Plant Wide Exergy Analysis of Petroleum Refinery

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Dedication

In honor of my parents, I have devoted my thesis to their constant support, encouragement, and love.

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Praising ALLAH, whose worth cannot be adequately expressed by words, whose riches cannot be tallied by calculators, whose summit of intellectual courage cannot be fully grasped by the deepest abysses of understanding, is due. His praise is due. His description is without limit, his eulogies are without edict, and His time is without end.

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Adil Sana

Abstract

In this work, plantwide exergy analysis of a petroleum refinery was conducted. An Aspen HYSYS® model of a petroleum refinery was used for collection of information to perform the exergy analysis. The plant wide model consisted of alkylation unit, reformer, naphtha hydrotreater, catalytic cracker, diesel hydrotreater, isomerization unit, hydrocracker, and kerosene hydrotreater. Seventeen (17) independent input streams and twenty-eight (28) output streams of the plant were considered for the analysis. The physical and chemical exergies of the streams were summed for assessing the overall exergy efficiency, exergy destruction, and improvement potentials of the plant. Exergy efficiency of the plant was 91.38% with exergy destruction of 704054.64 kW and exergetic improvement potential of 60707.50 kW. The current study gives an insight into the plant-wide transformation from physical exergies of the process streams and utilities into the chemical exergies of the fuels (product) produced in the refineries.

Keywords

Exergy analysis, Aspen HYSYS, Petroleum Refinery, Exergy Dstruction, Process Irreversibility, Exergy efficiency.

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Chapter 1

Introduction

1.1 Background

Energy has become the irrefutable key ingredient in all spheres of a modern world, from household to transport, infrastructure and agriculture. Prosperity and growth of any nation greatly relies 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 flexible approach is needed. The best way to fully utilize our resource is to increase efficiency of the process and bringing innovation to existing practice for this purpose. There is also recent growth observed in the renewable energy sector, mostly utilizing the solar and wind energy. Nevertheless, fossil fuels remain the persisting source of power.

1.1 Crude oil/Petroleum

Petroleum or crude oil also called “black gold” is liquid mixture which is very complex and found naturally. It mainly consists upon huge amount hydrocarbons and compounds of sulfur, oxygen and nitrogen. Waxes, fats and oils large molecules are broken down for the purpose of formation of petroleum which also results in the kerogen formation. This phenomena initiated millions of years ago, when small and tiny aquatic organisms prospered in the oceans and seas. As aquatic natural life died, it settled at bottom of the oceans and seas and became suppressed in deposits of clay, silt and sand. The regular deterioration by the effect of pressure and high temperature give rise to the formation of many different types of compounds. After the formation of petroleum, which is fluid in nature, it cannot move through the earth. Large oil pool and oil trap are required for formation of affordable petroleum refinery process. An *oil pool* is the basin of oil beneath the ground, may literally be a pool or it could be precipitations of oil collected in a highly porous rock such as sandstone. An *oil trap* is a non-porous rock formation that grasps the oil pool in one place. Apparently, in order to stay underground, the fluids – oil and associated gas – must be trapped, so that they cannot flow to the surface of the earth. The hydrocarbons gather in *reservoir rock,* the porous sandstone or limestone. The reservoir rock must have a lid of an impervious rock that will not allow the channel of the hydrocarbon fluids to the surface. After geologists of an oil company have positioned the general area in which petroleum is believed to be found, a well is drilled.

The raw form of the petrol is called crude oil which has low octane value. After process of refining, liquid fuels, lubricants, solvents and many other products are obtained which have higher octane values. (Speight et. al., 2002; Parkash, 2003; Hsuand Robinson, 2006; Gary et al., 2007; Speight, 2011a,b, 2014). The fuels resulting from petroleum subsidize nearly one-third to one-half of the whole world energy supply and are used not only for conveyance fuels (i.e., gasoline, diesel fuel, and aviation fuel, among others) but also to maintain the temperature of buildings. Petroleum products have a extensive diversity of practices that differ from gaseous and liquid fuels to near-solid equipment emollients. In addition, the residue of many refinery processes, asphalt—a once-maligned by-product—is now a finest value product for highway surfaces, roofing materials, and miscellaneous waterproofing uses.

1.1.1 Petroleum Refinery

Petroleum refinery process is required to make the finest usage of petroleum is first to isolate it into a small group of compounds. Petroleum processing is also called petroleum refiner. Petroleum refinery is the retrieval and/or production of usable or salable segments and products from crude oil, either by distillation or by chemical reaction of the crude oil constituents under the effects of heat and pressure [1]. There are different procedures for the production of different products. They can differ significantly with the kind of crude oil refined and with the settings of process of the refinery. The chief refinery processing units are diesel hydrotreater, kerosene hydrotreater, naphtha hydrotreater, catalytic cracker, hydrocracker, reformer, isomerization and alkylation unit. In short, petroleum refining is the parting of petroleum into fractions and the subsequent treating of these fractions to produce merchantable products (Speight and Ozum, 2002; Parkash, 2003; Hsu and Robinson, 2006; Gary et al., 2007; Speight, 2011a,b, 2014). The refining industry of petrol has been the theme of the four main forces that affect most industries and that have accelerated the expansion of new petroleum refining processes:

1. The demand for products such as gasoline, diesel, fuel oil, and jet fuel.
2. Feedstock supply, specifically the changing quality of crude oil and geopolitics between different countries and the emergence of alternate feed supplies such as bitumen from tar sand, natural gas, and coal.
3. Environmental regulations that include more stringent regulations in relation to sulfur in gasoline and diesel.
4. Technology development such as new catalysts and processes.

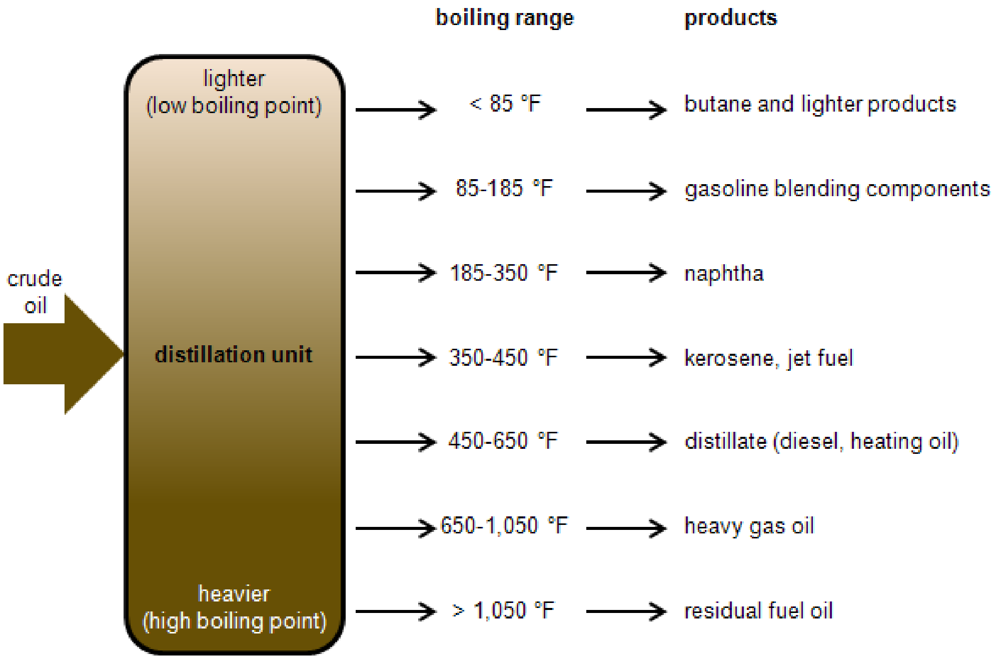

Figure 1 Crude Oil Distillation Units and Products(Source: U.S. Department of Energy Information Administration)

Petroleum refinery processes due to its highly demanded products, diesel fuel, kerosene, liquefied petroleum gas, jet fuel. The main refinery processing units are diesel hydrotreater, kerosene hydrotreater, naphtha hydrotreater, catalytic cracker, hydrocracker, reformer, isomerization and alkylation unit. Petroleum refinery is an energy-intensive industry. Thus, it is constantly anticipated to intensify the energy efficiency of the process to make it more practicable and maintainable.

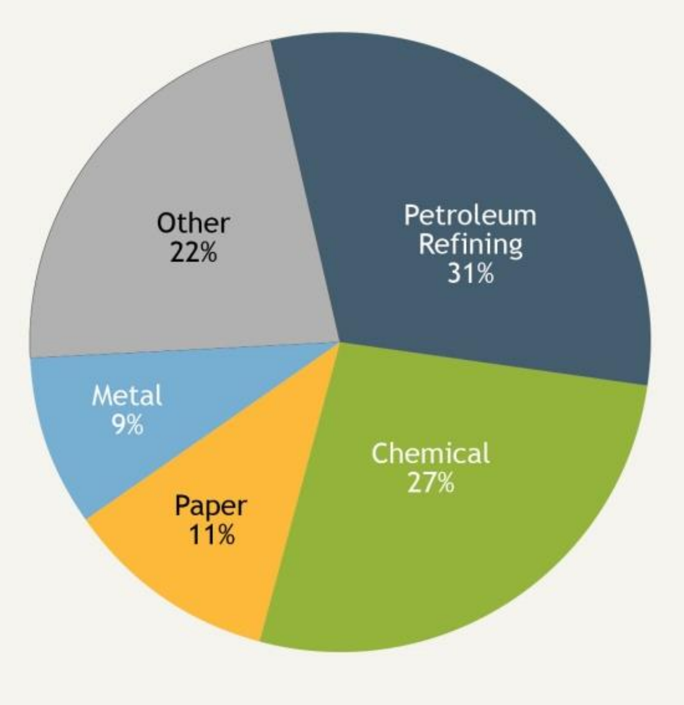

Figure 2 Energy use in 2010

By the comparison of data of the utilization of energy in different industries, it is inferred that energy use of petroleum refining is maximum having percentage of about 31.

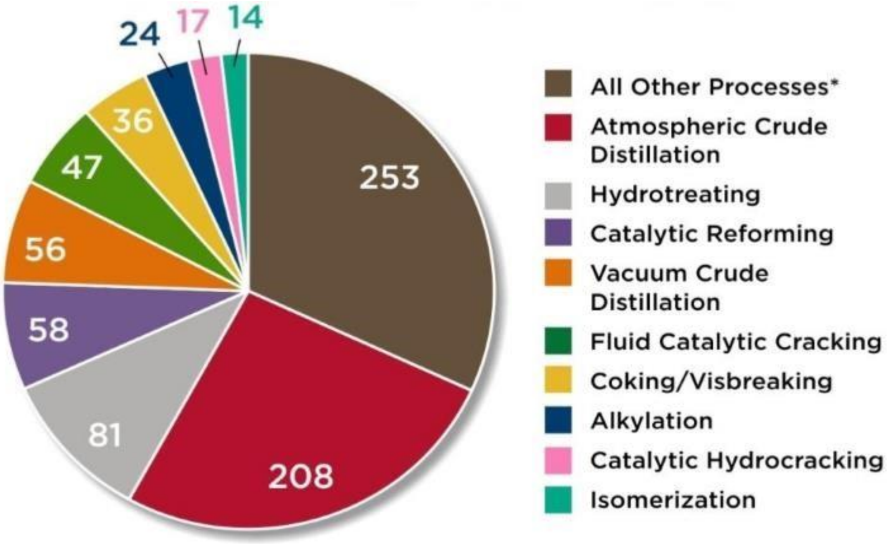

Figure 3 Energy Saving Opportunities by Petroleum Refining Process Studies (Energy Savings Per Year in Trillion BTUs) (Source: U.S. Department of Energy 2015)

From the above figure, it can be inferred that in the petroleum refinery atmospheric petroleum refinery is the process in which most amount of energy can be saved almost about 208 Trillion BTUs per year following hydrotreating process and catalytic reforming process having value of about 81 Trillion BTUs per year and 58 Trillion BTUs per year respectively.

