USE OF HEAT INTEGRATED DISTILLATION TECHNOLOGY IN CRUDE FRACTIONATION

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Executive Summary

Crude fractionation is a high-energy demand process, requiring approximately 3% of the total energy used in the United States. Currently, there are incentives to reduce energy usage due to rising costs of energy. A recent development in distillation technology that has shown potential savings of up to 60% is the heat-integrated distillation column (HIDC). HIDC columns save energy by recovering excess heat from the rectifying section for usage in the stripping section. However, this technology has only been applied to specific hydrocarbon systems. This study investigates the application of some HIDC concepts in crude fractionation.

Two new design of a column that applies HIDC to crude fractionation were developed. One was a basis off of the conventional crude fractionators with 34 trays and a compression ratio of 2:1. In order to obtain this compression ratio, the pump-around duties were drastically reduced to allow column convergence. The second column was similar to the conventional except it included 50 trays and a compression ratio of 2:1. The pump-around duties were also reduced to converge, but not as much as in the first column design. In both columns heat was slowly added to the stripping section from the rectifying section. As this was done, the furnace for the pre-heated feed was reduced by the same amount added to the stripping section. This ideally should reduce the required heating utility for the system. In doing so, the product specifications should remain relatively unchanged.

The first column design studied was found to require an increase in heating utility. This is due to the reduction of pump-around duties, which leads to a less optimized heat exchanger network. The product specifications do not remain constant. The residue becomes a heavier product, but also increases in flowrate. So, all of the valuable products are being lost to the residue.

The second column design studied was found to reduce the amount of heating utility required. This is due to the increase in number of trays and increase in pump-around duties from the first design. This leads to a more optimized heat exchanger network. The product specifications do not remain constant. The residue becomes a heavier product, but also increases in flowrate. So, the valuable gasoil product is being lost to the residue. This leads to a less economical system. Even though energy is being saved, even more of the products are being lost to the undesirable residue.

For the system and operating conditions, the HIDC concept does not improve crude fractionation. These results seem to display adverse affects to the system making it less economical. Further studies will be needed to substantiate these results by investigating different operating conditions and possibly a completely different column design more closely.

Introduction

Crude distillation is the separation process by which crude oil is refined into several different components. The major reason for the manufacturing of these products is their necessity in other refining processes. They are further refined to become parts of end products such as gasoline, diesel fuel, and jet fuel. To ensure the integrity of the products being sent to further processes downstream, the fractionated crude's specifications have to comprise of certain properties regarding density and boiling temperature. The specifications are determined by the American Society for Testing Materials D86 analysis of petroleum products. This method uses rapid batch distillation to determine the boiling ranges of the crude oil and its products.

The most common system used for the fractionation of this crude is referred to as the conventional method of distillation. 1 below, adapted from Bagajewicz, depicts this common processing system. As can be seen from the diagram, this process has some unique properties within the column. In order to compensate for not having a reboiler, the column requires pre-heated feed as well as steam.

The steam supplied to the column provides two important roles in helping to separate crude oil into multiple components. First, steam provides a means to strip components of the crude from their liquid phase and carry them up the column. Steam stripping is necessary for efficient separation of products throughout the column. Second, steam is used to avoid thermal cracking of hydrocarbons during fractionation by decreasing the temperature at which the hydrocarbons vaporize. Thermal cracking is the breakdown of the carbon-carbon bonds in long-chain hydrocarbons, making them into simpler structures. This causes the products to degrade into undesirable products and can lead to coking within the column. This phenomenon occurs above 360^{o}C at atmospheric pressure. If no steam was present, only hydrocarbons would provide pressure within the column. The temperature at which the vapor pressure of the hydrocarbon would equal atmospheric pressure would be much higher than the thermal cracking temperature of most crudes. However, since steam and hydrocarbon vapor are immiscible, adding steam decreases the partial pressure contribution necessary from hydrocarbon, lowering the temperature at which hydrocarbons vaporize. Of less significance, the steam is at a colder temperature than the feed. It can be used to cool the tray temperature.

