

SIMULATION AND HAZARD OPERABILITY ANALYSIS OF LIQUEFIED PETROLEUM GAS PLANT: A CASE STUDY

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Abstract: Liquefied petroleum gas (LPG) is a mixture of hydrocarbons essentially propane and butane. It has recently emerged as a sustainable and alternative fuel source to other conventional fossil fuels in several sectors such as residential, industrial, commercial and transportation. The environmental impact is seen as a positive influence as it reduces black carbon emissions by releasing less greenhouse gases as it undergoes combustion. In this study, a general overview about LPG was offered and the data required for simulating a flowsheet for LPG production was obtained from an LPG plant. Mass balance and energy balance were calculated manually and compared with those of the simulation performed by ASPEN HYSYS 12.0 using Peng-Robinson fluid package. A hazard and operability study for the equipment was carried out as well as their spacing to emphasize their importance on how they shape the safe feasibility of plant construction. It was found that 2209 kg/h of feed gas was mainly converted to 836.90 kg/h of sales gas and 1322 kg/h of LPG. By comparing manual calculations with HYSYS results, the duty for heat exchanger 2 was 55361.17 kJ/h, with error percentage of 3.90%. The sales gas temperature was 318.53 K with 1.42% deviation. Debutanizer condenser and reboiler duties were 892640.20 kJ/h and 746416.30 kJ/h, with deviations of 4.25% and 3.49% respectively. The hazard and operability studies and spacing showed that all the equipment must be positioned at safe distances apart from each other and they require the installation of alarms, sensors, and controllers to ensure a proper and safe production process.

Keywords: Liquefied petroleum gas; Environmental impact; Simulation; HAZOP; Equipment spacing

1. INTRODUCTION

Liquefied Petroleum Gas (LPG) is comprised of a multitude of hydrocarbons but essentially propane and butane. It is produced naturally within oil and gas reservoirs and can be produced by purification of natural gas or from petroleum refining with each method differing the composition of LPG. Chemical composition differs according to the nature petroleum, natural gas, and the extraction location. Propane and butane are the major constituents of LPG but there is a minor portion of propene, butenes, iso-butane and ethane as well. It should be noted that the composition of LPG differs due to the season whereas in winter, more propane is present while in summer, more butane is present. This preserves the storage pressure independently of the temperature. Petroleum refining often provides 10-15% LPG from its quantity while only 3% of LPG is obtained from natural gas. From crude oil refinery, the crude can enter a prefractionation column first before proceeding to remaining steps of atmospheric distillation. In this column, the top product mainly consists of light hydrocarbons such as propane and butane which are separated from the crude and condensed to be liquid. Thus, the separated liquid can be used for further processing or be individually used as LPG [1-3].

In the early 20th century, LPG started to gain popularity as a fuel source for internal combustion engines when it was often used for cooking and lighting fuel. There was a significant shift to LPG-fueled automobiles due to the oil crisis and increased oil prices that occurred in the 1970s. According to the global statistical review published by the World LPG Agency (WLPGA), in 2021, Russia held the first place for consuming LPG with a capacity of 4.4 million tons followed by Turkey's consumption of 3.9 million tons. The global domestic sector accounted for 44% of the overall consumption of LPG followed by descending order of the chemicals sector with 28%, refineries with 9%, transportation with 8% and agriculture with 1% [4-6].

Liquefied petroleum gas is produced on a worldwide level with an annual rate of 300 million tons per year. Its high energy content, 93.2 MJ/m^3 , makes it feasible to be produced in few amounts and offering the same energy amount making it more efficient than other fossil fuels like crude oil and gasoline. The storage and distribution are commonly performed with pressurized liquid LPG in gas cylinders or tanks. The combustion of LPG gives reduced levels of carbon monoxide (CO), carbon dioxide (CO₂), sulfur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM) [7-10].

I. Properties

Liquid LPG is naturally colorless, odorless, and invisible in a gaseous state. For safety reasons, a mercaptan is usually added as an odorizer to detect LPG at reduced concentrations. The properties are listed in table 1. It vaporizes at atmospheric conditions and can be liquefied only by pressure (0.7-0.8 Mpa). It is non-degradable and can be used extensively without extra treatment to make it usable. It can be stored easily in small cylinders or bulk tanks. It can reach remote and off-grid areas other conventional fuel sources cannot reach easily and does not require tremendous investments in the infrastructure as well [11-15].

Table 1: Properties of propane & butane

Property	Propane	Butane	Reference
Boiling Point (°C)	-45	-2	[1]
Liquid Density (kg/l)	0.5-0.51	0.57-0.58	
Gas Density/Air	1.4-1.55	1.9-2.1	
Latent Heat of Vaporization (kJ/kg)	358	372	
Calorific Value Btu/Ft ²	2500	3270	
Critical Temperature (°C)	96	152	[2]
Auto Ignition Temperature (°C)	459	405	
Critical Pressure (bar)	42.6	38	
Flammability Limits (vol%)	2.2-9.5	1.8-8.4	[16]
Molecular Weight	44	58	
Fire Point (°C)	510	490	[16]
Flash Point (°C)	-60 (LPG)		
Research Octane Number	110 (LPG)		
Flame Speed (m/s)	0.83 (LPG)		

II. Explosion incidents

Liquefied petroleum gas has the tendency to vaporize more than petrol so it can leak more rapidly even when stored in fuel tanks which could cause explosions as LPG is greatly flammable which is known as boiling liquid expanding vapor explosion (BLEVE). The initial phase equilibrium is disturbed, making LPG boil severely. Pressure quickly rebounds across the storage tank that cannot withstand such rebound if significant enough to damage it. In an open environment, LPG will vaporize at a rate much higher by 250-300 times its volume with great expansion. Having a density 1.5-2 times the air's density, LPG will easily spread and diffuse in air creating a larger flammable cloud which could get worse when encountering an ignitor. The concept of BLEVE was first conceptualized by Smith of the National Fire Protection Association which stated that when the liquid's temperature exceeds its boiling point at atmospheric pressure, the liquid-holding vessel immediately ruptures into two or more pieces [17-20].

The chances of LPG being prone to leak are relatively high as it is heavily utilized across versatile fields. In the industrial process, equipment aging, defects in design and human errors are of various reasons that can cause the production and transportation operations to encounter leakage of LPG. The consequences of these kinds of explosions are detrimental such as large fire accidents. On May 11th, 2004, an explosion occurred in the ICL Chemical Park in Glasgow, England which made the building collapse resulting in 9 fatalities, 45 injuries and having an impact across a 2km area [21-23].

In a similar vein, LPG transporting road tankers are known to be of large volume which make LPG susceptible to massive explosions that would be difficult to predict or even control when traffic accidents occur. The outcomes of such accidents would be even worse as they often happen in residential areas which could result in tremendous casualties. On August 27th, 2012, an LPG explosion took place in India that burned the surrounding environment and caused catastrophic casualties. In August 2018, a traffic accident occurred between several vehicles and an LPG tanker which resulted in 4 deaths, 145 injuries and 14 severely burned injuries. On June 13th, 2020, an LPG tanker explosion occurred in Wenling, China, which resulted in 20 deaths and 175 casualties. The explosion diameter

was nearly 260 meters which affected the surrounding environment, residential buildings, and vehicles. It also resulted in a huge economic loss which accounted for CNY 94.77 million [24-29].

III. Sensor application

Liquefied petroleum gas is known to be flammable, and leakage of high concentrations can lead to accidents. Due to the extensive use of LPG in cooking, lighting fuel, vehicles, heating, the number of accidents randomly increases annually. The chances of LPG leaking can occur for several reasons such as loose connections between supplier and receiver or improper handling and storage. As the leak reaches a certain extent, the BLEVE problem occurs creating a massive explosion leading to undesired casualties. Consequently, the role of gas sensors has become crucial in detecting leakages. There are reputable LPG sensors such as MQ-2, MQ-5, MQ-6 and MQ-306. In simple terms, as the gas molecules reach the sensor's surficial element, the resistance of the sensor's element changes and are transmitted as an electrical signal. The sensor is connected to an alarm that receives this signal which sounds the alarm to indicate that there is a leakage [30-33].

IV. Transportation fuel

Liquefied petroleum gas used in vehicles is known as Autogas. In 2019, Autogas was consumed by an amount of 27.2 million tons and accordingly, the production of Autogas vehicles reached nearly 28 million. Many countries have shifted focus towards LPG vehicles. For example, the LPG vehicles are estimated to be 4.7 million in Turkey, 3.1 million in Poland and 3 million in Russia. It is expected that the overall Autogas market will increase annually by 2% up till 2025 [34-37].

Naturally, LPG is a gaseous source of fuel that can be liquefied and has its volume reduced 240 times more than when in gaseous state which facilitates storage and transportation. The implementation of LPG in vehicles has increased and holds the third place after gasoline and diesel as the most utilized fuel source. If LPG is used alone in an engine, it can give satisfactory results in terms of power due to its high octane number which allows it to have a large compression air fuel ratio. Despite these merits, the efficiency of LPG vehicles is low due to its low heating value per unit volume and the internal pressure in engines is set below the full charging level for safety precautions. By adjusting the air fuel compression ratio, the efficiency of LPG engines can be optimized as well as the pollutant emissions [38-40].

Diesel engines are popular for their economic value, high efficiency, long lifespan, and low carbon emissions. Diesel engines operate with hot compressible air intake and ignition occurs due to high temperature and pressure releasing notable NO_x emissions. The focus has shifted to using other clean fuel sources to comply with environmental regulations [41-43]. Accordingly, using LPG for dual-fuel combustion in diesel engines achieves this goal. The high auto ignition temperature and octane number of LPG prevent it from burning during compression. It also does not dilute quickly, allowing it to be used for longer periods of time and the absence of sulfur helps to prolong the lifespan of the engine as well. It vaporizes and quickly mixes with air ensuring thermal efficiency and low PM emissions. Spark ignition (SI) engines are becoming more dependent on LPG due to their ecofriendly nature such being nontoxic, noncorrosive and its alike properties to gasoline. In addition, LPG is inexpensive compared to gasoline, has low carbon/hydrogen ratio, high octane number, excellent thermal efficiency, and no aromatics. A higher compression ratio up till 15:1 is hereby feasible, and the engine does not burn out quickly due to the high auto ignition temperature of LPG which prevents knocking [44,45].

V. Applications

Liquefied petroleum gas is tremendously implemented in a versatility of applications in almost every sector possible. Power generation is a crucial area where LPG can be efficiently utilized to replace pollutant fuels such as coal and diesel. For instance, LPG can be used as a 'connecting' fuel in countries with limited access to natural gas such as Greece, Argentina, and India. In other words, if feasible, LPG plants can be converted to natural gas plants. In addition, LPG can be employed in the agriculture sector where areas of limited access to high carbon energy sources and technologies can use the merits of cost effectiveness, less disruption and the ecofriendly compliance offered by LPG. In 2020, the demand for total energy in the agriculture sector in the European union reached 56% by using petroleum-based fuels. Studies have shown that when converting to LPG heating systems, commercial businesses like restaurants and hotels can decrease their carbon emissions by 30-40% instead of coal and by 20% instead of oil. In maritime industry, LPG can lessen the tremendous and harmful emissions and air pollutants caused by carbon-dense fuels. This also helps in preservation of marine life whereas oil spillages can be avoided [46-49].

LPG is heavily utilized in cooking and heating applications. The materials used for making cookers affect their lifespan. Durable stoves can last up to five years unlike cheaply made stoves that corrode

quickly. LPG stoves are shown to have a better efficiency at 50-60%. Unlike biomass, residential LPG cylinders can survive for 20 years or longer with regular maintenance. The International Energy Agency (IEA) states that more than 2.5 billion people use LPG mostly for their cooking in poor countries and even in countries of great income. It is also expected that over 2.8 billion people will have implemented LPG as their main means of cooking by 2030 [50-53].

As a potential replacement for LPG, bioLPG is a source of renewable fuels made from organic materials. It functions like normal LPG in terms of distribution, storage, markets, and in households as well. It is the same as ordinary LPG chemically. Thus, it could be used in place of LPG in all current uses, including transportation, cooking, and heating. The first batch of bioLPG was made in Europe a few years ago, and it is now becoming available in nations including the US, the UK, and the Netherlands although low-income nations do not currently generate or import bioLPG. Future efforts are dedicated to expanding the production of bioLPG as a whole new renewable fuel source to be implemented exactly as LPG like in cooking and transportation [54-57].

VI. Environmental impact

Governments all around the world seek to decarbonize their economies and effectively reduce the existential crises caused by climate change [58-61]. In 2021, nearly 25 billion BTU of fossil fuels were produced due to the tremendous usage of fossil fuels which was the main energy source for the U.S transportation sector alone. On a global level, the transportation sector alone accounts for 37% carbon dioxide emissions from end-user sectors, more than 20% consumed energy and responsible for 14% greenhouse gas emissions [58-61].

Domestic cooking heavily relies on fossil fuels, mainly biomass and particularly in rural areas. In 1990, the dependence on pollutant fuels was 50% which decreased to 36% in 2020. The decrease in using these pollutant fuels is a result of the trials to have cleaner fuels such as LPG, biogas, and ethanol. In India alone, studies have shown that due to the harmful usage of fossil fuels in domestic cooking, the air pollution there is about 20-50%. To the account of the World Health Organization (WHO), almost 3 billion people use fossil fuels and kerosene for cooking which skyrockets the death rate by 100 times for household air pollution (HAP) which causes 3.8 million premature deaths annually. These deaths are caused by numerous diseases such as ischemic heart disease (32%), strokes (23%), lower respiratory infection (21%), chronic obstructive pulmonary disease (19%) and lung cancer (6%).

Liquefied petroleum gas has distinctive chemical properties that make it in a highly purified condition without intricate pollutants like sulfur. It is known to be an ecofriendly fuel source as it is nontoxic and burns cleanly. Traces of nitrogen oxide (NO_x) and particulate matter (PM) are produced from LPG production which is much better when compared to the amounts produced from other fossil fuels or biomass. An integral key factor is that the sulfur percentage in LPG is very small and there is almost no PM as well. Studies have shown that compared to heavy fuel oils used as marine fuels, LPG emits 97% less sulfur oxide (SO_x), 20% less NO_x, 90% less PM while reducing carbon emissions barely by 20%. Liquefied petroleum gas can reduce black carbon emissions whereas it helps in the limitation of global warming [62-65]. It is essentially a fossil fuel, yet it helps in reducing the amount of respirable particulate matter better than solid fuels like kerosene. Accordingly, the demand for wood will greatly decrease which helps in mitigating deforestation and preserving the green state of the earth [66-68].

On a larger scale, ships are responsible for a considerable level of air pollution due to the enormous hazardous emissions about 2-3% of overall GHG emissions. The International Maritime Organization (IMO) developed a worldwide strategy that aims to reduce GHG emissions with a minimum of 50% during 2008-2050. By 2030, shipping's carbon emissions are expected to decrease by 34% all the way to a net 100% of zero carbon emissions by 2050. Since LPG is considered an economic and ecofriendly fuel source, its utilization as a marine fuel can help reduce the levels of air pollution. In South Korea, the possibility of using LPG can alleviate the negative impacts of using traditional carbon-based fuels on several accounts. Studies have shown that LPG decreased the annual consumption rate by 7.5-10.4% and the fuel price by 8.8-25.9% and the SO_x, NO_x and PM emissions were also cut down by 10-14% [69-71].

