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Comparative analysis of separation technologies for processing carbon dioxide rich natural gas in ultra-deepwater oil fields

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ABSTRACT

Offshore oil production in ultra-deepwater, with associated natural gas showing high carbon dioxide content and high gas to oil ratio, poses stringent constraints to upstream gas processing technologies. Under such circumstances, oil and gas are processed in Floating Production Storage and Offloading rigs, whose topside facilities are limited in terms of weight and footprint of equipment. Energy demands, supplied by on-site generation, also reduce the availability of space and weight to oil and gas processing. This work evaluates carbon dioxide separation alternatives applicable to this challenging scenario in terms of technical, economic and environmental aspects, considering early enhanced oil recovery as the destination of carbon dioxide. The Brazilian Pre-Salt fields are used as case study due to their unusual high capacity gas processing on the production topside, a consequence of the high gas to oil ratio and carbon dioxide content. The set of studied carbon dioxide separation technologies encompasses membrane permeation, chemical absorption by aqueous methyl diethanolamine with piperazine, physical absorption with propylene carbonate and hybrid variants physical absorption and membranes, membranes and chemical absorption, and two stages membrane, technically assessed by process simulation. Due to the continuous injection of carbon dioxide to enhanced oil recovery, the reservoir content of carbon dioxide increases along production life-cycle, which means that the performances of technologies have to be compared under short-term, mid-term and long-term carbon dioxide content in the associated gas, respectively, of 10%, 30% and 50% (mol), for gas production of 6 million sm^3/d. Chemical absorption exhibits the lowest hydrocarbon losses and the lowest specific electric power consumption at the expense of the highest footprint, for all investigated scenarios. The lowest life-cycle costs are for chemical absorption and two stages membrane, respectively \$0.57 and \$0.46 million/GJ of exported gas, while the largest cost belongs to the hybrid membrane and chemical absorption (\$1.78 million/GJ of exported gas). Chemical absorption holds the lowest carbon dioxide emission per ton of injected carbon dioxide (0.15 t/t), seconded by membrane permeation (0.19 t/t). Hybrid membrane and chemical absorption inherits the small footprint of membrane permeation and, despite its highest life-cycle cost, is recommended for flexibility reasons due to increasing carbon dioxide content in the reservoir life-time in cases of ultra-deepwater fields with high gas to oil ratio, high carbon dioxide content and early carbon dioxide enhanced oil recovery. Contrarily to the widely acceptance of membrane permeation as a leading small footprint solution, the overall performance analysis, under the adopted premises, remarkably favors chemical absorption.

1. Introduction

Offshore exploration and production (E&P) of oil and gas is moving from shallow waters (depth < 200 m) to deep waters (200 m < depth < 1500 m) and ultra-deep waters (depth > 1500 m).

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Brazil's estimated oil reserves on deepwater and ultra-deepwater fields have expanded from less than 15 BBbl in 2004 to more than 30 billion in 2009 due to the discovery of the Brazilian Pre-Salt fields, which is paralleled by African west coast pre-salt basin with over 30 BBbl of deepwater and ultra-deepwater reserves (Gaffney et al., 2010).

Extracting oil from huge reservoirs in ultra-deepwater, with high associated gas to oil ratio (GOR) and high CO_2 content, is a challenging dilemma. If the oil has to be produced, a huge flow rate of CO_2 rich gas has to be processed, separated and a convenient and safe destination of CO_2 has to be found. Furthermore, due to climate change protocols, the gas cannot be simply massively flared as frequently done not too long ago in offshore E&P. This implies, for instance, a primary processing of natural gas (NG) requiring several unusual features like a strict control of water dew point (WDP) and hydrocarbon dew point (HCDP), NG upgrading by efficient removal of CO_2 and huge machinery for re-injection of CO_2 at very high pressures. In other words, big oil and gas reservoirs, at ultra-deepwater, with high GOR and high CO_2 content, defy state-of-the-art production practices under such extreme circumstances. Consequently, this context drives new technologies and entails advancements in the design of Floating Production Storage and Offloading (FPSO) rigs (Islam et al., 2012).

