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**EVALUATION OF ENERGY CONSUMPTION TO PRODUCE METHANOL  
FROM CAPTURED CO<sub>2</sub>**

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**Abstract.** *One important concern of the modern society is to mitigate the climate change effects caused by increasing CO<sub>2</sub> emissions. A potential alternative is to convert recycled CO<sub>2</sub> into methanol, since it can be used as fuel diminishing the dependency of fossil fuels. The present study evaluates the energy consumption to produce methanol from recycled CO<sub>2</sub>. The CO<sub>2</sub> capture based on amine absorption and the CO<sub>2</sub> hydrogenation to methanol are modeled in Aspen Hysys and Aspen Plus, respectively, due to the availability of suited thermodynamic models. The methanol production plant shows an efficient energy integration so that no steam is required. On the other hand, the CO<sub>2</sub> capture plant still needs improvement to ensure the technical feasibility of the process. The total energy consumption of all compressors represents almost the total electricity demand of the plant (99.23%). The results show that the CO<sub>2</sub> capture consumes about 90% of the total energy consumed by the capture and conversion processes. For the given operational conditions, it is not technically feasible to produce methanol to be used as fuel because the resulting energy balance is negative, i.e., more energy is spent to produce methanol than is available by the fuel itself. Therefore, further improvements in the capture process are required.*

**Keywords:** *Mathematical model, CO<sub>2</sub> mitigation, Methanol production, Energy Integration and CO<sub>2</sub> capture*

## 1. INTRODUCTION

Global warming and the consequences of the greenhouse effect can be increasingly noticed by the world society, bringing unwanted effects to the entire population. The main greenhouse gases (GHG) emitted worldwide are CO<sub>2</sub> (82%), followed by CH<sub>4</sub> (11%), NO<sub>2</sub> (5%) and CFCs (2%, European Parliament, 2018). The energy industry is the sector that mostly contributes with the CO<sub>2</sub> emissions with 80% of global emissions (EDUCACLIMA, 2018). To address climate changes issues, it is mandatory develop alternatives to reduce CO<sub>2</sub> emissions. For that purpose, an industrial process can convert CO<sub>2</sub> into valuable products such as methanol via CO<sub>2</sub> hydrogenation. Methanol can be used as a fuel, is a platform for the chemical industry and a raw material for several industrial processes as biodiesel production, plastics manufacture, preparation of vitamins and hormones, among other applications (Cerqueira, 2018).

The methanol production through synthesis gas reforming is traditionally the main methanol-producing route at industrial scale worldwide. However, given the constant devaluation of emerging currencies, especially against the dollar, coupled with the increase in the price of synthesis gas, this route has lost competitiveness in some regions of the world. This opened a window of opportunities for further studies aiming at techno and economically more sustainable routes for methanol production (Spath and Dayton, 2003). The hydrogenation of CO<sub>2</sub> to produce methanol has been investigated by several authors (Van der Ham, 2012; Van Dal, 2012; Kiss, 2016; Abdelaziz, 2017; Zhang, 2017; Bonfim-Rocha, 2018) which address the system modeling and economic evaluation. Some studies show that the energy costs for capturing CO<sub>2</sub> and water electrolysis are higher than methanol production itself (Rivarolo et al, 2016; Rivera-Tinoco et al, 2016; Bellotti et, 2017; Bowker, 2019). The consumption of the CO<sub>2</sub> capturing plant represents about 12% and the electrolysis plant, about 80% (Belotti, 2017).

A relevant aspect of analysis for an industrial plant is the energy consumption, which allows ascertaining the equipment efficiency towards process improvement and costs minimization. In this sense, the present study aims to evaluate the energy consumption of a methanol production unit, adapting the model proposed by Van-Dal (2012) by adding the capture section in a more consistent way and evaluating the potential energy bottlenecks that may make the system technically unfeasible. The energetic analysis allows to identify the main consumers of electrical energy, as motors for pumping and compression, and of thermal energy, which translates into the consumption of utilities, such as cooling water (CW) and steam so as to identify the main energy demands of the system (Lazarini, 2016). An advantage of the model from Van-Dal (2012) is the excellent energy integration system. Energy integration is an industrial technique aimed at reusing thermal energy from process hot streams, which was previously underused. Due to this reuse, there is a decrease

in the energy consumption of utilities, such as boilers and cooling towers, consequently reducing pollutants emissions, effluents and, finally, operating costs. In other words, the energy integration applied to the production process results in both economic and sustainable benefits for the company (Lazarini, 2016).

