Determination of Optimal Cut Point Temperatures at Crude Distillation Unit using the Taguchi Method

Syed Faizan Ali , Nooryusmiza Yusoff

***Abstract*— This paper proposes a technique for optimizing crude cut points. Taguchi method is applied in the selection of the significant variables and their respective optimal levels for a fractionation process. The variables considered were the cut point temperatures of products, namely, naphtha, kerosene, light and heavy diesels, atmospheric gas oil and the residue. The variables were assigned lower and upper bounds with a difference of ± 13.9°C (± 25°F) from the standard straight-run cut points. A steady-state model of a Crude Distillation Unit (CDU)is used as a virtual plant to carry out the fractionation of 100 kilo barrels per day of crude oil. Straight-run cases comprising of three Malaysian crude oils, namely, Bunga Kekwa, Bintulu and Tembungo, were analyzed as single, binary and ternary crude feeds. In each case, an optimal configuration of variables was determined by minimizing the energy required for the production of one kilo barrel/day of diesel.**

***Index Term*-- Crude Distillation Unit, Cut-point Optimization, Diesel Production, Taguchi Method**

I. INTRODUCTION

Petroleum refineries have advanced periodically with the passage of time. Refinery operations for the creation of products such as Naphtha, Diesel, Kerosene and Gasoline have grown complex affecting the refinery profit. Limitations such as safety and environmental regulations, for maintaining plants to run at cleaner processes, are some constraints to achieve such profits [1].

Crude oil trapped in different reservoirs of the world of a specific field hold unique characteristics from one another on a physical and chemical basis [2]. The first classification of crude can be done in 'light' and 'heavy' crudes having respective importance with regard to profit extraction.

Classification of crude oil is based upon the difference in specific gravities and the proportion with which they form. Product demand is met by proportioned blending of crude. Seasonal scheduling of the crudes is carried out in order to produce optimized cuts [3]. The type of product requiring greater operating cost resulting in lesser profit is subtracted from the crude to meet the demand supply. Refineries fractionate these barrels of crude by their boiling points in order to obtain high value products such as gasoline, diesel, jet fuel, heating oil, fuel oil, lubricants, asphalt, coke, wax, and chemical feed stocks [4].

Many studies have been published related to crude distillation unit (CDU) study with reference to refinery planning and scheduling [5]-[7], estimation of product properties [8]-[9] and process control, modeling, simulation and optimization [10]-[12]. Optimization of a crude distillation unit using a binary feed was carried out on the basis of the gross profit instead of the costs inferred by energy and raw materials [10]. An atmospheric distillation unit subjected to transient behavior due to changes in the operating conditions can be improved by a suitable control strategy to obtain better operations [11]. An expert system was designed for a CDU to predict the product flow and temperature values by minimizing the model output error by genetic algorithm framework and maximizing the oil production subjected to control parameters [12].

Optimization has been previously carried out by devising a process control strategy, rigorous modeling and improved design specifications. The performance of the CDU using straight run cut points for several types of crude oil such as Tapis (44.8), Bintulu (36.0) and Terengganu (47.4) where the optimization objective was a profit function (total product value – feed cost – utility cost) using AspenTech DMC+ (an APC technology) [13]. The literature cited above deduces that the optimization based on the crude cut points have not been given much importance. Previously, straight run temperatures have been applied on every type of crude in order to optimize a crude distillation system. The objective of this article is a detailed design constituting the crude cut points to minimize the amount of energy utilized to produce a kilo-barrel per day of a product (for e.g. diesel) using optimized cut point temperatures.

This study can be regarded valuable for the operations personnel concerned with the planning and scheduling of the crude feed involving the blending of different crudes to reduce the supply-demand gap of the refinery products. It deals with a crude distillation unit modeled in Aspen HYSYS environment. The methodology devised for the crude optimization is based on a design of experiments technique known as Taguchi method. The optimization variable involved is the overall

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energy required in order to produce a kilo barrel of a product, which in this study is diesel.

Section II deals with the background study of the crude assays considered followed with the process description for simulating the process. Section III discusses the methodology of the paper formulated, initiating from the crude specification procedure in HYSYS, an overview to the Taguchi design of study and the devised case studies. In Section IV, the optimized results are outlined with emphasis on determining the cut-point recipe and shifting of TBP curves to produce such beneficial results. Finally, the last section concludes the study of this work and recommended future studies to this work.

II. BACKGROUND

A. Crude Assay

Refining engineers analyze the True Boiling Points (TBP) curves of the cuts present to determine the behavior of the crude distilled and various saleable products [14]. The crude assays considered are taken from the different fields of Malaysia namely Bintulu, Tembungo and Bunga Kekwa.

These crude assays have been obtained from the Assay manual published in December 2003 by KBC Advanced Technologies Inc. The samples date back to October 1994 (Bintulu), November 1997 (Bunga Kekwa) and October 1986 (Tembungo). With 0.5% sulfur content as a limit, sweet crude has been observed ranging from 0 to 0.08% by weight. The specific gravities and the sulfur content are shown in Tab. I:

TABLE I
CRUDE DATA

Crude Assay	API Values	Specific Gravity (15°C)	Sulfur content (wt. %)
Bintulu	36.0	0.8445	0.020
Tembungo	36.6	0.8415	0.064
Bunga Kekwa	36.9	0.8400	0.049

