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Energy Saving through Optimizing the Re-liquefaction Process for the Boil-off Gas Inside Propane Tank

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Abstract

It's well known that the propane boil-off gas (BOG) re-liquefaction process is essential for maintaining propane tank safety and facilitating propane recovery. It also saves a higher range of energy, capital, and operating costs. In this paper, the software Aspen Hysys was used to optimize the re-liquefaction process by substituting the closed loop of the propane cycle that was used as a refrigerant. Adding a heat exchanger economizer to the process will improve the overall performance of the propane BOG re-liquefaction process, reduce environmental impact, and increase energy efficiency. The results showed savings in capital cost of nearly 30,000,000 $. As well as decreasing the equipment utilization area. Furthermore, the operating conditions for the existing process and the modified process were the same. These findings highlight the importance of energy optimization and improving the overall efficiency of the propane fixed storage tank recovery process.

Keywords: *Boil-off gas (BOG), Liquefied petroleum gas (LPG), Re-liquefaction process, Propane refrigeration, Terminal.*

1. Introduction

Propane is an economical fuel option for furnaces. Also, it is mixed with butane to form liquefied petroleum gas (LPG) which is stored in bottles for cooking purposes. While storing the propane, boil-off gas (BOG) is formed and should be recovered. The calculated heat absorption from the surrounding air into the tank generated a BOG rate of 0.0049 kg/s, which costs 0.0069 $/s [1].

Keeping the propane stored for a long time led to an increase in heat leakage; this caused higher BOG production, also, changes in the gas composition was observed [2]. The implementation of simple liquefaction processes results in lower capital cost, reducing cargo loss and making the facilities economically viable. In addition, installing liquefaction systems becomes financially advantageous [3]. BOG generation depends on the composition. The boil off rate (BOR) is assessed in two ways, either measure the liquefied hydrocarbon volume in the tank or measure it as mass evaporated per unit of time [4].

The BOR is calculated using the following equation [5]:

$$BOR = \frac{V_{BOG} \times 24}{V_{lng} \times \rho} = \frac{Q \times 24 \times 3600}{\Delta H \times V_{lng} \times \rho} \times 100$$

where: BOR: % per day; V_{BOG}: volume of BOG in m^3/s; V_{lng}: volume of LNG in cargo tanks in m^3; ρ: density of LNG in kg/m^3; Q: heat exchange in Watts; ΔH: latent heat of vaporization in (joules per kelvin).

The impact of fluctuating ambient temperatures on BOG generation is critical and requires proposed methods to enhance the operational effectiveness of BOG compressors. Bigger propane plants with multiple sections make managing BOG harder [4]. Relevant thermodynamic and heat transfer equations were used to evaluate the economic impact of BOG in the LPG supply chain and audit storage tanks [5].

The quantities of heat absorbed by LPG from ambient air and produced due to the operation of transfer pumps quantified thereby giving a total BOG rate of 0.0293 kg/s. This represents a financial loss of 0.0098 $/s when an LPG is sold at 0.33 $/kg [6]. The main source of resistance in the storage tank shell comes from expanded perlite and concrete, while most of the resistance in the roof design comes from perlite, with some extra support from glass wool, an air gap, and a layer of concrete on top [7]. Computational fluid dynamics (CFD) is also used to simulate the full-scale of the hydrocabon storage tank. The transient behaviour of BOG was affected by hydrostatic pressure but not steady-state generation rates [8]. An LPG plant process is turned out to be using a special gas mix (mixed refrigerant) instead of pure propane. This method was the cheapest to install and run and wasted less energy [9]. There was a technique that reduces operating expenses by 11.75% as compared to conventional approaches, by managing LNG send-out to liquefy all BOG at the re-condenser [10].

