An Evaluation of a Progressive Crude Oil Distillation Scheme

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Executive Summary

Progressive crude distillation was proposed in 1987 as a possible energy saving alternative to the conventional crude distillation model present in the vast majority of refineries. Theoretical predictions indicated that progressive distillation could reduce the utility burden and also result in the extraction of more valuable light end components. This proposition was tested by designing and simulating a specific progressive distillation scheme. It was determined that the simulated scheme did produce utility savings of approximately 7% compared to conventional distillation for a heavy crude, while utility consumption increased by approximately 6% for a light crude. The production of gas oil did increase slightly in the progressive scheme for light crude, but not substantially enough to compensate for the increased energy losses.

Because of the apparent energetic savings presented by a progressive scheme for processing a heavy crude, economic calculations were performed to determine whether implementation of such a scheme is a worthwhile investment. It was determined that use of the progressive scheme could reduce annual hot utility costs by roughly $11 million. These savings in operational costs must be compared to the amount of capital necessary to build a progressive scheme. The primary capital investments for the progressive scheme are the addition of columns and the expansion of the cooling utility. These capital costs were determined to be approximately $5 million, yielding a pay-out time on the investment of less than 6 months. Consequently, the implementation of a progressive scheme for the processing of heavy crudes is strongly recommended.

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Introduction

The concept of progressive crude oil distillation was first proposed in a patent by Devos et al. (1987). The method outlined in the patent provided an alternative to the conventional method of crude fractionation, which has become a ubiquitous feature of modern petroleum refineries. Before embarking upon a discussion of progressive distillation, it is necessary to outline the basic theory behind conventional distillation, discuss its relative strengths and weaknesses, and define its role within the current petroleum refining process. In this context, progressive distillation can be introduced and its similarities and differences to the conventional model explained. Progressive distillation does not exhaust the list of possible alternatives to conventional fractionation. Therefore, a brief discussion of other alternatives and their merits will be included. The purpose of this paper is threefold: to explain the foundations of crude fractionation, to evaluate the claims of energy savings offered by progressive distillation and to study the profitability of adding a vacuum distillation column to several existing progressive distillation schemes.

Conventional Crude Distillation

The fractionation scheme present in most modern refineries has been utilized for over seventy years. A basic flow diagram for conventional distillation and associated unit operations is presented below in Figure 1.

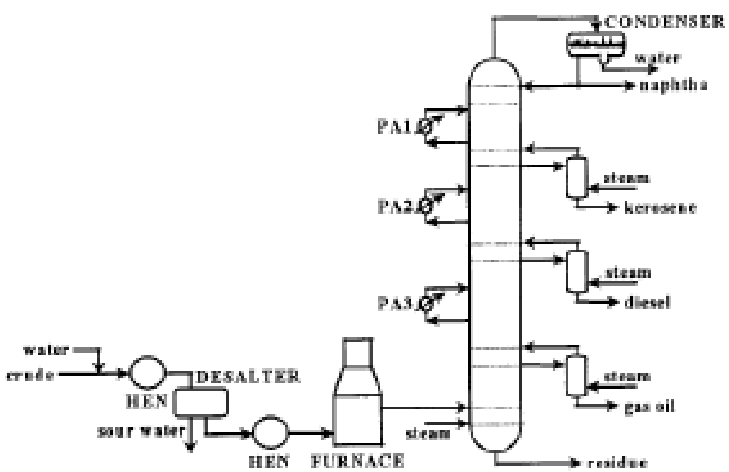

Figure 1. Process Flow Diagram for Conventional Distillation

The crude oil feed is combined with water and sent to a separator where inorganic compounds are extracted from the crude stream and the crude and water mixture is separated. The crude stream then travels through a heat exchanger network where it is preheated by hot streams from pumparounds downstream in the process. The purpose and usage of pumparounds are discussed in detail in the following paragraphs. The preheat train ultimately reduces the duty on the gas burning furnace, reducing the amount of gas consumed and the utility cost of operating the furnace. The purpose of the furnace is to heat the crude oil to the temperature of the feed tray in the column. Five product streams are withdrawn from the column. The products, given in order of decreasing boiling point, are residue, gas oil, diesel, kerosene, and naphtha.

The column itself is composed of numerous trays in series and can essentially be divided into two sections: a rectifying section and a stripping section. One of the distinguishing attributes of conventional distillation is that the entire heat required for the separation is added via the furnace. The rectifying section of the column uses this heat to separate the components of crude by means of their differing relative volatilities. The temperature of each tray decreases as the vapor proceeds up the column, allowing only the more volatile components to continue traveling upwards through the column. At the top of the column is a condenser, which can partially or totally condense the exiting vapor overhead stream. A portion of the condensate is refluxed to provide a liquid phase that cascades down the column, while the remainder of the condensate exits the column as distillate. The ratio of refluxed condensate to distillate is referred to as the reflux ratio and is an adjustable parameter. The refluxed liquid phase flows countercurrent to the rising vapor phase. In contrast to the vapor, as the liquid flows down the column it is enriched in the lower pure component boiling point, heavier components.

