EXERGY ANALYSIS OF A GAS COMPRESSION SYSTEM IN OFFSHORE OIL PLATFORMS

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Abstract. *Despite the recent decrease in oil price, the energetic matrix for the forthcoming decades still presents petroleum as the most relevant energy resource, with a significant price recovery expected for the following years. Environmental requirements tend to become stricter for all the industries, especially for energy companies. In this scenario, the rational use of natural resources and the energetic optimization play a key role for the Oil & Gas industry to assure a competitive edge. Among the analysis methods in use for assessing and improving the energetic efficiency, during last decades the Exergy Method has been highlighted as the most appropriated tool for these evaluations. This study performs exergy analysis in a typical process plant at a FPSO operating in the Brazilian shore waters, exploring the pre-salt layer. Special attention is given to the gas compression process plant, which has a* CO_2 *gas removal system by membranes. According to operational restrictions, the gas flow can be deviated from the* CO_2 *gas removal system, creating the operational modes. The operational mode A deviates all the gas from the* CO_2 *gas removal system, allowing just its re-injection into the reservoir. The mode B uses entirely the* CO_2 *removal system in a way that a maximum of gas exportation is possible. And the operational mode C treats partially the gas through the system, allowing partial exportation and re-injection of the gas. Scenarios related to the balance between exported and injected gas flows and its influence in the exergy balance are also presented. The influence of each operational mode and the scenarios in the exergy efficiency of the platform is verified, as well as at the specific exergy consumption,* CO_2 *emissions and emissions per unit of produced exergy. A rational efficiency range from 8.2 to 10.9% is verified, with operational mode A as the most eficcient; the process plant also presents specific exergy consumption varying from 645 to 760 kJ/m³ and specific* CO_2 *emissions from 7.8 to 9.6 kg/GJ, also with operational mode A as the most favorable one.*

Keywords: *exergy, exergy analysis, offshore platform, emissions.*

1. NOMENCLATURE

b	specific exergy	ORC	organic Rankine cycle
B	exergy	$\bar{R}$	universal gases constant
BS&W	base sediment and water	s	specific entropy
FPSO	floating, production, storage and offloading	SEC	specific exergy consumption
GOR	gas oil ratio	SE	specific emission
h	specific enthalpy	SG	specific gravity
HP	high pressure	T	temperature
IP	intermediate pressure	W	work
LHV	lower heating value	x	molar fraction
LP	low pressure		

1.1 Greek symbols

γ	activity coefficient	η	rational efficiency
φ	chem.exergy to net calorific value ratio	ε	Energy param. in a pot. energy function

1.2 Subscript symbols

b	boiling (ref.: temperature)	k	kinetic
ch	chemical	out	outlet
D	destruction	p	potential
i	i-th component in the mixture	ph	physical
in	inlet	pseudo	pseudo-component
j	j-th component in the mixture	0	refers to reference state

1.3 Superscript symbols

Q heat

2. INTRODUCTION

The exploration and production of oil and gas by offshore platforms is an energy intensive industry and the improvement of the process efficiency is decisive to keep this industry sustainable. From an economic point of view, better efficiency means less expense for producing the same amount of product; focusing in the environmental aspect, better efficiency can be seen as less impact generated to the environment for producing the required goods. In order to pursuit this continuous improvement of the process efficiency, an appropriated tool should be used to correct evaluate the process.

The exergy is the most suitable method to evaluate the thermal efficiency of processes, and is indicated as the most rational tool for complying with the ISO 50001 requirements (IPIECA, 2013). Recently, the number of articles regarding the use of exergy analysis at offshore platform has increased. The first study in this area was published by Oliveira Jr. and Van Hombeeck (1997) and pointed out the relevance of the pre-heating of petroleum at the global results of exergy. Voldsund et al. (2013) considered a real production day at a platform in the North Sea and pin-pointed the importance of anti-surge recycles at compression systems as a major contributor to exergy destruction; the compression recycling would be highlighted again in a study comparing four similar offshore platforms in the North Sea producing from different well fluids (Voldsund et al., 2014) and in another two studies which compared the effect of the lifetime of the platform at its efficiency (Nguyen et al., 2014a) (Nguyen et al, 2014b). The thermal load wasted by turbine exhaust gases is object of discussion by Nguyen et al. (2013); Bazzo and Kami (2015) presented the ORC as an alternative to use the thermal content of the exhaust gases before discharging them to the atmosphere. Aiming for reduction on greenhouse gases emission, Carranza Sánchez and Oliveira Junior (2015a) presented a CO_2 capture system applied in an offshore platform process plant. Carranza Sánchez and Oliveira Junior (2015b) analyzed the process object of this study in order to evaluate the influence of the different operational modes at the exergetic balance of the platform. Complementing the previous work, Carranza Sánchez and Oliveira Junior (2015c) applied energy and exergy criteria to evaluate and compare the performance of components and systems of the operational modes of the FPSO.