For apprehending an energy efficient design, the perception of exergy (useable energy) has been receiving the consideration of scientists and process engineers (Hinderink et al., 1996). Exergy analysis, which integrates both the first and the second laws of thermodynamics, empowers the process engineers proficient to classify, calculate and diminish the effect of irreversibilities and also to comprehend further energy efficient processes. (Querol et al., 2011).

1.1.2 Pakistani Crude Oil Production

Pakistan's petroleum reserves are estimated to contain over 9 billion barrels of crude oil and around 105 trillion cubic feet of shale oil and natural gas, according to the US Energy Information Administration (EIA). Pakistan imports crude oil and refined petroleum products on a net basis. According to FACTS Global Energy, crude oil imports increased by 12% annually between 2014 and 2015.

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.

Pakistan's oil consumption has increased steadily over time, reaching an average of 431 kBPD in 2015, greatly exceeding local output. Reduced oil prices and natural gas shortages have boosted oil usage, notably in the transportation and energy sectors. Pakistan presently has six petroleum refineries that operate mostly on imported crude oil and have a combined crude oil processing capacity of 390 kBPD. Pakistan State Oil, a state-owned corporation, has announced plans to construct a new refinery capable of processing between 200 and 250 thousand barrels per day of crude oil.

From 1994 to 2016, crude oil output in Pakistan averaged 65.74 kBPD, hitting an all-time high of 95 kBPD in January 2015. 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.

1.2 Thesis Outline

The rest of the thesis is ordered as follows. Chapter 2 discuss the literature review. Chapter 3 describes the process flow diagram of petroleum refinery in section 3.1 and in section 3.2, the brief introduction of input and output streams, and describe fundamentals of exergy analysis in section 3.3 followed by methodology in section 3.4. The calculated results are ranked and improvement of calculated parameters has been discussed in the Chapter 4 following conclusions of the work.

Chapter 2

Literature Review

2.1 Theoretical background

Worldwide challenges with environmental deprivation and restricted fossil assets have made it necessary for the sustainable use of energy, which requires a complete evaluation of energy use to improve the energy-intensive processes [2]. Assets have driven the search for optimum and sustainable operation of industries. Energy of 794 TBTU/year (26%) could be saved in petroleum refinery by adopting efficient operation and technological upgradation according to the report of US Department of Energy. For realizing energy efficient operation a quest for robust energy analysis mechanism is being investigated [3]. These evaluations also increase the profitability and the sustainability of processes of production. Energy analysis is the most widely used and conventional method for this purpose which is based on first law of thermodynamics and deals with the quantity of energy through processes and not the quality[2].

The effective use of energy can only be assessed by the consideration of both the first law of thermodynamics and the second law of thermodynamics, that is, by smearing the concept of exergy. In this concept, the quality of energy and its degradation in real procedures is accounted. Almost one century ago, the basic concept behind exergy was laid and ample individuals contributed to the practice and principles of the exergy. From 1930s to 1950s, the work on exergy got accelerated. Keenan (1951) and Rant (1956) introduced the concept of exergy in process industry [3]. The energy crises of the early 1970s further pushed researcher toward to find means for realizing energy efficient processes that trigger the use of exergy analysis. The progress during 1980s are summarized by Kotas (1985) and Szargut et al. (1988). In a study by Moran (1990) key contributions up to 1990s was reported. Other notable work on exergy are Boehm et al. (1992), Kouremenos et al. (1991), Reistad et al. (1991), Stecco and Moran (1990, 1992), Tsatsaronis et al. (1990), and Valero and Tsatsaronis (1992)[4].

2.2 Simulators based Exergy Analysis

For the purpose of process simulation process simulators are widely used such as Aspen HYSYS, Aspen Plus and CHEMCAD. However, most of these simulators do not contain the built-in functionality for calculation of complete exergy analysis (physical, chemical and mix exergy) and chemical), which is their drawback. Other environments have been used for the exergy analysis to cross this limitation, such as MatLab, Microsoft Excel and Fortan. They are connected with the process model simulated in simulators for the purpose of analyzing exergy efficiency of the process. "On-Line Exergy Analysis (Olexan)" is a tool for calculating exergy and is created using Visual Basic Application.

Li et al. develop Aspen Plus model of Liquid from coal (LFC) for exergy analysis. [5] K ochunni et al. also used Aspen HYSYS version 8.6 for comparison of reverse Brayton and Kapitza based LNG boil-off gas reliquefication system using exergy analysis. The process of CO_2 removal process from syngas using methyldiethanolamine activated by piperazine (a-MDEA) was modelled in Aspen HYSYS and visual basic code was integrated with Aspen HYSYS for performing exergy analysis[6]. Sánchez et al. did Exergy analysis of offshore primary petroleum processing plant with CO_2 capture [7]. Ojeda et al. did exergy analysis of enzymatic hydrolysis reactors for transformation of lignocellulosic biomass to bioethanol with the help of Aspen HYSYS[8]. Ojeda et al. used computer based tools of process engineering of energy analysis and exergy analysis, and LCA, using Aspen-HYSYS, Aspen HX-NET, and SimaPro life cycle assessment software for the identification of environmental impacts as well as exergy losses in the biofuels production process from lignocellulosic biomass[9]. Sheikhi et al. did Advanced Exergy Evaluation of an Integrated Separation Process with Optimized Refrigeration System using aspen HYSYS[10]. Stéphane Gourmelon used ProSimPlus for the purpose of process simulation and Exergy Analysis[11]. Ghannadzadeh et al. discussed the general methods for exergy balance in ProSimPlus process simulator[12].

All these process simulators have their drawbacks and limitation according to the different industries. All the process simulators do not deal with all the industries. As concerned with petroleum industry, the Aspen Plus cannot be used as it does not contain such specified equipment's which are specially used in petroleum industry. However, its merit is that it contains built in function of calculation of exergies. To deal with these limitations an Aspen HYSYS® based model of the Petroleum refinery is selected as Aspen HYSYS is specifically designed by keeping in mind of petroleum industry.

Exergy analysis of various processes of petroleum refineries have been performed and reported in literature. The use of Aspen HYSYS simulator, the subject of this study, has been reported for exergy analysis of various process units of the refinery. For instance, Ricardo et al. did exergy analysis on the crude oil mixtures and fractions, crude oil combined distillation unit also did exergoeconomic analysis, according to which cost of raw crude oil is the basic factor which affect the cost of production, transformation and operation costs. [13, 14]. Anozie et al. did exergy analysis on distillation column by the help of Aspen HYSYS and MS Excel and concluded that irreversibility rate and exergy efficiency will increase and decrease respectively by increasing the reference temperature. [15]. Darabi et al. also performed exergy analysis of distillation column with the help of Aspen HYSYS on stage by stage and found that splitted feed base case is highest efficient with the value of 95.70% and lowest rate of overall exergy[16]. Mestre-Escudero et al. did Process Simulation and Exergy Analysis of a Mercaptan Oxidation Unit in a Latin American Refinery using Aspen HYSYS. The basic case was found to be 84.21% exergy efficient while the other case having more technical improvement was found 81.95%. Although the basic case is more exergy efficient but in terms of product quality the alternative case was found better. [17]. Hu et al. did exergy analysis and optimization of Natural Gas Liquid Recovery Processes, according to which air cooler and column contributes more total exergy destruction[18]. The Exergy analysis is done on specific process or unit, like Rivero et al. did exergy analysis on diabatic distillation, absorption heat pumps, coking–gasification-combined cycle co- and tri-generation, fuel cells according to which distillation unit of isomerization unit, reactive distillation system and diabetic distillation unit have exergy losses of 54%, 55% and 65% respectively[19]. Junior et al. did exergy analysis on offshore platforms separation processes of petroleum refiner and found that in plant, major exergy consumers are compressions and heating operations.[20] Caballero et al. use process simulator PRO/II and did exergy analysis on FCC plant separation processes and concluded that fractionator column has maximum energy optimization potential[21]. Ibrahim et al did exergy study on stripper of delayed coker and found that it is 81.58% exergy efficient [22]. Lei et al. did thermodynamic analysis on preheating and fractionating process of delayed coker and concluded that preheating of feed is best for energy optimization and built an HEN(Heat Exchanger Network) by considering this aspect[23]. Lei et al. did exergy analysis on integrated heat exchange and fractionating processes of delayed coking units, according to which it is 97.3% exergy efficient and 38.1% improvement potential[24]. Chen et al. proposed improved flowsheet of delayed coking units and did exergy analysis, according to which 37.2% of energy consumption can be decreased[25]. Li et al. did exergy analysis on multi stage crude distillation unit and found that the amount of optimal stages of CDUs rest on the heat integration's exergy efficiency[26]. Akram et al. did exergy, uncertainty analysis and optimization of naphtha reforming process using Asper Plus, MatLab[27]. Agbo et al. did Naphtha hydrotreating unit exergy analysis using Aspen HYSYS, according to which column and heater has 21.4% and 14.6% exergy destruction and two heater has lowest exergy efficiency of 23.9% and 50.0%[28]. Bandyopadhyay et al. did exergy and pinch analysis on diesel hydrotreating unit and found that the exergy efficiency can be enhanced in letdown valves, air coolers and fired heaters[29]. Chegini et al. applied exergy analysis on hydrocracking process and found that from hot stock flue gasses 5.96MW exergy can be recovered[30]. Mutairi et al did fluid catalytic cracking unit's exergy analysis and concluded that there is 3.83MW decrease of process stream exergy losses in proposed network[31]. Nuhu et al. also did exergy and energy analysis on FCC unit and found that 61.2 percent exergy of system and fractionator has more energy losses[32]. Kafrudi et al. did exergy analysis also on FCC for the purpose of environmental study and found that waste gas has more than 660 MW exergy losses[33]. Ibrahim et al. applied exergy analysis on amine regeneration unit and concluded that regenerators and air coolers have 80% and 9% of overall exergy destruction respectively[34].

To the best of the author’s knowledge, no report has been reported on plant wide exergy analysis. Contribution of this work is listed below:

- Physical exergy of all input and output streams are calculated in Aspen HYSYS.
- Chemical exergy of all input and output streams of plant wide model of refinery are calculated.
- Exergy destruction, exergetic improvement potential and exergy efficiency of the plant are calculated based on physical and chemical exergy of all input and output streams.

Chapter 3

Process Description

In this section, the main process of petroleum refinery has been explained followed by the explanation of Aspen HYSYS model of petroleum refinery.