The stripping section of the column, as the name suggests, resembles the unit operation of stripping more than distillation. In the conventional distillation model, steam is fed at the bottom tray in the column and rises through the trays below the feed, stripping the lighter components to the rectifying section. Components in the crude are not being separated by a difference in relative volatility but by the stripping action of the steam. This stripping effect is further enhanced by a phenomenon known as the carrier effect, in which lighter component vapor aids in the vaporization of heavier components. In this sense, conventional distillation would be more adequately described as refluxed stripping.

Until this point, the dynamics of the trays themselves have not been discussed. In order for the column to accomplish adequate separation, intimate contact between the liquid and vapor phases must be maintained at each tray. This contact enables mass transfer between the two phases. Lighter, more volatile components will be stripped by the gas, while heavier, less volatile components will be absorbed by the liquid. To enable analytical consideration of the column, it is necessary to make assumptions about the behavior of the trays. This necessity led to the equilibrium stage concept for analyzing distillation columns, which states that the vapor and liquid streams at a given tray are in equilibrium. In other words, the temperature, pressure, and free energy of the vapor and liquid stream are equal. The equilibrium stage concept expresses a situation of ideality, which allows analytical consideration of the column. However, to realistically express a distillation column, some form of correction factor is required. These are provided by Murphree tray efficiencies, which quantify the departure from the equilibrium tray assumption for a given tray.

Two other features of conventional distillation are apparent in Figure 1: pumparounds and side strippers. The use of pumparounds was traditionally limited to controlling vapor and liquid flow rates within the column. However, the use of pumparounds provides benefits for energy integration and utility savings. A pumparound functions by withdrawing a side stream from a tray in the column, cooling the stream in a heat exchanger, and returning the stream to a tray higher in the column. Pumparounds do not disrupt the energy balance in the column, as they move streams from higher temperature trays to lower temperature trays after cooling them. Pumparounds are beneficial from an energetic standpoint because they preheat the crude stream by utilizing hot side streams from the column. This reduces the duty on the furnace producing savings in utility costs. An enlargement of the pumparounds can be seen in Figure 2.

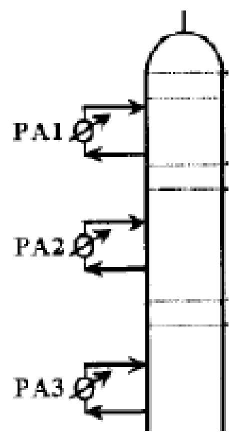

Figure 2. Pumparound Circuits

Side strippers are another feature of conventional distillation. These units function as small stripping columns, which are used to further resolve the product streams withdrawn from the column. The strippers operate by use of a steam medium which removes lighter components from the product streams and returns them to the column. The side strippers enable sharper product cuts in the products. The sharpness of the cut can be controlled by the amount of steam provided to the stripper, but a caveat exists. The addition of too much steam has the potential to flood the side strippers, drastically reducing the efficiency of the unit. An enlargement if the side stripper units can be seen in Figure 3.

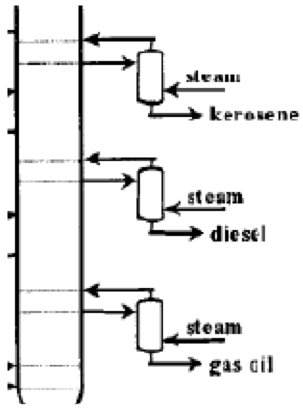

Figure 3. Side Stripping Units

With the basic unit operations of conventional distillation presented, it is possible to discuss how energy is provided to accomplish the separation. Three components contribute to utility consumption: the furnace duty, the duty of the condenser, and the steam provided to the column and side strippers. Investigations of energy savings should focus on methods that reduce, eliminate, or positively modify the need for these utilities.

Sequence Orientation in Distillation

With the concept of pumparounds and side strippers introduced, distillation from the standpoint of sequence orientation can be discussed. Two major orientations are available for distillation: indirect sequence and direct sequence. For the purpose of explaining the two sequences, it is useful to envision an example where a mixture contains three components and a separation of the components is desired. The three components in the mixture are A, B, and C. Component A has the lowest pure component boiling point, component C has the highest pure component boiling point, and the pure component boiling point of component B is intermediate. Figure 4 presents the indirect sequence for distillation of these components.