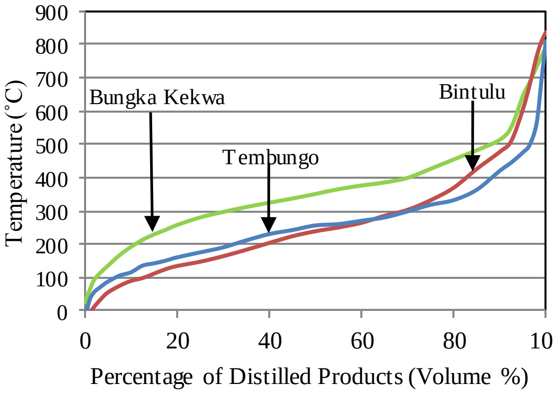


Fig. 1. True boiling point curves

From the HYSYS oil manager, the straight run analyses yield 25.6% diesel from Bintulu crude, 37.6% from Tembungo crude and 29.1% from the Bunga Kekwa crude; thus indicating that the Tembungo crude produces more diesel as compared to other two crudes. Fig. 1 shows that Bintulu and Tembungo have comparable TBP profiles whereas Bunga Kekwa crude comprises heavier components.

B. Process description

Fig. 2 shows the process flow diagram for a CDU simulated in Aspen HYSYS. The diagram consists of a pre-flash unit followed by a CDU. The feed to the CDU is preheated in a furnace.

Crude oil at a rate of 100 kilo barrel per day (kBPD) is fed to the pre-flash tower at a temperature of 232.2°C and a pressure 517.1 kPa. The pre-flash tower is responsible for separating the crude vapors and liquid entering into the crude column as a bottom feed. This is carried out to reduce the duty of the furnace to devise an economical process [15].

The furnace feed is the bottom product of the pre-flash tower operating at a pressure drop of 68.95 kPa with the crude being heated to 343.6°C. As shown in Fig. 2 the column consists of 29 stages with a partial condenser, three side strippers and three pumparounds. The heated crude is sent to in the tray 28. Side strippers comprising 3 stages have been utilized for diesel and atmospheric gas oil (AGO). Fractionation is increased by reducing the partial pressures with the aid of steam and a reboiler for Kerosene. The pressure drop of the CDU is 62.05 kPa with a top and bottom stage pressure of 144.8 kPa and 255.5 kPa, respectively. Internal reflux has been ensured by the installation of three pumparounds as in Tab II (A).

TABLE II (A)
PUMP AROUND SPECIFICATIONS

Pumparound	Location between trays	Duty (kW)	Flow (kBPD)
PA-1	1 and 2	-16,124	50
PA-2	16 and 17	-10,258	30
PA-3	21 and 22	-10,258	30

TABLE II (B)
SIDESTRIPPER SPECIFICATIONS

Side Stripper	Location between trays	Stripped by	Flow / Duty
SS-1	8 and 9	Reboiler	2199 kW
SS-2	16 and 17	Steam	1361 kg/hr
SS-3	21 and 22	Steam	1134 kg/hr