## 2. METHODOLOGY

The methanol production plant is composed by a capture and a conversion section, illustrated in Figure 1 and Figure 2, respectively. The capture process is based on amine absorption which is the most used process for this purpose, as evidenced in Abdelaziz (2017) and Øi (2012). To model the CO<sub>2</sub> capture plant, the commercial simulator Aspen Hysys® was used due to the availability of the acid gas thermodynamic model, which was developed to model the removal of acid gases such as hydrogen sulfide, sulfur dioxide, mercaptans and carbon dioxide from process streams (Øi, 2012). The acid gas model was validated with experimental data obtained by NIST (National Institute of Standards and Technology) at 1 bar and between 15 to 205 °C, available at the software database. Initially, a flue gas stream (3.73 mol% of CO<sub>2</sub>, 6.71% of water and 89.56% of N<sub>2</sub>) is absorbed by monoethanolamine (MEA) in an absorption column (C-02). The flue gas stream enters C-02 at 40 °C and 1.01 bar and the stream with MEA (30% by mass of MEA and 70% in water) enters at 32 °C and 1.1 bar (Øi, 2012). The CO<sub>2</sub> absorbed is then pumped to a distillation column (C-03), which regenerates the solvent and separates CO<sub>2</sub>. The solvent regeneration is a highly energy demanding process because of the large loads in the column, which increases the reboiler duty, and the low temperature in the condenser, where most of the CO<sub>2</sub> is present. The solvent recovered (173.2 °C and 1.1 bar) at C-03, when recycled to the absorption column C-02, heats the feed stream of C-03. The CO<sub>2</sub> (13.82 °C and 1 bar) is sent to the methanol synthesis plant. The flue gas to be treated comes from a thermoelectric plant, notably a leading segment in carbon dioxide emissions, with 71.3 ton/h, so that the plant's capacity is 27 t/year of CO<sub>2</sub> (Artanto et al., 2012). The hydrogen is produced through water electrolysis driven by solar energy, then its energy consumption has not been described.

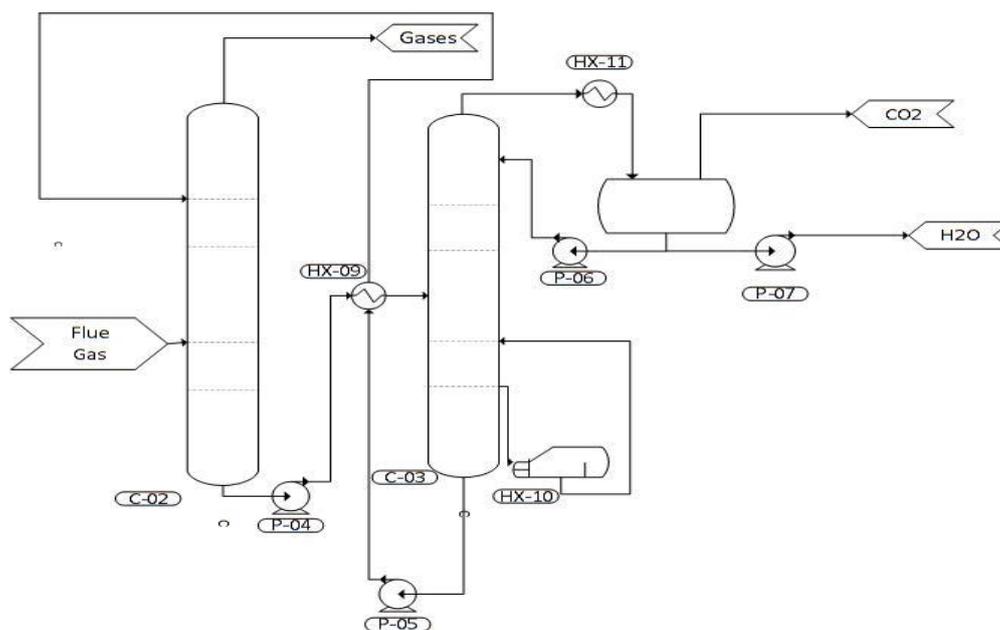


Figure 1. CO<sub>2</sub> capture plant.