This study performs an exergy analysis in an oil & gas production plant installed at an offshore FPSO operating in ultra deepwaters and exploring hydrocarbons from reservoirs located at the pre-salt layer of the Santos basin, southeast of Brazil. The well fluids are characterized for high GOR and presence of the contaminant CO_2, that needs to be removed for properly use of the gas by onshore consumers. Unlike previous works, this paper studies other production scenarios according to market gas demand.

3. THEORETICAL BACKGROUND

3.1 Exergy

According to Kotas (1995), exergy is the most convenient and natural standard to measure the maximum useful work possible to be obtained and delivered to consumers by a system interacting with the environment as a reference state. In this case, the standard environment considered as reference state has the temperature equals to 298.15 K, pressure of 101.325 kPa, and standard chemical composition of gases and their partial pressures in the atmosphere (Szargut et al., 1988).

The exergy balance for a control volume in steady-state, steady flow condition may be expressed by means of Eq. (1) (Kotas, 1995):

$$\dot{B}_D = \sum_{in} \dot{B}_i - \sum_{out} \dot{B}_j + \sum \dot{B}^Q - \dot{W} \quad (1)$$

Disregarding magnetic, radioactive, electrical and superficial tension effects, the specific exergy of a stream can be presented as follows in Eq. (2):

$$b = b_k + b_p + b_{ph} + b_{ch} \quad (2)$$

For an oil & gas process plant, the kinetic and potential amounts are negligible and will not be considered. The specific physical and chemical exergies can be calculated according to Eq. (3) and Eq. (4).

$$b_{ph} = (h - h_0) - T_0 (s - s_0) \quad (3)$$

$$b_{ch} = \sum_i x_i b_{ch}^i + \overline{R} T_0 \sum_i x_i \ln \gamma_i x_i \quad {}_{ch} \tag{4}$$

The specific chemical exergy for several substances can be found in textbooks about exergy. For high carbon hydrocarbon families, these values are no longer directly available and must be calculated by correlations. Additionally, the petroleum assays data usually discriminate just the first cuts of the hydrocarbons, and from a certain point on they are grouped and represented as "C10+", "C15+" or "C20+", for example. The simulation of these groups in the software is made using the pseudo-components (Aspen Hysys, 2014). Equation (5) presents the basic formulation to calculate the specific chemical exergy for pseudo-components.

$$b_{ch,\,pseudo} = \varphi_{pseudo} \left(LHV\right)_{pseudo} \tag{5}$$

The terms at the right side of Eq. (5) are defined by Riazi (2011) according to Eq. (6) and Eq. (7) – the term ε in Eq. (6) is defined by Eq. (8).

$$\varphi_{pseudo} = 1.0406 + 0.0144 \cdot \left(8.7743 \cdot 10^{-10} \cdot \varepsilon \cdot T_b^{-0.98445} SG^{-18.2753}\right)^{-1} \tag{6}$$

$$\left(LHV\right)_{pseudo} = 55.5 - 14.4 \cdot SG \tag{7}$$

$$\varepsilon = \exp\left(7.176.10^{-3} \cdot T_b + 30.06242 \cdot SG - 7.35 \cdot 10^{-3} T_b \cdot SG\right) \tag{8}$$

3.1 Process performance parameters

In this work, the exergy performance has been assessed by three different parameters, plus an specific parameter referring to environmental impact.

