Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 14 (22): 3070-3076, 2014
ISSN 1812-5654 / DOI: 10.3923/jas.2014.3070.3076

Taguchi's Parametric Design Approach for Determining the Significant Decision Variables in a Condensate Fractionation Unit

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Abstract: Taguchi method is used as an experimental design to efficiently determine the significant decision variables and their respective optimal levels contributing towards the most profitable operating mode of a Condensate Fractionation Unit (CFU). The present study aims to reduce the frequent optimization issues such as high market dynamics in term of fluctuation of price of condensate feedstock and products as well as the difficulties in determining the decisive variables for effective implementation of optimization strategy. For this purpose, a steady-state CFU model developed under HYSYS environment is used as a virtual plant to carry out the fractionation processes. Experiments are executed by utilizing the combination of process parameters (nine controllable and two noise factors) based on three-level of L_{27} and L_9 Taguchi orthogonal array with the help of analysis of mean, analysis of variance, signal-to-noise ratio analysis and response plots as the analytical tools. Maximum CFU profit can be obtained from an optimal configuration of both controllable and noise factors and this unique configuration is run in HYSYS for validation. Agreements are found in the results from HYSYS experiments with the calculated optimum profit values and the improved profit further verifies the optimality of configuration.

Key words: Condensate fractionation unit, Taguchi method refinerus, crude oil

INTRODUCTION

Refineries are a complex network of processes which convert crude oil into a range of refined products through a sequence of physical and chemical transformations. In the study, instead of crude oil, condensate feedstock is used in a Condensate Fractionation Unit (CFU) to produce refined products such as Liquefied Petroleum Gas (LPG), kerosene, light naphtha (LHN), heavy naphtha (HVN) and diesel. The hydrocarbons of condensate are similar to the crude oil except naphtha fraction in the condensate is much larger than that of the ordinary crude oil. Also, there is no heaviest product such as bitumen produced from the condensate.

All the refining profits heavily rely on producing finished products that yield the highest margins from the lowest crude oil whilst maintaining the optimum plant operating efficiency. The task remained challenging due to the frequent fluctuation of market price of petroleum products and the time-varying nature of condensate feedstock flow rates. Such challenges can be handled through Real Time Optimization (RTO). Hence, a systematic method in determining the significant decision variables is needed for the effective implementation of optimization strategy and this can be achieved through Taguchi method.

Numerous researchers have shown the successful implementations of Taguchi design in various engineering disciplines in selection of optimization. Yusoff *et al.* (2011) studied the Taguchi's parametric design approach for the selection of optimization variables in a Refrigerated Gas Plant (RGP) with the objective to determine the maximum RGP profit. The author used a dynamic model of RGP under HYSYS environment as test bed to perform the simulation. Seven controllable and two noise factors were studied in L_{27} and L_9 orthogonal arrays, respectively. Statistical tools like signal-to-noise ratio (SNR) and analysis of variance (ANOVA) were used to analyze the results. Three controllable factors were found to be the most influential parameters in reducing the energy utilization, namely the SRC103 and TC101 output where higher values of these factors enhanced the controlling of temperature while TC102 ensure a smooth separation of feed gas.

Two similar studies in determining the optimum conditions to remove dyes using the Taguchi method

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were done by Engin *et al.* (2008) and Barman *et al.* (2011). Orthogonal array L_{16} and L_{25} were employed to study effects of process parameters such as concentration, contact time, temperature and pH level towards the optimum dyes removal conditions, respectively. Both the results showed certain degree of agreement in which the concentration factor has the biggest contribution towards the dyes removal process. Ali and Yusoff (2012) applied Taguchi method in his study for the determination of optimal cut point temperature at Crude Distillation Unit (CDU). The author employed the Taguchi method to select the optimal cut point temperatures for maximizing the diesel yield at the lowest possible energy utilization. An L_{18} orthogonal array was selected to study a total of 8 factors and 3 levels. The results revealed that the cut-point temperatures of kerosene and heavy diesel are the most significant factors contributing towards the optimization of diesel in CDU.