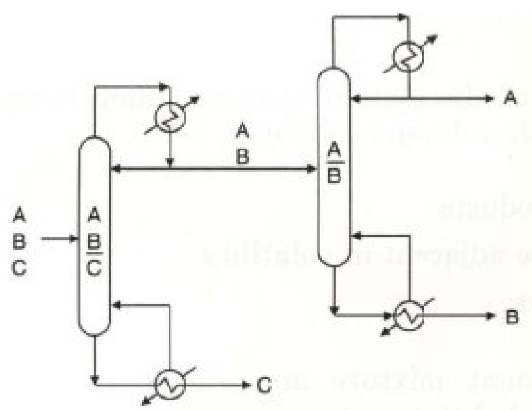

Figure 4. Indirect Sequence of Distillation

In the indirect sequence the heaviest component is removed first in a sharp cut. The lighter components then travel to the next column, where the process is repeated. Therefore, component C is extracted first and components A and B pass to the overhead column, where they are then separated.

Conventional crude distillation is an indirect sequence. The breakdown of the singular column into the indirect sequence can be seen below in Figure 5.

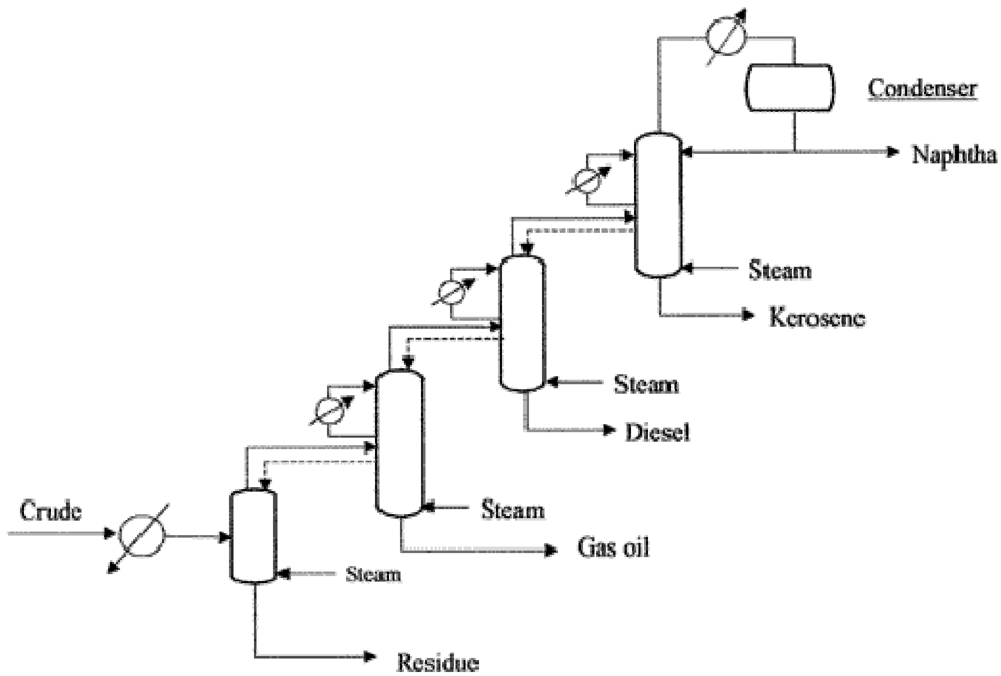

Figure 5. Conventional Distillation as an Indirect Sequence

In conventional distillation, the side strippers serve as a series of columns which remove the heaviest component from their respective feed mixtures. The pumparounds are analogous to condensers for each column. For example, in the first column the residue is removed, while gas oil, diesel, kerosene, and naphtha move to the next column in the series. This procedure continues until the components have been completely separated.

A direct sequence of distillation is the converse of the indirect sequence. In a direct sequence the lightest component is removed first in a sharp cut. The heavier components then travel to the next column, where the process is repeated. Referring to the example mixture of three components mentioned previously, in a direct sequence component A would be removed first, while components B and C would pass to a second column for separation. A direct sequence is depicted in Figure 6.

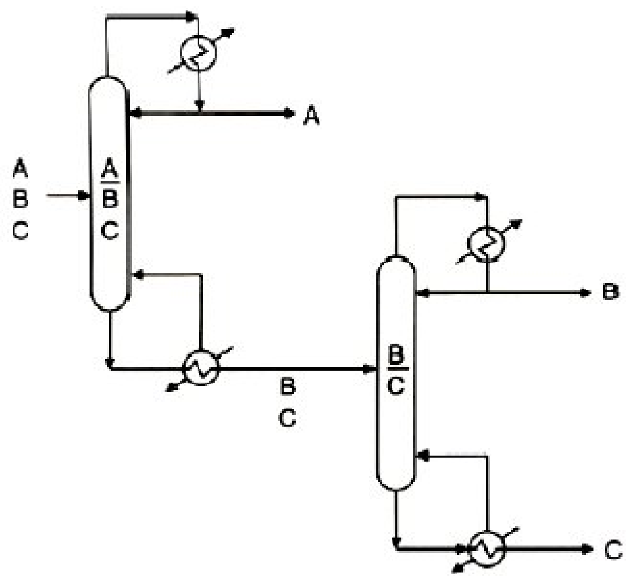

Figure 6. Direct Sequence of Distillation

Currently, the direct sequence is not widely used in industry for a crude distillation scheme. However, various studies have been conducted on its implementation, which will be discussed in the following sections. Because of the nature of the direct sequence, opportunities exist for energy savings unavailable in an indirect scheme. Progressive distillation is, in fact, a modification of the direct sequence.

