A Hybrid Approach for Cutpoint Temperatures Optimization of Crude Distillation Unit

By

Muhammad Amin Durrani

School of Chemical and Materials Engineering (SCME)

National University of Sciences and Technology (NUST)

2017

A Hybrid Approach for Cutpoint Temperatures Optimization of Crude Distillation Unit

Name: **Muhammad Amin Durrani**
Regn No: **NUST201362346MSCME67813F**

This work is submitted as a MS thesis in partial fulfillment of the requirement for the degree of

MS in Chemical Engineering

Supervisor Name: Dr. Iftikhar Ahmad

School of Chemical and Materials Engineering (SCME)
National University of Sciences and Technology (NUST)
August, 2017

This thesis is dedicated to my parents, my wife and my daughter

For their endless love, support and encouragement

Acknowledgement

Praise is due to **ALLAH** whose worth cannot be described by speakers, whose bounties cannot be counted by calculators, whom the height of intellectual courage cannot appreciate, and the divings of understanding cannot reach; He for whose description no limit has been laid down, no eulogy exists, no time is ordained and no duration is fixed.

I would like to acknowledge and express my sincere gratitude to my research **supervisor, Dr. Iftikhar Ahmad** and **co-supervisor, Dr. Arshad Hussain** for their endless support, supervision and affectionate guidance to steer me in the right direction whenever they thought I needed it. I would also like to extend my gratitude to **committee members; Dr. Muhammad Ahsan** and **Dr. Muhammad Zubair** for their valuable suggestions and guidance.

I would also like to thank **Dr. Muhammad Mujahid** (Principal School of Chemical and Materials Engineering) and **Dr. Arshad Hussain** (HOD Department of Chemical Engineering) for providing a research oriented platform to effectively utilize my skills in accomplishing this research work.

In the end, I must express my very profound gratitude to my parents, my wife and my loving daughter for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

Muhammad Amin Durrani

Abstract

Fractionation of crude oil in crude distillation unit (CDU) is an energy intensive process. It is carried out on the basis of cutpoint temperatures, i.e., the tray temperature of the CDU at which a product stream is separated. Rigorous optimization of cutpoint temperature is required for the unceasing scheduling of the feed where a substantial amount of energy in utilities is wasted. In this study, a novel optimization approach is proposed for the cutpoint temperatures optimization by hybridization of Taguchi and Genetic Algorithm. An Aspen HYSYS flowsheet is develop for CDU for three Pakistani crudes, i.e. Bobi, Kunnar and Zamzama. Optimization is carried out on lowering the energy consumption per unit production product, diesel. The proposed mechanism comprises of two phases; at first phase, Taguchi method is applied to optimize the cutpoint temperature followed by application of Genetic Algorithm for further optimization.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

Energy has become the irrefutable key ingredient in all spheres of a modern world; from transport to infrastructure, information technology, agriculture, household, etc. Prosperity and growth of any nation greatly rely on an uninterrupted energy supply. Demand of energy positively correlates with economic progress in a country. Due to the instability in prices coupled with the limited sources of energy production, there is an inevitable supply and demand gap. Therefore, the need for low-cost energy production is essential. Responding to the challenge of energy deficit a multifaceted approach is required. One key task is to increase resource efficiency and productivity, innovation also plays a key role. There is also recent growth observed in the renewable energy sector, mostly utilizing the wind and solar power. Even still, fossil fuels remain the dominant power sources.

Energy efficient design and operation of industrial processes has always been the focus of researchers due to the uncertain future of energy resources. Crude distillation unit (CDU) also called atmospheric distillation unit is one of the industrial processes which consumes energy and requires energy efficient processing. Crude distillation is a fractionation or separation process that splits up different constituents of crude oil on the basis of the difference in their volatility and boiling points. It is one of the most energy intensive processes where fractionation of various products, i.e. naphtha, kerosene, diesel, AGO, etc., is carried out. According to a report published by U.S. Department of Energy in June 2015, with applied research and development, there is a potential of saving 208 Trillion BTUs of energy annually alone in this distillation process. One way to save energy in CDU is to involve the optimization of cutpoint temperature. Cutpoint temperatures are the tray temperatures at which the product streams are separated. The cutpoints heavily depend on the crude composition and are therefore optimized whenever a new crude blend is incorporated into the feed. However, the manual tuning/optimization of cutpoint temperature becomes difficult due to the continuous scheduling of the feed crude blend, and a substantial amount of energy generated from utilities is lost. For realizing energy efficient operation of the distillation column, optimization of cutpoint temperature has been the focus of research.

A crude oil refinery or a petroleum refinery is a unit operation and industrial process which refines and processes crude oil into its various useful petroleum products like

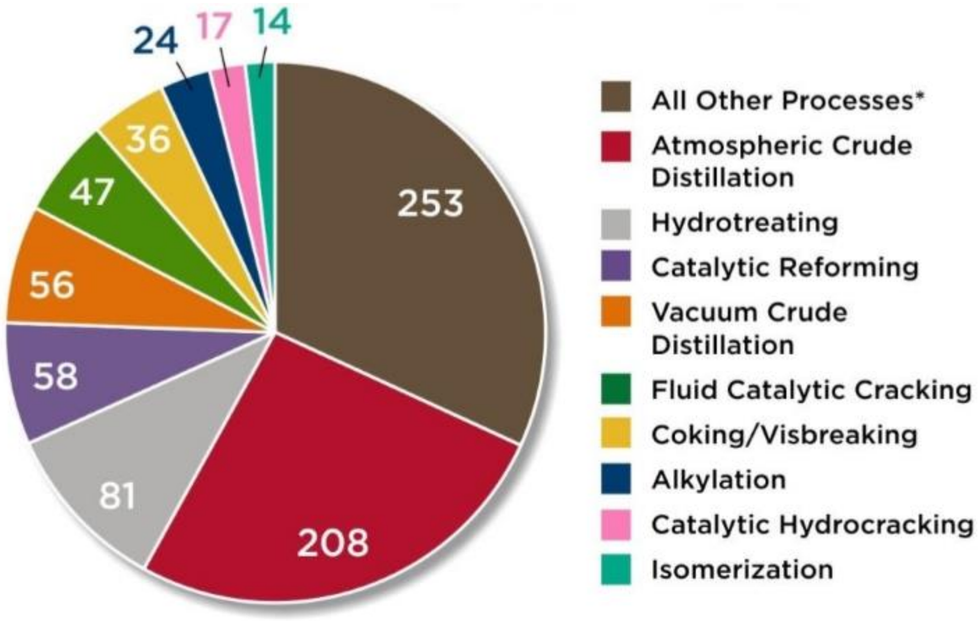


Figure 1.1: Energy Saving Opportunities by Petroleum Refining Process Studies (Energy Savings Per Year in Trillion BTUs) *(Source: U.S. Department of Energy 2015)*

liquefied petroleum gas, naphtha, diesel, kerosene, gas oil, etc. Petroleum refineries usually consist of large industrial complexes with widespread pipes across the refinery, transporting fluids streams around the refinery complex. Petroleum refinery has an important role in downstream processes in a petroleum industry.

The 1st step in a petroleum refinery is preprocessing of the crude oil. Afterwards, the fractionation of the crude oil takes place in the crude distillation unit (CDU). The initial cuts of crude oil are fractionated and are transported for further processing while contaminants of the crude oil are removed and discarded.

The yield is analyzed by evaluating the cutpoint temperatures. Performance of the standard measurements used in the evaluation of the crude assay is linked to the cutpoint temperatures. Cutpoint is a measure of unit yield. Cutpoint is the TBP (ASTM D2892) distillation temperature in which a same split between distillate products and residue products is achieved. D2892 distillations are reported in atmospheric equivalent temperature. Either weight percent or volume percent can be used; However, the most common practice plots distillation data versus volume percent distilled.

The difference in the specific gravities and difference in the proportion of formation of the crude oil determines the type of crude oil. Blending of crude oil in different proportions helps in fulfilling the various product demands. Optimization of the cuts can be attained by the seasonal scheduling of the crude oils. To meet demand supply shortfall, the products which have lesser profits and higher operating costs are removed from the crude oil [1]. Scheduling of the crude blend in refineries is a common routine. Every time when the scheduling takes place, the cutpoint temperatures are required to be tuned/optimized according to the type of crude fed to the CDU. Usually, the cutpoints vary from case to case because of the change in their properties and characteristics.

The main idea of this research is to develop an optimized model to reduce the cost of the refinery by reducing the amount of the energy required to produce a kilo barrel of diesel yield per day by optimizing its cutpoint temperatures.

This research holds importance for the petroleum refineries and the concerned refinery authorities who are responsible for the seasonal scheduling and planning of the crude blends for minimizing the demand-supply gap of the petroleum products. An Aspen HYSYS® model is employed for the purpose of crude oil distillation. The methodology followed is the drafting of experiments using Taguchi method followed by employing a much-optimized technique of hybridization of Taguchi and Genetic Algorithm (GA). Optimization is carried out by involving the total energy (kW) required to produce a kilo barrel of diesel yield per day (kBPD).

Recently there has been a lot of development going on in the industries especially the petroleum refinery industry. Crude oil that is extracted from various oil wells around the world possesses distinct properties and characteristics and are either classified as light oil or heavy oil. The light oil carries more lighter components and requires lesser energy to process which reduces the production cost of the refinery. The heavy oil on the contrary carries more of the heavier components and utilizes more energy to produce the required products.

Crude oil can also be categorized upon its specific gravity or API gravity. Specific gravity refers to the density ratio of crude oil to the density of a reference crude while API Gravity refers to the measurement of how heavy or light a petroleum liquid is compared to water. Crude oil with an API gravity higher than 31° are known as lighter oil, between 22° to 31° are known as medium light, between 10° to 22° API heavy and below 10° are the heavier oils [2]. Crude oil having API gravity between 40° to 45° is the lightest crude oil and is hence expensive than the rest of crudes. Above 45°, the molecular chains become shorter and are less valuable to the refineries.

The range of products of the refineries that are extracted via the distillation of the crude oil includes light off-gases, gasoline, diesel, jet fuel, heating oil, fuel oil, lubricants, asphalt, coke, wax, and chemical feed stocks. The cost of crude oil distillation is dependent on the number of valuable products that are produced from it and the energy expended to extract these products.

In a refinery, the energy is required and consumed in order to run the pumps, furnaces, desalters, heat exchangers, vacuums, heat and boil up the crude so that the products can be extracted at different stages in the distillation column at their respective boiling points.

1.2 Thesis Outline

Chapter 1 lays the basic motivation and background of the research work. Basic theoretical concepts of crude distillation process and literature review are discussed in Chapter 2. This chapter also includes a summary of research work already carried out for the development of CDU model and optimization tools along with the objectives of this research. Flowsheet development of CDU process in Aspen HYSYS® along with description model development has been discussed in Chapter 3. In Chapter 4 the current optimization methods and the proposed methodology for hybridization are discussed. Results are discussed in Chapter 5 while the conclusion of the thesis is discussed in Chapter 6.

Chapter 2

Theoretical Backgrounds, Literature Survey and Objectives

2.1 Theoretical Background

2.1.1 Crude Oil Definition

Crude oil is a mixture of various hydrocarbons which is naturally found deep under the ground. Crude oil upon heating in a fractionation column can be refined to various fuels and valuable petroleum products like liquefied petroleum gas, diesel, naphtha, kerosene, jet fuels and a variety of other petrochemical products. Crude oils are often named to the place of origin from where it belongs. Crude oils vary from region to region due to their contents and classified according to the difference of its specific gravity which is also known as their unit weight.

2.1.2 Cutpoint

Cutpoint temperatures are the tray temperatures at which the product streams are separated. The temperature gradient inside CDU varies at each tray with lowest temperature at the top and highest temperature at the bottom of the fractionation unit. The temperature of the tray from which the fractionate or product is extracted is termed as its cutpoint temperature. Cutpoint temperature plays a significant role in the consistency of the production of the yield, i.e., naphtha, kerosene, gas oils, residues, etc. The yield of specific cuts are calculated by its cutpoints which are the temperature on crude oil cumulative TBP curve. ASTM D-2892 standard is used to define the True Boiling Point (TBP) and is a reliable method to characterize the crude oil and crude blends in terms of their boiling point distributions [3]. Cuts on TBP curves helps in determining the behavior of the crude oil and is therefore widely used by the refinery engineers.

For obtaining the TBP curve, ASTM D2892 distillations are reported in atmospheric equivalent temperature. Either weight percent or volume percent can be used; However, the most common practice plots distillation data versus volume percent distilled.

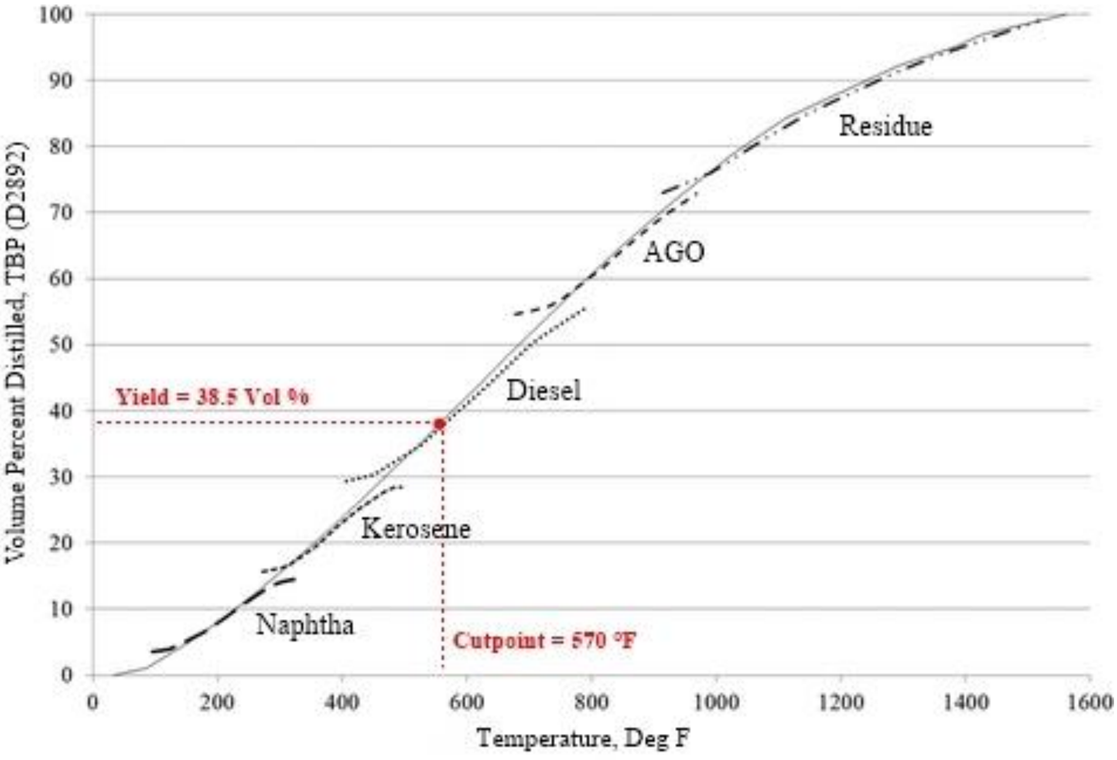


Figure 2.1: TBP Curve Diagram

2.1.3 Pakistani Crude Oil Production

The petroleum reserves of Pakistan may be estimated to over 9 billion barrels of petroleum oil and around 105 trillion cubic feet in shale oil and natural gas as reported by the United States Energy Information Administration (EIA). Pakistan is a net importer of crude oil and refined products. Crude oil imports grew an annual 12% from 2014 to 2015, according to FACTS Global Energy.