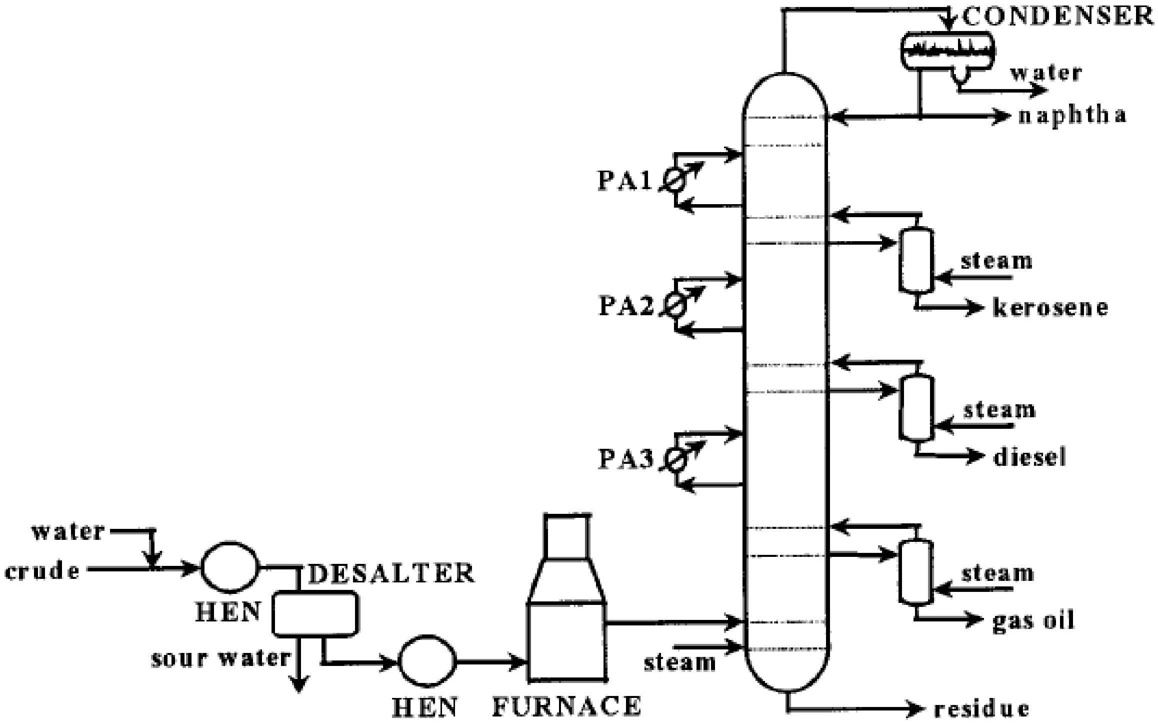

Figure 1: Conventional Column

Since there is no reboiler, pre-heated feed is the only source of enthalpy input to the conventional fractionation column. Therefore, the preheated feed must come into the column as mostly vapor. Due to the high amount of vapor feed, the rectifying section needs to be larger than the stripping section to allow for enough contact time for separation. The stripping section of the main column is small because of the relatively low liquid flowrates. Since the stripping section is so small, side columns are used to complete the stripping needed to accomplish the separation needed to meet the ASTM D86 product specifications.

Since the products of crude fraction are used within the refinery, it is important that the products have the specifications needed in these other processes. Each product specification of the main column is based on the ASTM D86 points at which 95% by volume of the product specified boils (henceforth, D86 points) as well as the temperature gaps between the products. The product gaps are determined by the D86 5% point of a heavy distillation minus the D86 95% point of the distillate directly above that one. Figure 2 displays the product gaps used for the conventional distillation column. For example, the product gap for the first side column is the Kerosene 95% minus the Naphtha 5%, which is set to 16.7 ^{o}C. The Kerosene These product gaps are controlled by the amount of steam added to the side column for stripping. For light crudes, the following temperatures were found for the boiling point ranges.

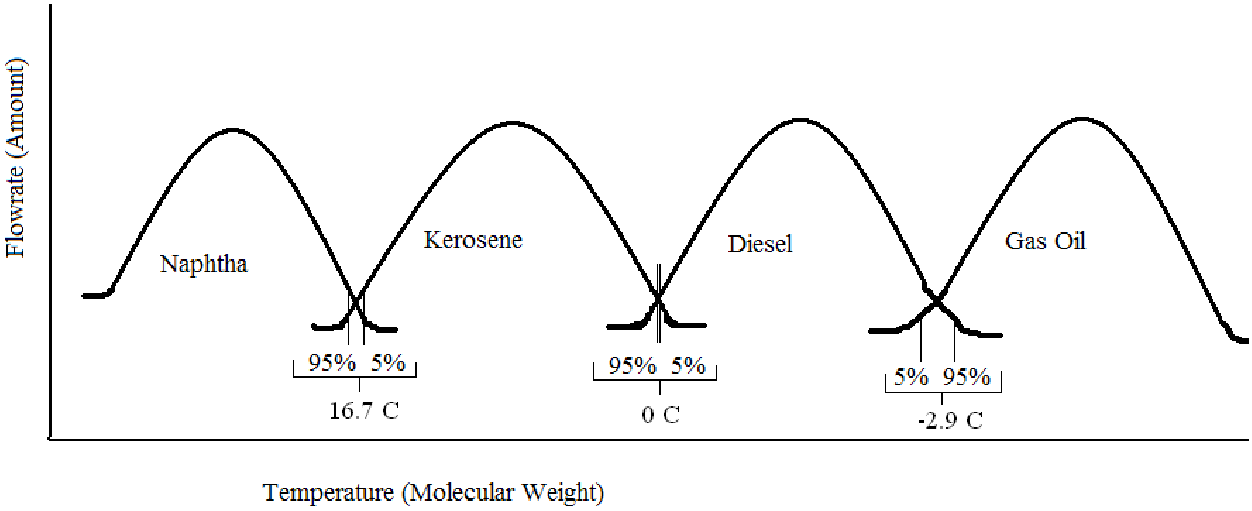

Figure 2: Product Gap Specifications

The preheated feed and steam required for the column also results in a high heat rejection in the condenser. The condenser is required in order to cool the naphtha into a usable liquid form. In an effort to reduce this heat rejection, pump-around circuits are used in the rectifying section of the column. The pump-around circuits pull a certain amount of the liquid on a tray, cool it to a certain temperature, and then return it two trays above the withdrawal. The duty of the pump-around circuits can be used as heating utility in other sections of the process.