Applications of the Direct Sequence

Bagajewicz and Ji (2002) explored the potential of one form of the direct sequence referred to as stripping-type crude distillation. Displayed in Figure 7, stripping-type distillation largely resembles a counter-current stripping column.

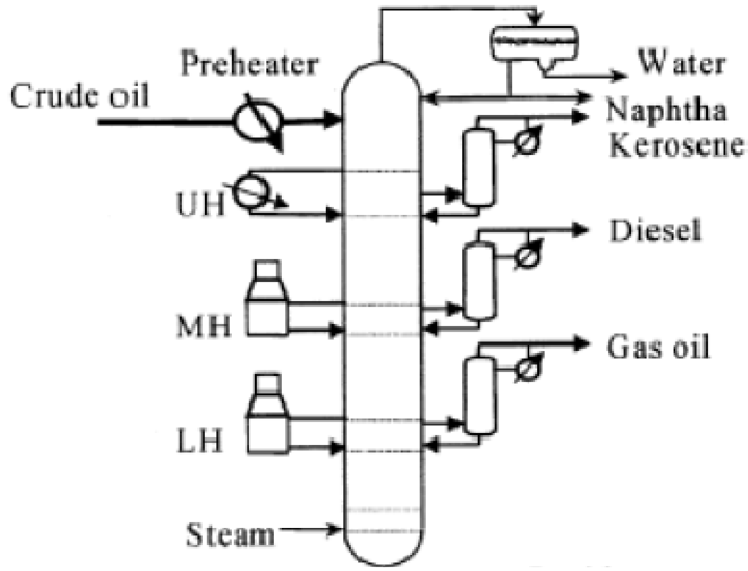

Figure 7. Stripping-type Distillation

The crude oil mixture is fed at the top of the column, while steam is fed at the bottom. The column contains several side distillation columns equipped with condensers. The role of these columns is analogous to the side strippers in a conventional distillation scheme as they sharpen the cuts of product streams. Additionally, several heaters are present which withdraw side streams and heat them as material moves down the column. This distillation scheme is depicted as a direct sequence below. Because the crude is fed near the top of the column, it does not have to be preheated to the high temperatures normal in a conventional column. Instead, the crude is heated in the side draws as it moves down the column. This design is displayed as a direct sequence in Figure 8.

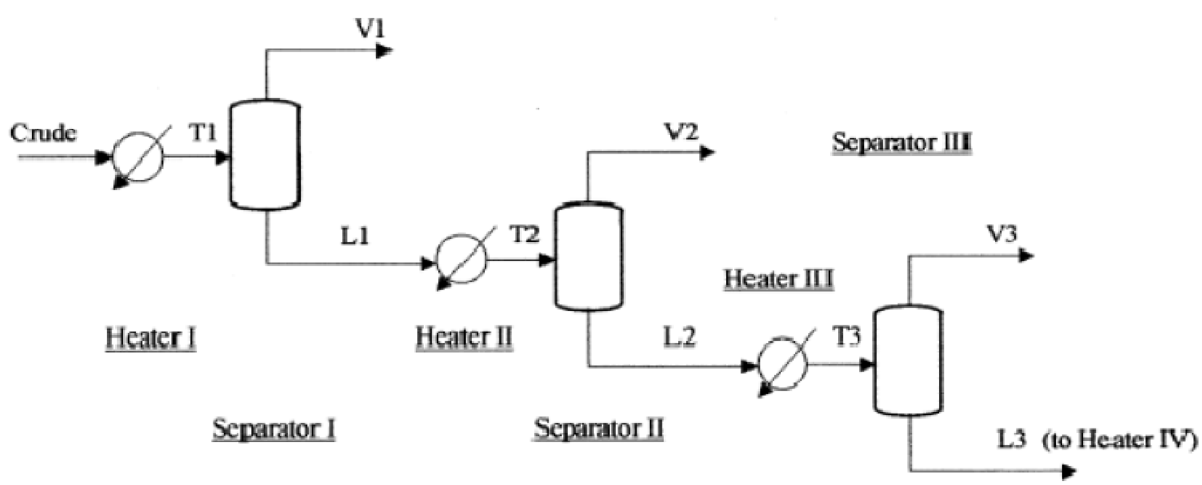

Figure 8. Stripping-Type Distillation as a Direct Sequence

The merits of this distillation scheme were evaluated by Bagajewicz and Ji (2002). Ultimately, stripping-style distillation does not produce energy savings when compared to conventional distillation. There are two prevailing reasons for this discrepancy. First, in stripping-style distillation the crude must ultimately be heated to a higher temperature to produce an amount of vaporization equivalent to conventional distillation. Secondly, because vapor products are removed as they are vaporized in stripping-style distillation, it prevents them from aiding in the vaporization of heavier components. Consequently, the carrier effect present in the conventional design is not observed in stripping-style distillation.