3.1 Process Flow Diagram of Petroleum Refinery

The units of petroleum refinery are delayed coker, catalytic cracking unit, hydrotreaters, reformer, hydrocracker, saturated gas plant, unsaturated gas plant, alkylation unit, amination unit, hydrogen plant, isomerization unit. Process flow diagram of petroleum refinery plant is shown in Figure 5. A delayed coker (DLC coker) is one of the types of coker which consists of furnace of multiple passes and heat the residual oil feed to its thermal cracking temperature. This produces petroleum coke and coker gas oil by conversion of long chain and heavy hydrocarbon molecules of the residual oil [37]. Catalytic cracking (CCU cat cracker) in petroleum refinery is a conversion process which produces gasoline, olefinic gases, and other petroleum products by converting the hydrocarbon fractions, high molecular weight and high boiling point of crude oils. Originally the process of thermal cracking was used for cracking of petroleum hydrocarbons but now almost it has been totally replaced by catalytic cracking, as it yields greater volumes of high-octane rating gasoline; and produces by-product gases, with more carbon-carbon double bonds (i.e. olefins), which are of greater financial values than the gases produced by thermal cracking[37]. In the Diesel hydrotreating (DHT Dist Hydrotreater) also called catalytic hydrogen treating is required to reduce unwanted components from straight-run diesel fraction at moderate pressures and higher temperatures in a reactor by selectively reacting these components with hydrogen [38]. For the production of products specifically suitable for marketing and commercial purposes such as jet fuel and kerosene, the kerosene hydrotreating (KHT Kero Hydrotreater) is used for upgradation of raw kerosene distillate. The problem of corrosion in fuel handling, aircraft engines and storage facilities can occur due to sulfur and mercaptans present in the raw kerosene cuts which come from the crude distillation unit while the problem of color stability in product is caused by the presence of nitrogen in the raw kerosene feed from some crude oils [39]. NSP Naphtha splitter is a splitting unit which splits hydrotreated naphtha in to heavy naphtha and light naphtha. The feed of the reformer is prepared by the removal of nitrogen and sulfur from the heavy naphtha streams which is treated by the help of naphtha hydrotreater (NHT Naphtha Hydrotreater) which is type of hydrotreater [40]. Catalytic Reformer (LPR Reformer) in which process of catalytic reforming occurs which produce major blending product for gasoline by converting low-octane straight run naphtha fractions (mainly naphtha which have more quantity of naphthenes called heavy naphtha) into low sulfur and high-octane reformate. The byproduct of catalytic reformer is Hydrogen which is the most valuable product as it is needed in processes of hydrocracking and hydrotreating processes whose demand has been increased in refineries [41]. Hydrocracker unit (HCD hydrocracker) is unit where process of hydrocracking takes place. The process of hydrocracking takes place in the hydrocracker which produce the high value transportation products and petrochemical feedstocks by conversion of low value petroleum feed-stocks [42]. SGP Sat Gas Plant separates the gas liquids from the refinery gas coming from the distillation units and other process units. The wet gas streams from the fraction receivers, TCC, overhead accumulators of delayed coker and FCC is used in UGP Unsat Gas Plant for recovery light hydrocarbons (C_3 and C_4 olefins). Alkylation unit (SFA Sulf Acid Alkylation) is unit where alkylation process takes place. An alkylation unit (alky) is a conversion process in which high octane gasoline, alkylate is produced by the conversion of isobutane and low-molecular-weight alkenes (mainly a blend of propene and butene) in petroleum refinery in the presence of acid catalyst such as sulfuric acid (H_2SO_4). The AMN Amine is where Amine gas treating occurs, also known as amine acid gas removal, gas sweetening and scrubbing, which are the group of processes that is required for the removal of carbon dioxide (CO_2) and hydrogen sulfide (H_2S) from gases by utilizing the aqueous solutions of numerous alkylamines (amines)[43]. As heavy amount of hydrogen is produced in petroleum refineries which is utilized in the process of hydroconversion and hydrotreating but in most of the cases Even though refineries yield a substantial amount of hydrogen required for hydrotreating and hydroconversion processes but in many cases, more hydrogen is required primarily for sour crudes to make them more refined. So, to meet the demand of Hydrogen, hydrogen plant (HYD Hydrogen Plant) is required in petroleum refinery. For the purpose of preparation of feed of alkylation unit, isobutane is required which is produced by the conversion process called isomerization process occurs in isomerization unit (IS4 C4 Isom) in petroleum refinery from the normal butane (n-C4). Fuel system (PFS Plant Fuel System) which is required in petroleum refinery for the purpose of collection, preparation and distribution of gas fuel and liquid fuel, which are provided to the operating units when and so required[44]. SRU Sulfur Recovery denotes unit which recover elemental sulfur by conversion from hydrogen sulfide(H_2S). For this purpose, Claus process is used [45]. Gasoline, Distillate and Fuel Oil Blending processes are the final step in petroleum refinery process in which final finished product is obtained by the mixing of optimum blend of components among various petroleum streams. Splitting unit (TEE-100) splits stream. Mixing unit (MIX-100) mix streams.

3.2 Aspen HYSYS Mode of Petroleum Refinery

Petroleum shift reactors (short-cut models for refinery reactors) are used in the simulated petroleum refinery wide aspen HYSYS model to make flowsheet. Granular set of pseudo-components (of the order of 50-70 components) are added to signify the crude that represent the petroleum assays in the basis environment of Aspen HYSYS. Crudes of two kings have been used which are sour crudes of Arab Light, Arab Heavy and Bachequero and sweet crudes of Alaska North Slope, Forties Blend and Tiajuana Light. Vacuum and atmospheric distillation columns are simulated utilizing short-cut distillation column in which the sour crude and sweet crude are separately processed. Petroleum shift reactors has been used for the simulation of all of the main petroleum refinery equipments which are diesel hydrotreater, naphtha hydrotreater, kerosene hydrotreater, catalytic cracker, alkylation, hydrocracker, isomerization and reformer. The base of the models is delta base shift concept. Every model is denoted by the key dependent variable set which are usually utilities, product flowrates and product qualities etc. and the key independent variables set which are usually feed qualities and feed flowrates with their basic state values quantified. This concept is called delta base shift concept. The independent variables utilizing the linear equations set whose coefficients are derivatives of independents with respect to the dependents at the base point are utilized for the calculation of dependent variables for the varied base point conditions. In Aspen HYSYS petroleum refinery model, the first principles models are available which are usually utilized for the calculation of derivatives.

3.3 Streams of Petroleum refinery

Input and output streams considered in this plant are discussed in section 3.3.1 and 3.3.2 respectively.

3.3.1 Input Streams

The input streams considered for this analysis shown in PFD are table in Table 1.

Table 1 Input streams data

Input	**Flowrate kg/h**
CD2 Feed	350200.00
CD1 Feed	233300.00
Purchased C4M	7277.29
iC4	17843.82
H2S adjusted to SAMN	1637.03
Natural Gas	339.61
hyl to DHT	34.15
h2 to KHT	29.74
hyl to NHT	102.02
hyh to HCD	2010.61
h2 to Isom	9.40
hyl to PFS	2025.30
Purchased nC4	12840.00
H2S adjusted to SRU	1799.93
Total Sul	589.96
hyl to TGT	0.02

The “CD1 Feed” and “CD2 Feed” streams are of sweet and sour crudes respectively. “Purchased C4M” is the stream which consist of i-Butane, 1-

Butene and n-Butane and in petroleum refinery this stream is input of the Unsaturated Gas Plant which is denoted by “UGP Unsat Gas Plant” in the process flow diagram. “iC4” consist of i-butane and input of “SFA Sulf Acid Alkylation”. “H2S adjusted to SAMN” consist of H_2S and input of AMN Amine. “Natural Gas” consist of Methane and input of HYD Hydrogen Plant. “hyl to DHT” consist of hydrogen and input of DHT Dist Hydrotreater. “h2 to KHT” consist of hydrogen and input of KHT Kero Hydrotreater. “hyl to NHT” consist of hydrogen and input of NHT Naphtha Hydrotreater. “hyh to HCD” consist of hydrogen and input of HCD hydrocracker. “h2 to Isom” consist of hydrogen and input of IS4 C4 Isom. “hyl to PFS” consist of hydrogen and input of PFS Plant Fuel System. “Purchased nC4” consist of n-Butane and input of IS4 C4 Isom. “H2S adjusted to SRU” and “Total Sul” both streams consist of H_2S and they are inputs of SRU Sulfur recovery.

3.3.2 Output Streams

The output streams considered for this analysis shown in PFD are table in Table 2.

Table 2 Output streams data

Output	**Flowrate Kg/h**
VR2 to Fuel Oil	9.62
DLC Coke	5407.00
NSP water	0.01
SGP c5+ and others	9.38
iC4 to SFA	2094.00
SFA nc3	4283.98
Alk. loss	509.29
IS4 to SFA	17880.00
H2S total	4988.80
h2 to HCD	2010.61
hyl	0.00
hyl from SLPR	2200.63
PFS C1 to HYD	4749.92
C2+ to Fuel	21839.21
H2S to SRU	5485.00
Sulfur	589.96
Total Sul	589.96
URG Regular	222600.00

UPR Premium	5004.00
LRG Leaded Reg	26090.00
JET Kero/Jet	68110.00
Dist loss	0.00
HSF Hi Sulfur Fuel Oil	20190.00
LSF Low Sulfur FuelOil	72131.85936
FO loss	1.539
Diesel	106701.3845
Export Diesel	573.7667075
LPG	32890

"VR2 to Fuel Oil" consist of pseudo-components and output of Crude Units. "DLC Coke" consist of pseudo-components and output of DLC Coker. "SGP c5+ and others" consist of Hydrogen, Ethylene, H_2S, Propene, 1-Butene and pseudo-components and output of X-100. "iC4 to SFA" consist of i-Butane and output of SGP Sat Gas Plant. "SFA nc3" consist of Propane and output of SFA Sulf Acid Alkylation. "Alk. loss" consist of pseudo-components and output of TEE-100. "IS4 to SFA" consist of i-Butane and stream in SFA Sulf Acid Alkylation. "H2S total" consist of H_2S and output of MIX-100. "h2 to HCD" and hyl from SLPR" consist of Hydrogen and output of HYD Hydrogen Plant. "PFS C1 to HYD" consist of Methane and output of PFS Plant Fuel System. "C2+ to Fuel" consist of Hydrogen, Ethylene, Ethane, Propane and pseudo-components and output of PFS Plant Fuel System. "H2S to SRU" consist of H_2S and output of SRU Sulfur Recovery. Sulfur" consist of pseudo-components and output of SRU Sulfur Recovery. "Total Sul" consist of H_2S and output of SRU Sulfur Recovery. "URG Regular" and "UPR Premium" consist of n-Butane and pseudo-components and output of Gasoline Blending. "LRG Leaded Reg" consist of n-Butane and pseudo-components and output of Gasoline Blending. "JET Kero/Jet" consist of pseudo-components and output of Distillate Blending. "HSF Hi Sulfur Fuel Oil, LSF Low Sulfur Fuel Oil and FO loss" consist of pseudo-components and outputs of Fuel Oil Blending. "Diesel and Export Diesel" consist of pseudo-components and outputs of TEE-100. "LPG" consist of Propane and traces of i-Butane and output of MIX-100.

