F
Pump-around 3 (PA 3) Return Temperature	450 °F
Pump-around 1 (PA 1) Heat Rate	50 10^6 Btu/hr
Pump-around 2 (PA 2) Heat Rate	50 10^6 Btu/hr
Pump-around 2 (PA 2) Heat Rate	40 10^6 Btu/hr
Tray efficiency main column	60 %
Tray efficiency side strippers	50 %

simulations, the furnace load, the crude feed temperature, the draw rates and the pump-around rates are determined by the program and not set beforehand. To characterize the feeds and products pseudo-component flowrate distributions are used. Figure 4 shows the curves for the base case. These plots consist of the molar flowrate of each pseudo-component as a function of their boiling point. The thicker curve in this figure corresponds to the crude feed. The curves corresponding to naphtha, kerosene, gas-oil and residue are also included. These curves add up to the crude feed.

DESIGN FLEXIBILITY

Several parameters of the base case were changed maintaining all the others constant to study their effect on the overall performance.

Pump-Around Duty

Consider eliminating pump-around (PA1), i.e., changing the specification form from 50 10^6 Btu/hr to zero. The flowrate of the product streams is summarized in Table IV indicating that a variation of less than 0.9% is observed.

The pseudo-component rate distribution is not shown, as differences between the base case and the design without a pump-around are

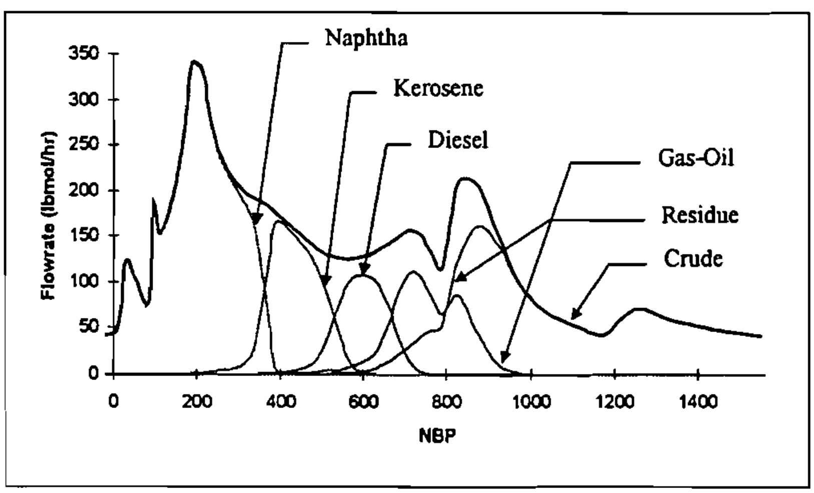

FIGURE 4 Base case pseudo-component flowrate distribution.

TABLE IV Effect of eliminating pump-around 1 (PA1) (Flowrates on dry basis)

Product	*Flowrate Base Case (lbmol/hr)*	*Flowrate No Pump-Around PA1 (lbmol/hr)*
Overhead	2895	2900
Kerosene	1038	1033
Diesel	682	682
Gas-Oil	743	743

unnoticeable. The same effect was observed by varying the heat duty of all the other pump-around circuits. Additionally, the exact amount of heat eliminated from the pump-around is introduced in the condenser.

Thus pump-around duties have essentially no effect on the production rate, nor they change the product composition in any sizable amount.

Figure 5 shows the effect of eliminating pump-around PA1 on the vapor and liquid tray rates of the column.

In the presence of the pump-around, liquid flowrates increase, as expected, to later decrease to a value in the first tray that is lower than the one observed without the pump-around. Vapor flowrates, decrease as expected. This contradicts column profiles presented by Watkins (1979)

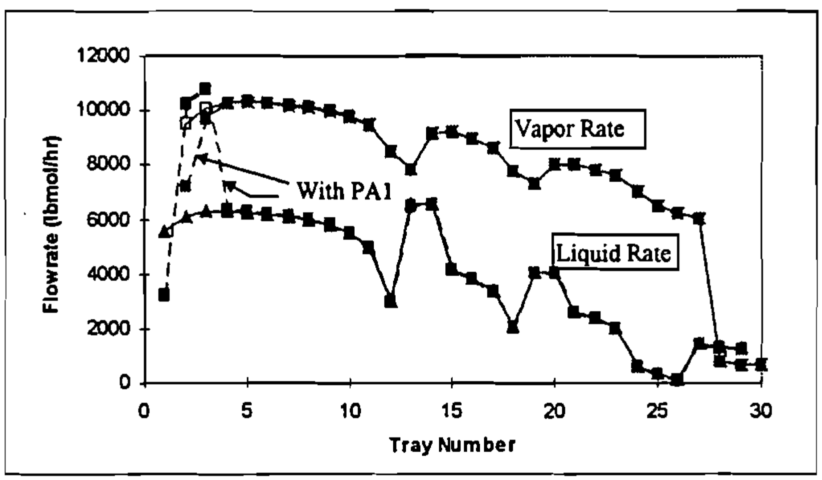

FIGURE 5 Base case and column without PA1 flowrate profile.

where both liquid and vapor flowrates are reduced. The same is shown in Perry (page 13–93).

Figure 6 shows the temperature profile for the base case. As the first pump-around is eliminated, the effect on the temperature profile is only seen in the first 4–5 trays. The differences are shown in Figure 7.

To further compare the effect of pump-around circuits, all of them have been eliminated. Flowrate profiles are compared in Figure 8.