Although a purely direct sequence was not superior to the conventional design in regards to energy savings, this does not exhaust the possibilities of applying the direct sequence. Modifications of the direct sequence may produce a better energetic situation. One such modification, which has been suggested to reduce utility consumption compared to the conventional design, is progressive distillation.

Progressive Distillation

Progressive distillation was first suggested by Devos et al. (1987) in United States Patent No. 4,664,785. The concept behind progressive distillation was described as such: "The process consists in successively separating increasingly heavy petroleum cuts at the head of a plurality of columns." The definition in the patent allows for ambiguity, and several different potential designs are suggested. One proposed design is presented in Figure 9.

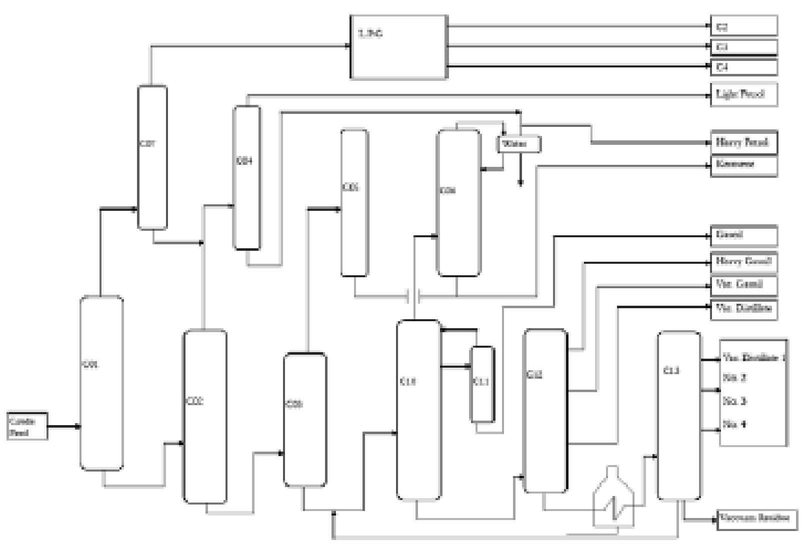

Figure 9. Possible Progressive Distillation Scheme

Figure 9 demonstrates the feature common to all progressive distillation schemes. After the initial separation, the arrangement bifurcates into two series of columns. The overhead from the top series is withdrawn as a product stream, while the bottoms travel to the next column in the series. The overhead from the bottom series is combined with the bottoms from the top series, while the bottoms from the bottom series travel to the next column. The process is repeated until the desired products are extracted from the top series of columns. The final bottoms stream from the bottom series is residue.

Progressive distillation is a variant of the direct sequence, but it differs significantly from a purely direct sequence. As noted earlier, in a purely direct sequence, the lightest component of the mixture is removed first in a sharp cut. In a progressive distillation scheme, the separations are not sharp. In addition to the lightest component, portions of the second lightest component will be separated, as well. This concept is more readily explained by examining Figure 10. The first column removes all naphtha and some kerosene in the top stream, while the balance of kerosene and all heavier components advance to second column in the bottom series. This procedure is repeated until separation into the desired components is complete.