The exergetic optimization BOG re-liquefaction systems were investigated utilizing a thermodynamic model along with genetic algorithm-based optimization [8]. Significant gains in thermodynamic performance were observed in optimized systems when compared to the basic case [10]. Sensitivity analysis emphasizes the positive effects of greater expander mass ratios and compressor pressure ratios on exergetic efficiency. However, increasing the pressure ratio of the BOG compressor results in a decrease in its exergetic efficiency [11]. The addition of BOG re-liquefaction systems to cryogenic tanks, employing the Joule Thomson cycle, has been shown to provide significant economic benefits over typical fuel supply configurations. A cost analysis shows that adding re-liquefaction systems can cut total annual costs (TAC) by at least 9.4% [12].

Reducing compressor effort that used in reliquefaction process can be achieved by lowering the refrigerant temperature in the compressor cooler. This was accomplished by replacing a warmer saltwater stream at 30°C with cold liquid propane via a heat exchanger [13]. A powerful model has been constructed to estimate the BOG rate in LNG storage tanks, with correction factors and a rollover coefficient based on manufacturer specifications. The model emphasised the impact of tank pressure and LNG vapor pressure variations on BOR, and it provided a dynamic safety analysis approach that forecasts tank pressure changes using the ideal gas law [14,16].

In a case, dual mixed refrigerant (DMR) technology has been suggested for carriers' storage tanks to enhance energy efficiency. Thermodynamic analysis using Aspen HYSYS shows a 25% reduction in overall energy consumption, with a re-liquefaction capacity of 4557.6 kg/h and a specific energy consumption (SEC) of 0.589 kWh/kg [15].

Propane is frequently stored and transported at low temperatures using cryogenic tanks. But a part of the propane continuously evaporates due to heat intrusion, creating what is known as BOG. The refrigerated closed-loop process of pure propane, which is used in the reliquefaction process of propane BOG, will be replaced with an improved methodology in order maintain the duty, capital, and operating expenses of the current process.

Insufficient handling of the BOG results in energy loss and safety issues. In the following sections, we present a trail technique to avoid needless energy in the propane re-liquefaction process.

2. Methodology

The methodology is used to clarify the advancement of replacing the current propane refrigeration closed loop process in an Egyptian company, which is used to cool down the hot liquid in the re-liquefaction process. The new process includes an economizer heat exchanger. The study is done for the process in the holding mode, which means that the only effect on the propane storage tank temperature is the outside temperature of the atmosphere which raises the tanks temperature by exchanging heat. Propane is separately stored in double wall full containment tanks with suspended deck under certain pressure.

2.1. Storage tank specifications

Table 1 illustrates the adequate design of the propane storage tank. The tank consists of an inner and an outer tank, a concrete foundation and a suspended deck. The space between the inner tank and the outer tank is filled with insulation material. The inner and outer tanks are connected by pipes, which act as heat bridges. The inner tank is not gastight so that the space between the two tanks is filled with LPG/ propane/ butane vapors.

Table 1. Propane storage tank specification.

Specification	Inner tank	Outer tank
Nominal diameter	49 m	51 m
Height	30 m	32.8 m
Tank maximum capacity	53876 m^3	
Tank description	Double wall full containment with suspended deck	
Design pressure	-0.005/0.14 barg	
Design temperature	-48°C	-48/45°C

2.2. Simulation basis and steps

The study includes the simulation of the propane BOG re-liquefaction process. This model is simulated through Aspen Hysys (Version 10). The Peng-Robinson (PR) equation of state (EOS) could be suitable for the modeling. The simulation is divided into two main sections, as follows:

- Simulating the existing overall process in an Egyptian company including:
  1) Re-liquefaction process of BOG.
  2) Refrigeration process of pure propane (refrigerant)
- Simulating the re-liquefaction process (modified) of propane BOG.

Simulation is done for the modified process in condition as the following:

1) No gas carrier being unloaded to the tank.
2) The Ring-main is already warmed up (the liquid content is vaporized).
3) No export via pipelines from the tanks is performed.

In the modified process, the rate of BOG generation depends on the heat ingress into the tank only.