The high heat demand of the preheated feed and the high heat rejection of the condenser create an energy exhausting procedure. The conventional method of crude fractionation consumes 2% of crude oil processed. With this high energy demand, distillation accounts for 50-60% of the energy used within a refinery. These distillation processes have huge areas of opportunity in energy reduction. In the past, operational and capital investment changes were made to increase the energy efficiency of this method. The operational changes included adjusting the reflux ratio, minimizing the excess air to the furnace, and lowering the steam usage in the columns. These types of changes can improve energy usage, but the majority of improvement can be made in the area of capital investments. These capital investment changes include plant-wide energy planning, heat recovery equipment, and new column designs.

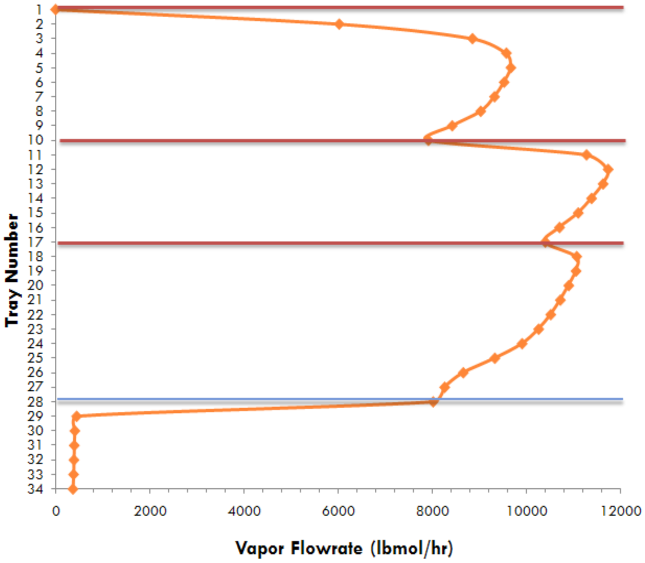

Figure 3: Vapor Flowrate Profile

Heat-Integrated Distillation Column

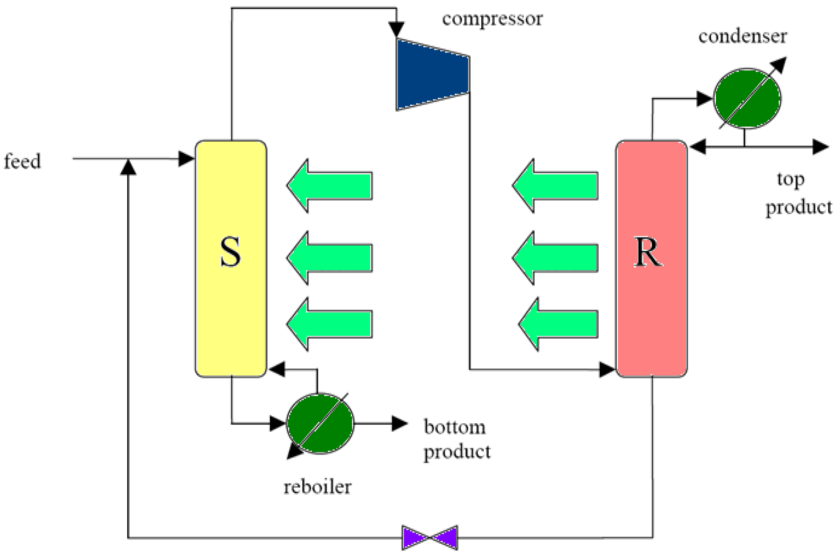

Figure 4: Heat-Integrated Distillation Column

The heat-integrated distillation column (HIDC) is a relatively new design concept applied to distillation systems. In the design, the rectifying section of and stripping section is split into two separate pieces of equipment. Conceptually, excess heat is transferred from the rectifying section of the column into the stripping section of the column. By doing so, the heat-integrated distillation column can lower the overall energy needed by the system by integrating it between the rectifying and the stripping section.

Figure 4 is a diagram of a typical heat-integrated distillation column. This depiction has the stripping and the rectifying sections in two separate columns with relatively the same number of trays in both. The rectifying section operates at a higher pressure than the stripping section. This causes the rectifying section to increase in amount of heat available. The heat available in the rectifying section is used to heat the cooler stripping section. This not only decreases reboiler duty, but ideally should reduce condenser duty to zero.

The heat-integrated distillation has been shown to be able to have energy savings of 25% to 50%. The Japanese have constructed a pilot plant that has used 60% less energy than the conventional method (Olujic). The most important governing factor is the compression ratio used within the between the two sections of the system. Figure 5 adapted from Iwaskabe shows the ratio between the energy needed of the heat-integrated column and the conventional for various compression ratios and number of stages. The figure illustrates that as the number of stages increase, the amount of energy used for a heat-integrated column decreases more than the conventional method. The figure also depicts that as the compression ratio is increased, the amount of energy use in the HIDC is less than that of the conventional system.