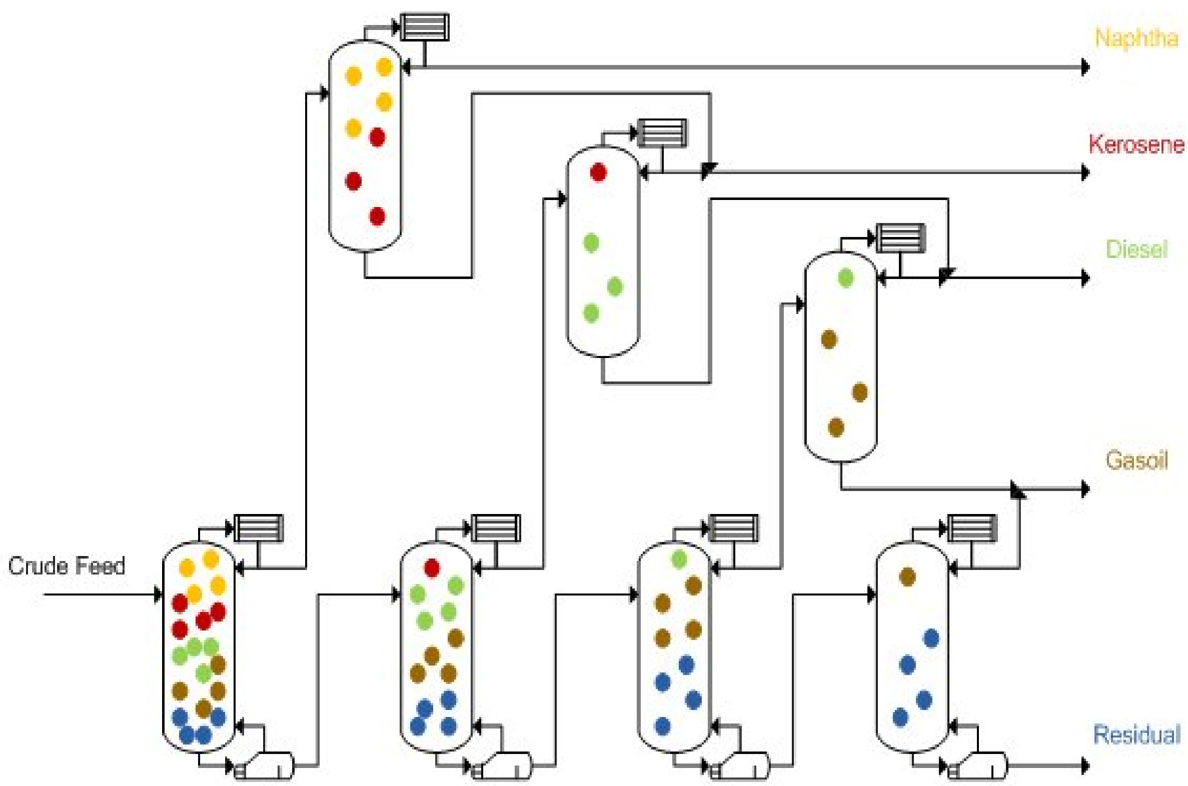

Figure 10. Demonstration of Progressive Distillation

The fact that progressive distillation produces several loose separations is one of its key advantages over both purely direct and indirect sequences. Because only loose separations are performed, less utility heat is required to preheat the crude feed stream. Another energetic advantage of progressive distillation is the presence of a larger number of columns and, therefore, a larger number of trays. Because the degree of separation is dependent on the number of trays and the heat added to the column, by increasing the number of trays the heat demand can be reduced. According to the European company Technip, who implemented a progressive distillation scheme, utility savings of 34% were possible for a heavy crude petroleum. Furthermore, Technip reported being able to extract a higher percentage of the more valuable light end products compared to conventional distillation.

Dobesh et al. (2008), in their study on a particular implementation of the progressive distillation scheme, reported utility savings for both light and heavy crude. The results presented below do not agree with this assessment. Verification of the implementation suggested by Dobesh et al. (2008) revealed that progressive crude distillation does not provide the predicted energy savings. To determine whether modifications of this proposed implementation might create a more favorable energetic situation, the terminal columns in the bottom series were converted to vacuum columns and the simulations were modeled using PRO/II. Vacuum columns operate in the same fashion as standard distillation columns only at pressures below ambient conditions. This enables components to evaporate at lower temperatures. The purpose of installing the vacuum columns was twofold: to determine if the reduced heating duty afforded by vacuum distillation could reduce the utility demand on the progressive distillation column and to see if a larger percentage of more valuable light components could be extracted.

Results

The results for a progressive scheme were mixed when compared to conventional distillation. For lighter crudes, it was discovered that progressive distillation provided no energetic benefit, and in fact increased demand on both the hot and cold utilities. However, for a heavy crude, progressive distillation revealed a significant reduction in the hot utility compared to conventional distillation. Figure 11 presents utility consumption for a light crude in both a progressive and conventional distillation sequence.

