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Optimization of Energy Consumption of the Debutanizer Column, Using Genetic Algorithm

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Abstract: In the light of the emissions associated with fossil fuel combustion and their associated health and environmental impacts, natural gas is becoming increasingly attractive when compared with other fuels. The separation of natural gas liquids (NGL) in gas processing is energy-intensive, which is performed by a series of column among them the debutanizer column. This latter is used to separates C4 cuts and lighter components from NGL, typically gasoline, requiring modeling and optimization to reduce energy consumption. This work presents a rigorous methodology for modeling and optimization energy consumption of debutanizer column. This methodology is to develop a statistical model that will be used to test the variation of the energy consumed by the process, depending on columns parameters that have a great influence on this consumption. An experimental design was implemented and the data required for modeling were obtained by numerical simulations studies of debutanizer column, basing on Peng-Robinson (PR) thermodynamic model. Simulation results were validated successfully and the resulting model will be operated, using a genetic algorithm. The genetic algorithm modeling allows us determining the optimal values of reflux ratio and pressure of column, which provide savings in energy consumption for NGL separation process.

Keywords: Energy consumption, Genetic algorithm, distillation column, NGL separation

Introduction

Throughout the world, oil and gas are fossil energy sources exploited until now in various industrial processes such as the manufacture of chemicals, sugar mills, cement factories, the phosphate industry and others. They are also used as fuel in combustion engines. This intense demand raises the problem of global warming, due to greenhouse gas emissions, on the one hand and on the other hand, the risk of exhaustion of oil and natural gas reserves. The use of renewable energy resources, such as solar energy, wind energy and biomass are not yet economically competitive solutions to replace fossil fuels, as they are under development. As a result, industrial processes still need to be optimized to minimize their energy consumption and increase their efficiency. Refineries are among the most energy-consuming industries and this consumption leads to high operating costs and significant greenhouse gas emissions, polluting the environment.

The separation of petroleum fractions or gases is carried out, mainly, using different unit operations based on distillation columns. These operations occupy an essential place in the entire manufacturing process for oil and gas products in particular, and often constitute a major part of the manufacturing cost. High energy consumption is one of the main characteristics of distillation. This consumption can reach 50% of the total energy required of a distillery and represents approximately 3% of global energy consumption (Tgarguifa et al., 2017, 2018). It is therefore necessary to optimize this unit and improve its performance, to have a more efficient and less energy-consuming separation process. The separation of liquid natural gases (LNG) is carried out by a series of three columns, called deethanizer, depropanizer and debutanizer, which requires large energy consumption (Mandis et

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al., 2022). The debutanizer is used to separate butane cuts (C4) and lighter components of LNG, generally gasoline (Chun & Kim, 2013). The most widely used separation technique is distillation, which is one of the most important separation units in the chemical and process industries (Jones, 2015). Its disadvantage is that its energy consumption accounts for more than 70% of the total energy consumption of the industry (Liu et al, 2017).

Many researchers have generally used different methods to optimize the energy consumption of the distillation column. Kiss et al. (2012) proposed energy-efficient distillation technologies, allowing the right choice to be made for a given separation task at the early stages of design. Practically, many methods are used to optimize the distillation column of certain mixtures containing butane. Osuolale and Zhang (2014) developed a neural network-based strategy for modeling and optimization of energy efficiency in the distillation column applied to different separation mixtures and in particular to that containing butane. Jung et al. (2012) sought to improve the energy efficiency of the LNG separation process, by testing various complex configurations such as double prefractionator arrangement, double wall separation column (DDWC) and agrawal arrangement. The comparison of these three configurations with the conventional method allowed them to recommend the DDWC integrating the debutanizer and the deisobutanizer. Response surface methodology (RSM) coupled with the Box-Behnken design technique was used to optimize the separation of a ternary mixture of normal C4-C6 paraffin from the split-wall column (Sangal et al, 2013). Based on the Petlyuk sequence and using a multi-objective genetic algorithm, Gutiérrez-Antonio and Briones-Ramírez (2009) developed a tool for optimizing distillation columns. This tool has been tested on different ternary mixtures; three of them contain butane and propane. From the results obtained, the authors concluded that the method can be generalized to optimize chemical and petrochemical installations.