In addition to marine ships, small vessels in Korea have begun to employ LPG in their engines. Despite their small sizes, small vessels individually do not comply with the IMO regulations yet as a whole, they represent a large portion of air pollution. All small fishing vessels account for a notable 17.3% GHG emissions in the marine sector. According to the studies of life cycle assessment (LCA) method done on LPG, 2.2 and 1.2 million tons of GHG emissions were reduced compared to gasoline and diesel, respectively. BioLPG was also found to reduce GHG emissions by an overall amount of nearly 8 million tons when replacing both gasoline and diesel in the engines of small boats. Thus, all

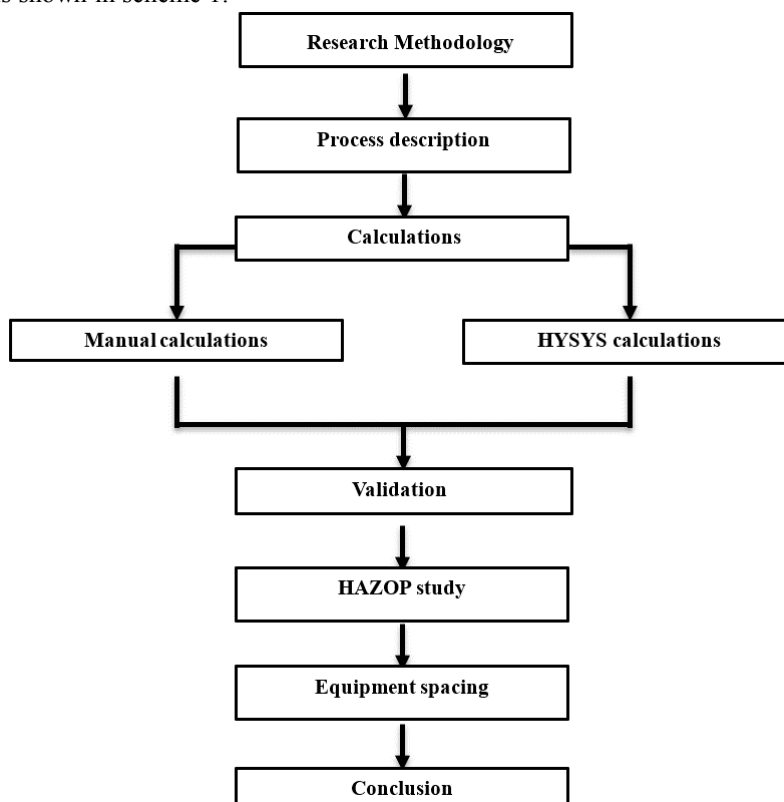
international governments should seek to employ LPG and even bio-LPG as marine fuels based on ecofriendly and economic regulations to help preserve the environment and reduce the overall operating costs [72-73].

In a similar vein, the transportation sector contributes heavily to the greenhouse gas emissions through release of CO₂ and consequently increasing global warming. In 2015, the Paris agreement was made to reach a phase where no carbon emissions would occur by 2050. This would require the usage of vehicles that do not depend on carbon-based fuels by any means. Automobiles alone account for an egregious 93.8% of road emissions. To alleviate the significant carbon emissions, LPG helps in achieving this purpose as it is known to reduce NO_x emissions by 5-10% and by 50% compared to diesel and gasoline vehicles respectively. It also helps in reduction CO and CO₂ emissions by 30% and 15% respectively compared to gasoline vehicles. Many countries have shifted focus on using LPG as fuel for vehicles. For instance, Poland has 1550 companies that are dedicated to LPG installation services for vehicles [74, 75].

Furthermore, switching to LPG across multiple sectors helps in achieving the sustainable development goals (SDGs) at an accelerated rate. From another perspective, LPG can alleviate the labor time in cooking and gathering of firewood which can impact the human health especially of women and girls. Therefore, the goal of gender equality can be achieved with the help of LPG application. Given the low cost and affordability of LPG, the SDG of having an affordable and clean energy source can also be met by implementation of LPG. Overall, the SDGs that are required to be achieved by 2030, can be accomplished more effectively and rapidly by utilization of LPG to ensure successful fulfillment of SDGs such as gender equality, zero hunger, affordable and clean energy, good health and well-being, climate action, life below water, life on land and responsible consumption and production [76, 77].

2. METHODOLOGY

This study first offered a thorough background about LPG and several aspects covering its pivotal role in several sectors such as its versatile applications, ecofriendly properties, economic value, and environmental impact. A given LPG plant flowsheet was explained and simulated using Aspen HYSYS 12.0. Manual calculations were also made and compared to those of HYSYS while offering possible reasons on why deviations occurred. HAZOP study and equipment spacing were carried out followed by a conclusion summarizing the findings of this study and future recommendations. The process identification is shown in scheme 1.



Scheme 1: The flowchart of the process identification

3. PROCESS DESCRIPTION

Feed gas, consisting of carbon dioxide, methane, ethane, propane, i-butane, n-butane, i-pentane, and n-pentane, enters the first heat exchanger from the tube at 2209 kg/h, temperature 27.41°C and pressure 1961 kPa. The feed goes out from the heat exchanger at different conditions and enters the three-phase separator. It helps in the initial separation of the feed gas into liquid and gas phases before entering the depropanizer. It also reduces the heating load from the reboiler in the depropanizer. The hydrocarbons are then collected at the bottom of the three-phase separator due to high density.

There are two streams that will enter the 35-trayed depropanizer from two different trays which are the 7th and 14th giving two streams which are the light products and heavy products streams. The light products stream includes all the ethane that entered the tower within the feed, some propane, and a small percentage of iso-butane. That stream returns to the heat exchanger alongside the feed stream. The heavy products stream includes two components which are the rest of the propane in the column and all the products that are heavier than propane. The amount of the butane in the overhead stream must be controlled because butane can be considered as LPG to avoid the loss of butane. Liquefied petroleum gas quantity is regulated by controlling the flow of the reflux and the temperature at the bottom of the column. The bottom stream of the depropanizer goes to the 30-trayed debutanizer at the 10th tray. There are also two streams with light and heavy products. The light products stream has four components which are propane, butane, iso-butane in the tower and a few amounts of iso-pentane. The heavy products stream has all the products that are heavier than butane.

The amount of iso-butane must be controlled because the excess will waste the LPG product and it can be controlled by adjusting the flow of the reflux and the temperature at the bottom of the tower. The liquefied petroleum gas can be stored in three ways to the sales gas, LPG storage and condensate tank. The flowsheet of the whole process is illustrated in Figure (1).

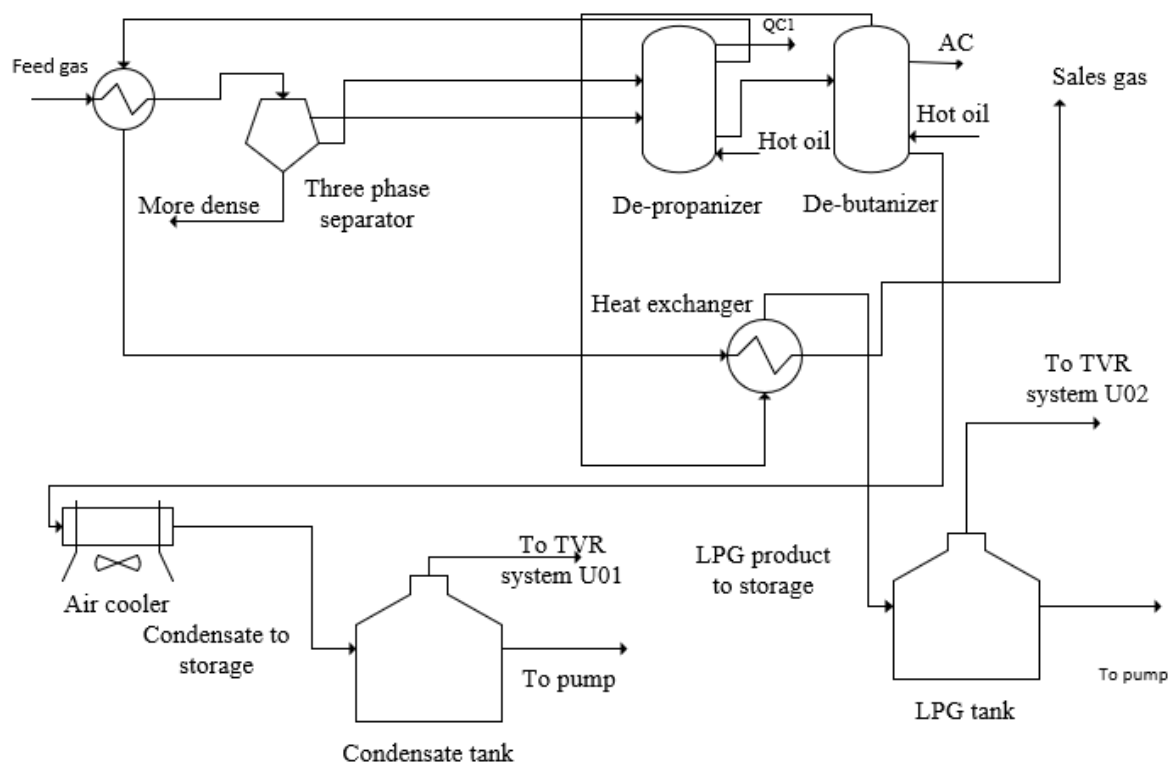


Figure 1: Process flow diagram for LPG production

4. SIMULATION

Figure 2 and 3 demonstrate the whole flow sheet and heat exchanger & separators of the process that was simulated by using Aspen HYSYS respectively.

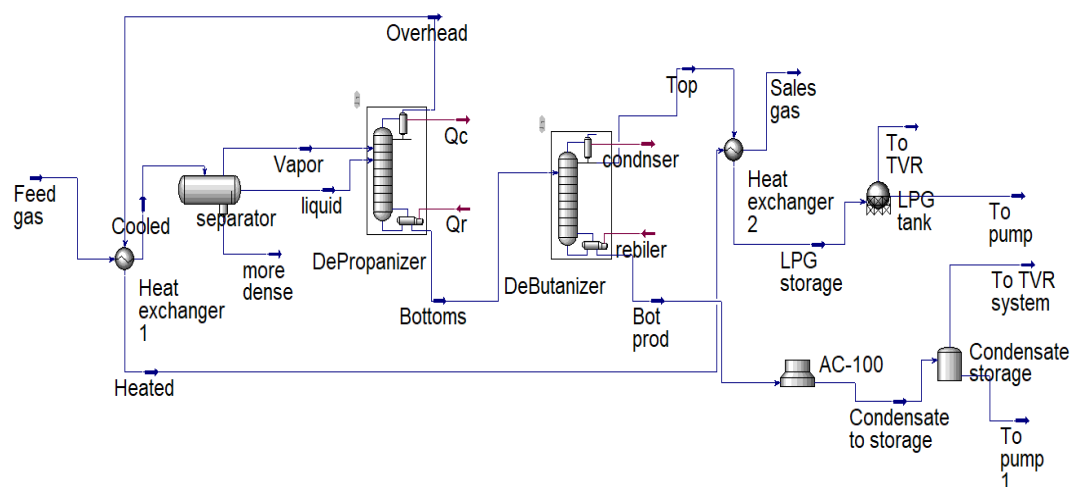


Figure 2: HYSYS process flow sheet

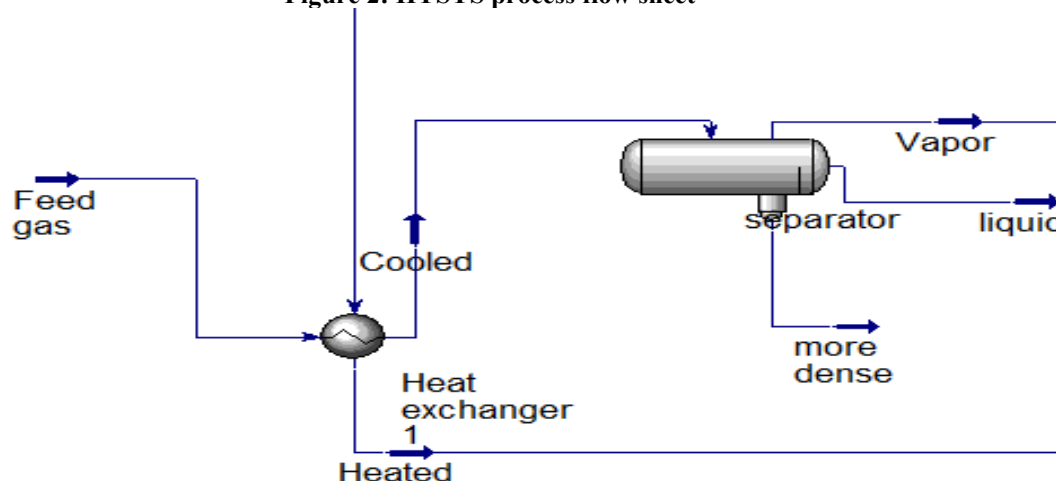


Figure 3: Heat exchanger & separator

The feed of the process contained mainly methane, ethane, propane, and iso-butane. The highest mole concentration is propane while C6+ was not found in the feed as listed in table 2.

Table 2: Feed compositions

	Mole Fractions	Vapour Phase	Liquid Phase
Nitrogen	0.0000	0.0000	0.0000
CO2	0.0268	0.0369	0.0095
Methane	0.2735	0.4020	0.0538
Ethane	0.1779	0.2121	0.1194
Propane	0.3104	0.2512	0.4115
i-Butane	0.1141	0.0590	0.2082
n-Butane	0.0856	0.0362	0.1700
i-Pentane	0.0067	0.0015	0.0155
n-Pentane	0.0050	0.0009	0.0119
C6+*	0.0000	0.0000	0.0000

The feed that entered heater exchanger 1 through the tube side had the following conditions as shown in table 3.

Table 3: Feed conditions

Stream Name	Feed gas	Vapour Phase	Liquid Phase
Vapour / Phase Fraction	0.6309	0.6309	0.3691
Temperature [C]	27.41	27.41	27.41
Pressure [kPa]	1961	1961	1961
Molar Flow [kgmole/h]	59.60	37.60	22.00
Mass Flow [kg/h]	2209	1175	1034
Std Ideal Liq Vol Flow [m3/h]	4.757	2.757	2.001
Molar Enthalpy [kJ/kgmole]	-1.130e+005	-1.027e+005	-1.306e+005
Molar Entropy [kJ/kgmole-C]	140.0	162.0	102.3
Heat Flow [kJ/h]	-6.735e+006	-3.861e+006	-2.873e+006
Liq Vol Flow @Std Cond [m3/h]	5.121	701.0	1.975
Fluid Package	Basis-1		
Utility Type			

The feed temperature decreased from 27° C to 24° C before it entered the separator as shown in figure 4. The three-phase separator was used for two purposes; it separated C₁ and C₂ from other components in gaseous phase from the vapor stream and ensured the absence of any traces of heavy components. Since the crude oil used in the process was refined, there were almost no heavy components and the flow rate of the more dense stream was almost zero as listed in table 4 and table 5.

Table 4: Separator streams compositions

	Cooled	liquid	Vapor	more dense
Nitrogen	0.0000	0.0000	0.0000	0.0000
CO2	0.0268	0.0100	0.0382	0.0100
Methane	0.2735	0.0561	0.4209	0.0561
Ethane	0.1779	0.1245	0.2141	0.1245
Propane	0.3104	0.4155	0.2392	0.4155
i-Butane	0.1141	0.2036	0.0534	0.2036
n-Butane	0.0856	0.1644	0.0322	0.1644
i-Pentane	0.0067	0.0146	0.0013	0.0146
n-Pentane	0.0050	0.0112	0.0008	0.0112
C6+*	0.0000	0.0000	0.0000	0.0000

Table 5: Separator conditions

Name	Cooled	liquid	Vapor	more dense
Vapour	0.5960	0.0000	1.0000	0.0000
Temperature [C]	24.00	24.00	24.00	24.00
Pressure [kPa]	1932	1932	1932	1932
Molar Flow [kgmole/h]	59.60	24.08	35.52	3.123e-015
Mass Flow [kg/h]	2209	1124	1085	1.457e-013
Std Ideal Liq Vol Flow [m3/h]	4.757	2.183	2.574	2.831e-016
Molar Enthalpy [kJ/kgmole]	-1.137e+005	-1.306e+005	-1.023e+005	-1.306e+005
Molar Entropy [kJ/kgmole-C]	137.6	101.5	162.0	101.5
Heat Flow [kJ/h]	-6.779e+006	-3.144e+006	-3.635e+006	-4.077e-010

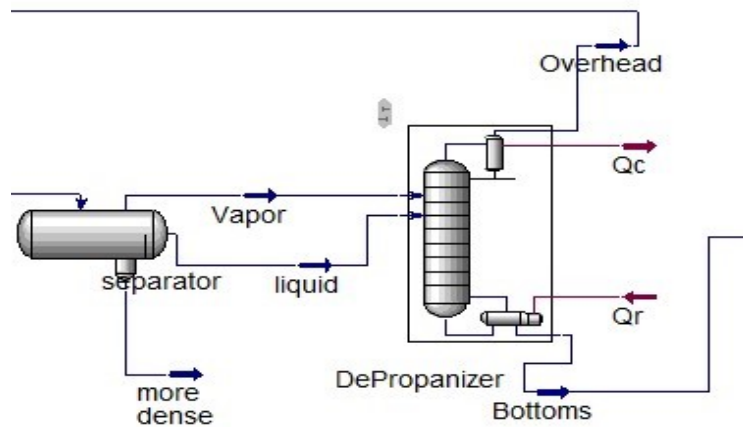


Figure 4: DePropanizer

The three-phase separator was also used to reduce the heating load on the reboiler in the depropanizer. The vapor and liquid streams entered the depropanizer from different sections, the vapor was entered from a lower tray than the liquid so that it could separate any traces of C_1 and C_2 from the liquid. The gases were withdrawn from the top section of the column while liquids were withdrawn from the bottom section. The connections for the depropanizer are shown in figure 5.