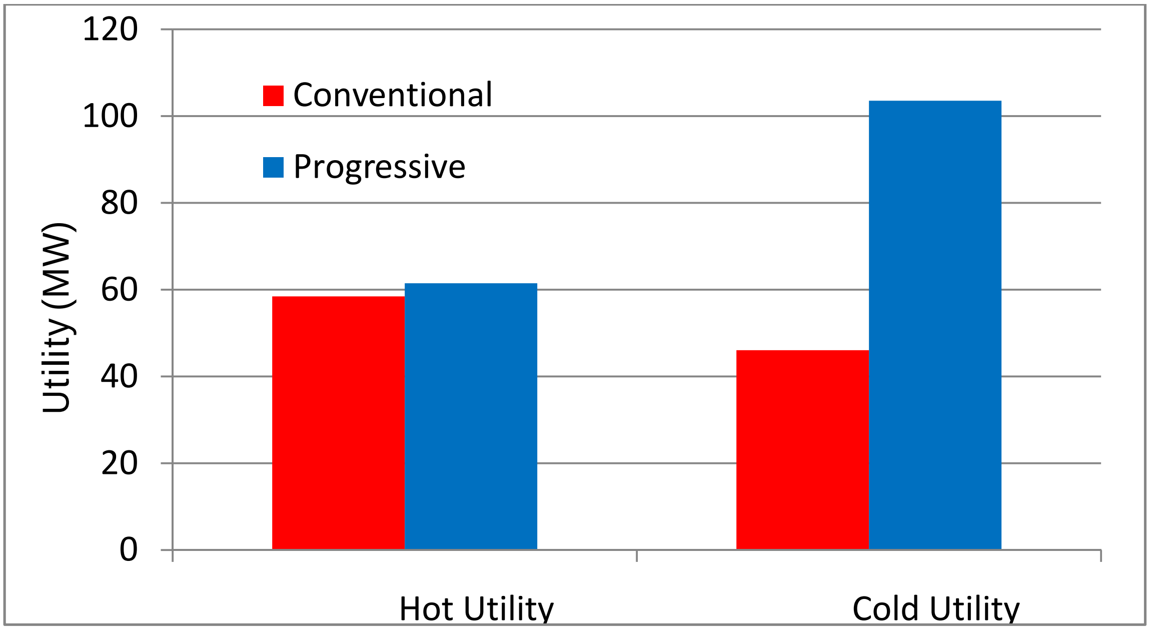

Figure 11. Utility Consumption for a Light Crude

As mentioned above, for a light crude progressive distillation provided no significant benefit from an energetic standpoint. It can be seen both the hot and cold utility are higher for the progressive scheme. An estimation of the hot utility cost of processing a light crude for both conventional and progressive distillation can be seen in Figure 12.

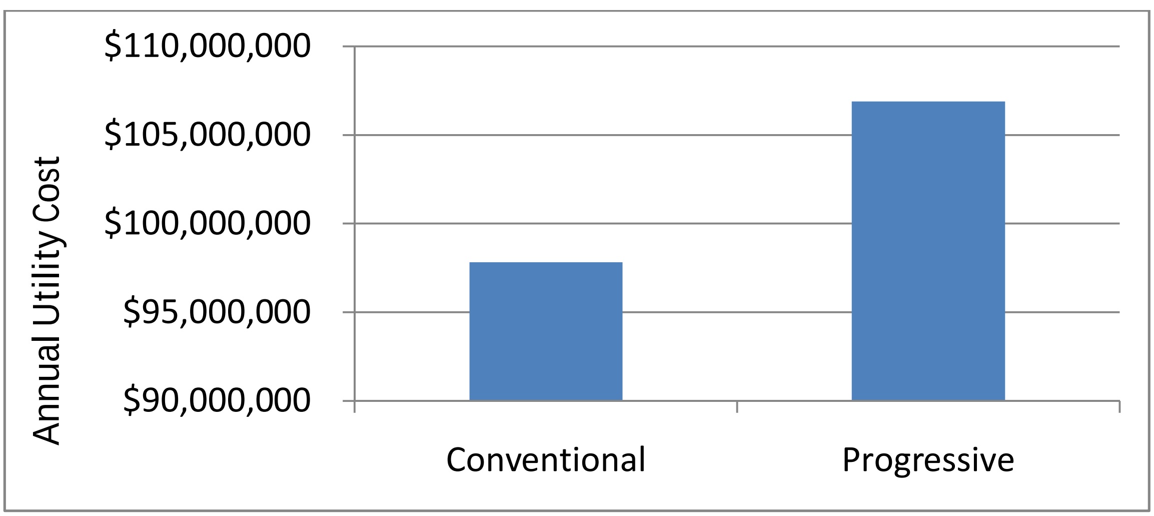

Figure 12. Operational Costs of a Hot Utility for Processing a Light Crude

The increase in hot utility for the progressive scheme is more dramatically pronounced when comparing operational costs for the conventional and progressive models. Utility costs were calculated at a natural gas price of $10.82/MMBTU. As predicted from theory, the progressive model did reduce the furnace utility of the process. However, these furnace savings were offset by the dramatic increase in stripping stream required by the progressive layout.

The results for processing of a heavy crude were more favorable for the progressive scheme. Figure 13 presents utility consumption of both a progressive and conventional distillation sequence for a heavy crude.