Tavan et al. (2016) used the MSR and the desirability function to study the effects of temperature, operating pressure and feed stage on the deethanizer column relating to new modernized installations. This study shows that production capacity has been improved, using optimal parameters. Concerning the optimization of the debutanizer column, we distinguished the work which consists of examining the concept of internal heat integration (Jana, 2010). This method allowed an improvement in energy consumption, by developing a new configuration incorporating additional costs linked to the purchase of new equipment. This work aims optimize the debutanizer column and study the performance of the industrial process of a natural gas separation unit. To do this purpose, data available in the literature relating to an industrial liquefied gas separation unit were exploited (Luyben, 2013).

Industrial Process

Natural gas is a fossil fuel present naturally in gaseous form in the porous rocks of the subsoil. It is a mixture whose main constituent is methane (CH4) but we also find ethane, propane as well as butane. Liquid hydrocarbons recovered from LNG are generally separated by three columns (Figure 5.1). The deethanizer separates ethane from propane and heavier components. The depropanizer separates propane from butanes and heavier components. The debutanizer separates the butane from the residues from the previous column. It is the separation of completely miscible liquid mixtures based on the boiling point difference and volatility of the components in the mixture. However, the lightest products are obtained at the top of the column and the heaviest components remain at the bottom of the distillation column. We conventionally carry out a sequential distillation of C2 to C4, from gasoline (Gasoline C5+), followed by the distillation of iC4, from nC4 (James, 2009). Figure 5.1 shows the three separation columns each equipped with a partial condenser and a reboiler. Based on an example of an industrial LNG separation process (Luyben, 2013), the operation of these three units is described and their operating conditions are grouped together in table 5.1.

Deethanizer

The charge for the first column of the process, derived from the demethanizer, is composed of traces of C1, small quantities of hydrocarbons of type C2, C3, C4 and C5+. This charge feeds the deethanizer column, on stage 15, minimizing the charge of the refrigerated condenser. This 1.23 m diameter column is made up of 31 stages operating at 21 bar to be well under the critical pressure of ethane which is 48 bar. At this pressure, the reflux rate temperature is 264 K, requiring cooling to 1.734 MW. The base of the column is at 363 K, so a low temperature heat source is required (2.108 MW). The C2/C3 separation is not difficult. The design specifications are 1 mol% C3 in the distillate and 0.34 mol% C2 in the bottoms. The required reflux rate is 1.258. The purity of the ethane product is 97.06%.

Depropanizer

The second column of the process is the depropanizer made up of 51 stages. The residual current from the dethanizer feeds the column at stage 24, which minimizes the use of the reboiler. This column operates at 17 bar, to reach a reflux temperature equal to 322 K. For cooling the condenser, water is used. The depropanizer column is a distillation column intended to separate propane from other components depending on the volatility of the substances. The composition of the distillation and bottoms products also depends on the feed composition introduced into the feed tray. The design specifications are 0.6 mol% C4 (sum of iC4 and nC4) in the distillate and 0.1 mol% of C3 in the funds. The required reflux ratio is 2.114 and the reboiler capacity is 1.656 MW of low pressure steam.

Debutanizer

The debutanizer is the main column used to separate butane from LNG containing C3 to C7 hydrocarbons (Luyben. 2013). This column is equipped with 30 stages, a condenser and a reboiler. The feed to the column derived from the depropanizer is composed of traces of C3, quantities of the hydrocarbon type, C4 and C5 +. This mixture feeds the debutanizer column with a total molar flow rate equal to 142.4 k mol/h, at stage 16, which minimizes the reboiler's tasks. The separation in the debutanizer is carried out between butane and gasoline with a reflux rate of 2.2 at 322 K. At the top of this column, butane (iC4 / nC4) is obtained at 7.1 atm and at the bottom a gasoline cut containing hydrocarbon chains, type C5+, is obtained. Subsequently, the downstream deisobutanizer column separates isobutane (iC4) from normal butane (nC4), due to the lower volatility of iC4/nC4 (Ould Brahim & Abderafi, 2021).