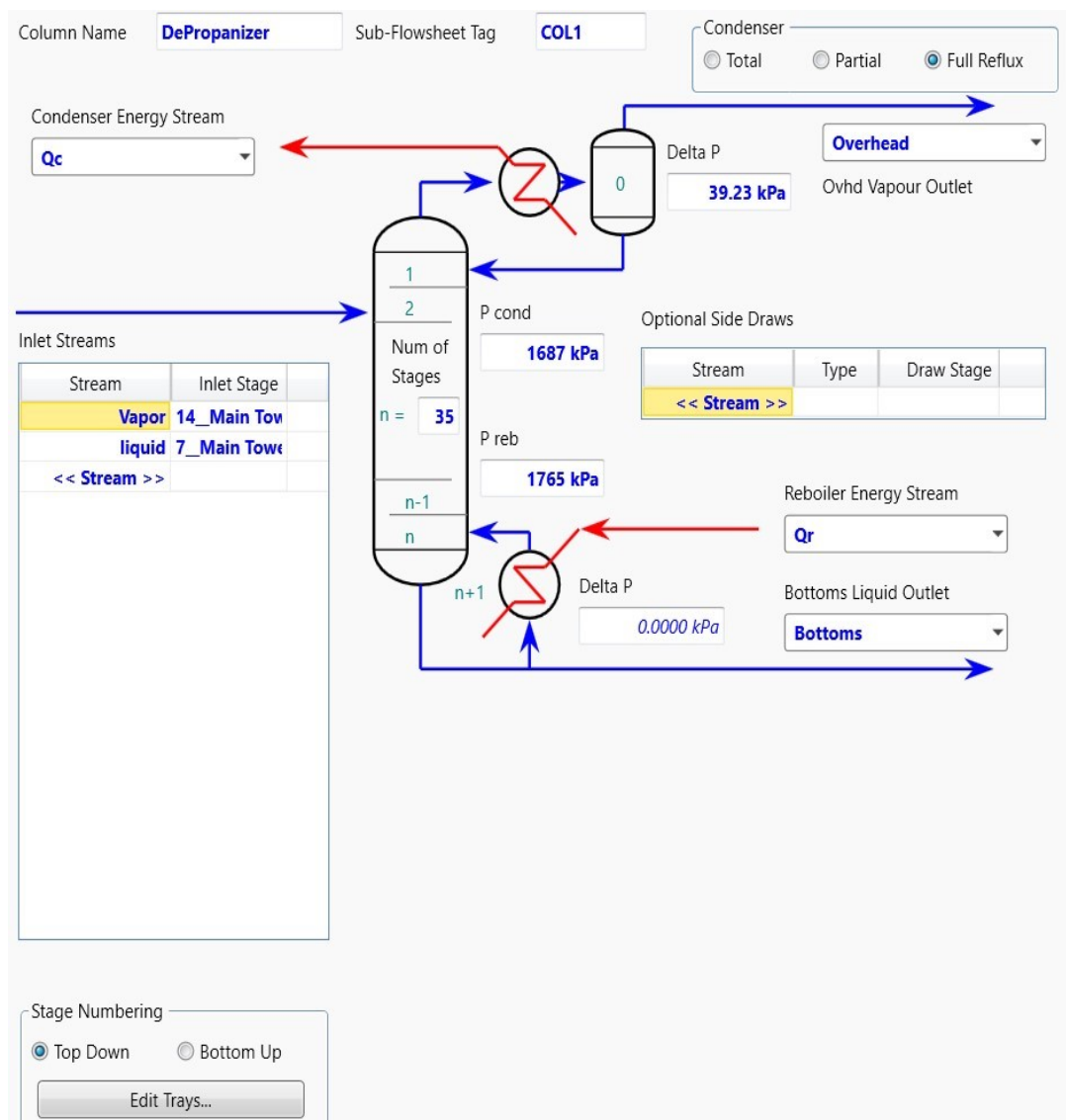


Figure 5: DePropanizer connections

The gases withdrawn from the top section entered the condenser, since the condenser was a reflux condenser, the condensates were refluxed to the depropanizer with reflux ratio 1.5. The gases left the condenser and entered the heat exchanger from the shell side to increase the temperature of the gases which are later used as sales gas as shown in table 6.

The bottoms of the depropanizer that entered the debutanizer are mainly propane and butane and traces of pentanes. The debutanizer separated propane and butane from pentanes where the propane and butane left from the top section after being condensed and then entered heat exchanger 2 from the shell side where they were cooled down before they entered the LPG storage tank. The connections of the debutanizer are shown in figure 6 and figure 7.

Table 6: Overhead compositions

	Mole Fractions	Vapour Phase
Nitrogen	0.0000	0.0000
CO ₂	0.0488	0.0488
Methane	0.4981	0.4981
Ethane	0.3240	0.3240
Propane	0.1290	0.1290
i-Butane	0.0001	0.0001
n-Butane	0.0000	0.0000
i-Pentane	0.0000	0.0000
n-Pentane	0.0000	0.0000
C ₆ +*	0.0000	0.0000

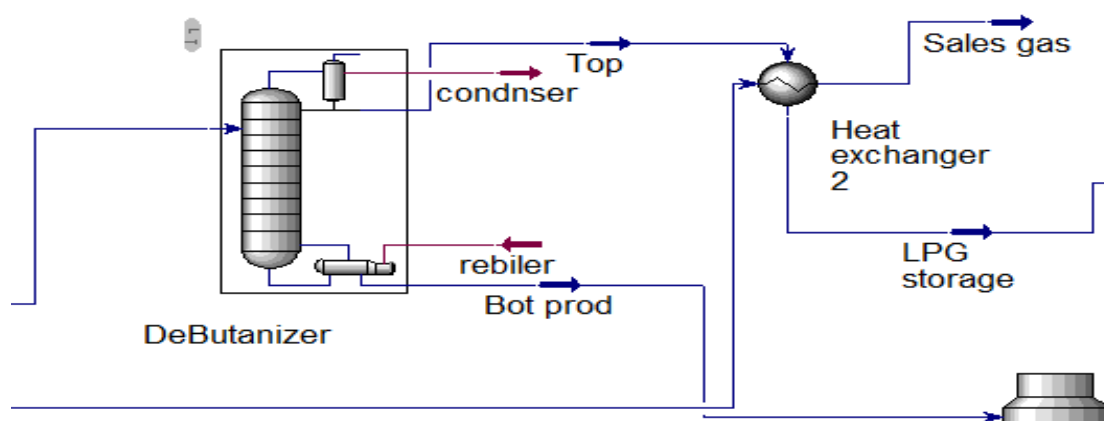


Figure 6: Debutanizer

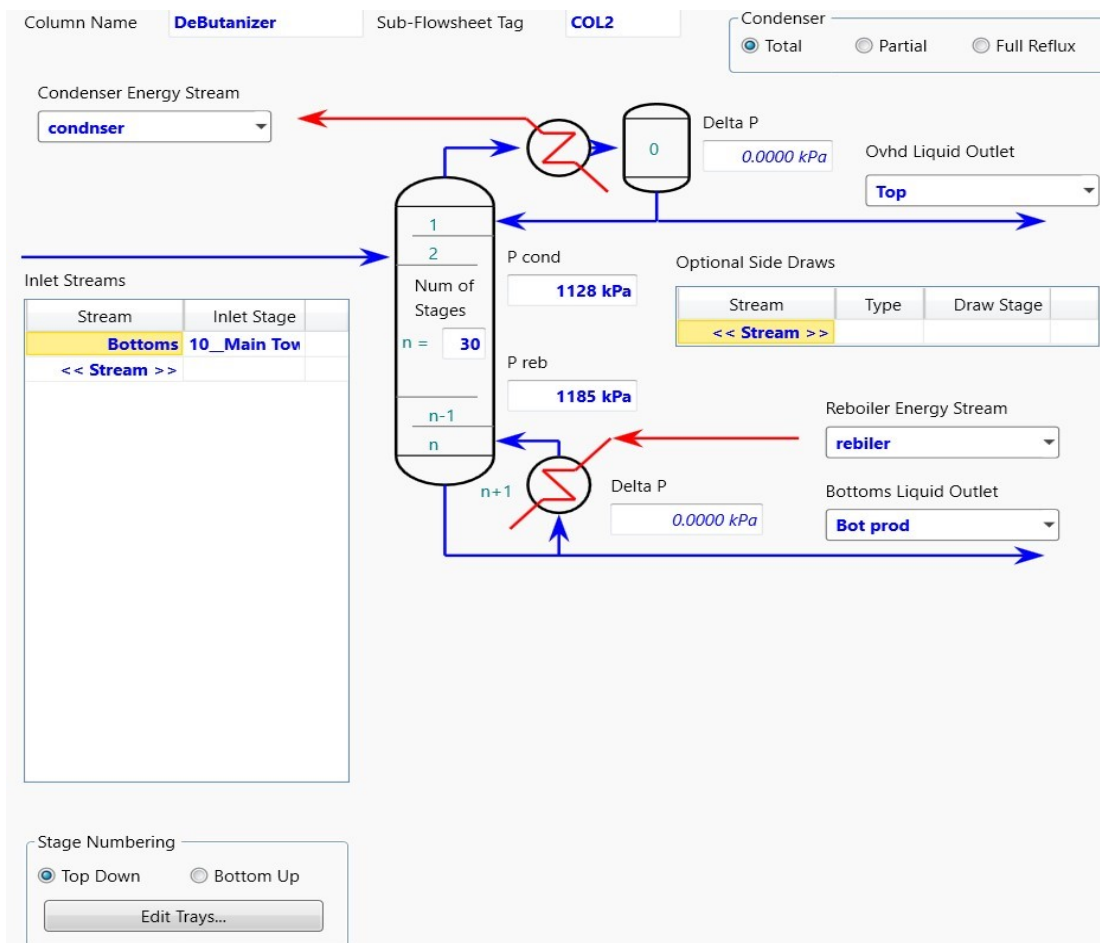


Figure 7: Debutanizer connections

The top stream that left the debutanizer contained propane, butane, traces of pentane as shown in table 7.

Table 7: Top stream compositions

	Mole Fractions	Liquid Phase
Nitrogen	0.0000	0.0000
CO2	0.0000	0.0000
Methane	0.0000	0.0000
Ethane	0.0000	0.0000
Propane	0.5454	0.5454
i-Butane	0.2597	0.2597
n-Butane	0.1947	0.1947
i-Pentane	0.0002	0.0002
n-Pentane	0.0000	0.0000
C6+*	0.0000	0.0000

The liquefied petroleum gas (LPG) was stored at 900 psi so that the LPG is maintained in a liquid state at temperature 30-35° C as shown in figure 8. The gas that entered from the tube side was heated and left as sales gases to be used separately as shown in table 8 and table 9.

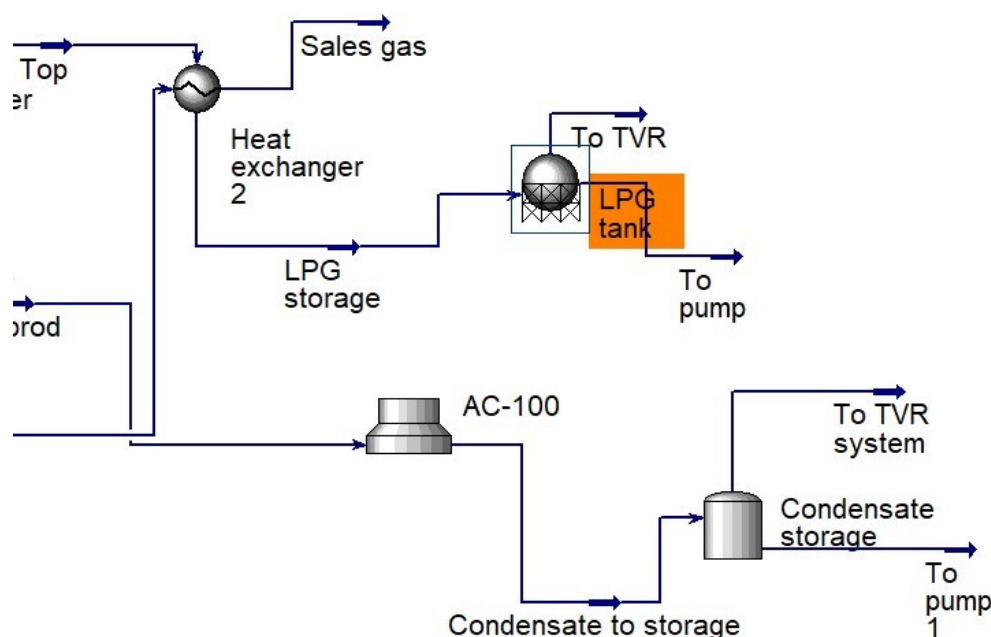


Figure 8: Heat exchanger & storage tanks

Table 8: Heat exchanger 2 conditions

Name	Heated	Sales gas	Top	LPG storage
Vapour	1.0000	1.0000	0.0000	0.0000
Temperature [C]	9.000	41.00	48.38	33.87
Pressure [kPa]	1608	1579	1128	900.0
Molar Flow [kgmole/h]	32.72	32.72	26.18	26.18
Mass Flow [kg/h]	836.9	836.9	1321	1321
Std Ideal Liq Vol Flow [m3/h]	2.223	2.223	2.454	2.454
Molar Enthalpy [kJ/kgmole]	-9.885e+004	-9.723e+004	-1.312e+005	-1.333e+005
Molar Entropy [kJ/kgmole-C]	166.1	171.7	99.25	92.85
Heat Flow [kJ/h]	-3.235e+006	-3.182e+006	-3.435e+006	-3.488e+006

Table 9: LPG Storage tank conditions

Name	LPG storage	To pump	To TVR
Vapour	0.0000	0.0000	1.0000
Temperature [C]	33.87	33.87	33.87
Pressure [kPa]	900.0	900.0	900.0
Molar Flow [kgmole/h]	26.18	26.18	0.0000
Mass Flow [kg/h]	1321	1321	0.0000
Std Ideal Liq Vol Flow [m3/h]	2.454	2.454	0.0000
Molar Enthalpy [kJ/kgmole]	-1.333e+005	-1.333e+005	-1.114e+005
Molar Entropy [kJ/kgmole-C]	92.85	92.85	146.2
Heat Flow [kJ/h]	-3.488e+006	-3.488e+006	-0.0000

The bottom products of the debutanizer were mainly pentanes, the stream was cooled using an air cooler before it entered the condensate storage tank where it was stored at temperature below 50° C as shown in table 10.