The first parameter used to evaluate the exergy performance is the *exergy efficiency* or *rational efficiency*. It relates the total amount of useful exergy of the process per the total exergy of the fuel, as presented in Eq. (9):

$$\eta_b = \frac{\dot{B}_{useful}}{\dot{B}_{fuel}} \tag{9}$$

Another parameter that has been used in some other studies involving exergy analysis in offshore platform is the specific exergy consumption by volume. This parameter is important because it reveals how much exergy has been spent in order to generate each cubic meter of equivalent oil – see Eq. (10). The equivalent oil volume considers not just the oil produced to tanks but also the total amount of export gas, where 1 Sm³ of gas corresponds to $9.68 \cdot 10^{-4}$ m³ of oil.

$$SEC_{volume} = \frac{\dot{B}_{fuel}}{\dot{q}_{equiv.oil}} \tag{10}$$

The *CO_2 emissions* is the parameter strictly related to environmental aspect and basically shows the mass ratio of CO_2 being generated by the process and sent to the atmosphere.

However, the simple evaluation of emissions can lead to incorrect conclusions. The sustainability concept mentions that the environmental impact generated by a certain human activity must be evaluated according to the benefits it generates. A rational way of assess the sustainability level of a process would be relating the environmental impact per the benefit generated for society – in order to evaluate that, Eq. (11) presents the parameter *specific CO_2 emissions*.

$$SE_{CO_2} = \frac{\dot{m}_{CO2}}{\dot{B}_{useful}} \tag{11}$$

4. SYSTEM DESCRIPTION

The main purpose of an offshore production process is to separate the well fluid into three basic phases: water, oil and gas. At the end of the process, each phase must attend to pre-stablished requirements in order to receive a proper destination.

A simplified process flow diagram for the FPSO is presented in Fig. 1. The well fluids are received in the FPSO and the pressure is reduced to a desired level at the *manifold*. The first sub-system is the *primary separation* and it consists of a series of vessels that promotes the separation of water, oil and gas using gravitational and electrostatic principles. The outlet of this first system presents oil within the expected requirements (BS&W < 0.5%) and ready to be kept in the cargo tanks; the water separated from this sub-system still contain traces of oil in its composition, which will be removed afterwards in the *produced water* sub-system. At this point, the gas phase has contaminants and characteristics that still not comply with the necessary requirements in order to be properly destined, in a way that all the following sub-systems are necessary just to treat this phase (exception made to *fuel gas* and *electrical generation* sub-systems). The path of gas continues through the *vapor recovery unit*, which elevates the pressure of the LP and IP streams back to the HP stream level, in a manner that they all can be compressed by the *main compression* sub-system. The discharge of this compression sub-system delivers a gas with enough pressure to allow the treatment of this stream in the next three sub-systems. The first gas treatment sub-system is the *gas dehydration*, which is projected to remove 99% of the water contained in the gas stream (molecular sieves are used to adsorb the water). After that, the *dew point adjust* sub-system removes the heavy hydrocarbon cuts of the gas stream by a high pressure/temperature break through a valve (Joule-Thompson effect). These first two gas treatment sub-systems basically remove any traces of liquid from the gas stream, which is necessary to allow a proper use of the third and last gas treatment sub-system. The *CO_2 removal* sub-system uses membranes that segregates the CO_2 (the main gas contaminant) from the gas stream, and after that the permeate gas (with high CO_2 content) is directed to the *CO_2 compression* sub-system which elevates this stream pressure up to the *injection compression* suction pressure level; after that, this gas receives another increment of pressure up to the level it can be injected back into the reservoir. Downstream the CO_2 removal membranes, there is also a stream of treated gas (with low CO_2 content). This stream goes straight to *export compression* sub-system, which can lead either to the *fuel gas* and *electrical generation* sub-systems, or to the suction of the injection compressors, as well to the export gas header (which will deliver this product by a pipeline to the consumers onshore). The gas exported must comply with a maximum of 5.0% CO_2 molar content in the gas.

The power in order to run the equipment is supplied by 4 x 25MW gas turbines, which uses a part of the gas as fuel to produce the required work. Before being discharged to the atmosphere, part of the heat from the turbines exhaust gases is recovered at the waste heat recovery unit (WHRU), which uses this energy to heat up the petroleum upstream the primary separation sub-system (the separation is enhanced with a high temperature of the petroleum).