2.3 Simulation of propane re-liquefaction process (existing)

The composition of the propane BOG that was routed from the storage tank into the screw compressor's suction for recovering the propane in the form of liquid with pressure and temperature almost identical to the tank by the re-liquefaction process. The composition of the mixture consists mainly of propane at 97.5 mole%, with a small fraction of ethane at 2.5 mole%. Table 2 provides the condition of the propane BOG parameters.

Table 2. Parameters of propane (boil-off gas).

BOG Inlet stream	
Inlet temperature, °C	- 39.7
Inlet pressure, barg	0.02
Mass flow, Kg/h	687

The process simulation of re-liquefaction propane BOG which is applied in an Egyptian company illustrated in Figure 1. From Figure 1, it is comprehensible that in order to liquefy the BOG into its original form, each BOG generated inside the tank requires a certain quantity of cold propane as a refrigerant for heat transfer.

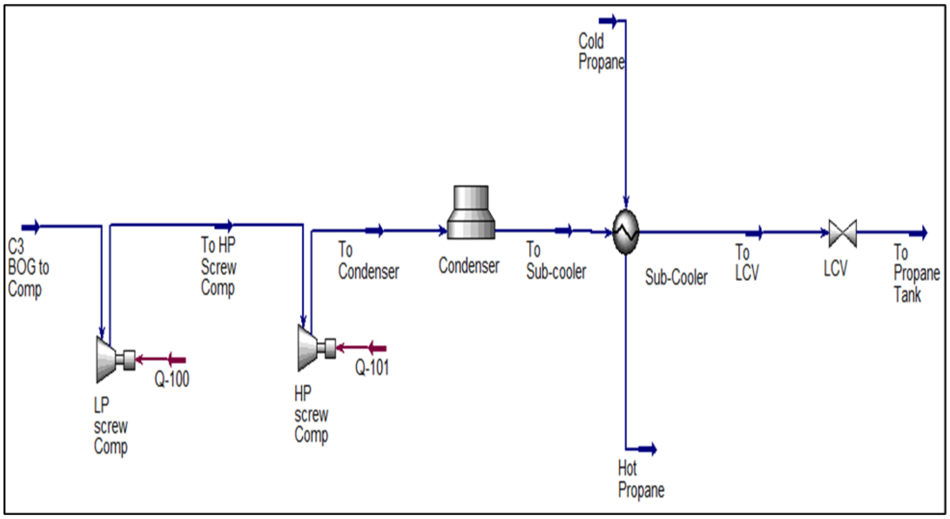

Figure 1. Simulation of the re-liquefaction process for propane BOG.

2.4. Simulation of propane re-liquefaction process (modified)

This section showed the simulation for the BOG re-liquefaction process with the new modification, which shows how the refrigeration cycle will be replaced by a heat exchanger economizer, provides a visual representation of the methodical shift towards increased sustainability and efficiency. The sequential steps involved in implementing this change into practice are shown in Figure 2.

A heat exchanger with two pipelines functioning as inlets substitutes for the pure propane refrigeration loop. The second pipeline inlet has a regular pipeline and is directed to the tube side of the heat exchanger for being cooled, whereas the first pipeline intake to the economizer has a throttling valve for reducing the pressure and temperature of the inlet stream, which functions as a cooling flow and directs to the shell side of the heat exchanger.