Table 10: Condensate storage tank conditions

Name	Condensate to st	To pump 1	To TVR system
Vapour	0.0000	0.0000	1.0000
Temperature [C]	45.00	45.00	45.00
Pressure [kPa]	160.7	160.7	160.7
Molar Flow [kgmole/h]	0.6978	0.6978	0.0000
Mass Flow [kg/h]	50.27	50.27	0.0000
Std Ideal Liq Vol Flow [m3/h]	8.032e-002	8.032e-002	0.0000
Molar Enthalpy [kJ/kgmole]	-1.733e+005	-1.733e+005	-1.490e+005
Molar Entropy [kJ/kgmole-C]	70.07	70.07	144.4
Heat Flow [kJ/h]	-1.209e+005	-1.209e+005	0.0000

5. MASS BALANCE

The calculations of the overall mass balance and component mass balance are represented by equations (1) and (2)

Overall mass balance: Σ Moles of the entering feed = Σ Moles of the exiting feed (1)

*Component mass balance: Σ [mole fraction of the component * molar flow rate of the stream] entering = Σ [mole fraction of the component * molar flow rate of the stream] exiting* (2)

I. Heat exchanger 1

The calculations of the overall mass balance of the heat exchanger are given in equation (3) and the heat exchanger 1 HYSYS simulation is shown in Figure (9)

The molar flow of the tube side in = molar flow of the tube side out,

The molar flow of the shell in side = molar flow of the shell out side (3) (3)

- Feed gas stream = cooled stream
- Overhead stream = Heated stream
- Molar flow rate of the feed gas stream = 59.6 kgmole/h,
- Cooled stream = 59.6 kg mole/h

The compositions of the feed gas stream = compositions of the cooled stream

II. Three-phase separator

The calculations of overall mass balance and component mass balance of the separator are given in equations (4) and (5) by using the given data of the feed stream which is represented in Table 11 & the separator HYSYS simulation as shown in Figure (9)

Cooled stream = Vapor stream + Liquid stream + more dense stream (4) (4)

From the HYSYS simulation, it was determined that the separator has efficiency = 60% liquid separation from vapor.

The molar flow rate entering the separator = 59.6 Kgmole/h *60% = 35.7 Kgmole/h liquid; 59.6 - 35.7 = 23.9Kgmole/h vapor

From HYSYS, the dense stream = 0 Kgmole/h

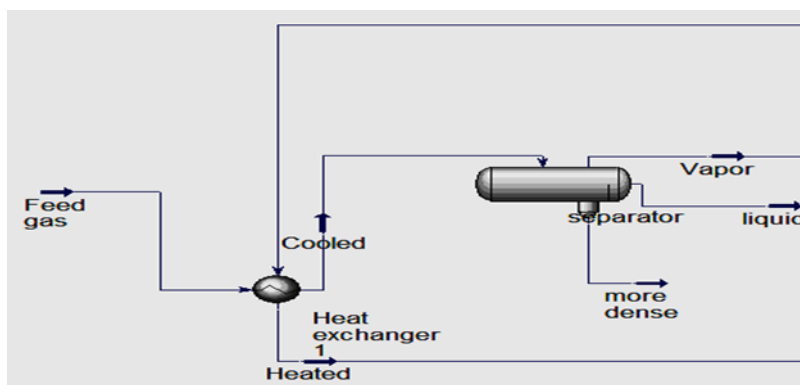


Figure 9: Heat exchanger 1 & separator

Table 10: Feed gas stream compositions

Component mole fraction	Feed gas
Nitrogen	0
Carbon Dioxide	0.0268
Methane	0.2735
Ethane	0.1779
Propane	0.3104
i-Butane	0.1141
n-Butane	0.0856
i-Pentane	0.0067
n-Pentane	0.005
C6+*	0

Since the compositions were only defined in the feed stream, the feed stream was considered to comprise propane, butane, and other components. The liquid stream compositions were calculated and assumed based on the separation efficiency:

Propane mole fraction in liquid stream = 0.4

Butane mole fraction in liquid stream = 0.2

Other components mole fraction = 0.4

Component mass balance

$$[\text{Component mole fraction} * \text{feed molar flow rate}] = [\text{component mole fraction in liquid stream} * \text{liquid molar flow rate}] + [\text{component mole fraction in vapor stream} * \text{vapor molar flow rate}] \quad (5)$$

The components are propane, butane and the other components.

Propane: [propane mole fraction] * [feed molar flow rate] = [propane mole fraction in liquid stream * liquid molar flow rate] + [propane mole fraction in vapor stream * vapor molar flow rate]
 $59.6 * 0.3 = 35.7 * 0.4 + 23.9 * \text{propane mole fraction in vapor stream}$
 propane mole fraction in vapor stream = 0.15

Butane: [Butane mole fraction] * [feed molar flow rate] = [Butane mole fraction in liquid stream * liquid molar flow rate] + [Butane mole fraction in vapor stream * vapor molar flow rate]
 $59.6 * 0.2 = 35.7 * 0.2 + 23.9 * \text{butane mole fraction in vapor stream}$, butane mole fraction in vapor stream = 0.2

Other components: [other components mole fraction] * [feed molar flow rate] = [other components mole fraction in liquid stream * liquid molar flow rate] + [other components mole fraction in vapor stream * vapor molar flow rate]
 $(59.6 * 0.5) = (35.7 * 0.4) + (23.9 * \text{other components mole fraction in vapor stream})$, other components mole fraction in vapor stream = 0.65

III. Depropanizer

Since the depropanizer efficiency depends on the amount of propane separated from the entering mixture, the HYSYS results showed an efficiency percentage = 45%

The molar flow rate of the stream entering (59.6 kg mole/h) * efficiency [45%] = bottoms molar flow rate [26.8 kg mole/h]

Overhead stream = [molar flow rate of entering stream (59.6) – bottoms molar flow rate (26.8) = 32.7 kg mole/h, also consider that the other components separated from the propane and butane mixture as the overhead stream ≈ 0.9 [mole fraction] and has only few traces in the bottom stream.

For the overhead stream: Other components mole fraction ≈ 0.99 , in the bottoms = 0.01

Propane and butane mole fraction ≈ 0

Component mass balance

The component mass balance of depropanizer was calculated by equation (6) and the depropanizer HYSYS simulation is shown in Figure (10).

$$\begin{aligned}
 & [Vapor \text{ molar flow rate} * \text{component mole fraction in vapor}] + [liquid \text{ molar flowrate} \\
 & * \text{component mole fraction in liquid}] \\
 & = [Overhead \text{ mole flow rate} * \text{component mole fraction in overhead}] \\
 & + [Bottoms \text{ molar flow rate} \\
 & * \text{component mole fraction in bottoms}] \qquad (6)
 \end{aligned}$$

Propane: [Vapor molar flow rate * propane mole fraction in vapor] + [liquid molar flowrate * propane mole fraction in liquid] = [Overhead mole flow rate*propane mole fraction in overhead] + [Bottoms molar flow rate*propane mole fraction in bottoms]
 $(23.9 * 0.15) + (35.7 * 0.4) = (32.7 * 0) + (26.9 * \text{propane mole fraction in bottoms});$ propane mole fraction in bottoms = 0.61

Butane: [Vapor molar flow rate*butane mole fraction in vapor] + [liquid molar flowrate * butane mole fraction in liquid] = [Overhead mole flow rate * butane mole fraction in overhead] + [Bottoms molar flow rate * butane mole fraction in bottoms]
 $(23.9 * 0.2) + (35.7 * 0.2) = (32.7 * 0.01) + (26.9 * \text{butane mole fraction in bottoms});$ butane mole fraction in bottoms = 0.38

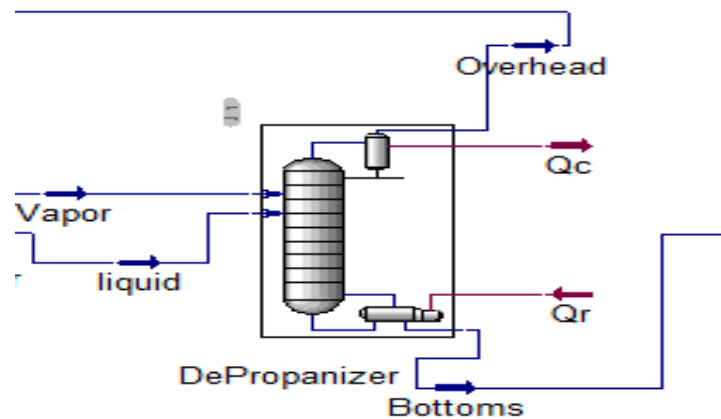


Figure 10: Depropanizer

IV. Debutanizer & heat exchanger 2

The heat exchanger 2 and depropanizer entering and exiting streams were demonstrated from the HYSYS simulation represented in Figure (11).

Feed entering Debutanizer = bottoms stream of depropanizer = 26.9 kg mole/h [molar flow rate]
 HYSYS results showed that the debutanizer distillation column separated 97% between any other components and butane and propane [LPG]; $26.9 * 97\% = 26.1$ kg mole/h [Top stream], and the remaining = 0.8 [bottom product stream] kgmole/h

In the debutanizer, the mixture of butane and propane are separated completely with very small traces of the other components: Butane and propane mixture [LPG] mole fractions = 0.55 and 0.45 based on the HYSYS simulation.

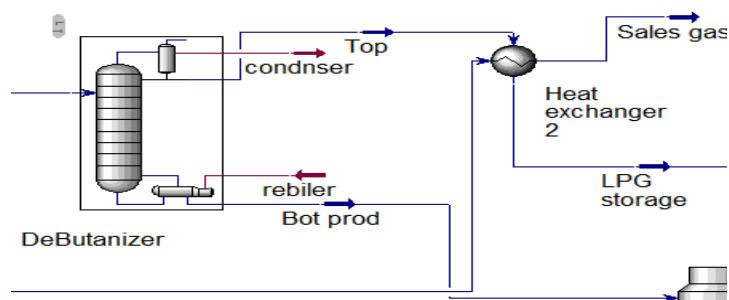


Figure 11: Debutanizer & heat exchanger 2

For the heat exchanger 2: Top stream = LPG storage stream and shell out stream from the first heat exchanger = sales gas stream. The rest of the equipment are storage tanks so no further mass balance was applied. After applying the equations of the mass balance for each equipment. Table 12 and Table 13 were provided to show the calculated results. The molar flow rate of each stream and their components mole fraction are listed in Tables 12 and 13 respectively.

Table 11: Streams molar flow rates

Streams	Feed gas	Cooled	Heated	Vapor	Liquid	More dense	Overhead	Bottoms	Top	Bot. prod	LPG storage	Sales gas
Flow rate (kgmol/h)	59.6	59.6	32.7	23.9	35.7	≈0	32.7	26.8	26.1	0.8	26.1	32.7

Table 12: Component mole fractions

Streams / Comp mole fraction	Feed gas	Cooled	Heated	Vapor	liquid	More dense	Overhead	Bottoms	Top	Bot prod	LPG storage	Sales gas
Propane	0.31	0.31	≈0	0.15	0.4	0	≈0	0.61	0.6	0	0.55	≈0
Butane	0.2	0.2	≈0	0.2	0.2	0	≈0	0.38	0.5	0	0.45	≈0
Other components	0.5	0.5	0.99	0.65	0.4	0	0.99	0.01	0	0.99≈1	0	0.99

6. ENERGY BALANCE

All energy balance calculations for each type of equipment were performed in this section.

I. Heat capacity calculations

The calculations of the heat capacity of a mixture (cp_{mix}) were performed using equations (7,8,9). The necessary thermodynamic constants for each component in this case were obtained from (Coulson & Richardson's Chemical Engineering. Vol. 6, Chemical Engineering Design, 4th Ed), as listed in Table 14.

$$cp_{mix} = \sum A_i + \sum B_i T + \sum C_i T^2 + \sum D_i T^3 \quad (7)$$

$$T \text{ (K)}, cp_{mix} \text{ (kJ/kgmol}\cdot\text{K)}$$

$$Q = n \int_{T_i}^{T_o} cp dt \quad (8)$$

$$Q = n \times \int_{T_i}^{T_o} \sum A_i + \sum B_i T + \sum C_i T^2 + \sum D_i T^3 dt \quad (9)$$

$$n \text{ (kgmol/h)}$$

Table 13: Thermodynamic constants of heat capacity (cp_{mix})

Component	A	B	C	D
N ₂	3.12E+01	-1.36E-02	2.68E-05	-1.17E-08
CO ₂	1.98E+01	7.34E-02	-5.60E-05	1.72E-08
Methane	1.93E+01	5.21E-02	1.20E-05	-1.13E-08
Ethane	5.41E+00	1.78E-01	-6.94E-05	8.71E-09
Propane	-4.22E+00	3.06E-01	-1.59E-04	3.21E-08
I-butane	-1.39E+00	3.85E-01	-1.85E-04	2.90E-08
n-butane	9.49E+00	3.31E-01	-1.11E-04	-2.82E-09
I-pentane	-9.53E+00	5.07E-01	-2.73E-04	5.72E-08
n-pentane	-3.63E+00	4.87E-01	-2.58E-04	5.30E-08

II. Overhead gases-feed gas heat exchanger

Shell and tube heat exchanger was utilized to heat the overhead gases (251.08 K) produced by depropanizer and to cool down the feed gases (300.41 K), thereby facilitating the separation of liquids (40.40% of the feed gases) from gases in the three-phase separator, as shown in Figure 9.

The calculations aimed to determine the heat capacity value (cp_{mix}) for the overhead gases stream (32.72 kgmol/h), which was fed to the shell side of the heat exchanger (overhead gases-feed gas). This stream was primarily composed of methane (49.81%), ethane (32.40%), and propane (12.90%), as listed in Table 15.

Table 14: Heat capacity (cp_{mix}) calculations for shell side

Component	Composition (y_i)	Ay_i	By_i	Cy_i	Dy_i
N ₂	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO ₂	4.88E-02	9.66E-01	3.58E-03	-2.73E-06	8.37E-10
Methane	4.98E-01	9.59E+00	2.60E-02	5.96E-06	-5.64E-09
Ethane	3.24E-01	1.75E+00	5.77E-02	-2.25E-05	2.82E-09
Propane	1.29E-01	-5.45E-01	3.95E-02	-2.05E-05	4.15E-09
I-butane	7.50E-05	-1.04E-04	2.88E-05	-1.38E-08	2.17E-12
n-butane	5.16E-06	4.89E-05	1.71E-06	-5.71E-10	-1.45E-14
I-pentane	7.58E-10	-7.22E-09	3.84E-10	-2.07E-13	4.34E-17
n-pentane	8.11E-11	-2.94E-10	3.95E-11	-2.09E-14	4.30E-18
Total	1.00E+00	1.18E+01	1.27E-01	-3.97E-05	2.17E-09

The calculated and provided specifications for the shell and the tube sides of the heat exchanger (overhead gases-feed gas), including the property of interest (the inlet temperature of overhead gases), determined to be 251.08 K, are listed in Table 16.

Table 15: Energy balance results of (overhead gases-feed gas) heat exchanger

Shell side		
Specifications	Overhead (Inlet)	Heated (Outlet)
Temperature (K)	251.08 (Calculated)	282.00
Molar flow (n.) (kgmol/h)	32.72	32.72
Molar enthalpy (kJ/kgmol)	1322.64	
Heat gained (Q) (kJ/h)	43281.35	
Tube side		
Specifications	Feed gas	Cooled
Molar flow (n) (kgmol/h)	59.60	59.60
Temperature (K)	300.41	297.00
Molar enthalpy at saturated liquid (h_l)(kJ/kgmol)	-126947.02	
Molar enthalpy at saturated vapour (h_v)(kJ/kgmol)	-106139.08	
Molar enthalpy difference between saturated vapour and saturated liquid (kJ/kgmol) ($h_{vl} = h_v - h_l$)	20807.94	
Inlet and outlet molar enthalpies (kJ/kgmol)	-113819.29	-114545.49
Heat lost = $n \times (h_{out} + h_{inlet})$ (kJ/h)	43281.35	

III. Top-heated heat exchanger

The shell and tube heat exchanger was employed to cool down the LPG (26.19 kgmol/h) produced from the top of the debutanizer to the storage temperature (306.89 K). Additionally, it played a role in further heating the overhead gases of the depropanizer, initially heated by the feed gases, to attain the necessary temperature for sales gases (318.53 K), as shown in Figure 11.