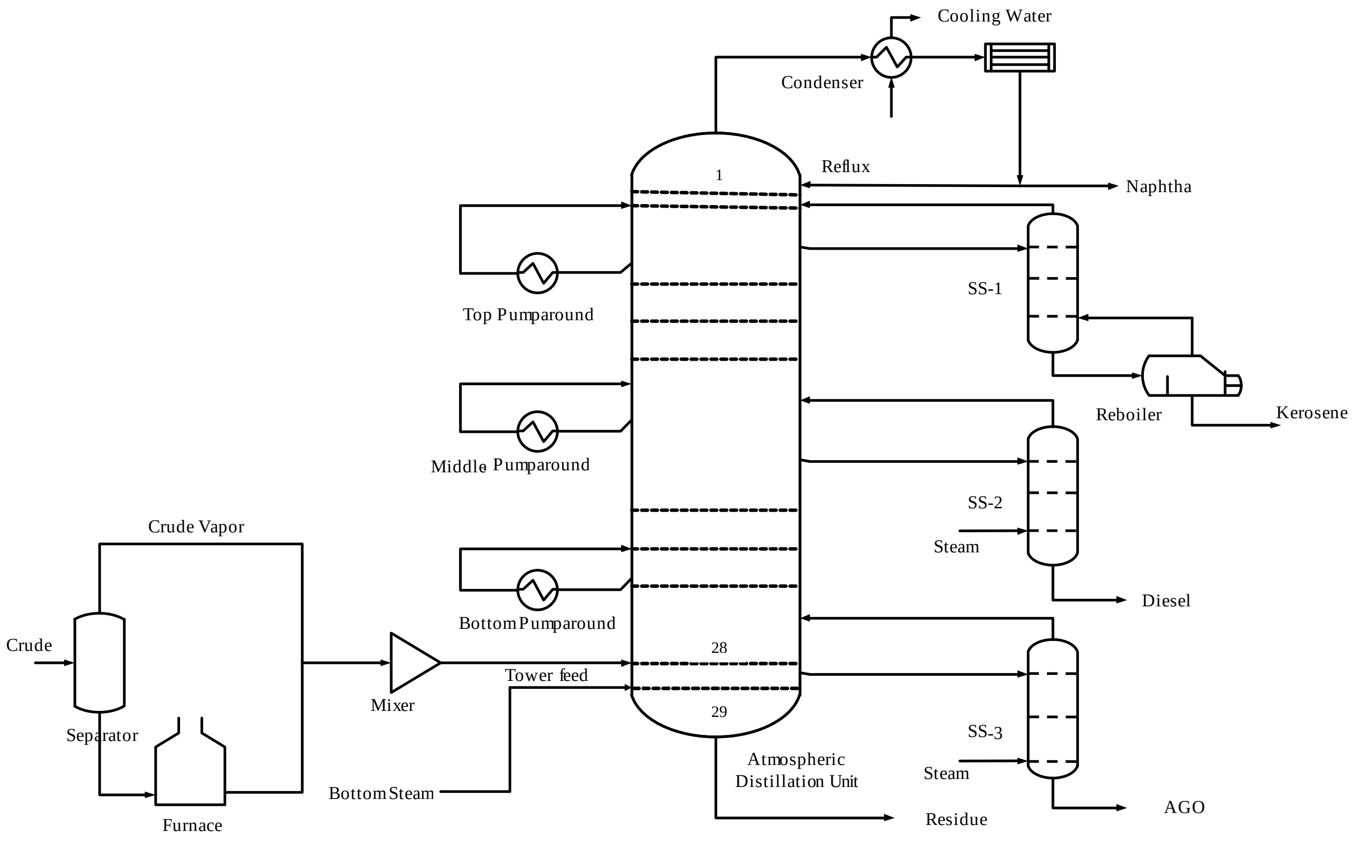


Fig. 2. Process Flow Diagram of CDU

The partial condenser is operated at a pressure of 135.83 kPa with waste water as the side product. The distillate (naphtha) rate is maintained at 20 to 25 kBPD. The reflux ratio is fixed at 1.7 corresponding to a reflux flow rate of 34 to 42 kBPD. The bottom steam entering at tray 28 is exchanging heat twice, i.e. absorbing heat from the liquid flowing down the trays and then exchanging heat with the upward flowing vapors, entered at a rate 3402 kg/hr at 190.6˚C and 1034 kPa. The over flash is specified at the tray 27 with 3.5% of the feed.

Straight run analyses have been carried out to determine the volume percent of the distilled products namely Off-gas, Naphtha, Kerosene, Diesel, AGO and Residue. These products are further subjected to physical and chemical separation processes for better quality in, for example; the vacuum distillation unit (VDU), fluid catalytic cracking unit (FCCU) and hydrocracker. The summary of the process configuration is shown in the Tab. III.

TABLE III
CDU SPECIFICATIONS

Parameter	Value
No. of ideal trays	29
Temperature	169.2˚C (top stage) 355.6˚C (bottom stage)
Pressure	144.8 kPa (top stage) 255.5 kPa (bottom stage)
No. of pumparounds	3
No. of side strippers	3
Feed rate	100 kBPD
Feed Location	Tray 28
Feed Temperature	343.6˚C
Feed Pressure	448.2 kPa
Reflux ratio	1.7
Condenser type	Partial Condenser

III. METHODOLOGY

A. *HYSYS Crude Specification*

In HYSYS, components and the thermodynamic fluid package (Peng-Robinson) are defined to create the simulation basis. In HYSYS Oil manager characterizes the crude assay to generate the hypothetical components with their respective physical and critical properties. The correlations and calculations performed in the oil manager are all in accordance with the API technical data book.

The crude assay is defined with the TBP assay type to generate an internal TBP curve at atmospheric conditions for the characterization method. The assay definition is based on the API gravity, distillation data and the input composition of the components from Methane- Pentane (C_1-C_5). However, sulfur contents are not specified in this work. The extreme ends of the distillation TBP curve are extrapolated.

Aspen HYSYS calculates the blend of a single or multiple crudes with their respective flow rates defined. The numbers of cuts are defined using the values for boiling point ranges as shown in the Tab. IV. It generates the hypothetical components on the ‘light ends free’ basis to obtain more accurate results. Half of the crude is fractionated into the cuts ranging from gas oil to a low boiling point gas. Initial boiling point (IBP) has been determined as a weighted average boiling point from the components present in the first volume percent if the distilled crude. The boiling points of these components are utilized as 1% of the IBP and 98% of the final boiling point (FBP). The FBP is determined similarly using the components found from 98-100% of the distilled crude. Later the assay is distributed by specifying the cut input information before it can be installed into the simulation environment.

The calculation of the energy per diesel product flow has been carried out by considering the pure energy streams entering and exiting into the system and not by the energy withheld by the material streams, thus only accounting for the energy consumption due to utilities only.

TABLE IV
TBP RANGES AND CUTS[6]

TBP range	ΔT	No. of cuts
< 38°C (<100°F)		Pentanes and Lighter
38 – 427°C (100-800°F)	14 °C	28
427 – 649°C (800-1200°F)	28 °C	8
649 – 871 °C (1200-1600°F)	56 °C	4

B. *Taguchi Method*

Taguchi design is a statistical technique to optimize the process design problems in different engineering disciplines. It implies the formation of a layout of the experiments by the combination of factors to obtain the number of tests to be performed. Besides Taguchi method, the factorial design methods are also utilized to examine the combination of factors involved to arrive at the best product. It has certain shortfalls with respect to the number of parameters involved, which are as follows:

- Time consuming and costly
- Different outputs of the different configuration of the same experiment
- Influence of factors cannot be determined

Taguchi method is considered as an off-line optimization method for the designing of system from the parameters involved. System design can be considered as the formation of the experiments on the basis the engineering principles employed and process limitations. Parametric design determines the optimum state due to the design factors at a specific point.

In the beginning, Taguchi design has been only used in the manufacturing sector to devise the most economical way of building equipments with the best performance. Later it evolved and proved quite helpful in the process industry to characterize the performance of an operation and has been proven highly effective in order to study the effects of the multiple factors involved and the influence of the factors on the performance of an experiment.