In this study, Taguchi method for the design of experiment, SNR and statistical tools such as ANOM and ANOVA are applied to determine the significant decision variables in CFU. Taguchi crossed-orthogonal experiments employing L_{27} internal and L_9 external arrays are performed on the steady-state CFU model in HYSYS to investigate the influences of 9 controllable and 2 noise factors at 3-levels each on the maximization of CFU profit.

CFU PROCESS

A steady-state model of the Condensate Fractionation Unit (CFU) under HYSYS environment is developed and utilized as a test bed for the Taguchi Design of Experiment (DOE). The Process Flow Diagram (PFD) of this model is shown in Fig. 1. The CFU is designed to fractionate condensate into valuable products such as LNG, kerosene, LHN, HVN and diesel. Condensate will be heated up before entering the Condensate fractionator column C-101. In C-101, wild naphtha will be stripped off overhead and kerosene will be separated as side draw to kerosene stripper column C-102. Bottom product which is diesel will be routed to storage while the overhead wild naphtha will be routed to the naphtha stabilizer column C-103 where the LPG will be separated overhead and petrochemical naphtha (PCN) which consists of LHN and HVN at the bottom. The LPG will be sent to LPG sphere for storage. The PCN from the bottom of C-103 will be separated to LHN and HVN stream in the Naphtha Splitter Column C-104. Here, LHN will be removed overhead while HVN will be removed at the bottom. Products will be sent to storage. A plant model usually contains huge number of variables available for manipulation. Hence, for an effective implementation of optimization strategy, proper selection of optimization

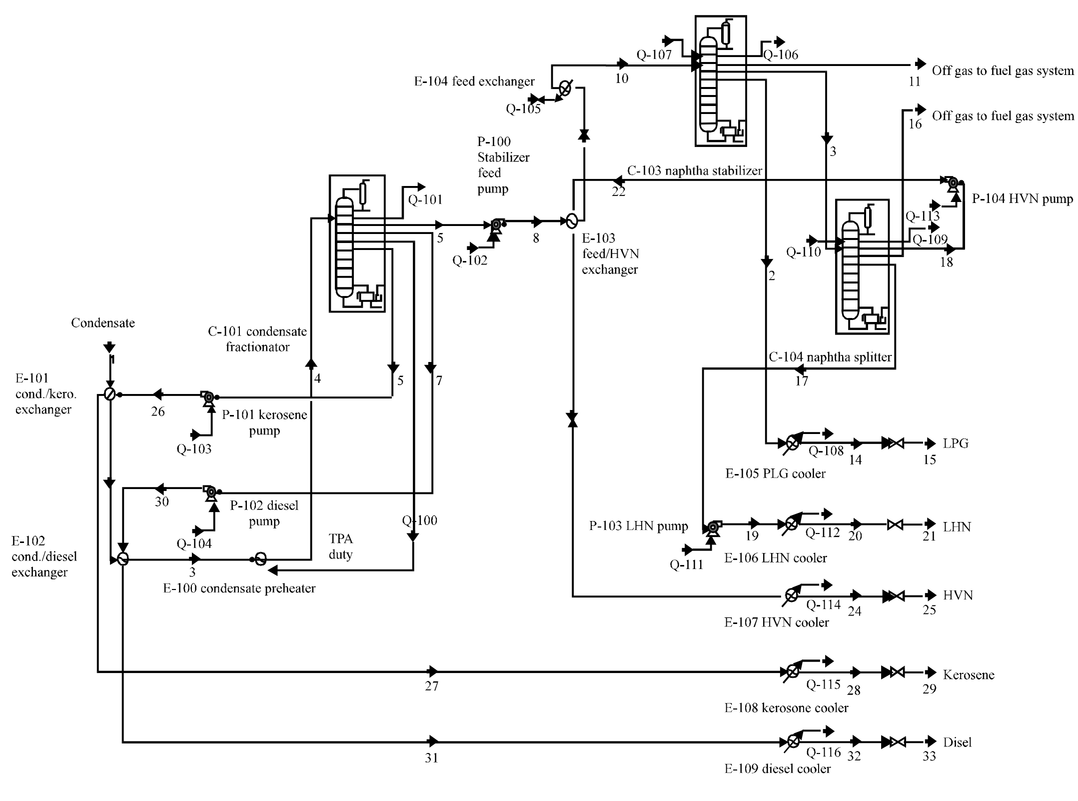

Fig. 1: CFU process flow diagram

variables which are significant towards the process optimization is essential. This task may be performed using the Taguchi method.