Recently, Pakistan increased the overall crude oil production from 70 kilo barrels per day (kBPD) in 2011 to 95 kBPD in 2015. The recent explorations and discoveries are the reason for the increase in crude oil production. Pakistan is continuously seeking to increase the domestic oil production to an adequate amount by announcing new exploration projects to self-sustain and meet the national oil demand.

Oil consumption of Pakistan has grown over time and averaged 431 kBPD in 2015, far outpacing domestic production. Lower oil prices and natural gas shortages have contributed to increased oil consumption, particularly in the transportation and power sectors.

There are currently six petroleum refineries in Pakistan that are operating mostly on the imported crude oil with a total crude oil processing capacity of 390 kBPD. Pakistan State Oil, a state-owned company, has announced its intention to build a new refinery that will process 200 to 250 kBPD of crude oil. No timeline for completion has been given, as the project is still in its initial stage.

Crude oil production in Pakistan has been averaged at 65.74 kBPD from 1994 until 2016, reaching an all-time high of 95 kBPD in January of 2015 and a record low of 50 kBPD in April of 1999. Crude Oil Production in Pakistan remained unchanged at 89 kBPD in December from 89 kBPD in November of 2016.

Some regional Pakistani crude oils were tested, and it was found that the northern regions (mostly Punjab) had a better quality of crude oil than that of the southern regions (Sindh). The northern region crude was of the sweet type belonging to the light crude class and contained more saturated aromatics and polar contents while the southern region crude was of a sour type and belonged to the medium class of crude oils with lesser saturated aromatics and polar contents.

2.1.4 Crude Distillation Unit

The crude distillation unit (CDU) also known as atmospheric distillation unit (ADU) is one of the major energy consumers in a petroleum refinery which uses between 35 – 40% of the overall energy used by all the processes in the refinery. CDU being one of the complex unit in separation processes bears the highest operating cost in the overall refinery. CDU processes the crude oil and separates the various products by their cutpoints or boiling points. The separated products from the raw crude are off-gas, naphtha, diesel, kerosene, jet fuels, gas oils, etc. These products are sent for further processing to other complexes like vacuum distillation, naphtha cracking and reforming unit etc. to further refine and increase the value of the products [4].

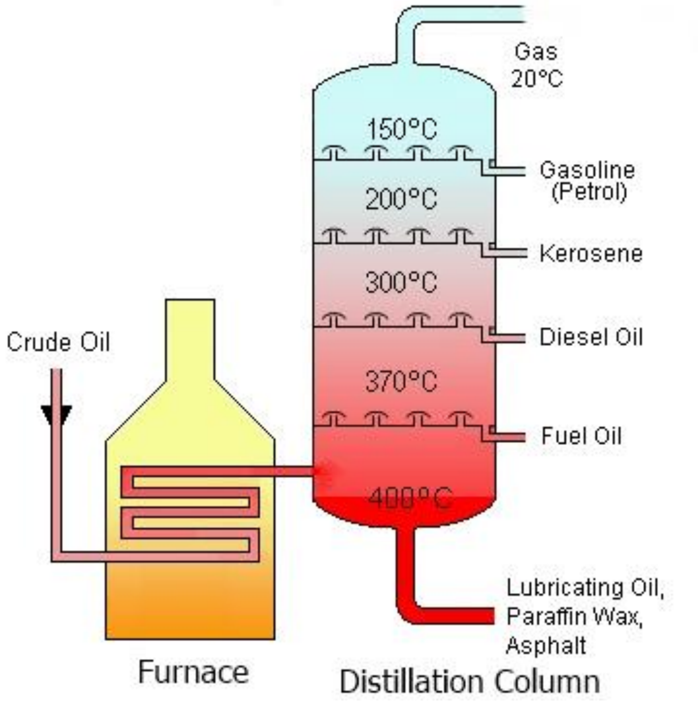


Figure 2.2: Crude Distillation Process

Hundreds of various hydrocarbon compounds are present in crude oils like paraffin, naphthene, and aromatics as well as organic sulfur compounds, organic nitrogen compounds and some oxygen containing hydrocarbons such as phenols.

Rather than producing products with a single boiling point, the crude distillation column produces products with a boiling range. Like for example, naphtha which is collected as an overhead product is further processed and refined into gasoline. Various hydrocarbon compounds are present in a single naphtha cut. Naphtha has an initial boiling point of around 35 °C, and the final boiling point of naphtha can reach to up to 200 °C. Similarly, all other cuts produced in the crude distillation column have different boiling ranges.

The second cut that is withdrawn at the side of the distillation column is the kerosene cut which is also known as jet fuel. The kerosene has an initial boiling point of around 150 °C and the final boiling point can go up to 270 °C. Kerosene also consists of various hydrocarbon compounds that are present in it.

Below kerosene, another cut known as diesel is drawn from the side of the distillation column. Diesel has an initial boiling point around 180 °C and final boiling point around 315 °C. The overlapping in boiling ranges always exist, and therefore the boiling ranges are never perfect and sharp.

Atmospheric gas oil (AGO) or heavy fuel oil cuts are withdrawn below diesel having a significant wide boiling range. Similar to other cuts, a subsequent refining process is required for further useful products to be extracted.

The 1st step in a petroleum refinery is preprocessing of the raw crude oil. Afterwards, the fractionation of the crude oil takes place in the crude distillation unit (CDU). The initial cuts of crude oil are fractionated and are transported for further processing while contaminants of the crude oil are removed and discarded.

Understanding the fundamentals of crude unit operation is important for the better and effective design, modifications, operations, and troubleshooting of crude oil refinery processes.

2.2 Literature Survey

Energy efficient design and operation of the industrial process has been the focus of research due to the uncertain future of energy resources. Crude distillation unit (CDU) also called atmospheric distillation unit is a fractionation or separation process that splits up different constituents of crude oil on the basis of the difference in their volatility and boiling point. It is one of the most energy intensive processes where fractionation of various products, i.e., naphtha, kerosene, diesel, AGO, etc. is carried out. According to an American report, with applied research and development there is a worldwide potential of saving 208 TBtu/year of energy alone in a CDU. One of the energy saving opportunity in CDU is optimization of cutpoint temperature. Cutpoint temperatures are the tray temperatures at which the product streams are separated. The cutpoints heavily depend on the crude composition and are therefore optimized whenever a new crude blend is incorporated into the feed. However, the manual tuning/optimization of cutpoint temperature becomes difficult due to the continuous scheduling of the feed crude blend and a substantial amount of energy generated from utilities is lost. For realizing energy efficient operation of the distillation column, optimization of cutpoint temperature has been the focus of researchers.

For realizing energy efficient operation of the distillation column, optimization of cutpoint temperature has been the focus of researchers. Multiple researches have been published related to optimization of CDU by planning, scheduling and strategizing of crude oil blends [1, 5, 6]. In [7], the effects of a binary feed on CDU optimization was studied. In [8], the behavior of a CDU was studied by analysis of various extreme operating conditions through a dynamic simulation. In another study [9], a proficient system was developed using artificial neural networks for prediction of unknown input values of the CDU while genetic algorithm was applied for optimization of the CDU with minimum output error and maximum oil production rate. Distillation blending and cutpoint temperature optimization were carried out using monotonic interpolation in [10]. In [11], optimization of cutpoint temperatures of CDU was carried out through Taguchi method. Taguchi method is quick, straightforward and easy to apply; however, it does not examine combinations of all design parameters and is very poor in estimating the parameters that have the maximum effect on the performance and hence is generally applied in the initial stages of the process development [12].

In this research, we propose a novel method of cutpoint temperature optimization based on hybridization of Taguchi and Genetic Algorithms. A crude distillation unit is designed using Aspen HYSYS® for three Pakistani crudes, i.e., Bobi, Kunnar, and Zamzama. Optimization is carried out on lowering the energy consumption (E) per unit production of product stream (V), diesel. Initially, Taguchi method is applied to optimize the cutpoint temperatures to obtain a minimum E/V value followed by execution of Genetic Algorithm to minimize its value further.

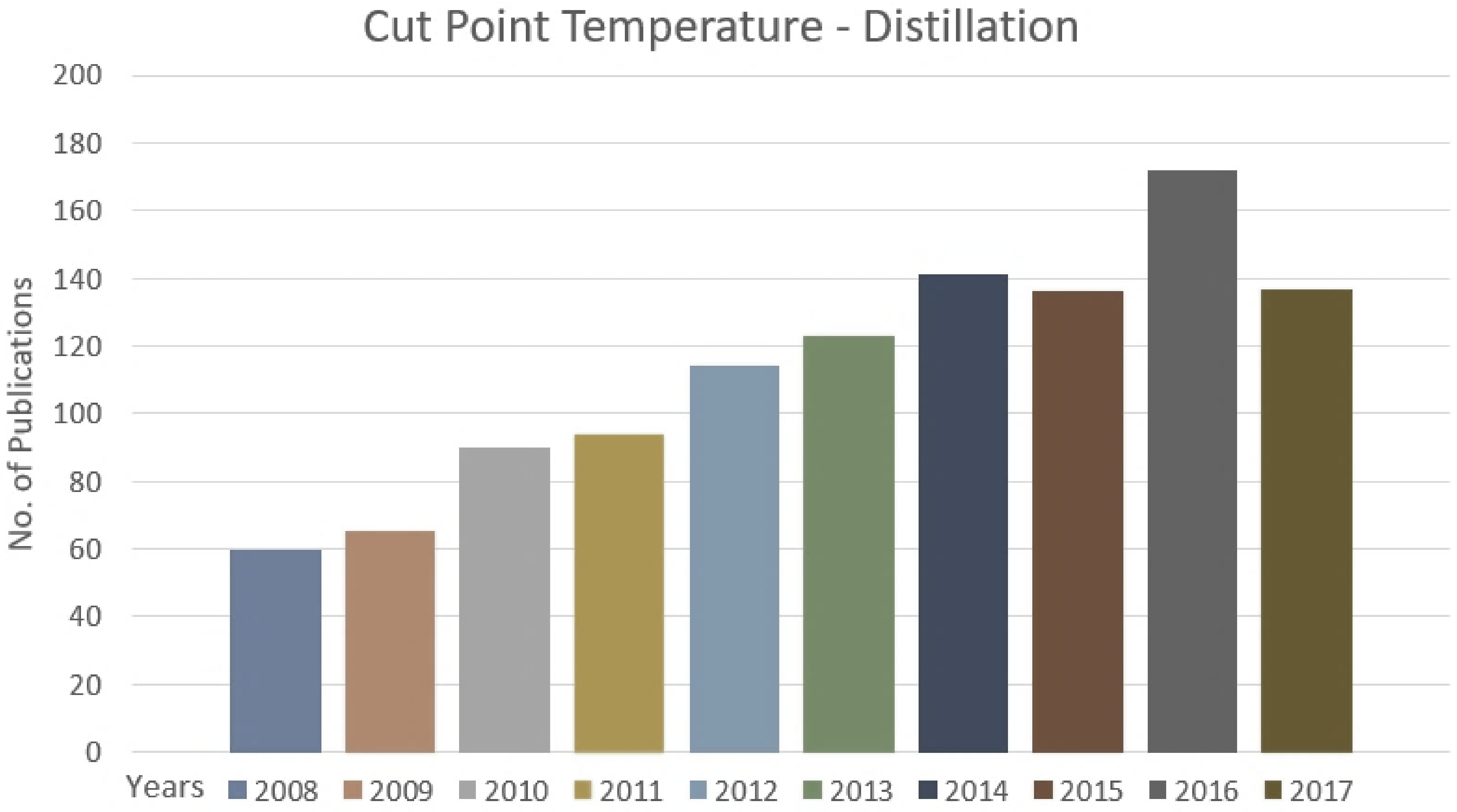


Figure 2.3: Distillation and Cutpoint Temperature Research Trend of Past 10 Years (Source: Science Direct)

Chapter 3

Development of a CDU Optimization Tool

3.1 Specifications of Pakistani Crude Oil

In this research, three Pakistani crudes, i.e., Bobi, Kunnar, and Zamzama. All three crudes are characterized as a sweet and light crude oil having a specific gravity ranging between 0.75 to 0.76, containing Sulphur less than 0.05 weight percent and water contents less than 0.05 volume percent. Seven feed cases with an equal ratio were devised out of the three crudes: 3 single crude feeds (Bobi, Kunnar, and Zamzama), 3 crude binary blend feeds (Bobi-Kunnar Blend, Bobi-Zamzama Blend, and Kunnar-Zamzama Blend) and one ternary blend feed (Bobi-Kunnar-Zamzama Blend). A detailed description of the Pakistani crude assays is shown in Table 3.1. The Aspen HYSYS® generated TBP curves for three Pakistani Crudes are shown in Figure 3.1.

Table 3.1: Pakistani Crude Oil Specifications *(Source: ENAR Petroleum Refining Facility, Pakistan)*

Method	**Test Description**	**Bobi**	**Kunnar**	**Zamzama**
D-1298	Specific Gravity 60/60 F	0.7513	0.7934	0.7588
D-1551	Total Sulphur Content (Wt.%)	0.05	0.0376	0.0083
D-96	B.S (Vol %)	0.05	< 0.05	< 0.05
D-95	Water Content (Vol %)	0.02	< 0.05	< 0.05
D-3230	Salt Content Lb/1000 bbl	< 1	4.5	Nil
D-445	Kinematic Viscosity 40 C (cSt)	0.8	1.27	0.78

