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New Technologies To Enhance the Distillation Yield of Petroleum Fractionation

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ABSTRACT: We review the performance of different technologies published in a recent patent by Ji and Bagajewicz (2007) aimed at increasing distillates yield. We also present different implementation schemes composed of various combinations of the two technologies and compare both distillate yield and energy expenditure to the current conventional distillation process for light, intermediate, and heavy crudes. We demonstrate sizable increases of yield as well as significant profit. The criteria for analysis were yield, energy savings, gross margin, and potential extra revenue for each scheme. While the comparisons are made on the basis of grassroots design, we took one technology and assumed a retrofit of an existing column via simple change in the heat recovery, to assess the extra investment needed.

■ INTRODUCTION

Crude oil is mainly a complex mixture of hundreds of hydrocarbon molecules, which are separated in an oil refinery into useful crude oil products, such as naphtha, kerosene, diesel, and different gasoils by means of fractionation. The design has evolved through the years and, although variations can be observed, industry has settled on one scheme that is considered a reference, namely, an atmospheric column, with pump-around circuits (pump-back was abandoned and a recently proposed stripping-type column was also proven energetically inefficient[1]), stripping using steam (reboilers are not used) and side strippers followed by a vacuum column that also has pump-around circuits and main steam injection instead of a reboiler.[2−4] This conventional scheme is summarized in Figure 1 for an atmospheric fractionation unit, where the details of the heat exchanger network that uses hot products, the pump-around circuits, and the condenser to heat the feed are omitted and replaced by a heating duty represented by a circle and the caption "HEN".

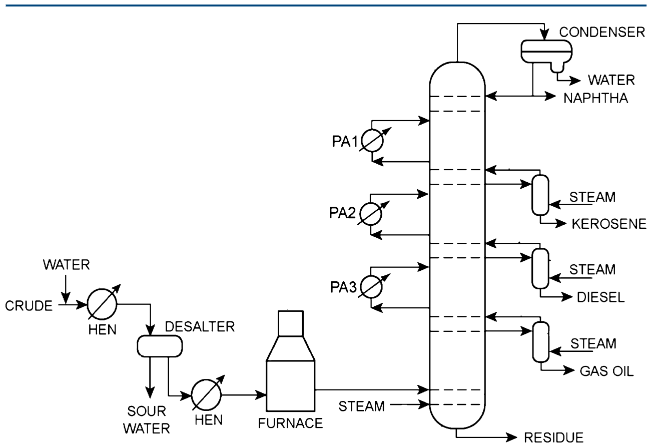

Figure 1. Conventional distillation column[2−4]

Sometimes, the atmospheric column is preceded by either a flash or a prefractionation column.[5] This has been advanced to include the thermal coupling of the prefractionation with the crude distillation unit resulting in a decrease in energy usage. Unfortunately, this design brings high complexity with it as illustrated by Amminudin et al.[6] A new design was proposed by Kim,[7] and it is still complex. Other recently proposed schemes, the stripping type, have been proven not to be competitive.[5] In a recent patent,[8] Ji and Bagajewicz proposed two schemes that can improve the distillation yield in atmospheric and vacuum columns. One scheme is based on the removal of most of the intermediate (medium range molecular weight) components from the feed to the column, so that the entire light fraction (not removed) can enhance their carrier effect on the remaining intermediates (gasoil in atmospheric columns and heavy vacuum gasoil in vacuum columns). The other proposed scheme is based on removing part of the flash zone vapor feed from the stripping trays, separating some gasoil from this vapor and reinjecting the rest in the bottom of the column.

This article analyzes five technologies, which were obtained by introducing variants into each of the technologies proposed in the patent[8] and also by combining them. We identify their yield enhancement capabilities, and we show the effect on energy expenditure. In all cases, we chose light, intermediate, and heavy crude to assess the proposed schemes. We finalized with some economic analysis and a preliminary assessment of a simple retrofit of existing units.

■ CONVENTIONAL DISTILLATION

Conventional distillation is an energy demanding process that has been used for over 70 years in the refining industry. Crude oil

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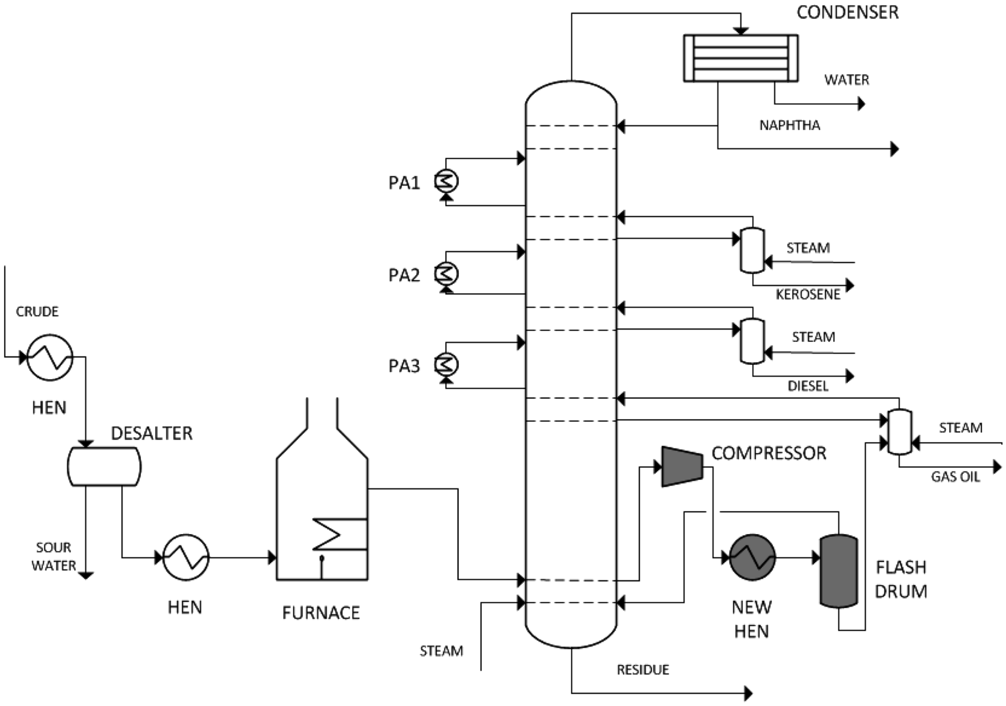

Figure 2. Technology I.

fractionation columns are used to separate crude oil into products such as naphtha, kerosene, diesel, and gasoil. Light distillate products are the most profitable; hence the design of the atmospheric column is targeted toward maximizing the production of these light components.[2]

The conventional design shown in Figure 1, is composed of an atmospheric column that acts mostly as a rectifying section, strippers which are used to remove the desired components, and several pump-around systems throughout the column, which are used to reduce the heating duty of the condenser. The stripping section, in turn, is relatively small with just a few trays.