TAGUCHI METHOD

Taguchi's parametric design is a powerful statistical method to produce high quality product and optimize the process design problems in a cost efficient way by reducing process variation through robust design of experiments. The consistency of process performance can be achieved by making a system insensitive towards the influences of various uncontrollable factors (Roy, 2001). Herein lays Taguchi's contribution to the discipline and structure to the design of experiments. It offers an alternative solution where the conventional factorial design is simplified into a unique methodology involved the establishment of a series of experiments through the balanced characteristic of orthogonal array, a unique icon of Taguchi method, to identify the optimum combination of the parameters which has the most influence on the performance and least variance from the targeted design standard (Yang *et al*., 2007). Taguchi method can be used an off-line optimization technique where it involves a three-stage process, namely, system design, parametric design and tolerance design. In current study, parametric design is employed to obtain the optimum level of process parameters leading to maximum plant profit. The terms namely, parameters, variables and factors are synonyms used throughout this study. Factors can be categorized into controllable and noise factor. The former is used to manipulate the process while the latter is used to evaluate the degree of severity of their effects to the desired process.

A case study: The methodology devised for the optimization of the economic performance in the current study is based on the Taguchi method and the flow diagram is illustrated in Fig. 2. The first step is the problem formulation where the objective function, factors and levels are defined. The objective function (Eq. 1) is to achieve the highest profit based on the identification of significant decision variables and their optimal configurations:

$$P = \sum_{i=1}^{I} R_i - C_{Feed} - C_{Utilities} \quad (1)$$

where, P is the profit, R_i (I = 5) are the revenues, C_{Feed} is the cost of condensate feed and $C_{Utilities}$ is the operational expenses. Product values are the sales of refined products such as LPG, LHN, HVN, kerosene and diesel. The operational expenses are mainly due to the cost of utilities. The economics data which comprises of prices and corresponding units of the component of revenues and expenses is shown in Table 1.

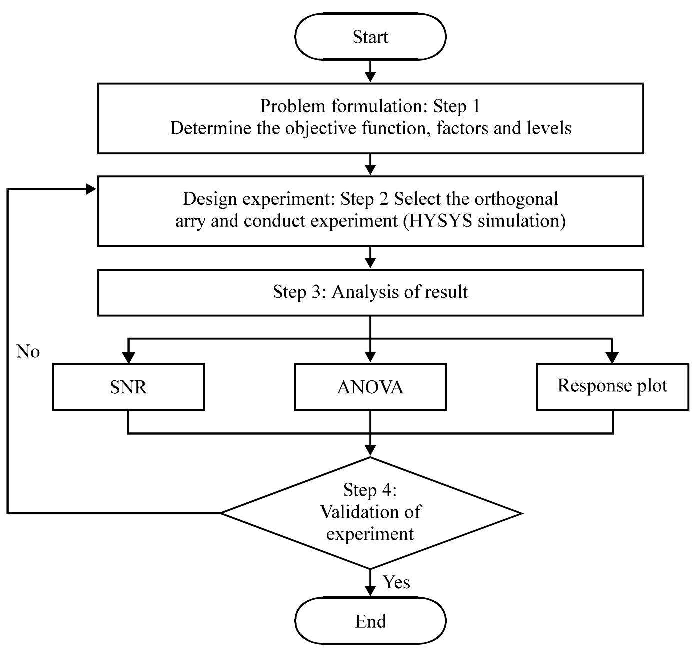

Fig. 2: Flow diagram of taguchi method

Table 1: Economics data

Component	Price (RM kg^{-1})	Utility	Price (RM/MWh)
Condensate	2.49	Steam duty	89.90
LPG	2.54	Electricity	233.30
LHN	2.83		
HVN	2.74		
Kerosene	3.37		
Diesel	2.96		

