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HAZOP ANALYSIS OF AN ATMOSPHERIC PETROLEUM DISTILLATION UNIT AND SIMILARITY IN SUSTAINABLE AVIATION FUEL (SAF) PRODUCTION PROCESSES

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ABSTRACT

The production of petroleum products stands out worldwide, among the production processes of non-renewable energies, as the best known worldwide. In this work, an atmospheric distillation column that processed 100,000 barrels/day (662.5 m3/h) of crude oil was simulated using the CHEMCAD® software. From this procedure, the Process Flow Diagram (PFD) and the Piping and Instrumentation Diagram (PI&D) were obtained for the unit, corresponding to its automation. Subsequently, a HAZOP (Hazard and Operability Study) analysis was conducted in order to identify risks in the unit that, although not dangerous, could compromise its ability to achieve its productivity. The main risks of the process were related to fires, explosions and environmental contamination from leaks and ruptures in pipes, pumps, heat exchangers, the column itself, among other equipment. The HAZOP analysis was able, through the use of the guide words, to identify the possible operational risks arising from deviations in the operating intentions, such as the possibility of fires, explosions, environmental contamination and its consequences. It was possible to identify the risks that are associated with the selection of materials, the mechanical design of the equipment and the specifications of the accessories. Therefore, the study carried out is an important survey to reduce possible failures in the oil industry. And, this study being a deepening of the distillation processes for petroleum products. It is understood that its deepening, as a result of the development of new renewable products, especially sustainable aviation fuels (SAFs), due to being similar purification processes, employ the same methodology to identify possible failures in production.

Keywords: Atmospheric Distillation. R&D. Unit Operations.

INTRODUCTION

Among all the existing process industries, petroleum refining is considered to be the one in which complexity is increased to the maximum. This complexity is intrinsically related to three main factors: the unit operations themselves, the control of refining processes, and aspects related to safety and the environment. Regarding these last two topics, it is well emphasized by Fahim *et al.* (2009) that all routine services in a refinery must be in accordance with high standards of safety and operability.

As the main process of large refineries, the atmospheric distillation of petroleum has delicate aspects of operation and safety that must be taken into account in the design of any refining unit. This is due to the fact that the stop of this unit operation, for any reason, will lead to the stop of the entire plant when it is in operation.

HAZOP (Hazard and Operability Studies) analysis is a technique developed to identify and evaluate risks, or safety problems, in a plant of processes and operational problems that, although not dangerous, could compromise the plant's ability to achieve the productivity foreseen in the project (AIChE, 1992). Matos (2009) and Dunjó et al. (2010) define that HAZOP analysis is the most comprehensive method used in the chemical industry as a means of identifying risks. Santos and Theobald (2013) define HAZOP as an inductive, qualitative and structured technique.

The HAZOP technique, according to Sinnott (2005), was developed by the Petrochemical Division of Imperial Chemical Industries (ICI), in England, and was first reported by Lawley in 1974, in the book entitled *Operability Studies and Hazard Analysis*.

The methodology is based on a structured procedure that generates questions, based on a set of "guide words", applied to critical points of the system under study (nodes), aiming to discover all possible deviations from normal operating conditions (TELLES, 2003), identifying the causes responsible for such deviations and the respective consequences (AGUIAR, 2008).

Although there are several studies that report the results of the HAZOP analysis applied to highly complex and high-risk processes, its practical application is practically non-existent when it comes to the atmospheric distillation of petroleum, and even though this operation is of high importance. Therefore, this work intends to fill a gap with regard to the understanding of the risks of this type of unit, as well as to serve as an application guide for future projects.

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METHODOLOGY

PROCESS SIMULATION

As in any process project, the construction of the PI & D diagram follows the elaboration of the PFD (*Process Flow Diagram*). This shows the arrangement of unit operations in the process, the connections between the currents, the flows (preferably mass or molar), their compositions and operating conditions such as pressure and temperature (SINNOTT, 2005).

To construct the PFD of the atmospheric distillation process of petroleum, a real case study was considered, which was modeled and simulated with the simultaneous resolution of mass and energy balances with the aid of the CHEMCAD® software. This case study was proposed by Fahim *et al.* (2009). The implementation of the proposed case in the chosen software was carried out following the procedure proposed by (ROCHA, 2009). The atmospheric column in question had the ability to process 100.000 barris/dia (662,5 m3/h) of previously desalted crude oil. The thermophysical data of the petroleum used for modeling and simulation were also obtained from Fahim et al. (2009). Table 1 presents the true boiling point (PEV) data, and the oil used had a *29.32 °API equal to*.

Table 1 - PEV data for used oil.

% in Volume Collected	Boiling Point ()$°F$
0,0	15,0
4,5	90,0
9,0	165,0
14,5	240,0
20,0	310,0
30,0	435,0
40,0	524,0
50,0	620,0
60,0	740,0
70,0	885,0
76,0	969,0
80,0	1015,0
85,0	1050,0

Table 02, according to simulations, shows the composition of *Light Ends* measured as a percentage in volume.

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Table 2 - Composition of *Light Ends*.

Component	% Volume of Liquid
Methane	0,0065
Ethane	0,0225
Propane	0,32
i-Butane	0,24
n-Butane	0,82
Total	1,409

The operating conditions of this system, as well as all the specifications used, are described in Table 3.

Table 3 - Operating Conditions.

