Journal of Cleaner Production 200 (2018) 269–281

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Lifetime oriented design of natural gas offshore processing for cleaner production and sustainability: High carbon dioxide content

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ARTICLE INFO

Article history:
Received 5 February 2018
Received in revised form
19 July 2018
Accepted 27 July 2018
Available online 30 July 2018

Keywords:
Lifetime-oriented design
Reservoir decline curve
CO_2 capture
EOR
Process optimization
Membrane permeation

ABSTRACT

Production of natural gas in deepwaters with high gas-to-oil ratio and high carbon dioxide (CO_2) content challenges the design of offshore processing due to area and weight limitations. Furthermore, cleaner production and process sustainability impose sending the separated CO_2 to early enhanced oil recovery, which has economic benefit but gradually increases %CO_2 in raw gas, paralleled by decaying oil and gas flowrates. These conditions favor CO_2 capture by membrane permeation (MP) for bulk removal and chemical absorption (CA) for polishing removal. Hybrid MP-CA has greater flexibility to face varying production and %CO_2, demanding lifetime-oriented process design. CO_2 production profile is estimated adopting %CO_2 retained in source rock (0%, 60%) and gas flowrate predicted by empirical production decline curves. Under transient gas production MP area and operational conditions are optimized via non-linear programming at five points of process lifetime constrained by %CO_2 in injected fluid above 75%mol. Treated gas reaches sale specification (%CO_2 < 3%mol) in the CA unit placed downstream MP. The obtained best design matched targets, but was more impacted by decreasing flowrate of raw gas than by increasing %CO_2.

1. Introduction

The carbon budget is the cumulative amount of CO_2 in the atmosphere corresponding to 450 ppm. For a 50% chance of keeping average global warming below 2 °C by 2050, the budget is estimated to be approximately 275 Gt of carbon (1008 Gt CO_2) (IPCC, 2014a). To limit emissions rate, carbon taxes and cap-and-trade mechanisms are expanding worldwide (Energy Institute at Haas, 2016), intensifying the risk of "stranded assets" (Carbon Tracker, 2017). Consequently, three quarters of proven reserves of coal, oil, and natural gas may be unburnable (IPCC, 2014b), contributing to reduce life expectancy of Oil & Gas (O&G) business.

The Organization of Petroleum Exporting Countries acknowledges that the O&G industry could be overinvesting, building excess capacity (Musarra, 2017), while to achieve the expected return out of capital expenditure (CAPEX) production life needs to be extended. Although proven oil reserves are expanding as offshore exploration and production (E&P) is increasingly moving to remote areas and deeper waters thanks to unstoppable development of offshore E&P (Exploration and Production) technology, the easy oil era has come to an end (ironically, not because reserves are drying). Gerasimchuk et al. (2017) named "zombie energy" the production from these fields that, although receiving strong government subsidies ("negative carbon taxes"), will remain unburned. However,

Abbreviations: Bbl, Barrels of Petroleum Liquids (1 bbl = 0.159 m^3); *BBL*, Billion Barrels of Petroleum Liquids; CO_2, Carbon Dioxide; *CA*, Chemical Absorption; *CAPEX*, Capital Expenditures; *CEPCI*, Chemical Engineering Plant Cost Index; *COMP*, Compressor; *E&P*, Exploration and Production; *ENG*, Exported Natural Gas; *EOR*, Enhanced Oil Recovery; *EROI*, Energy Return over Invested Energy; *E-IG*, Energy fraction associated to injection gas; *E-RNG*, Energy fraction associated to raw natural gas; *FPSO*, Floating Production Storage and Offloading; *GAMS*, General Algebraic Modeling System; *GOR*, Gas to Oil Ratio; *HC*, Hydrocarbon; *HCDPA*, Hydrocarbon Dew-Point Adjustment; HRWH, Heat Recovery Water Heater; *IG*, Injection Gas; *JT*, Joule-Thompson; *LCC*, Life-Cycle Cost; *LHV*, Lower Heating Value; MDEA, Methyl-Diethanolamine; *MP*, Membrane Permeation; *MUSD*, Million United States Dollars; *NG*, Natural Gas; *NLP*, Non-Linear Programming; *O&G*, Oil & Gas; *OPEX*, Operational Expenditures; PHW, Pressurized Hot Water; PZ, Piperazine; *RNG*, Raw Natural Gas; *RS*, Response Surface; *SG*, Storage Gas; *sm^3*, standard m^3; *USD*, United States Dollar; *WDPA*, Water Dew-Point Adjustment.

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https://doi.org/10.1016/j.jclepro.2018.07.271
0959-6526/

Nomenclature

A, $A/FEED$	Permeation area (m^2) and permeation area per feed unit ($m^2/Nm^3/h$)
b	Arps' exponent
d	FPSO working days per y (d)
D_I	Reservoir nominal decline rate (y^{-1})
E_i	Annual average molar flow of ENG from each FPSO (10^6 sm^3/d)
f	Objective function in NLP optimization
F_1	RS input factor #1 CH_4 or CO_2 feed partial pressure
F_2	RS input factor #2 CO_2 or CH_4 feed partial pressure
F_3	RS input factor #3 area per feed unit ($m^2/Nm^3/h$)
F_{3i}	RS input factor #3 area per feed unit for each stage ($m^2/Nm^3/h$)
F_4	RS input factor #4 permeate pressure (bar)
F_5	RS input factor #5 feed temperature (K)
F_{FEEDi}	Feed molar flow rate for each stage (10^6 sm^3/d)
F_i	Annual average molar flow of RNG fed to each FPSO (10^6 sm^3/d)
FP	Equipment foot-print (m^2)
H_i	Annual gas *hold-up* in the reservoir (10^6 sm^3)
I_i	Annual average molar flow of IG from each FPSO (10^6 sm^3/d)
L	MP permeate phase
n	Number of FPSOs connected to the reservoir
PP_{CH4}, PP_{CO2}	Feed CH_4 and CO_2 partial pressures (bar)
P_{PERM}	Permeate pressure (bar)
q_I	Initial production flow rate (10^6 sm^3/d)
$q(t)$	Production flow rate (10^6 sm^3/d)
$REC^L{}_{CH4}$	RS response #1 CH_4 %recovery in permeate
$REC^L{}_{CO2}$	RS response #2 CO_2 %recovery in permeate
S_i	Annual average molar flow of SG (10^6 sm^3/d)
t	Time
T_{FEED}	Feed temperature (K)
$x^0{}_{CO2}$, x_i	Reservoir CO_2 molar fractions: initial and for y i
$x^{ENG}{}_{CO2}$, $x^{IG}{}_{CO2}$	Annual average CO_2 molar fractions: for ENG and for IG
y	year