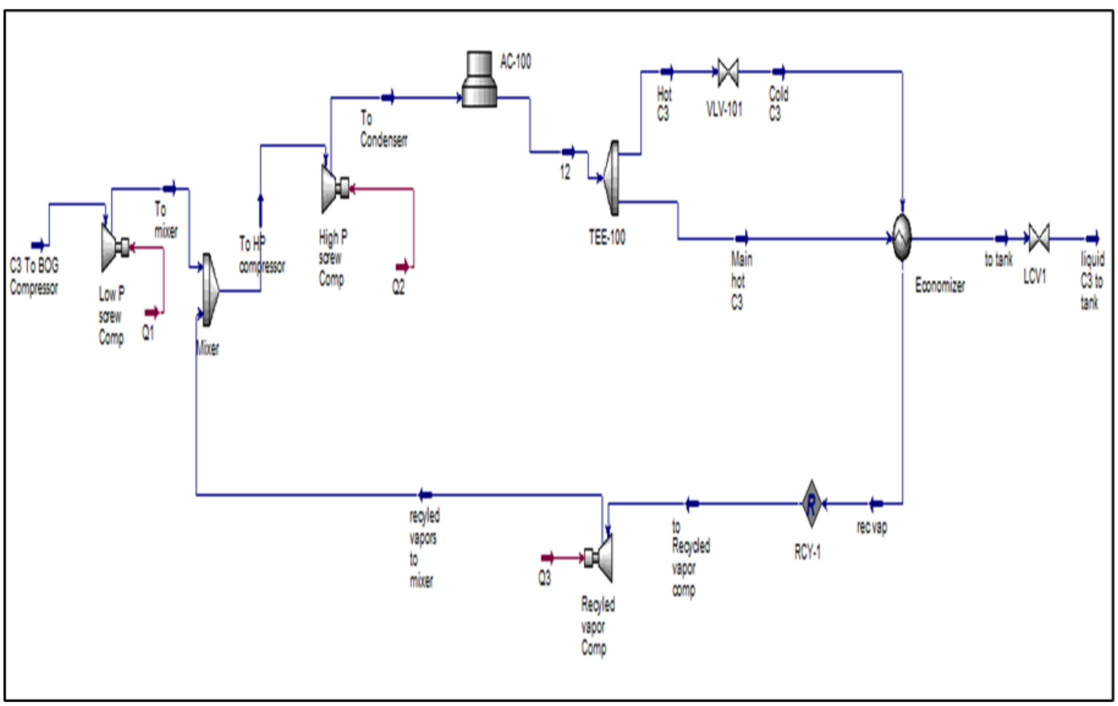

Figure 2. Simulation of re-liquefaction process of propane BOG with an economizer heat exchanger (MOC).

Table 3 shows the operating parameters for the propane stream after being broken down by the throttling valve and directed to the shell side of the economizer for cooling the hot liquid propane stream, which is directed to the tube stream as follows:

Table 3. Parameters of cold propane stream after the throttling valve.

Inlet cold propane to economizer	
Inlet temperature, °C	-33
Inlet pressure, barg	0.5312
Molar flow, kmol/h	17.11

2.5. Refrigeration process simulation (pure propane as refrigerant)

The modeling of pure propane's refrigeration process makes it easier to simulate the actual process, including compressors, expansion valves, and heat exchangers. As well as investigating alternate refrigeration cycles. which can assess the effects of different parameters on system performance, dependability, and environmental sustainability. Through virtual experimentation, which will ultimately lead to breakthroughs in refrigeration technology.

A simulation of the pure propane refrigeration process is utilized to emphasize the energy usage, operating expenses, and utilized area.

Table 4 shows the pure propane operating parameters which are directed to the sub-cooler (shell side) to cool down the hot liquid propane.

Table 4. Parameters of inlet pure propane as refrigerant to sub-cooler.

Refrigerant propane to sub-cooler	
Inlet temperature, °C	- 38
Inlet pressure, barg	0.2
Mass flow, kg/h	157.59

The process is a closed-loop refrigeration using propane as the refrigerant. The refrigerant propane, when boiled in the sub-cooler, is converted into vapor phase. The propane vapors (0.1 barg and -40°C) after leaving the sub-cooler it passes through a suction drum to remove liquid droplets.