The calculation results for the heat capacity (cp_{mix}) of the heated stream, primarily composed of methane (49.81%) and ethane (32.40%), fed to the tube side of heat exchanger (Top-Heated), are listed in Table 17.

Table 16: Heat capacity (cp_{mix}) calculations for tube side

Component	Composition (y_i)	Ay_i	By_i	Cy_i	Dy_i
N2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2	4.88E-02	9.66E-01	3.58E-03	-2.73E-06	8.37E-10
Methane	4.98E-01	9.59E+00	2.60E-02	5.96E-06	-5.64E-09
Ethane	3.24E-01	1.75E+00	5.77E-02	-2.25E-05	2.82E-09
Propane	1.29E-01	-5.45E-01	3.95E-02	-2.05E-05	4.15E-09
I-butane	7.50E-05	-1.04E-04	2.88E-05	-1.38E-08	2.17E-12
n-butane	5.16E-06	4.89E-05	1.71E-06	-5.71E-10	-1.45E-14
I-pentane	7.58E-10	-7.22E-09	3.84E-10	-2.07E-13	4.34E-17
n-pentane	8.11E-11	-2.94E-10	3.95E-11	-2.09E-14	4.30E-18
Total	1.00E+00	1.18E+01	1.27E-01	-3.97E-05	2.17E-09

The summary of both calculated and provided specifications for the shell and tube sides of the heat exchanger (Top-Heated), including the calculated sales gas temperature (318.53 K), is tabulated Table 18.

Table 17: Energy balance results of heat exchanger 2

Shell side		
Specifications	Top (inlet)	LPG storage (outlet)
Temperature (K)	321.39	306.89
Molar flow (n) (kgmol/h)	26.19	26.19
Molar heat capacity (cp_{mix}) (kJ/kgmol. K)	145.78	
Heat lost (Q) (kJ/h)	55361.17	
Tube side		
Specifications	Heated (inlet)	Sales gas (outlet)
Temperature (K)	282.00	318.53 (Calculated)
Molar flow (n) (kgmol/h)	32.72	32.72
Molar enthalpy (kJ/kgmol)	1691.78	
Heat gained (Q) (kJ/h)	55361.17	

IV. Depropanizer column

The depropanizer column was employed to separate propane from the vapor phase (35.52 kgmol/h) and the liquid phase (24.08 kgmol/h) which were separated in the three-phase separator during the separation of feed gases (31% propane), as demonstrated in Figure 10.

The calculations for the heat capacity (cp_{mix}), used to determine the sensible heat duty for the partial condenser of the depropanizer column, are listed in Table 19.

Table 18: The heat capacity (cp_{mix}) calculations for condenser

Component	Composition (y_i)	Ay_i	By_i	Cy_i	Dy_i
N2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2	3.13E-02	6.20E-01	2.30E-03	-1.75E-06	5.37E-10
Methane	2.47E-01	4.75E+00	1.29E-02	2.95E-06	-2.79E-09
Ethane	3.36E-01	1.82E+00	5.99E-02	-2.33E-05	2.93E-09
Propane	3.85E-01	-1.63E+00	1.18E-01	-6.11E-05	1.24E-08
I-butane	5.51E-04	-7.66E-04	2.12E-04	-1.02E-07	1.59E-11
n-butane	5.49E-05	5.21E-04	1.82E-05	-6.08E-09	-1.55E-13
I-pentane	2.09E-08	-1.99E-07	1.06E-08	-5.70E-12	1.19E-15
n-pentane	3.11E-09	-1.13E-08	1.51E-09	-8.02E-13	1.65E-16
Total	1.00E+00	5.56E+00	1.93E-01	-8.33E-05	1.31E-08

The latent heat calculations for each component in the inlet stream, mainly composed of methane (24.7%), ethane (33.6%), and propane (38.5%), to the partial condenser, are listed in Table 20.

Table 19: Calculations of latent heat for condenser feed mixture (λ_{mix})

Component	Composition (y_i)	λ (kJ/kgmol)	$y_i\lambda_i$ (kJ/kgmol)
N2	0.00E+00	5.58E+03	0.00E+00
CO2	3.13E-02	1.72E+04	5.37E+02
Methane	2.47E-01	8.19E+03	2.02E+03
Ethane	3.36E-01	1.47E+04	4.95E+03
Propane	3.85E-01	1.88E+04	7.24E+03
I-butane	5.51E-04	2.13E+04	1.17E+01
n-butane	5.49E-05	2.24E+04	1.23E+00
I-pentane	2.09E-08	2.47E+04	5.16E-04
n-pentane	3.11E-09	2.58E+04	8.01E-05
Total	1.00E+00	-	1.48E+04
Condenser lost heat (Q_{cond}) (kJ/h)	7.24E+05		

The calculations for the heat capacity (cp_{mix}) used to determine the sensible heat for the reboiler of the depropanizer column, are tabulated in Table 21.

Table 20: Heat capacity (cp_{mix}) calculations for reboiler

Component	Composition (y_i)	A_{yi}	B_{yi}	C_{yi}	D_{yi}
N2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2	3.06E-14	6.05E-13	2.25E-15	-1.71E-18	5.25E-22
Methane	1.29E-17	2.47E-16	6.70E-19	1.54E-22	-1.45E-25
Ethane	3.16E-07	1.71E-06	5.63E-08	-2.19E-11	2.76E-15
Propane	6.41E-01	-2.71E+00	1.96E-01	-1.02E-04	2.06E-08
I-butane	2.07E-01	-2.88E-01	7.97E-02	-3.83E-05	6.00E-09
n-butane	1.38E-01	1.31E+00	4.58E-02	-1.53E-05	-3.90E-10
I-pentane	8.13E-03	-7.75E-02	4.12E-03	-2.22E-06	4.66E-10
n-pentane	5.70E-03	-2.07E-02	2.78E-03	-1.47E-06	3.02E-10
Total	1.00E+00	-1.78E+00	3.29E-01	-1.59E-04	2.70E-08

The overall energy balance results for the partial condenser of the depropanizer, including the condenser duty (857173.96 kJ/h) obtained using data from HYSYS, are listed in Table 22.

Table 21: Energy balance results of condenser using data from ASPEN-HYSYS

Partial condenser			
Sensible heat part			
Specifications	Inlet to condenser	Reflux	Overhead
Temperature (K)	287.17	256.00	256.00
Molar flow (n') (kgmol/h)	81.81		
Heat lost (Q) (kJ/h)	132994.99		
Latent heat of condensation			
Specifications	Inlet to condenser	Reflux	Overhead
Molar flow (n') (kgmol/h)	81.81	49.08	32.73
Temperature (K)	256.00	256.00	256.00
Latent heat lost by condenser (Q_{cond}) (kJ/h) $= Reflux \times \lambda_{mix}$	724178.97		
Total heat lost by condenser (Q_{cond}) (kJ/h)	857173.96 (Calculated)		

The results of the energy balance performed for the reboiler of the depropanizer column, including the total reboiler duty (872177.14 kJ/h), are tabulated in Table 23.

Table 22: Energy balance results for reboiler using some data from HYSYS

Reboiler			
Sensible heat part			
Specifications	To reboiler	Boilup	Bottoms
Temperature (K)	338.63	344.02	344.02
Molar flow (n') (kgmol/h)	86.09		
Heat gained (Q) (kJ/h)	43136.30		
Latent heat of reboiler			
Specifications	To reboiler	Boilup	Bottoms
Molar flow (n') (kgmol/h)	86.09	59.22	26.87
Temperature (K)	344.02	344.02	344.02
Molar enthalpy at saturated liquid (h_l)(kJ/kgmol)	-126100.00		
Molar enthalpy at saturated vapour (h_v)(kJ/kgmol)	-112100.00		
Molar enthalpy difference between saturated vapour and saturated liquid was calculated by equation (10) (kJ/kgmol)	14000.00		
Latent heat gained =n × h_{vl} (kJ/h)	829040.83		
Total heat gained by reboiler (Q) (kJ/h)	872177.14 (Calculated)		

V. Debutanizer column

In the debutanizer column, the bottom stream (25.29% i-butanenes and 18.98% n-butane) from the depropanizer was fed to separate the butanes to produce a more purified LPG in the top stream (26.18 kgmol/h), as explained in Figure 11.

The calculations for the heat capacity (cp_{mix}) of the inlet vapor stream (45.50% butanes) from the top of the column into the total condenser were performed to determine the required sensible heat, as tabulated in Table 24.

Table 23: Heat capacity (cp_{mix}) calculations for condenser

Component	Composition (y_i)	A_{yi}	B_{yi}	C_{yi}	D_{yi}
N2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2	8.12E-15	1.61E-13	5.96E-16	-4.55E-19	1.39E-22
Methane	2.30E-18	4.43E-17	1.20E-19	2.75E-23	-2.60E-26
Ethane	1.44E-07	7.80E-07	2.57E-08	-1.00E-11	1.26E-15
Propane	5.45E-01	-2.30E+00	1.67E-01	-8.65E-05	1.75E-08
I-butane	2.60E-01	-3.61E-01	9.99E-02	-4.79E-05	7.52E-09
n-butane	1.95E-01	1.85E+00	6.45E-02	-2.16E-05	-5.50E-10
I-pentane	2.94E-04	-2.80E-03	1.49E-04	-8.03E-08	1.68E-11
n-pentane	2.74E-05	-9.92E-05	1.33E-05	-7.06E-09	1.45E-12
Total	1	-0.818973817	3.32E-01	-1.56E-04	2.45E-08

The overall energy balance results for the total condenser and the reboiler of the debutanizer column are presented in Table 25.

Table 24: Energy balance results of condenser & reboiler with HYSYS data

Total Condenser			
Sensible Heat Part			
Specifications	Inlet to condenser	Reflux	Top
Temperature (K)	330.62	321.39	321.39
Molar flow (n') (kgmol/h)	52.37	26.19	26.18
Heat lost (Q) (kJ/h)	44246.20		
Latent heat of condensation			
Specifications	Inlet to condenser	Reflux	Top
Molar flow (n') (kgmol/h)	52.37	26.19	26.18
Temperature (K)	321.39	321.39	321.39
Molar enthalpy at saturated liquid (h _l)(kJ/kgmol)	-131300.00		
Molar enthalpy at saturated vapour (h _v)(kJ/kgmol)	-115100.00		
Molar enthalpy difference between saturated vapour and saturated liquid, based on equation (10) (kJ/kgmol)	16200.00		
Latent heat lost = $n' \times h_{vl}$ (kJ/h)	848394.00		
Total heat lost by condenser (Q _{cond}) (kJ/h)	892640.20 (Calculated)		
Reboiler			
Specifications	To reboiler	Boilup	Bot prod
Molar flow (n') (kgmol/h)	44.01	43.32	0.69
Temperature (K)	401.5	401.5	401.5
Molar enthalpy at saturated liquid (h _l)(kJ/kgmol)	-157430.29		
Molar enthalpy at saturated vapour (h _v)(kJ/kgmol)	-140200.00		
Molar enthalpy difference between saturated vapour and saturated liquid was calculated by using equation (10) (kJ/kgmol)	17230.29		
Heat gained by reboiler (Q _{reb}) (kJ/h)	746416.30 (Calculated)		

VI. Air cooler

The air cooler was used to lower the temperature of the debutanizer's bottom stream (401.47 K), primarily composed of pentanes (i-pentane and n-pentane), to the required storage temperature (318 K), as demonstrated in Figure 12.

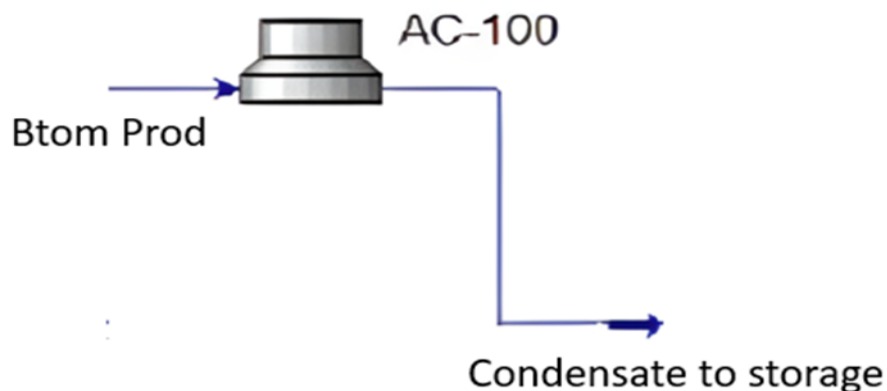


Figure 12: Air cooler to cool debutanizer btom stream to storage temperature

The calculations for the heat capacity (cp_{mix}) of the debutanizer's bottom stream (99.95% pentanes), which was cooled by the air cooler, are listed in Table 26.

Table 25: Heat capacity (cp_{mix}) calculations for air cooler

Component	Composition (y_i)	A_{yi}	B_{yi}	C_{yi}	D_{yi}
N ₂	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO ₂	9.90E-31	1.96E-29	7.27E-32	-5.54E-35	1.70E-38
Methane	9.84E-31	1.89E-29	5.13E-32	1.18E-35	-1.11E-38
Ethane	5.25E-24	2.84E-23	9.35E-25	-3.64E-28	4.57E-32
Propane	1.35E-10	-5.72E-10	4.15E-11	-2.15E-14	4.35E-18
I-butane	9.73E-06	-1.35E-05	3.75E-06	-1.80E-09	2.82E-13
n-butane	5.14E-04	4.88E-03	1.70E-04	-5.70E-08	-1.45E-12
I-pentane	5.68E-01	-5.41E+00	2.88E-01	-1.55E-04	3.25E-08
n-pentane	4.31E-01	-1.56E+00	2.10E-01	-1.11E-04	2.29E-08
Total	1.00E+00	-6.97E+00	4.98E-01	-2.66E-04	5.54E-08

The energy balance results for the air cooler, including its duty (8068.10 kJ/h) and volumetric flow of air ($3.60E+05$ m³/h), are listed in Table 27.

Table 26: Energy balance results of air cooler

Air Cooler		
	Bot Prod (inlet)	Condensate to Storage (outlet)
Temperature (K)	401.47	318.00
Molar flow (n') (kgmol/h)	0.69	0.69
Heat lost (Q) (kJ/h)	8068.10 (Calculated)	
Volumetric air flow (m ³ /h)	3.60E+05	

VII. Simulation results vs manual calculations

The validation of the manual calculation by comparing them with HYSYS computational results for several pieces of equipment is discussed in this section.

There was a slight difference between the manually calculated value of the duty of the heat exchanger (overhead gases-feed gas), and that was calculated by HYSYS, as shown in Figure 13.

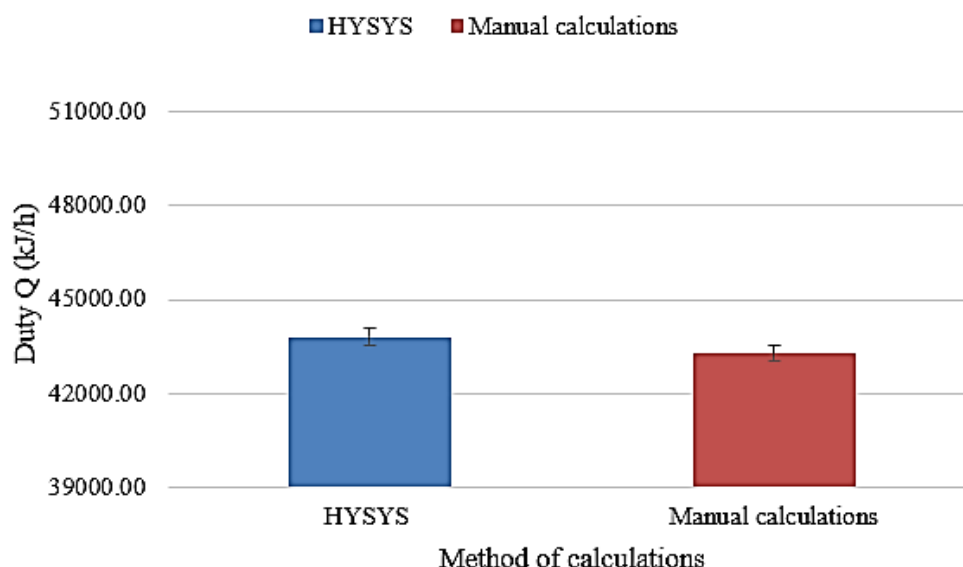


Figure 13: Error in calculations for (overhead-feed gas) heat exchanger duty

The error percentage in calculations and the difference in values between the manually calculated duty for the heat exchanger (overhead gases-feed gas) and that computed by HYSYS are listed in Table 28.