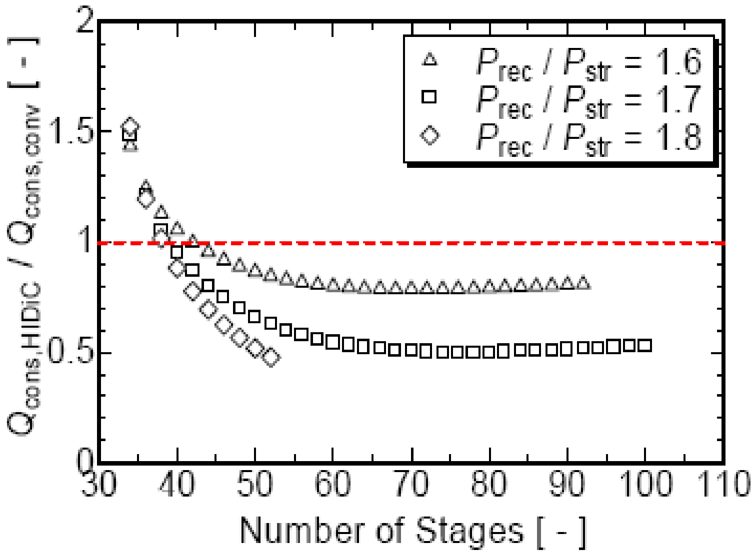

Figure 5: Energy Conservation with Compression Ratio

An increase in compression ratio has also shown potential in reduction of column size. With reduction of area, the capital investment will decrease and causes an increase in gross profit. Figure 6 adapted from Iwaskabe demonstrates that as the compression ratio is increased, the heat

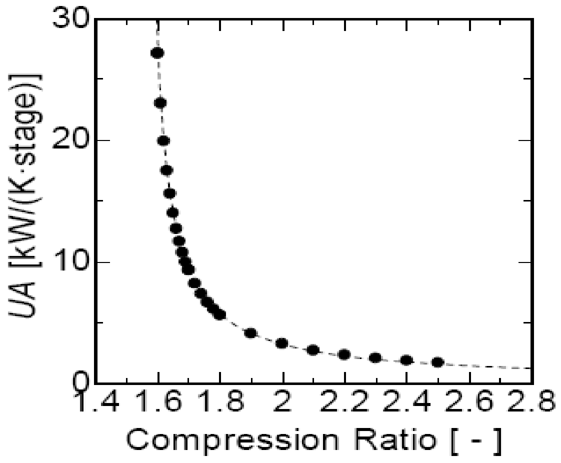

Figure 6: Reduced Area with Compression Ratio

transfer area required will decrease. As the area is smaller, there will be smaller energy loses to the environment. These benefits could greatly assist the crude fractionation in its energy consumption. There are some concerns with implementation including if there is efficient vapor loads for heat and mass transfer in the top and bottoms trays of the column. Figure 7 from Hugill displays the vapor and liquid flow throughout the trays. As can be seen from this figure, the vapor and the liquid loads are very low at the top of the stripping section and the bottom of the rectifying section. These vapor loads may be too low for efficient mass transfer and heat transfer because both depend on contacting area between moving fluids.

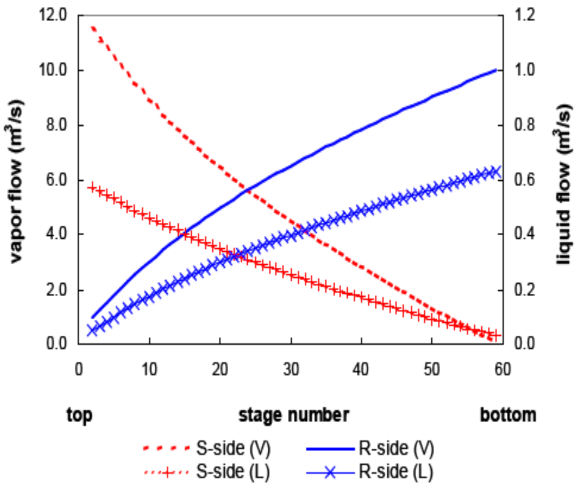

Figure 7: Vapor and Liquid Loads

Comparison between Conventional and Heat-Integrated System

Simulations were run to build a conventional distillation system and then modifications were made on the simulation in order to see if the conventional system could incorporate the concepts of heat integration. The new design for crude fractionation is given in figure 8. This design depicts the application of HIDC within crude fractionation. The compressor and valve were added to the system to allow for the difference of the pressure. Within this system the ASTM D86 points and the product gaps were maintained the same for all products. Most of the operating conditions were also maintained to have a direct comparison to the conventional method.