Table 2: Description of factors and levels for CFU

	Levels			
Factors	1	2	3	Description
A (°C)	122.00	124.00	126.00	C-101 stage 28 temperature
B (°C)	304.00	306.00	308.00	C-101 bottom stage temperature
C (kg h^{-1})	23139.00	25710.00	28281.00	C-102 kerosene prod. Flow rate
D (kg h^{-1})	288900.00	321000.00	353100.00	C-101 top pump-around flow rate
E (°C)	83.00	84.00	85.00	C-103 top stage temperature
F (kPa)	1137.00	1177.00	1217.00	C-103 top stage pressure
G (°C)	150.40	151.40	152.40	C-104 bottom stage temperature
H (°C)	80.07	81.07	82.07	C-104 top stage temperature
I (kPa)	103.40	106.40	109.40	C-104 top stage pressure
J (kg h^{-1})	330338.00	347724.00	365110.00	Condensate flow rate
K (RM kg^{-1})	2.42	2.49	2.56	Condensate price

For the selection of controllable and noise factors as well as the levels (low, medium and high values), inputs from experienced operators are essential. There are nine controllable factors (A to I) and two noise factors (J and K) selected in the current study. Description of factors and levels for CFU is given in Table 2.

The Taguchi method involves designing and conducting experiments. An L_{27} (3^9) orthogonal design made up of 9 controllable factors and 3-levels is used as the internal array whereas, an L_9 (3^2) design made up of 2 noise factors and 3-levels is used as the external array. Based on the Taguchi's DOE, only 27 experiments from the internal array required to be conducted for each runs from the external array. Thus, a total of 243 (=27×9) experiments are required to be executed. A conventional full factorial design approach requires 19, 683 (3^9) experiments. In order to measure and study the simultaneous effects of all the 9 controllable factors under the influences of the 2 noise factors towards the objective function, Case Study function in HYSYS Data Book is used. It enables the selection and manipulation of both the independent and dependent variables simultaneously.

Two average values namely the average of factor k at level l in Case m, $\bar{x}^m_{kl}$ and the average of factor k over all levels l in each Case m, $\bar{x}^m_k$ are required to be calculated during the ANOM and ANOVA:

$$\bar{x}^m_{kl} = \frac{1}{N_R}\sum_{n=1}^{N_R} x^{mn}_{kl} \quad (2)$$

$$\bar{x}^m_k = \frac{1}{L}\sum_{l=1}^{L} \bar{x}^m_{kl} \quad (3)$$

where, N = 27 and M = 9 are the number of runs in the internal and external array, respectively and N_R = 9, k = 9 and L = 3 are correspondingly the number of repeated levels, factors and levels. Variance V_k^m can be calculated as follow:

$$V^m_k = \frac{\sum_{l=1}^{L}(\bar{x}^m_{kl} - \bar{x}^m_k)^2}{L^m_k - 1} \quad (4)$$

In ANOVA, the percentage contribution C^m_k can be calculated according to Eq. 5:

$$C^m_k = \frac{100V^m_k}{\sum_{k=1}^{K} V^m_k} \quad (5)$$

Out of the 243 experiments conducted based on the crossed-orthogonal arrays of L_{27} and L_9, only one run will yield the highest profit margin. A response plot constructed from the average values of profit of factor k at levels l = 1, 2 and 3 against the corresponding controllable factors can be used to determine the optimal configuration of factors contributing towards the highest profit margin. In addition, it can also provide preliminary visual assessment of trends in terms of steepness of slopes for the average contributions of individual factors at all levels. Optimum profit in Case m, x^m_{opt} is calculated through the summation of global mean, $\bar{x}^m$ for the same case with maximum differences of average values of factor k at level l, $\bar{x}^m_{kl}$ from the corresponding average values at all levels, $\bar{x}^m_k$ (Yusoff *et al*., 2011):

$$x^m_{opt} = \bar{x}^m + \left(\sum_{k=1}^{K} \max\left(\bar{x}^m_{kl}\right) - \bar{x}^m_k\right) \quad (6)$$