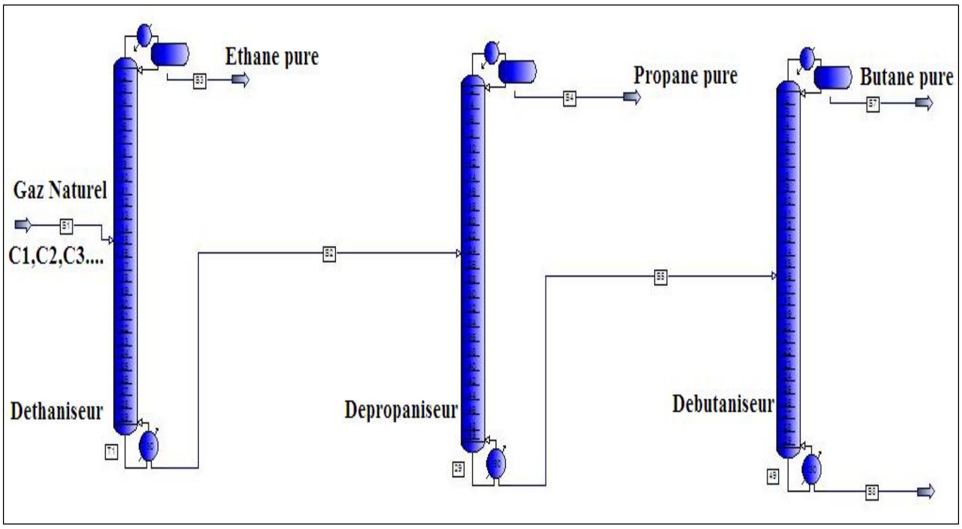

Figure 1. Diagram relating to the LNG separation process

Table 1. Operating conditions of the LNG separation process (Luyben, 2013)

Component	Alimentation	Deetahnizer	Depropanizer	Debutanizer
Methane	0.0096	0.0196		
Ethane	0.4779	0.9706	0.0066	
Propane	0.2613	0.0097	0.9875	0.0018
i-Butane	0.0664		0.0057	0.4605
n-Butane	0.0757		0.0002	0.5354
i-Pentane	0.0379			0.002
n-Pentane	0.0287			0.0002
Hexane	0.0287			
Hepthane	0.0139			
F (kg/h)	24487.096			
T (°C)	35.05			
P (bar)	25.1			
Pureté		0.9706	0.9875	0.9959
Q_R(MW)		2.20	1.60	1.02
Q_c(MW)		1.80	1.60	1.30

Method

Sensitivity Analysis

Based on the literature, the main factors which influence the distillation process and which can potentially be modified by the operator are the feed rate, reflux rate and column pressure (Jobson, 2014). Concerning the first parameter, for a separation column to operate properly, good contact must be maintained between the liquid and the vapor at each plate of the column. At low flow rates, there will be insufficient liquid on the trays or liquid will pass through perforations in the tray. At too high a flow rate, the space between the plates will be filled with liquid which causes clogging of the column. In both cases, the separation efficiency will be reduced or even interrupted. However, the effect of the pressure at the top of the column and the reflux rate on the thermodynamic efficiency were tested. To perform the LNG separation column simulation, all column operating variables are kept fixed except reflux rate and pressure, allowing their effects on energy consumption to be tested of the reboiler and the condenser, as well as on the purity. Operating parameters vary depending on the separation unit. In our previous work (Ould Brahim & Abderafi, 2016), different pressure values, generally applied in refineries, were tested. For the dethanizer, the pressure was varied from 16 to 23 atm and for the depropanizer, the pressure was varied from 14 to 19 bar. Optimal values are obtained by sensitivity analysis.
In this study, the same procedure described was followed, for the choice of intervals. We sought to find the values which make it possible to obtain more or less a balance between the separation efficiency and the energy requirements of the column. Therefore, the reflux rate was varied between 1.1 and 2.53 and the pressure between 5.3 and 8.23 atm. These operating variables do not have the same dimensions, which makes it difficult to compare their coefficients. Normalized (or coded) values are used; Table 2 shows the coded variables for reflux rate and pressure. This method of coding can increase the precision of the models in order to obtain homogeneous equations and simple calculation procedures. Note, that the statistical models can only be used within the ranges of operating variables used; no extrapolation is permitted. The central composite plane was chosen, modifications in this area consist of choosing the axial values on the faces and defining only one focal point, because all variables are deterministic in the case of digital experiment design. In this case, nine experiments are generated by the experimental design.