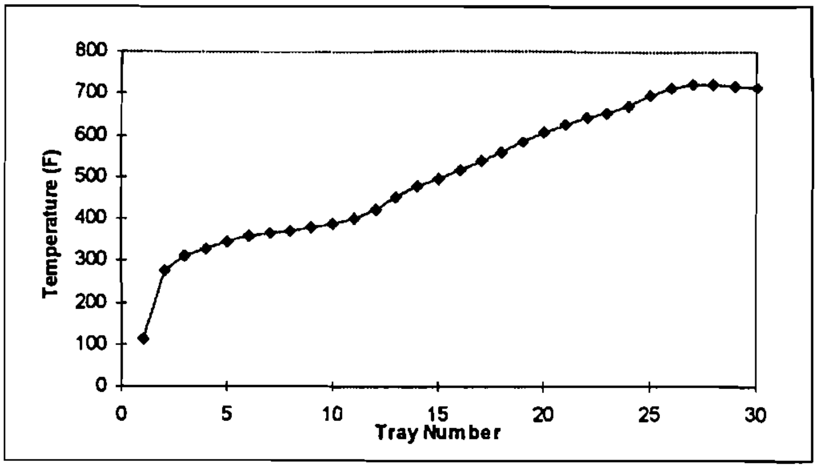

FIGURE 6 Base case and column without PA1 temperature profile.

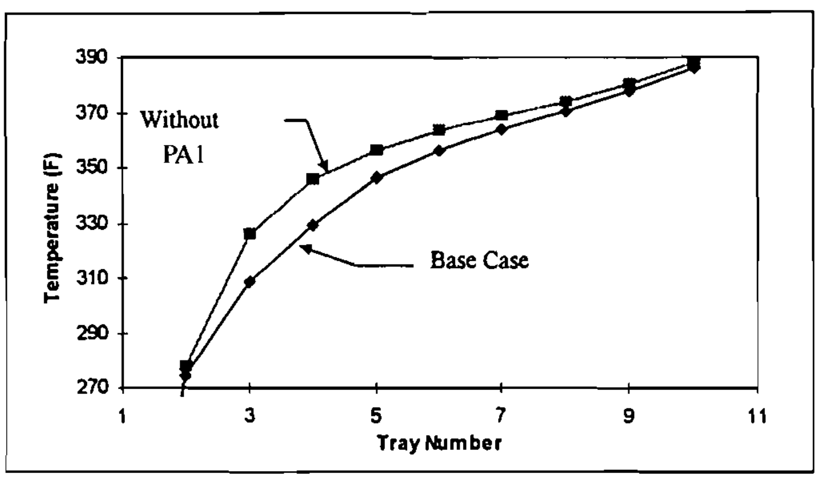

FIGURE 7 Temperature profiles.

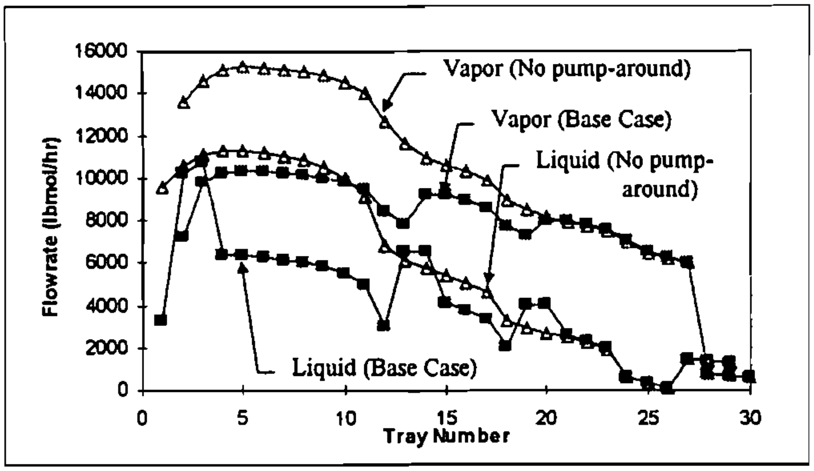

FIGURE 8 Base case and column without Pump-Around flowrate profiles.

Watkins (1979) states that the flowrate profiles of both liquid and vapor are reduced by the same percentage (40% in his Fig. 2.5) when pump-around circuits are introduced. Reduction takes place in the case of vapor, and this reduction is, naturally, dependent on the duty of the pump-around circuits. The claimed reduction in liquid rates takes place, although at the top of the column flowrates are similar in both cases. In the presence of pump-around circuits the temperature throughout the column reduces. Figure 9 shows the effect. Heat duty differences are summarized in Table V.

The difference in furnace duty corresponding to the change in crude feed temperature is $1.7 \cdot 10^6$ Btu/hr. Assuming a furnace inlet of 450 °F, this difference is about 0.3% of the total furnace duty. Table VI compares the product flowrates.

Type A columns (with pump-around circuits) require a slightly higher furnace duty (higher crude inlet temperature) and as a result a slightly higher cooling duty. The presence of pump-around circuits slightly decreases the amount of overhead and kerosene, increasing the amount of heavy products. Thus, although the effect is mild, type U columns have better separation efficiency.