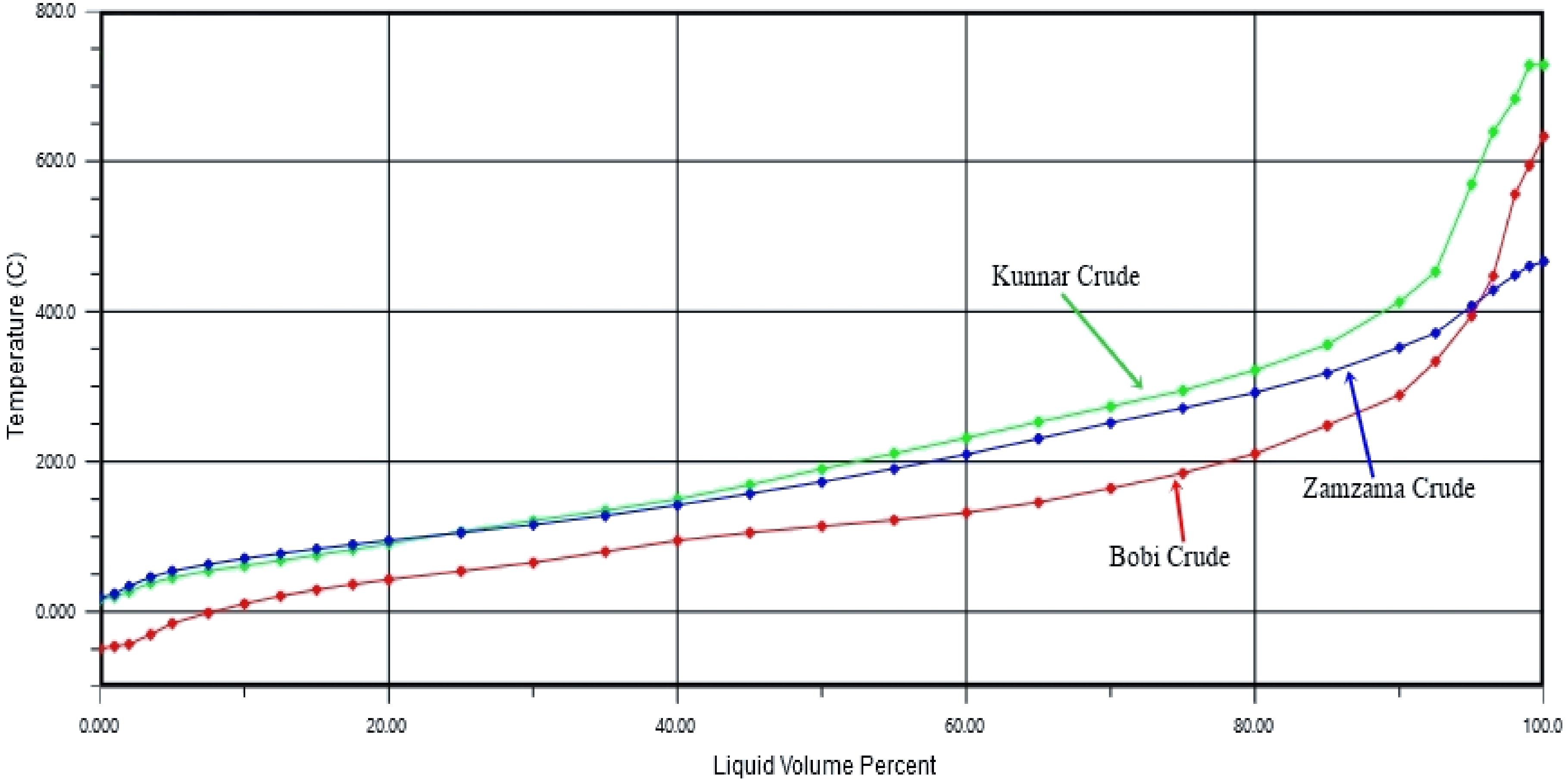


Figure 3.1: Aspen HYSYS generated TBP curves for the three Pakistani Crudes

3.2 Process Description and Model Development

Crude oil at 450 °F of temperature and 75 psia of pressure is pumped at the rate of 100 kilo barrel per day (kBPD) to the preflash column to separate vapours at the top and liquid at the bottom. The bottom liquid crude extracted from the pre-flash column is then sent to the furnace to pre-heat the crude oil before it can be pumped to the fractionation column. The vapor and liquid separation are done to reduce the duty and save energy on the furnace making it an economically viable process [13].

The bottom liquid crude that is drawn from the pre-flash column is heated to 650 °F in the furnace resulting in a pressure drop of 10 psia.

The distillation column comprises of 29 trays and is linked to three side-strippers, three pump-arounds and a 3-phase partial condenser. The hot crude from the furnace is introduced at the bottom in tray 28 of the column. Three side-strippers each having 3 tray sections are used for diesel, kerosene and gas oil. A reduced partial pressure is achieved with the help of steam for AGO and diesel, and a reboiler for kerosene helps in increasing of product separation. The top tray pressure of the column is 19.70 psia with a pressure drop of 9.00 psia while the bottom pressure is 32.70 psia. Three pump-arounds are installed to carry an internal reflux within the column with parameters shown in Table 3.2. Parameters of the Side-Strippers are shown in Table 3.3.

The 3-phase partial condenser is operating with a pressure of 9.00 psia removing a side product of waste water. Naphtha product being the distillate is extracted with a maintained rate of 20 to 25 kBPD. The reflux is maintained at a ratio of 1.7.

Table 3.2: Pump-Around Parameters

Pump Around	Draw Stage	Return Stage	Duty (kW)	Flow (kBPD)
Pump Around - 1	Tray 2	Tray 1	-16118.912	50.00
Pump Around - 2	Tray 17	Tray 16	-10257.489	29.99
Pump Around - 3	Tray 22	Tray 21	-10257.489	30.00

Table 3.3: Side-Stripper Parameters

Side-Strippers	Draw Stage	Return Stage	Stripping By	Flow / Duty
Side Stripper - 1	Tray 9	Tray 8	Reboiler	2198.039 kW
Side Stripper - 2	Tray 17	Tray 16	Steam	1362.000 kg/hr
Side Stripper - 3	Tray 22	Tray 21	Steam	1135.000 kg/hr

Steam at a rate of 3402 kg/h at 375 °F temperature and 15 psia pressure is introduced at the bottom of the column at the 28th stage which exchanges heat twice, i.e., absorption of heat from the liquid that is pouring downwards from the above tray and from the vapours that are vaporized from the lower tray. 3.5% of the feed is specified as an over-flash at 27th tray. Parameters used for the Aspen HYSYS® model development are shown in Table 3.4.

Table 3.4: CDU Parameters

Parameter	**Value**
Number of Total Stages	29
Column Temperature	70.99˚C (top) 338.57˚C (bottom)
Column Pressure	135.8 kPa (top) 225.5 kPa (bottom)
Number of pump-arounds	3
Number of side-strippers	3
Crude Inlet Rate	100.00 kBPD
Crude Inlet Location	Stage 28
Crude Inlet Temperature	328.60 ˚C
Crude Inlet Pressure	448.20 kPa
Condenser Category	Partial Condenser
Fluid Package	Peng-Robinson

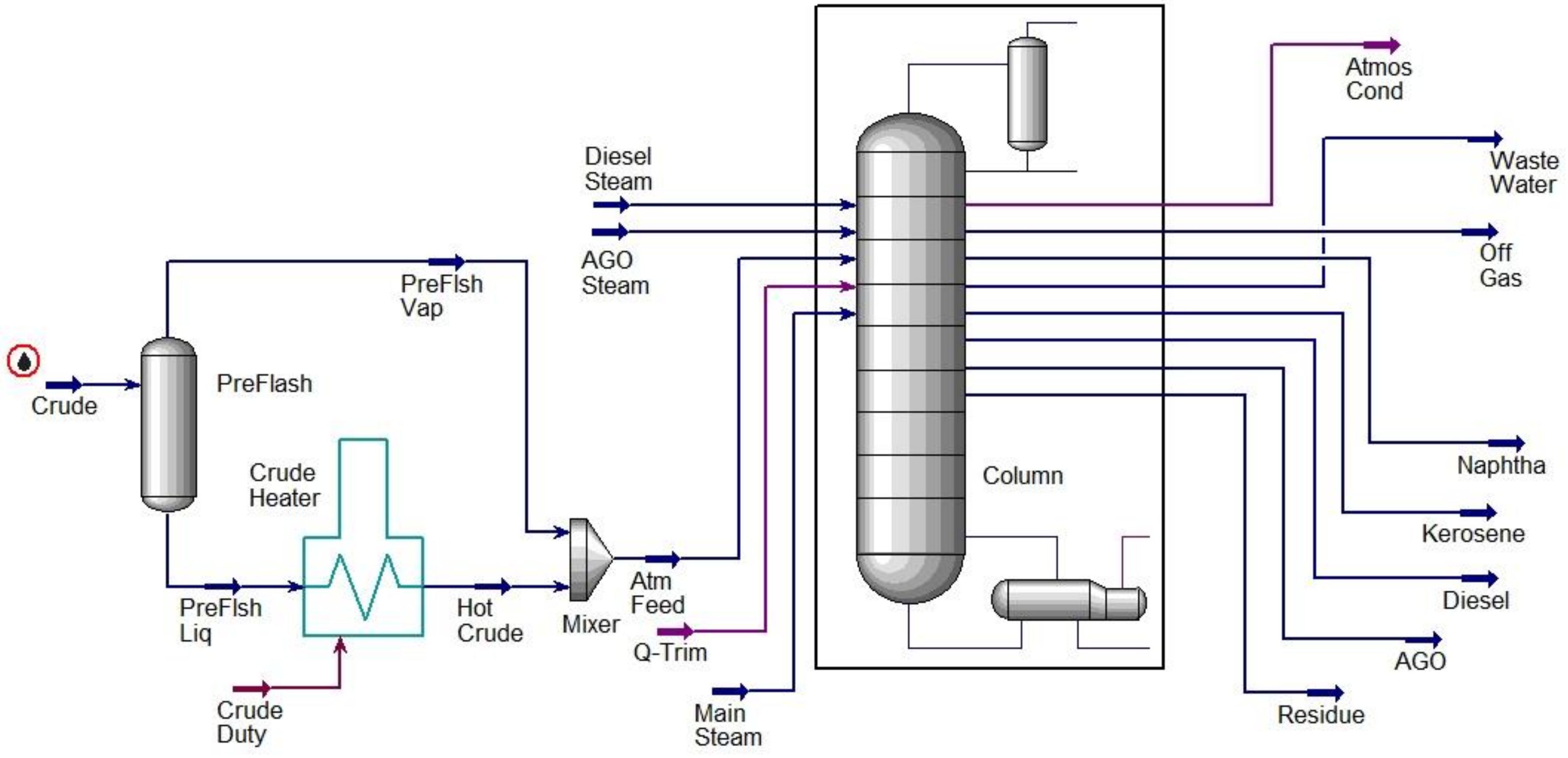


Figure. 3.2: Crude Distillation Unit Process Flow Diagram

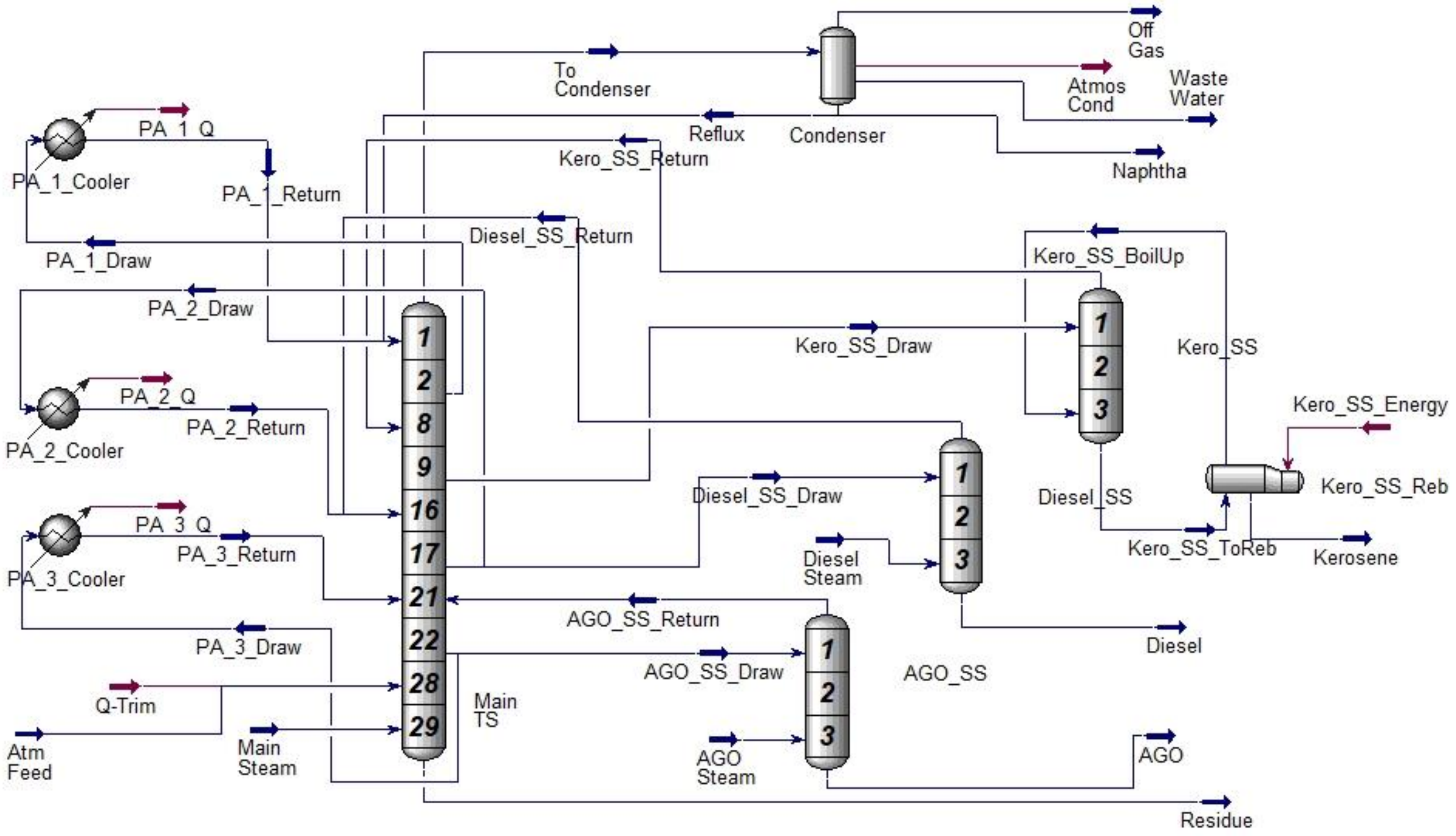


Figure. 3.3: Column Environment Flow Diagram

3.3 MATLAB® and Aspen HYSYS® Interfacing and Cutpoint Temperatures Optimization

The algorithm developed using MATLAB® is schematically explained in following steps:

1. Run the Aspen HYSYS® CDU simulation.
2. Connect MATLAB® with Aspen HYSYS® using OLE 1 automation link [14].
3. Identify the cutpoint temperatures in the HYSYS simulation.
4. Apply Taguchi method to the straight run cutpoint temperatures.
5. Calculate the Taguchi optimized cutpoint temperatures using MATLAB®.
6. Verify the Taguchi optimized results by applying them to the Aspen HYSYS® and calculate the E/V result.
7. Apply GA to the Taguchi optimized cutpoint temperatures for the hybrid approach optimization.
8. GA will generate a number of initial population of the Taguchi optimized cutpoint temperatures and run them on the HYSYS simulation.
9. GA calculations will continue till the stopping criteria have reached.
10. The hybrid optimized result will be achieved after the stopping criteria have reached.

