Proceedings of the 6th International Conference on Process Systems Engineering (PSE ASIA)
25 - 27 June 2013, Kuala Lumpur.

Profit Maximization of a Crude Distillation Unit

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Abstract

At the scheduling layer, a weekly decision is made to be sent to the optimization layer. Short-term scheduling decisions are implemented on a crude distillation unit to process three blends over a three week period. Operational optimization is carried out to maximize the net profit within the acceptable limits of ASTM D86 temperatures, as the product property, for all products other than the residue. A nonlinear steady state model is used to simulate a crude distillation unit later optimized using sequential quadratic programming (SQP) algorithm. Substantial increase in the profit margin throughout the implementation period was observed.

Keywords: Crude distillation unit, profit maximization, SQP

1. Introduction

Distillation processes in a refinery are considered to be one of the complicated separation processes in chemical industries. Crude distillation unit (CDU) operations for the fractionating crude have grown complex due to crude scheduling. Various global conditions along with economic crises have accounted for tightened product specifications in rising market competition.

Optimization ensures utilization of the available resources to the fullest and managing issues like energy consumption, environmental regulations and efficient raw material usage. Refineries have to deal with different types of crude oil blending to process a profitable feed to follow a scheduling strategy. Scheduling involves the loading and unloading of the crude at specific times and sequences followed by the feed to a crude distillation unit.

The refineries are required to schedule blends of different crudes to meet the market demand. Optimization in the operating conditions of a crude distillation unit is required to achieve better economic benefits. In order to shift the production towards those distillates which carry added incentives for the refiners, optimization and instant rectification of the processing conditions is required. The quality of the products needs to be analyzed by rigorous monitoring of the feed.

1.1. Profit Maximization of CDU

Objective functions based on profit along with system constraints in a refinery are generally considered to be nonlinear optimization problems. Sequential quadratic programming (SQP) has become increasingly popular amongst nonlinear optimization techniques (Wang, 2003). Diez et al. (2005) discusses the challenges and opportunities of using SQP for optimization in petroleum refineries. It was observed that SQP is suitable for constrained nonlinear problems but may perform poorly with model discontinuities. Handogo (2012) carried out profit maximization of a crude distillation unit using Aspen Plus where the preflash column furnace temperature was considered as a decision variable. ASTM D86 temperatures were taken as product quality specifications for heavy naphtha and light kerosene. More et al. (2010) inferred the sensitivity of the product flow constraints on the crude feed calculations for binary crude mixtures in a CDU where a profit function was maximized. Lopez et al. (2009) developed an optimization model of the CDU at ECOPETROL S.A. refinery with heat integration and metamodeling using PRO/II. CONOPT solver was used to carry out the optimization for the 3 atmospheric distillation units and the preheating train. Inamdar et al. (2004) optimized an industrial crude distillation unit based on Aspen HYSYS. A multi-objective optimization was taken as an objective function with coil outlet temperature, product and pumparound flowrates as the decision variables whereas the product properties were accounted as constraints. It was found that the algorithm has the ability to reduce the complexity of the problem leading to less computation time. Basak et al. (2002) deduced that significant increase in the profitability can be attained by performing online optimization of an industrial crude distillation unit. Model tuning parameters were incorporated along with the back calculation of TBP curves to simultaneously maximize the net profit by keeping the product properties within a certain range.

It can be deduced that the above literatures study the optimization of a CDU considering different process variables. It does account for the profit maximization of a CDU based on the scheduling decisions of crude blending at weekly basis. The objective of this work is to determine the benefits of implementing a three week scheduling decision at the CDU. These benefits are evaluated as the profit margin before and after optimization. A profit function considered as an objective function, comprising ten decision variables and eight constraint variables, is maximized using SQP. The test bed is a steady state crude distillation unit, where the nonlinear model equations and the SQP solver are embedded in the Aspen HYSYS 7.3 environment.