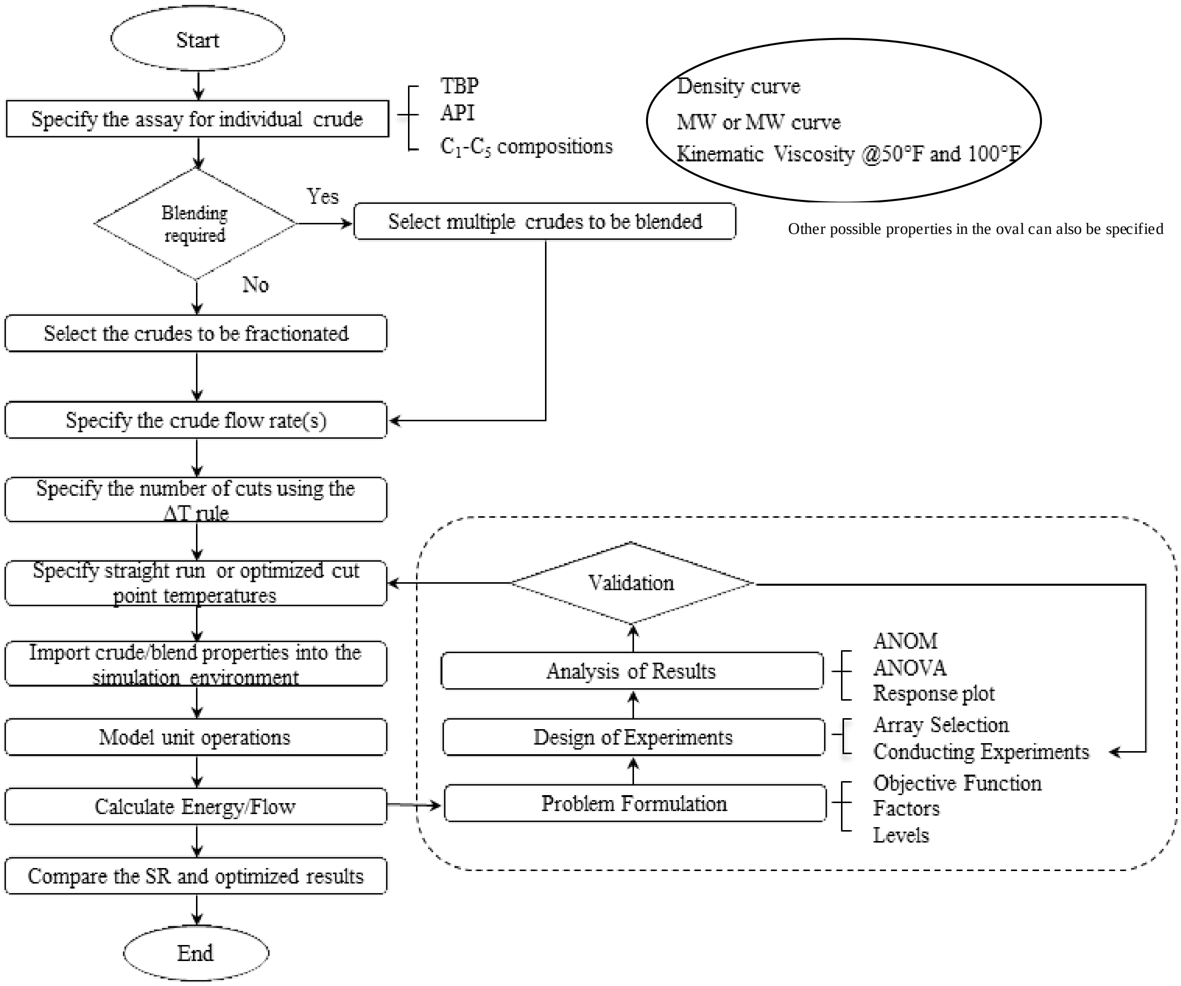
Reliable results can be obtained via standard tables known as orthogonal arrays which are helpful in designing the experiments. The factors represent the design parameters that influence the performance whereas levels are the values by which an experiment is conducted. With two levels of factors the behavior is fundamentally assumed to be linear where the non-linear response can be observed with the latter levels [16].

Taguchi method is used for the selection of optimization variables to minimize the energy consumption in crude distillation unit [17]. A systematic procedure was designed for the selection of optimization variables in a refrigerated gas plant (RGP), later validated on HYSYS, and showed noteworthy concurrence amongst all cases [18]. It was proposed that the concentration of a surfactant, zeolite bed height and flow rate of the waste water are the significant factors in detecting color removal from textile dye bath effluents in a zeolite fixed bed reactor [19].

The consistency of the performance is analyzed by determining the effects of the factors involved and obtaining the optimum configuration for the best performance by analysis of means (ANOM) or analysis of variance (ANOVA). The model factors are found by calculating the Signal to Noise (S/N) ratio or weight factors to come up with a robust design [20]. The measured result of these experiments constitutes a quality characteristic which in this case is the minimum energy requirement for the unit production of diesel.