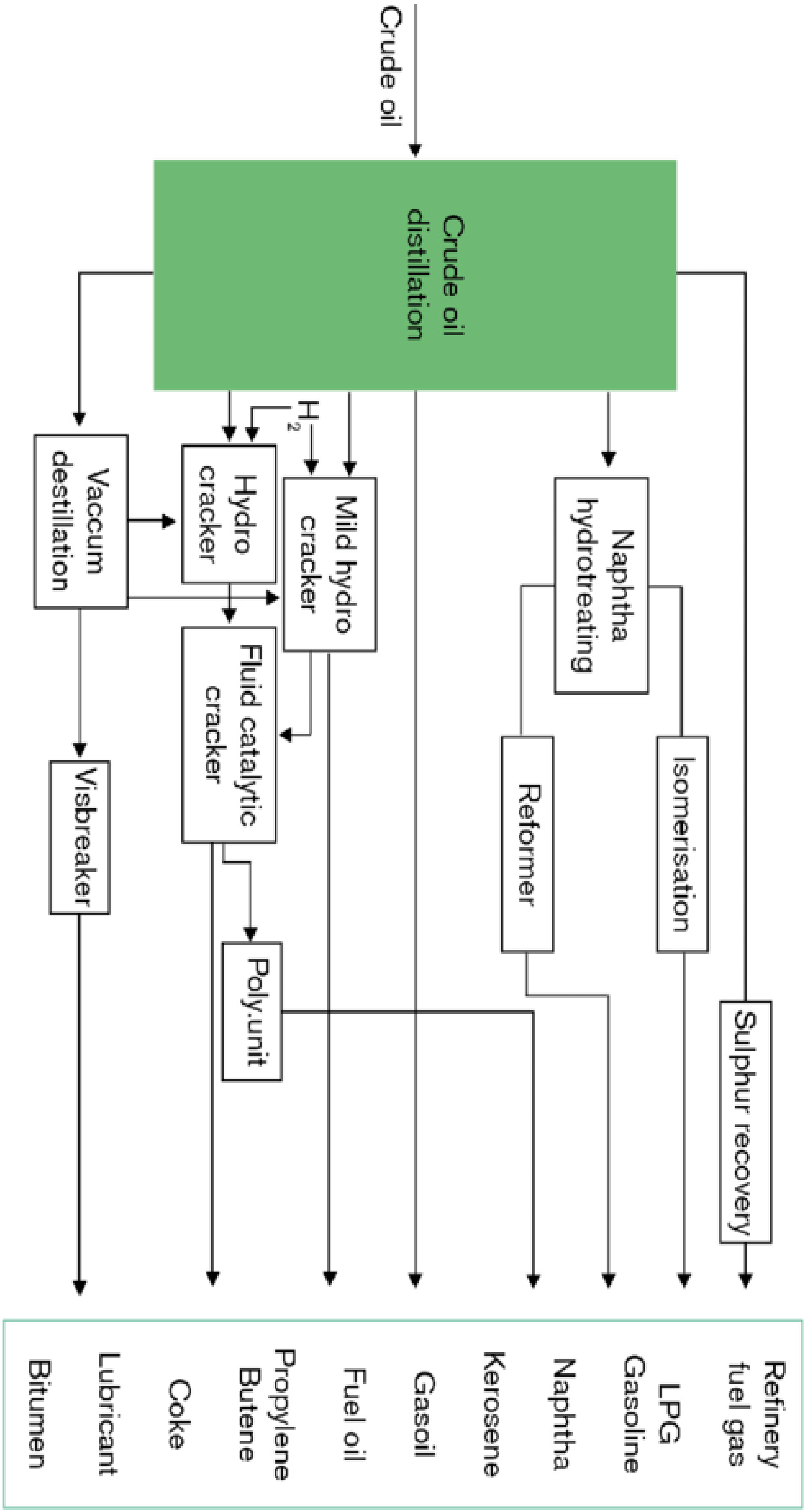

Figure 4 Block Flow Diagram of Petroleum Refinery

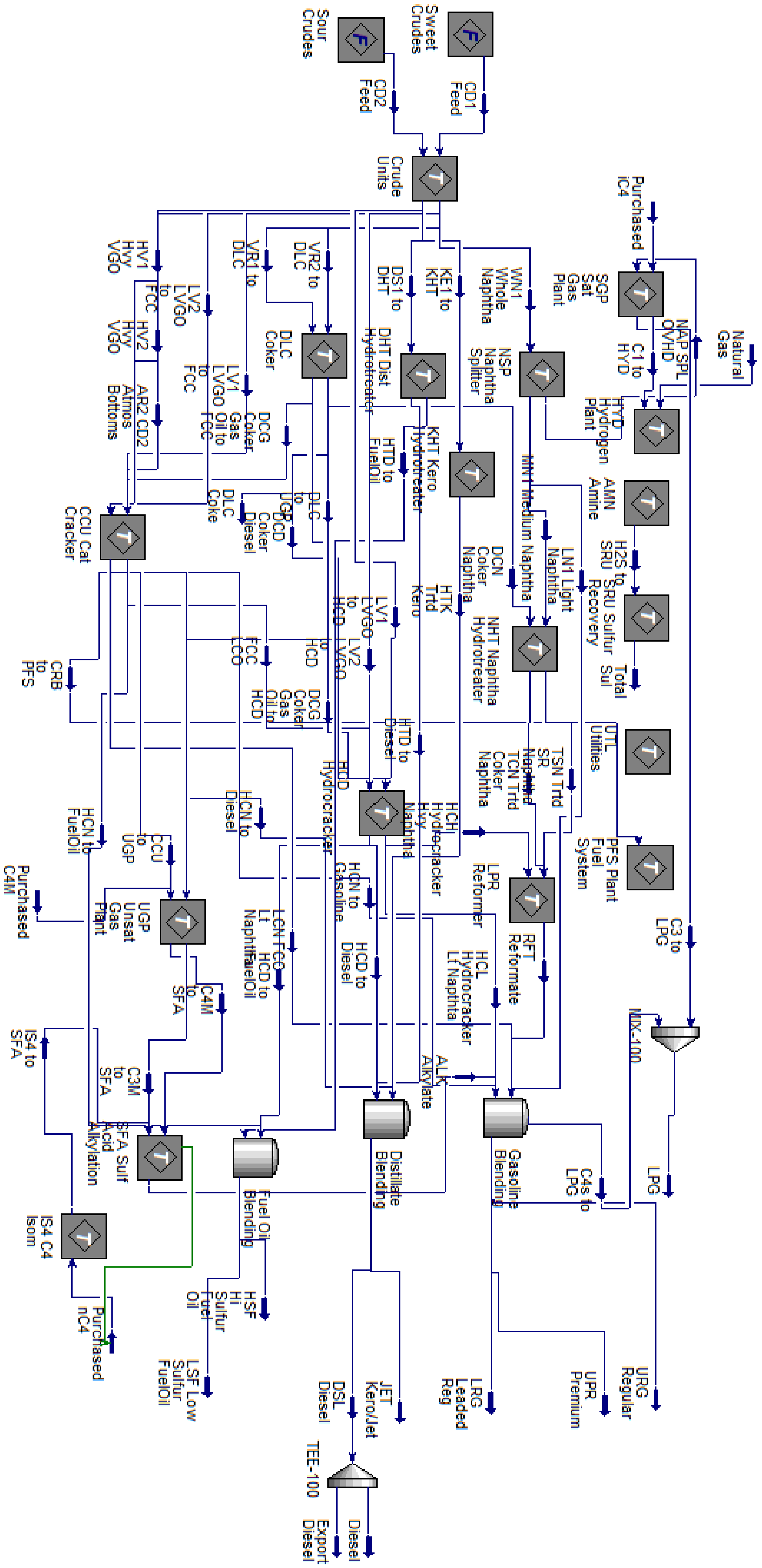

Figure 5 Process Flow Diagram of Petroleum Refinery

3.4 Fundamentals of Exergy Analysis

Exergy analysis integrates both first and second laws of thermodynamics and allows the process engineers to design the process more energy efficient by recognizing, computing and diminishing the process irreversibilities.

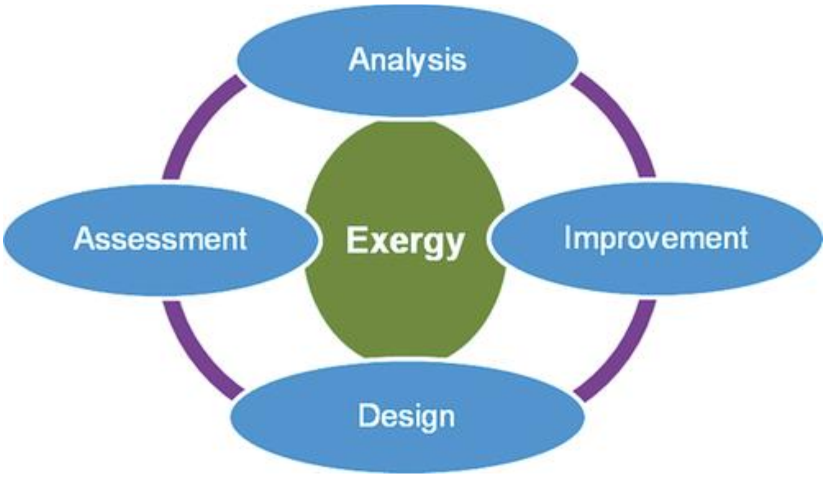

Figure 6 Fundamentals of Exergy

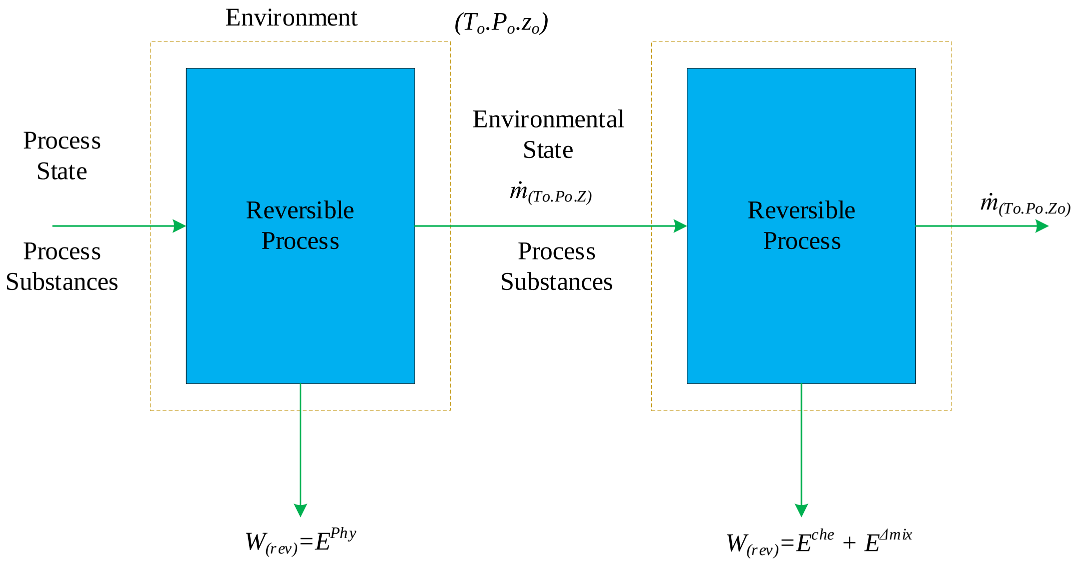

Figure 7 Concept of Exergy. where P, T denotes temperature and pressure respectively while molar flowrate is denoted by $\dot{m}$ [35]

The basic exergy expression by disregarding the terms of potential and kinetic exergy, relative to thermomechanical reference is defined as;

$$E_x = (H - H_0) - T_0(S - S_0) \tag{1}$$

where E_x = Molar Exergy (kJ/mol), H = Molar Enthalpy (kJ/mol), T = Temperature (K) and S = Molar Entropy (kJ/mol K).

The exergy perception is able to cope with this three E's model because of its implications not only in terms of energy but also in terms of economy and ecology.