2. Methodology

2.1. Problem Formulation

The objective function for maximizing the profit of the crude distillation unit is as follows:

$$\begin{aligned} \max \text{ Profit} &= C_{p,n}F_{p,n} + C_{p,k}F_{p,k} + C_{p,d}F_{p,d} + C_{p,a}F_{p,a} + C_{p,r}F_{p,r} \\ &- C_{c,j,1}F_{c,j,1}x_{c,j,1} - C_{c,j,2}F_{c,j,2}x_{c,j,2} - C_f Q_f - C_{con}Q_{con} - C_{p1}Q_{p1} \\ &- C_{p2}Q_{p2} - C_{p3}Q_{p3} - C_{reb}Q_{reb} - C_{s,b}F_{s,b} - C_{s,ds}F_{s,ds} - C_{s,as}F_{s,as} \end{aligned} \tag{1}$$

subject to

$h_m = 0$ (∀m= material and energy balances, vapor and liquid summation and equilibrium equations)

$g_i = y_i - y_i^{\max} \le 0; \quad \forall i = 1,\ldots,4$

This nonlinear problem will be optimized by the SQP solver, built in the Aspen HYSYS environment, where; C refers to cost and F as flowrate. Annotations denote p of the products: n) naphtha, k) kerosene, d) diesel, a) AGO, and r) residue; c,j, 1 and 2 as binary crudes constituting: Bintulu, Tembungo and Bunga Kekwa. Q as duties of: f) the furnace duty, con) condenser duty, p1, 2, 3) top, middle and bottom pumparound duty, and reb) reboiler duty; and s as steam of: b) bottom steam, ds) diesel side stripper steam, and as) AGO side stripper steam streams.

The constraints ‘h’ refers to the equality constraints where m are the number of model equations to be converged. The model equations are based on equilibrium stage, comprising material and energy balances, equilibrium and summation equations, which are presented in Dave et al. (2003). These equations will be solved using Modified HYSIM technique with specified tolerances. Also, g_i is reflects the inequality constraints where y_i^{max} are the maximum limits of the ASTM D86 95% temperatures, i of the products: 1) naphtha, 2) kerosene, 3) diesel, and 4) AGO.

Ten decision variables considered for profit maximization are the top, middle and bottom pumparound (T/M/BPA) flowrates; the coil outlet temperature (COT); the main steam flowrate; four product flowrates and the reflux flowrate (RF). The COT is related to the problem as function of furnace duty:

$$f(Q_f) = (F_c, CIT, COT)$$

Where F_c is the total flowrate of the crudes blended and CIT is the coil inlet temperature at 232°C. Similar relations can be built for the pumparound flowrates with their respective duties. The constraints involve certain operational constraints in order to constitute a rigorous model. They are overflash flowrate, and pump around duties. The ASTM D86 temperature, at which 95% of the product is vaporized, is accounted as the product property constraint for the side distillates.

2.2. Case Study

The Malaysian light crudes namely Bintulu (API°: 36.0), Tembungo (API°:36.6) and Bunga Kekwa (API°:36.9) are considered. Three binary blends comprise the above crudes entering as the feed at 100 kbpd. The volume percentages are taken from Ali (2012) in which crude cut point optimization was performed using Taguchi method.

Consider a constant feed flow rate of 100 kbpd of blended crudes to be processed at the CDU. Three cases of scheduling decisions are selected as follows: Case I: the blending of Bintulu crude (42.1 vol. %) and Tembungo crude (57.9 vol. %) valued at $108.9/bbl; Case II: Bunga Kekwa crude (58.0%) and Tembungo crude (42.0%) valued at $108.3/bbl, and Case III: Bintulu crude (34.5%) and Bunga Kekwa crude (64.5%) valued at $109.0/bbl, are sequentially implemented on Weeks 1, 2 and 3.

2.3. Process briefing

Fig. 1 shows the process flow diagram for a CDU simulated in Aspen HYSYS. The diagram consists of a pre-flash unit followed by a crude distillation unit. The process for operating a crude distillation unit was described by Ali and Yusoff (2012).