Unit Load	T= 250C; P= 101,3 kPa $\dot{v}$ = 1,00 x 105 barris/dia (662,5 m3/h)
Load Heater	T=330°C (heating temperature); ΔP =34,47 kPa (5psia) (pressure drop).
Atmospheric Column	Nt = 29 (number of theoretical stages); ΔPc = 9psia (62.05kPa) (in the condenser); Pc=135,8 kPa (condenser pressure); Pf = 218.6 kPa (bottom pressure); Tc = 37.8 ^{0C} (Non-capacitor temperature); Tpts=121,1 ^{0C} (Temperature at the top stage); Tbts = 315,60 C (Temperatura no fundo); Fp= 28 (feeding stage); Qp = 28 (thermal load of the bottom).
Steam for *Column Stripping*	T = 190,6 ^{0C}; P = 1034,2 kPa $\dot{M}_{ms}$ = 3402 kg/k(mass flow).
Steam for *Diesel Oil Side* Stripper	T = 148,9 $^{0C; P = 344,7 kPa}$; $\dot{M}_{ds}$ = 1360,8 kg/h.
Steam for *AGO Side* Stripper	T = 148,9 $^{0C; P = 344,7 kPa}$; $\dot{M}_{As}$ =1134 kg/h.
General Specifications	Naphtha Flow = 152.4 m3/he; 7,91 x 106 kJ/h (en Stripper de querosene).

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The reflux conditions in which *pumpsaround* were used are shown in Table 4. It shows the withdrawal and return stages for the fractionation column.

Table 4 - Specifications for *pumpsarounds*.

Pump around	Withdrawal Stage	Return Stage	$\dot{v}(barris/dia)$	Thermal Load (Btu/h)
PA 1	2	1	50000	-5,80 x 107
PA 2	17	16	30000	-3,90 x 107
PA 3	22	21	30000	-3,69 x 107

The data related to the lateral strippers of the system are presented in Table 5. It identifies the location of material depletion and return in which the fluid dynamics of the tower was obtained.

Table 5 - Specifications the side strippers.

Stripper	Withdrawal Stage	Return Stage	$\dot{v}(barris/dia)$
Kero - SS	9	8	9300
Diesel - SS	17	16	19250
AGO - SS	22	21	4500

After entering all this data into the CHEMCAD® software, the mass and energy balances were solved. With the results obtained, the PFD of the process was constructed, which is presented in Figure 1. The flows evaluated in Figure 1 were, therefore, the operating intentions for the unit. That is, they are the ones that must be kept at their fixed points (set points).

From the PFD, presented below (Figure 01), the IP&D diagram for the unit was constructed based on the suggestions given by Nisenfeld and Seemann (1981) and Kister (1992). The diagram also shows the valve fault position selections: whether fail-close (FF) or fail-open (FA)

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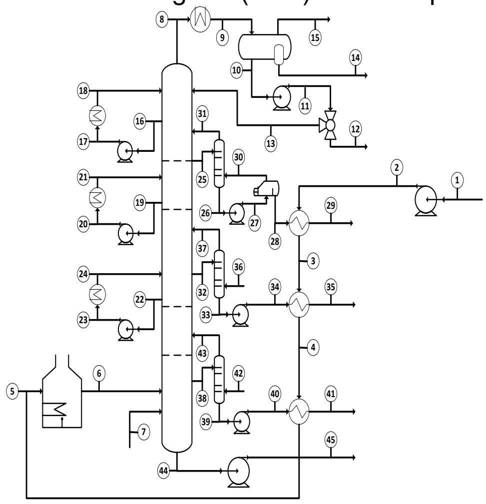
Figure 1 – Process flow diagram (PFD) for atmospheric distillation.



CONSTRUCTION OF THE HAZOP SPREADSHEETS AND ANALYSIS OF THE RESULTS

With the subsystems and study nodes selected, the stage of construction of the HAZOP spreadsheets for the possible deviations followed. That is, each variable (parameter) in this table was analyzed for each study node identified in Figures 2 and 3.

Figures 2 and 3 show the Control (PI&D) and node marking flowcharts. The control loops were developed with a systematic feedback. To this end, temperature, level and flow sensors redirect their signals to controllers that check the values obtained in the sensors with the standard design setpoints.

The entire safety analysis process, using the HAZOP study, has as evaluation data the simulation, initially carried out at CHEMCAD.® The fractions presented in Table 2 (Composition of Light Ends) were fed into the diagram in Figure 1. As a result of the simulation, the compositions of each process stream are obtained (Table 6). And, with the obtaining of these data, all the conditions under which the operation of the atmospheric distillation system presented was estimated is monitored. Knowing that each piece of equipment, designed and developed, has its data relations and technical specification sheets. And, with this data, it was possible to monitor fatigue, mechanical and thermal stress conditions that each equipment can withstand in the processing unit.

And, in this process monitoring, the control of the unit becomes extremely important, since each equipment, choice of material, sealing gaskets, has a safety limit which must be respected.

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Table 6 – Input and output currents in the petroleum distillation unit.

Current	1	2	3	4	5	6	7	8
Vapor Fraction	0,00	0,00	0,00	0,00	0,00	0,63	1,00	1,00
T ()$°C$	27,0	27,1	47,0	88,0	98,0	330,0	190,6	133,8
P ()kPa	101,3	517,1	482,6	448,2	413,7	379,2	1034,2	197,9
Mass Flow ()kg/h	5,82x105	5,82x105	5,82x105	5,82x105	5,82x105	5,82x105	3,40x103	1,86x105
Current	12	13	14	15	16	19	22	25
Vapor Fraction	0,00	0,00	0,00	1,00	0,00	0,00	0,00	0,00
T ()$°C$	38,9	39,8	39,8	39,8	156,30	264,0	320,6	205,7
P ()kPa	135,8	135,8	135,8	135,8	198,7	213,6	218,6	205,8
Mass Flow ()kg/h	1,11x105	6,92x104	5,71x103	0,00	2,57x105	1,68x105	1,75x105	6,23x104
Current	28	32	34	36	38	40	42	45
Vapor Fraction	0,00	0,00	0,00	0,00	0,00	0,0	1,00	1,00
T ()$°C$	234,8	264,0	245,1	148,9	320,6	291,3	148,9	344,2
P ()kPa	197,9	213,6	197,9	344,7	218,6	197,9	344,7	197,9
Mass Flow ()kg/h	5,09x104	1,25x105	1,11x105	1,36x103	3,37x104	2,72x105	1,13x103	2,81x105

The process flowchart used in the simulation has already been shown Figure 1. In this step, all the input and output streams of the process are evaluated in order to obtain the highest degree of purity in the output chains. The input and output currents are listed in Table 6. In these are presented the process conditions that are monitored and monitored at all times in automation and control systems. And, with this, it is possible to predict data to the processing equipment and points of failure.