Before crude oil enters the column, it goes through a desalination process. For this, crude oil is mixed with water and then heated to temperatures of about 100 °C−150 °C, depending on the crude. A heat exchanger network that uses heat from the product streams and pump around streams is used to achieve these temperatures. A desalter is used to extract sour water from the crude oil, which is then sent to another heat exchanger network to increase the temperature to around 360 °C.

This heated crude oil enters the distillation column into a flash zone where the vapor and liquid phases separate. As the vapor product rises through the column the temperature in the trays decreases so that the top of the column is rich in light components. The vapor at the top of the column is condensed, part of the components is sent back into the column as liquid, and the other part is collected as distillate product. Trays allow the liquid that comes back into the column to come into contact with vapor, allow for mass transfer between the phases, and have varying liquid and vapor compositions along the length of the column. This feature in conventional distillation allows for the design to include side strippers throughout the column where a desired product will be rich in a specific section of the column. Steam injection into the strippers facilitates the control of lighter components in the product.[2−4]

Another characteristic of conventional crude distillation is the presence of pump around circuits. These systems cool some of the liquid and then pump it back into the column at a higher tray. They act as a distributed reflux; therefore, the duty of the condenser is reduced. A study done by Bagajewicz[3] showed that columns with pump-around systems required higher furnace duty and decreased the amount of distillate products. Nevertheless, pump around systems are still used in industry because of the benefit of energy savings. Since cooling takes place at higher temperatures, these systems act as an energy source into the heat exchanger networks used to preheat the crude oil.

A conventional distillation column may also be followed by a vacuum column used for further processing residue.[2] Some intermediate products (gasoil) are usually still present in the residue; these products give more profit if they are separated from the residue. Operating at lower pressures reduces the temperature at which the desired components boil, and would imply less use of energy to obtain these components.

■ NEW TECHNOLOGIES

Technology I:[8] In this technology, a portion of the vapor from the top tray of the stripping section is removed before it enters the flash zone (Figure 2). This vapor stream is compressed before being cooled and sent to a flash drum. The liquid product from this flash is then sent to the gasoil side stripper. In turn, the vapor stream from the flash drum is reintroduced at the bottom of the column. Because this contains some steam and some light components that are not usually in the last tray of the conventional design, they create a "carrier effect," where the lighter components and steam promote the vaporization of heavier components. The carrier effect is extensively discussed by Bagajewicz and Ji.[5] Since the intermediate components are removed in the flash this also allows a greater volatility gap between the lighter hydrocarbons and leftover intermediate hydrocarbons resulting in better separation of the crude. Increasing the prefractionation stream's pressure using a

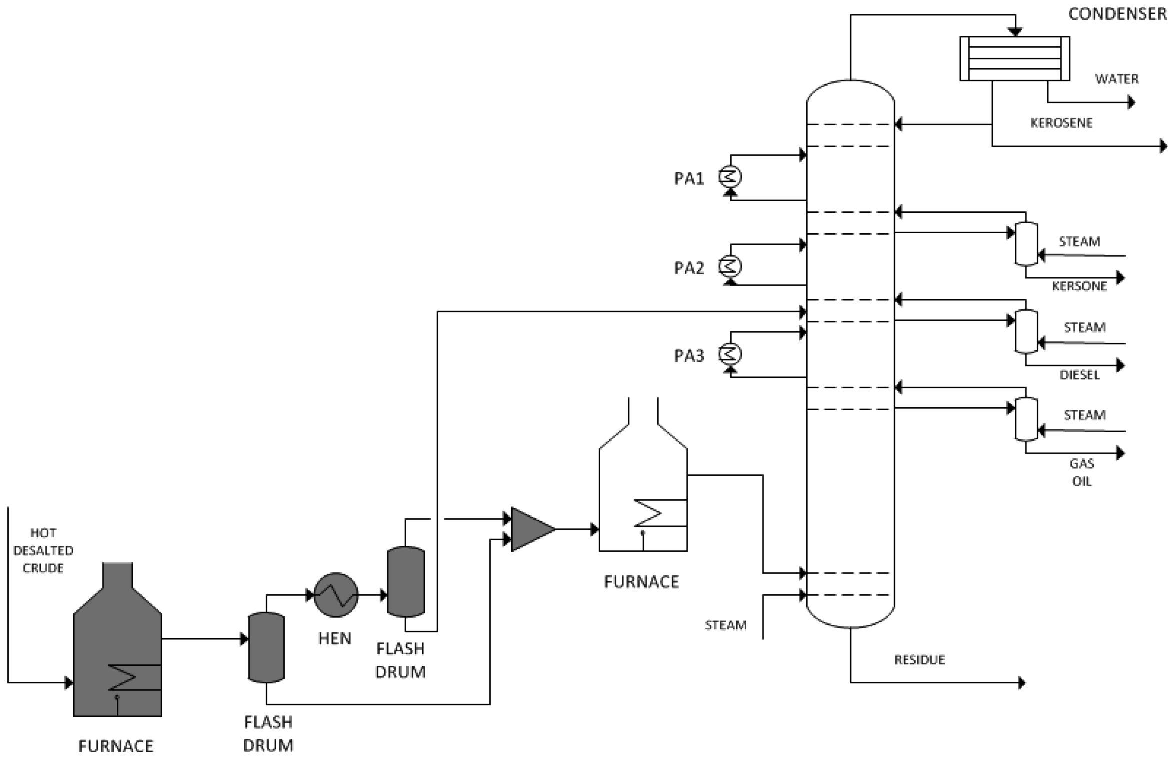

Figure 3. Technology II.