All these sub-systems presented at this section and illustrated by Fig. 1 comprise the control volume analyzed in this current study. The cooling medium is not explicit outlined, but is also considered in the balance, as well as the heating medium. The typical utilities sub-systems (instrument air, sewage treatment, fresh water generation, offloading, diesel treatment sub-systems, etc.) are not considered, as their influence in the exergy balance is not significant, as already highlighted by previous studies. Exception is made to the *water injection* sub-system, which pumps requires massive power to run, affecting the exergy balance – and for that reason this sub-system was included in the analysis.

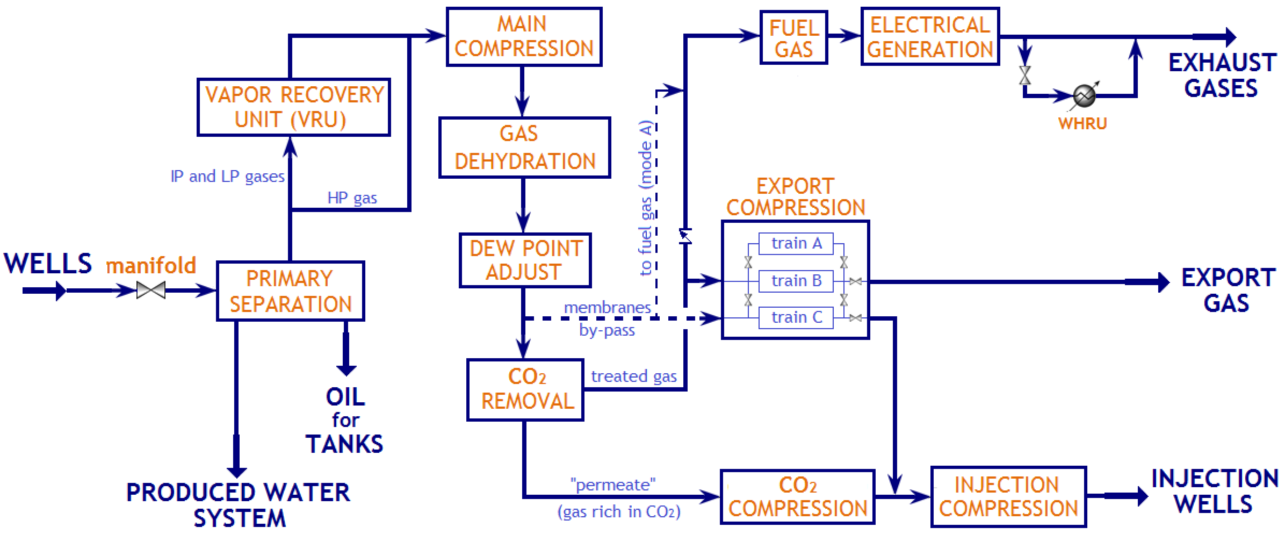

Figure 1. Process flow diagram of the FPSO production process in study.

4.1 Operation modes

The option for using or not the CO_2 removal membranes generates three operational modes. The operational mode A by-passes completely this sub-systems – see dotted line at Fig. 1 – in such way the gas can only be re-injected into the reservoir (as it is under specified in order to be exported). The operational mode B consists of fully alignment and treatment of the gas through the membranes. Finally, the operational mode C refers to a partial use of the membranes – in this mode, the by-passed gas is directed to a specific train at export compression sub-system, and the treated gas goes to the other two trains of this sub-system (this study considered the rate of 2,500,000 Sm³/d of gas aligned to the membranes for this operational mode C).

4.2 Production scenarios

The amount of export gas sent to consumers may vary according to the market demand. As the market cannot always absorb all the treated gas produced by the platform, there are moments when it is necessary to inject a higher amount of gas into the reservoir – generating a variation between the export and injection gas flow. In order to analyze the effect of this variation in the exergy balance, some production scenarios were created among the three operational modes, as described at Tab. 1.

Table 1. Production scenarios according to market gas demand.