From the PI&D diagram of the unit (Figure 2), the subsystems and study nodes were selected. Figure 3 shows these selections. The Flowchart has a chain line that consists of pumping oil from an oil desalting system. Thus, although not listed in the process flowsheet, the entire hydrocarbon load has already been treated in the desalting plant.

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Figure 2 – Piping and Instrumentation (PI&D) diagram for atmospheric distillation of petroleum.

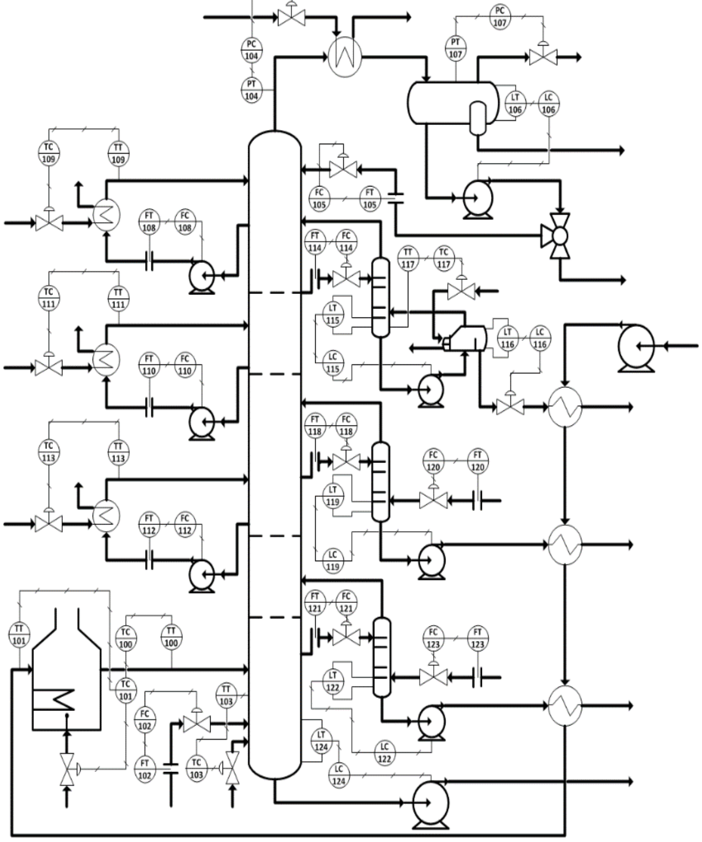
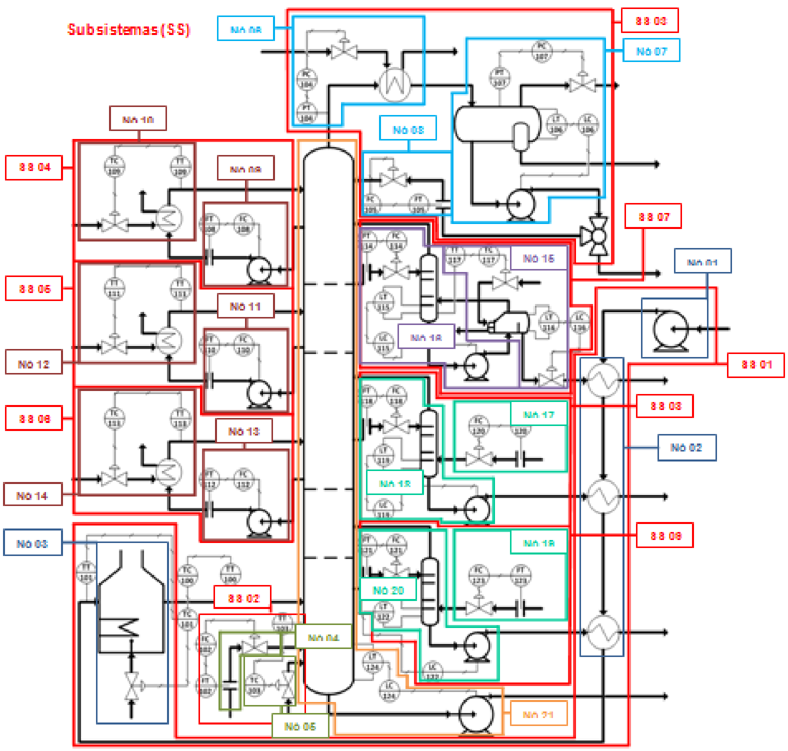


Figure 3 – Selected study systems and nodes.



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RESULTS

With the simulation data, process flowcharts and automation, the safety study involving the HAZOP methodology was applied and evaluated in the following tables (Tables 07 to 19). The surveys, used for atmospheric distillation columns, deepening of flow chains, mass, automation are approached in terms of a production system that can help in the in-depth knowledge of processes and reduction of possible industrial accidents. This, when used in new processes, in the case of sustainable aviation fuels (SAFs), enables a greater mastery of preventive and predictive actions.

After the evaluation of the process and automation flowcharts, and with the help of Table 07, the data of the oil after leaving the desalting plant is pumped through the exchanger battery, in order to recover the energy of fractions that leave the tower, and is directed to the furnace to receive the final thermal load before being fed into the column.

Table 07 – Worksheet for node 1.