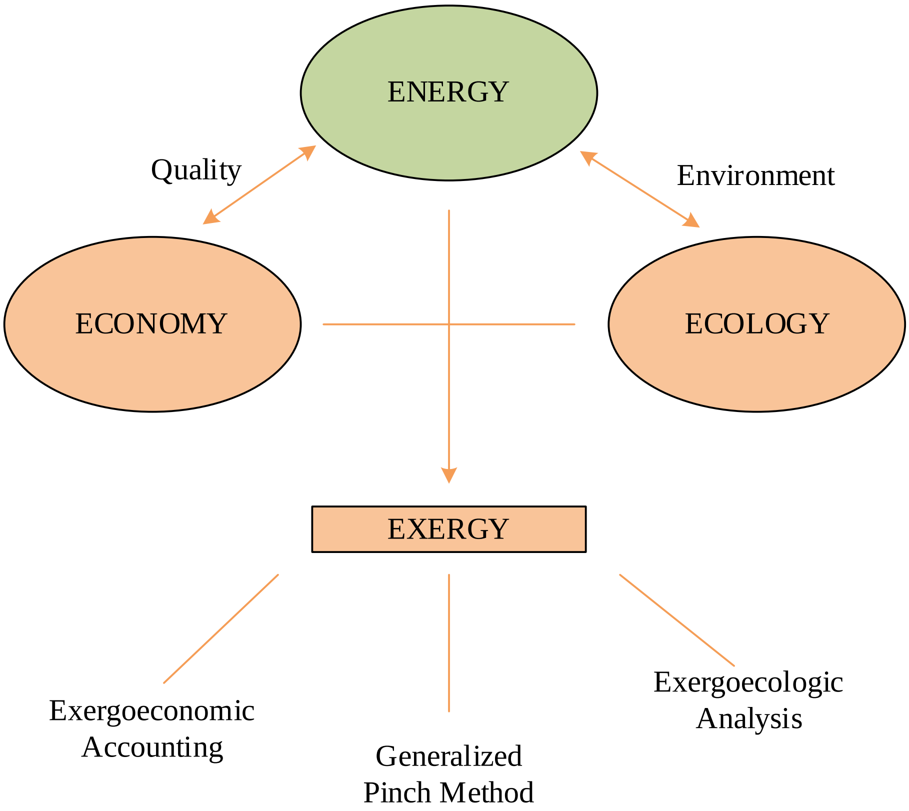

Figure 8 Energy–economy–ecology connection[19]

Physical exergy: Physical exergy is maximum work that can be attained through physical processes by taking a stream from an initial state to a thermo-mechanical equilibrium state with the environment. On molar basis, physical exergy is defined as

$$E_{x_{phys}} = \Delta_{actual\rightarrow 0}\left[L\left(\sum_{i=1}^{n} x_i H_i^l - T_0 \sum_{i=1}^{n} x_i S_i^l\right) + V\left(\sum_{i=1}^{n} y_i H_i^v - T_0 \sum_{i=1}^{n} y_i S_i^v\right)\right] \tag{2}$$

where S_i and H_i denotes enthalpy and entropy respectively at reference pressure and temperature of pure chemical components of material stream. L, V and x_i are liquid fraction of the stream, vapor fraction of the stream, and the molar fraction of component i, respectively[3].

Chemical exergy: Chemical exergy is the maximum possible work accomplished by taking a material stream from a state of thermo-mechanical equilibrium to a state of chemical and thermo-mechanical equilibrium with the environment. The mathematical form for calculation of standard chemical exergy assuming ideal gas behavior

$$E_{x^o_{chem,REF-i}} = RT_0 ln\left[\frac{P_0}{P_{REF-i}}\right] \tag{3}$$

where $E_{x^o_{chem,REF-i}}$= Chemical Exergy (kJ/mol), R = Ideal Gas Constant (kJ/mol K) and P = Pressure (kPa). The mathematical form for calculation of chemical exergy of components which do not exist in reference environment is

$$E_{x^0_{chem,i}} = \Delta_f G^i_0 - \sum_j v_j E_{x^0_{chem,j}} \tag{4}$$

where $E_{x^0_{chem,i}}$= Standard chemical exergy of any species i, $E_{x^0_{chem,j}}$= Standard chemical exergy of the element j in species i and $\Delta_f G^i_0$ = Gibbs energy of formation. At the reference temperature and pressure i.e T_o and P_o respectively, the higher heating value *"HHV"* is equal to specific chemical exergy. [36] The chemical exergy of multicomponent material stream is determined by;

$$E_{x_{chem}} = L_0 \sum_{i=1}^{n} x_{0,i} E_{x^{0l}_{chem,i}} + V_0 \sum_{i=1}^{n} y_{0,i} E_{x^{0v}_{chem,i}} \tag{5}$$

where $E_{x_{chem}}$= Chemical Molar Exergy (kJ/mol), L = Liquid Fraction and V = Vapor Fraction.

The sum of physical exergy and chemical exergy is called total exergy.

$$E_x = E_{x_{phys}} + E_{x_{chem}} \tag{6}$$

Process irreversibility or Exergy Destruction: Process irreversibility indicates that the total amount of exergy destroyed through each process unit. It is the difference in exergy of input and output streams.[2]

$$E_{x_{ds}} = E_{x_{in}} - E_{x_{out}} \tag{7}$$

Exergy Efficieny: It is a bench mark that depicts the nearness of a system to the ideal. It delivers a more evocative assessment of the performance of a process than orthodox energy efficiency. Among numerous exergy efficiency expressions anticipated in the literature, the simplest and most commonly used is fraction of the output exergy to input exergy of a process denoted by equation [2]

$$\eta = \frac{E_{x_{out}}}{E_{x_{in}}} \tag{8}$$

Exergetic Improvement Potential: Improving exergy efficiency and diminishing irreversibility are restricted by scientific and monetary limitations. Therefore, the exergetic improvement potential is assessed to depict the magnitude and compare conceivable improvement potentials of processes.

$$IP = (1 - \eta)E_{x_{ds}} \tag{9}$$

Exergetic improvement potential is a resultant of exergy efficiency and irreversibility as expressed in equation[2].

3.5 Methodology

The methodology implemented in this work comprises the following steps:

1. Aspen HYSYS model of petroleum refinery was utilized to extract process information into the Microsoft Excel. Input and output streams of simulated model are identified.
2. Physical exergies of each input and output stream were calculated by the help of extracted process information in Microsoft Excel by equation (1).

3. Chemical exergies of each input and output stream were calculated by the help of extracted process information in Microsoft Excel using equations (4, 5).
4. Total exergy of input and output streams were calculated by the help of calculated values of physical and chemical exergies by using equation (6).
5. Based on general equations (7,8 and 9), exergy destruction or process irreversibility, exergetic improvement potential and exergy efficiency were calculated respectively.

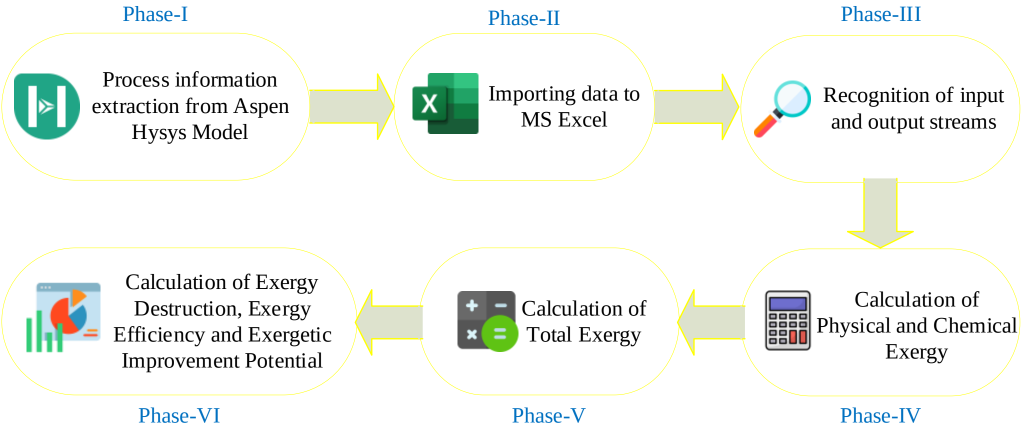

Figure 9 Methodology implemented in this work

Chapter 4

Result and Discussions

In section 4.1, method adopted for calculations of plant wide exergy destruction or process irreversibility, exergy efficiency and energetic improvement potential has been discussed.

4.1 Plant wide Exergy Analysis

Plant wide exergy analysis performed in this study include exergy destruction, exergy efficiency and exergetic improvement potential. Physical exergy of input and output streams are discussed in section 4.1.1. Section 4.1.2 describe chemical exergy analysis of input and output streams and are ranked from largest to smallest value. Section 4.1.3 describes the overall exergy analysis of petroleum refinery and the methods and parameters by which exergy efficiency, exergetic protentional and exergy destruction can be improved.

4.1.1 Physical Exergy

For calculation of value of physical exergy of streams, the process information was extracted from the simulated Aspen HYSYS petroleum refinery model in Microsoft Excel. By the help of the extracted data, physical exergies of stream is calculated in Microsoft excel. The physical exergies of input and output streams are ranked from highest to lowest values in Table 3 and Table 4 respectively. Top five input streams with respect to values of physical exergies are “CD2 Feed”, “CD1 Feed”, “Purchased nC4”, “Purchased C4M” and “iC4” with the values of 204.19 kW, 132.72 kW, 129.83 kW, 94.42 kW and 76.86 kW respectively. The lowest input stream with the respect to values of physical exergy is “hyl to TGT” and “Total Sul” with the value of approximately equal to 0 kW and 0.03 kW respectively. Top five output streams with respect to values of physical exergies are “LSF Low Sulfur FuelOil”, “Diesel”, “JET Kero/Jet”, “URG Regular” and “IS4 to SFA” with the values of 8367.51 kW, 2602.79 kW, 1691.97 kW, 1366.52 kW and 475.86 kW respectively. The reason for higher physical exergy value is that these streams have higher flowrates, temperature and pressure. The lowest output stream with the respect to values of physical exergy is C2+ to Fuel with the value of -12.78 KW, the reason for being lowest is that it has low flowrate, temperature and pressure. For side-by-side comparison, highest five input and output streams with respect to physical exergies are graphically represented in Figure 10 and Figure 11 respectively.

Table 3 Physical exergy of input streams

Input	**Exergy (kW)**
CD2 Feed	204.19
CD1 Feed	132.72
Purchased nC4	129.83
Purchased C4M	94.42
iC4	76.86
hyh to HCD	64.05
Natural Gas	29.74
h2 to Isom	6.90
H2S adjusted to SRU	4.17
H2S adjusted to SAMN	3.54
hyl to NHT	3.25
hyl to PFS	1.29
hyl to DHT	1.09
h2 to KHT	0.95
Total Sul	0.03
hyl to TGT	0.00

Table 4 Physical exergy of output streams

Output	**Exergy (kW)**
LSF Low Sulfur FuelOil	8367.51
Diesel	2602.79
JET Kero/Jet	1691.97
URG Regular	1366.52
IS4 to SFA	475.86
HSF Hi Sulfur Fuel Oil	214.01
LRG Leaded Reg	91.46
hyl from SLPR	70.10
h2 to HCD	55.00
UPR Premium	36.20
iC4 to SFA	29.47
DLC Coke	26.52
SFA nc3	18.47

Export Diesel	14.00
H2S to SRU	12.69
H2S total	10.80
Sulfur	7.89
LPG	6.97
Alk. loss	5.20
VR2 to Fuel Oil	2.18
Total Sul	0.03
SGP c5+ and others	0.01
FO loss	0.01
NSP water	0.00
Dist loss	0.00
hyl	0.00
PFS C1 to HYD	-2.61
C2+ to Fuel	-12.78