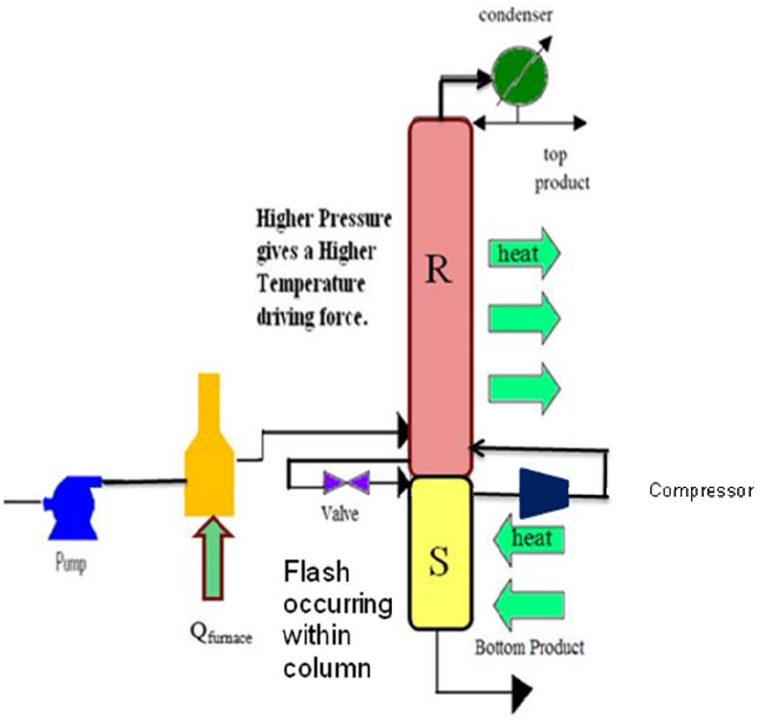

Figure 8: Modified Heat-Integrated Distillation Column

The one major difference is the pressure variation between the rectifying and stripping section. In the conventional, the column was maintained at an atmospheric pressure. The heat-integrated column the rectifying section will need to be at a much greater pressure than the stripping section. This is depicted in figure 9, where the pressure differential is only 1 atm. In order to obtain the increased pressure in the HIDC, the pump-around duties were drastically reduced. This may affect the heat integration within the heat exchanger network. The pressure was required in order to have heat to integrate within the column. When looking at the temperature ranges for the conventional method, there are no trays that have temperatures above those of the stripping section. Therefore, no additional heat can be added from the rectifying section to the stripping section. Referring to figure 9, there are a few trays in the rectifying section of the HIDC that have tray temperatures above that of the stripping section.

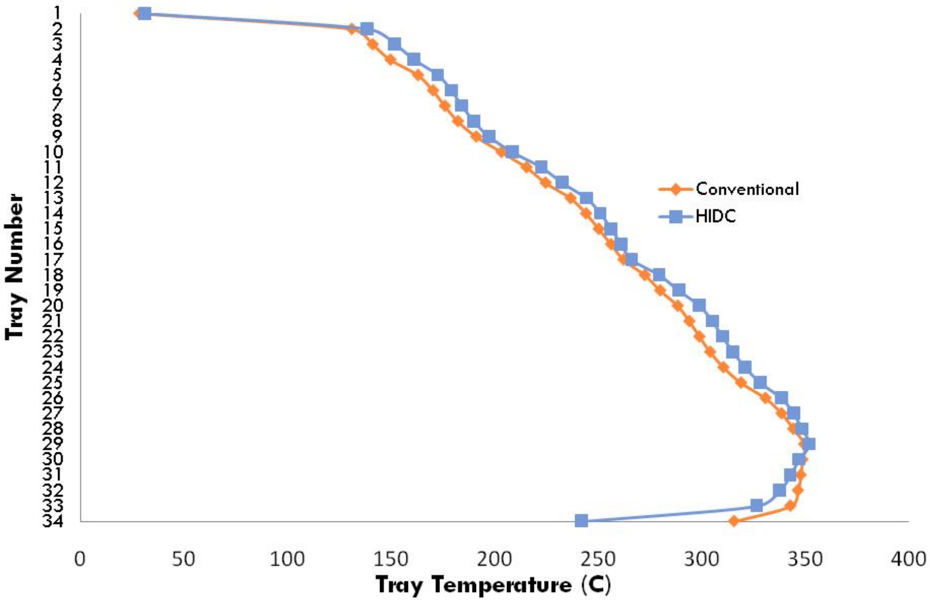

Figure 9: Heat Availability

Economic Analysis

The economic analysis of the system was used as the basis to determine feasibility of the project. The economic analysis was based on a differential profit that calculated the gross profit increase from the conventional method. In the gross profit analysis, the utility costs and profit from products were the other factors considered. The utility costs were based on the increase in hot and cold utility. The hot utility was priced at $0.085/kWh for 2002 and was scaled up for 2008 using Marshall and Swift factors. The following equation was used to determine the cost in required hot utility.

$$E = U + 0.7\sum H_i^s + W$$

The total energy E is the minimum heating utility U plus 70% of the total enthalpy of steam required H and the energy required by the compressor W. The cold utility was priced based on the amount of cooling water required at \$0.135/m^3 for 2002. The total utility cost differential was based on the following equation.

$$(E_{conv}-E_{new})*Cost_{heat}+(C_{conv}-C_{new})*Cost_{water}+W$$

The total cost is the difference in conventional and new system energy costs, and difference in conventional and new system cooling water costs, and the cost of energy from the compressor. The majority of the total cost is due to the energy for heating and steam for stripping. The profit for the system was calculated based on the changes in product flowrates. The following equation was used to determine the profit differential from the conventional method.