System/Subsystem 01: Pumping and Heating		Parameters: Flow and pressure		Node 01: Crude Charge Pump and Pipelines	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
1	Flow	(2)Less; (3)No	(2) Oil supply problems; Leakage in the pipes (due to fractures in the pipes and/or flanges) and/or in the pump.	(2) Reduction in production; Possibility of fires and/or explosions in the event of leaks and environmental contamination.	(2) Improve logistics; Review the chemical compatibility of construction materials and review mechanical design.
			(3) Failure of flow control valves: Leakage in the pipeline.	(2) Possibility of fires and environmental contamination.	(2) Check the mechanical design of pipes and pumps and review controllers
			(3) Failure of power supply; Loss of the pump due to corrosion in the rotor; rupture of the pipes.	(3) Possibility of fires and environmental contamination.	(3) Design auxiliary system for power outage case.
	Pressure	(2)Less	(2) Loss in pump efficiency.	(2) reduction in pump load height; Loss of production,	(2)Review the chemical compatibility of materials

Temperature was not selected as a variable to be evaluated due to the fact that the flow rates of the withdrawals can vary within a given range, and it is not necessary,

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therefore, to control the exit temperatures of the crude load in each exchanger. As will be seen later, the temperature of the load entering the column will be adjusted by the heater/oven. Also, lower temperatures of the side recessions will not be achieved only by the use of preheaters. It will then be necessary to further cool these chains using additional heat exchangers (Nisenfeld; Seemann, 1981).

In the evaluation of this node, the safety analyses detected the possibility of fires and environmental contamination as the greatest consequence. The causes were emphasized in the problems in the piping and ruptures of pipes. However, the calculation of the wall thickness of the pipes (Schedule) must follow the pressures of the project. And, the biggest factor that can occur in these circumstances would be corrosion due to improper choice of materials.

In Table 08, charge preheaters, the study is shown emphasizing the battery of exchangers used in the use of energy from the distillation system. In this evaluation, it can be observed that, for the monitored variables, the immediate problems are the complete shutdown of the unit, in the simplest case a low production, with the possibility of fires and loss of operators. Greater attention must be paid to the desalting system of the extracted oil and sent to the refining unit.

Table 08 – Worksheet for node 2.

System/Subsystem 01: Pumping and Heating		Node 02: Preheaters of load 01, 02 and 03.		Parameters: Flow and pressure	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
2	Flow	(2)Less; (3)No	(2) Leakage in the hull or pipes caused by corrosion, fouling or thermal fatigue.	(2) Possibility of fires, explosions and mixing of liquids from hull and pipes.	(2) Review chemical compatibility of materials and mechanical design of exchangers.
			(3) Obstruction in the hull caused by fouling; Tube obstruction caused by coke; rupture of the hull or tubes (mirrors) by thermal expansion.	(3)Complete shutdown of the unit if atmospheric distillation occurs; explosion in case of ruptures; Environmental contamination	(3)Evaluate the efficiency of the desalting plant; Review the chemical compatibility of materials; Verify the mechanical design of the exchangers with emphasis on fluid flow.
	Pressure	(2)Less	(2)High hull loss caused by saline fouling; Pressure loss in pipes caused by coke deposition	(2) Low flow rate and production.	(2) Evaluate the efficiency of the desalting machine; Use smaller diameter pipes.

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Table 08 shows the furnace heater. In this system, temperatures above 340° C should be avoided. Since, according to Bombardelli *et al.* (2005), this will prevent the formation of coke and, finally, will not favor the appearance of scale. In this system, as shown in Figure 2, there was the addition of a two-level cascade control system in the heater/furnace. This type of strategy is more efficient for temperature control than a simple feedback-type strategy, due to the inherent slower response of a temperature control loop (Smith; Corripio, 2008). Therefore, with the system in question, the temperature oscillations around the fixed point (*set point*) will be smaller, as required in Table 09.

Table 09 – Worksheet Referring to node 3.

System/Subsystem 01: Pumping and Heating		Node 03: Heater/Furnace Charge		Parameters: Flow, pressure and temperature	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
3	Flow	(2) Less, (3) None	(2) Leaks in heat exchange tubes caused by fatigue or corrosion.	(2) Fires or explosions; environmental contamination.	(2) Review the selection of construction materials; review the mechanical design of the exchangers.
			(3) Total obstruction in the pipes caused by salt or coke; gas control valve failure; rupture of the heat exchange tubes.	(3) heater stop in case of valve failure; possibility of fire; environmental contamination.	(3)Evaluate the efficiency of the desalting plant; Review the chemical compatibility of materials; Check the mechanical design of the exchangers.
	Pressure	(1)More, Less	(1)Rise by increasing the temperature by increasing the steam fraction.	(1)Weakening of construction materials and possible rupture; ruptures and/or leaks with the possibility of fires; environmental contamination.	(1) Addition of a stricter control system, which avoids fluctuations in the heater outlet temperature (Furnace)
			(2)Loss of pressure in the pipes caused by saline scale and/or coke	(2) Heated crude oil will not have sufficient pressure to flow to the column; reduction in production.	(2)Evaluate the efficiency of the desalting machine in the case of saline scale; Avoid working at temperatures above 3400C.
	Temperature	(1)More, (2)Less	(1) Failure of the fuel gas flow control and/or control system.	(1) An increase in temperature may cause thermal expansion of the construction material.	(1) Select valves and/or control system in which a tuning of the control occurs correctly.
			(2) Problem in the supply of combustible gas to the furnace; Gas flow control valve failure.	(2)Reduction of the temperature of the load for the column and consequent loss of efficiency in separation	(2)Design an auxiliary gas supply system; check the operation of the valves; review the operation of the controllers.

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Table 10 shows the nodes referring to the sending of steam from the furnace to the bottom of the column for heating and *stripping* at the base of the column. To this end, the elements to be monitored are relevant to the variables of flow, pressure and temperature. Because, since it is a question of drag and heating, the changes in the flow will have as its main problem the inadequate separation of the oil fractions.

Table 10 – Worksheet Referring to nodes 4 and 5.