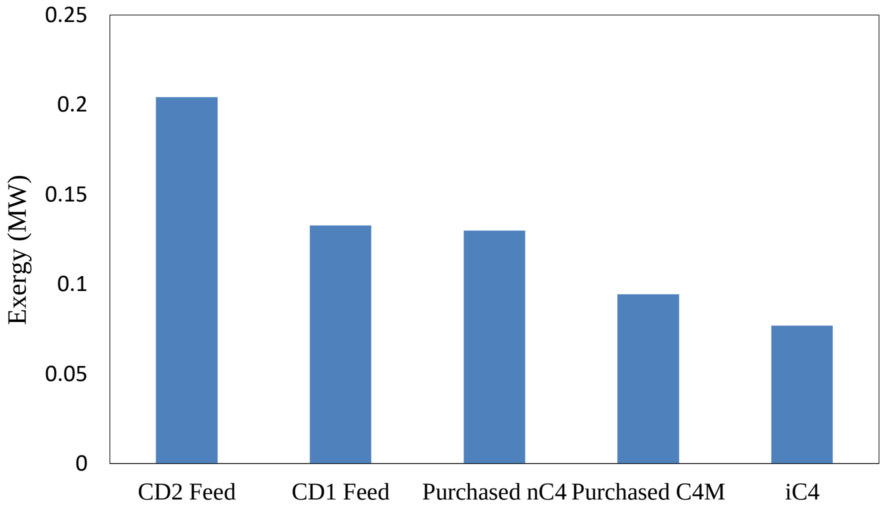

Figure 10 Physical exergy of input streams

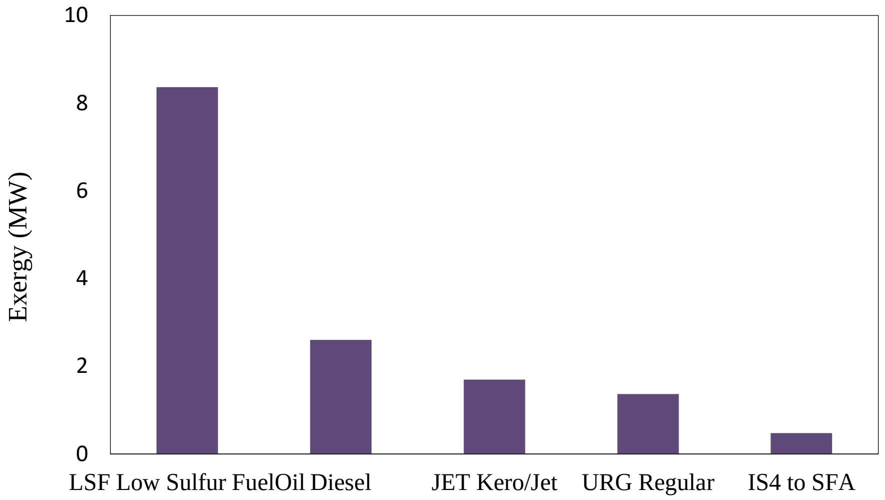

Figure 11 Physical exergy of output streams

4.1.2 Chemical Exergy

For the calculation of chemical exergy of streams, the values standard chemical exergy of components of streams are used, same approach has been reported in literature. By the using the extracted data from the Aspen HYSYS petroleum refinery model in Microsoft excel chemical exergies of input and output streams has been calculated which are shown from highest to lowest value in Table 5 and Table 6. Top five input streams with respect to values of chemical exergies are “CD2 Feed”, “CD1 Feed”, “iC4”, “Purchased nC4” and “Purchased C4M” with the values of 4244715.83 kW, 2822217.14 kW, 243712.03 kW, 175783.7 kW and 98496.17 kW respectively. The lowest input stream with the respect to values of chemical exergy is “hyl to TGT” with the value of 0.65 kW. Top five output streams with respect to values of chemical exergies are “URG Regular”, “Diesel”, “LSF Low Sulfur Fuel Oil”, “JET Kero/Jet” and “LPG” with the values of 2424179.18 kW, 1310055.89 kW, 881611.61 kW, 868345.74 kW and 457662.05 kW respectively, the higher values are due to higher flowrates, temperature and pressure of streams. The lowest output stream with the respect to values of chemical exergy is “hyl” with the value of approximately equal to 0 kW because it has low flowrate almost equal to zero. For side-by-side comparison, highest five input and output streams with respect to physical exergies are graphically represented in Figure 12 and Figure 13 respectively.

Table 5 Chemical exergy of input streams

Input	**Exergy (KW)**
CD2 Feed	4244715.83
CD1 Feed	2822217.14
iC4	243712.03
Purchased nC4	175783.70
Purchased C4M	98496.17
hyl to PFS	78960.48
hyh to HCD	78387.73
H2S adjusted to SRU	8202.08
H2S adjusted to SAMN	7459.78
Natural Gas	5202.38
hyl to NHT	3977.59
Total Sul	2688.40
hyl to DHT	1331.23
h2 to KHT	1159.35
h2 to Isom	366.49
hyl to TGT	0.65

Table 6 Chemical exergy of output streams

Output	**Exergy (kW)**
URG Regular	2424179.18
Diesel	1310055.89
LSF Low Sulfur FuelOil	881611.61
JET Kero/Jet	868345.74
LPG	457662.05
LRG Leaded Reg	283488.33
C2+ to Fuel	249330.96
IS4 to SFA	244206.12
HSF Hi Sulfur Fuel Oil	234428.33
hyl from SLPR	85795.80
h2 to HCD	78387.77
PFS C1 to HYD	72762.62
SFA nc3	59611.94
UPR Premium	54498.52
DLC Coke	39050.54
iC4 to SFA	28599.98
H2S to SRU	24994.54
H2S total	22733.43
Export Diesel	7044.58
Alk. loss	5548.82

Total Sul	2688.40
Sulfur	1507.69
VR2 to Fuel Oil	109.79
SGP c5+ and others	100.04
FO loss	15.64
Dist loss	0.01
NSP water	0.00
hyl	0.00

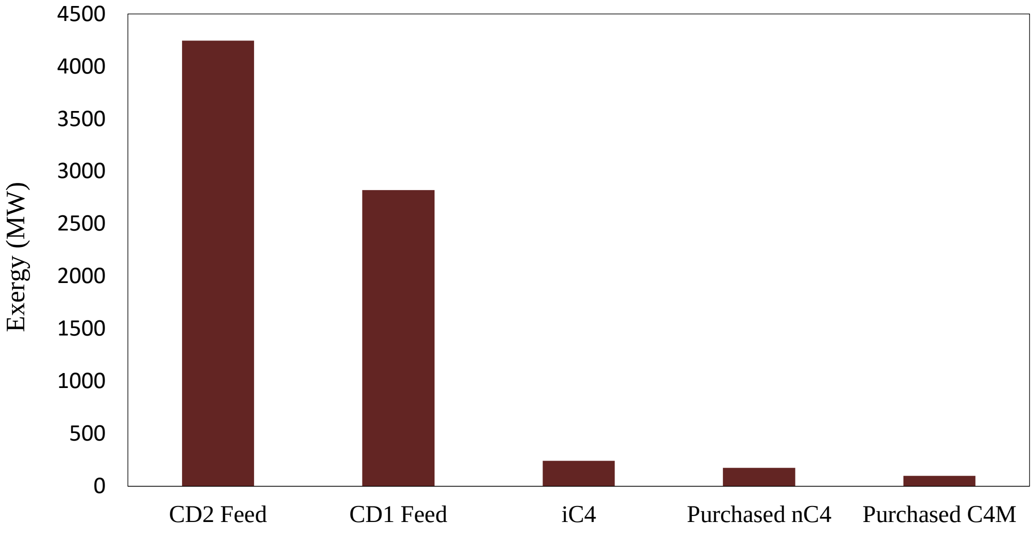

Figure 12 Chemical exergy of input streams

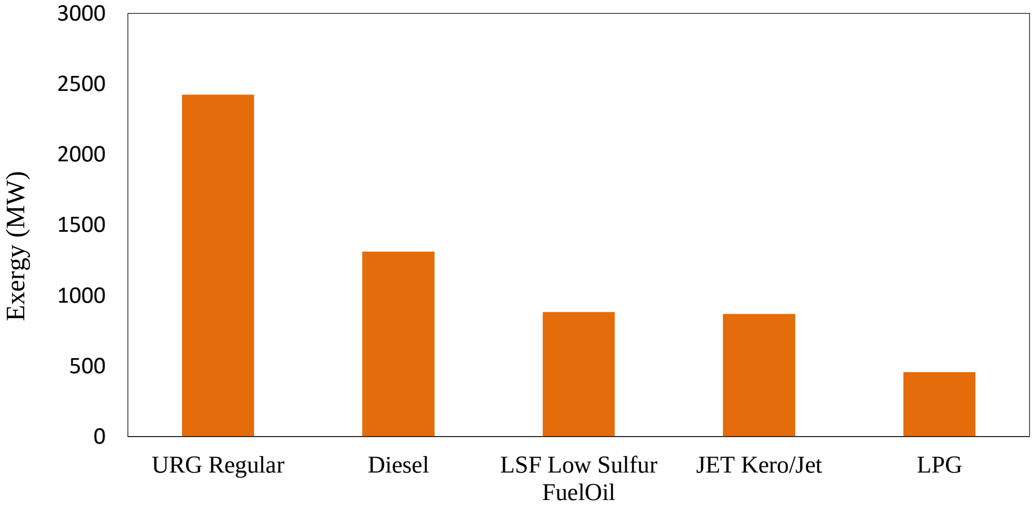

Figure 13 Chemical exergy of output streams

4.1.3 Overall Exergy Analysis

Total exergy is sum of the physical and chemical exergy of each stream. By utilizing the values of both chemical and physical exergy, total exergy of input and output streams have been calculated which are shown from highest and lowest value in Table 7 and Table 8 respectively. Top five input streams with respect to values of total physical exergy are “CD2 Feed”, “CD1 Feed”, “Utilities”, “iC4” and “Purchased nC4” with the values of 4244920.02kW, 2822349.86 kW, 391852.93 kW, 243788.89 kW and 175913.52 kW respectively. The lowest input stream with the respect to value of total exergy is “hyl to TGT” with the value of 0.65 kW. Top five output streams with respect to values of total exergy are “URG Regular”, “Diesel”, “LSF Low Sulfur Fuel Oil”, “JET Kero/Jet” and “LPG” with the values of 2425545.70 kW, 1312658.68 kW, 889979.13 kW, 870037.71 kW and 457669.01 kW respectively, the higher values are due to higher flowrates, temperature and pressure of streams. The lowest output stream with the respect to values of total exergy is “hyl” with the value of approximately equal to 0 kW because it has low flowrate almost equal to zero. For side-by-side comparison, highest five input and output streams with respect to total exergies are graphically represented in Figure 14 and Figure 15 respectively.