$$\sum_i (i_{new}-i_{conv})*Price_i$$

The profit is the summation of the differences in the profit of the product flowrates of the new system and the conventional method. The prices of products were based on current market values. These market values are

- Naphtha-\$110/bbl
- Kerosene-\$95/bbl
- Diesel-\$109.90/bbl
- GasOil-\$75.90/bbl
- Residue-\$67.90/bbl
- Crude Feed-\$98/bbl

Results

The first column studied was the modified conventional column with a compression ratio of 2:1 between the rectifying section and the stripping section. In this column, various amounts of heat was taken from the hottest rectifying tray (tray 28) and added to the coldest stripping tray (tray 33). Any duty that was transferred between the sections of the column was also reduced at the furnace. For example, if 1 MW of duty was transferred from the rectifying section into the stripping section of the column, the furnace duty would be reduced by 1 MW, resulting in a reduced furnace temperature.

In doing so, the effects on utility and products were monitored. The main concept of the HIDC is the reduction in energy required for the system. As can be seen in figure 10 the energy required for the HIDC increases as more energy is integrated within the column. This is due to the reduction of the pump-around duties in order to converge the column. The reduction of these duties leads to a less optimized heat exchanger network. The increase in utility also increases the cost associated with the utility. This will decrease the amount of gross profit from the product quality and flowrates.

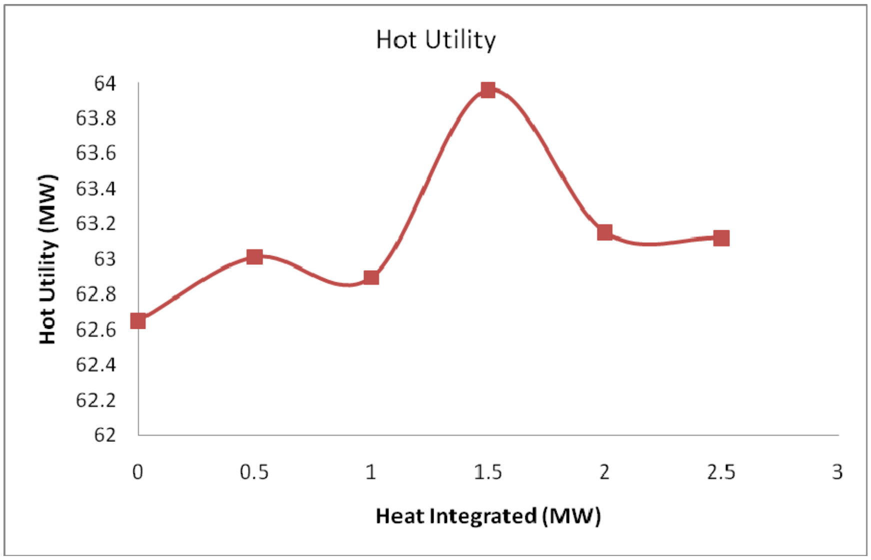

Figure 10: Required Heating Utility

The effects on the quality of the products were also investigated. The products become heavier as more residue is being recovered. As can be seen in figure 11, the D86 product points stay relatively unchanged except for gasoil and residue. As more heat is being integrated, the residue becomes heavier and the gasoil becomes lighter. Usually, the residue becomes heavier due to it lossing the lighter products to more desiable products.

Figure 12 shows the product flowrates as heat is being integrated. The residue actually increases in flowrate while gas oil decreases as more heat is transferred between the column sections. Therefore, the more desireable products are lossing components to the residue. The majority being lost is gasoil, but there are slight decreases in naphtha, kerosene, and diesel.

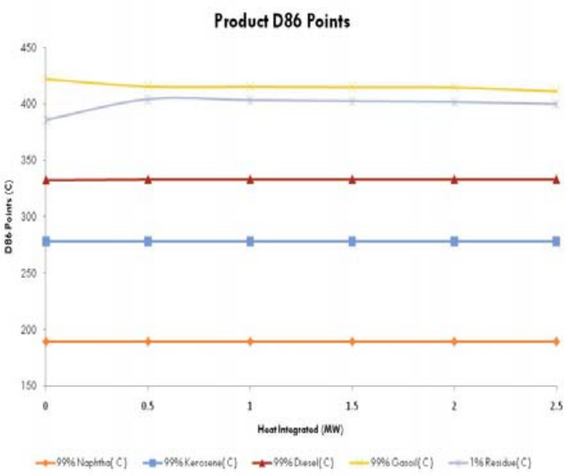

Figure 11: D86 Product Points

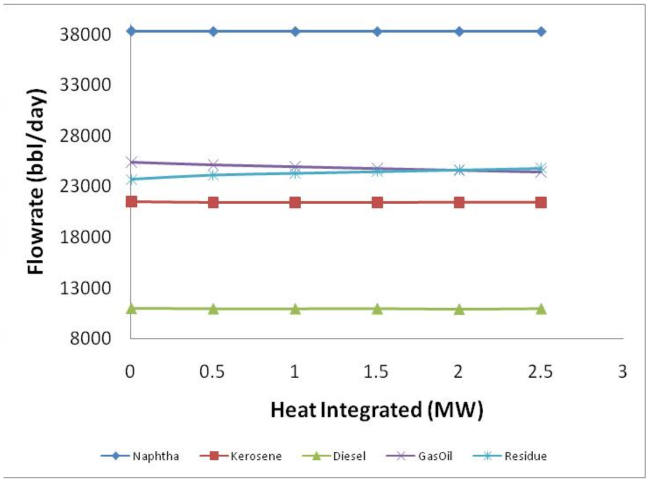

Figure 12: Product Flowrates

This process is easily seen as economical due to increased energy costs and decrease in profit from product flowrates. The exact loss in gross profit is illustrated in figure 13. Overall, the gross profit decreases as more heat is being integrated. The maximum profit was found at 2.5 MW with a gross profit at -$2.1 million.