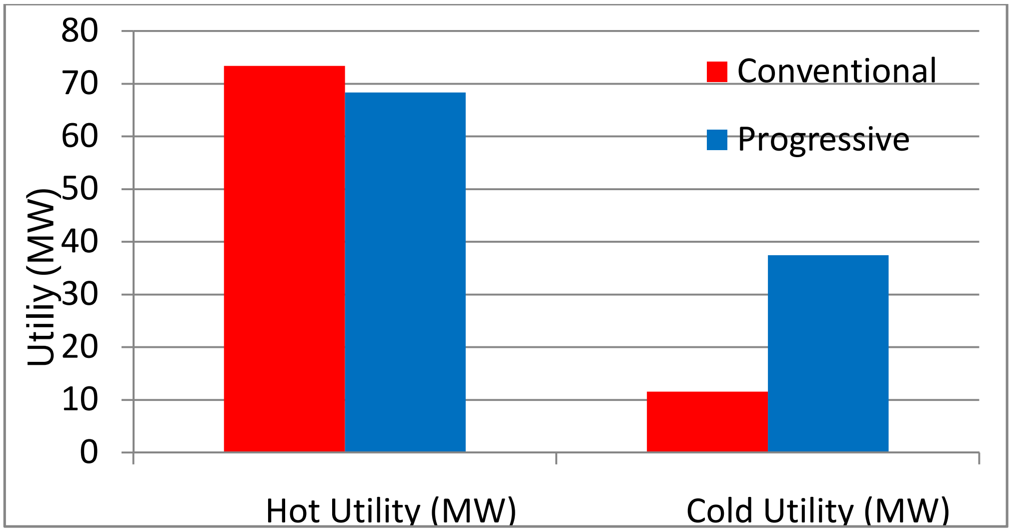

Figure 13. Utility Consumption for a Heavy Crude

Although the cold utility is once again greater for the progressive model, the reduction in hot utility consumption is significant. These results present the impetus for further consideration of progressive distillation, especially for heavy crudes. Figure 14 demonstrates the potential operational savings possible with a progressive scheme when processing a heavy crude.

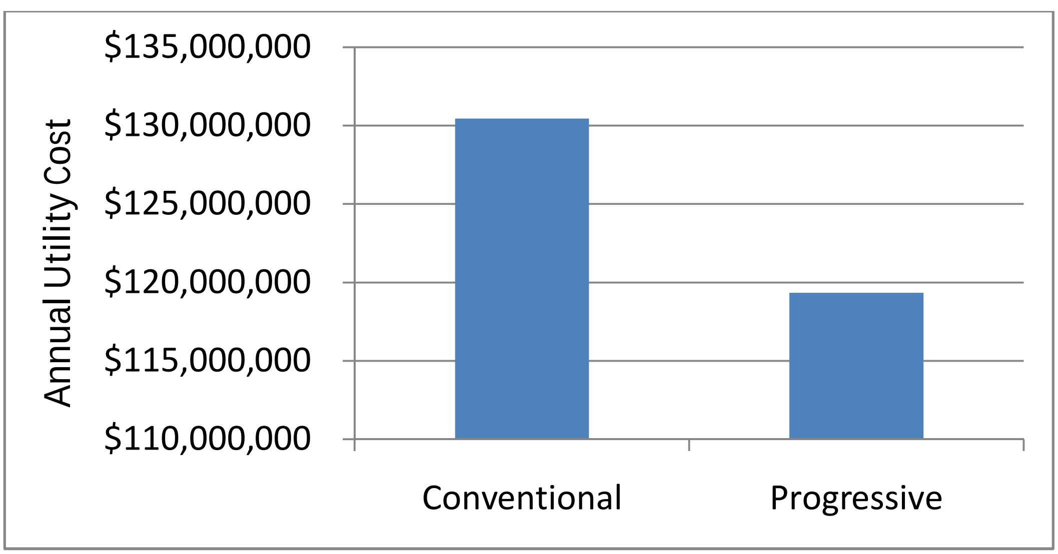

Figure 14. Operational Costs of a Hot Utility for Processing a Heavy Crude

Figure 14 clearly demonstrates the economic driver behind progressive crude distillation, but any operational savings must be balanced against capital considerations. Because progressive distillation involves several columns compared to the single column used in conventional distillation, the capital costs associated with its construction will be much greater. Furthermore, for all cases studied, the cold utility drastically increased in the progressive model. Although the impact of increased cooling utility on operational costs will be negligible, several capital considerations are present. To handle an increased cooling water flow rate, the cooling tower, heat exchangers, and piping would likely have to be upgraded. These capital costs as well as the operational savings and pay-out time are shown in table 1.

Cold Utility Expansion	$1,350,000
Column Expansion	$3,648,000
Annual Energy Savings	$11,115,000
Pay Out Time (years)	0.45

Table 1. Economic Data for Progressive Crude Distillation of a Heavy Crude

Table 1 clearly indicates that installation of a progressive distillation sequence is a industrially reasonable investment. With a pay-out time of under six months, development of a progressive scheme will rapidly pay for itself and produce continuous, long-term energy savings.

Conclusions

Progressive crude distillation shows promising results when used to process a heavy crude. Its ability to drastically reduce the furnace utility is especially beneficial for crudes of this nature. An economic analysis of a working progressive crude distillation scheme revealed that installation would be a worthwhile investment, providing long-term energy savings. Consequently, it can be recommended that progressive crude distillation be implemented in the processing of heavy crudes.

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