Table 7 Total Exergy of Input Streams

Input	**Total Exergy (kW)**
CD2 Feed	4244920.02
CD1 Feed	2822349.86
Utilities	391852.93
iC4	243788.89
Purchased nC4	175913.52
Purchased C4M	98590.58
hyl to PFS	78961.77
hyh to HCD	78451.78
H2S adjusted to SRU	8206.24
H2S adjusted to SAMN	7463.33
Natural Gas	5232.11
hyl to NHT	3980.84
Total Sul	2688.43
hyl to DHT	1332.32
h2 to KHT	1160.30
h2 to Isom	373.40
hyl to TGT	0.65

Table 8 Total Exergy of Output Streams

Output	**Total Exergy (kW)**
URG Regular	2425545.70
Diesel	1312658.68
LSF Low Sulfur FuelOil	889979.13
JET Kero/Jet	870037.71
LPG	457669.01
LRG Leaded Reg	283579.79
C2+ to Fuel	249318.18
IS4 to SFA	244681.98
HSF Hi Sulfur Fuel Oil	234642.35
hyl from SLPR	85865.90
h2 to HCD	78442.78
PFS C1 to HYD	72760.01
SFA nc3	59630.40
UPR Premium	54534.72
DLC Coke	39077.06
iC4 to SFA	28629.45
H2S to SRU	25007.23
H2S total	22744.23
Export Diesel	7058.58
Alk. loss	5554.02
Total Sul	2688.43
Sulfur	1515.58
VR2 to Fuel Oil	111.98
SGP c5+ and others	100.05
FO loss	15.64
Dist loss	0.01
NSP water	0.00
hyl	0.00

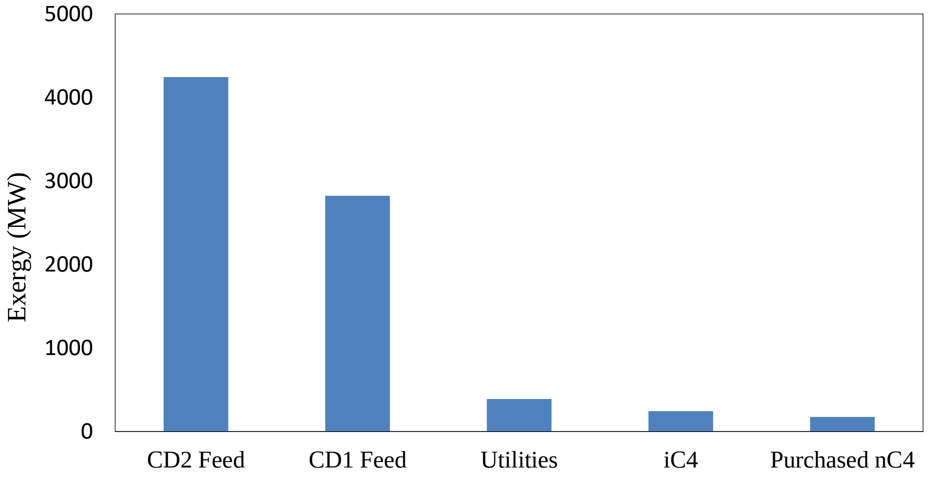

Figure 14 Total exergy of input streams

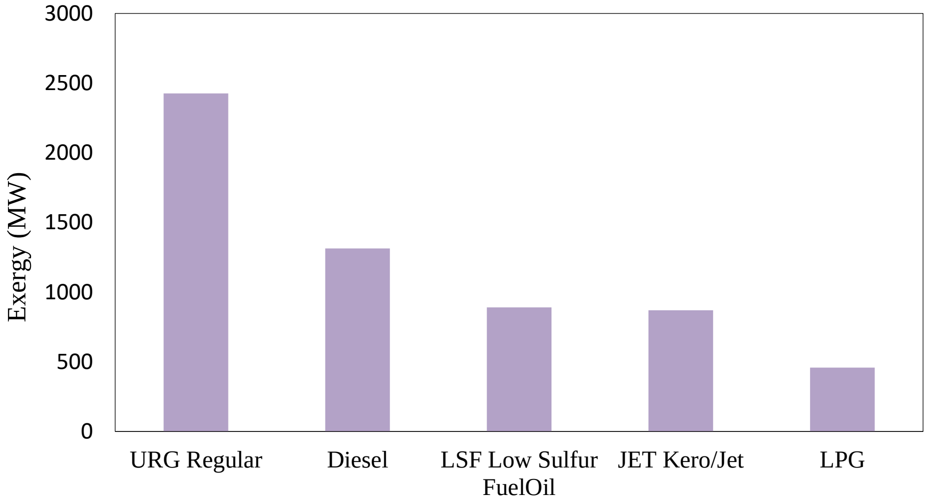

Figure 15 Total exergy of output streams

By comparison between exergy of top five input streams, it has observed that the input streams have very nominal values with respect to the value of utilities section. As there are ample reaction zones and energy losses in the petroleum refinery which causes the lowering of temperature and pressure due to which the utilities energy input is used due to which there are drastic change in input and output physical exergy values.

The input streams contain low quality and raw form of fuels which have low octane number. The purpose of petroleum refinery is to convert these into high quality fuels having high octane numbers by passing through different separation and reactive zones and providing exergy by the help of utilities. As the petroleum refinery is endothermic process, due to which the drop in physical exergy is inserted in the form of chemical exergy.

As plant wide total input exergy of all input streams is 8165266.98 kW and total output exergy is 7461212.34 kW as shown in Table 9. Based on these calculations, the exergy destruction and exergetic improvement potential value calculated by equation (7) and equation (9) is 704054.64 kW and 60707.50 kW respectively. As the exergy destruction or process irreversibility is a measure of the quantity of exergy destroyed in a process. Irreversibility phenomena is caused by:

- Non-homogeneities produced from mixing two or more components with diverse temperatures, pressures, and concentrations.
- The effect of dissipation is arisen by electric resistance, friction, inelasticity, pressure drop or viscosity.
- Chemical reactions in which produced entropy is proportional to extent of reaction[46, 47]

Improvement in exergy efficiency and minimizing the exergy destruction or process irreversibility are restricted by economic and technological constraints. Exergetic improvement potential is estimated to specify the magnitude and compare possible improvement potentials of processes. Value of exergy efficiency calculated by equation (8) is 91.38%. Based on the calculated results of the petroleum refinery exergy analysis, the exergy efficiency can be improved and exergy destruction or process irreversibility and exergy improvement potential can be decreased by the implementations of engineering solutions, which will make the process more energy efficient, feasible and economical. However, it is very important to evaluate the suggested engineering solutions before their implications on the basis of economic evaluation through exergoeconomics studies [2].

Table 9 Exergy Analysis

Total Exergy (KW)	
Total Input	8165266.98
Total Output	7461212.34
Exergy Destruction	704054.64
Exergy Efficiency	0.91
Exergetic Improvement Potential	60707.50

Conclusions

In plant-wide model, exergy of 391852.93kW of utility was consumed. The reason behind this provision is that the petroleum refinery is overall an endothermic process which utilizes the exergy. Total input exergy of all input streams was 8165266.98 kW and total output exergy was 7461212.34 kW. The drop in physical exergy is transformed in the form of chemical exergy. The process model was found 91.38% exergy efficient with exergy destruction of 704054.64 kW and exergetic improvement potential of 60707.50 kW. The current study is solely performed on the input and output streams of plant wide petroleum refinery but in the future studies, exergy analysis can be executed on equipment level for investigating the equipment level improvement potentials.

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Appendix

Table 10 Streams data of petroleum refinery

Streams	Temperature (F)	Pressure (kPa)	Mass Flow (kg/h)
CD1 Feed	70	1480.28	233348
CD2 Feed	70	1480.28	350242
WN1 Whole Naphtha	69.8504	790.801	109018
VR1 to DLC	1206.31	790.801	5251.7
AR2 CD2 Atmos Bottoms	842.759	101.325	9822.98
VR2 to DLC	1157.94	790.801	96224
HV1 Hvy VGO	796.24	790.801	75602.7
HV2 Hvy VGO	790.367	790.801	86440.4
LN1 Light Naphtha	122.13	101.325	30236.6
MN1 Medium Naphtha	275.337	101.325	78772.4
DCN Coker Naphtha	212	790.801	13804.1
LV1 LVGO to FCC	667.192	790.801	2857.15
LV2 LVGO to FCC	664.934	790.801	8927.86
DCG Coker Gas Oil to FCC	212	790.801	2.80147
DCG Coker Gas Oil to HCD	212	790.801	28011.9
DCD Coker Diesel	212	790.801	16106.3
TSN Trtd SR Naphtha	212	101.325	69734.8
TCN Trtd Coker Naphtha	212	101.325	11693.4
HCH Hydrocracker Hvy Naphtha	212	101.325	15902.2
LPR to SGP	211.786	101.325	13213.6
HCD to SGP	211.879	101.325	2753.46
NHT to SGP	211.741	101.325	1969.73
DHT to SGP	211.896	101.325	47.6235
KHT to SGP	211.896	101.325	43.1764
CCU to UGP	211.745	101.325	36955.8
CDU to SGP	0.14016	101.325	6507.78
nC4 to IS4	70	790.801	5352.19
NHT H2S	212	101.325	414.721
KHT H2S	212	101.325	194.584
DHT H2S	212	101.325	231.807
DLC H2S	212	790.801	1769.77
CCU H2S	212	101.325	557.059
HCD H2S	212	101.325	1820.86
H2S to SRU	212	101.325	5485.22
iC4 to SFA	70	790.801	2093.68
IS4 to SFA	212	790.801	17881.1
RFT Reformate	212	101.325	84611.5
LCN FCC Lt Naphtha	212	101.325	70051
HTK Trtd Kero	212	101.325	18082.6

VR1 to Fuel Oil	1206.31	790.801	40946.6
VR2 to Fuel Oil	1157.94	790.801	9.61715
HCL Hydrocracker Lt Napthta	212	101.325	3444.3
IS4 to SGP	210.617	790.801	319.06
C2 to Fuel	70	790.801	3928.97
C1 to HYD	70	100	2236.57
C3 to LPG	70	790.801	3286.83
C3 to PFS	70	790.801	3286.83
iC4 to Gaso	70	790.801	2.09577
nC4 to Gaso	70	790.801	9245.48
LPG	47.7965	101.325	3288.93
URG Regular	173.27	101.325	222589
UPR Premium	183.46	101.325	5003.97
LRG Leaded Reg	179.406	101.325	26090.4
C4s to LPG	11.0173	101.325	2.09577
C4M to SFA	70	101.325	29648.9
C3M to SFA	70	101.325	12095.5
UGP to PFS	70	101.325	9842.57
KE1 to KHT	457.514	101.325	18245.2
DS1 to DHT	591.716	101.325	21117.4
DS1 to Blending	591.716	101.325	41638.6
KE1 to Blending	457.514	101.325	61081.9
FCC LCO	212	101.325	36012.9
CCS CCU Slurry	212	101.325	15386.5
ALK Alkylate	212	101.325	50419.5
IS4 Ohd to SGP	210.617	790.801	319.06
JET Kero/Jet	397.057	101.325	68113.2
DSL Diesel	399.101	101.325	107275
HSF Hi Sulfur Fuel Oil	308.628	101.325	20189.1
FO loss	212	101.325	1.53865
Purchased nC4	70	790.801	12839.6
Purchased C4M	70	790.801	7277.29
HCN to Gasoline	212	101.325	5675.43
HCN to Diesel	212	101.325	5616.98
Natural Gas	70	790.801	339.61
Diesel	399.101	101.325	106701
Export Diesel	399.101	101.325	573.767
DLC Coke	212	790.801	5407
PFS C1 to HYD	70	100	4749.92
SFA nc4 to SGP	212	101.325	4578.28
DLC to UGP	209.296	790.801	7353.92
CRB to PFS	212	101.325	7505.46
HCN to FuelOil	212	101.325	3562.05
LSF Low Sulfur FuelOil	783.663	101.325	72131.9

HTD to Diesel	212	101.325	17356
HTD to FuelOil	212	101.325	3470.65
HCD to Diesel	212	101.325	31612.3
HCD to FuelOil	212	101.325	28956.7
NAP SPL OVHD	96.0991	101.325	9.34261
hyl to DHT	212	101.325	34.1455
h2 to KHT	212	101.325	29.7368
hyh to HCD	212	101.325	2010.61
hyl to NHT	212	101.325	102.024
h2 to Isom	212	790.801	9.40043
hyl from SLPR	212	101.325	2200.63
Total Sul	95	101.325	589.964
hyl to TGT	95	101.325	0.01678
hyl to PFS	95	101.325	2025.3
Dist loss	211.861	101.325	0.00053
SFA nc3	212	101.325	4283.98