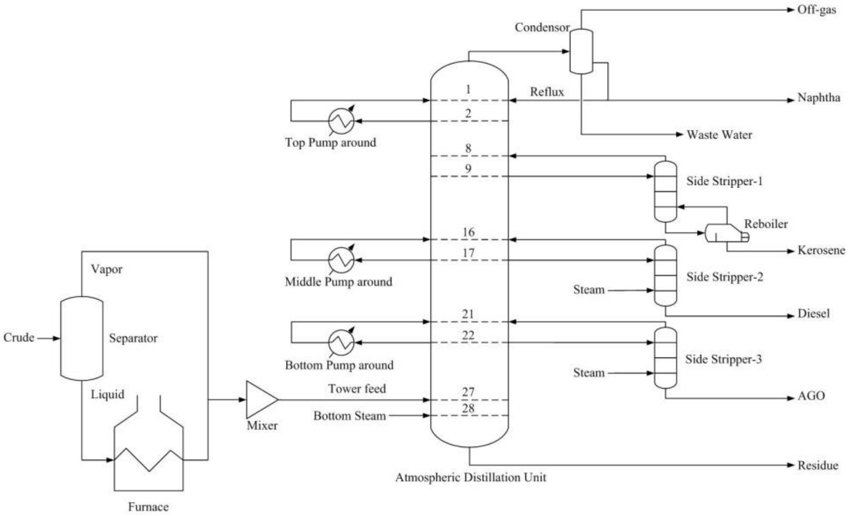

Figure 1. Process flow diagram of a CDU

3. Results and Discussion

The bounds of the selected decision variables reflect the design limitations and safety of the operating unit. The product flowrates are maintained at ±10% deviation from the base case value to avoid plant instability. The pumparound flow is varied by ±20% and the duties by ±10%. The coil outlet temperature is operated within ±5°C temperatures to avoid thermal cracking of the crude due to excess heating and to provide favorable conditions for the flash zone of the column. The temperature of the crude feed was kept between 335 and 340°C. The bottom steam varied from 0.9 to1.4 kg/bbl of stripped liquid, whereas the overflash is maintained at 3 to 5% of the feed to avoid over consumption of the utilities. The reflux ratio was kept between 1 and 3 while manipulating the reflux rate.

Tab. I show the changes of the decision variables from their respective base cases determined after optimization. The top pumparound was found to operate at a greater flowrate, for the latter cases with comparison to Case I, in order to maintain a stable energy balance. Lesser net vapor flow on the first tray was found in Case II and III as compared to Case I. This required greater flowrate to ensure efficient vapor condensation keeping the pumparound duty within the acceptable design limits. Increased vapor flow on the top tray in Case I resulted in greater liquid flow to the condenser.

Table I: Optimized Variables

	Case I		Case II		Case III	
Variables	Base	Opt	Base	Opt	Base	Opt
TPA (kbpd)	50	44.5	50	60.0	50	60
MPA (kbpd)	30	25.4	30	29.4	30	24
BPA (kbpd)	30	24.0	30	24	30	24
COT (°C)	343.3	340.6	343.3	340.6	343.3	340.6
BS (kg/hr)	3402	4082	3402	4082	3402	4802
NF (kbpd)	19.3	17.4	9.7	8.7	14.3	13.9
KF (kbpd)	15.5	17.0	11.0	12.2	11.1	12.0
DF (kbpd)	32.3	35.5	32.5	35.7	28.0	31.0
AF (kbpd)	5.3	5.8	9.2	10.1	9.0	10.0
RF (kbpd)	27.0	43.3	19.2	27.9	19.1	24.3

The rise in the reflux ratio for all the cases depicts a high reflux flowrate back into the distillation column. After optimization, the flow of the residue product was reduced by 3.3 to 4.5 kbpd for all cases. To meet the available capacity of the stocks, major portion from the residue shifted to diesel product. The diesel product has risen by 2.6 to 3.8 kbpd. Increments in kerosene and AGO flows were observed for all optimized cases maximum up to their maximum limits. Similarly, naphtha flow exhibited reduced flows to their respective minimal limits.

The steam requirement was increased to 1.14 kg per stripped product for sufficient vaporization of the liquid feed coming from the rectifying section. The steam was limited to 4082 kg/hr to avoid increased condensation of steam at the overhead temperature by maintaining equal partial pressure of steam with the vapor pressure of water. For this case a water draw-off side stream was also provided. The bottom steam flowrate increased by 7 % after optimization, which accounts for a negligible deduction from the profit for all the cases.

The optimized result also resulted in the increase of the energy cost. The furnace energy cost was considered only for heating from 232°C to COT, since crude preheating up to 232°C is achieved by heat integrated streams of the refinery. The increase in the energy cost was by 5.1 to 7.5% of the increase in the profit per week. Cases I, II and III, which represent their respective blends of crudes mentioned in Table III, reported a net profit per barrel of crude increase of $1.25, $1.30 and $1.25. Fig. 2 illustrates the profit obtained per week for each case.