Pump-Around Return Temperature

The effect of return temperature was investigated, while maintaining the same duty. The return temperature of the higher pump-around (PA1) was reduced by 15 °F. Since the duty is maintained, this is equivalent to reducing

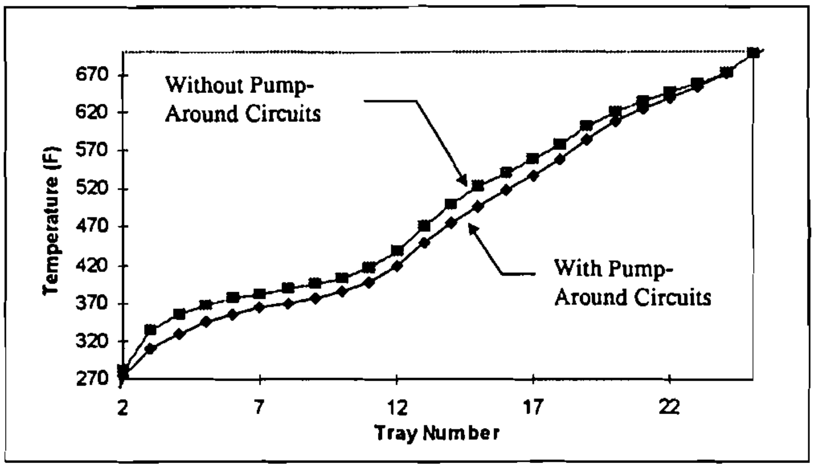

FIGURE 9 Base case and column without Pump-Around temperature profile.

TABLE V Heat Duty comparison between type A and type U columns

	Type A (*Base Case*)	*Type U* (*No. Pump-Around circuits*)
Condenser (Btu/hr)	$-150\ 10^6$	$-287.1\ 10^6$
PA1 (Btu/hr)	$-50\ 10^6$	0
PA2 (Btu/hr)	$-50\ 10^6$	0
PA3 (Btu/hr)	$-40\ 10^6$	0
Feed Temperature (°F)	724.5	723.1

TABLE VI Comparison of performance (Flowrates are on a dry basis)

Product	*Flowrate Type A* (*lbmol/hr*)	*Flowrate Type U* (*lbmol/hr*)
Overhead	2895	2921
Kerosene	1038	1047
Diesel	682	671
Gas-Oil	743	709
Residue	1188	1198

the pump-around flowrate. Figure 10 shows the effect on the liquid flowrate profile. Only the first 5 trays are included as no perceptible variations are observed below. Additionally, no change is observed in the vapor traffic or condenser duty.

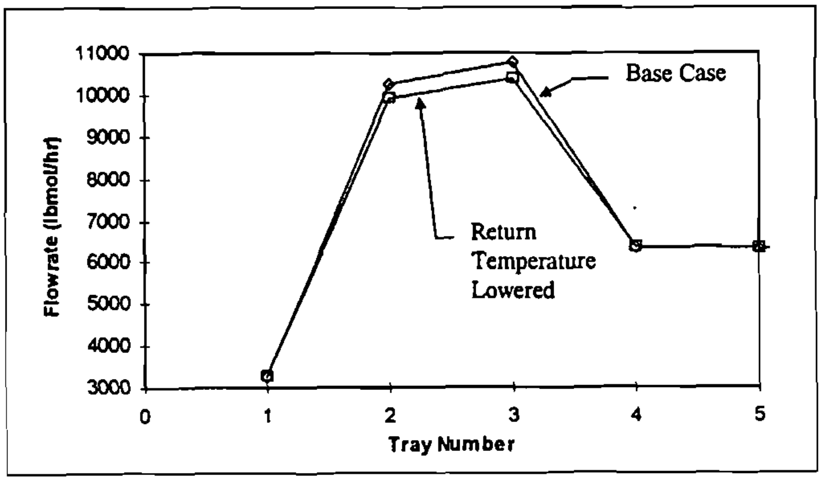

FIGURE 10 Effect of Pump-Around return temperature on liquid rates.

Replacement of Pump-Around Circuits by Coolers

Direct cooling in a tray is equivalent to a pump-around circuit with the same duty discharging on that tray. Figure 11 shows the effect on the column traffic. Product rates are exactly the same as in the case were the pump-around has been eliminated.

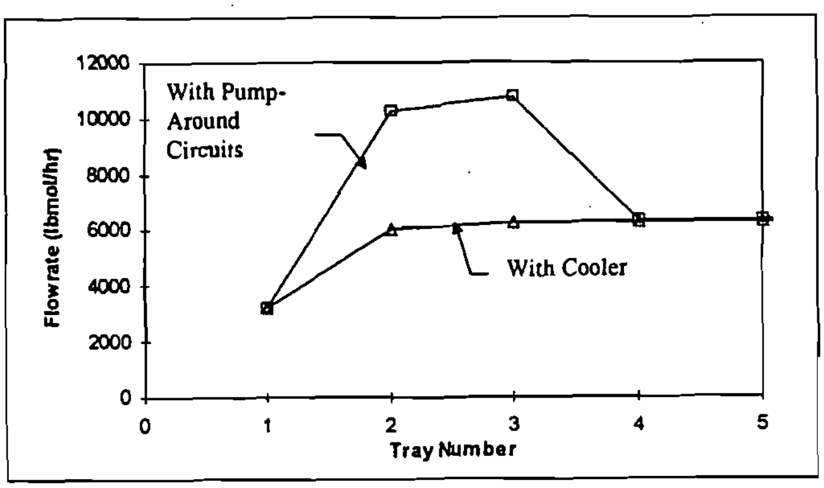

FIGURE 11 Effect of replacing a Pump-Around with tray cooling on column traffic.