System/Subsystem 02: Steam to the column		Nodes 04 and 05: Steam supply lines for *stripping* and heating the bottom of the column		Parameters: Flow, pressure and temperature	
Knot	Variables	Guide Words	Cause	Consequence(s)	Providencia (s)
4 and 5	Flow	(1)More, (2)Less, (3)None	(1)Steam flow control valve or control system failure.	(1) Excess steam inside the column and thus interference with the separation; overheating at the bottom of the column causing the formation of coke and damaging the equipment.	(1)Check the actuation of the valves and review the control tuning of the meshes.
			(2)Problems in the steam generation system; failure of steam flow control valves; leak in the steam pipes.	(2) Lack of steam in the *stripping section* of the column impairing the evaporation of the light fraction; decrease in temperature at the bottom of the column impairing separation.	(2)Check the performance of the valves; review the control tuning of the meshes and verify the assembly of the pipes in regulatory terms.
			(3)Failure of the control valves (off); problems in the steam generation system and rupture of the steam pipes.	(2)Accidents in the unit with possible damage to the operator; stopped at the unit.	(3) Check the performance of the valves; review the mechanical design of the pipes; Conduct a HAZOP study on the boilers to avoid shutting down.
	Pressure	(1)More, (2)Less	(1)Problems in the steam generation system due to pressure control in the boilers.	(1) Pipe ruptures with ruptures and leaks.	(1) Perform a HAZOP analysis on the boilers.
			(2) Problems in the steam generation system.	(2) The steam for *stripping* will not have enough pressure to reach the column; loss of efficiency in separation and loss of efficiency in heating the base of the column.	(2)Perform a HAZOP analysis on the boilers.
	Temperature	(1)More, (2)Less	(1) Problems in the steam generation system due to the control loop in the temperature of the boilers.	(1)Stresses in the pipes with possible ruptures and leaks.	(1) Perform a HAZOP analysis on the boilers.
			(2)Problems in the steam generation system caused by the temperature control loop in the boilers.	(2) Low temperatures in *stripping* and heating steam reduce	(2)Perform a HAZOP analysis on the boilers.

				fractionation, reducing production.	

As shown in Tables 09 and 10, it would be necessary to insert backup (or redundant) systems to supply instrument air to the aforementioned control valves, as these valves are considered critical points in the operation. Also, as emphasized in Table 10, it would be necessary to carry out a HAZOP study on the boiler. This study is, however, predictable, since the analysis can and should be applied to all process equipment in any project (Kletz, 2001).

Table 11 and Figure 3 show that temperature was not selected as a variable to be studied in the condenser (Node 06), even though this is a thermal exchange system. This is due to the fact that the top vapor to be condensed was at its dew point, and this is shown in the simulation of the case study. That is, the temperature 138.80C of current 8 (top steam) corresponded to the temperature of the dew point. Therefore, a variation in the pressure of this current will affect this temperature by displacing the thermodynamic equilibrium (Smith *et al.*, 2005).

Table 11 – Worksheet Referring to node 6.

System/Subsystem 03: Top		Parameters: Flow and pressure		No. 06: Condenser.	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
6	Flow	(1)More, (2)Less, (3)None	(1) Failures in the cooling water control valves or control system.	(1)Reduction of pressure at the top of the spine causing an increase in heavy fractions.	(1)Check the performance of the valves; review the feeling of control of the knitwear.
			(2)Leaks in the condenser shell or steam piping; leaks in the cooling water; control valve failures.	(2)Possibility of fires due to steam leakage; increased pressure at the top of the spine; condensate current decrease (NAFTA).	(2) Adequacy of the mechanical design of the pipe and review tuning of controllers.
			(3) Total obstruction of the refrigeration pipe by saline fouling; pipe rupture; rupture of the steam outlet pipe at the top.	(3)|Possibility of fires in the event of explosions with spillage and possible environmental contamination.	(3) Control the salinity of cooling water; chemical compatibility of construction materials and review mechanical design.
	Pressure	(2)Less	(2) Saline fouling in condenser hull with pressure drop elevation.	(2) Coolant with difficulties in draining in the condenser shell.	(2) Control the salinity of the cooling water and perform a HAZOP study on the pumping system.

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Therefore, if the column pressure control acts correctly, the temperature of the top will inevitably be controlled indirectly. If the temperature increases, the pressure will increase causing the control system to act on the water valve (opening), increasing the rate of condensation of vapors and consequently reducing the pressure. If the temperature decreases, the pressure will also decrease, causing the control valve to act on the water valve (closing), reducing the rate of condensation of vapors and consequently reducing the pressure.

Table 12 shows the study involving the three-phase separator and the material sending pump (Node 7). In this evaluation, the biggest problems that may occur are due to mechanical weaknesses or inadequate material selection. And, as a consequence of these causes, there is the possibility of fires, burning of hydrocarbons, overcoming their flash points and reaching their point of combustion.

And, as seen in other nodes, the control system, presented here, has the function of maintaining *setpoints* that are based on the structural maintenance of the equipment. With this, the vapour pressure variable is monitored and controlled.

Table 12 – Worksheet Referring to node 7.

System/Subsystem 03: Top		Parameters: Flow, pressure and level		No. 07: Three-phase separator and pump	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
7	Flow	(2)Less; (3)No	(2) Leaks in the pipes, pump or three-phase separator caused by embrittlement of building materials.	(2) Possibilities of fires and explosions; environmental contamination.	(2) Review the selection of construction materials; review mechanical design.
			(3) Rupture of the separator or pump pipes caused by embrittlement of the construction materials.	(3) Complete stop of the unit; possibility of fires and environmental contamination.	(3) Review the selection of construction materials; review mechanical design.
	Pressure	(1)More; (2)Less	(1) Failure of the pressure control valve or control system.	(1) Pressure increase in the separator.	(3) Select a suitable valve; review the control tuning and use a relief or safety valve.
			(2) Failure of the pressure control valve or control system and loss of pump efficiency caused by corrosion in the rotor.	(2) Vaporization of heavier hydrocarbons, which exited in the refinery's gas stream, instead of exiting in the NAFTA stream.	(2) Select a suitable valve or control system; review the tuning of controllers.

In the case of three-phase separator pressure control, a modification to the system to include a relief (or safety) valve is shown in Figure 04.