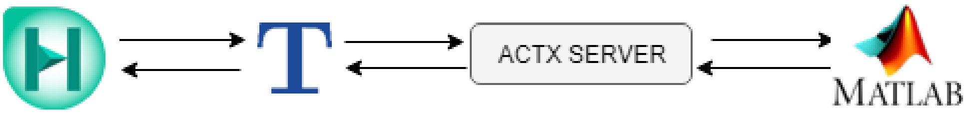


Figure 3.4: Simplified Block Diagram of CDU Optimization Model

Chapter 4

Hybridization of Taguchi and Genetic Algorithms for Cutpoint Temperature Optimization

4.1 Taguchi Method

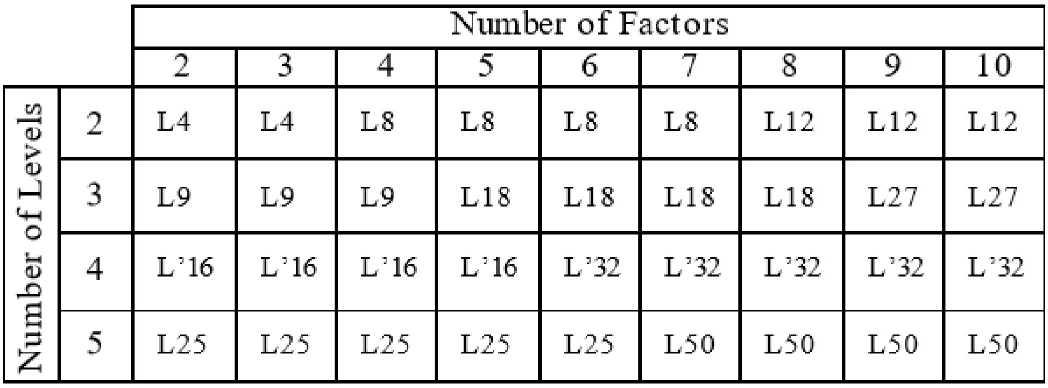
Taguchi method is a statistical technique based on the concept of robust engineering with an objective to improve the quality of the engineered product [15]. The deviations and non-uniformity from the ideal performance or function aids in measuring the engineered quality of the product. The controlling factors for engineered quality can be optimized by assigning into a form of orthogonal arrays which can help in reducing the designing space for the robust optimization. An orthogonal array can provide a balanced set of experimental trials and hence assist in obtaining better results. Benefits of using Taguchi method are saving time and cost for conducting a large set of experiments, identifying of unique ways of experiments, simplifying the interpretations of data and by identifying the influence caused by all factors. Remarkable results have been achieved by employing Taguchi method for the parametric designs in engineering. Examples like Taguchi method was applied to an injection molding process to select the parameters to produce the best quality product [16]. In a more complex engineering design, the parameters for a gas refrigerant plant was optimized using the internal and external array approach for optimizing the variables of the gas plant [17]. In another example, the strength of a biomechanical cervical ring cage was optimized using the Taguchi method [18].

Taguchi method employs design of experiments (DOE) which is a systematic approach to determine the connection between the factors influencing a process with the output of the process. Mechanism of Taguchi method involves the identification of the objective function, quality characteristics and controlling factors and their levels. Factors and levels for the optimization of the CDU are shown in Table 4.1. An array selector is used for the identified factors and levels for the determination of the standard orthogonal array (OA) as shown in Table 4.2. The standard orthogonal array (OA) matrix L9 is selected for the identified 4-factors and the 3-levels as shown in Table 4.3. Using the OA matrix, trial runs are conducted, and a response plot diagram is drawn against those values. The response plot diagrams are analyzed by the quality characteristics and objective function which gives an optimized solution. The optimized solutions are then verified by comparing the results with the straight run values.

Table 4.1. Factors and levels for the optimization of CDU

Factors		**Level 1**	**Level 2**	**Level 3**
A	Naphtha Cutpoint Temperature	-5ºC	Straight Run Temp	+5ºC
B	Kerosene Cutpoint Temperature	-5ºC	Straight Run Temp	+5ºC
C	Diesel Cutpoint Temperature	-5ºC	Straight Run Temp	+5ºC
D	AGO Cutpoint Temperature	-5ºC	Straight Run Temp	+5ºC

Table 4.2: Orthogonal Array Selector



		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

Table 4.3: L9 (4-factors 3-levels) DOE standard orthogonal array

Trials	Factor A	Factor B	Factor C	Factor D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

A step-wise flow diagram of the application of Taguchi method is shown in Figure 4.1.

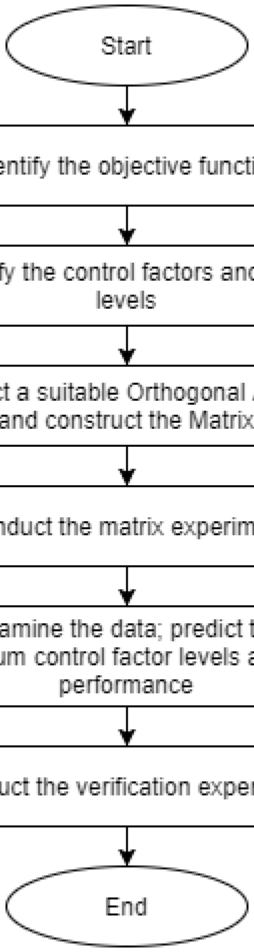


Figure 4.1: Taguchi method flow diagram

4.2 Genetic Algorithm (GA)

Genetic Algorithm (GA) is a problem-solving calculation process which tries to find solutions on the basis of the evolutionary theory of nature. GA computes solutions with a set of population represented by chromosomes. By application of GA, a generation of new population forms. The new generation of the population is hoped to be better from the previous generation. The new solutions are evaluated and selected to reproduce a new set of population if it has qualified the fitness function. The process repeats till it has reached the stopping criteria or condition either by reaching a specified number of populations or the best solution.

Genetic Algorithms (GA) area type of evolutionary algorithms that mimics the process of biological evolution. First developed by John Holland in the early 1970s, GA is based on the concepts of natural selection and genetic inheritance. Genetic algorithms are domain independent and can be applied to several problems in many fields. Many researchers have used GA's to evaluate the solution of difficult problems whose objective functions lack the properties of continuity, differentiability, etc. [19].

GA encodes potential solutions into data structures that are similar to chromosomes and maintains a population of such chromosomes during searches. It requires an objective function that assign a scalar payoff (or reward) to any particular solution. GA start searching for an optimal solution once their presentation scheme and evaluation function is established. It proceeds with creating an initial population of a certain number of strings or chromosomes, called the population size. Next step is to evaluate each solution in the initial population by payoff function. Better solutions are awarded high payoffs while rest of the solutions are awarded a lower payoff. Next generation is then generated by employing genetic operators like mutation, crossover, etc. on these evaluations. This procedure is repeated unless an optimal solution(s) is (are) found or a maximum number of iterations or population is reached or relative difference between solutions is less than a certain limit. Schematics of GA are shown in Figure 4.2. A brief description of components of GA are given below:

1. **Representation:** Genetic algorithm needs the solutions or individual in a population to be represented in the form of chromosomes. Structure of a problem and the type of genetic operators that will be used depends upon the representation scheme used. Specific alphabets are used to develop a sequence of the gene that makes the chromosome. Binary digits (0 and 1) and real value numbers can constitute these specific alphabets. It has been shown that

chromosomes encoded using real value numbers results in more efficient GAs and produce better solutions. Table 4.4 shows the example of chromosomes.

2. **Selection Function:** Successive generations in GA are generated by selection of individuals from a previous generation. Selection is based on the concept that every individual has a chance or probability of being selected once or more than once, based on their fitness value, for reproduction in the next generation. Roulette wheel selection, scaling techniques, tournament, elitist models and ranking methods are some of the selection schemes. Assignment of the probability of selection to individuals is a common step in all of these schemes. There are various methods for this assignment like a roulette wheel, linear ranking and, geometric ranking.
3. **Genetic Operators:** Search mechanism opted by GA are provided by genetic operators. Genetic operators create new solutions in the population by applying operations to existing solutions. Crossover and mutation are two basic genetic operators which are widely used. Both are analogues to their counter parts in actual genetic processes. Crossing over take two individual chromosomes and transfer portion of these chromosomes between the both to produce two new chromosomes. While in mutation a single chromosome is altered at a single location to produce a new chromosome. Examples of Crossover and Mutation are shown in Table 4.5 and Table 4.6.
4. **Initialization or Initial Population:** GA needs an initial population to start the procedure for finding the best solution as shown in Figure 4.2. The initial population can be produced by generating random solutions inside the upper and lower bound of the variables. Another method is to seed the initial

population with already established best solutions to improve the existing solutions. The remainder of the population can be randomly generated solutions.

5. **Termination:** GA operations are terminated once a termination criterion is met. The termination criterion can be anyone or combination of the followings:
   a. A number of generations reaches a specified maximum value.
   b. Population converges to a single solution.
   c. Difference among solutions becomes smaller than a specified threshold.
   d. Best solution doesn't improve over a specified number of generations.
   e. Evaluation values reach some acceptable threshold.
6. **Evaluation or Objective Functions:** Many different forms of evaluation functions can be used to determine the fitness of each solution produced during the search. These functions are independent of GA and should meet the requirement that they can map the population into a partially ordered set. In this research, GA was used to optimize 9 operation parameters of all the phases of naphtha reforming process. As in online applications, the changes made to the operational parameters should not be large, so the lower and upper bounds of parameter search space were selected to be 5% above and below of the non-optimized parameters. Optimization was terminated when relative difference among solutions become smaller than $1 \times 10{-}4$. The objective function was developed using artificial neural networks discussed in the next section.

Table 4.4: Chromosomes

Chromosome 1	1101100100110110
Chromosome 2	1101111000011110

Table 4.5: Crossover

Chromosome 1	11011 | 00100110110
Chromosome 2	11011 | 11000011110
Offspring 1	11011 | 11000011110
Offspring 2	11011 | 00100110110

Table 4.6: Mutation

Original offspring 1	110**1**111000011110
Original offspring 2	110110**0**1001101**1**0
Mutated offspring 1	110**0**111000011110
Mutated offspring 2	110110**1**1001101**0**0

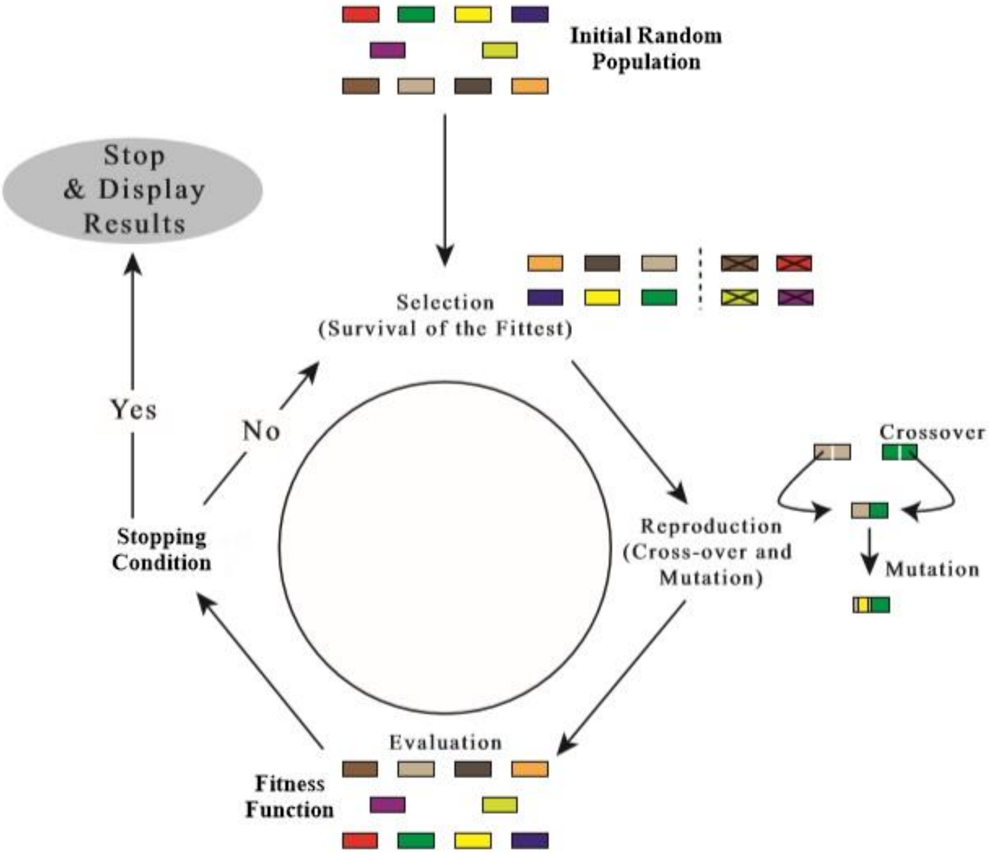


Figure 4.2: Schematics of GA

4.3 Proposed Hybridization Approach

Since Taguchi method is a tested optimization technique which is quick, straightforward and easy to apply; however, it does not examine combinations of all design parameters and is very poor in estimating the parameters that have the maximum effect on the performance and hence is generally applied in the initial stages of the process development. Also, GA will produce a combination of large uncontrollable numbers of population and generations if not restricted to a certain level. Taguchi method helps in limiting the number of levels by forming an optimized recipe of the levels with a broader difference. To perform optimization with a narrower difference in a number of values, application of GA on the Taguchi optimized values can further polish the optimization process. Hence the need for a Hybrid, combination of Taguchi and GA, an optimization technique is essential.

The major steps involved in the proposed hybrid approach for optimization are as follow:

1. A detailed process model of CDU is develop using Aspen HYSYS® with the specifications mentioned in Chapter 3.
2. Perform a straight run analysis of cutpoint temperatures and calculate the E/V value.
3. For optimization of cutpoint temperatures using the Hybrid approach, 1st the Taguchi method is applied. The number of controlling factors and levels are specified.
4. Design of experiment is determined by a standard orthogonal array for the number of specified factors and levels.
5. The result of the Taguchi method is analyzed by the objective function and quality characteristics.

6. The Taguchi resulting E/V values are validated and compared with the straight run values.
7. GA is applied to the Taguchi optimized cutpoint temperatures, and an initial population of the cutpoint temperature is generated.
8. Fitness function and the upper and lower limits of the cutpoint temperatures are specified.
9. New generations of the cutpoint temperatures are formed by the selection, reproduction, crossover and/or mutation of the old cutpoint temperatures.
10. The E/V value against the new generation of cutpoint temperatures are evaluated. If the fitness function and/or stopping criteria is satisfied, optimization is achieved otherwise step 9 and 10 are repeated.

A schematic representation of the proposed hybrid approach for optimization is shown in Figure 4.3.