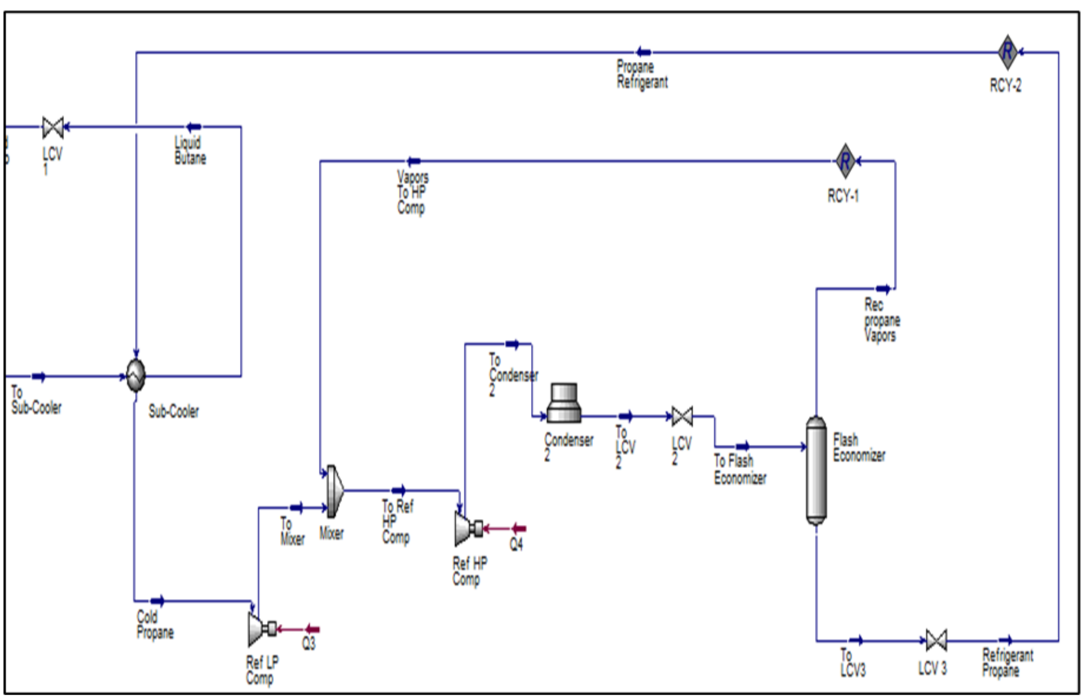

Figure 3. Propane refrigeration process (regeneration as a liquid).

A stream of saturated refrigerant vapor flows from the horizontal suction drum into the low-pressure suction port of screw compressor. Another stream of saturated refrigerant vapor (3.85 barg and 0.8°C flows from the upper of two vertical flash economizer into the intermediate pressure port. The compressor increases the vapors stream pressure. The refrigerant vapor from the compressor outlet is condensed in the air-cooled condenser (the maximum design inlet air temperature for the condenser design is 45°C.

The condensed refrigerant then flows into two refrigerant liquid receivers. Some of the refrigerant liquid receiver outlet stream is bypassed through the filter dryer, where moisture is captured. The mainstream of liquid refrigerant flows out of the refrigerant liquid receiver into two liquid control valves to break down the temperature and pressure, then to the two-flash economizer. The outlet liquid from the bottom of the flash economizer passed through another level control valve for more breakdown of temperature and pressure through throttling (-38°C and 0.2 barg). Finally, liquid refrigerant then flowed into the shell side of the subcooler to cool down the hot liquid propane (tube side).

2.6. Area utilization for propane refrigeration closed loop

The goal of this section is to give an extensive understanding of the way that optimal area usage affects plant productivity overall, equipment accessibility, and operational performance. The below equipment list Table indicate the importance of Appling the new modification as it will reflect on the deduction the cost. The overall equipment for refrigeration of pure propane (refrigerant) that is used in the process will be mentioned in Table 5.

Table 5. Propane refrigeration closed loop main equipment.

Equipment list for propane refrigeration closed loop	Quantity
Screw compressor (two stages)	4
Oil separator	4
Oil pumps	8
Oil filter	8
Oil heater	4
Air cooler fan	3
Pure propane receiver	2
Flash economizer	2
Level control valve	6
Surge drum	4
F&G protection system for the process	
Instrument air header	
Hand valves and other fittings	

In addition to lowering equipment costs, modification promotes a more powerful and sustainable operational framework. This change guarantees the durability of current assets.