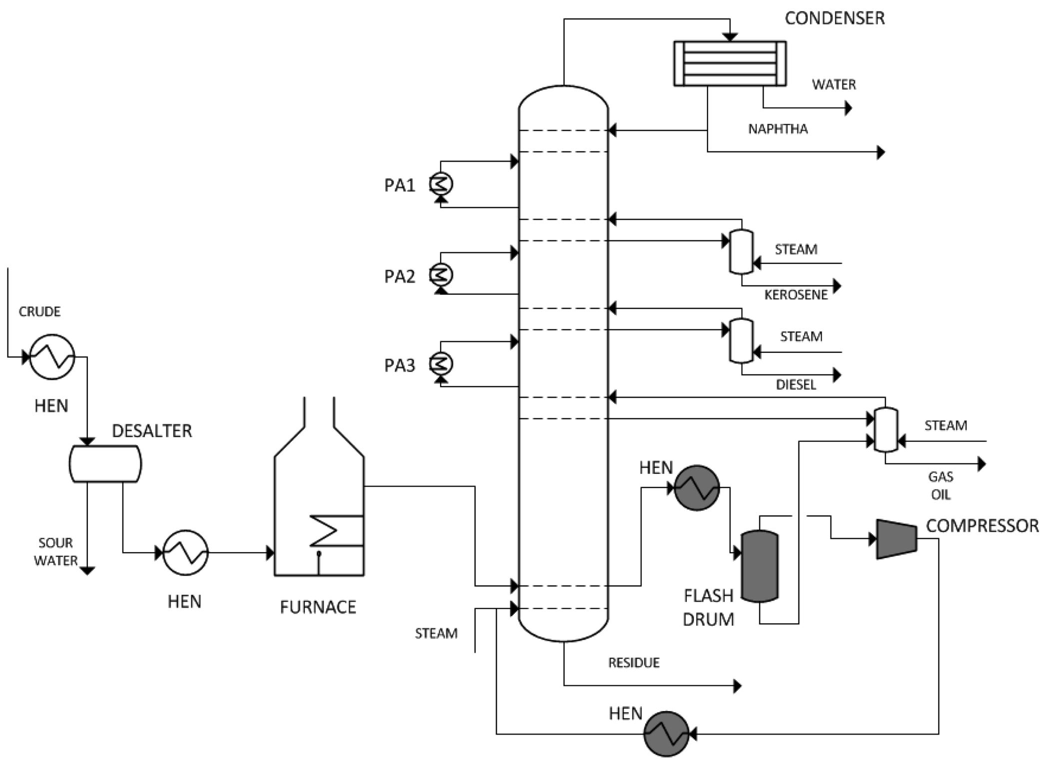

Figure 4. Technology III.

compressor increases the product gaps between the different types of distillates. This increases the yield of gasoil and diesel while decreasing the production of residue. It is assumed that the liquid from the flash feeds the gasoil side-stripper.

Technology II:[8] In this technology, desalted crude is heated to a high temperature (close to the column feed temperature) and is fed to a flash drum, which separates the crude into a light vapor stream and a heavy liquid stream (Figure 3). The vapor from this flash is then cooled and partially condensed. A second flash separates the mixture sending the vapor to merge with the liquid from the first flash and introduced to the column after passing through a furnace. In turn, the liquid from the second

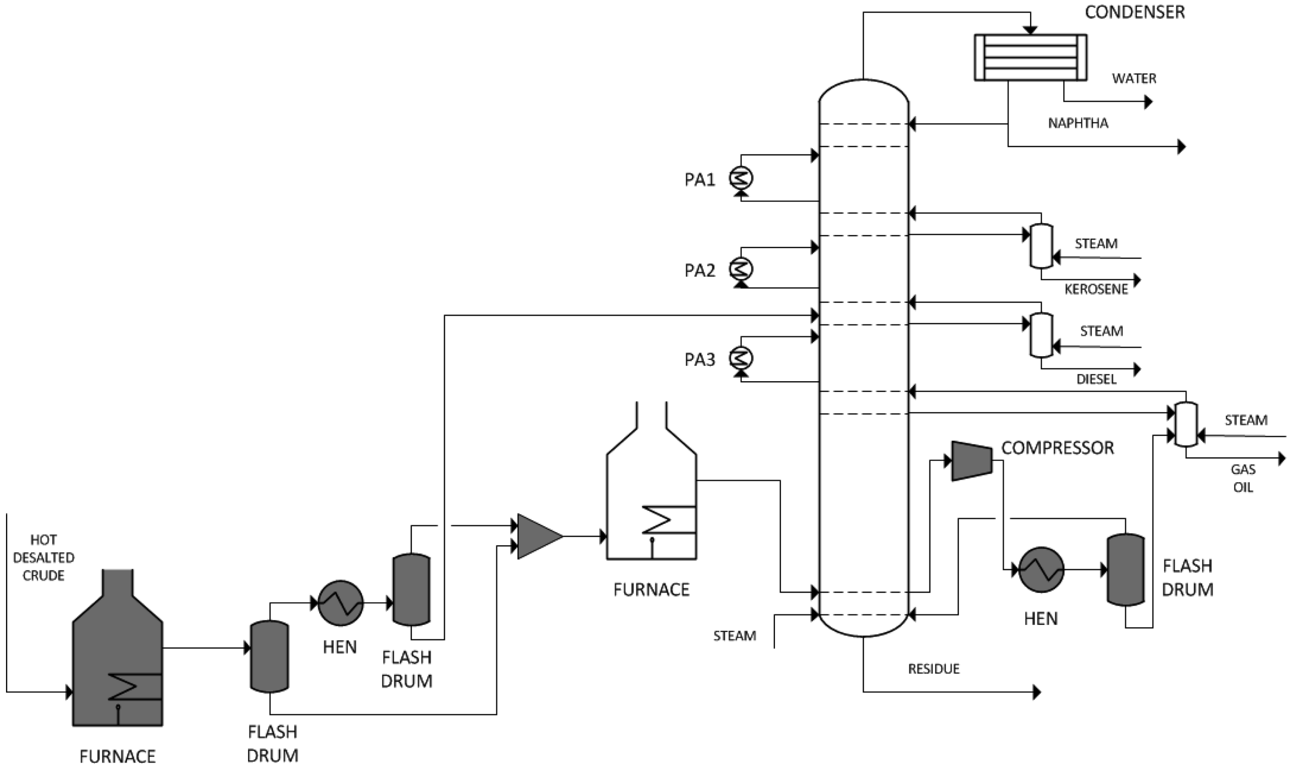

Figure 5. Technology IV.

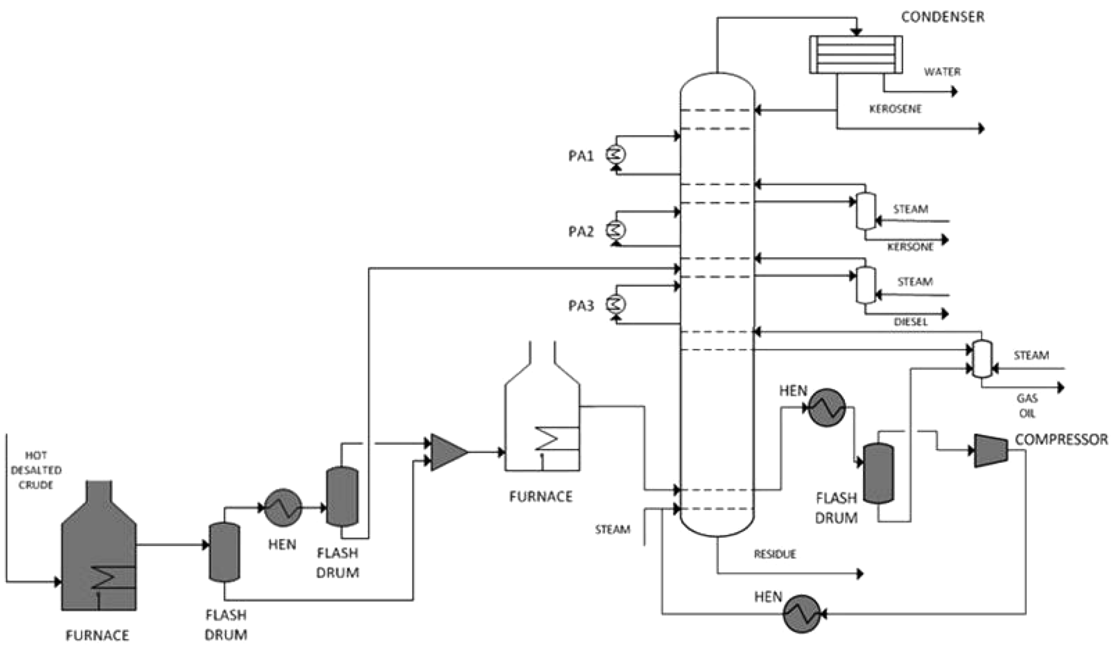

Figure 6. Technology V.

flash is introduced in the column at a tray that is in between the diesel and the gas-oil draw.