	Gas export flow rate (x 10^6 Sm³/d)									
Operational modes	3.00	2.75	2.50	2.25	2.00	1.75	1.50	1.25	1.00	0.00
A										I
B	II	III	IV	V	VI	VII	VIII	IX	X	XI
C							XII	XIII	XIV	XV

Obviously, considering the operational mode A, there is just one feasible production scenario, and that would be zero gas export. For operational mode C, there are some no feasible scenarios due to lack of enough treated gas in order to comply with the demanded gas export flow. Steps of 0.25 MSm³/d were considered between each production scenario; except to the first export step, which presents a step of 1.00 MSm³/d due to a minimum export gas rate limitation inherent to this FPSO process plant.

5. SIMULATION

The simulation was done using the software Aspen Hysys® v.8.6 (Aspen Hysys, 2014) and the Peng-Robinson property package was used to characterize the properties (Peng, D-Y. and Robinson, D.B., 1976).

The well fluid considered composition reflects one of the petroleum blends found in the pre-salt layer of the Santos Basin (BG Group, 2015) and it was simulated according to the composition presented at Tab. 2.

Table 2. Well fluid composition.

Element	**C1**	**C2**	**C3**	**n-C4**	**i-C4**	**n-C5**	**i-C5**	**n-C6**	**n-C7**	**n-C8**	**n-C9**	**n-C10**
Molar %	51.48	7.10	4.89	1.18	0.90	0.86	0.59	1.13	1.65	2.11	1.70	1.56
Element	**n-C11**	**n-C12**	**n-C13**	**n-C14**	**n-C15**	**n-C16**	**n-C17**	**n-C18**	**n-C19**	**C20+[1]**	**CO2**	
Molar %	1.26	1.15	1.19	0.98	0.96	0.75	0.68	0.69	0.63	7.65	8.27	

[1]compound represents a pseudo-component.

Table 3 presents the main boundary conditions used for modeling the process at Aspen Hysys®. A basis model was built to simulate the FPSO production process with flexibility to alter some parameters when required, allowing the simulation of all the production scenarios. For all studied scenarios, the oil production and water injection were considered at maximum capacity.

The calculation of exergy variables is not within the logic of the software Aspen Hysys®, being necessary to create user variables in order to obtain the chemical and physical exergies of each stream (Abdollahi-Demneh et al., 2011).

Table 3. Boundary conditions for the Aspen Hysys® process simulation

Parameter	**Unit**	**Value**	**Parameter**	**Unit**	**Value**
FPSO oil production capacity	bbld	180,000	Export compression disch. pressure	kPa	25,000
FPSO gas production capacity	Sm³/d	6,000,000	Injection compression disch. pressure	kPa	49,500
FPSO gas export capacity	Sm³/d	3,000,000	CO_2 memb. min operat. gas flow rate	Sm³/d	1,250,000
Max.allowed CO_2 content at gas export	%	5.0	CO_2 mol.ratio treated/permeate streams	%	0.18-0.82
FPSO water injection capacity	Sm³/d	24,000	CO_2 membranes inlet pressure	kPa	5,300
Well pressure (ups.manifold)	kPa	2,900	CO_2 memb. permeate outlet pressure	kPa	400
Well temp. (ups.manifold)	°C	45	CO_2 memb. treated gas outlet pressure	kPa	4,750
Pressure dwns. manifold	kPa	2,300	Heat exchangers pressure drop	kPa	50

Oil heating temp (dwns. primary sep)	°C	90	Gas cooling temperature[1]	°C	40
HP stream (primary sep.)	kPa	2,000	Polytropic effic. - pumps and compr.	%	75
IP stream (primary sep.)	kPa	770	Water inj. Pump disch. pressure	kPa	25,000
LP stream (primary sep)	kPa	244	Heating medium closed circuit flow	kg/s	211.3
VRU 1st stage disch. pressure	kPa	770	Gas turbine exhaust gases temp.	°C	505
VRU 2nd stage disch. pressure	kPa	2,050	Heating medium return temp.	°C	100
Main compression disch. pressure	kPa	7,945	WHRU inlet heating medium pressure	kPa	1040
CO_2 compression disch. pressure	kPa	25,110			

[1]except for the coolers in the export compression systems, that cool the gas down to 50°C.