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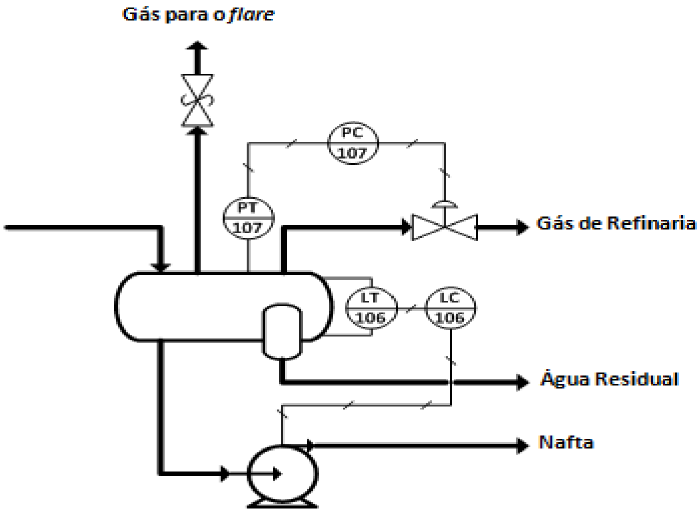
Figure 04 – PI&D diagram with pressure relief system.



In this system, if the pressure exceeds a maximum in the event of a failure of the pressure control system, the relief valve will reduce the pressure of the separator by sending the amount of surplus gas to a *flare* (burner).

Table 13 evaluates the material backflow ratio in the tower. The reflux ratio for the case study was calculated by the CHEMCAD software as being equal to 0.637. This value represented the intention of operation for the system studied. A deviation that reduces the flow rate of the reflux current will impair fractionation because there will be a smaller amount of liquid to transfer the mass of the heavier components from the vapor phase to the liquid phase (Perry; Green, 2008).Conversely, a deviation that increases the flow rate of the reflux current will increase the liquid inventory in the column, requiring a greater amount of energy to vaporize this excess liquid, to keep molar flows of descending liquid and rising vapor approximately equal (McCabe *et al.*, 1985).

The study element of nodes 9, 11 and 13 are the *pump around* . And, since it is the reflux of hydrocarbon fractions that will be removed from a plate and recirculated to a higher stage, in order to optimize mass transfer, the biggest impact would be leaks with the possibility of fires. And, again, for this case, the temperature variable was not evaluated, even though the study node had a thermal exchange equipment. This is due to the fact that the temperature control is carried out by adjusting the cooling water flow, and this variable has already been evaluated. Therefore, the study of temperature would be a redundancy.

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Table 13 – Worksheet for node 8.

System/Subsystem 03: Top		Parameter: Flow Rate		Node 08: Reflux current at the top	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
8	Flow	(1)More; (2)Less; (3)No	(1) Failure of the flow control valve or control system.	(1) Increased reflux will cause an increase in the thermal load in the reboiler.	(1) Select valves and/or control system in which a tuning of the control occurs correctly.
			(2)Failure of flow control valves or control system.	(2) Reduction in the flow rate of the reflux current will impair the fractionation of the currents of interest.	(2) Select valves and/or control system in which a correct control tuning occurs.
			(3) Rupture of the pipe due to embrittlement of the construction material.	(3)Possibility of fires and explosions; complete shutdown of the unit and environmental contamination.	(3)Review the selection of construction materials; review mechanical design.

Table 14 – Worksheet Referring to nodes 9, 11 and 13.

Systems/Subsystems 04, 05 and 06: *Pump around system*		Parameters: Flow and pressure		Nodes 09, 11 and 13: Withdrawal pumps and pipes	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
9, 11 and 13	Flow	More, Less, None	(1)Steam flow control valve or control system failure.	(1) Reduced the liquid level in the dish and reduced the efficiency in phase separation.	(1) Select valves and/or control system in which a correct control tuning occurs
			(2) Leaks in the heat exchange tubes caused by fatigue or corrosion or in the pumps; Failure of flow control valves	(2) Possibility of fires in the event of ruptures, with loss of material or personnel; environmental contamination.	(2) Select valves and/or control system in which a correct control tuning occurs.
			(3) Failure to supply power to the pump; Loss of pump caused by corrosion; Rupture of pipes caused by corrosion.	(3) Possibility of fires and explosions; complete shutdown of the unit and environmental contamination.	(3) Design auxiliary system for power supply; Review the chemical compatibility of materials and verify piping design
	Pressure	Less	(2) Loss of pump efficiency due to corrosion	(2) Reduction of head height.	(2) Review the selection of construction materials; review mechanical design.

As observed in Tables 14 and 15, the results were generalized to three subsystems (04 to 06) and six study nodes (09 to 14). This is explained by the fact that the subsystems (pump around) and the study nodes have operational similarity, even though they do not have the same operating intentions, as shown in Figure 1.

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Table 15 – Worksheet referring to nodes 10, 12 and 14.

Systems/Subsystems 04, 05 and 06: *Pumpsaround System*		Parameters: Flow and pressure		Nodes 10, 12 and 14: Cooling systems	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
10,12 and 14	Flow	(1)More; (2)Less; (3)No	(1) Steam flow control valve or control system failure.	(1) Reduction of the temperature in the return plate, reducing the amount of steam by increasing condensation and impairing fractionation.	(1) Select valves and/or control system in which a tuning of the control occurs correctly.
			(2) Leaking exchanger shell; leaks in cooling water pipes; leaks between tubes and exchanger shell; Failure of flow control valves (over-closing) and/or control systems.	(2) Possibilities of fires and explosions; Overheating of the return current; plant shutdown.	(2) Review the selection of construction materials; review mechanical design and control loop and its instrumentation.
			(3) Obstruction of the exchanger hull caused by saline scale; Obstruction in the tubes by coke deposit; and damage from leaks in the pipes due to mechanical fatigue	(3) Possibility of fires and explosions with loss of material and personnel; environmental contamination and plant shutdown.	(3) Control the salinity of cooling water; review the selection of construction materials and mechanical design.
	Pressure	(2)Less	(2) Saline fouling in condenser hull with pressure drop elevation.	(2) The cooling fluid (water) will have difficulty draining into the shell of the exchanger.	(2) Control the salinity of the cooling water and perform a HAZOP study on the pumping system.