As a consequence of the second flash, the feed to the column has a small amount of components in the range of gas-oil and diesel consisting of the residue, the light ends, and a small fraction of the aforementioned intermediates. Thus, the light ends create a "carrier" effect on the intermediates that are left and help to increase their separation in the flash zone. As a result, the yield of gasoil increases. While this technology is shown with two furnaces, there is a way of using a single furnace with two separate cold fluid passes. In addition, the temperature from the first furnace is a parameter requiring optimization. We assumed the temperature is the temperature of the crude to the column.

Technology III. This is a variant of Technology I. In this case, instead of compressing the stream extracted from the flash zone, the stream is first cooled and sent to the flash (Figure 4). The vapor from the flash is now compressed and sent to the bottom of the column. The advantage of this variant is 2-fold: (a) the compressor operates at a lower temperature and (b) the compressed flow rate is lower.

Technology IV. Combination of technologies I and II (Figure 5).

Technology V. This is a combination of technologies II and III (Figure 6).

EVALUATION

A light, an intermediate, and a heavy crude oil were chosen for process modeling and for further comparison to previous results. We used a throughput of 120,000 bpd with a column inlet temperature at 360 °C. The 34 tray column operates with 3 pump-arounds and five products. The crude assays used and the conditions that the different products need to meet are listed in Tables 1 through 5.

Table 1. Crude Oil Distillation Curves

	NBP °C		
vol % distilled	light	intermediate	heavy
5	45	94	133
10	82	131	237
30	186	265	344
50	281	380	482
70	382	506	640
90	552	670	N/A

Table 2. Crude Oil Light Components

	light-end composition vol %		
component	light	intermediate	heavy
ethane	0.13	0.1	0.0
propane	0.78	0.3	0.04
isobutane	0.49	0.2	0.04
n-butane	1.36	0.7	0.11
isopentane	1.05	0.0	0.14
n-pentane	1.3	0.0	0.16
total	5.11	1.3	0.48

Table 3. Crude Oil Feed Crude Density

feed type	crude density (API)
light	36.0
intermediate	27.7
heavy	20.0

Table 4. Product Cut Specifications

product	D86 (95%)
naphtha	182 °C
kerosene	271 °C
diesel	327 °C

Table 5. ASTM 5%−95% Gap Specifications

	light (°C)	intermediate (°C)	heavy (°C)
kerosene−naphtha	16.7	16.7	30.8
diesel−kerosene	0	2	4.4
gasoil−diesel	−2.9	−3.6	−6.6

All of the technologies distillation designs were simulated using Pro II (SIMSCI) using version 9.1. In all cases, the same specs, including gaps corresponding to the ones used in the conventional distillation case are strictly met. We allowed the atmospheric gasoil ASTM D86 95% point (and end point) to vary and we operate at the same overflash ratio. The total minimum heat utility for each case was obtained using pinch technology with an HRAT of 15 °C. This is a conservative choice, as in our experience lower HRAT like 10 °C, or even 5 °C can be profitable. The energy required by the compressors (all technologies except technology II) was added to the energy calculations. The energy for the furnace was determined by subtracting the hot utility from the total minimum heating utility.

The gross margin for the technologies and the conventional distillation was determined as the difference between revenue and cost of sales. In addition, the extra profit for each technology was also analyzed in order to compare the technologies against conventional crude distillation.

The cost includes the cost for steam, natural gas, and electricity to run the compressors as well as the raw materials (crude). These are summarized in Table 6.

Table 6. Prices[9]

item	price
crude oil ($/bbl)	108.64
naphtha ($/bbl)	113.68
kerosene ($/bbl)	126.00
diesel ($/bbl)	128.10
gasoil ($/bbl)	130.20
residue ($/bbl)	102.90
steam ($/1000-lb)	5.70
electricity ($/KW-h)	0.07
natural gas ($/KW-h)	0.02

As the intent of this analysis is to determine the viability and profitability of these technologies, we did not place a focus on any optimization. Thus, the steam injection, pump-arounds, tray hydraulics, and draws are designed to be within reason but not optimized.

RESULTS

Yields. When the new technologies were compared against the conventional case, it was found that the yield of naphtha and kerosene remained relatively the same as in the conventional distillation case. Meanwhile, diesel had some small variance (15 bbl/h difference or less). Finally, the yield of gasoil increased in all technologies while the production of residue decreased.

Technology IV and V showed the highest increase in gasoil production in all cases (Figures 7, 8, 9), with Technology IV performing slightly better than Technology V. The Technology IV gasoil production increases by 11% in the light case, 18% in the intermediate case, and 19% in the heavy case. This corresponds to a reduction in residue of −10.7% in the light case, −4.4% in the intermediate case, and −2.8% in the heavy case. Diesel also sees some small adjustments, but it is less than 3% in all cases. All other products see minimal to no adjustment.

Figure 7 provides an overview of the change in production for the light crude in each technology. As it indicates, Technologies I and III impact the production of gasoil less than Technology II. Technologies IV and V are combinations of Technologies I, II, and III and thus exhibit the effect of Technology II enhanced by Technologies I and III. Figure 8 provides the intermediate crude results, and Figure 9 provides the heavy crude results.

Energy Savings: After the minimum utility was obtained for an HRAT of 15 °C, the energy consumption in each of the technologies was found by taking into account the amount of natural gas used by the furnace and the steam used in the column

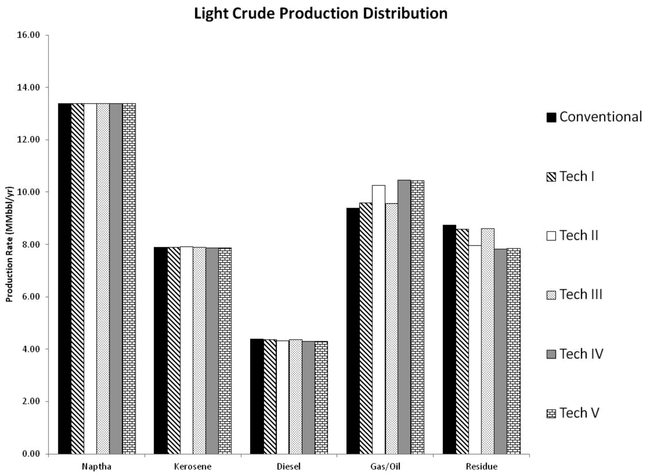

Figure 7. Light crude production in MMbbl/yr (basis: 120 000 bpd throughput).