6. RESULTS AND DISCUSSION

Figure 2 presents the behavior for the exergy parameters according to each production scenario analyzed. Fig. 2a represents the rational efficiency; Fig. 2b, the specific exergy consumption among the production scenarios. The CO_2 emissions parameter is observed in Fig.2c, and in the Fig. 2d one can see the specific CO_2 emissions parameter.

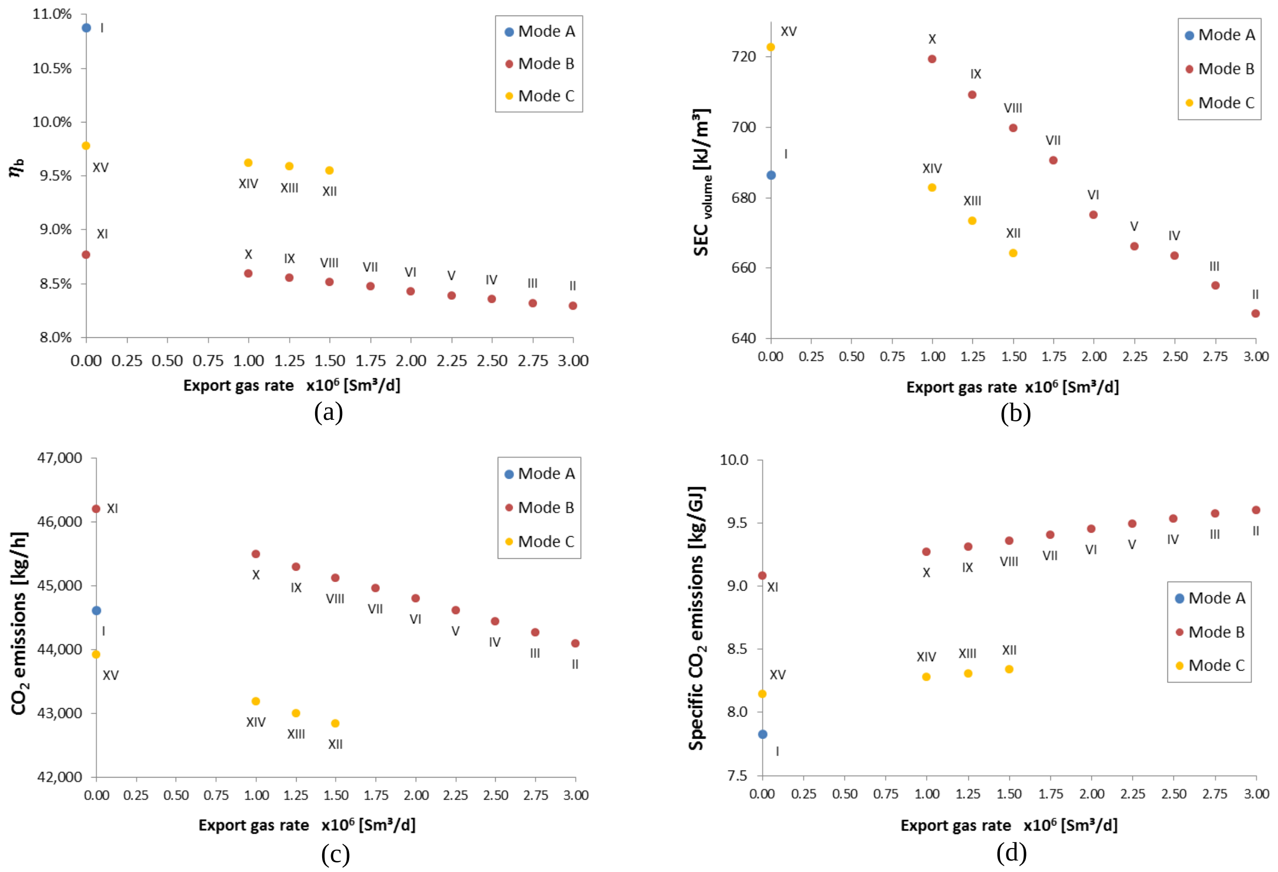

Figure 2. Exergy parameters (rational efficiency, specific exergy consumption per volume, CO_2 emissions and CO_2 emissions per produced exergy) results for each production scenario.

Overall, the exergy performance of the FPSO improves, as the CO_2 membranes are progressively by-passed – except for the parameter CO_2 emissions. That is observed by a clear tendency for each parameter when the different operational modes are considered.