Table 2. Variables codées, pour le taux de reflux et lapression

X_i	Code X_i	-1	0	1
Taux de reflux (RR)	X_{RR}	1.1	1.819	2.53
P(atm)	X_P	5.3	6.765	8.23

Genetic Algorithm

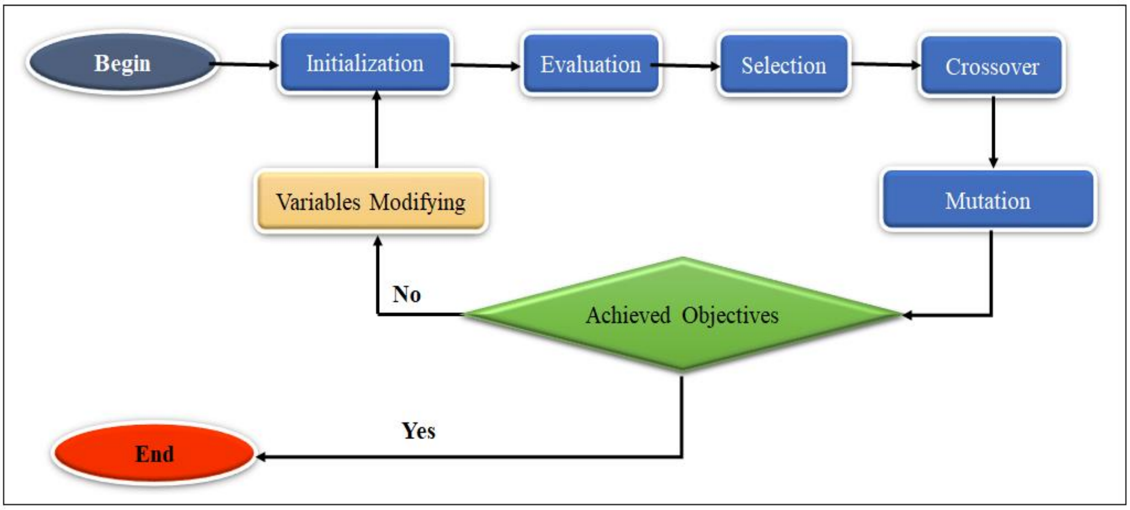

Figure 2. Genetic algorithm procedure

The genetic algorithm is based primarily on perceptions of natural evolution and the biological principles of natural selection (Alam et al., 2020). It is one of the simple and easy-to-use optimization methods that has allowed them to be applied in several engineering fields. To achieve the objective of the studied system, GA manages the problem by following different steps efficiently (Figure 2). The calculation of the genetic algorithm begins by initializing the independent variables with random values, Initially, a population, which consists of a certain number of individuals, is generated randomly within the lower and upper bounds of the decision variables (constraints). Then, the evaluation is carried out to ensure the availability of a solution. Furthermore, three evolution operators in genetic algorithms are applied. The first is selection which involves choosing the individuals best suited to the problem, followed by crossover to ensure the reproduction of the particularities of the chosen individuals and finally, mutation which is a random alteration of the particularities of an individual. If the objective is achieved, the results are considered; otherwise, the reset is performed with other variables and the calculation is restarted from the beginning, until convergence (Lambora et al., 2019). The optimization problem studied consists of minimizing the amount of heat from the condenser and reboiler as a function of the reflux rate and pressure at the head of the debutanizer column, using the optimization technique based on the algorithm genetic.

Model Simulation and Procedure

The set of equations that govern the operation of the distillation column is obtained basing on the equations of mass and energy balances and equilibrium conditions to be fulfilled by every stage of the process (Tgarguifa et al., 2017). Each stage, receives a diet feed, a fluid flow from the upper stage and a steam flow of the lower tray, a liquid extraction, a steam extraction and a heat input can be considered. The fugacity coefficient, φ_i, is obtained by a thermodynamic model like an equation of state (EOS). Among the many cubic EOS of Van der Waals type currently available, the equation proposed by Peng and Robinson is widely used due to its simplicity and flexibility, for hydrocarbons fractions (Peng & Robinson, 1976).