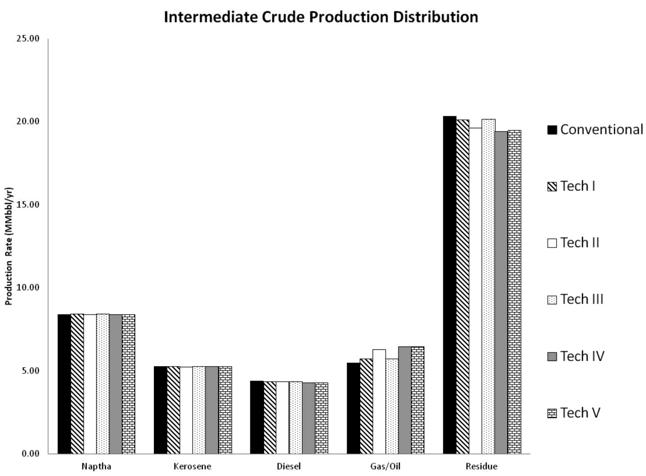

Figure 8. Intermediate crude production in MMbbl/yr (basis: 120 000 bpd throughput).

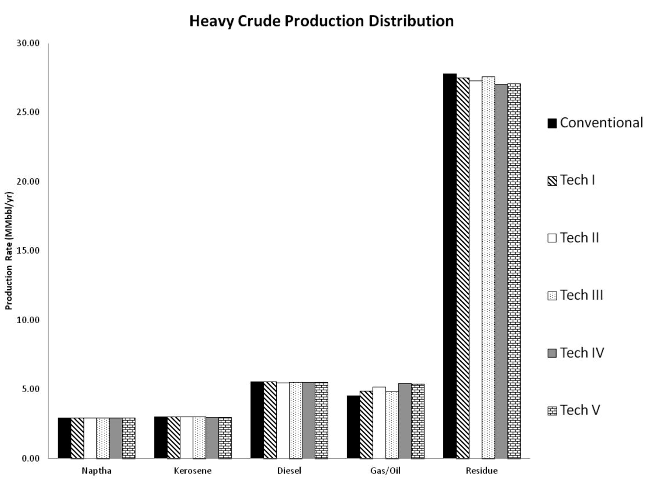

Figure 9. Heavy crude production in MMbbl/yr (basis: 120 000 bpd throughput).

and side strippers. The electricity was associated with the work of the compressor. Table 7 shows the percent change in total energy consumption with respect to the base case (conventional design). Technology IV sees the largest increase in energy costs. The largest increase is approximately a 4.2% increase with the heavy crude. With the exception of Technology I for the heavy crude, Technologies I, II, and III all have an energy increase less than or equal to 1.5%. Technology V is close to (within 1%) of the energy costs of Technology IV.

Gross Profit Margin. Total gross profit was estimated by taking the amount of revenue from selling naphtha, diesel, kerosene, gas/oil, and residue minus the cost of energy used by each technology minus the cost of crude oil (Table 8). The gross margin per barrel was obtained for each technology and the conventional case. Overall, the light crude generated the highest gross margin over all the technologies. This is because the lighter crudes carry a higher fraction of the more valuable lighter components.

Technology IV and V had the highest gross margins with the gross margin of Technology IV being slightly higher in the light, intermediate, and heavy cases. Technology II performs better than Technologies I and III, but does not perform quite as well as the combinations of Technologies IV and V. This shows that the gross profit margin is the greatest by combining the two technologies. The additional profit is summarized in Table 9 with Figure 10 providing a graphical view.

Comparison with Industry Values: The economics of this study was compared with industry values of the refinery gross margin. According to *Petroleum Refining Technology and Economics*, for an average 92,552 BPSD refinery, the gross margin was reported to be on average \$3.00−\$4.50/bbl.[2] For a 196,936 BPSD sized refinery, the gross margin was reported to be on average \$5.00−\$7.00+/bbl.[2] In this study, the average gross margins for all three crudes for 120,000 bpd throughput were determined to be between \$9.50−\$10.50/bbl for the light crude, \$4.50−\$5.50/bbl for the intermediate crude, and \$2.5−\$3.00 for the heavy crude. The technologies proposed in this paper achieve a gross margin on the upper end of the gross margins reported in literature (\$2.50 to \$10.50/bbl for our crudes with each technology versus \$3.00 to \$7.00/bbl from literature). It should be noted that prices vary over time and region, therefore comparison is difficult. For instance, the November 2013 refinery gross margin listed by the Oil and Gas Journal is closer to \$10.15/bbl for the U.S. Gulf Coast.[10]

Gasoil Quality. We controlled the D86 95% Points of all products except gasoil and the residue. In addition, we forced the same (or very close to the same) gaps between kerosene and naphtha, diesel and kerosene, and gasoil and diesel. We allowed the D86 95% value of gasoil and residue to vary between each technology as the gasoil yield increases and the residue yield decreases. Thus, we provide Table 10 to indicate the product quality for gasoil in each technology. As Table 10 indicates for gasoil, these points never increase more than 20 °C and do not exceed 462 °C.

Hydraulic Changes. To provide a better assessment of the hydraulics and the issue of flooding, Figures 11 through 16 illustrate the liquid flow (m^3/h) and the vapor flow (1000 m^3/h) on each tray for technology V and the conventional case. All the other technologies exhibit similar or smaller deviations. Technology V, as it is the combination of two technologies exhibits deviation in the stripping section as well as in the rectifying section. As the figures indicate, Technology V exhibits a reduction in liquid and vapor flow across the rectifying section and an increase in the stripping section. Technology V is closest to the conventional design when using the light crude and furthest when using the heavy crude.