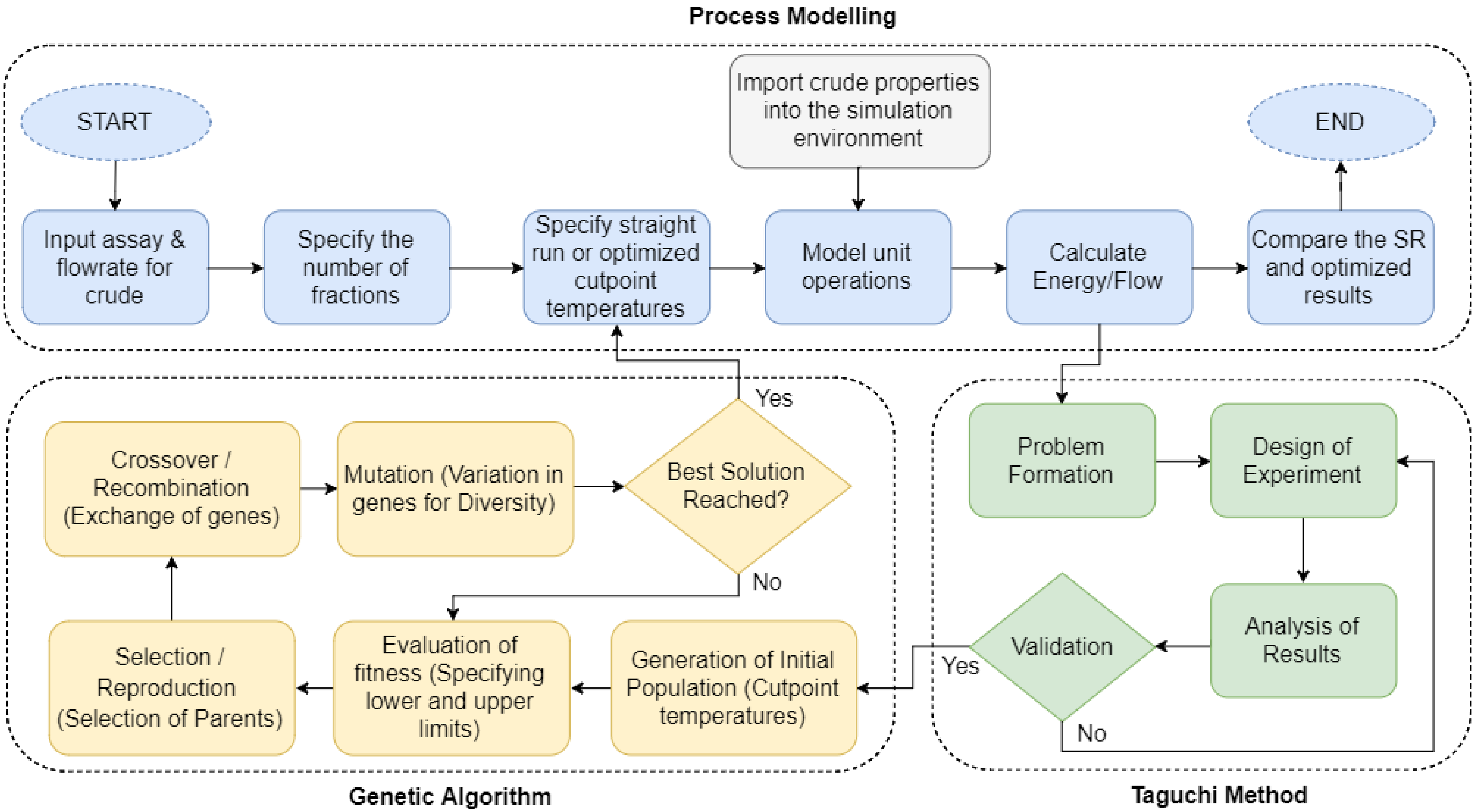


Figure 4.3: Recommended approach for optimizing cut point temperatures

Chapter 5

Result and Discussions

Seven feed cases with an equal ratio were devised out of the three Pakistani crudes: 3 single crude feeds (Bobi, Kunnar, and Zamzama), 3 crude binary blend feeds (Bobi-Kunnar Blend, Bobi-Zamzama Blend and Kunnar-Zamzama Blend) and one ternary blend feed (Bobi-Kunnar-Zamzama Blend).

The seven cases devised for the application of Taguchi method are as follow:

Case 1: Bobi Oil Crude
Case 2: Kunnar Crude
Case 3: Zamzama Crude
Case 4: Bobi + Kunnar Blend
Case 5: Bobi + Zamzama Blend
Case 6: Kunnar + Zamzama Blend
Case 7: Bobi + Kunnar + Zamzama Blend

Seven CDU models for the seven cases of crude feeds were developed using the data and parameters mentioned in Chapter 3. The crude feed data, also discussed in Chapter 3, for each case with a flow rate of 100 kBPD are entered in the Aspen HYSYS® oil manager. A spreadsheet is developed identifying the cutpoint temperatures, diesel draw rate and the energy streams in Aspen HYSYS® simulation environment.

5.1 Taguchi Results

Taguchi method was applied for optimization of the cutpoint temperatures of the three Pakistani crude oils with seven blend cases. Four controlling factors cuts (i.e., naphtha, kerosene, diesel, and gas oil) were identified, and these factors were assigned three levels of cutpoint temperatures. The three levels of the cutpoints chosen were ± 5ºC to the straight run cutpoint temperatures. For the 4-factors and 3-levels, the standard L9 orthogonal array is chosen from the orthogonal array selector. The orthogonal array selector and the standard matrix for an L9 orthogonal array are discussed in Chapter 4.

A total of 9 trial runs for each case is required and a total of 63 trials for all 7 cases. Trial runs are performed by entering the cutpoint temperatures assigned by the levels for each factor in the Aspen HYSYS® simulation.

The objective function *lower is better* was applied as the measure of robustness for this study which is the minimum utilization of energy for the production of diesel yield. Response plots for all cases are drawn for the resulting E/V values obtained against all the cutpoint temperatures. Cutpoint with minimum E/V parameters were selected from the response plot diagrams.

5.1.1 Case 1: Bobi Crude

5.1.1.1 Straight Run Parameters

The straight run parameters were obtained by entering data of the crude feed according to Case 1 in the Aspen HYSYS® model as shown in Table 5.1.

Table 5.1: Straight run parameters for Case 1.

S.No.	**Products**	**Straight Run Parameters**
1	Naphtha Cutpoint Temperature	103 °C
2	Kerosene Cutpoint Temperature	126 °C
3	Diesel Cutpoint Temperature	242 °C
4	AGO Cutpoint Temperature	411 °C
5	Diesel Yield	36.9430 kBPD
6	Energy / Diesel Yield	708.5412 kW/kBPD

5.1.1.2 Levels and Factors

Three levels of the cutpoint temperatures of the four controlling factors were formed using the straight run cutpoint temperatures as the basis for Case 1 as shown in Table 5.2.

Table 5.2: Factors and levels for Case 1

S.No.	**Factors**	**Level 1**	**Level 2**	**Level 3**
1	Naphtha	98 °C	103 °C	108 °C
2	Kerosene	121 °C	126 °C	131 °C
3	Diesel	237 °C	242 °C	247 °C
4	AGO	406 °C	411 °C	416 °C

5.1.1.3 Applying Orthogonal Array Matrix

L_9 (3^4) Orthogonal Array matrix was formed using the three levels and four factors for Case 1 and E/V value was calculated by manually entering the cutpoint temperatures for each trail in Aspen HYSYS® simulation as shown in Table 5.3.

Table 5.3: L_9 (3^4) Orthogonal Array of Case 1

Trails #	**Naphtha**	**Kerosene**	**Diesel**	**AGO**	**Energy/Product**
Trial 1	98°C	121°C	237°C	406°C	641.7839 kW/kBPD
Trial 2	98°C	126°C	242°C	411°C	716.9464 kW/kBPD
Trial 3	98°C	131°C	247°C	416°C	960.4682 kW/kBPD
Trial 4	103°C	121°C	242°C	416°C	726.6354 kW/kBPD
Trial 5	103°C	126°C	247°C	406°C	661.2924 kW/kBPD
Trial 6	103°C	131°C	237°C	411°C	892.9307 kW/kBPD
Trial 7	108°C	121°C	247°C	411°C	683.8334 kW/kBPD
Trial 8	108°C	126°C	237°C	416°C	822.5985 kW/kBPD
Trial 9	108°C	131°C	242°C	406°C	803.5215 kW/kBPD

5.1.1.4 Taguchi Calculations

Taguchi calculations for Case 1 are carried out by taking the mean of the E/V for each of the three levels for all four controlling factors as shown in Table 5.4.

Table 5.4: Taguchi Calculations for Case 1

S.No.	Factors	Levels	Energy / Diesel Yields
1	Naphtha	1	773.0662 kW/kBPD
		2	760.2862 kW/kBPD
		3	769.9845 kW/kBPD
2	Kerosene	1	684.0842 kW/kBPD
		2	733.6125 kW/kBPD
		3	885.6402 kW/kBPD
3	Diesel	1	785.7711 kW/kBPD
		2	749.0344 kW/kBPD
		3	768.5314 kW/kBPD
4	AGO	1	702.1993 kW/kBPD
		2	764.5702 kW/kBPD
		3	836.5674 kW/kBPD

5.1.1.5 Response Plot

Response plot for Case 1 was drawn for the resulting E/V values obtained from the three levels of cutpoint temperatures of the four factors as shown in Figure 5.1.

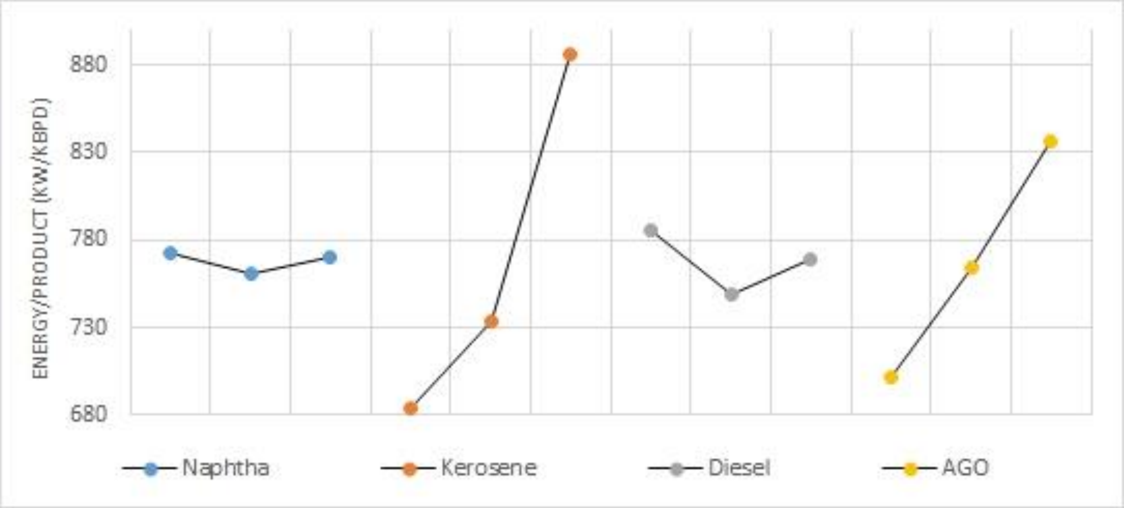


Figure 5.1: Taguchi response plot for Case 1 (Bobi Crude)

5.1.1.6 Taguchi Optimized Parameters

Cutpoint with minimum E/V parameters were selected from the response plot diagram. Optimized cutpoint temperatures are entered in Aspen HYSYS® model for Case 1 and the resulting optimized E/V and diesel draw rate is noted as shown in Table 5.5.

Table 5.5: Optimized Parameters for Case 1

S.No.	**Products**	**Optimized Parameters**
1	Naphtha Cutpoint Temperature	103°C
2	Kerosene Cutpoint Temperature	121°C
3	Diesel Cutpoint Temperature	242°C
4	AGO Cutpoint Temperature	406°C
5	Diesel Yield	41.12148 kBPD
6	Energy/Diesel Yield	616.753317 kW/kBPD

5.1.2 Case 2: Kunnar Crude

5.1.2.1 Straight Run Parameters

The straight run parameters were obtained by entering data of the crude feed according to Case 2 in the Aspen HYSYS® model as shown in Table 5.6.

Table 5.6: Straight run parameters for Case 2

S.No.	Products	Straight Run Parameters
1	Naphtha Cutpoint Temperature	97 °C
2	Kerosene Cutpoint Temperature	150 °C
3	Diesel Cutpoint Temperature	255 °C
4	AGO Cutpoint Temperature	408 °C
5	Diesel Yield	25.5019 kBPD
6	Energy / Diesel Yield	1241.7421 kW/kBPD

5.1.2.2 Levels and Factors

Three levels of the cutpoint temperatures of the four controlling factors were formed using the straight run cutpoint temperatures as the basis for Case 2 as shown in Table 5.7.

Table 5.7: Factors and levels for Case 2

S.No.	Factors	Level 1	Level 2	Level 3
1	Naphtha	92 °C	97 °C	102 °C
2	Kerosene	145 °C	150 °C	155 °C
3	Diesel	250 °C	255 °C	260 °C
4	AGO	403 °C	408 °C	413 °C

5.1.2.3 Applying Orthogonal Array Matrix

L_9 (3^4) Orthogonal Array matrix was formed using the three levels and four factors for Case 2 and E/V value was calculated by manually entering the cutpoint temperatures for each trail in Aspen HYSYS® simulation as shown in Table 5.8.

Table 5.8: L_9 (3^4) Orthogonal Array of Case 2

Trails #	**Naphtha**	**Kerosene**	**Diesel**	**AGO**	**Energy/Product**
Trial 1	92 °C	145 °C	250 °C	403 °C	1131.6828 kW/kBPD
Trial 2	92 °C	150 °C	255 °C	408 °C	1267.8053 kW/kBPD
Trial 3	92 °C	155 °C	260 °C	413 °C	1482.8700 kW/kBPD
Trial 4	97 °C	145 °C	255 °C	413 °C	1323.4983 kW/kBPD
Trial 5	97 °C	150 °C	260 °C	403 °C	1059.8494 kW/kBPD
Trial 6	97 °C	155 °C	250 °C	408 °C	1525.5770 kW/kBPD
Trial 7	102 °C	145 °C	260 °C	408 °C	1052.1120 kW/kBPD
Trial 8	102 °C	150 °C	250 °C	413 °C	1661.2214 kW/kBPD
Trial 9	102 °C	155 °C	255 °C	403 °C	1198.4025 kW/kBPD

5.1.2.4 Taguchi Calculations

Taguchi calculations for Case 2 are carried out by taking the mean of the E/V for each of the three levels for all four controlling factors as shown in Table 5.9.

Table 5.9: Taguchi Calculations for Case 2

S.No.	Factors	Levels	Energy / Diesel Yields
1	Naphtha	1	1294.1194 kW/kBPD
		2	1302.9749 kW/kBPD
		3	1303.9120 kW/kBPD
2	Kerosene	1	1169.0977 kW/kBPD
		2	1329.6254 kW/kBPD
		3	1402.2832 kW/kBPD
3	Diesel	1	1439.4938 kW/kBPD
		2	1263.2353 kW/kBPD
		3	1198.2772 kW/kBPD
4	AGO	1	1129.9783 kW/kBPD
		2	1281.8314 kW/kBPD
		3	1489.1966 kW/kBPD

5.1.2.5 Response Plot

Response plot for Case 2 was drawn for the resulting E/V values obtained from the three levels of cutpoint temperatures of the four factors as shown in Figure 5.2.

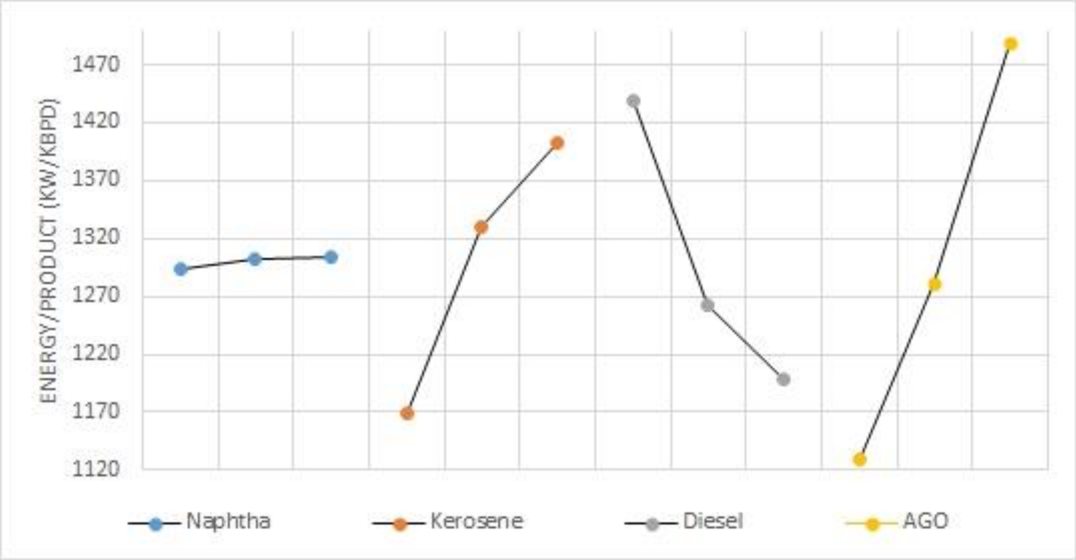


Figure 5.2: Taguchi response plot for Case 2 (Kunnar Crude)

5.1.2.6 Taguchi Optimized Parameters

Cutpoint with minimum E/V parameters were selected from the response plot diagram. Optimized cutpoint temperatures are entered in Aspen HYSYS® model for Case 2 and the resulting optimized E/V and diesel draw rate is noted as shown in Table 5.10.