After compression, the H<sub>2</sub> and CO<sub>2</sub> streams feed the reactor at 210°C and 78 bar. The remaining H<sub>2</sub> is removed in the flash drums (V-01 and V-02). At the distillation column (C-01) water and methanol are separated to recover methanol with 99% purity at the top. According to Van-Dal (2012), the kinetic model from Vanden Bussche and Froment (1996) with Langmuir-Hinshelwood-Hougen-Watson (LHHW) adsorption is considered. Regarding the thermodynamic model, the Soave Redlich-Kwong model with Huron-Vidal modification (SRK-HV) is the most frequently used to describe the vapor phase because it can predict the non-ideality of the vapor phase with non-condensable compounds such as H<sub>2</sub>. At pressures below 10 bar, non-random two-liquid model with Redlich-Kwong modifications (NRTL-RK) is indicated (Van Der Ham, 2012). All binary interaction parameters are available in the software database. The prediction of the vapor-liquid equilibrium of the mixture methanol-water was compared with experimental data from NIST at 1 bar and temperatures between 63.67°C and 99.17°C to validate the thermodynamic models. Given the availability of flue gas, 82500 t/year of methanol is produced for a CO<sub>2</sub>:H<sub>2</sub> feed ratio of 7.3 (Van-Dal, 2012).

The energy balance determines the main points of energy consumption and their impacts on the energetic analysis of the plant. The energetic integration takes place at three points in the process. The reactor (RX-01) product is split into two streams: one stream preheats the reactor load, the other provides the necessary heat to the reboiler and further heats the distillation column load. As a result of the energetic integration, there is no need of steam in synthesis section. Unlike the flowsheet proposed by Van-Dal (2012), the present flowsheet does not consider a cooler before the flash drum (V-01) to reduce the consumption of utilities such as cooling water (CW) without losing the product specification.

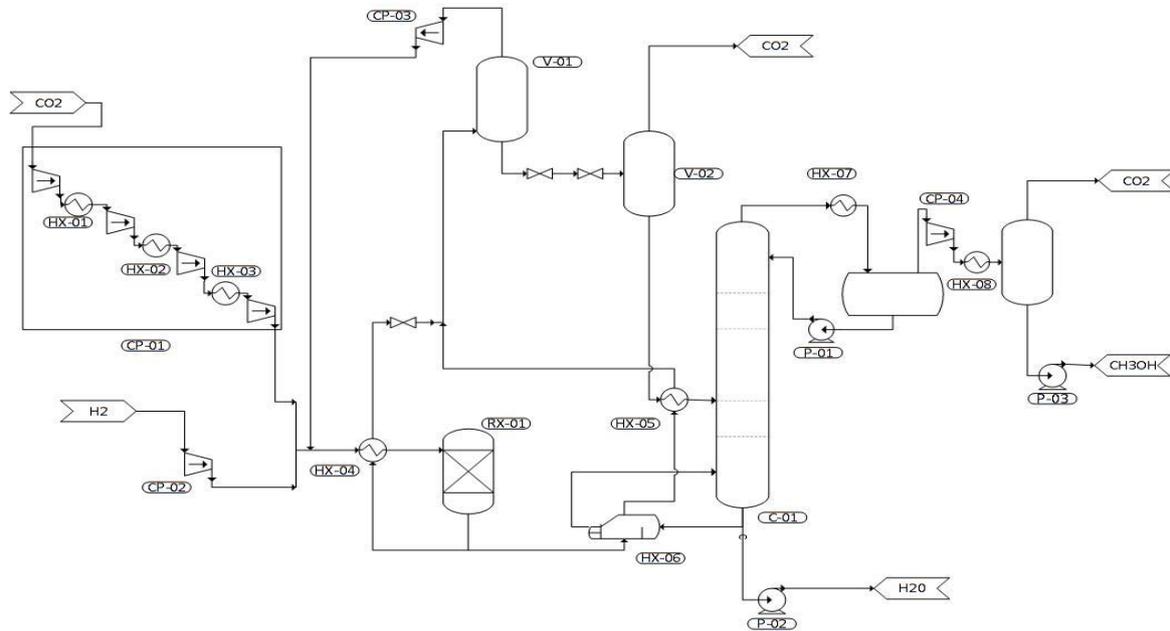


Figure 2. Methanol synthesis plant.

### 3. RESULTS AND DISCUSSION

Firstly, the thermodynamic models need to be validated. The acid gas was used to model the CO<sub>2</sub> capture with amine, while SRK-HV and NRTL-RK were used at the synthesis section. Vapor liquid Equilibrium (VLE) data for the mixture methanol-water were obtained from the NIST database in the simulator and compared with the model predictions in Figure 3. The model can represent the data reasonably well with relative deviations of 1.64% for SRK-HV and 0.36% for NRTL-RK, indicating that the models are valid. Figure 4 compare the VLE experimental data with the prediction by acid gas model. The relative deviation observed was 6.35%, confirming the validity of the model.