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Table 7. Energy Cost and % Increase

		technology type				
	conventional	I	II	III	IV	V
feed type	\$/bbl	% change	% change	% change	% change	% change
light	0.21	1.2%	1.5%	1.1%	2.6%	2.6%
intermediate	0.23	1.2%	0.4%	0.7%	3.7%	3.2%
heavy	0.17	2.5%	0.7%	0.8%	4.2%	3.2%

Table 8. Gross Profit Margins

		technology type				
	conventional	I	II	III	IV	V
feed type	\$/bbl	\$/bbl	\$/bbl	\$/bbl	\$/bbl	\$/bbl
light crude	\$9.92	\$10.03	\$10.42	\$10.01	\$10.51	\$10.49
intermediate	\$4.84	\$4.98	\$5.28	\$4.95	\$5.40	\$5.43
heavy	\$2.44	\$2.62	\$2.76	\$2.59	\$2.93	\$2.90

Table 9. Extra Profit

	technology type				
	I	II	III	IV	V
	\$/bbl	\$/bbl	\$/bbl	\$/bbl	\$/bbl
light crude	\$0.11	\$0.50	\$0.09	\$0.59	\$0.57
intermediate	\$0.14	\$0.44	\$0.11	\$0.56	\$0.59
heavy crude	\$0.18	\$0.32	\$0.15	\$0.49	\$0.46

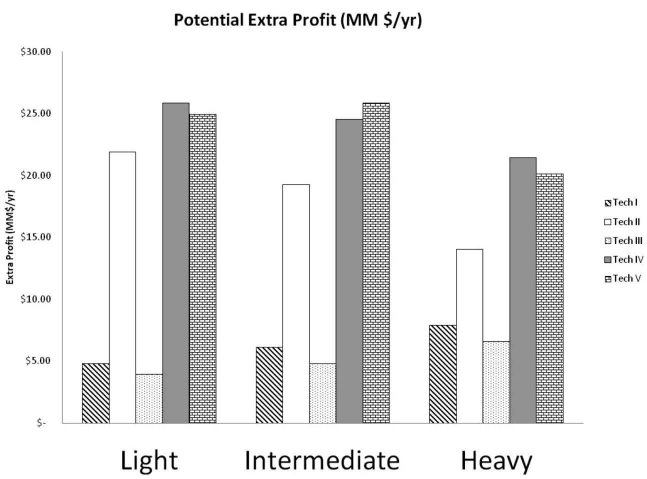

Figure 10. Potential extra profit in MM\$/yr (basis: 120 000 bpd throughput).

To further investigate the issue and make sure that no significant changes in diameter are needed, or that a retrofit situation will not be constrained by hydraulics, we took the case of Technology III, which exhibits the largest change in the stripping section. The column was designed with 34 trays and a vapor draw-off at tray 30 (before the feed at tray 29). To assess the issue of flooding, we sized the conventional tray column until we achieved no greater than 65% flooding for the conventional case. We then added Tech III to the column with a vapor draw-off of 2150 m^3/h (the amount we drew-off in our evaluation of the Technology III). We found that we could double it before flooding becomes a problem.

We performed this same analysis for Technology II as there is a sharp decrease in the liquid flow in the rectifying section of the column. Technology II shows smaller flows, so flooding is not an issue, but weeping or small tray hold-up might. Thus, we took the

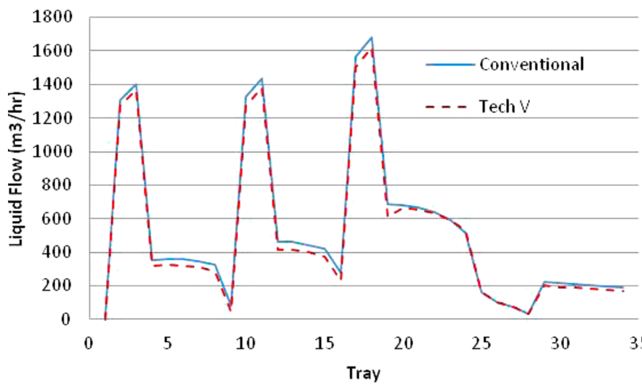

Figure 11. Liquid flow rate for conventional case and Technology V (light crude).

Table 10. Gasoil D86 95% Point and End Points

	Conventional	Tech I	Tech II	Tech III	Tech IV	Tech V
		Light Crude				
D86 95% Point (% volume)	436.2	437.3	446.4	437.4	446.9	447.0
D86 End Point (% volume)	449.8	450.7	460.9	450.8	462.0	462.0
		Intermediate Crude				
D86 95% Point (% volume)	426.3	428.7	441.5	428.9	442.8	442.9
D86 End Point (% volume)	441.2	443.7	457.3	443.7	459.8	459.9
		Heavy Crude				
D86 95% Point (% volume)	399.4	402.6	407.2	402.7	409.7	409.9
D86 End Point (% volume)	412.0	417.6	425.6	417.8	429.6	429.9

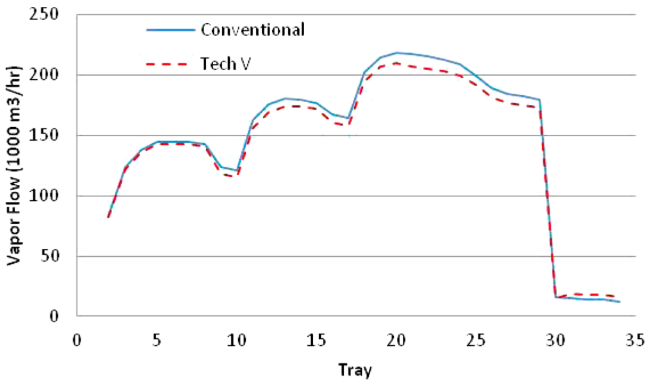

Figure 12. Vapor flow rate for conventional case and Technology V (light crude).

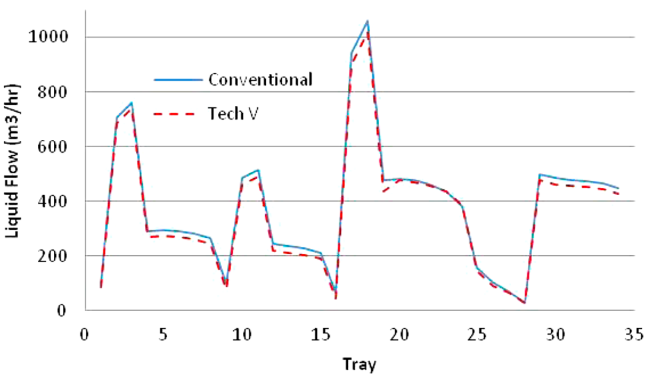

Figure 13. Liquid flow rate for conventional case and Technology V (intermediate crude).

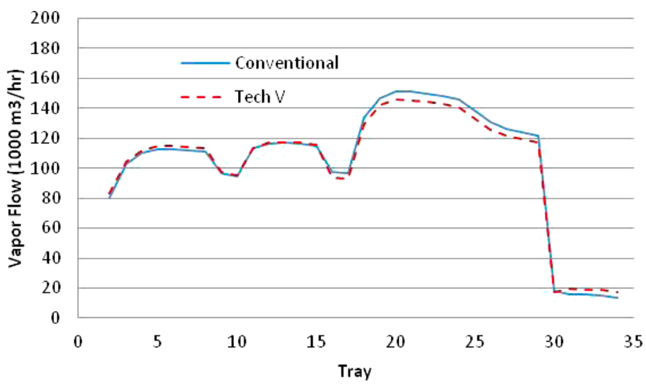

Figure 14. Vapor flow rate for conventional case and Technology V (intermediate crude).

tray exhibiting the largest liquid reduction and found that the flooding factor reduced from 65% to 55%, still within the operational region. Clearly, caution must be taken to prevent further reduction or tray efficiency may suffer.