And, the verification of the evaluation points makes it possible to analyze the flow in which the control element, valves, is responsible for a large part of the verified causes. And, leakage factors caused by failure in the primary treatment system are reported in the recirculation in the separation plates. And yet, the safety of the unit may have serious consequences with risks to the operator and the environment around it.

In Table 16, the temperature and liquid level in the operation of the reboiler are already controlled by the steam flow and inlet and outlet flows, so it was not necessary to discuss the influence of these variables.

The steam to be used for heating in the reboiler is saturated steam, at a temperature above that required for the hydrocarbon steam stream entering the *stripper*. The analysis of this temperature of the heating steam is also not necessary, due to its saturation condition, since its pressure already determines its temperature.

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Table 16 – Worksheet Referring to node 15.

System/Subsystem 07: *Side Stripper* 01		Parameters: Flow and pressure		Node 15: Side *stripper* reboiler 01	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
15	Flow	(1)More, (2)Less, (3)None	(1) Failure of the steam flow and reboiler level control valves (over-opening) and/or the control systems.	(1) Losses for fractionation; Rupture of pipes due to thermal fatigue.	(1) Select valves and/or control system in which a tuning of the control occurs correctly.
			(2) Leaks in the reboiler tubing or shell; Failure of the steam flow control valves or control system.	(2) Possibilities of fires and explosions; failure in the stripper system and inadequate fractionation of the fluid; Flooding of liquid in the equipment.	(2) Review the selection of construction materials; review mechanical design and tuning of plant control.
			(3) Problems in the steam generation system (Boilers); Hull and pipe rupture; Level and flow valve failures.	(3) Possibility of fires and explosions; complete shutdown of the unit and environmental contamination.	(3) Conduct a HAZOP study on the boilers; review the selection of mechanical material; review mechanical design.
	Pressure	(1)More, (2)Less	(1) Problems in the steam generation system due to pressure control in the boilers.	(1) Excess pressure may cause ruptures in the pipes.	(1) Perform a HAZOP study on the steam generation system (Boilers).
			(2) Problems in the steam generation system.	(2) Insufficient pressure for the stripper process and fractionation outside the specified in the project	(2) Conduct a HAZOP study on the steam generation system (Boilers).

The node evaluated in the study in Table 17 corresponds to the *Stripper system.* In this evaluation the united change of the observations of node 15 is only the level to be controlled. In this evaluation, as well as in others, the possibility of flooding of the liquid and vapor contact system (Stripper), fires and failure in the flow of material is observed. And, as adjustments, the mesh must be controlled, avoiding leaks due to lack of chemical compatibility of the materials and mechanical design.

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Table 17 – Worksheet Referring to node 16.

System/Subsystem 07: *Side Stripper* 01		Parameters: Flow, pressure and level		No 16: *Bomba at* Stripper	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
16	Flow	(1)More, (2)Less, (3)None	(1) Flow control valve failure in side withdrawal or control system.	(1) The increase of the liquid flow rate to the column, which if not controlled by the level control system, will cause the flooding of the *stripper*.	(1) Select a properly designed control valve; Review the tuning of controllers
			(2) Leaks in the pipes, pump or strippper; Failure of the flow control valve of the side withdrawal.	(2) Possibilities of fires and explosions; environmental contamination; Reduction of liquid and vapor contact.	(2) Review chemical compatibility of construction materials; verify mechanical design; Select a suitable valve and review the tuning of controllers
			(3) Failure to supply power to the pump; Loss of pump caused by corrosion; Rupture of pipes caused by corrosion.	(3) Possibilities of fires and explosions with material and human losses; environmental contamination and plant shutdown.	(3) Design auxiliary system for power supply; Review the chemical compatibility of materials and verify piping design.
	Pressure	(2)Less	(2) Loss of head on the strippers caused by coke deposition; loss of pump efficiency.	(2) Reduction of liquid and vapor contact; Reduction of liquid flow due to low pressures.	(2) Review the design and referential flow; review the selection of materials chemically compatible with fluids.
	Level	(1)More; (2)Less	(1) Level control system failure (including sensors).	(1) Excess liquid at the bottom of the tower causing flooding	(1) Review the level sensors and controllers.
			(2) Level control system failure (including sensors).	(2)Risk of cavitation in the pumping system	(2) Review the control loop and controller tuning

Similar to *pumpsarounds*, the last two side *strippers* have similar operational aspects, with similar objectives. Therefore, the results in Table 18 refer to *strippers* 02 and 03.

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Table 18 – Worksheet referring to study nodes 17 to 20.