RESULTS AND DISCUSSION

All experiments are conducted using the CFU steady-state model developed under HYSYS environment. The output of the experiments is in term of production flow rates. The objective function (Eq. 1) is employed to obtain the profit value. Results of the cross-orthogonal arrays are presented in Table 3. The profit is presented in the expression of x^{nm} where, m = 1,..., 9 and n = 1,..., 27 represent the external and internal runs, respectively. Cases m = 1,...,9 are categorized as Group I (cases 1-3), Group II (cases 4-6) and Group III (cases 7-9) in the following discussion due to their similarity in term of noise factors configuration (factor l, plant load and factor k, condensate feed prices).

Effects of noise factors: Global means for Cases 1, 2 and 3 (Group I) are 110108, 86984 and 63861 RM h^{-1}, respectively. For Cases 4, 5 and 6 (Group II), the global means are 115265, 90924 and 66584 RM h^{-1} whereas, the global means for Cases 7, 8 and 9 (Group III) are 120414, 94856 and 69299 RM h^{-1}, respectively. Means for Group I (cases 1, 2 and 3), Group II (cases 4, 5 and 6) and Group III (cases 7, 8 and 9) are 86984, 90924 and 94856 RM h^{-1}, respectively. It is noteworthy that a difference of about 4000 RM h^{-1} is noticed between Groups I and II and between Groups II and III.

This difference is caused by the presence of noise factor 1 (plant load). The amount of condensate feed increases when the plant load is increased which further contribute towards a greater CFU profit due to the additional production of LPG, LHN, HVN, Kerosene and Diesel products. However, a higher amount of condensate feed will cause the equipment loads to reach the upper constraints whereas under loading is undesirable as the CFU profit will decrease and the fractionation operation will become economically unfeasible. On the other hand, the effect of noise factor K which is the condensate feed price can also be deduced. It is noteworthy that the highest values of average profit in each Groups I, II and III are generated from K_1 (factor K, level 1) configuration. This is caused by the different economic values of the condensate feed. Highly priced condensate feed decreases the CFU profit while the cheaper one increases it.

Averaged profit analysis: For the CFU averaged profit analysis, means values of profit from Cases 1-9 are calculated in a row-by-row basis (Yang *et al*., 2007). Equation 2 and 3 are employed in order to calculate the averages of factors k. The highest ranking is given to a factor with the highest deviation, E_k value. The results indicated that the order of importance in a descending sequence is ACHIGDFBE. Ranking from ANOM is

Table 3: Results of Taguchi cross-orthogonal array experiments

	Profits ('000 RM h^{-1})									
Run	x^{1n}	x^{2n}	x^{3n}	x^{4n}	x^{5n}	x^{6n}	x^{7n}	x^{8n}	x^{9n}	$\bar{x}^{n}$
1	109.1	98.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4
2	109.0	98.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4
3	110.8	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6
4	106.9	98.1	98.1	98.1	98.1	98.1	98.1	98.1	98.1	98.1
5	108.7	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3	98.3
6	107.4	98.2	98.2	98.2	98.2	98.2	98.2	98.2	98.2	98.2
7	110.7	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6
8	110.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6
9	110.9	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6
10	107.8	98.2	98.2	98.2	98.2	98.2	98.2	98.2	98.2	98.2
11	109.5	98.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4
12	109.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4
13	111.4	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6
14	111.8	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7
15	110.1	98.5	98.5	98.5	98.5	98.5	98.5	98.5	98.5	98.5
16	112.5	98.8	98.8	98.8	98.8	98.8	98.8	98.8	98.8	98.8
17	110.3	98.5	98.5	98.5	98.5	98.5	98.5	98.5	98.5	98.5
18	109.1	98.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4	98.4
19	112.4	98.8	98.8	98.8	98.8	98.8	98.8	98.8	98.8	98.8
20	109.8	98.5	98.5	98.5	98.5	98.5	98.5	98.5	98.5	98.5
21	112.7	98.8	98.8	98.8	98.8	98.8	98.8	98.8	98.8	98.8
22	112.3	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7
23	111.1	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6
24	106.8	98.1	98.1	98.1	98.1	98.1	98.1	98.1	98.1	98.1
25	109.7	98.5	98.5	98.5	98.5	98.5	98.5	98.5	98.5	98.5
26	111.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7
27	110.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6
Mean	110.1	87.0	63.9	115.3	90.9	66.6	120.4	94.9	69.3	90.9