We therefore conclude that the column diameter for all these options can safely be the same. The largest discrepancy occurs in the heavy case, but it is still within reason. This helps in the economic comparison, as one can only consider the extra cost of new equipment and compare it with the increase in revenues. This is a matter to consider by each designer, as we do not perform such comparison.

Economics for Higher Recirculation Rate. The economic evaluation for Technology 3 discussed above was for a draw-off of 2150 m^3/h. Increasing the draw-off will affect the D86 95%

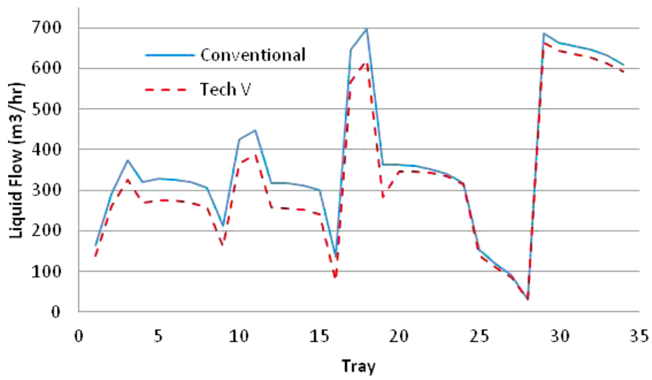

Figure 15. Liquid flow rate for conventional case and Technology V (heavy crude).

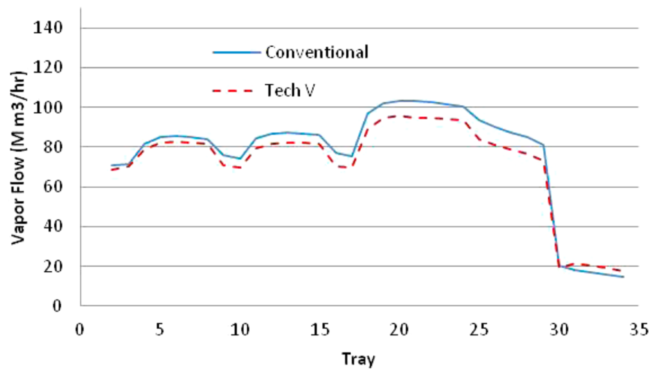

Figure 16. Vapor flow rate for conventional case and Technology V (heavy crude).

volume fraction temperature and the economics. For a 2-fold increase in vapor draw-off, the D86 95% point of the gasoil is 439 °C (the end point is 452 °C) and the extra profit increases by nearly $5 million dollars per year (based on 2014 values).

Energy Savings and Distillate Yield in Simple Retrofit Scenarios. Up until now, economic calculations have been done for grassroots design with an optimized (maximum energy recovery) crude preheat heat exchanger network. However, there is energy to be captured even for nonoptimized networks. For each of the new technologies discussed, we considered a simple scenario: one (or two) heat exchangers with a minimum temperature approach of 15 °C, each installed to further preheat the crude entering furnace as shown in Figures 17, 18, and 19. Figures for technologies IV and V were not included as they are combinations of other technologies. We primarily focus on Technology II in this study as Technology I and III provide a hot stream that is comparatively small to the other hot streams. Technology II requires the cooling of a large hot stream and additional heating of the crude.

Table 12 summarizes the energy retrofit results from the installation of Technology II for the light crude. As we are considering only a simple retrofit, we assume three possible furnace inlet temperatures (FIT) before the addition of Technology II and assess the area addition under those conditions. The minimum utility does not see significant change (less than 1 MW) between the conventional case and Technology II. We assumed an overall heat transfer coefficient for a plate exchanger of 0.45 kW/(m^2·K). As Table 12 indicates, the largest exchanger needed is about 700 m^2 for the 270 °C furnace inlet temperature.

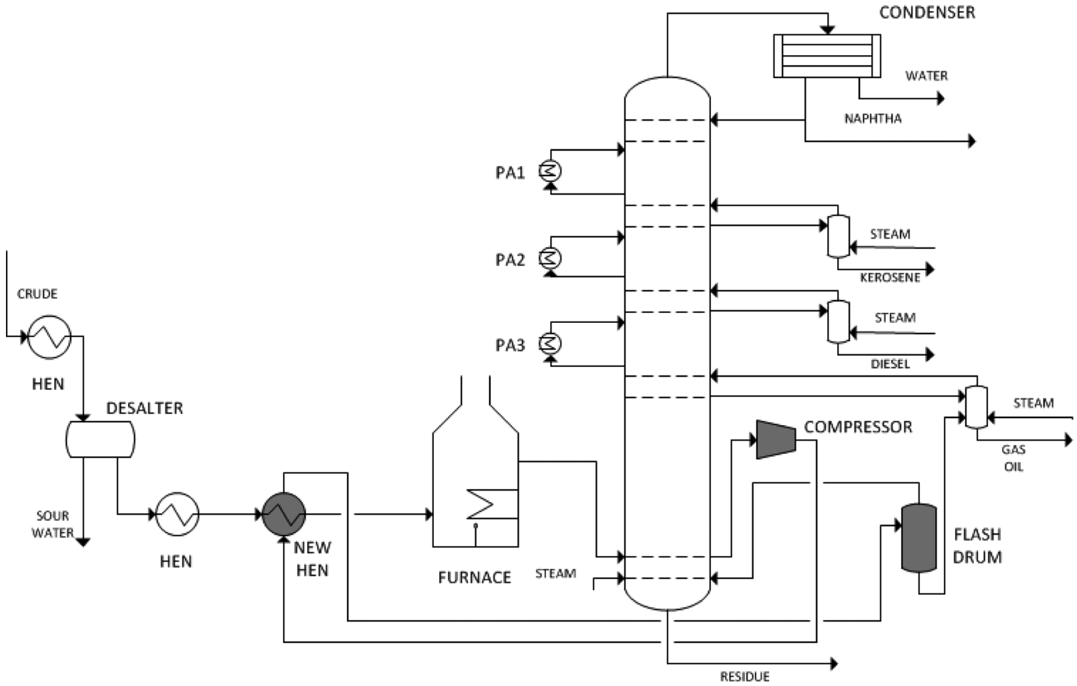

Figure 17. Simple retrofit design for Technology I.