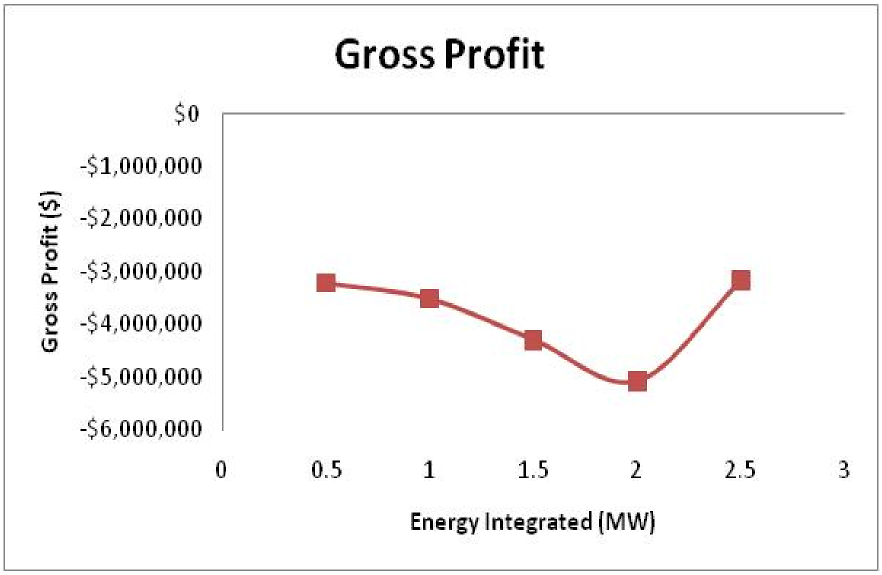

Figure 13: Gross Profit

An additional study was done to determine the feasibility of this type of project. In this column additional trays were added to the stripping section of the column. This was done to more closely replicate the standard HIDC. In this column, various amounts of heat was taken from the hottest rectifying tray (tray 28) and added to the coldest stripping tray (tray 49). Any duty that was transferred between the sections of the column was also reduced at the furnace. For example, if 1 MW of duty was transferred from the rectifying section into the stripping section of the column, the furnace duty would be reduced by 1 MW, resulting in a reduced furnace temperature.

In doing so, the effects on utility and products were monitored. The main concept of the HIDC is the reduction in energy required for the system. As can be seen in figure 14 the energy required for the HIDC decreases as more energy is integrated within the column. This is due to the additional trays in the stripping section allows for less reduction of the pump-around duties. This allows for a more optimal heat exchanger network and therefore less heating utility required. This will increase the amount of gross profit from the product quality and flowrates.

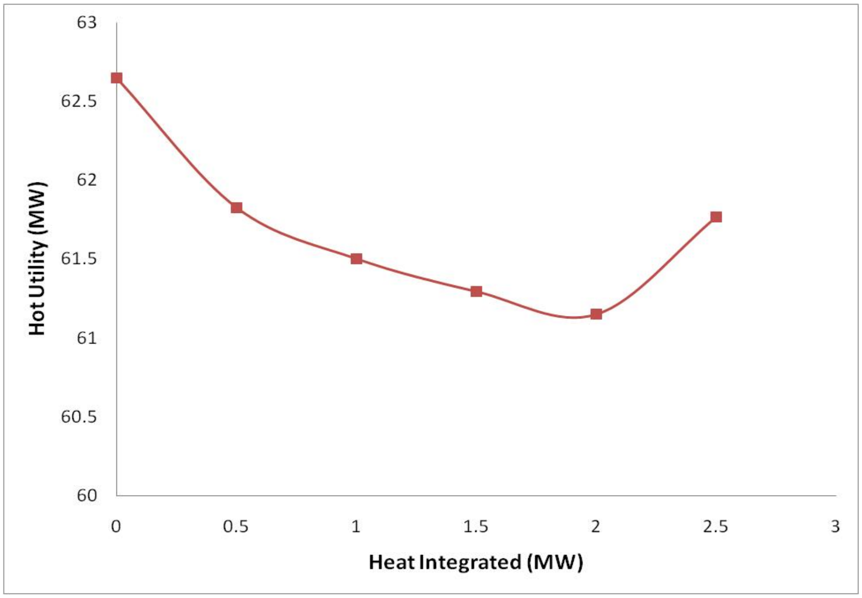

Figure 14: Required Heating Utility

The effects on the quality of the products were also investigated. The products become heavier as more residue is being recovered. As can be seen in figure 15, the D86 product points stay relatively unchanged except for gasoil and residue. As more heat is being integrated, the residue becomes heavier and the gasoil becomes lighter. Usually, the residue becomes heavier due to it lossing the lighter products to more desiable products.