Pump-Around Role in Heat Integration

In view of all the above results, one could conclude that pump-around circuits have no positive effect in crude fractionation. Not even the benefits claimed by Watkins and reproduced in Perry that the traffic in the column is balanced. One might ask, then, what is the advantage of Type A columns?

The real advantage of Type A columns versus Type U columns might rely in the fact that cooling takes place in pump-around circuits at a higher temperature. Therefore the opportunities for heat integration may increase. The pinch point of both Type A and Type U arrangements is (not surprisingly) at 329 °F when a minimum approach of 10 °F is used. Table VII summarizes these opportunities for the present case study.

The advantage of type A columns is unquestionable. Moreover, most of the reduction is obtained by reducing heat demand below 600 °F, as the temperature level of the pump-around circuit suggests.

Thus pump-around circuits are efficient means of providing higher level temperature sources that are of great help in increasing the energy efficiency of crude units.

Plate Efficiency of the Stack of Trays Between Pump-Around

Various claims exist in the literature regarding the effect of the pump-around circuits on the separation efficiency of the stack of trays laying in between these trays. Watkins (1979) claims that the two or three trays in between the draw and the return of a pump-around are equivalent to one theoretical tray. The claim is also cited by Perry (page 13–92): "...pump-around circuits..., *are believed* to be equivalent for mass-transfer purposes to only one tray each". To confirm the validity of this statement, a few concentration profiles were compared. Figure 12 plots the concentration profile of the vapor leaving trays 2, 3 and 4 for our base case.

If the pump-around circuit was equivalent to one tray, then the profile for tray 2 should be close to the profile for tray 4. Although these trays are not in equilibrium, (60% efficiency was assumed) the effect suggested by the

TABLE VII Energy integration horizons for type A and type U columns

Minimum utility	*Type A*	*Type U*
Overall (10^6 Btu/hr)	258.7	363.3
Furnace (10^6 Btu/hr)	167.7	175.1
Steam (600 °F) (10^6 Btu/hr)	91.0	188.2

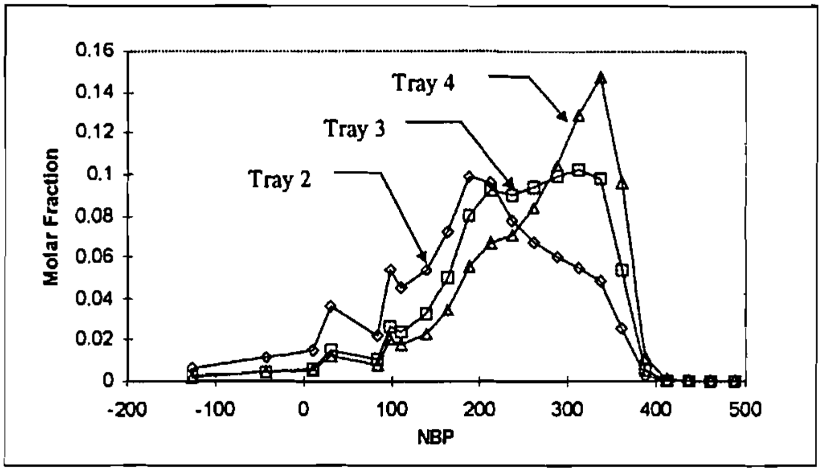

FIGURE 12 Concentration profiles of the vapor leaving trays 2, 3 and 4.

aforementioned statement is not observed, i.e., the composition of the vapor leaving tray 4 is not close to the composition of the vapor leaving tray 2. On the contrary a definite separation trend is observed. The effect of a pump-around can be explained by analyzing the pump-around circuits in binary systems using Mc-Cabe Thiele diagrams. Consider the pump-around circuit around plate p depicted in Figure 13.

Since

$$L^{*} = L + P + W \tag{1}$$

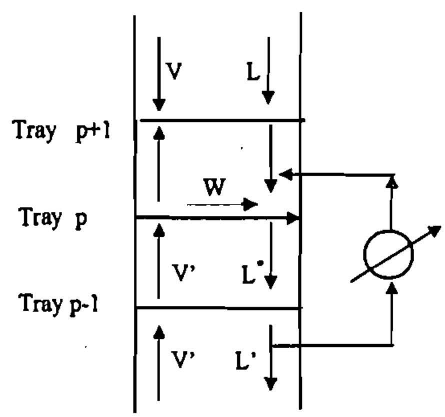

FIGURE 13 Pump-Around circuit around tray p.

$$L' = L^* - P \tag{2}$$

$$V' = V + W \tag{3}$$

Therefore

$$\frac{L^*}{V'} > \frac{L'}{V'} > \frac{L}{V} \tag{4}$$

Using a material balance around trays $p+1$, p and $p-1$ one can determine that the operating lines above and below the pump-around circuit intersect the 45° line at the point (x_D, x_D), whereas the operating line inside the circuit intersects the 45° line at a point above X_D. The operating line below the pump-around circuit and the operating line within the ciruit intersect at $x = x_{p-1}$. Figure 14 shows the complete Mc-Cabe Thiele diagram for the section.

The presence of the pumps-around shifts operating lines closer to the equilibrium line. Therefore, more trays are needed for a desired separation. For the case of crude fractionation, however, this effect is not noticeable. Therefore:

Pump-around circuits are not equivalent to one theoretical tray. In theory, they exhibit a larger number of trays for a given desired separation, but this effect is not noticed in crude columns.