Table 27: Duty calculation difference

Property	HYSYS	Manual calculations
Heat exchanger duty Q (kJ/h)	43810.00	43281.35
$\text{Error \%} = \frac{\text{Calculated value} - \text{HYSYS value}}{\text{Calculated value}} \times 100\% \quad (11)$		1.22

The manually calculated duty value for the heat exchanger (Top-Heated) closely aligned with that was computed by HYSYS, as illustrated in Figure 14.

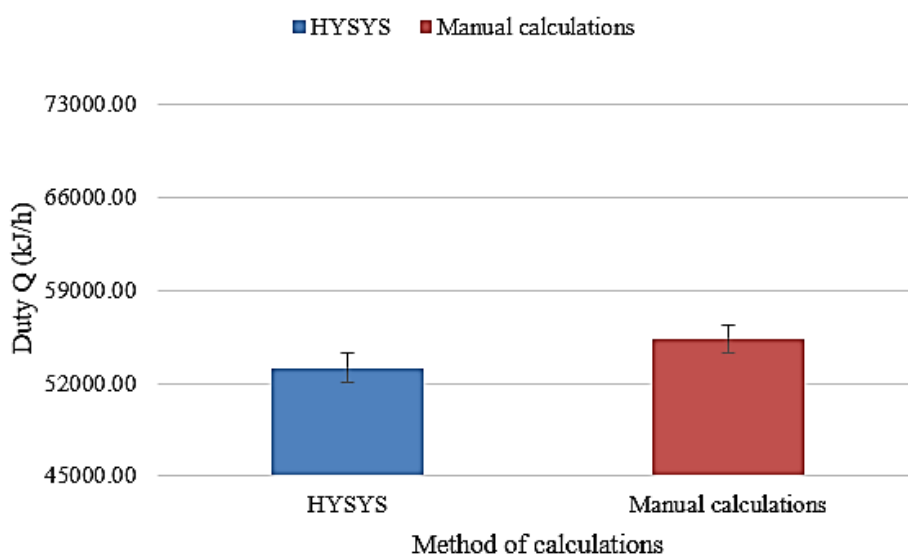


Figure 14: Error in calculations for (Top-Heated) heat exchanger duty

The difference between the manual calculations value and HYSYS computation value for the temperature of heat exchanger (Top-Heated) was less than 5%, as demonstrated in Figure 15.

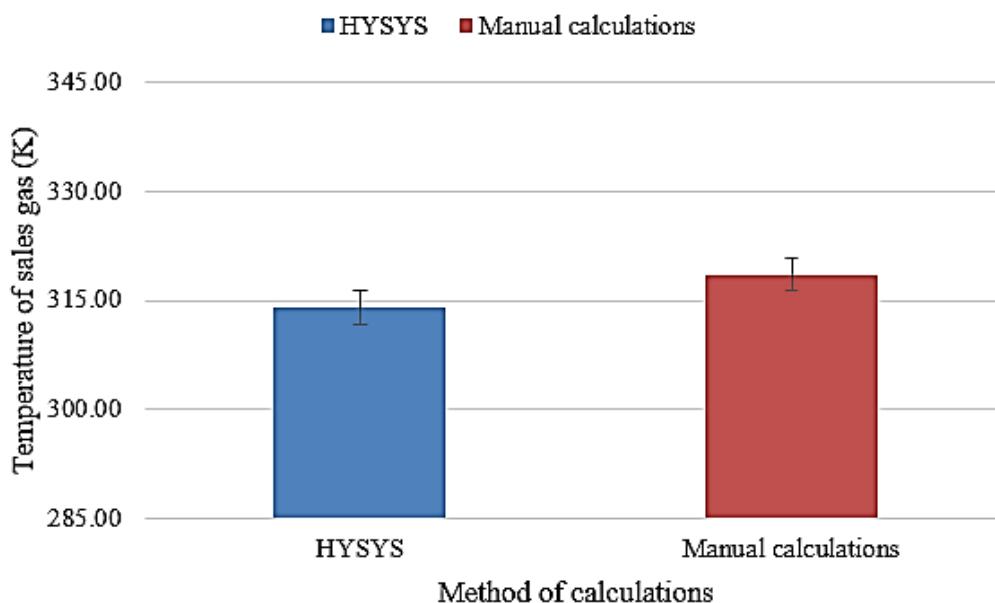


Figure 15: Error in calculations for sales gas temperature manually & HYSYS

The error percentages in manual calculations for the duty, and the sales gas temperature, when compared with HYSYS results of (overhead gases-feed gas) heat exchanger, are listed in Table 29.

Table 28: Error percentage & sales gas temperature difference & exchanger duty

Property	HYSYS	Manual calculations
Heat exchanger duty Q (kJ/h)	53200.00	55361.17
Temperature of sales gas (K)	314.00	318.53
Based on equation 11, error % in duty	3.90	
Based on equation 11, error % in temperature	1.42	

There was a slight difference in values for the condenser duty of the debutanizer column between manual calculations and HYSYS computational results, as illustrated in Figure 16.

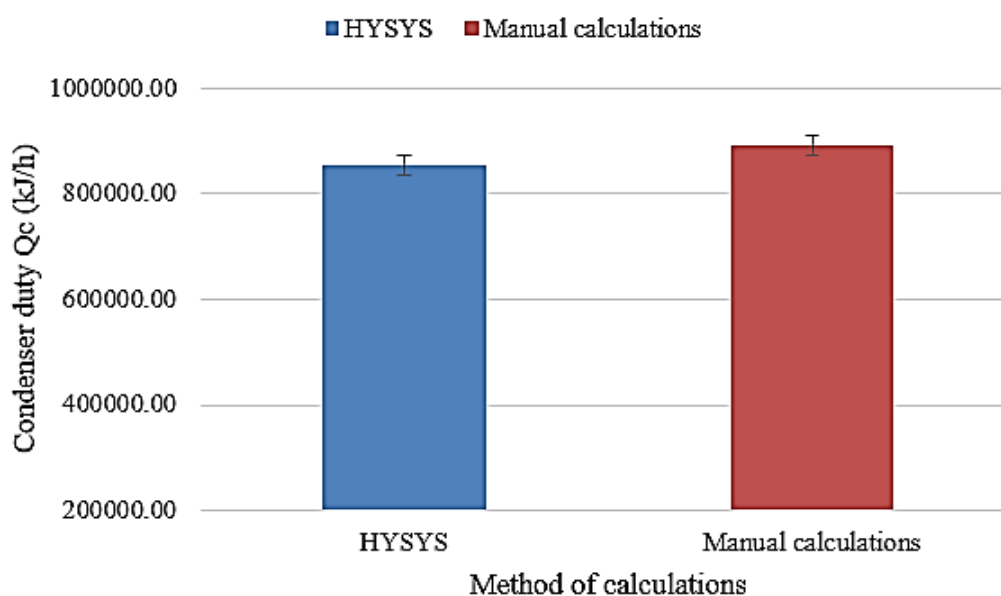


Figure 16: Manual & HYSYS calculations for duty of debutanizer condenser

The calculation errors for the condenser duty value of the debutanizer, comparing manual calculations with HYSYS results, are listed in Table 30.

Table 29: Error percentage between HYSYS & manual calculations

Property	HYSYS	Manual calculations
Condenser duty Q (kJ/h)	854700.00	892640.20
Based on equation 11, error %	4.25	

The manual calculations for reboiler duty value of the debutanizer closely aligned with that obtained from HYSYS, as explained in Figure 17.

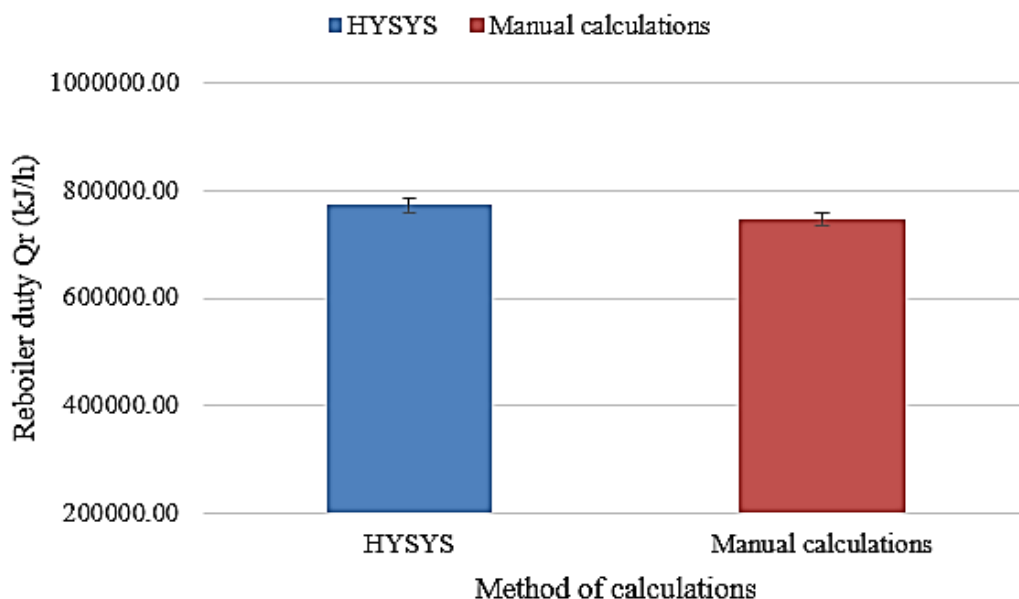


Figure 17: Manual & HYSYS calculations of reboiler duty of debutanizer

Manual calculations showed results very close to compared to those obtained from HYSYS, as listed in Table 31.

Table 30: Error percentage in duty calculations of reboiler of debutanizer

Property	HYSYS	Manual Calculations
Reboiler duty Q (kJ/h)	772500.00	746416.30
Based on equation 11, error %	3.49	

The calculations for condenser duty of the depropanizer by HYSYS and manual calculations are illustrated in Figure 18.

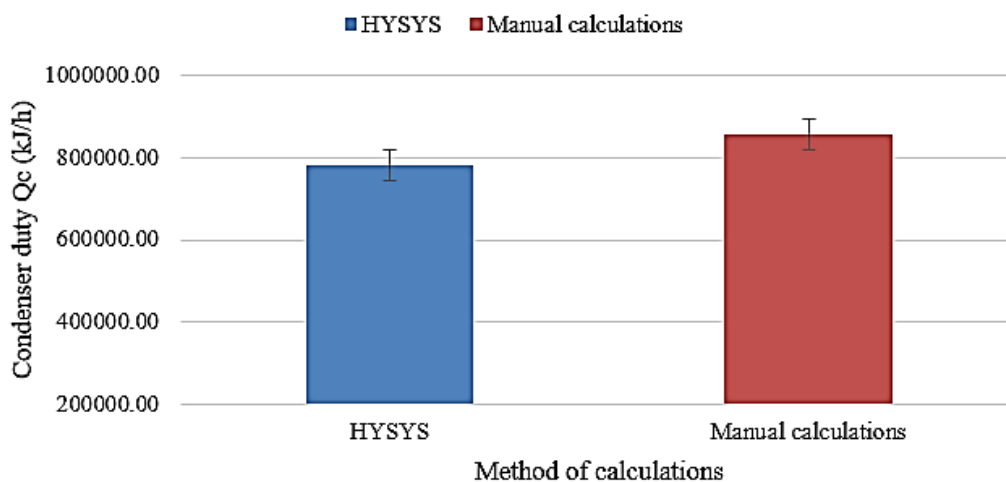


Figure 18: Condenser duty of depropanizer by HYSYS & manual calculations

The calculations for condenser duty of the depropanizer by HYSYS and manual calculations resulted in small difference in values, as tabulated in Table 32.

Table 31: Error percentage in condenser duty of depropanizer

Property	HYSYS	Manual calculations
Condenser duty Q (kJ/h)	783100.00	857173.96
Based on equation 11, error %	8.64	

Manual calculations yielded very close values for the reboiler duty to those obtained from HYSYS, as demonstrated in Figure 19.

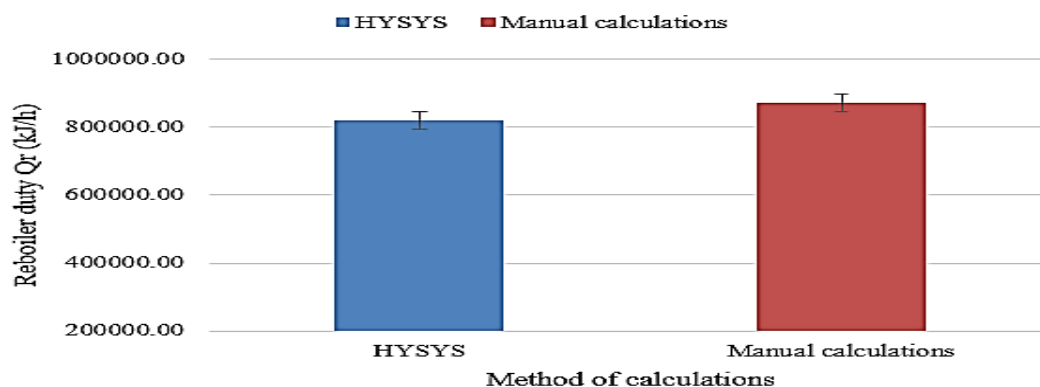


Figure 19: Calculations of reboiler duty manually & by HYSYS

The variation in the reboiler duty value between manual calculations and HYSYS computational results of the depropanizer is listed in Table 33.

Table 32: Error percentage in reboiler calculations of depropanizer

Property	HYSYS	Manual Calculations
Heat exchanger duty Q (kJ/h)	820400.00	872177.14
Based on equation 11, error %	5.94	

To examine the possible reasons for the deviations in the results, this study was compared to other cases. After thorough examination of other cases, some possible reasons can turn out to be the difference in used equipment regarding design and specifications such as those of a distillation column in number of trays and type. The design of employed heat exchangers and other equipment Variations in operation conditions within the LPG production process and the chosen fluid package in simulation can contribute to the occurrence of deviations [78-79].

Regarding the deviation between manual and HYSYS calculations, several factors could have affected such deviations. One of these factors is the discrepancies between the constants used for heat capacity calculations, sourced from Coulson's book, and the values within the applied fluid package. Another source of error lay in HYSYS accounting for all present compounds, even those with very small compositions that were neglected in manual calculations. These misalignments resulted in an acceptable margin of error of about 10%.

7. HAZARD & OPERABILITY STUDY

In this section, Hazard and Operability Studies (HAZOP) were conducted on several types of equipment, including the depropanizer column, the liquified petroleum gas (LPG) storage tank, the three-phase separator, heat exchanger 1, and the air cooler.

I. Depropanizer column

When applying HAZOP to the depropanizer column, three critical parameters—flow rate, level, and temperature—were chosen for investigation. Keywords associated with the flow rate were none, less, and more. The selection of "none" and "less" aimed to capture scenarios of no feed flowrate or insufficient feed flowrate, potentially leading to dryness or hazardous concentrations in the depropanizer. Conversely, "more" was chosen to represent an excess increase in feed flowrate, which could result in flooding, diminished separation performance, or reduction in the tower temperature. Regarding the level parameter, variations—both decreases and increases—were considered. An excess high level could impact the pressure, influencing it negatively, and leading to a reversed flow of the feed, while low levels could cause reduction to the productivity and affecting separation efficiency. Consequently, the keywords "high" and "low" were employed to express different level states. The third factor, temperature, was examined for its potential impact on condenser load and product quality. An excessive increase could strain the condenser and diminish product quality, while a significant decrease might compromise the separation of essential light products. Also, temperature fluctuation

was identified as a critical factor negatively affecting column performance and separation efficiency. Keywords "high", "low", and "fluctuation" were chosen to comprehensively study the temperature's influence on column performance, as clarified in Table 34.