Following the numerical experimental plan, the calculation of the heating powers of the condenser and the reboiler as well as the purity was carried out, using the Pro II simulation software. This calculation was carried out by simulation of the debutanizer column, choosing the model descibed above. The data on the LNG separation feed conditions necessary for this simulation were used.

Results and Discussion

Simulation Model Validation

Firstly, the data in Table 1 are used to test the accuracy of the simulation model for a distillation column. The thermodynamic model which is the Penge-Robinson equation of state was chosen, for the prediction of the process properties, using the Pro II process simulation software. The accuracy of the model was tested by comparing the predicted values of reboiler and condenser heat quantity, and product purity, to experimental data, for the three columns studied. The calculated results are compared by calculating the relative error, using the following equation:

$$E(\%) = \frac{|V_e - V_c|}{V_e} \times 100 \tag{5.1}$$

Where, V_c and V_e are the calculated values and experimental values, respectively. The results obtained are grouped in table 3. This table shows comparison between calculated and experimental values. This comparison allows us to note that the results are satisfactory, if we consider the experimental error. However, the model used is reliable and can be used to conduct numerical simulation and for process optimization.

Table 3. Comparison between calculated and experimental values

	Déethanizeur			Dépropanizeur			Débutaniseur		
	V_e	V_c	E (%)	V_e	V_c	E(%)	V_e	V_c	E(%)
E_r (MW)	2,108	2,20	4,3	1,611	1,600	0,6	1,02	1,00	1,96
E_c (MW)	1,734	1,7	1,9	1,656	1,600	3	1,301	1,30	0,08
Pureté	0,970	0,974	0,3	0,987	0,995	7	0,9959	0,9937	0,002
	Ethane			Propane			Butane		

Debutanizer Optimization by GA

The GA method described above was followed to optimize the responses and exactly determine the optimal values with their coordinates. Using MATLAB software, the simulation data obtained were used with the GA. The reflux rate and the pressure at the top of the column were used as research variables, to minimize the energy consumption of the condenser and reboiler and taking into account the purity of the butane, as a constraint equal to 0.99. At the end of the execution of the algorithm (after 176 iterations), several solutions are obtained, with some redundant values which is due to the fact that the algorithm chooses an initial population randomly. Figure 3 shows the pareto front giving different solutions of optimal values relating to the energy consumption of condenser and reboiler obtained from GA. This figure shows that the minimum value of fitness is equal to 2.06 for reboiler and 2.263 for condenser. These values correspond to reflux rate of 1,105 and pressure of 5.301 atm; it allows to deduce that the minimum consumption of the condenser is equal to 0.984 MW and that of the reboiler is equal to 0.614 MW. These obtained optimal values are compared with their corresponding experimental values given in table 1 for debutanizer. This comparison clearly shows a reduction in energy consumption of 39.8% for the reboiler and 24.31% for the condenser. The use of optimal variables allows a gain in total operating energy equal to 38.37%.