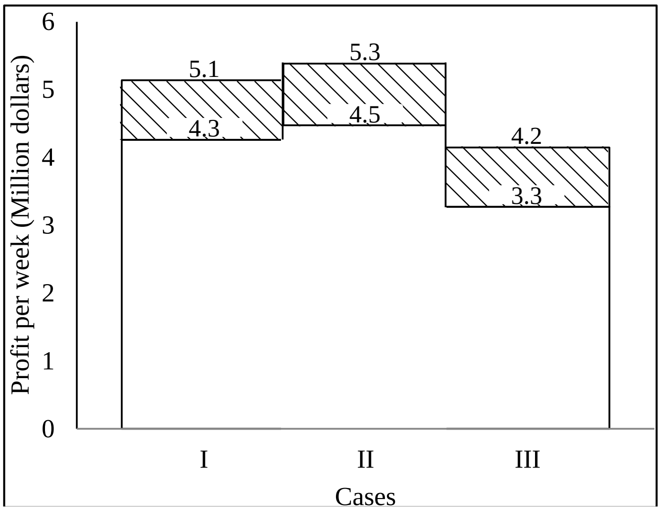

Figure 2. The benefits (▨) of implementing scheduling decisions

Fig. 2 illustrates the significant increase in profit margin, represented by the shaded region that has been obtained after carrying out optimization. The product sales have risen by 1.1 to 1.2% due to increased production of the diesel in all the cases. The base value profit, represented by the region below the shaded region, was found to be $4.3, $4.5 and $3.3 million during their respective weeks. The increase in the profit from its respective base case is presented by the shaded region. It was found to rise by $0.88, $9.1 and $0.88 million dollars for case I, II and III respectively. Before optimization, the process configuration provides a total profit of $12.0 million for the complete short-term scheduling period of 3 weeks. The profit increased to $14.7 million after optimization, thus proving the feasibility of operational optimization of the short-term scheduling strategy considered.

Case I produces greater distillates, 75% of the feed, than the other blends as the residue flowrate is quite low for its corresponding base case. Case II holds $5.3 million of the largest total profit as compared to $5.1 and $4.2 million for Case I and II respectively. Case III constitutes the least of the total profit than the other cases. On the contrary, it shows the largest percentage of the profit margin by 26.8% in comparison to 20.5% and 20.4% for case I and II respectively. At weekly basis, this optimization routine accounts for an average increase of the profit margin to $4.88 million, whereas the base cases reported a profit of $4.0 million. The product properties as ASTM D86 95% temperatures are presented in Tab. II.

Table II: Constraints

		Case I		Case II		Case III	
Constraints	Max	Base	Optimal	Base	Optimal	Base	Optimal
y_1 (°C)	180.0	151.2	142.9	156.4	148.2	145.0	142.3
y_2 (°C)	270.0	230.6	226.6	232.9	231.2	224.6	224.6
y_3 (°C)	345.0	320.8	324.4	340.6	344.6	336.2	343.6
y_4 (°C)	410.0	398.8	406.5	405.2	410.0	390.5	410.0

Here y represents the ASTM D86 95% temperature and the subscripts define the side distillates of which the flowrates were manipulated. Tab. II mostly shows an increasing trend in the product properties for the heavy distillates. The column parameters, such as pumparound duties and overflash flowrate, are not presented as they were satisfied by the optimizer. The ASTM values show that the blends fractionated each week has the potential of increasing the heavy distillates products for greater profit as compared to naphtha and kerosene downstream products.

4. Conclusion and Recommendation

Profit maximization for the weekly scheduling strategy was successfully carried out to process different crudes blended in specific proportions. Weekly average profit of $0.89 million was obtained by optimizing the scheduling decision at the operational level. Cases I, II and III are beneficial in terms of the greater total profit, distillate flow and profit margin respectively. The total profit margin for three weeks was $2.7 million higher than the base cases. Optimization for this study was carried out using all the decision variables. It is recommended to use Taguchi method, which is a parametric design technique to determine the significance of variables.

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