Table 5.10: Optimized Parameters for Case 2

S.No.	Products	Optimized Parameters
1	Naphtha Cutpoint Temperature	92 °C
2	Kerosene Cutpoint Temperature	145 °C
3	Diesel Cutpoint Temperature	260 °C
4	AGO Cutpoint Temperature	403 °C
5	Diesel Yield	29.5178 kBPD
6	Energy/Diesel Yield	960.8743 kW/kBPD

5.1.3: Case 3: Zamzama Crude

5.1.3.1 Straight Run Parameters

The straight run parameters were obtained by entering data of the crude feed according to Case 3 in the Aspen HYSYS® model as shown in Table 5.11.

Table 5.11: Straight run parameters for Case 3

S.No.	Products	Straight Run Parameters
1	Naphtha Cutpoint Temperature	94°C
2	Kerosene Cutpoint Temperature	135°C
3	Diesel Cutpoint Temperature	260°C
4	AGO Cutpoint Temperature	450°C
5	Diesel Yield	37.5265 kBPD
6	Energy / Diesel Yield	1104.1242 kW/kBPD

5.1.3.2 Levels and Factors

Three levels of the cutpoint temperatures of the four controlling factors were formed using the straight run cutpoint temperatures as the basis for Case 3 as shown in Table 5.12.

Table 5.12: Factors and levels for Case 3

S.No.	Factors	Level 1	Level 2	Level 3
1	Naphtha	89 °C	94 °C	99 °C
2	Kerosene	130 °C	135 °C	140 °C
3	Diesel	255 °C	260 °C	265 °C
4	AGO	445 °C	450 °C	455 °C

5.1.3.3 Applying Orthogonal Array Matrix

L_9 (3^4) Orthogonal Array matrix was formed using the three levels and four factors for Case 3 and E/V value was calculated by manually entering the cutpoint temperatures for each trail in Aspen HYSYS® simulation as shown in Table 5.13.

Table 5.13: L_9 (3^4) Orthogonal Array of Case 3

Trails #	**Naphtha**	**Kerosene**	**Diesel**	**AGO**	**Energy/Product**
Trial 1	89 °C	130 °C	255 °C	445 °C	1069.6010 kW/kBPD
Trial 2	89 °C	135 °C	260 °C	450 °C	1106.1850 kW/kBPD
Trial 3	89°C	140 °C	265 °C	455 °C	1236.4065 kW/kBPD
Trial 4	94 °C	130 °C	260 °C	455 °C	1121.0646 kW/kBPD
Trial 5	94 °C	135 °C	265 °C	445 °C	1010.6627 kW/kBPD
Trial 6	94 °C	140 °C	255 °C	450 °C	1283.3162 kW/kBPD
Trial 7	99 °C	130 °C	265 °C	450 °C	1039.4912 kW/kBPD
Trial 8	99 °C	135 °C	255 °C	455 °C	1211.0949 kW/kBPD
Trial 9	99 °C	140 °C	260 °C	445 °C	1133.3918 kW/kBPD

5.1.3.4 Taguchi Calculations

Taguchi calculations for Case 3 are carried out by taking the mean of the E/V for each of the three levels for all four controlling factors as shown in Table 5.14.

Table 5.14: Taguchi Calculations for Case 3

S.No.	Factors	Levels	Energy / Diesel Yields
1	Naphtha	1	1137.3975 kW/kBPD
		2	1138.3478 kW/kBPD
		3	1127.9927 kW/kBPD
2	Kerosene	1	1076.7189 kW/kBPD
		2	1109.3142 kW/kBPD
		3	1217.7049 kW/kBPD
3	Diesel	1	1188.0041 kW/kBPD
		2	1120.2138 kW/kBPD
		3	1095.5201 kW/kBPD
4	AGO	1	1071.2185 kW/kBPD
		2	1142.9974 kW/kBPD
		3	1189.5220 kW/kBPD

5.1.3.5 Response Plot

Response plot for Case 3 was drawn for the resulting E/V values obtained from the three levels of cutpoint temperatures of the four factors as shown in Figure 5.3.

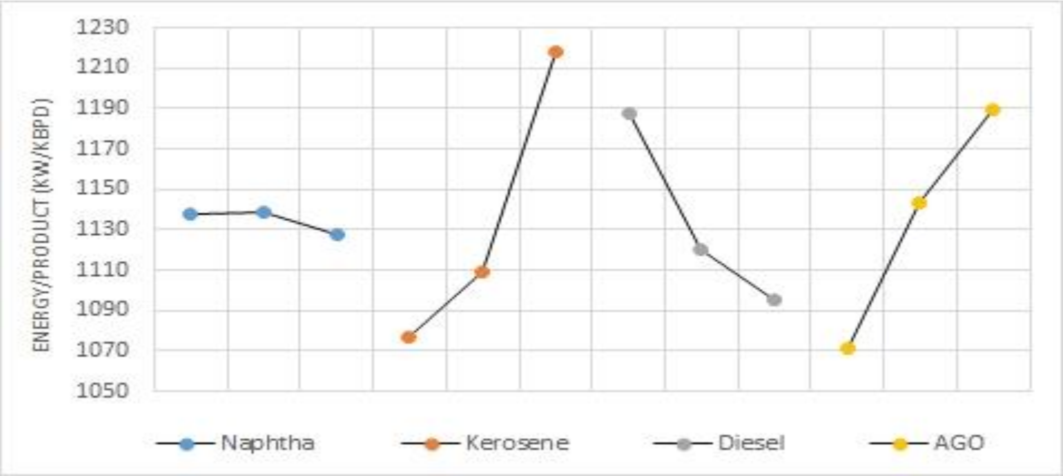


Figure 5.3: Taguchi response plot for Case 3 (Zamzama Crude)

5.1.3.6 Taguchi Optimized Parameters

Cutpoint with minimum E/V parameters were selected from the response plot diagram. Optimized cutpoint temperatures are entered in Aspen HYSYS® model for Case 3 and the resulting optimized E/V and diesel draw rate is noted as shown in Table 5.15.

Table 5.15: Optimized Parameters for Case 3

S.No.	**Products**	**Optimized Parameters**
1	Naphtha Cutpoint Temperature	99°C
2	Kerosene Cutpoint Temperature	130°C
3	Diesel Cutpoint Temperature	265°C
4	AGO Cutpoint Temperature	445°C
5	Diesel Yield	40.0928 kBPD
6	Energy/Diesel Yield	979.3025 kW/kBPD

5.1.4 Case 4: Bobi + Kunnar Blend

5.1.4.1 Straight Run Parameters

The straight run parameters were obtained by entering data of the crude feed according to Case 4 in the Aspen HYSYS® model as shown in Table 5.16.

Table 5.16: Straight run parameters for Case 4

S.No.	Products	Straight Run Parameters
1	Naphtha Cutpoint Temperature	95°C
2	Kerosene Cutpoint Temperature	180°C
3	Diesel Cutpoint Temperature	270°C
4	AGO Cutpoint Temperature	410°C
5	Diesel Yield	17.9844 kBPD
6	Energy / Diesel Yield	1380.0277 kW/kBPD

5.1.4.2 Levels and Factors

Three levels of the cutpoint temperatures of the four controlling factors were formed using the straight run cutpoint temperatures as the basis for Case 4 as shown in Table 5.17.

Table 5.17: Factors and levels for Case 4

S.No.	Factors	Level 1	Level 2	Level 3
1	Naphtha	90 °C	95 °C	100 °C
2	Kerosene	175 °C	180 °C	185 °C
3	Diesel	265 °C	270 °C	275 °C
4	AGO	405 °C	410 °C	415 °C

5.1.4.3 Applying Orthogonal Array Matrix

L_9 (3^4) Orthogonal Array matrix was formed using the three levels and four factors for Case 4 and E/V value was calculated by manually entering the cutpoint temperatures for each trail in Aspen HYSYS® simulation as shown in Table 5.18.

Table 5.18: L_9 (3^4) Orthogonal Array of Case 4

Trails #	**Naphtha**	**Kerosene**	**Diesel**	**AGO**	**Energy/Product**
Trial 1	90°C	175°C	265°C	405°C	1218.7184 kW/kBPD
Trial 2	90°C	180°C	270°C	410°C	1388.9529 kW/kBPD
Trial 3	90°C	185°C	275°C	415°C	2177.0034 kW/kBPD
Trial 4	95°C	175°C	270°C	415°C	1902.4179 kW/kBPD
Trial 5	95°C	180°C	275°C	405°C	1085.9062 kW/kBPD
Trial 6	95°C	185°C	265°C	410°C	1835.0577 kW/kBPD
Trial 7	100°C	175°C	275°C	410°C	1151.8592 kW/kBPD
Trial 8	100°C	180°C	265°C	415°C	2231.8117 kW/kBPD
Trial 9	100°C	185°C	270°C	405°C	1382.3102 kW/kBPD

5.1.4.4 Taguchi Calculations

Taguchi calculations for Case 4 are carried out by taking the mean of the E/V for each of the three levels for all four controlling factors as shown in Table 5.19.

Table 5.19: Taguchi Calculations for Case 4

S.No.	Factors	Levels	Energy / Diesel Yields
1	Naphtha	1	1594.8916 kW/kBPD
		2	1607.7939 kW/kBPD
		3	1588.6604 kW/kBPD
2	Kerosene	1	1424.3318 kW/kBPD
		2	1568.8903 kW/kBPD
		3	1798.1238 kW/kBPD
3	Diesel	1	1761.8626 kW/kBPD
		2	1557.8937 kW/kBPD
		3	1471.5896 kW/kBPD
4	AGO	1	1228.9783 kW/kBPD
		2	1458.6233 kW/kBPD
		3	2103.7443 kW/kBPD

5.1.4.5 Response Plot

Response plot for Case 4 was drawn for the resulting E/V values obtained from the three levels of cutpoint temperatures of the four factors as shown in Figure 5.4.

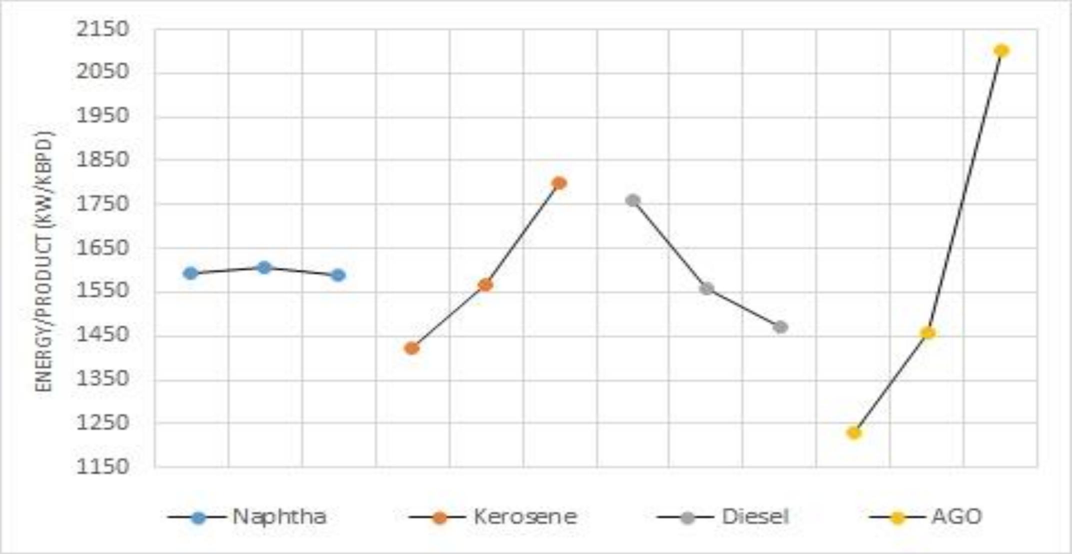


Figure 5.4: Taguchi response plot for Case 4 (Bobi + Kunnar Blend)

5.1.4.6 Taguchi Optimized Parameters

Cutpoint with minimum E/V parameters were selected from the response plot diagram. Optimized cutpoint temperatures are entered in Aspen HYSYS® model for Case 4 and the resulting optimized E/V and diesel draw rate is noted as shown in Table 5.20.

Table 5.20: Optimized Parameters for Case 4

S.No.	**Products**	**Optimized Parameters**
1	Naphtha Cutpoint Temperature	100°C
2	Kerosene Cutpoint Temperature	175°C
3	Diesel Cutpoint Temperature	275°C
4	AGO Cutpoint Temperature	405°C
5	Diesel Yield	20.6988 kBPD
6	Energy/Diesel Yield	1010.4445 kW/kBPD

5.1.5 Case 5: Bobi + Zamzama Blend

5.1.5.1 Straight Run Parameters

The straight run parameters were obtained by entering data of the crude feed according to Case 5 in the Aspen HYSYS® model as shown in Table 5.21.

Table 5.21: Straight run parameters for Case 5

S.No.	Products	Straight Run Parameters
1	Naphtha Cutpoint Temperature	100°C
2	Kerosene Cutpoint Temperature	170°C
3	Diesel Cutpoint Temperature	260°C
4	AGO Cutpoint Temperature	370°C
5	Diesel Yield	16.7744 kBPD
6	Energy / Diesel Yield	901.8565 kW/kBPD

5.1.5.2 Levels and Factors

Three levels of the cutpoint temperatures of the four controlling factors were formed using the straight run cutpoint temperatures as the basis for Case 5 as shown in Table 5.22.

Table 5.22: Factors and levels for Case 5

S.No.	Factors	Level 1	Level 2	Level 3
1	Naphtha	95 °C	100 °C	105 °C
2	Kerosene	165 °C	170 °C	175 °C
3	Diesel	255 °C	260 °C	265 °C
4	AGO	365 °C	370 °C	375 °C

5.1.5.3 Applying Orthogonal Array Matrix

L_9 (3^4) Orthogonal Array matrix was formed using the three levels and four factors for Case 5 and E/V value was calculated by manually entering the cutpoint temperatures for each trail in Aspen HYSYS® simulation as shown in Table 5.23.

Table 5.23: L_9 (3^4) Orthogonal Array of Case 5

Trails #	**Naphtha**	**Kerosene**	**Diesel**	**AGO**	**Energy/Product**
Trial 1	95°C	165°C	255°C	365°C	643.9804 kW/kBPD
Trial 2	95°C	170°C	260°C	370°C	900.88711 kW/kBPD
Trial 3	95°C	175°C	265°C	375°C	905.3253 kW/kBPD
Trial 4	100°C	165°C	260°C	375°C	808.1105 kW/kBPD
Trial 5	100°C	170°C	265°C	365°C	631.0277 kW/kBPD
Trial 6	100°C	175°C	255°C	370°C	1058.9449 kW/kBPD
Trial 7	105°C	165°C	265°C	370°C	665.0500 kW/kBPD
Trial 8	105°C	170°C	255°C	375°C	1059.0371 kW/kBPD
Trial 9	105°C	175°C	260°C	365°C	840.2856 kW/kBPD

5.1.5.4 Taguchi Calculations

Taguchi calculations for Case 5 are carried out by taking the mean of the E/V for each of the three levels for all four controlling factors as shown in Table 5.24.