In the current research, Taguchi method has been used to devise a recipe for increased diesel production in a crude oil as in Fig. 3. The objective (Eqn. 1) is to select the optimal cut point temperatures for maximizing diesel yield at the lowest energy utilization. In this case, 3 levels namely nominal as well as lower and upper bounds have been considered.

$$\frac{\text{Energy}}{\text{Diesel Product Flow}} = \frac{E}{V} \tag{1}$$



Other possible properties in the oval can also be specified

Fig. 3. Proposed methodology cut point optimization

The experiments to be conducted using the proposed methodology are designed using the Taguchi method explained below;

1) Design of Experiments

Since the model of CDU is based on first principles, the significance of the factors involved can be systematically established through Taguchi method. The next step is the designing of experiments and simulating them on HYSYS. The selection of standard orthogonal array is based on the number of factors and the levels involved. Three levels have been considered because Aspen HYSYS calculates the blend using the following Tab. III for boiling point ranges with their designated number of cuts. Since the cut points fall in the range of the 426.7°C, therefore the difference of the upper and lower bounds from the reference cut points has been taken as 13.9°C (25°F).

For 8 factors and 3 levels, an L_{18} array is selected as shown in the Tab. V. The rows and columns represent the test runs and factors involved respectively.

TABLE V
ARRAY SELECTOR[21]

		Number of Factors								
		2	3	4	5	6	7	8	9	10
Number of Levels	2	L4	L4	L8	L8	L8	L8	L12	L12	L12
	3	L9	L9	L9	L18	L18	L18	L18	L27	L27
	4	L’16	L’16	L’16	L’16	L’32	L’32	L’32	L’32	L’32
	5	L25	L25	L25	L25	L25	L50	L50	L50	L50

Note: ‘apostrophe accounts for the modified arrays from the standard ones.

Since three crudes are involved, the number of case studies is seven ($2^3-1=7$). It is noteworthy that only 18 experiments needs to be conducted as in Tab. VI, for each of the 7 runs in order to determine the responses of the 8 factors involved. Therefore, a total of 126 experiments need to be carried out. This is more beneficial and easy as compared to $7 \times (3^7) + 7 \times (2^1) = 15,323$ experiments designed by full factorial design approach.

TABLE VI
L_{18} ARRAY

Experiments	T1	T2	T3	T4	T5	T6	T7	T8
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	3	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

2) *Analysis of Results*

The final step is the analysis of results with the help of the statistical means such as ANOM and ANOVA, averages of factor k at level l in case m, $\bar{x}_{kl}^{m}$ is taken as sum of respective factorial values.

$$\bar{x}_{kl}^{m} = \sum \bar{x}_{kl}^{m} \qquad \forall k=1,\ldots,K;\ \forall l=1,\ \ldots,\ L;\ \forall m=1,\ \ldots,\ M \tag{2}$$

Where;

K= 7 and L=3 are correspondingly numbers of factors and levels.

Average of factor k in each case m, x_k is calculated as:

$$\bar{x}_{kl}^{m} = \sum_{kl}^{L} \bar{x}_{kl}^{m}\, l;\ \forall k = 1,\ldots,K \tag{3}$$

These two averages are used to calculate V_k^m . The denominator is called degrees of freedom of factor k over all levels L in case m, $(DOF)_k^m$.

$$V_k^m = \frac{\sum_{l=1}(\bar{x}_{kl}^{m} - \bar{x}_{kl}^{m})^2}{(DOF)_k^m} \tag{4}$$

Percentage contribution C_k^m is determined as follows:

$$C_k^m = \frac{100\, V_k^m}{\sum\limits_{k=1}(V_k^m)};\ \forall k = 1,\ldots,K \tag{5}$$

The validation of the optimized recipe obtained is based upon the ANOM and the ANOVA rankings. If the rankings are in compliance with each other, an optimized run is performed subjected to the optimal configuration of the cut point temperatures to calculate the objective function for a respective case.

C. *Case Studies*

The cases considered for the optimization of the CDU are:

- Single crude: Bintulu (Case I), Tembungo (Case II) and Bunga Kekwa (Case III)
- Binary crudes: Bintulu–Tembungo (Case IV), Tembungo–Bunga Kekwa (Case V) and Bunga Kekwa–Bintulu (Case VI)
- Ternary crudes: Bintulu-Tembungo–Bunga Kekwa (Case VII)

The amount of different flow rates calculated for crude blending is based on the ratio of the diesel production of the crudes considered in order to produce maximum amount of diesel. From the straight run analysis of the different crudes that Tembungo was found to be the best crude for diesel production followed by Bunga Kekwa and Bintulu.

IV. RESULTS AND DISCUSSIONS

The simulations have been performed using specifications such as product flow rate constraints and duties of condenser, pumparounds and reboiler. All experiments are conducted using steady-state model developed under HYSYS environment. Consistency has been maintained in the units prior to the calculations. The experiments are conducted using the default cut point temperatures in the HYSYS environment as shown in the Tab. VII. The temperature difference between the cuts in Tab. IV is considered as a reference for setting the lower and the upper bound for the experiments.

TABLE VII
CUT POINT TEMPERATURES AND VALUES AT EACH LEVEL

Products	Factor	S.R Cut points (˚C)	Level 1 (˚C)	Level 2 (˚C)	Level 3 (˚C)
Off-gas	A	10	10	23.9	-
Light S.R	B	70	56	70	84
Naphtha	C	180	166	180	194
Kerosene	D	240	226	240	254
Light Diesel	E	290	276	290	304
Heavy Diesel	F	340	326	340	354
Atmospheric Gas Oil	G	370	356	370	384
Residue	H	1200	1144.5	1175	1200

Note: S.R: Straight run method

These cut-point temperatures are used to predict the amount of extract of the petroleum fraction to be made, and define the pseudo component as midpoint normal boiling point (NBP).