the installed capacity “locks in” fuel dependency, as they are intensive in capital and long lived, hence production will last to return investments, slowing the transition to lower-carbon energy (Gerasimchuk et al., 2017).

Although the extension of subsidies can be argued, the fact is that remote oil and gas reserves pose a general decline in energy return of energy invested (EROI) (Hall et al., 2014), as more energy is demanded for E&P operation, enforcing the need for sustainability-oriented design of E&P. It is worth noting that the Brazilian Pre-Salt oil reserves are distant from shore (>340 km), in ultra-deepwaters (>2000 m) (Gaffney et al., 2010), with high Gas-to-Oil Ratio (GOR) – greater than 400 standard m^3 of gas/m^3 of oil (sm^3/m^3) – and with association to CO_2-rich gas ~44 %mol (Arinelli et al., 2017).

Floating Production Storage and Offloading (FPSO) platforms have been utilized in remote offshore areas without infrastructure for many years but grew in importance with the push by offshore industry into ever deeper waters (Shimamura, 2002). FPSO are preferred for being mobile, self-sufficient, with high storage capacity and without the need of local piping infrastructure for oil transport. Compared to fixed platforms, FPSOs offer the advantages of being more rapidly developed, requiring lower initial investment, and keeping their aggregate value for longer time, since they can be reallocated to other fields, and having lower abandonment costs (Yu et al., 2015).

With huge deepwater reservoirs, Brazilian Pre-salt impacted the FPSO scenario. Currently, 178 FPSOs (90 contractor owned and 88 operator owned) are operating worldwide (44 in Brazil) being 126 converted vessels. Additionally, 19 are not working but are available for redeployment (2 in Brazil) and 12 are on order (8 in Brazil), totaling 209 FPSOs (Barton et al., 2017). These FPSO and deep offshore projects demand very sizeable investments that must be optimized and protected (Thiabaud et al., 2011). In fact, for extending use of fossil energy beyond 2050, increased energy efficiency is sought in E&P along with minimization of CO_2 emissions.

It is relevant to the present study that oil production is dependent on the capacity of processing the associated high CO_2-rich natural gas (NG). In offshore processing of CO_2-rich NG, the main destination for the separated CO_2 is Enhanced Oil Recovery (CO_2-EOR). The CO_2 storage potential in EOR is high: 60% of injected CO_2 can be retained in the reservoir (Gazalpour et al., 2005). CO_2 reinjection reduces oil density and viscosity, improving its fluidity and increasing reservoir production, monetizing CO_2. CO_2-EOR recovers 1–3 bbl (barrels) of oil per injected ton of CO_2, increasing, thus, the reservoir economic lifetime (Luu et al., 2016).

High gas-to-oil ratio (GOR), associated with high CO_2 content (Gaffney et al., 2010), challenges the design of FPSOs, due to the impact in area and weight required by the NG processing plant (Andrade et al., 2015). In this case, uncommon steps are needed, such as Water Dew Point Adjustment (WDPA) and Hydrocarbon Dew Point Adjustment (HCDPA), efficient H_2S and CO_2 removal and high-pressure CO_2 reinjection (Formigli Filho et al., 2009).

Fig. 1 shows the gas processing steps on the topside of Brazilian Pre-Salt deepwaters FPSO, highlighting CO_2 separation while illustrating the flow profile and increasing CO_2 content in the reservoir along operating lifetime. The mixed oil, gas and water stream arrives in the FPSO through risers and proceeds to three-phase separation, from where each fraction is directed to its treatment. The gas stream is compressed and dehydrated for WDPA avoiding hydrate formation in the transportation pipeline. Next, NG is sent to HCDPA to remove heavier fractions. The gas then proceeds to CO_2 separation via membrane permeation (MP), where it is split into permeate – a CO_2-rich stream compressed to be dispatched as Injection Gas (IG) – and retentate, a CO_2-poor stream compressed and exported to onshore facilities as NG for sale. Compression for dispatching treated NG and CO_2-rich fluid for EOR challenge energy and area availability on FPSO topside. Composition specification of the CO_2-rich stream to be reinjected is also an important design premise.

From an environmental point of view CO_2-EOR is beneficial because it allows for the storage of part of the CO_2 injected while increasing oil recovery (Kwak et al., 2014) - 50% according to the authors. Gazalpour et al. (2005) suggests a “gross” CO_2–retention efficiency of approximately 60% at CO_2 breakthrough if separation and reinjection is not considered after the breakthrough. The unretained CO_2 is responsible for a steady rise in CO_2 content of produced NG along reservoir operation lifetime, concomitantly to the decrease in NG production due to depletion. This extreme scenario challenges the design of offshore NG processing plants, mainly concerning CO_2 separation, demanding advancements in FPSO design for enhanced production (Islam et al., 2012).

In fact, sustainability of NG processing – and its survival as