Table 5.24: Taguchi Calculations for Case 5

S.No.	Factors	Levels	Energy / Diesel Yields
1	Naphtha	1	816.7309 kW/kBPD
		2	832.6944 kW/kBPD
		3	854.7909 kW/kBPD
2	Kerosene	1	705.7136 kW/kBPD
		2	863.6506 kW/kBPD
		3	934.8519 kW/kBPD
3	Diesel	1	920.6541 kW/kBPD
		2	849.7610 kW/kBPD
		3	733.8010 kW/kBPD
4	AGO	1	705.0979 kW/kBPD
		2	874.9607 kW/kBPD
		3	924.1576 kW/kBPD

5.1.5.5 Response Plot

Response plot for Case 5 was drawn for the resulting E/V values obtained from the three levels of cutpoint temperatures of the four factors as shown in Figure 5.5.

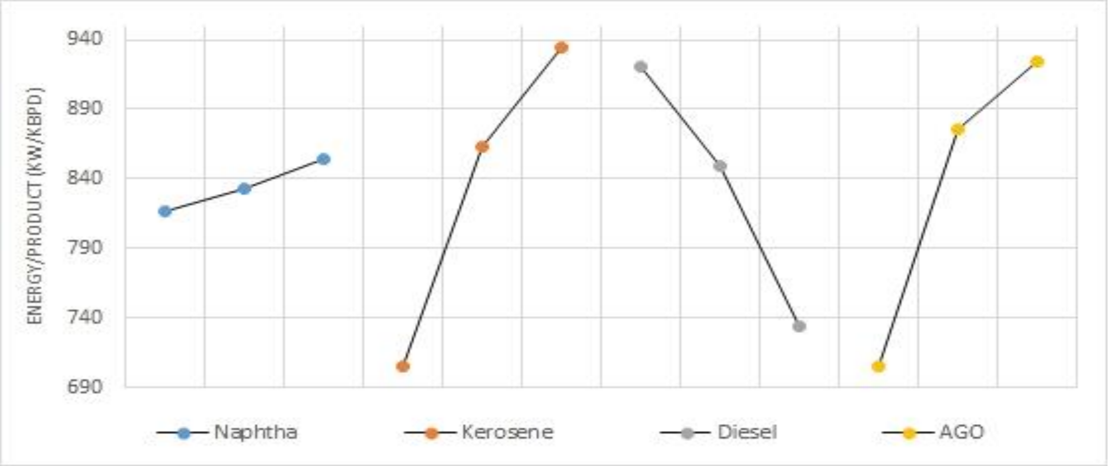


Figure 5.5: Taguchi response plot for Case 5 (Bobi + Zamzama Blend)

5.1.5.6 Taguchi Optimized Parameters

Cutpoint with minimum E/V parameters were selected from the response plot diagram. Optimized cutpoint temperatures are entered in Aspen HYSYS® model for Case 5 and the resulting optimized E/V and diesel draw rate is noted as shown in Table 5.25.

Table 5.25: Optimized Parameters for Case 5

S.No.	**Products**	**Optimized Parameters**
1	Naphtha Cutpoint Temperature	95°C
2	Kerosene Cutpoint Temperature	165°C
3	Diesel Cutpoint Temperature	265°C
4	AGO Cutpoint Temperature	365°C
5	Diesel Yield	22.2313 kBPD
6	Energy/Diesel Yield	532.2659 kW/kBPD

5.1.6 Case 6: Kunnar + Zamzama Blend

5.1.6.1 Straight Run Parameters

The straight run parameters were obtained by entering data of the crude feed according to Case 6 in the Aspen HYSYS® model as shown in Table 5.26.

Table 5.26: Straight run parameters for Case 6

S.No.	Products	Straight Run Parameters
1	Naphtha Cutpoint Temperature	142°C
2	Kerosene Cutpoint Temperature	170°C
3	Diesel Cutpoint Temperature	240°C
4	AGO Cutpoint Temperature	370°C
5	Diesel Yield	17.9171 kBPD
6	Energy / Diesel Yield	1072.7263 kW/kBPD

5.1.6.2 Levels and Factors

Three levels of the cutpoint temperatures of the four controlling factors were formed using the straight run cutpoint temperatures as the basis for Case 6 as shown in Table 5.27.

Table 5.27: Factors and levels for Case 6

S.No.	Factors	Level 1	Level 2	Level 3
1	Naphtha	137 °C	142°C	147 °C
2	Kerosene	165 °C	170 °C	175 °C
3	Diesel	235 °C	240 °C	245 °C
4	AGO	365 °C	370 °C	375 °C

5.1.6.3 Applying Orthogonal Array Matrix

L_9 (3^4) Orthogonal Array matrix was formed using the three levels and four factors for Case 6 and E/V value was calculated by manually entering the cutpoint temperatures for each trail in Aspen HYSYS® simulation as shown in Table 5.28.

Table 5.28: L_9 (3^4) Orthogonal Array of Case 6

Trails #	**Naphtha**	**Kerosene**	**Diesel**	**AGO**	**Energy/Product**
Trial 1	137 °C	165 °C	235 °C	365 °C	711.7695 kW/kBPD
Trial 2	137 °C	170 °C	240 °C	370 °C	725.9096 kW/kBPD
Trial 3	137 °C	175 °C	245 °C	375 °C	722.2421 kW/kBPD
Trial 4	142 °C	165 °C	240 °C	375 °C	1053.6182 kW/kBPD
Trial 5	142 °C	170 °C	245 °C	365 °C	935.8248 kW/kBPD
Trial 6	142 °C	175 °C	235 °C	370 °C	1209.0882 kW/kBPD
Trial 7	147 °C	165 °C	245 °C	370 °C	1052.4531 kW/kBPD
Trial 8	147 °C	170 °C	235 °C	375 °C	1350.1080 kW/kBPD
Trial 9	147 °C	175 °C	240 °C	365 °C	1210.7636 kW/kBPD

5.1.6.4 Taguchi Calculations

Taguchi calculations for Case 6 are carried out by taking the mean of the E/V for each of the three levels for all four controlling factors as shown in Table 5.29.

Table 5.29: Taguchi Calculations for Case 6

S.No.	Factors	Levels	Energy / Diesel Yields
1	Naphtha	1	719.9737 kW/kBPD
		2	1066.1771 kW/kBPD
		3	1204.4416 kW/kBPD
2	Kerosene	1	939.2803 kW/kBPD
		2	1003.9475 kW/kBPD
		3	1047.3646 kW/kBPD
3	Diesel	1	1090.3219 kW/kBPD
		2	996.7638 kW/kBPD
		3	903.5066 kW/kBPD
4	AGO	1	952.7860 kW/kBPD
		2	995.8170 kW/kBPD
		3	1041.9894 kW/kBPD

5.1.6.5 Response Plot

Response plot for Case 6 was drawn for the resulting E/V values obtained from the three levels of cutpoint temperatures of the four factors as shown in Figure 5.6.

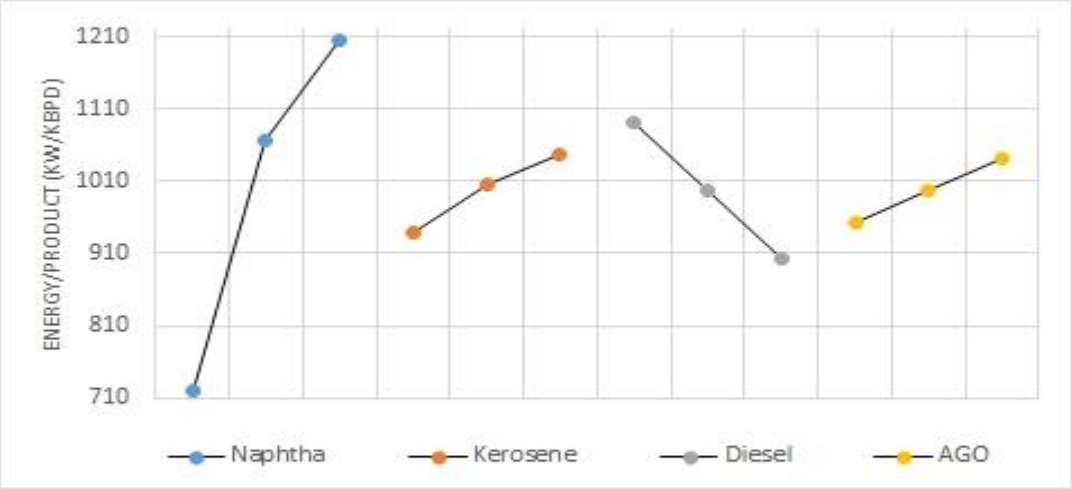


Figure 5.6: Taguchi response plot for Case 6 (Kunnar + Zamzama Blend)

5.1.6.6 Taguchi Optimized Parameters

Cutpoint with minimum E/V parameters were selected from the response plot diagram. Optimized cutpoint temperatures are entered in Aspen HYSYS® model for Case 6 and the resulting optimized E/V and diesel draw rate is noted as shown in Table 5.30.

Table 5.30: Optimized Parameters for Case 6

S.No.	**Products**	**Optimized Parameters**
1	Naphtha Cutpoint Temperature	137°C
2	Kerosene Cutpoint Temperature	165°C
3	Diesel Cutpoint Temperature	245°C
4	AGO Cutpoint Temperature	365°C
5	Diesel Yield	21.2102 kBPD
6	Energy/Diesel Yield	594.6953 kW/kBPD

5.1.7 Case 7: Bobi + Kunnar + Zamzama Blend

5.1.7.1 Straight Run Parameters

The straight run parameters were obtained by entering data of the crude feed according to Case 7 in the Aspen HYSYS® model as shown in Table 5.31.

Table 5.31: Straight run parameters for Case 7

S.No.	Products	Straight Run Parameters
1	Naphtha Cutpoint Temperature	96°C
2	Kerosene Cutpoint Temperature	145°C
3	Diesel Cutpoint Temperature	289°C
4	AGO Cutpoint Temperature	425°C
5	Diesel Yield	32.6028 kBPD
6	Energy / Diesel Yield	1900.2067 kW/kBPD

5.1.7.2 Levels and Factors

Three levels of the cutpoint temperatures of the four controlling factors were formed using the straight run cutpoint temperatures as the basis for Case 7 as shown in Table 5.32.

Table 5.32: Factors and levels for Case 7

S.No.	Factors	Level 1	Level 2	Level 3
1	Naphtha	91 °C	96 °C	101 °C
2	Kerosene	140 °C	145 °C	150 °C
3	Diesel	284 °C	289 °C	294 °C
4	AGO	420 °C	425 °C	430 °C

5.1.7.3 Applying Orthogonal Array Matrix

L_9 (3^4) Orthogonal Array matrix was formed using the three levels and four factors for Case 7 and E/V value was calculated by manually entering the cutpoint temperatures for each trail in Aspen HYSYS® simulation as shown in Table 5.33.

Table 5.33: L_9 (3^4) Orthogonal Array of Case 7

Trails #	**Naphtha**	**Kerosene**	**Diesel**	**AGO**	**Energy/Product**
Trial 1	91°C	140°C	284°C	420°C	1815.7584 kW/kBPD
Trial 2	91°C	145°C	289°C	425°C	1899.2102 kW/kBPD
Trial 3	91°C	150°C	294°C	430°C	1910.3010 kW/kBPD
Trial 4	96°C	140°C	289°C	430°C	1691.6151 kW/kBPD
Trial 5	96°C	145°C	294°C	420°C	1754.4040 kW/kBPD
Trial 6	96°C	150°C	284°C	425°C	2066.3829 kW/kBPD
Trial 7	101°C	140°C	294°C	425°C	1715.6409 kW/kBPD
Trial 8	101°C	145°C	284°C	430°C	1913.0470 kW/kBPD
Trial 9	101°C	150°C	289°C	420°C	2030.6295 kW/kBPD

5.1.7.4 Taguchi Calculations

Taguchi calculations for Case 7 are carried out by taking the mean of the E/V for each of the three levels for all four controlling factors as shown in Table 5.34.

Table 5.34: Taguchi Calculations for Case 7

S.No.	**Factors**	**Levels**	**Energy / Diesel Yields**
1	Naphtha	1	1875.0899 kW/kBPD
		2	1837.4673 kW/kBPD
		3	1886.4391 kW/kBPD
2	Kerosene	1	1741.0048 kW/kBPD
		2	1855.5537 kW/kBPD
		3	2002.4378 kW/kBPD
3	Diesel	1	1931.7294 kW/kBPD
		2	1873.8182 kW/kBPD
		3	1793.4486 kW/kBPD
4	AGO	1	1866.9307 kW/kBPD
		2	1893.7447 kW/kBPD
		3	1838.3210 kW/kBPD

5.1.7.5 Response Plot

Response plot for Case 7 was drawn for the resulting E/V values obtained from the three levels of cutpoint temperatures of the four factors as shown in Figure 5.7.

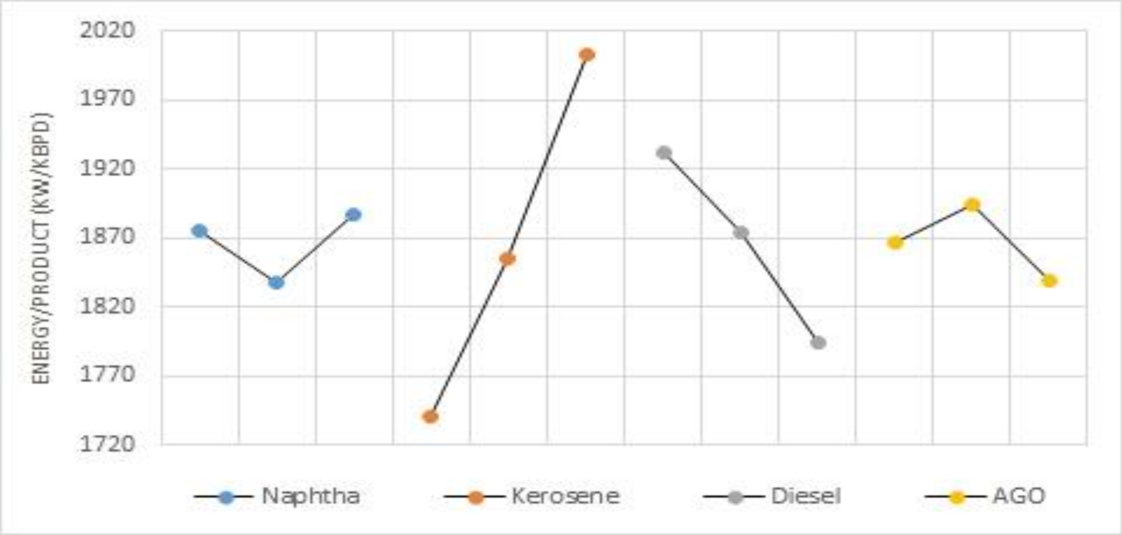


Figure 5.7: Taguchi response plot for Case 7 (Bobi + Kunnar + Zamzama Blend)

5.1.7.6 Taguchi Optimized Parameters

Cutpoint with minimum E/V parameters were selected from the response plot diagram. Optimized cutpoint temperatures are entered in Aspen HYSYS® model for Case 7 and the resulting optimized E/V and diesel draw rate is noted as shown in Table 5.35.