A. *Taguchi Results*

For the base case, the objective function values (Eq. 1) are 1714.8, 2646.2, 1762.3, 2146.8, 2321.3, 2003.3 and 2191.2 in kW/kBPD. To calculate the optimal recipe, the factors are ranked using the analysis of mean (ANOM) results. This way the significance of factors can be determined. Eqs. (2) and (3) are used to calculate the averages of the factors k which are ranked from 1 to 9.The ranking is based on the difference of the lowest from the global mean. This difference is noted as D_k, where highest value of D_k is assigned the highest ranking.

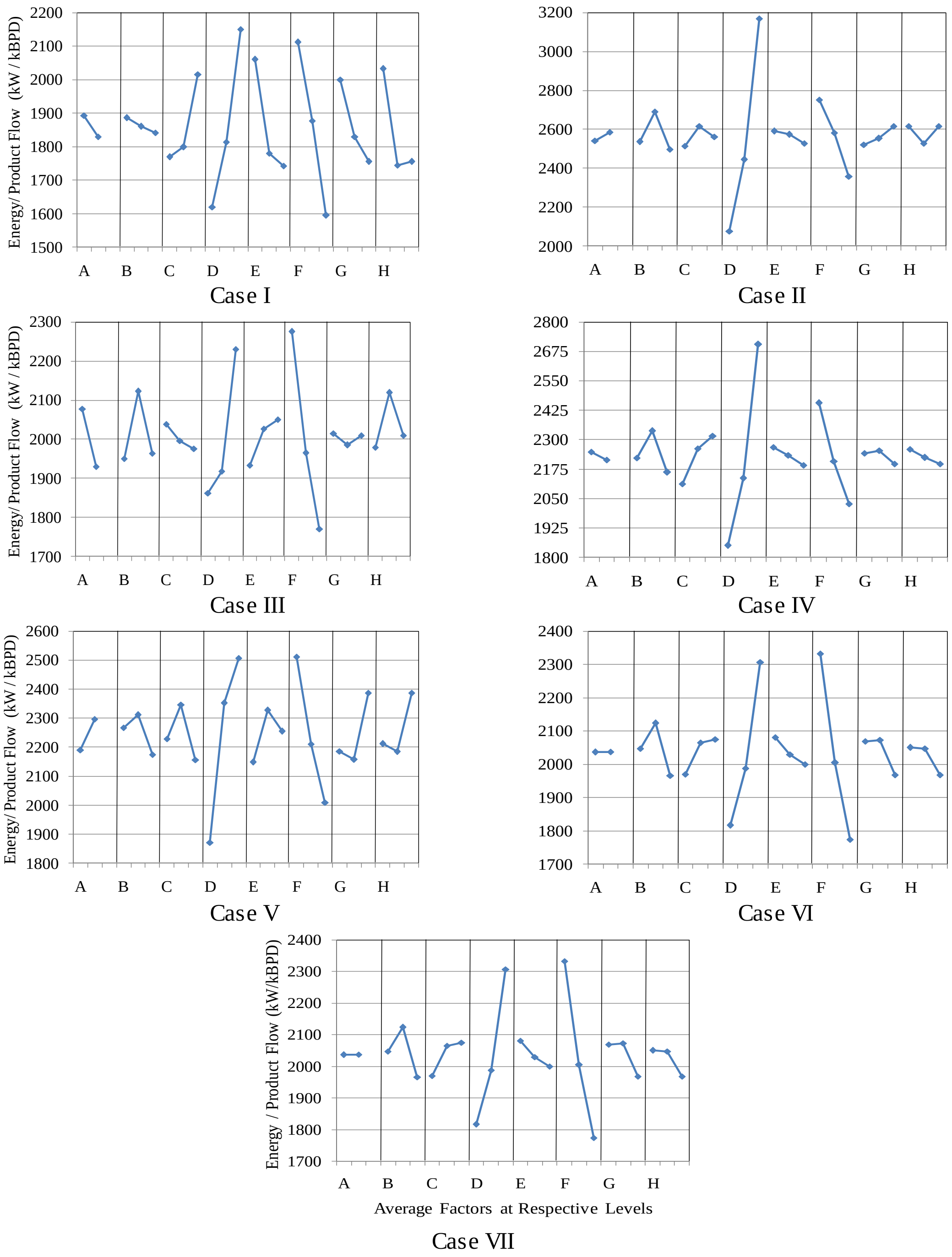


Fig. 4. Response plots for Cases: (I) Tembungo, (II) Bintulu, (III) Bunga Kekwa, (IV) Tembungo – Bintulu, (V) Tembungo – Bunga Kekwa, (VI) Bunga Kekwa – Bintulu, (VII) Tembungo – Bintulu – Bunga Kekwa

Ranking from ANOM is verified from the (analysis of variance) ANOVA results. The sum of the squares of the factor involved, represent the variation of the experimental result from the data average where the larger value represents a significant factor and vice versa. The degree of freedom $(DOF)_k$ is calculated to be one less than the number of levels. It is used to obtain the population variance of all the possible experiments. Finally, the relative important factor k is indicated with regard to the percentage contribution.

The optimal configuration of the cut point temperatures was based upon the 'the lower the better' principle of quality through averaged energy/product response plots. Thus, another set of experiments subjected to the optimal configuration has been performed known as the optimized run. Optimal recipe shown in Fig. 4 infer that steep slopes can reveal the significance of the factors involved. The steeper the slope the more significant a variable is. The averages of the energy/product flow (kW/kBPD) are based upon the ANOM results. The optimal configuration of the cut point temperatures are shown in Tab. VIII.