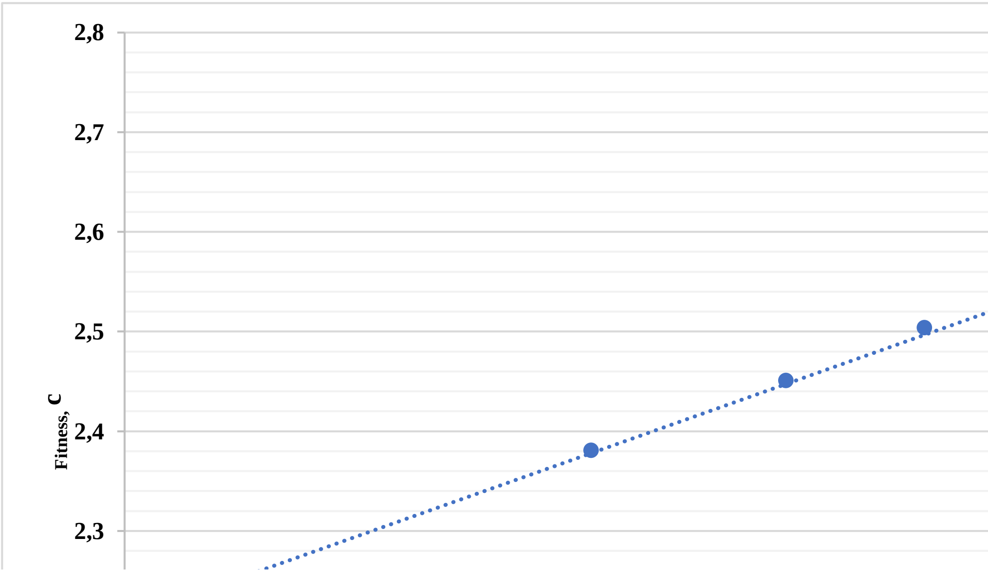

Figure 3. Pareto front obtained from GA.

Overall Process Performance

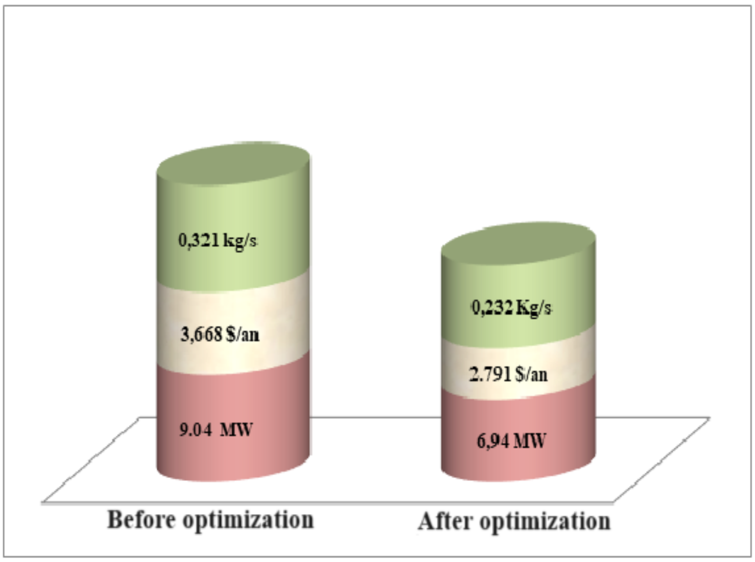

Figure 4. Comparison of the LNG separation process, before and after optimization

To evaluate the performance of the overall LNG separation process, the optimal values of pressure and reflux rate, obtained for the two columns of the Deethanizer and depropanizer in our previous work (Ould Brahim and Abderafi, 2016) and those of the debutanizer found in this study. These values were used to calculate the energy consumed, the operating cost and the concentrations of greenhouse gas emissions, for the studied LNG separation process. The energy cost used for steam production was \$0.028/kWh; this cost was estimated based on the average price of industrial fuel, which corresponds to \$300/tonne in September 2016, according to the International Energy Agency. The electricity cost used in the calculation was \$0.0672/kWh, obtained from the US Energy Information Administration in October 2016. The results obtained from these parameters are compared to those of the process before optimization (Figure 4). This comparison shows us that the quantity of total energy consumed was reduced by 23.26%, the operating cost by 23.91% and CO2 emissions by 27.73%. These results allow us to conclude on the performance of the optimized LNG process.

Conclusion

In this work, particular attention was paid to the debutanizer of the NGL separation unit. Its optimization was successfully carried out using Genetic Algorithm, by testing the effect of variation in pressure and reflux rate on the energy consumption of the condenser and reboiler, by simulation. The results showed that the industrial process is sensitive to the operating conditions studied and particularly the reflux rate has a significant effect on the energy consumption of the distillation column. Then, the performance of the optimized NGL separation process showed a reduction in the amount of total energy consumed, operating cost and greenhouse gas emissions by 23.26%, 23.91% and 27.73%, respectively. The evaluation results showed us a reduction in energy consumption which is accompanied by a reduction in operating costs and greenhouse gas emissions.

Recommendations

The performance of the industrial liquefied gas separation process can be further improved if renewable energies are exploited to minimize their energy consumption and increase their efficiency. For this, it is recommended to carry out a technico-economic study, to have a separation process that is more efficient, less energy-consuming, respectful of the environment and low-cost production.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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