Table 33: Depropanizer column HAZOP

Parameter	Guideword	Possible Cause	Consequence	Action
Flow	None	Inlet pipe blockage or fracture The valve failed to open. Control valve shut. The pump failed to work	Column dries out. No separation and dangerous concentrations would be obtained.	Installation of a low-level alarm Check the schedules and procedures of maintenance. Make a bypass. Complete shut down to the whole plant.
	Less	Inlet pipe blockage or fracture The Valve failed to open. Control valve shut. Pump failed to work.	Column dries out. Low efficient separation	Installation of a low-level alarm Check the schedules and procedures of maintenance. Make a bypass. Complete shut down to the whole plant.
	More	The control valve was completely open. The pumping capacity was increased. The control valve failed to handle the flow	Flooding problem in the column Low separation efficiency Temperature decrease Rise at bottom of the column	Installation of a high-level alarm Check the schedules and procedures of maintenance. Installation of flow controllers
Level	High	Blockage of one or all the outlet streams from the column Excess feed flowrate	Over-pressure reflux drum Reverse flow of the liquid to the column.	Installation of a high-level alarm Check the schedules and procedures of maintenance
	Low	Partial blockage or leakages of the inlet pipe	Low products yield Low separation and dangerous concentrations would be obtained Undesired product quality	Installation of a low-level alarm Check the procedures and schedules of maintenance. Valve installation
Temperature	High	Excessive heater/furnace duty for the feed	Load increase of on the condenser Low quality of the products	Installation of a high temperature sensor Check the procedures and schedules of the maintenance.
	Low	In sufficient heating Low heater efficiency due to many problems such as fouling	Low separation efficiency Low product quality	Installation of low temperature sensor Check maintenance procedure and schedule.
	Fluctuation	The heating source isn't stable Fluctuation in the feed flowrate	Undesired product quality Bad separation efficiency	Installation of temperature sensor Check the maintenance procedures for heating and cooling equipment, and valves

II. Storage tank

When HAZOP studies were performed for the LPG storage tank, three critical parameters were identified for comprehensive study: discharge flow, temperature, and pressure. Specifically addressing flow, three guide words, “none”, “low”, and “more”, were chosen to illustrate the impact of the discharge of on the product supply. A scenario of no or insufficient product flowrate could potentially diminish product supply, while an increased discharge flowrate might lead to pump overload and an oversupply of the product. Shifting focus to level of LPG in the tank, the guide words “low” and “high” were selected. High level could cause a pressure increase in the tank, thus causing leakage of LPG. Conversely, low level of LPG in the tank would result in negative impact on the product supply. In terms of pressure, the study concentrated on high pressure scenarios, which could be hazardous due to high vapor pressure inside the tank, causing a possible explosion, as explained in Table 35.

Table 34: Storage tank HAZOP

Parameter	Guideword	Possible Cause	Consequence	Action
Flow	None	Outlet pipe blockage or fracture The Valve failed to open. Control valve shut. Pump failed to work	No supply for product	Check the schedules and procedures of maintenance.
	Low	Pipe blockage or fracture The Valve failed to open. Control valve shut. Pump failed to work	Low product supply	Check the schedules and procedures of maintenance.
	More	The control valve was completely open. The pumping capacity was increased. The control valve failed to handle the flow.	Oversupply of the product Product loss	Check the schedules and procedures of maintenance.
Level	High	The inlet valve was completely open. The pumping capacity was increased. The control valve failed to handle the flow.	More vapors and loss of the product Gas leakage and over pressure Fire hazards	Installation of a high-level sensor Check the procedures and schedules of maintenance.
	Low	Inlet pipe blockage or fracture The Valve of the inlet failed to open. Control valve shut. Pump failed to work	Leakage of the product Low product supply to storage tank	Installation of a low-level sensor Check the procedures and schedules of maintenance.
Pressure	High	Excessive temperature in the tank and insufficient cooling	Large amounts which cause Explosion	Pressure sensor installation

III. Three-phase separator

The hazard analysis of the three-phase separator encompassed a study of the effect of two key parameters: pressure and temperature. Concerning separator pressure, an increase to very high level could detrimentally impact separation efficiency and potentially lead to an explosion or low separation efficiency. Hence, the selected guide word was "high". Regarding temperature, a very high temperature could yield undesired compounds leaving the separator as vapour instead of liquid. Conversely, a low temperature might prove insufficient for effectively separating the vapours, also could resulted in pressure increase in the separator, as demonstrated in Table 36.

Table 35: Three-phase separator HAZOP

Parameter	Guideword	Possible Cause	Consequence	Action
Pressure	High	Chock valve open failure	Separation vessel explosion or crack	Installation of relieve valve.
		Control loop failure	Negatively affect the separation efficiency	Installation of pressure sensor Check the maintenance schedules continuously.
Temperature	High	Very hot surrounding Excessive heating	Pressure increase If it is very high, this can cause vessel fatigue	Temperature sensors installation Cooling utilities
	Low	Insufficient heating utility	Low vapors separation	Temperature sensor installation

IV. Shell & tube heat exchanger & air cooler

Shell and tube heat exchanger as well as air cooler operate on imperative conditional states that are highlighted as temperature, pressure, flow, composition, and corrosion. The quantity of the flow controls the regulation of the temperature and pressure within the pipeline system and a small defect or irregularity can lead to severe consequences like total shutdown or damage of equipment. Accordingly, safety of the equipment depends on their design as they withstand certain levels of pressure or temperature and if exceeded, the equipment itself can explode or the pipelines can be blocked or cracked leading to leak or even contamination of the surroundings. If the fluid is contaminated with unwanted impurities, problems such as fouling, scaling and corrosion may arise causing unexpected casualties and problematic outcomes. The HAZOP studies of the heat exchanger and air cooler were listed in Table 37 and Table 38 respectively.

Table 36: Shell & tube heat exchanger HAZOP

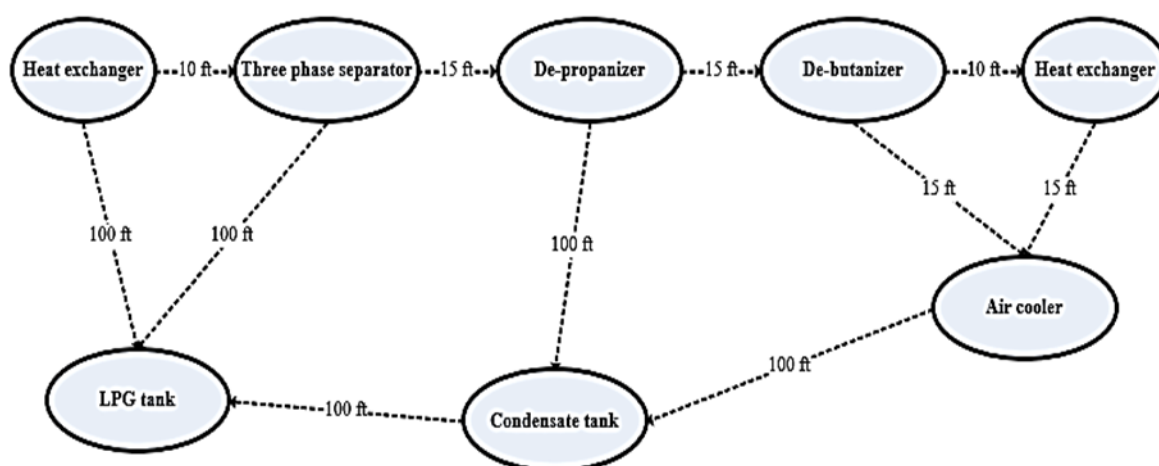
Parameter	Guideword	Causes	Consequences	Action
Flow	None	Inlet cooling water valve cannot open	Process fluid temperature cannot be lowered accordingly	Installation of temperature sensor before and after the process fluid line. Installation of High Temperature Alarm
	Less	Leakage in pipe Blockage in pipe	Process fluid temperature becomes too low or constant	Installation of waterflow meter Installation of High Temperature Alarm
	More	Inlet cooling water valve cannot close	Process fluid temperature decreases	Installation of temperature sensor before and after process fluid line. Installation of Low Temperature Alarm
Pressure	Low	Process fluid valve failure	More pressure required to move the fluid	Installation of low-pressure alarm
	High		Tube bursting	Installation of high-pressure alarm
Temperature	Low	Too much cooling water Heat losses across piping	Process fluid temperature becomes too low	Installation of temperature sensor before and after process fluid line. Installation of Low Temperature Alarm
	High	Not enough cooling water Heat losses across piping	Process fluid temperature becomes too high	Installation of temperature sensor before and after the process fluid line. Installation of High Temperature Alarm
Composition	Contamination	Tube leakage and cooling water flows in and becomes contaminated	Process fluid is contaminated and outlet temperature becomes too low	Proper maintenance and operator alert
Corrosion	More	Cooling water becomes hard	Less cooling and tube cracking	Proper maintenance
Services	Failure	Following an irregular maintenance schedule	Possible shutdown of the equipment	Proper follow-up of maintenance schedules consistently

Table 37: Air cooler HAZOP

Parameter	Guideword	Causes	Consequences	Action
Flow	None	One or more fans fail to function or they can be broken	Process fluid temperature cannot be lowered or becomes constant	Installation of temperature sensor before and after the process fluid line Installation of airflow meter Installation of High Temperature Alarm Proper maintenance and operator alert
	Less			
	More	One or more fans function at a higher speed than expected	Process fluid temperature is lowered more than required	
Services	Failure	Following an irregular maintenance schedule	Possible shutdown of the equipment	Proper follow-up of maintenance schedules consistently

8. EQUIPMENT SPACING

Equipment spacing is essential to provide safe locations of the utilized equipment across the plant. For example, if any explosion happens and equipment spacing was not considered, it may affect other equipment and cause other severe problems. The required tables for equipment spacing were obtained. The spacing was demonstrated in Figure 20.

**Figure 20: Plant equipment spacing**

9. FUTURE WORK

For future development of LPG production plants, it is strongly recommended to make comprehensive pinch analyses. These analyses are necessary for determination of potential mass and energy integration processes, aiming to minimize losses in both materials and energy, therefore reducing overall production costs.

Special design for each piece of equipment within the plant and introducing additional equipment should be thoroughly performed to simulate the real plant condition and offer a valuable opportunity for in-depth studies. These investigations, covering aspects such as energy consumption, material efficiency, and economic studies, are crucial for enhancing production output and minimizing costs of the real plant. The results obtained from such studies can provide a more accurate and realistic reflection of real-world scenarios.

In summary, pinch analyses and customized equipment designs in simulations hold great potential for optimizing LPG production processes. These efforts contribute to increased production efficiency and play a pivotal role in cost reduction, aligning with the industry's commitment to sustainability and economic viability.

10. CONCLUSION

The world always seeks to find new sources of fuel that are clean, reliable, efficient, and sustainable rather than traditional hydrocarbon-based fuels. Liquefied petroleum gas is a spectacular choice that validates all the green requirements and represents a fas. A simulation was conducted on Aspen HYSYS 12.0 based on Peng-Robinson fluid package according to data obtained from an LPG plant in Egypt. Feed gas of 2209 kg/h contained 31.33% butanes and 36.94% propane which was converted to LPG of 1322 kg/h. The resultant compositions in mass percentages were 52.32% butanes and 47.63% propane. As for sales gas, a flowrate of 836.9 kg/h was produced comprising 31.25% methane, 38.10% ethane, 22.24% propane and its temperature was 318.53 Kelvin. It was shown that all the manual calculations were validated and verified by HYSYS as the maximum and overall error percentage did not exceed 10%. The HAZOP studies were conducted for various pieces of equipment which showed the importance of installing relief valves, regulators, alarms, and sensors. This was to maintain proper and safe functioning of LPG production. Equipment spacing was carried out to allocate each type of equipment within the minimum safe spacing between them.

References

- [1] Ukpaukure, Y. H., Aimikhe, V., & Ojapah, M. (2023). The Evaluation of Liquefied Petroleum Gas (LPG) Utilization as an Alternative Automobile Fuel in Nigeria. *Open Journal of Energy Efficiency*, 1(1), 1-12.
- [2] Yeo, S., Kim, J., & Lee, W. (2022). Potential economic and environmental advantages of liquid petroleum gas as a marine fuel through analysis of registered ships in South Korea. *Journal of Cleaner Production*, 330, 129955.
- [3] Ma, Q., Zhong, M., Guo, Y., You, J., He, Y., Chen, J., & Zhang, Z. (2022). Study on the characteristic of boiling expansion process of superheated LPG and its vapor cloud explosion. *Journal of Loss Prevention in the Process Industries*, 78, 104831.
- [4] Şişman, E., Çankaya, S., Keçeci, E., Teymourfamianasl, M., Uçar, Z. U., Bulut, B., & Pekey, B. (2023). Identifying the environmental hotspots of sulfur-free odorant for LPG storage and filling by life cycle approach. *Science of the Total Environment*, 886, 163816.
- [5] WLPGA. (2023, June). LPG's Role in the Energy Transition. World LPG Association.
- [6] Puzzolo, E., Cloke, J., Parikh, J., Evans, A., & Pope, D. (2020). National scaling up of LPG to achieve SDG 7: Implications for policy, implementation, public health and environment.
- [7] De Jong, P., Torres, E. A., De Melo, S. V., De Santana, D. M., & Pontes, K. V. (2023). Socio-economic and environmental aspects of bio-LPG and bio-dimethyl ether (Bio-DME) production and usage in developing countries: The case of Brazil. *Cleaner and Circular Bioeconomy*, 6, 100055.
- [8] Khan, K. (2019). GAPS Guidelines GAP.2.5.2 A publication of Global Asset Protection Services LLC OIL AND CHEMICAL PLANT LAYOUT AND SPACING. Nedu.edu.
- [9] H, T., & Cong, L. (2023). Modeling and control design for distillation columns based on the equilibrium theory. *Processes*, 11(2), 607.
- [10] Mohsen, M. J., Al- Dawody, M. F., Jamshed, W., Din, S. M. E., Abdalla, N. S. E., Abd-Elmonem, A., Iqbal, A., & Shah, H. H. (2023). Experimental and numerical study of using of LPG on characteristics of dual fuel diesel engine under variable compression ratio. *Arabian Journal of Chemistry*, 16(8), 104899.
- [11] Aishwarya, K., Nirmala, R., & Navamathavan, R. (2021). Recent advancements in liquefied petroleum gas sensors: A topical review. *Sensors International*, 2, 100091.
- [12] Woo, S., Lee, J., & Lee, K. (2021). Experimental study on the performance of a liquefied petroleum gas engine according to the air fuel ratio. *Fuel*, 303, 121330.
- [13] WLPGA. (2023, June). LPG's Role in the Supply Debate. World LPG Association.
- [14] Fosudo, T., Kar, T., Windom, B., & Olsen, D. B. (2024). Low-carbon fuels for spark-ignited engines: A comparative study of compressed natural gas and liquefied petroleum gas on a CFR engine with exhaust gas recirculation. *Fuel*, 360, 130456.
- [15] Kashyap, S., Pramanik, S., & Ravikrishna, R. (2024). A review of energy-efficient domestic cookstoves. *Applied Thermal Engineering*, 236, 121510.