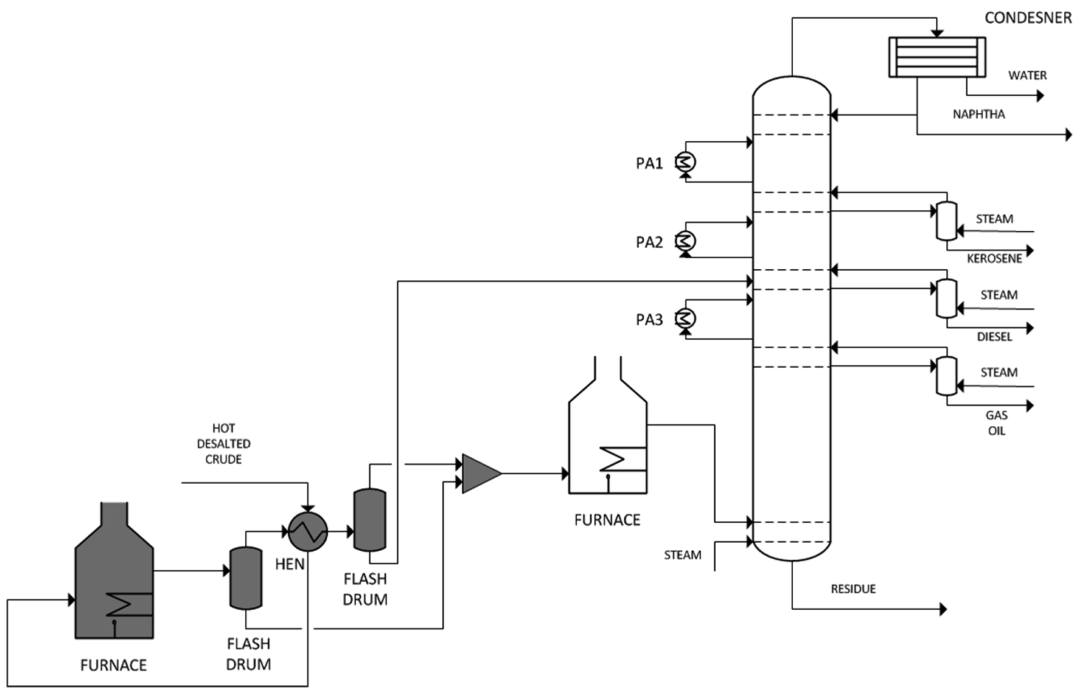

Figure 18. Simple retrofit for Technology II.

■ OPERATIONAL CONCERNS

These designs are not void of operational issues that need consideration during design and operation. In Technology II, IV, and V, the flash zone hydraulics are different from the conventional case resulting in less traffic and additional vapor stripping. Thus, flooding and entrainment are concerns that require consideration during a grassroots design, and also a detailed study when the technologies are added to existing columns.

In the case of grassroots design of Technologies II, IV, and V, one can use only one furnace with two separate coils. In retrofit design, changes in existing furnaces may not be possible and a new furnace may be necessary. If the retrofit of existing units is accompanied by energy integration using the examples we outlined above, or a more comprehensive retrofit to save even more energy, the retrofit of the existing furnace might be possible. That said, if no energy retrofit is performed, an additional furnace is needed if the existing one is operating at maximum capacity. Economics is likely to dictate that energy retrofit is more profitable than a new furnace.

For Technologies I and III, hydraulic concerns exist as vapor is removed from the flash zone and returned at a lower tray. Once

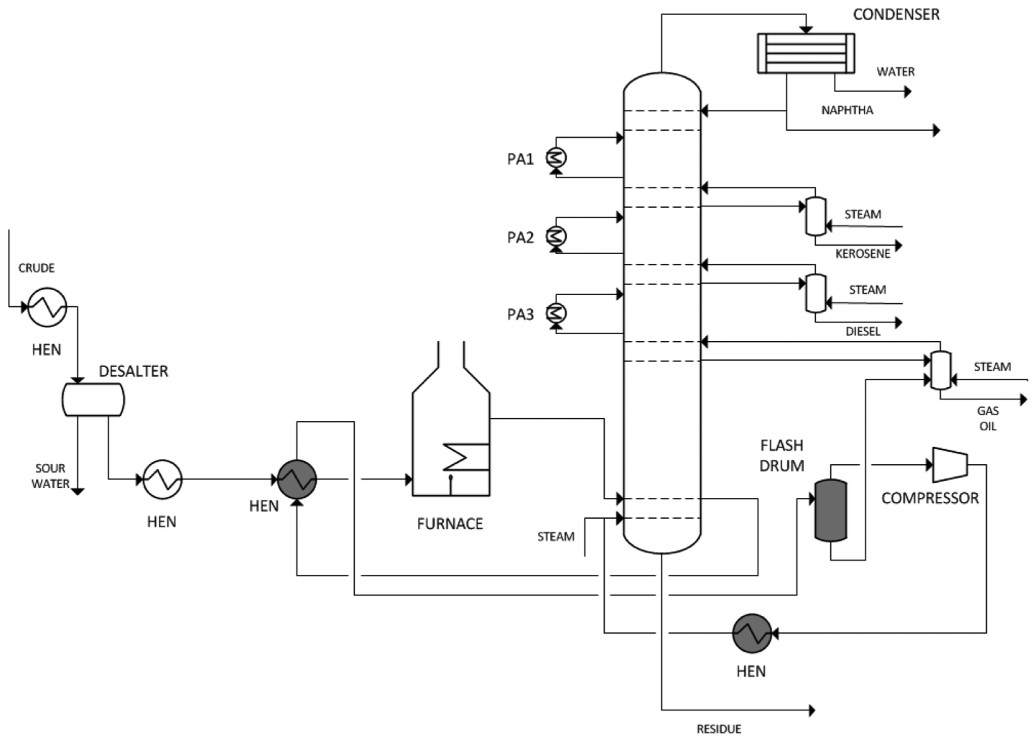

Figure 19. Simple retrofit for Technology III.

Table 12. Energy Savings of Technology II. Retrofit Case for Light Crude

		Technology II		
FIT	units	230 °C	250 °C	270 °C
conventional furnace utility	MW	84.61	72.77	60.67
second furnace utility (Technology II)	MW	14.12	14.12	14.12
first furnace utility (Technology II)	MW	67.31	55.47	43.36
energy savings after retrofit	MW	3.18	3.18	3.19
exchanger area	m^2	407.7	515.8	703.1

again, flooding is a concern and was considered in our report. The compressor is another challenge, as it needs to operate at a high temperature with saturated vapor particularly in the case of Technologies I and IV. This is an expensive unit, and thus needs further consideration.

Another concern left to future work is the impact of these technologies on the final fuels produced by the residue and gasoil due to issues with sulfur content and specific gravity.

CONCLUSIONS

We have evaluated combinations of two new technologies proposed recently for the increase of crude distillation column yields. We also analyzed the case of simple retrofit of existing units and found that there are economic incentives as well. We found that in almost all densities of crude the economic incentive to use these technologies exists. We expect that variations in crude TBP curves of the same density should obtain similar results. In addition, for Technologies II, IV, and V, the temperature of the outlet of the first furnace, the temperature of the flash, and the feed tray of the liquid were not optimized. Finally, we should point out that the increased throughput of gasoil may lead to a different density and sulfur content, which may affect operations downstream and should be analyzed. These issues are left to future work.

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Notes

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