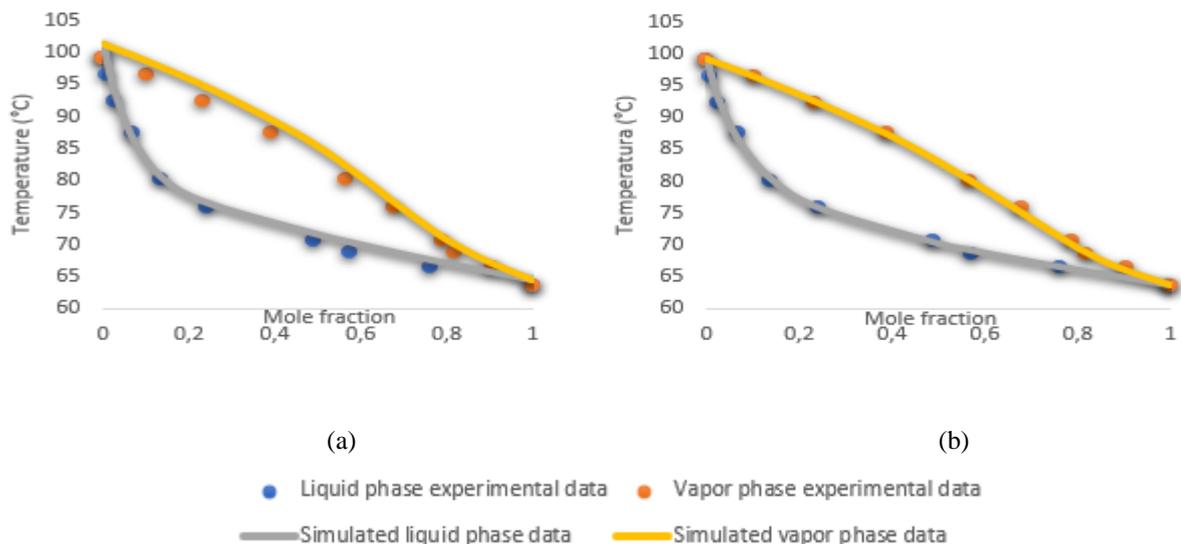


Figure 3. Thermodynamic model validation for the VLE of the methanol-water mixture at 1 bar: (a) SRK-HV and (b) NRTL-RK.

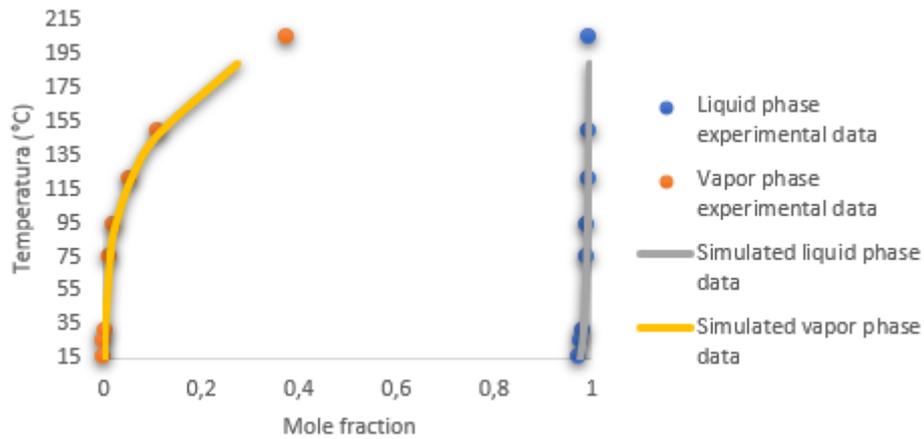


Figure 4. Thermodynamic model validation for the VLE of the water-CO<sub>2</sub> mixture at 1 bar: acid gas.

For the analysis of energy consumption, pumps, compressors and administrative facilities were considered and the results are shown in Table 1. The electricity each pump and compressor consume was ascertained from its head and power. Low power pumps are not so usual in industrial applications, then a minimum allowed value of 0.5 hp was adopted for P-02 and P-06. The pumps energy consumption is 97.98 kW, therefore does not represent such a relevant portion of the total energy consumption of the process (0.75%). Compressor CP-01 presented the higher energy consumption due to the higher flow processed by this equipment and because it is a multiple stages compressor to prevent exceeding the maximum allowed outlet temperature (200 °C) when using carbon steel. The total energy consumption of all compressors is 17176.30 kW, what represents almost the total electricity demand of the plant (99.23%). The remaining 0.01% refer to the lighting of administrative buildings and signage in the industrial area.

Table 1. Energy consumption of heat exchangers and pumps.