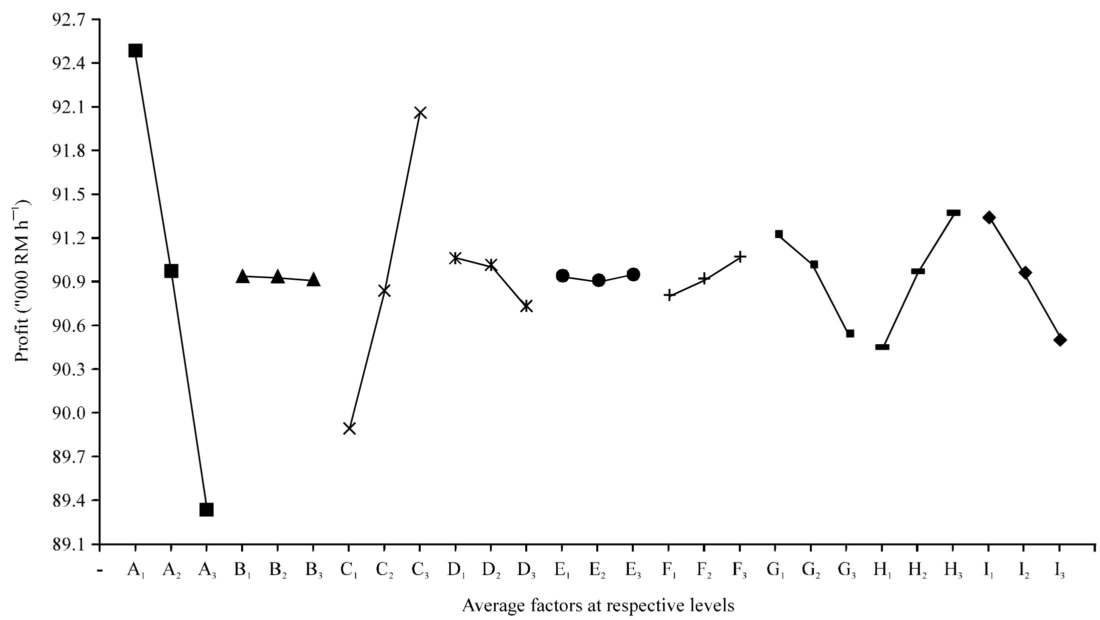

Fig. 3: Response plot for averaged profit analysis

Table 4: Analysis of variance for average profit

Parameters	A	B	C	D	E	F	G	H	I
$(DOF)_k$	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
V_k ('000)	2494.00	0.1923	1178.00	32.72	0.5275	16.76	122.80	213.90	175.20
C_k	58.90	0.00	27.83	0.77	0.01	0.40	2.90	5.05	4.14
R_k	1.00	9.00	2.00	6.00	8.00	7.00	5.00	3.00	4.00

verified with ranking from ANOVA. Percentage contribution, C_k^m calculated from variance, V_k^m is used to determine the significance of factors. A factor with the highest value of C_k^m is the most important factor. Ranking of factors based on ANOVA is presented in Table 4. The descending order of importance of the 9 controllable factors is ACHIGDFEB. The results are found similar to the one obtained from ANOM except for the last two factors, in which E and B switch places.