3. Results and discussion

The results highlight comparison between temperature, pressure, flow rate and vapor fraction, offering insights into practical solutions for optimizing the propane BOG which formed inside the storage tanks. This approach not only meets the requirements of national emission standards but also adds economic value by recovering valued products.

3.1. Comparison between the operating condition of propane BOG re-liquefaction process

Figure 4 describes the comparison between the operating condition for the process before and after the modification, which highlights that there is no major difference in the values from which the modification will not have an undesirable effect on the whole process from the operation condition side.

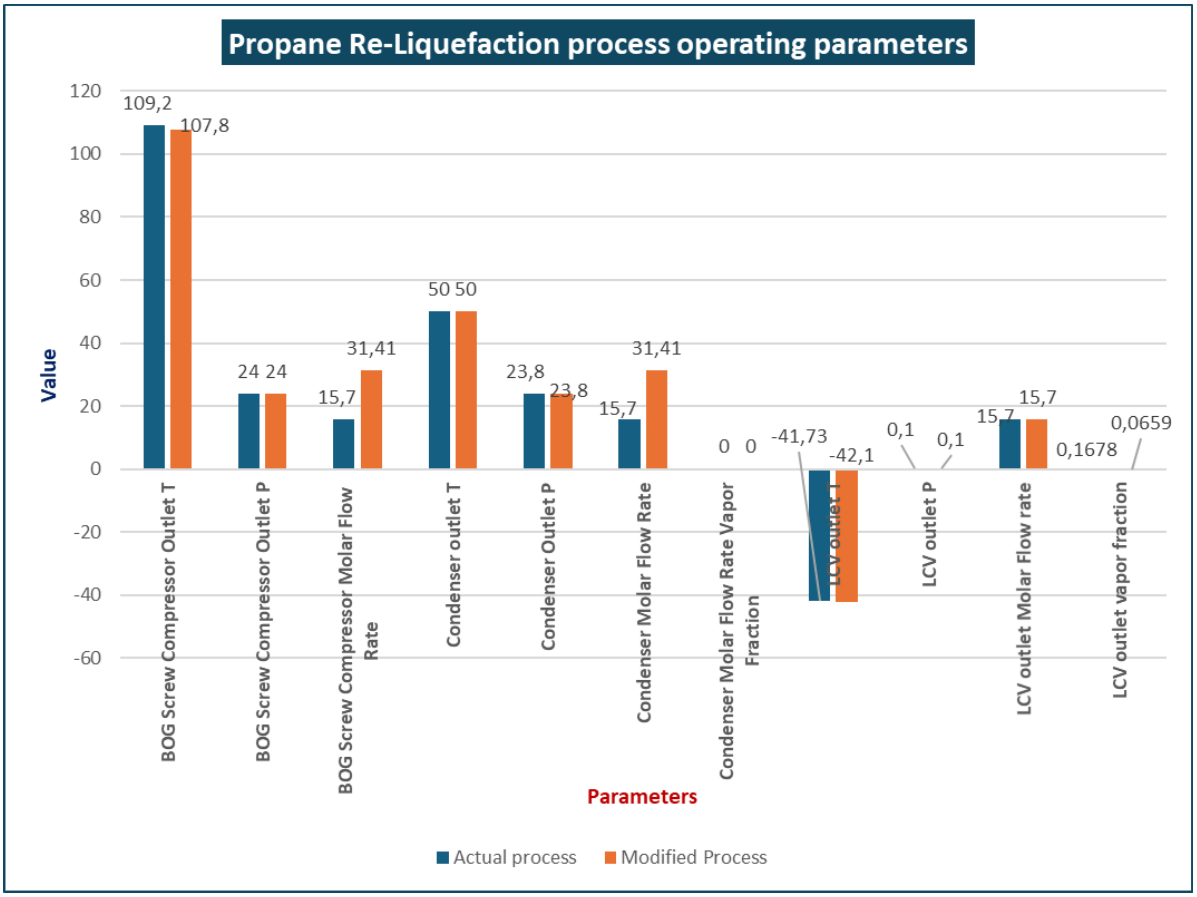

Figure 4. Operating condition comparison for the propane BOG Re-liquefaction process.