The rational efficiency, for instance, has the higher results for mode A (scenario I), which considers the complete by-pass of the CO_2 removal membranes; and in the opposite side, the operational mode B (scenarios II to XI) presents the lower efficiencies. Important parameters to understand this behavior are the pressures (inlet and outlets) at the CO_2 membranes: as presented in Tab. 3, the pressure drop from inlet to permeate outlet stream at the membranes are significant, which incur in higher exergy destruction for that subsystem; additionally, in order to send this permeate gas to injection compression sub-system, a compression from 400 to 25,110 kPa is performed by CO_2 compression sub-system, which increases considerably the power demand of the FPSO production process, impacting in the total amount of fuel exergy consumption. Another aspect to be observed is that for the different production scenarios within the same operational mode, one may say that the rational efficiency decreases as the demanded export gas rate increases. The increment of the export gas means less demand of the injection compression sub-system (as less gas is being directed for the injection wells), and whether in one hand that represents less demand of electrical power for the gas turbines – which would actually improve the efficiency, as the consumed fuel exergy decreases in this situation – in the other hand, less demand of electrical power also means less product being generated by the process, as the fuel gas is also accounted as a product. At the end, the decrease of product exergy has a higher influence comparing to the decrease of consumed fuel exergy at Eq. (9), resulting in less rational efficiency for higher export gas rates.

Analyzing the parameter SEC_{volume} one may observe a similar behavior among the operational modes, being the mode A the most favorable, as it consumes less exergy (again, due to lower exergy destruction as the CO_2 membranes are not aligned) in order to produce the same volume of equivalent oil. However, the best results of SEC_{volume} (i.e. lower values) within an operational mode occur for higher export gas rates. That is explained for the decrease of consumed fuel exergy in the same time the produced equivalent oil volume increases (as the export gas is accounted for equivalent oil).

The only parameter not related with exergy considered in this study was the CO_2 emissions, and that one has a specific behavior: it represents the only case which operational mode A is not the most favorable. And the fuel gas composition would explain this case. The gas used by the gas turbines is taken downstream of export compression sub-system, which receives the gas either from the CO_2 membranes treated gas outlet stream, or from the CO_2 membranes by-pass. When the CO_2 membranes are used (entirely or even partially), the fuel gas taken to be used at the gas turbines is treated gas, with low CO_2 content. This possibility of using part of treated gas for fuel gas is not feasible with the complete by-pass of the membranes (i.e. operational mode A), and the gas burned at turbines has already a higher CO_2 content, discharging to the atmosphere exhaust turbine gases with more CO_2 within it.

The importance of relating pure environmental based parameters with an exergy based parameter is highlighted by the *specific CO_2 emissions* parameter. Analyzing it, the operational mode A has again the best performance. Despite a higher CO_2 emission rate, the operational mode A produces higher product exergy, compensating the negative impact of emissions. The crossover of environmental based parameters with exergy based parameters presents itself as a much more relevant analysis. And the specific emissions parameter (or another with the same purpose) possibly being considered as a sustainability based parameter, as it relates the negative impact of human activity together with the benefits this same activity generates for the consumers.

7. CONCLUSION

This study assess the exergy performance of a gas process plant installed in a FPSO platform operating in Santos basin, southeast of Brazilian shore waters and producing from reservoirs located at the pre-salt sub-sea layer. The process plant is the same one analyzes previously at Carranza Sánchez and Oliveira Junior (2015b), and in this study a series of production scenarios was analyzed in order to verify the impact on the exergy performance.

This FPSO production process is one of the most complex created at the industry due to the high pressures involved and number of sub-systems contained in order to treat the produced gas. For that reason, the authors suggest for future studies the analysis of different well fluids (including different levels of CO_2 content in the well fluids) in order to evaluate the impact at the exergy performance.

The relation of different area parameters presents itself as a relevant subject and can avoid mislead conclusions that could be made when analyzing pure parameters, as it has been pointed out by the analysis of the specific CO_2 emissions parameter. For that reason, a future study from this system including economic aspects in the exergy analysis (i.e. exergoeconomic analysis) is recommended.

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9. RESPONSIBILITY NOTICE

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