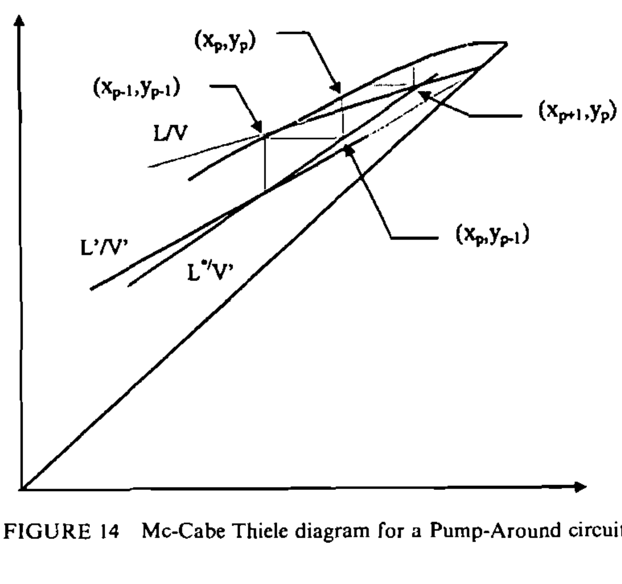

FIGURE 14 Mc-Cabe Thiele diagram for a Pump-Around circuit.

Steam Stripping

Steam stripping is another feature of crude fractionation that has been investigated. Steam injected to side-strippers has been varied. As a result, essentially the same product distribution is obtained, if the appropriate draw rates are used. Table VIII summarizes the results of varying the steam rates to the kerosene side-stripper.

Kerosene Product distributions are compared in Figure 15. Both distributions have almost identical rates, except in the range of 200–350°F, where a slight larger amount of lights is stripped for a larger steam rate. The difference is however of no practical importance.

The effect on the overhead product distribution is imperceptible. The stripping effect is really mild. In terms of energy supply, it is apparent that a high usage of steam and cooling water is used to recover only a small

TABLE VIII Effect of steam in side-strippers

Kerosene Stripping Steam Rate (lb/hr)	*Overhead (lbmol/hr)*	*Overhead Water (lbmol/hr)*	*Kerosene Draw (lbmol/hr)*	*Kerosene Stripper Return (lbmol/hr)*	*Kerosene Product (Dry basis) (lbmol/hr)*	*Condenser Duty (Btu/hr)*
4000	2898	1077	1302	477	1038	$-150\ 10^6$
2000	2887	967	1227	280	1051	$-146\ 10^6$
400	2864	881	1139	78.6	1078	$-142\ 10^6$
20	2844	862	1101	1	1099	$-140\ 10^6$

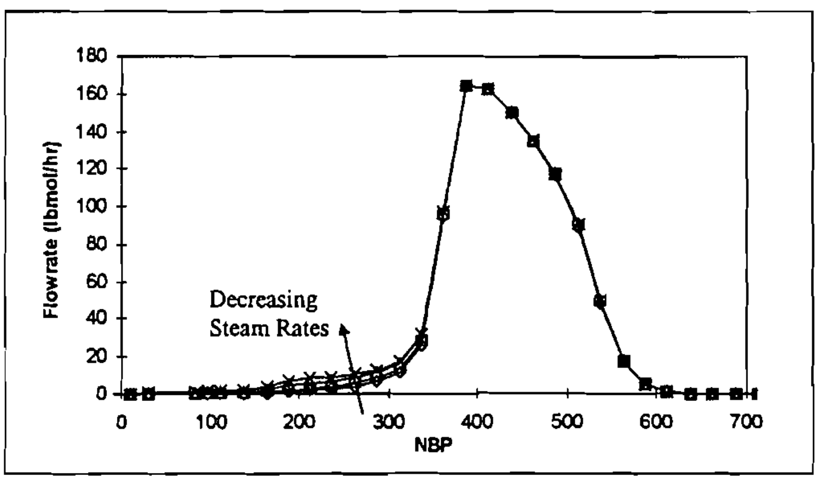

FIGURE 15 Kerosene distribution as a function of steam rates.

fraction of light components. For example, by comparing the base case and the smallest steam injection case (20 lb/hr), one finds that in the base case one spends approximately 5.3 10^6 Btu/hr more in a form of steam injection and 10^7 Btu/hr more in condenser cooling duties to just recover 1.9% of the overhead. This corresponds to about 12 gallons of naphtha. A similar study was performed varying the rate of steam injection in other side-strippers observing similar results.

Steam injection in side-strippers does not affect product distribution significantly, with the adverse effect of increasing the condenser duty unnecessarily.

If one uses the Gap between products to study the effect one might conclude otherwise. Table IX shows the different ASTM D86 (760 mmHg) Gaps.

The other gaps remain practically unchanged. This raises questions about the validity of the use of Gaps as good separation indicators.

Main Steam Injection

Main column steam injection has obvious effects on product component distribution. The effect, depicted in Figure 16, shows the effect of doubling the steam rate on the gas-oil distribution.

The overall rate of gas-oil on a dry basis is 55 lbmol/hr larger (6.9%). The effect on diesel is to increase it in 1.3%. The effect on lighter products is insignificant. The condenser duty increases to 164 10^6 Btu/hr. The column temperature profile is affected by a few degrees (5 °F smaller in the bottom to 2–3 °F smaller in the top portion) and obviously the column liquid and vapor rates increase. The most important effect is the one observed on the furnace duty. The column feed temperature was lowered to 720 °F resulting in a saving of 5.3 10^6 Btu/hr. However, doubling the steam rate resulted in an increase of 13.3 10^6 Btu/hr in the steam.