- [16] Hashem, G. T., Al- Dawody, M. F., & Sarris, I. E. (2023). The characteristics of gasoline engines with the use of LPG: An experimental and numerical study. *International Journal of Thermofluids*, 18, 100316.
- [17] Hu, Q., Qian, X., Shen, X., Zhang, Q., Ma, C., Pang, L., Liang, Y., He, F., & Yuan, M. (2022). Investigations on vapor cloud explosion hazards and critical safe reserves of LPG tanks. *Journal of Loss Prevention in the Process Industries*, 80, 104904.
- [18] Yang, D., Peng, K., Zheng, J., Xie, B., Wang, J., Xu, B., & Li, F. (2024). Consequences analysis of the LPG tank truck traffic accident: A case study of the Wenling explosion accident. *Journal of Loss Prevention in the Process Industries*, 87, 105228.
- [19] Kim, J. K., Jeong, B., Choi, J., & Lee, W. (2023). Life cycle assessment of LPG engines for small fishing vessels and the applications of bio LPG fuel in Korea. *Journal of Marine Science and Engineering*, 11(8), 1488.
- [20] Mazri, M. (2017b). HAZOP for Distillation column Parameter.
- [21] Ibrahim, H. A., & Syed, H. (2018). Hazard analysis of crude oil storage tank farm. *International Journal of ChemTech Research*, 11(11), 300–308.
- [22] De J Penelas, A., & Pires, J. C. (2021c). HAZOP Analysis in terms of Safety Operations Processes for oil production units: A case study. *Applied Sciences*, 11(21), 10210.
- [23] Galante, E., Costa, D., Haddad, A., & Santos, I. (2014b). Risk Assessment for Hexamine Nitration into RDX. *Journal of Aerospace Technology and Management*, 6(4), 373–388.
- [24] Jeong, J. W., Baek, S., Kim, Y., Woo, S., Lim, Y., & Lee, K. (2024). Investigation of CO₂ and PN emission characteristics according to the propane content for a LPG engine. *Fuel*, 357, 129877.
- [25] Kumar, Pramod. "Fire disaster following LPG tanker explosion at Chala in Kannur (Kerala, India): August 27, 2012." *Burns* 39, no. 7 (2013): 1479-1487.
- [26] Tomos, B. a. D., Stamford, L., Welfle, A., & Bows- Larkin, A. (2024). Decarbonising international shipping – A life cycle perspective on alternative fuel options. *Energy Conversion and Management*, 299, 117848.
- [27] Bariha, N., Mishra, I. M., & Srivastava, V. C. (2016). Fire and explosion hazard analysis during surface transport of liquefied petroleum gas (LPG): A case study of LPG truck tanker accident in Kannur, Kerala, India. *Journal of loss prevention in the process industries*, 40, 449-460.
- [28] Maźziel, M. (2023). Liquefied Petroleum Gas-Fuelled Vehicle CO₂ emission modelling based on portable emission measurement system, On-Board diagnostics data, and Gradient-Boosting machine learning. *Energies*, 16(6), 2754.
- [29] Woo, S., Lee, J., & Lee, K. (2023). Investigation of injection characteristics for optimization of liquefied petroleum gas applied to a direct-injection engine. *Energy Reports*, 9, 2130–2139.
- [30] Galceran, S. J. D., Villarico, F. J. H., Omaso, J. J. C., Estaniel, L. C. P., Saldo, I. J. P., Calo, J. R. D., & Dandoy, M. J. P. (2023). Development and Comparison of Arduino Based MQ-2 and MQ-6 LPG Leak Sensors. *American Journal of Sensor Technology*, 7(1), 1-9.
- [31] Goswami, Sumitra, and Ashok Dangi. "Arduino-Based Milk Quality Monitoring System." (2021): 245-249.
- [32] Gokulanathan, S., P. Manivasagam, N. Prabu, and T. Venkatesh. "A GSM based water quality monitoring system using Arduino." *Shanlax International Journal of Arts, Science and Humanities* 6, no. 4 (2019): 22-26.
- [33] Wei, C., Li, H., Luo, Z., Yu, Y., Yu, M., Zheng, K., Su, B., Qi, B., & Wang, F. (2024). Experimental and reaction kinetics studies on deflagration characteristics of liquefied petroleum gas-air mixture with different compositions in confined space. *Fuel*, 358, 129972.
- [34] Totouom, A. (2024). Women's decision-making power and the adoption of liquefied petroleum gas for cooking in Cameroon. *Energy Policy*, 184, 113912.
- [35] Özer, S., Demir, Ü., & Coşkun, G. (2023). Experimental investigation of the effects of coolant temperature in a turbocharged stratified injection (TSI) engine fuelled with gasoline and liquefied petroleum gas. *Fuel*, 343, 127988.
- [36] Ifeanyichukwu, E., & Stella, I. C. (2023). Simulation of the Production of Liquefied Petroleum Gas (Lpg) from Flare Gas System. *Journal of Oil and Gas Research Reviews*, 3(1), 28-34.

- [37] ElBadawy, K. M., Teamah, M. A., Shehata, A. I., & Hanfy, A. A. (2017). Simulation of Liquefied Petroleum Gas (LPG) Production from Natural Gas Using Fractionation Towers. *International Journal of Advanced Scientific and Technical Research*, 6(7), 148-153.
- [38] Woo, Seungchul, Juho Lee, and Kihyung Lee. "Experimental study on the performance of a liquefied petroleum gas engine according to the air fuel ratio." *Fuel* 303 (2021): 121330.
- [39] Jaworski, Artur, Maksymilian Mądziel, Hubert Kuszewski, Kazimierz Lejda, Mirosław Jaremco, Krzysztof Balawender, Mirosław Jakubowski, Pawel Wos, and Krzysztof Lew. *The impact of driving resistances on the emission of exhaust pollutants from vehicles with the spark ignition engine fuelled with petrol and LPG*. No. 2020-01-2206. SAE Technical Paper, 2020.
- [40] Winkler, S. L., J. E. Anderson, L. Garza, W. C. Ruona, R. Vogt, and T. J. Wallington. "Vehicle criteria pollutant (PM, NO_x, CO, HCs) emissions: how low should we go?." *Npj Climate and atmospheric science* 1, no. 1 (2018): 26.
- [41] Al-Hossainy, A. F., M. Sh Zoromba, M. H. Abdel-Aziz, M. Bassyouni, A. Attar, M. Zwawi, A. A. I. Abd-Elmageed, H. A. Maddah, and A. Ben Slimane. "Fabrication of heterojunction diode using doped-poly (ortho-aminophenol) for solar cells applications." *Physica B: Condensed Matter* 566 (2019): 6-16.
- [42] Bassyouni, M., F. H. Akhtar, A. Hussain, and A. Umer. "Biodiesel production and investigations on the performance of diesel engine using jatropha oil." *ATE* 2 (2012): 77-88.
- [43] Elhenawy, Yasser, Mohamed Bassyouni, Kareem Fouad, Abdelfatah Marni Sandid, Mostafa Abd El-Rady Abu-Zeid, and Thokozani Majozi. "Experimental and numerical simulation of solar membrane distillation and humidification–dehumidification water desalination system." *Renewable Energy* 215 (2023): 118915.
- [44] Chaichan, M. T., & Al-Sheikh, S. A. K. (2001). Study of performance of spark ignition engine fueled with methane. *Al- Jufra J. for sci. & Eng.*, 1
- [45] Mady, Ahmed, Omar Mahmoud, and Abdel Sattar Dahab. "Nanoparticle-based drilling fluids as promising solutions to enhance drilling performance in Egyptian oil and gas fields." *International Journal of Industry and Sustainable Development* 1, no. 1 (2020): 24-38.
- [46] Abdallah, Lamiaa, and Tarek El-Shennawy. "A feasibility study for utilizing waste heat to generate electrical power using organic Rankine cycle (ORC)." *International Journal of Industry and Sustainable Development* 4, no. 1 (2023): 1-9.
- [47] Al Baroudi, Hisham, Adeola Awoyomi, Kumar Patchigolla, Kranthi Jonnalagadda, and Edward J. Anthony. "A review of large-scale CO₂ shipping and marine emissions management for carbon capture, utilisation and storage." *Applied Energy* 287 (2021): 116510.
- [48] Zhang, Zhien, Shu-Yuan Pan, Hao Li, Jianchao Cai, Abdul Ghani Olabi, Edward John Anthony, and Vasilije Manovic. "Recent advances in carbon dioxide utilization." *Renewable and sustainable energy reviews* 125 (2020): 109799.
- [49] Seo, Youngkyun, Cheol Huh, Sangick Lee, and Daejun Chang. "Comparison of CO₂ liquefaction pressures for ship-based carbon capture and storage (CCS) chain." *International Journal of Greenhouse Gas Control* 52 (2016): 1-12.
- [50] Sharma, Ashutosh, Jyoti Parikh, and Chandrashekhar Singh. "Transition to LPG for cooking: A case study from two states of India." *Energy for Sustainable Development* 51 (2019): 63-72.
- [51] Bansal, Mohit, R. P. Saini, and Dheeraj Kumar Khatod. "Development of cooking sector in rural areas in India—A review." *Renewable and Sustainable Energy Reviews* 17 (2013): 44-53.
- [52] Chowdhury, Shahana Afrose, and Ayesha Tasnim Mostafa. "Sustainable Energy for Rural Household Cooking in Developing Countries." In *Affordable and Clean Energy*, pp. 1214-1222. Cham: Springer International Publishing, 2021.
- [53] Chen, Kimball C., Matthew Leach, Mairi J. Black, Meron Tesfamichael, Francis Kemausuor, Patrick Littlewood, Terry Marker et al. "BioLPG for clean cooking in sub-Saharan Africa: present and future feasibility of technologies, feedstocks, enabling conditions and financing." *Energies* 14, no. 13 (2021): 3916.

- [54] Thoday, K.; Benjamin, P.; Gan, M.; Puzzolo, E. The Mega Conversion Program from kerosene to LPG in Indonesia: Lessons learned and recommendations for future clean cooking energy expansion. *Energy Sustain. Dev.* **2018**, *46*, 71–81
- [55] Johnson, E. Process Technologies and Projects for BioLPG. *Energies* **2019**, *12*, 250.
- [56] Kypridemos, C.; Puzzolo, E.; Aamaas, B.; Hyseni, L.; Shupler, M.; Aunan, K. Pope Daniel Health and Climate Impacts of Scaling Adoption of Liquefied Petroleum Gas (LPG) for Clean Household Cooking in Cameroon: A Modeling Study. *Environ. Health Perspect.* **2020**, *128*, 047001
- [57] Bruce, N.; de Cuevas, R.A.; Cooper, J.; Enonchong, B.; Ronzi, S.; Puzzolo, E.; MBatchou, B.; Pope, D. The Government-led initiative for LPG scale-up in Cameroon: Programme development and initial evaluation. *Energy Sustain. Dev.* **2018**, *46*, 103–110
- [58] Hussain, Ahmad, Aamir Farooq, Mohammad Ismail Bassyouni, Hani Hussain Sait, Mahmoud Abo El-Wafa, Syed Waheedul Hasan, and Farid Nasir Ani. "Pyrolysis of Saudi Arabian date palm waste: A viable option for converting waste into wealth." (2014).
- [59] Aboelela, Dina, Habibattallah Saleh, Attia M. Attia, Yasser Elhenawy, Thokozani Majozi, and Mohamed Bassyouni. "Recent Advances in Biomass Pyrolysis Processes for Bioenergy Production: Optimization of Operating Conditions." *Sustainability* **15**, no. 14 (2023): 11238.
- [60] Abdel-Aal, H. K., M. Sadik, M. Bassyouni, and M. Shalabi. "A new approach to utilize hydrogen as a safe fuel." *International Journal of Hydrogen Energy* **30**, no. 13-14 (2005): 1511-1514.
- [61] Maddah, Hisham A., M. Bassyouni, M. H. Abdel-Aziz, M. Sh Zoromba, and A. F. Al-Hossainy. "Performance estimation of a mini-passive solar still via machine learning." *Renewable Energy* **162** (2020): 489-503.
- [62] Gould, Carlos F., and Johannes Urpelainen. "LPG as a clean cooking fuel: Adoption, use, and impact in rural India." *Energy Policy* **122** (2018): 395-408.
- [63] Bond, Tami C., and Haolin Sun. "Can reducing black carbon emissions counteract global warming?." (2005): 5921-5926.
- [64] Aminzadegan, Sajede, Mohsen Shahriari, Fahime Mehranfar, and Borna Abramović. "Factors affecting the emission of pollutants in different types of transportation: A literature review." *Energy Reports* **8** (2022): 2508-2529.
- [65] Aakko-Saksa, Päivi T., Kati Lehtoranta, Niina Kuittinen, Anssi Järvinen, Jukka-Pekka Jalkanen, Kent Johnson, Heejung Jung et al. "Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options." *Progress in Energy and Combustion Science* **94** (2023): 101055.
- [66] Bager, Simon L., U. Martin Persson, and Tiago NP dos Reis. "Eighty-six EU policy options for reducing imported deforestation." *One Earth* **4**, no. 2 (2021): 289-306.
- [67] Pendrill, Florence, U. Martin Persson, Javier Godar, Thomas Kastner, Daniel Moran, Sarah Schmidt, and Richard Wood. "Agricultural and forestry trade drives large share of tropical deforestation emissions." *Global environmental change* **56** (2019): 1-10.
- [68] DeFries, Ruth S., Jessica Fanzo, Pinki Mondal, Roseline Remans, and Stephen A. Wood. "Is voluntary certification of tropical agricultural commodities achieving sustainability goals for small-scale producers? A review of the evidence." *Environmental research letters* **12**, no. 3 (2017): 033001.
- [69] Kim, Jeong Kuk, Byongug Jeong, Jae-Hyuk Choi, and Won-Ju Lee. "Life cycle assessment of LPG engines for small fishing vessels and the applications of bio LPG fuel in Korea." *Journal of Marine Science and Engineering* **11**, no. 8 (2023): 1488.
- [70] Wang, Yang, Qun Cao, Long Liu, Yue Wu, Hongyu Liu, Ziyang Gu, and Cunxi Zhu. "A review of low and zero carbon fuel technologies: Achieving ship carbon reduction targets." *Sustainable Energy Technologies and Assessments* **54** (2022): 102762.
- [71] Ngang, Emmanuel Anye, and Claude Valery Ngayihi Abbe. "Experimental and numerical analysis of the performance of a diesel engine retrofitted to use LPG as secondary fuel." *Applied Thermal Engineering* **136** (2018): 462-474.
- [72] Krantz, Gustav, Christian Moretti, Miguel Brandão, Mikael Hedenqvist, and Fritjof Nilsson. "Assessing the Environmental Impact of Eight Alternative Fuels in International Shipping: A Comparison of Marginal vs. Average Emissions." *Environments* **10**, no. 9 (2023): 155.

- [73] Vedachalam, Sundaramurthy, Nathalie Baquerizo, and Ajay K. Dalai. "Review on impacts of low sulfur regulations on marine fuels and compliance options." *Fuel* 310 (2022): 122243.
- [74] Mądziel, Maksymilian. "Liquified Petroleum Gas-Fuelled Vehicle CO₂ Emission Modelling Based on Portable Emission Measurement System, On-Board Diagnostics Data, and Gradient-Boosting Machine Learning." *Energies* 16, no. 6 (2023): 2754.
- [75] Jaworski, Artur, Maksymilian Mądziel, Hubert Kuszewski, Kazimierz Lejda, Mirosław Jaremco, Krzysztof Balawender, Mirosław Jakubowski, Pawel Wos, and Krzysztof Lew. *The impact of driving resistances on the emission of exhaust pollutants from vehicles with the spark ignition engine fuelled with petrol and LPG*. No. 2020-01-2206. SAE Technical Paper, 2020.
- [76] Fouad, Kareem, Mohamed Bassyouni, Mohamed Gar Alalm, and Mamdouh Y. Saleh. "Recent developments in recalcitrant organic pollutants degradation using immobilized photocatalysts." *Applied Physics A* 127, no. 8 (2021): 612.
- [77] Sherif, Sayed A., M. A. Sadek, F. H. Ashour, and M. Bassyouni. "Effects of surface treatment of ground rice husk on the polyurethane based on castor oil." *Polymers and Polymer Composites* 17, no. 8 (2009): 481-485.
- [78] Elhefnawy, Waleed, Fatma K. Gad, Nadia A. Elsayed, and Walaa M. Shehata. "Simulation and Optimization Analysis of Natural Gas Liquid (NLG) Recovery Process from Natural Gas." *Journal of Petroleum and Mining Engineering* 19, no. 1 (2017): 90-102.
- [79] Belhocine, Amel, Riad Bendib, and Youcef Zennir. "Simulation and analysis of a petrochemical process (deethanizer column-mle field) using hysys aspen simulator." *Algerian Journal of Signals and Systems* 5, no. 2 (2020): 86-91.