TABLE VIII
RECIPE FOR OPTIMUM DIESEL YIELD

Cases	Recipe							
Factors	A	B	C	D	E	F	G	H
Base Case	1	2	2	2	2	2	2	3
I	1	3	1	1	3	3	3	2
II	1	3	1	1	3	3	1	2
III	2	3	1	1	1	3	1	1
IV	2	3	1	1	3	3	3	3
V	1	3	3	1	1	3	2	2
VI	1	3	1	1	3	3	3	3
VII	2	3	1	1	3	3	1	3

Tab. VIII shows great deal of consistency from a specific level involved of the factors B, D, and F. These factors correspond to cut point temperatures of the light straight run, kerosene and heavy diesel, respectively. The contributing factors calculated from the ANOM results revealed that only the cut-point temperature of kerosene and heavy diesel are responsible for the optimization of diesel in a crude distillation unit. This can also be validated from the steepness of the slopes shown by the two factors. The shifting of the levels caused the diesel range to expand much wider as compared to their base cases. The final boiling point of the kerosene cut was reduced and for heavy diesel it increased. This resulted in the higher production of diesel resulting and the vapors climbing up to the condenser discharged much greater energy from the system.

The minimum value of energy/product flow (kW/kBPD) for the optimum configuration for the all the cases was calculated after conducting simulation of similar process configuration but different cut-points as shown in Tab. VII. Thorough inspection of the above configuration reveal that the optimum recipe of the Case I and II are alike except factor G which switches from level 3 to 1. This trend is observed due to the fact that the TBP curves for Bintulu and Tembungo are quite alike. And later in their TBP curves they deviate from one another, thus causing the switching of the level G. Similarly Case VI also comprises of identical level of factors with Case I except for factor H which changes from level 2 to 3. The resemblance of these two cases deduces an interesting point that Case I has the best optimum value in the category of single crude feed. Similarly, Case VI shows the finest results amongst binary crude feed in terms of energy utilization for a kilo-barrel of production. On the contrary Case II reflects higher objective function because the straight run analysis of Bintulu crude produced the lowest amount of diesel production in comparison to the other two crudes.

B. *Cases Studies*

The global means for the cases of single crude feed (I, II and III) were 1861.2, 2563.8 and 2003.2, respectively, in the unit of kW/kBPD. The diesel production increased up by 6.9, 7.4 and 8.9 kBPD respectively. For optimal runs in Cases I and II the energy usage was reduced by 32.4% and 22.9%, respectively. Case III reported an increase by 25.5% from its straight run analysis as shown in the Fig. 5.

The global mean for the binary crude feed Cases (IV, V and VI) were found to be 2230.3, 2243.3 and 2036.9 respectively in kW/kBPD. As for the ternary crude feed (Case VII), the objective function was calculated as 2256 kW/kBPD from the 18 experiments performed. The diesel yield was also increased by 7.5kBPD because the usage of such crude feed to a comparatively greater federate as compared to the others. This ratio was calculated on the basis of the S.R analysis of the single crude feed. Tembungo crude was kept 27.3% and 27.5% higher than Bintulu and Bunga Kekwa respectively. Bunga Kekwa feed was kept 47.5% higher than Bintulu to produce greater diesel.

According to the HYSYS oil manager, the first two cases have shown commendable increase in the light diesel fraction. The remaining of the cases notified a greater increase in the heavy diesel fraction as compared to the light diesel fraction off the entire diesel production.

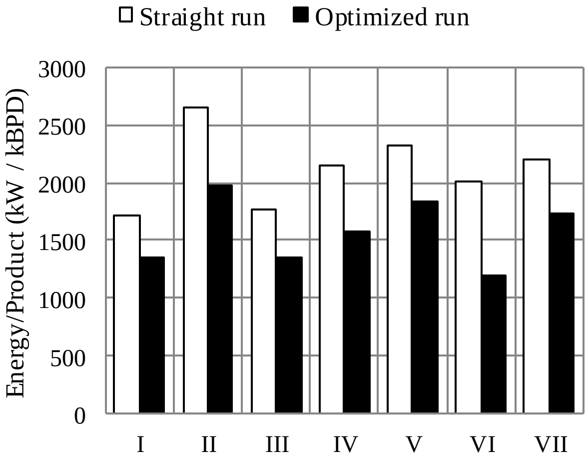


Fig. 5. Trends of energy requirement for a barrel of product for various case studies

Since diesel is fractionated through n-cetane, it is recognized with its cetane index, which is a measure of its knocking tendency. The cetane index has been kept within a range of 49 to 55 with the percentage change to its corresponding straight run is Tab. VII.

The pour points for the diesel stream were estimated using the ASTM D97 method. The pour points for the straight run experiments are reported in Tab. XI along with the temperature deviation of the optimized runs with their respective straight runs.

Some experiments indicated reduced AGO flow rates depicting that a major portion of the AGO cut has been shifted to the diesel yield as shown in the Fig. 6 below.