Equipment	Energy consumed (kW)
P-01	0,88
P-02	0,37
P-03	0,71
P-04	90,08
P-05	5,09
P-06	0,37
P-07	0,48
CP-01	14347,31
CP-02	2276,14
CP-03	464,72
CP-04	88,13

The thermal energy consumption from heat exchangers were evaluated and the results are summarized in Table 2. The thermal energy consumption translates into consumption of utilities such as cooling water and steam. Among the three exchangers with positive thermal charge, which would need a hot utility, the HX-04, HX-05, HX-06 and HX-09 do not consume any utility due to the fact that they are already energetically integrated. The steam flow saved with the integrations in both sections was approximately 807.27 t/h, which corresponds to the consumption of low-pressure steam that would be necessary if there was no energy integration. The HX-10, which is the reboiler of the stripping column C-03, is the only steam consumer in the process. The synthesis section does not consume steam. The remaining exchangers

demand a cold source of energy, supplied by cooling water. Total CW consumption is 27690.40 t/h. The removal of the exchanger before V-01, as discussed in Section 2, saved 450121.7 kW, which would correspond to 659.62 t/h of CW.

Table 2. Energy consumption of heat exchangers and consumption of utilities in the methanol plant.

Equipment	Thermal load (J/s)	Utility	Utility flow (t/h)
HX-01	-651287.48	Cooling water	40.07
HX-02	-852225.74	Cooling water	52.43
HX-03	-885411.85	Cooling water	54.47
HX-04	12156287.30	Energetically integrated	-
HX-05	5603897.57	Energetically integrated	-
HX-06	2387395.06	Energetically integrated	-
HX-07	-3654431.11	Cooling water	224.81
HX-08	-3244986.35	Cooling water	199.62
HX-09	62861111.11	Energetically integrated	-
HX-10	492411222.22	Steam	804.56
HX-11	-440833333.33	Cooling water	27118.93

In order to identify the energy bottlenecks of the plant, Figure 5 compares the amount of energy that each process unit consumes. The solvent regeneration at the CO<sub>2</sub> capture section consumes most of the process energy (90%), being, therefore, the main point of attention for the technical viability of the process. This is due to the fact that a large flow passes through the column, requiring a large load on the refrigerator and, as the top product is CO<sub>2</sub>, the top temperature is very low, requiring more load on the condenser HX-11. For this purpose, we investigated how the plant capacity influence the energy consumption of the plant. Table 3 illustrates this sensitivity analysis, where 100% capacity corresponds to the base case. The energy generated corresponds to the energy produced by methanol if all of its production is used as fuel. When the capacity is 60% of the base case, there is the most favorable energetic balance point for the system. Any case simulated indicate a potential for energy production greater than the total consumed, showing that the process might be technically unfeasible if methanol is used as fuel.

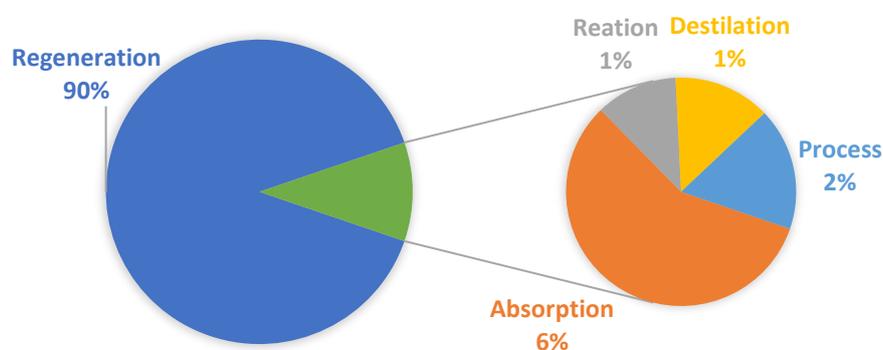


Figure 5. Energy consumption in the capture and synthesis steps for methanol production.

Table 3. Energy balance of the system.

Flow (kg/h)	Energy consumed (kWh)	Energy generated (kwh)	Energy Balance (kWh)
9417,81	4094388592,46	483287557,50	-3611101034,96
7534,25	3687654647,33	386630046,00	-3301024601,33
6027,40	3587373589,80	309304036,80	-3278069553,00
4821,92	3527174003,51	247443229,44	-3279730774,07
3857,53	3484316862,34	197954583,55	-3286362278,79

#### 4. CONCLUSIONS

We can then conclude that: the thermodynamic models adopted represented the system satisfactorily, however the results indicate that it is not technically possible to produce methanol as a fuel by capturing CO<sub>2</sub> from a flue gas stream due to the fact that the amount of energy consumed exceeds the amount of energy that would be generated. The regeneration process represents the largest energy consumption of the system, reaching 90% of the total consumption, requiring further studies aiming at its feasibility.

#### 5. ACKNOWLEDGEMENTS

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