Systems/Subsystems 08 and 09: *Side Strippers* 02 and 03		Parameters: Flow, pressure, temperature and level		Nodes 17 to 20: *Strippers* and pumps	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
17 to 20	Flow	(1)More, (2)Less, (3)None	(1) Failure of the side outlet flow control valve or control system. Steam flow control valve failure for the stripper.	(1) Flooding of the stripper caused by the increase of liquid flow rate and the excess steam will cause drag of heavy components to the top.	(1) Select valves and/or control system in which a tuning of the control occurs correctly.
			(2) Leaks in the pipes, pump or stripper; Control valve failure, side withdrawal, or control system.	(2)Possibility of fires or explosions; Environmental contamination; Reduction of liquid in liquid contact and steam causing problems in fraction separation	(2)Review the selection of construction materials; Verify mechanical design; Review automation and instrumentation design.
			(3)Failure in the power supply system for the pump; Loss of the pump due to corrosion; Obstruction of sections of the pipe; Control valve failure	(3)Possibility of fires and explosions; complete shutdown of the unit and environmental contamination.	(3) Design auxiliary system to supply power to the pumps; Remove the bun; Review the selection of construction materials; Review mechanical design; Review valve control system.
	Pressure	(1)More; (2)Less	(1)Problems in the steam generation system due to pressure control in the boilers.	(1)Rupture in the steam transport pipes with the possibility of leaks.	(1)Perform a HAZOP study on the steam generation system (Boilers).
			(2)High pressure loss on the stripper plates due to coke deposition on the valves; Loss of efficiency in pumps due to corrosion; Problems in the steam generation system.	(2) Difficulties in flowing fluids through the stripper with reduced liquid and vapor contact; Reduction of hydrocarbon vaporization.	(2) Selection of valve materials that do not suffer corrosion by coke; review the chemical compatibility of materials; Perform a HAZOP analysis on the boilers.
	Temperature	(1)More (2)Less	(1)Problems in the steam generation system due to pressure control in the boilers.	(1)Excessive vaporization of liquid and increase of heavy fractions with poor phase separation.	(1)Perform a HAZOP study on the steam generation system (Boilers).
			(2)Problems in the steam generation system caused by the temperature control loop in the boilers.	(2) Lower vaporization rate of lighter components.	(2)Perform a HAZOP study on the steam generation system (Boilers).
	Level	(1)More (2) Less	(1) Failure of the level control system or instrumentation used.	(1)Excess liquid in the *stripper* which may cause flooding in the separation equipment.	(1) Review the tuning of control and instrumentation used.
			(2)Failure in the level control system or instrumentation used.	(2)Reduction of the liquid level in the *stripper* with the occurrence of cavitation problems in the pump	(2)Review the tuning of control and instrumentation used

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The main unit operation of the refining unit is the distillation column (Table 19). The unit may suffer from material flow problems in and out. In the case of leaks, pipe rupture may occur due to the possibility of fires. The measures to be taken involve the mechanical designs and the chemical compatibility of the materials. And, for the column, the temperature was evaluated in the steam system for heating. The increase in pressure at the bottom could occur in two ways: either by overheating due to the increase in the temperature of the heating steam, or by increasing the pressure of the *stripping steam*. In both cases, an excessive increase in pressure could cause ruptures in the construction material of the column, with the possibility of accidents, and total shutdown of the unit and/or refinery.

Table 19 – Worksheet referring to study node 21.

Systems/Subsystem: Distillation Column		Parameters: Flow, pressure and level		Or 21: Coluna atmosférica	
Knot	Variables	Guide Words	Cause(s)	Consequence(s)	Providencia (s)
16	Flow	(2)Less, (3)None	2)Leaks in the pipes or pump.	(2) Possibility of fires or explosions; Environmental contamination.	(2)Review the selection of construction materials; Check mechanical design.
			(3) Pipe obstruction by coke; Valve clogging on any liquid contact plate and value; Failure in the power supply system for the pumps; Embrittlement of mechanical material.	(3)Possibility of fires and explosions; complete shutdown of the unit and environmental contamination.	(3) Design the piping so that there is no coke deposition; Design auxiliary system for energy supply; Review mechanical design and inspect welds.
	Pressure	(2)Less	(2)High loss in the column plates due to obstruction due to coke deposition; Loss of efficiency in the pump caused by corrosion.	(2)Difficulties in steam flow reducing liquid and steam contact; Reduced liquid runoff due to low pump efficiency	(2)Review mechanical design and selection of construction materials.
	Level	(1)More; (2)Less	(1) Level control system failure (including sensors).	(1) Excess liquid at the bottom of the tower causing flooding	(1) Review the level sensors and controllers.
			(2) Level control system failure (including sensors).	(2)Risk of cavitation in the pumping system	(2) Review the control loop and controller tuning

The distillation process, as approached for the study of petroleum, can, according to F.A.S. MOTA *et al,* (2025), be incorporated into a distillation system of fractions that have separation ranges that require process evaluations and automation. Thus, a control strategy that involves separation in plates, lateral separation for recirculation of non-condensables, can be used with the same configuration of these PFD. Thus, the surveys carried out by

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F.A.S. MOTA *et al,* (2025), which evaluate aspects of ester distillation, can be approached with the same action used for petroleum distillation processes. Emphasizing that, the process presented by the researchers portrays studies of separation of ester bands that can be evaluated as a precursor of sustainable aviation fuels (SAFs).

CONCLUSION

The development of the work led to the elaboration of a study referring to a case proposed in the literature, which was modeled and simulated with the aid of the CHEMCAD ® software. And as observed in the results and discussions, it served as a delimitation of the operating intentions for the operation of the unit.

As demonstrated, the HAZOP analysis was able, through the use of guide words, to identify the possible operational risks arising from deviations in the operating intentions, such as the possibility of fires, explosions, environmental contamination and its consequences. It was possible to identify the risks that are associated with the selection of materials, the mechanical design of the equipment and the specifications of the accessories.

In addition to the risks, it was possible to identify deviations that are related to the loss of production of the unit due to its stoppage, loss of production of a specific product (fraction or lateral withdrawal) and the non-proper functioning of a given equipment. Regarding this last topic, the reduction in the efficiency of the pumps, reduction of liquid/vapor contact, flooding of equipment (of the atmospheric column, strippers and/or the three-phase separator) and the reboiler of the lateral stripper 01, failure of valves and/or control systems were the main problems verified by these possible failures. Mechanical failures that may occur in the unit are in many cases due to chemical incompatibility between the mechanical material and the products that the system processes. As a result, the length of construction standards and mechanical designs that follow certain standards are extremely important for the correct functioning of the system.

After evaluations carried out in studies carried out by F.A.S. MOTA *et al,* (2025), it is understood that the studies carried out for distillation towers for petroleum can, after mass flow and volumetric adjustments, be used for ester obtaining systems, in this way, the actions carried out in this development can be used as a scientific basis for new fuels of the future.

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