Table 5.35: Optimized Parameters for Case 7

S.No.	**Products**	**Optimized Parameters**
1	Naphtha Cutpoint Temperature	96°C
2	Kerosene Cutpoint Temperature	140°C
3	Diesel Cutpoint Temperature	294°C
4	AGO Cutpoint Temperature	430°C
5	Diesel Yield	36.5994 kBPD
6	Energy/Diesel Yield	1691.3749 kW/kBPD

5.2 Hybrid Approach Results

To achieve further optimization Genetic Algorithm was applied to the Taguchi optimized cutpoint temperatures of all seven crude feeds cases using the Aspen HYSYS® and MATLAB® interface. The application of Aspen HYSYS® and MATLAB® interface has already been described in section 3.3, and the mechanism of behind the working of Genetic Algorithm has been described in section 4.2.

Genetic Algorithm was applied with an upper and lower bound of ±2.5 °C of the Taguchi optimized cutpoint temperatures, population of 100, iteration of 10 Generations and Tolerance Function of 1e-4.

The comparison between straight run, Taguchi method and hybrid optimization approach is shown in Table 5.36 – 5.38 and Figures 5.8 – 5.9.

		UNIT	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7
Straight Run	Energy/Prod	kW/kBPD	718.2	1406.29	1104.12	1380.02	901.86	1072.72	1900.21
	Diesel Yield	kBPD	37.02	23.47	37.52	17.98	16.77	17.92	32.6
Taguchi Optimization	Energy/Prod	kW/kBPD	616.75	960.87	979.30	1010.44	532.26	594.69	1691.37
	Diesel Yield	kBPD	41.12	29.52	40.09	20.69	22.23	21.21	36.599
Hybrid Approach Optimization	Energy/Prod	kW/kBPD	530.08	898.91	895.41	712.16	438.65	481.2	1602.57
	Diesel Yield	kBPD	45.29	30.04	41.59	23.17	22.73	19.95	38.36

Table 5.36: Result Comparison: Straight Run vs. Taguchi vs. Hybrid Model

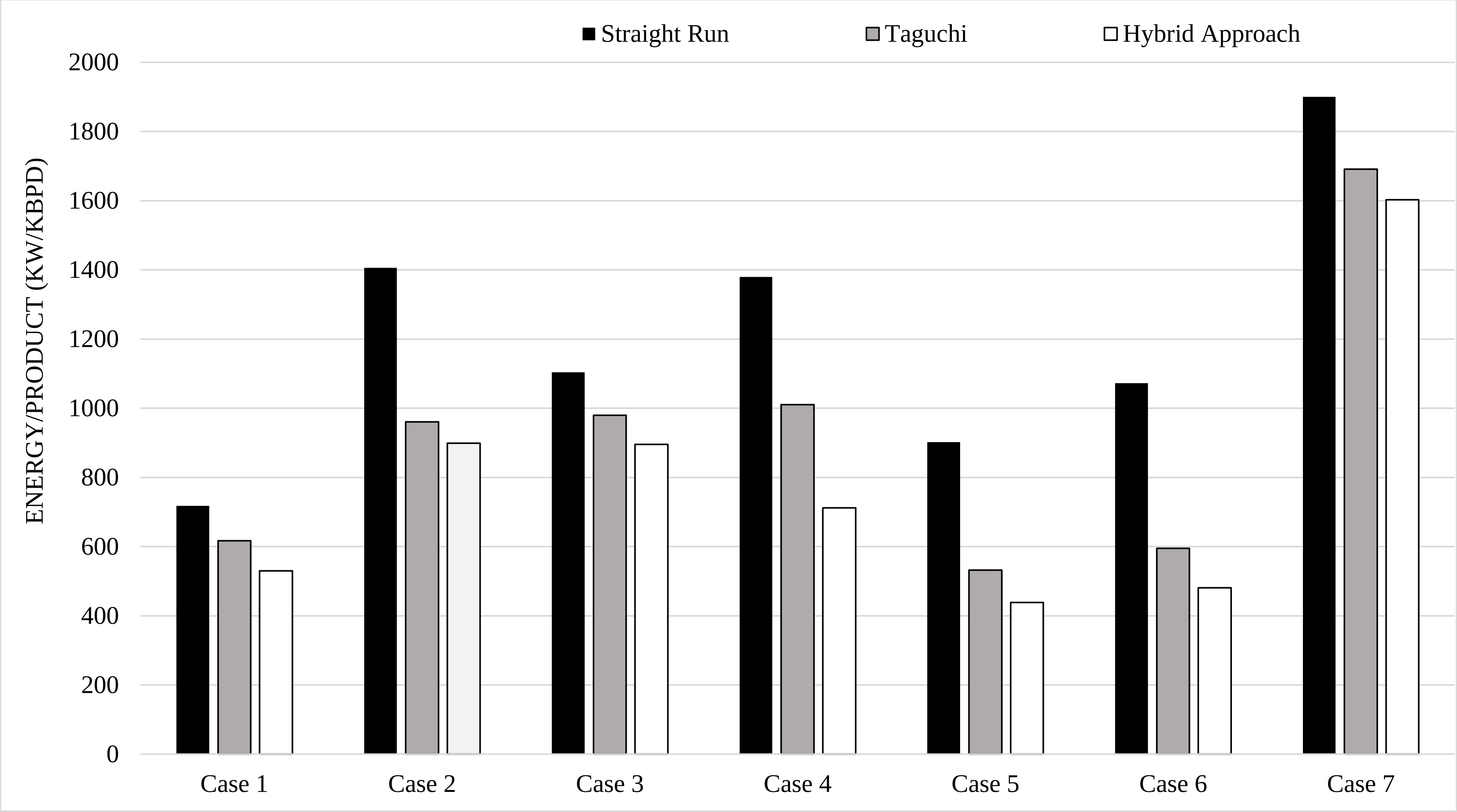


Fig. 5.8: Trend of energy required for a kilo barrel of diesel yield for 7 case studies

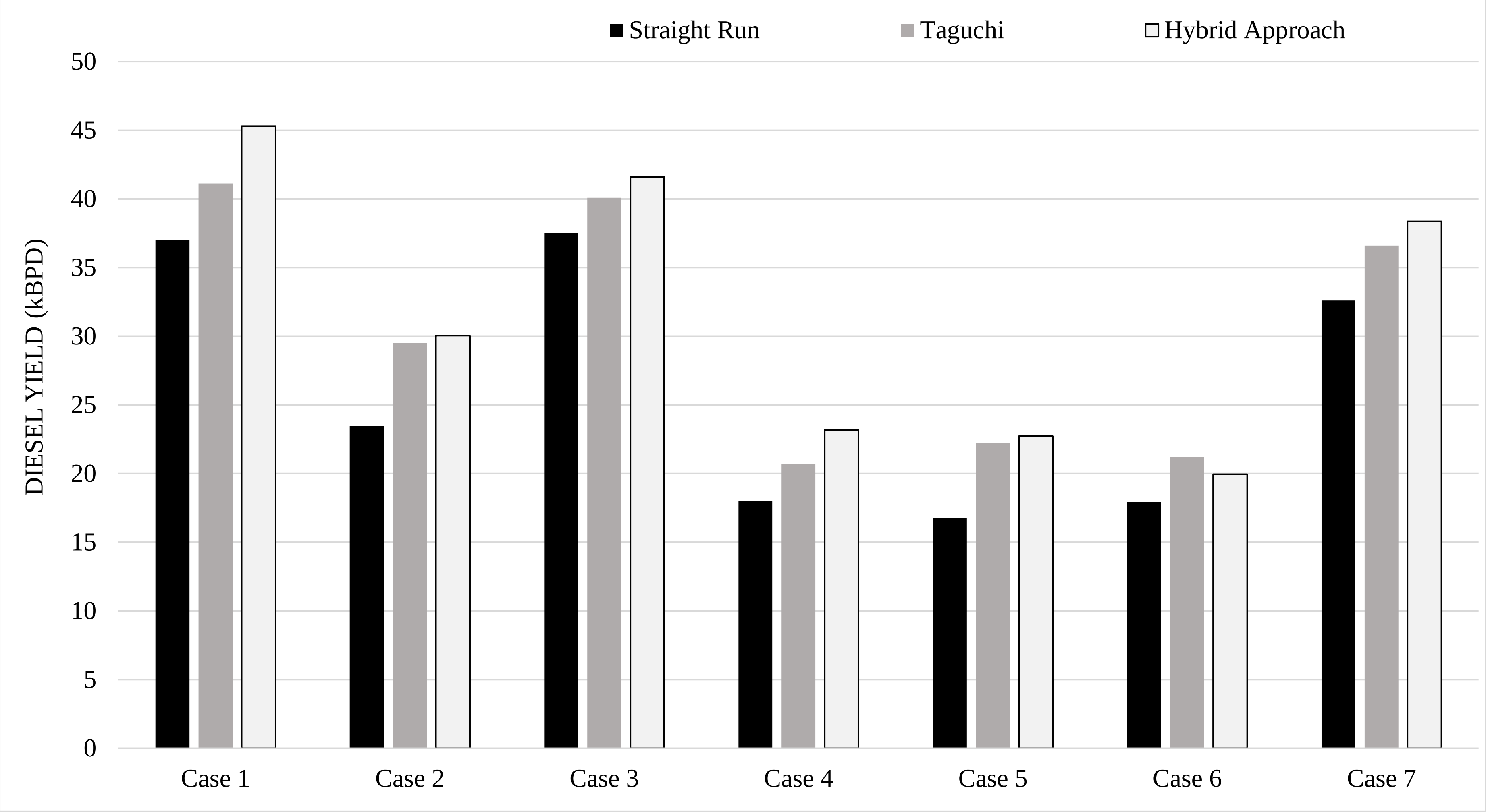


Fig. 5.9: Trend for increase in kBPD of diesel yield for 7 case studies

Results in Table 5.37 show optimization in energy for the CDU through the Taguchi and hybrid approach. In the Taguchi method, a significant amount 10.99% to 44.56% of energy was optimized for the production of kilo barrel of diesel. In case of hybrid approach, a much-optimized result from 15.66% to 55.14% was observed.

Table 5.37: Optimized percent of Energy / Diesel

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**
Taguchi Model	14.12%	31.67%	11.30%	26.78%	40.98%	44.56%	10.99%
Hybrid Model	26.19%	36.08%	18.90%	48.39%	48.64%	55.14%	15.66%

Results in Table 5.38 show the increase in diesel production rate through the Taguchi and hybrid approach. In the Taguchi method, an increase of 6.84% to 32.56% in the diesel production was observed. In case of hybrid approach, an increase of 11.33% to 35.54% in diesel production was observed.

Table 5.38: Optimized percent of Diesel production

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**
Taguchi Model	11.07%	25.77%	6.84%	15.09%	32.56%	18.36%	12.27%
Hybrid Model	22.34%	28.00%	10.84%	28.83%	35.54%	11.33%	17.67%

Chapter 6

Conclusion

In this research, a novel optimization approach is proposed for cutpoint temperatures optimization by hybridization of Taguchi and Genetic Algorithm. The proposed mechanism is applied to an Aspen HYSYS® based model of CDU for three Pakistani crudes, i.e., Bobi, Kunnar, and Zamzama. An interface for the Aspen HYSYS® CDU model with the MATLAB® for the application of Genetic Algorithm is also developed. Optimization of the cutpoint temperature is carried out on lowering the energy consumption per unit production product, diesel.

In the Taguchi method, a significant amount 10.99% to 44.56% of energy was optimized for the production of kilo barrel of diesel. In case of hybrid approach, a much-optimized result from 15.66% to 55.14% was observed.

Also, using the Taguchi method, an increase of 6.84% to 32.56% in the diesel production was achieved. In case of hybrid approach, an increase of 11.33% to 35.54% in diesel production was achieved.

References

1. Saharidis, G.K., M. Minoux, and Y. Dallery, *Scheduling of loading and unloading of crude oil in a refinery using event-based discrete time formulation.* Computers & Chemical Engineering, 2009. **33**(8): p. 1413-1426.
2. Muhammad, A. and R.B. de Vasconcellos Azeredo, *1 H NMR spectroscopy and low-field relaxometry for predicting viscosity and API gravity of Brazilian crude oils–A comparative study.* Fuel, 2014. **130**: p. 126-134.
3. Nedelchev, A., et al., *Boiling point distribution of crude oils based on TBP and ASTM D-86 distillation data.* Petroleum & Coal, 2011. **53**(4): p. 275-290.
4. Fahim, M.A., T.A. Al-Sahhaf, and A. Elkilani, *Fundamentals of petroleum refining*. 2009: Elsevier.
5. Liang, B., et al., *A novel scheduling strategy for crude oil blending.* Chinese Journal of Chemical Engineering, 2010. **18**(5): p. 777-786.
6. Robertson, G., A. Palazoglu, and J. Romagnoli, *Refining Scheduling of Crude Oil Unloading, Storing, and Processing Considering Production Level Cost.* Computer Aided Chemical Engineering, 2010. **28**: p. 1159-1164.
7. More, R.K., et al., *Optimization of crude distillation system using aspen plus: Effect of binary feed selection on grass-root design.* chemical engineering research and design, 2010. **88**(2): p. 121-134.
8. Gonçalves, D.D., F.G. Martins, and S.F. De Azevedo, *Dynamic simulation and control: application to atmospheric distillation unit of crude oil refinery.* Computer Aided Chemical Engineering, 2010. **28**.
9. Motlaghi, S., F. Jalali, and M.N. Ahmadabadi, *An expert system design for a crude oil distillation column with the neural networks model and the process optimization using genetic algorithm framework.* Expert Systems with Applications, 2008. **35**(4): p. 1540-1545.
10. Kelly, J.D., B.C. Menezes, and I.E. Grossmann, *Distillation blending and cutpoint temperature optimization using monotonic interpolation.* Industrial & Engineering Chemistry Research, 2014. **53**(39): p. 15146-15156.

11. Ali, S.F. and N. Yusoff, *Determination of Optimal Cut Point Temperatures at Crude Distillation Unit using the Taguchi Method.* 2012.

12. Eşme, U., *Application of Taguchi method for the optimization of resistance spot welding process.* Arabian Journal for Science and Engineering, 2009. **34**(2): p. 519.

13. Benali, T., D. Tondeur, and J.N. Jaubert, *An improved crude oil atmospheric distillation process for energy integration: Part I: Energy and exergy analyses of the process when a flash is installed in the preheating train.* Applied Thermal Engineering, 2012. **32**: p. 125-131.

14. Salahshoor, K., et al. *Practical design and implementation of a control loop performance assessment package in an industrial plant*. in *Control Conference (CCC), 2011 30th Chinese*. 2011. IEEE.

15. Roy, R.K., *A primer on the Taguchi method, Society of Manufacturing Engineers.* Ann Arbor, Mich, USA, 1990.

16. Jamaludin, K.R., et al., *Optimizing the injection parameter of water atomised SS316L powder with design of experiment method for best sintered density.* Chiang Mai J. Sci, 2009. **36**(3): p. 349-358.

17. Yusoff, N., M. Ramasamy, and S. Yusup, *A simulation study on dynamics and control of a refrigerated gas plant.* 2008.

18. Yang, K., E.-C. Teo, and F.K. Fuss, *Application of Taguchi method in optimization of cervical ring cage.* Journal of Biomechanics, 2007. **40**(14): p. 3251-3256.

19. Davis, L., *Handbook of genetic algorithms.* 1991.