TABLE IX Effect of steam in side-strippers

Kerosene Stripping Steam Rate (lb/hr)	*Naphtha/ Kerosene Gap (°F)*
4000	39
2000	35
400	28
20	16

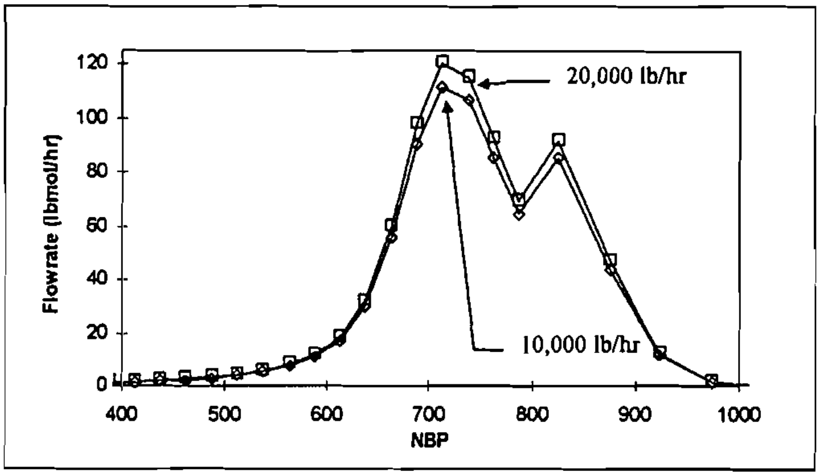

FIGURE 16 Gas-oil distribution as a function of steam rates.

An increase in steam rate decreases the furnace heat duty in an amount that is lower than the heat added by the additional steam. Lowering the steam is therefore desirable as long as large temperatures are not reached.

Column Overflash

Column overflash is, according to Watkins (1979), "the extra amount of vaporization above that required by material balance considerations, which is taken to ensure that adequate reflux will be available in the trays between the flash zone and the lowest side-stream product draw tray". Specifically, it is defined as the quotient of the volumetric flowrate of liquid flowing off the tray above the feed and the volumetric flowrate of the feed. Figure 17 compares the flowrate profiles for an overflash of 3% and an overflash of 1%. Figure 18 shows the temperature profiles for the lower portion of the column.

Figure 17 indicates that for a smaller overflash the temperature in the column are lower and Figure 18 shows a lower traffic upwards. In turn, even though all the specifications are met, i.e., the different products have the corresponding 95% D86 (or TBP) temperature, the flowrates of products are altered. Figure 19 shows the product distribution changes for Gas-Oil and the Residue. Changes for Diesel are lower than 2.5% whereas the changes for Kerosene and Naphtha are imperceptible.

Mostly, the reduction in rate is uniform for all components, reflecting the same degree of separation. In addition the condenser duty is lowered to

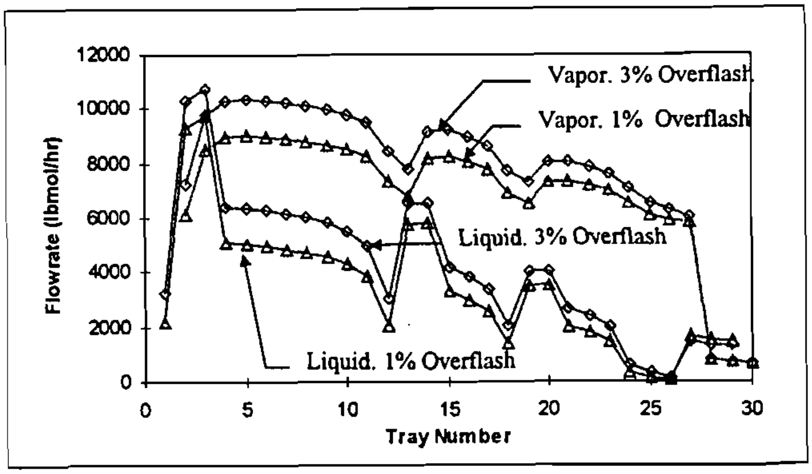

FIGURE 17 Flowrate profiles. Base case vs. column with 1% overflash.

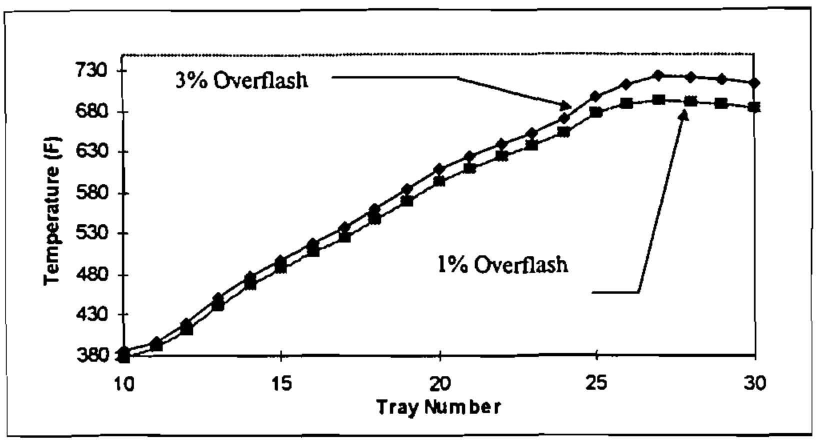

FIGURE 18 Temperature profiles. Base case vs. column with 1% overflash.