TABLE XI
RESULTS FOR OPTIMIZED RUNS

Cases	I	II	III	IV	V	VI	VII
Optimized run Energy/Barrel of Product (kW/kBPD)	1352.6	1972.8	1358.2	1572.6	1842.3	1187.4	1729.2
Percent Optimized (%)	21.1	25.4	22.9	26.7	20.6	40.7	21.1
S.R Cetane Index C.I (ΔC.I%)	52.07 (-0.71)	48.59 (-1.2)	50.08(-0.8)	52.12 (-0.7)	52.95 (0.3)	53.33 (-0.5)	53.52 (0.4)
S.R ASTM D97 Pour point ˚C (ΔP.P)	-6.37 (-1.1)	-20.05 (-0.8)	25.2 (-1.0)	-13.16 (0.5)	14.06 (0.9)	11.58 (-0.8)	6.10 (1.7)

Note: ΔC.I% = Percentage difference of the Cetane index; ΔP.P = Difference of Pour point values within straight and optimized run

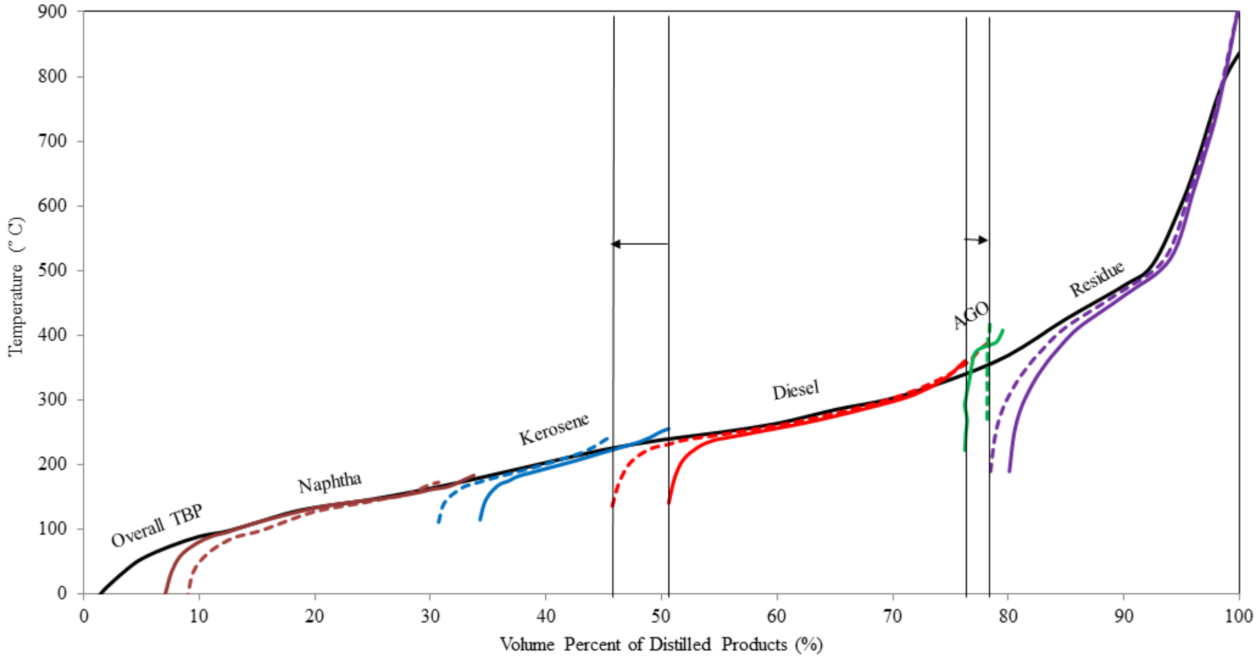


Fig. 6. Curve Shifting of Bintulu Crude: Straight run (—) v/s Optimized run (----)

For Case II, the increase in the diesel production is observed due to shifting of all the product TBP curves. As shown in Fig. 6, diesel range has expanded both ways by extracting 4.9 kBPD from Kerosene and 1.9 kBPD from AGO. Shift in the IBP of diesel from 140.9˚C to 136.3˚C and FBP 360.6˚C to 387.4˚C resulted in a greater lighter fraction of diesel.

The increase of the diesel TBP curve was up to 6.8 kBPD as compared to the straight run product TBP curve. The shift from the dashed line to the solid line can be observed in each of the product against the overall TBP curve to the optimized product configuration.

CONCLUSION

The fractionation of light crudes and their blends have been optimized by manipulating 8 cut-point temperatures. In general, the utilization of Taguchi method has increased the diesel production whilst decreasing energy consumption. The optimized recipes were significantly different from their respective base cases. The optimal recipes of all cases showed that 20 to 41% benefits can be achieved as compared to straight run temperatures. Two factors namely D and F, i.e., the cut points of Kerosene and Heavy Diesel, respectively, are significant for the optimization of the objective function.

NOMENCLATURE

Abbreviations

API	American Petroleum Institute
AGO	Atmospheric Gas Oil
ANOM	Analysis of Means
ANOVA	Analysis of Variance
CDU	Crude Distillation Unit

BPD	Barrels per day
FBP	Final Boiling Point
FCCU	Fluid Catalytic Cracker Unit
IBP	Initial Boiling Point
TBP	True Boiling Point
NBP	Normal Boiling Point
VDU	Vacuum Distillation Unit

Variables

C_k^m	Percentage contribution of factor *k* in case *m* (%)
D_k	Difference between the lowest and the global mean
$(\mathrm{DOF})_\mathrm{k}^\mathrm{m}$	Degree of Freedom at level *k* in each case *m*
k	Number of factors
K	Total number of factors
kW	kilo Watt
l	Number of levels
L	Total number of levels
m	Number of experiments in an array
M	Total number of experiments
V_k^m	Variance of factor *k* at level *l*
$\bar{x}_{kl}^m$	Average of objective function value due to factor *k* at level *l* in each case *m*
x_k^m	Average of objective function value due to factor *k* over all levels *L* in each case *m*
x^m	Average of objective function value in each case *m*

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