Results of ANOM and ANOVA indicate that factors A, C, H, I and G are contributing to the maximization of CFU profit. Factor A (58.9%) deals with the controlling of C-101 top-stage temperature in which it affects the rate of production of wild naphtha, kerosene and diesel. Effect of factor C is also significant with 27.8% contribution. It deals with the kerosene flow rate constraint. Kerosene has the highest economic value among the 5 refined products. An increase in factor C increases the kerosene production which further contributing towards a higher profit. Factor H, I and G has a contribution of 5.1, 4.1 and 2.9%, respectively. The factors are employed to manipulate the operating temperature and pressure of C-104 which bring variation in term of LHN and HVN production flow rates. In contrast, the effects of factor B, D, E and F are found trivial with a percentage contribution of 0.005, 0.77, 0.01 and 0.39%, respectively.

Validation: Maximum profit could be obtained from the configuration A_1 B_1 C_3 D_1 E_3 F_3 G_1 H_3 I_1 based on the response plot (Fig. 3) of averaged profit analysis. This optimal configuration is run in HYSYS for validation. Additional 9 runs of experiments are required to compare the experimental and calculated values of profit at optimum configuration (Table 5). In this study, small deviation values of less than 1% for all Cases 1-9 are obtained. This indicates that the optimal configuration of controllable factors for all the Cases 1-9 is successfully found.

In addition, optimal configuration of noise factors can also be deduced from the global means of profit in all Cases 1-9. Based on the 243 experiments conducted, configuration J_3 K_1 in Run 21 Case 7 yields a maximum profit of 123155 RM h^{-1}. Combined with the configuration of noise factors J_3 K_1 from the previous results, the optimal configuration of both controllable and noise factors is A_1 B_1 C_3 D_1 E_3 F_3 G_1 H_3 I_1 J_3 K_1 which yields the highest profit of 124248 RM h^{-1}.

Table 5: CFU profits at optimal conditions

Case	Validation run ('000 RM h^{-1})	Optimum profit from ANOM ('000 RM h^{-1})	Deviation (%)
1	113.71	114.11	0.35
2	90.58	90.98	0.44
3	67.46	67.86	0.59
4	119.00	119.40	0.34
5	94.66	95.06	0.42
6	70.32	70.72	0.57
7	124.25	124.67	0.34
8	98.69	99.11	0.42
9	73.13	73.55	0.57

CONCLUSION

Significance of 9 controllable and 2 noise factors influencing the CFU profit is studied by conducting 243 experiments in a Taguchi crossed-orthogonal array set up. The results showed that 5 controllable factors handling the pressure, temperature and production flow rate top the ranked list with a total percentage contribution of 98.2% while the contribution of the other four factors are found trivial. Maximum CFU profit can be acquired from an optimum configuration of both controllable and noise factors based on the response plots of the averaged profit and SNR. The results of validation are compared with the calculated optimum profits. Remarkable agreements with an average deviation of 0.45% are found in all Cases 1-9 and the improved profit further verifies the optimality of configuration. As a conclusion, Taguchi method has a great potential application in the highly competitive and dynamic oil and gas industry due to its robustness of performance in handling the noise factors and minimum amount of experiment which helps saving up time and resources.

REFERENCES

Ali, S.F. and N. Yusoff, 2012. Determination of optimal cut point temperatures at crude distillation unit using the Taguchi method. Int. J. Eng. Technol., 12: 36-46.

Barman, G., A. Kumar and P. Khare, 2011. Removal of Congo red by carbonized low-cost adsorbents: Process parameter optimization using a Taguchi experimental design. J. Chem. Eng. Data, 56: 4102-4108.

Engin, A.B., O. Ozdemir, M. Turan and A.Z. Turan, 2008. Color removal from textile dyebath effluents in a zeolite fixed bed reactor: Determination of optimum process conditions using Taguchi method. J. Hazard. Mater., 159: 348-353.

Roy, R.K., 2001. Design of Experiments using the Taguchi Approach: 16 Steps to Product and Process Improvement. Johan Willey and Sons, ISBN: 0471361011, New York.

Yang, K., E.C. Teo and F.K. Fuss, 2007. Application of taguchi method in optimization of cervical ring cage. J. Biomech., 40: 3251-3256.

Yusoff, N., M. Ramasamy and S. Yusup, 2011. Taguchi's parametric design approach for the selection of optimization variables in a refrigerated gas plant. Chem. Eng. Res. Design, 89: 665-675.