126.5 10^6 Btu/hr (15.6% reduction). Finally the feed temperature reduces to 692 °F, which represents a reduction of 39.7 10^6 Btu/h.

An increased overflash has the effect of increasing the gas-oil rate and the residue rate, while affecting very little the rate of other products. The gas-oil composition profile remains mostly the same. A significant reduction in furnace duty is observed.

The above result has its importance in various aspects. First, there are the intricacies of how this will affect the design of the vacuum column, a subject

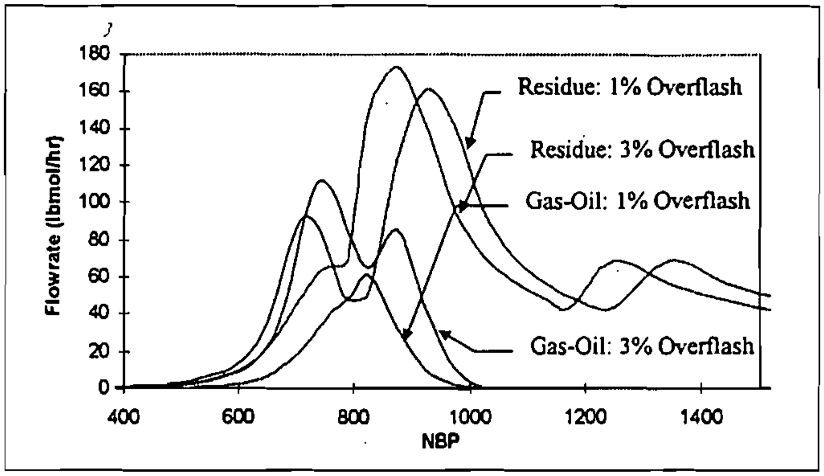

FIGURE 19 Flowrate profiles. Base case vs. column with 1% overflash.

that is not studied in this paper. Second, one may ask how a change in main steam rate can compensate for this reduction of rates. Indeed, as noticed above, an increase in steam rates increases the gas-oil production shifting the component distribution towards more lights. For this purpose the flowrate of steam was varied until the flowrate of gas-oil (on a dry basis) reached the same value as in the base case. The flowrate needed was 39,665 lb/hr. Table X shows the resulting product rates. Gas-Oil Product distributions are compared in Figure 20.

Liquid flowrates are lower and vapor flowrates are higher (Fig. 21). Finally, the temperature profile is shown in Figure 22.

The temperature of the feed is also lower (525 °F). This implies that the furnace duty has been lowered by 239 10^6 Btu/h at the expense of increasing

TABLE X Base case vs. column with 1% overflash and increased main steam (Flowrates on dry basis)

Product	*Flowrate Type A (lbmol/hr)*	*Flowrate Type U (lbmol/hr)*
Overhead	2895	2887
Kerosene	1038	1036
Diesel	682	696
AGO	743	743
Residue	1188	1184

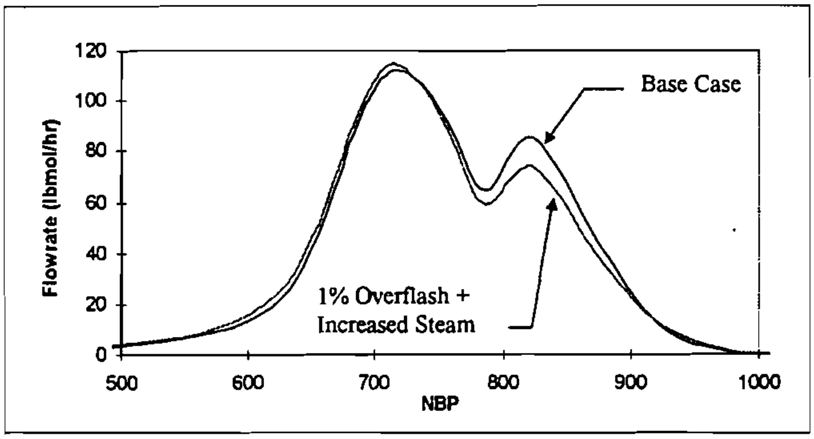

FIGURE 20 Gas-oil distribution for 1% overflash and increased main column steam.

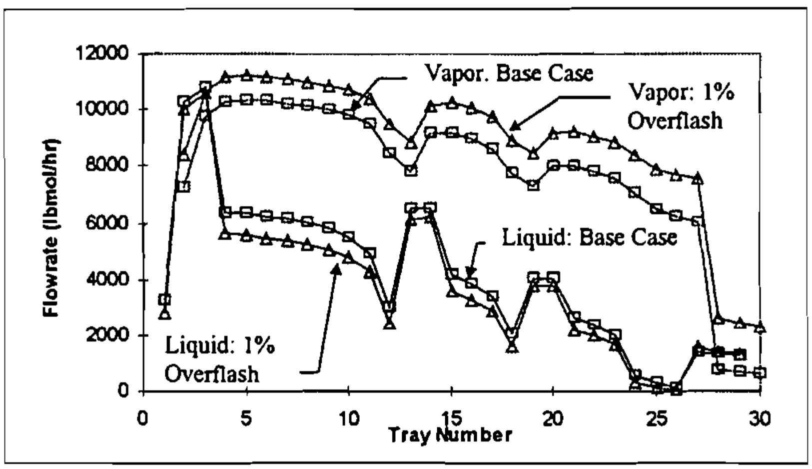

FIGURE 21 Flowrate profile of base case vs. 1% overflash and increased main column steam.

the steam enthalpy rate by 39.5 10^6 Btu/hr. In addition, the condenser duty increases tp 169 10^6 Btu/hr, a 12.7% increase. When a pinch analysis is performed for a minimum approach of 10 °F a pinch temperature of 378 °F is obtained. Minimum heating utilities are given in Table XI.