Note: The final parameters of the stream after the level control valve (LCV1) as mentioned in Figure 1 will be exposed to minor losses in temperature and pressure according to heat ingress to the pipeline and friction losses.

3.2. Optimum splitting ratio of mainstream for the modified process

The splitter, which is located after the condenser, is the heart of the modified process, as it controls the quantities of propane that will be separated and enter the heat exchanger (hot for the tube side and cold for shell side) which is responsible for cooling down the propane hot liquid. Which means that the stream is cooling down by itself.

Performing numerous trials to determine the optimal ratio that will provide us with the best results for both the method and operating conditions that are closest to the real operating conditions. Figure 5 describes in detail the trails of changing the splitting ratio and shows the most optimum value that will lead to the best condition of the process of re-liquefaction propane as:

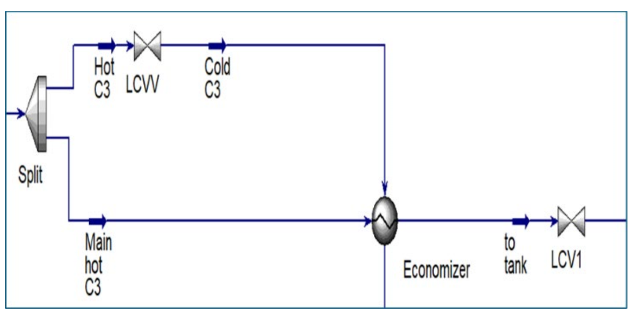

Figure 5. Splitting ratio of mainstream for propane.

Table 6 shows the optimum ratio of splitting the mainstream which reflects that on the operating condition of the liquid stream that entering the storage tank after the re-liquefaction process:

Table 6. Splitting ratio for the mainstream of propane re-liquefaction process.

	Hot C_3	Main hot C_3	Temperature of economizer outlet stream to LCV1	Heat exchanger condition	Outlet stream of LCV1 vapor fraction
Splitting %	10 %	90 %	43.08°C	Accepted	0.5146
	20 %	80 %	34.01°C	Accepted	0.4501
	30 %	70 %	21.56°C	Accepted	0.3674
	40 %	60 %	3.6°C	Accepted	0.2572
	50 %	50 %	-23.6°C	Accepted	0.1039
	51 %	49 %	-27.2°C	Accepted	0.0853
	52 %	48 %	-30.93°C	Accepted	0.0659
	53 %	47 %	-43.4°C	Accepted	0.0457

From Table 6, it noted that the percentage of splitting is optimum at 48% of the main hot C_3, as the quantity of hot C_3 which will pass through the throttling valve (LCVV) should be high to handle the main hot C_3 to the required temperature and pressure. Also, if we choose the last percentage (53%,47%) it will pass through LCV1 and go for lower temperature that will affect the tank wall design temperature which is equal - 48°C as per Table 1.

4. Conclusion

The study's findings highlight how significant energy conservation is in the re-liquefaction process. Which is utilized to handle the problem that results from the temperature differential between the atmosphere and the liquid inside the propane tank. The study shows that the existing re-liquefaction process of propane BOG can be replaced with a new modification by splitting the inlet stream of the economizer into 2 streams, one acting as a cold stream after being broken down by the throttling valve (shell side) and the other as hot stream (tube side). Also, it gives nearly identical operating parameters to the existing process, which means it can operate smoothly. By eliminating the propane refrigeration loop, the unit's capital cost, which includes main equipment, utilities, safety devices, etc., will decrease.

The study also indicates that the proposed modification not only simplifies the re-liquefaction process but also reduces the complexity of the overall system. The only concern will go to the operating time, which will be higher as the percentage of the splitting stream is nearly half, which means the other half of the stream will be sent back again to the compression cycle in the process and increase the recovery time. The following studies may concentrate on optimizing the split ratio to reduce the effect on operation time while maintaining efficiency advantages.

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