Figure 16 shows the product flowrates as heat is being integrated. The residue actually increases in flowrate while gas oil decreases as more heat is transferred between the column sections. Therefore, the more desireable products are lossing components to the residue. The majority being lost is gasoil, but there are slight decreases in naphtha. There are also slight increases in kerosene and diesel resulting from the losses in naphtha.

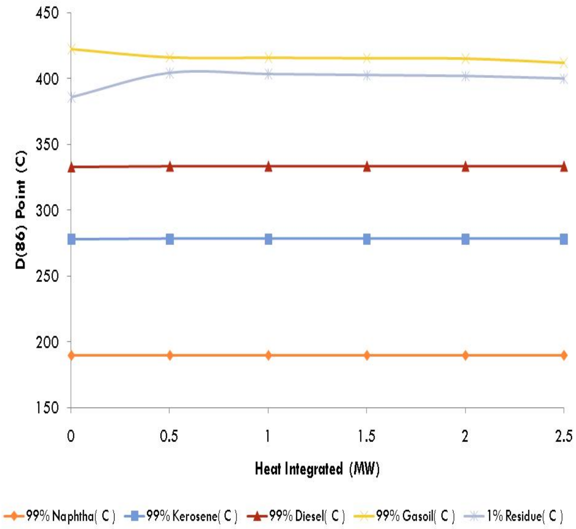

Figure 15: D86 Product Points

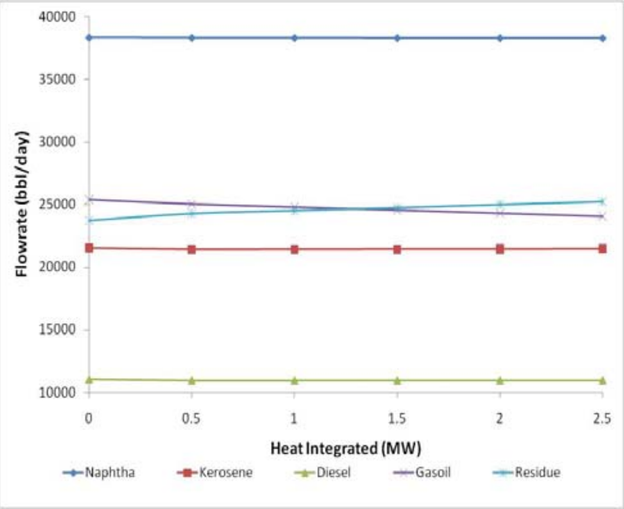

Figure 16: Product Flowrates

This process is not as easily seen as whether it is economical or not. The exact gross profit is illustrated in figure 17 to determine if the savings in energy is enough to make up for the loss in profit of the products. The maximum profit was found at 0.5 MW with a gross profit at -$2.6 million. So the profit from products is decreasing at a faster rate than the decrease in energy costs. This is due to the profit losses being more expensive than the savings of the cost of energy.

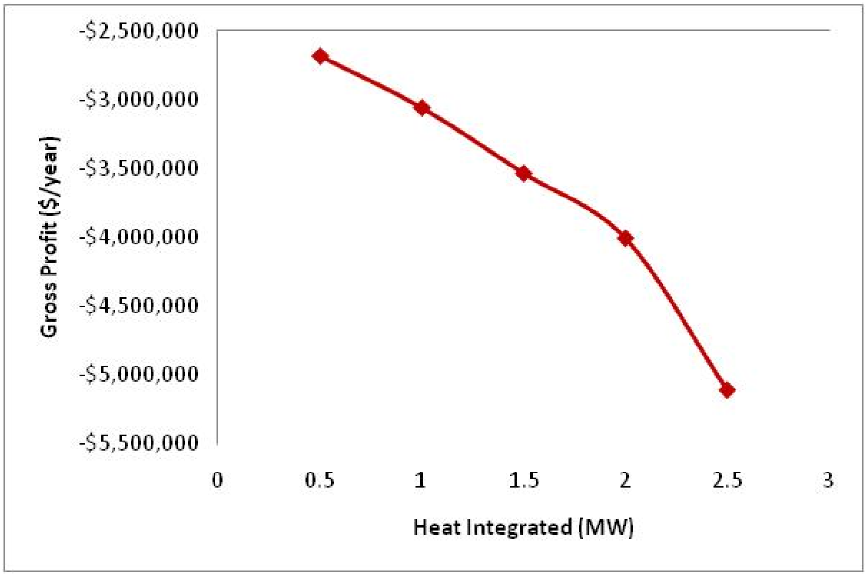

Figure 17: Gross Profit

Conclusions

For the systems studied, the heat-integrated distillation column made the system less economical for crude fractionation. The HIDC lost gasoil product to the residue, an undesirable product. Even though one system did save energy it was not enough to counteract the loss in products. HIDC does not seem like a feasible adjustment to crude fractionation, but further studies will be required to substantiate these results.

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