Therefore, low overflash with large steam usage provide a reduction of 56.1 10^6 Btu/hr. In addition, furnace usage is reduced by 49.8 10^6 Btu/hr.

Reductions in overflash can be compensated by an increased main column steam injection, resulting in substantial gains in energy efficiency.

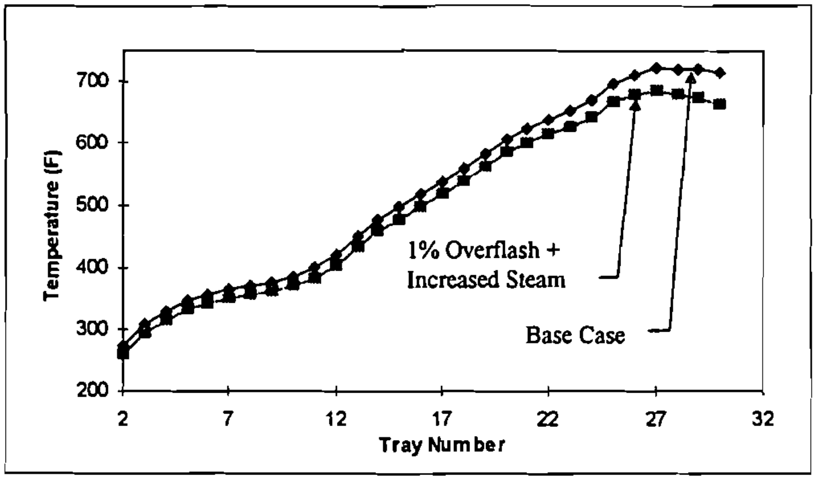

FIGURE 22 Temperature profiles of base case vs. 1% overflash and increased main column steam.

TABLE XI Energy integration horizons for type A vs. 1% overflash and increased main column steam

Minimum utility	*Type A*	*1% Overflash*
Overall (10^6 Btu/hr)	258.7	163.1
Furnace (10^6 Btu/hr)	167.7	117.9
600 °F Steam (10^6 Btu/hr)	91.0	45.2

Use of Reboilers

Various claims have been made regarding the advantage of the use live steam instead of reboilers. As it was analyzed in the introductory discussion, steam injection has been considered advantageous because it lowers the temperature, and eventually by implication, lowers the energy requirements. Figure 23, taken from Liebmann and Dhole (1995), shows that for low degree of vaporization steam stripping is more efficient, whereas when larger degrees of vaporization are needed, reboiling should be used.

The first effect noticed is that the use of reboilers requires, as anticipated, larger temperatures. The steam injection was substituted by a reboiler with the same duty. In comparison to the base case, the feed temperature increases to 729°F and as a consequence the furnace duty is increased by 6.25 Btu/h. Not only the temperature profiles are larger, especially in the reboiler, where the temperature raises from 713°F to 755°F, but flowrate profiles are lower, and additionally, product rates are lower (11% and 9%

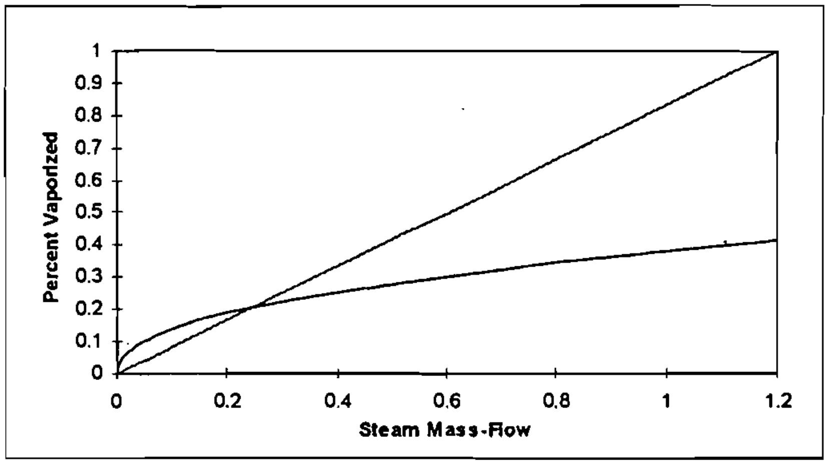

FIGURE 23 Steam vs. reboiler efficiency.

less diesel is produced). When a reboiler was added in the side-strippers it was found that almost twice as much energy is needed to obtain the same separation pattern, with only some gain in condenser cooling duty, as in the previous case.

The usage of a reboiler in the main fractionation column and side-strippers as opposed to steam injection has been ruled out due to the high temperatures needed for a certain degree of separation. This study confirms this statement.

CONCLUSIONS

This paper studied the design flexibility of atmospheric crude distillation units. Pump-around circuits have been found to be effective only to remove heat at higher temperature, helping thus in energy integration. The myth that pump-around circuits are equivalent to one theoretical tray has been proven wrong. Steam injection has been studied and it was found that it has not a noticeable effect on product composition distribution. Main steam injection has been found beneficial from the point of view of energy integration. Additionally, the combined usage of large steam injection with smaller overflash has been shown to have large energy savings. Finally, the effect of reboilers has been quantified and it was confirmed that its usage is not recommended.

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