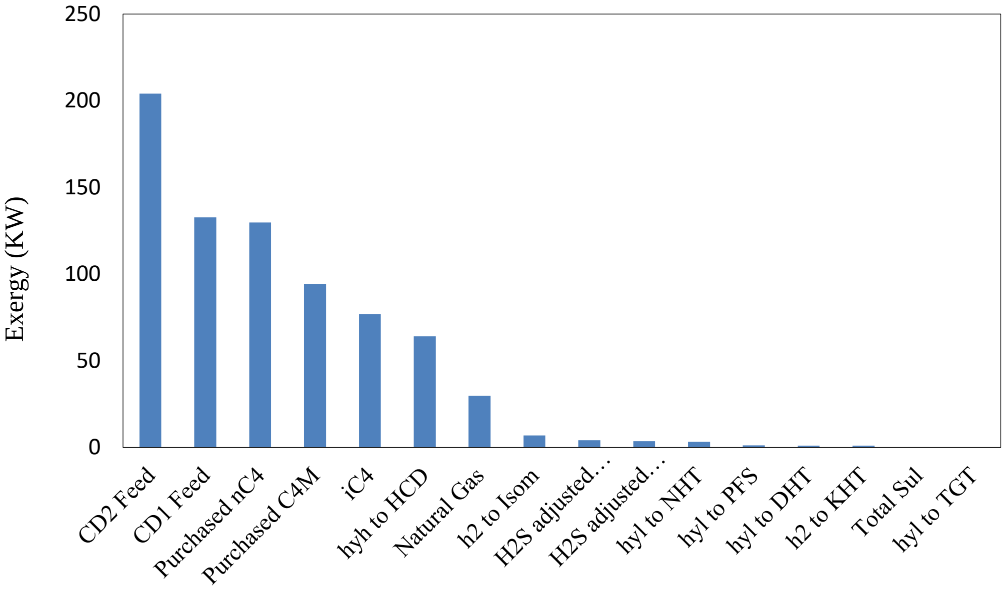

Figure 16 Physical exergy of input streams ranked from highest to lowest value

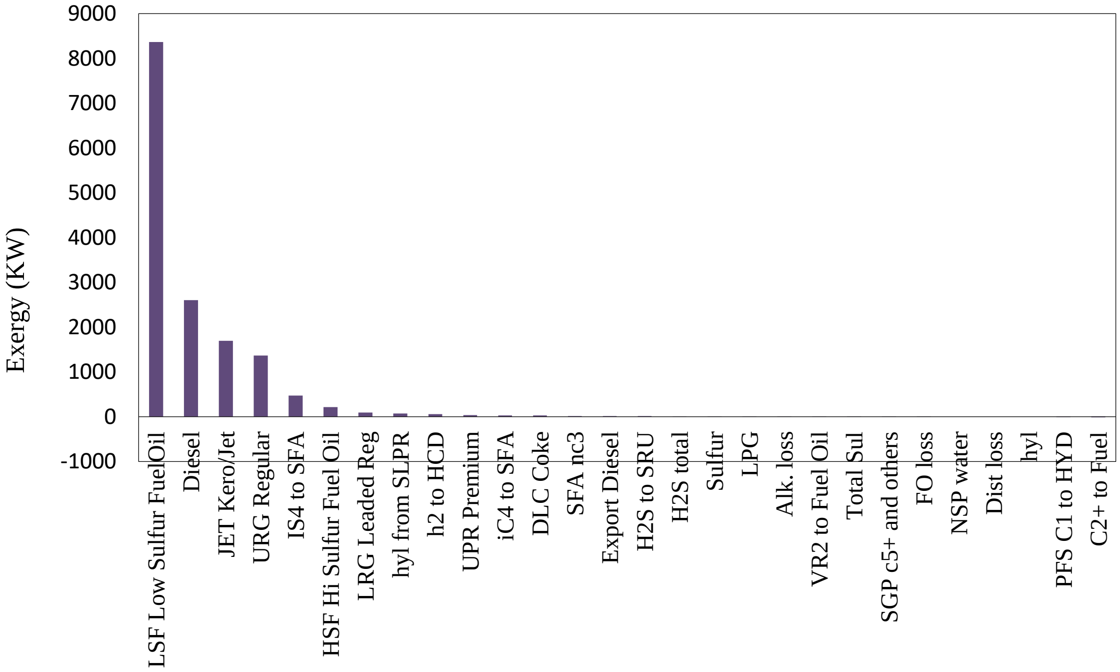

Figure 17 Physical exergy of output streams ranked from highest to lowest value

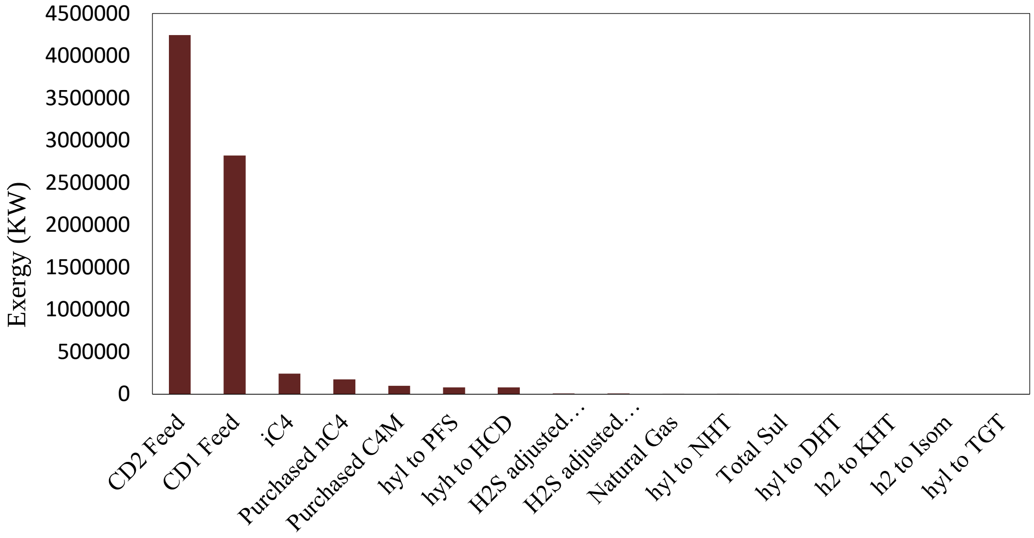

Figure 18 Chemical exergy of input streams ranked from highest to lowest value

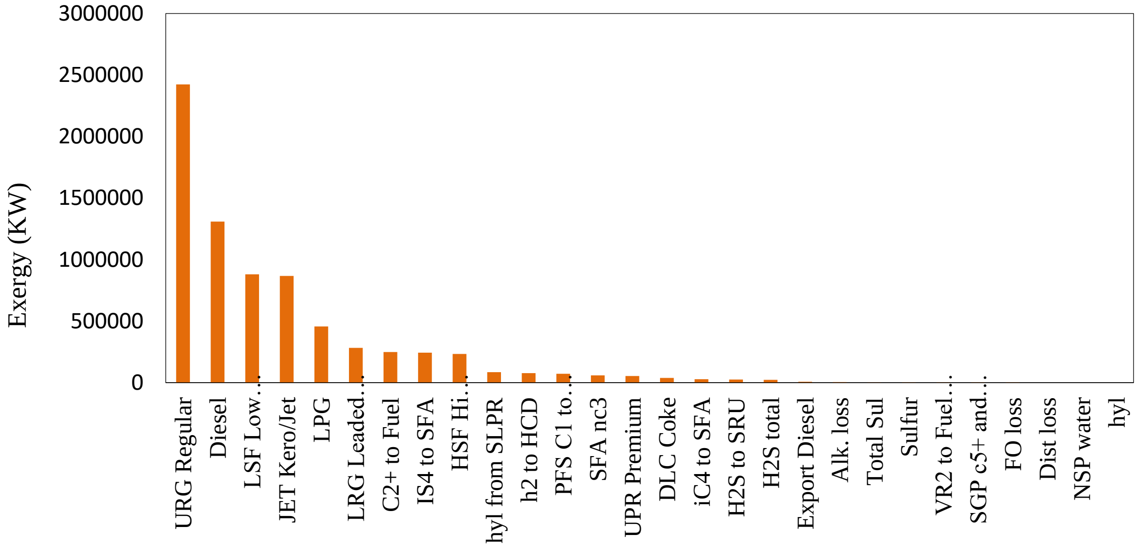

Figure 19 Chemical exergy of output streams ranked from highest to lowest value

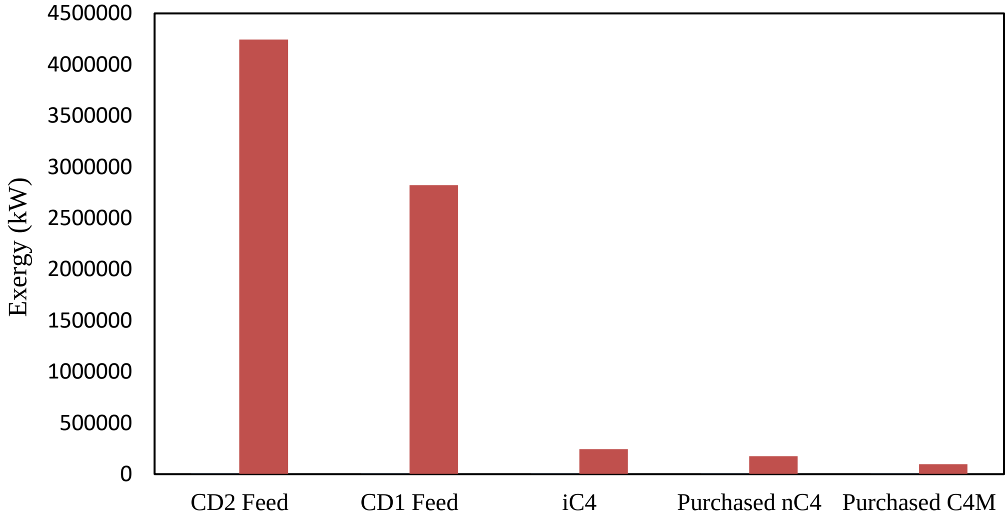

Figure 20 Comparison of input physical and chemical exergies

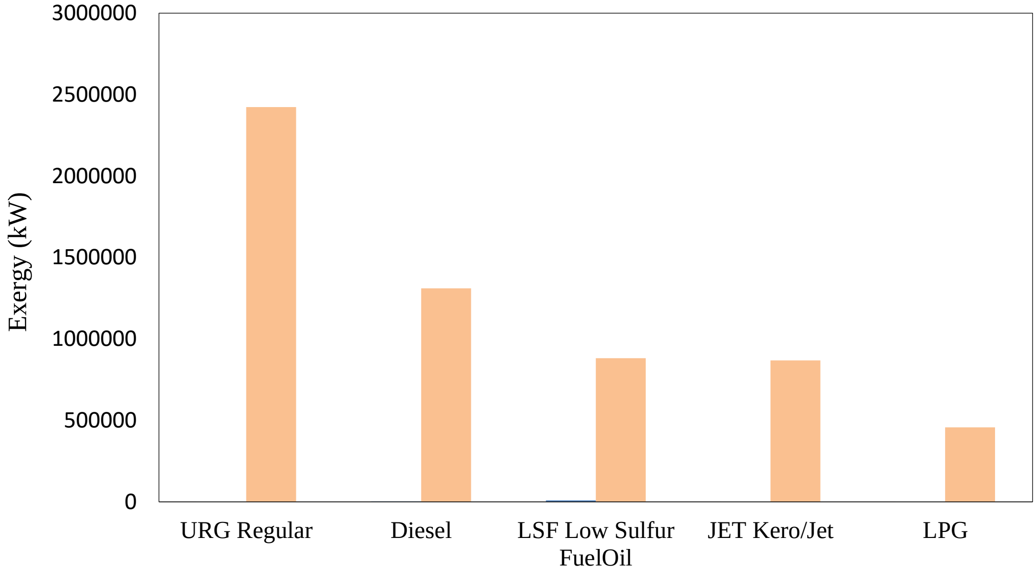

Figure 21 Comparison of output physical and chemical exergies