FPSOs are preferred in frontier offshore oil fields as they are mobile, self-sufficient, gas and oil production rigs with high capacity of oil storage that can be easily positioned for production at the appropriate location not requiring local pipeline infrastructure to export oil. FPSOs are also advantageous in case of political and weather instabilities: under such circumstances, they simply disconnect and move temporarily to a safer location. Additionally, FPSOs offer advantages of earlier cash flow because they are faster to develop than fixed platforms, require reduced upfront investment, hold retained value as they can be relocated to other fields, and abandonment costs are less than for fixed platforms (Yu et al., 2015). Currently, approximately 160 FPSOs are in operation worldwide (Modec, 2015). These vessels are designed with production capacities over 100,000 barrels per day of oil and 6 $MMsm^3/d$ of gas.

On the FPSO topside, additional considerations come to scene, namely: (i) safety (larger deck area and fewer decks for single equipment); (ii) standardization (supply chain can ensure delivery of components); (iii) contracting flexibility; (iv) relocation (FPSO reuse in case of reservoir underperformance); and (v) decommissioning (D'souza and Granherne, 2011). Furthermore, processing NG in ultra-deep waters is a particular challenge in FPSO design, as in Brazilian Pre-Salt oil fields with average GOR of 250 m^3/m^3 or higher and associated gas with high CO_2 content (Gaffney et al., 2010). Consequently, whenever high GOR and CO_2 content occur, the main impact in terms of area and weight requirements is caused by the gas processing plant, which demands installation of equipment for WDP and HCDP adjustments, removal of CO_2 and removal of H_2S (Formigli Filho et al., 2009), resulting large gas processing plants (Pinto et al., 2014).

This challenging design drives the present analysis, which focuses on the gas processing burden connected to E&P of oil in ultra-deepwater offshore fields with high associated GOR and CO_2 content. The main constraints for offshore production of oil concern costs and the environment. This motivates a comparative assessment of CO_2 separation alternatives on technical, economic and environmental grounds. Environmental aspects acquire relevance in ultra-deepwater due to the high energy consumption by topside gas processing plants.

Most analyses of alternative technologies for CO_2 separation focus on flue gas applications and rely exclusively on energy efficiency and solvent degradability (Léonard et al., 2014; Zhang et al., 2013a; Cousins et al., 2011). Evaluation of technical and economic performance are equally available (Nuchitprasittichai and Cremaschi, 2011; Rubin et al., 2012; Vaccareli et al., 2014). A relevant issue in this work consists on simultaneously approaching technical, economic and environmental performances of a set of alternative technologies for CO_2 separation in the scenario of primary gas processing in ultra-deepwater oil fields with high GOR and CO_2 content. The Brazilian ultra-deepwater oil fields, with a challenging combination of high CO_2 content and high gas flow rates within a limited processing space, drives the main premises adopted in the study.

It is worth noting that environmental performance is most often neglected in comparative analyses of NG processing (Valenti et al., 2011; Pellegrini et al., 2010; MacDowell et al., 2010), as opposed to flue gas applications which are inherently motivated by environmental concerns. Furthermore, the increase in NG demand, pushed by the expanding offer, is considered the main resource for transitioning energy mixes to lower carbon levels, and results in a growing energy generation by thermal power, aggravated by the development of other market niches for NG (Vahl and Filho, 2015). The sustainability of this path depends primarily on CO_2 managing technologies, mainly in the upstream segment, with adoption of appropriate CO_2 separation and destination.

The study is structured in five sections, including this introduction. In Sec. 2, background information on deepwater E&P is presented, with a compilation of FPSO design operating in Brazilian Pre-Salt fields. The adopted methodology, based on process simulation, is presented in Sec. 3, with the theoretical framework used in all analyses. Sec. 4 discusses results with conclusions following in Sec. 5.

2. Background information

2.1. Brazilian oil reserves versus FPSO approach

Fig. 1 presents the oil produced in the Brazilian ultra-deepwater reserves in the Pre-Salt basin, with FPSOs indicated according to the milestone of first oil produced. Fig. 1 also depicts the required topside for gas processing and the E&P scenario in ultra-deepwater. Gas from oil-gas-water separators is compressed prior to removal of H_2S and dehydrated for WDP adjustment, following CO_2 removal, NG compression for exportation, and CO_2 compression for injection in the field.

Table A1 in Appendix A (Supplementary Materials) lists the main features of producing units. Capacities, CO_2 removal, energy consumption and topside dry weight are the main specificities of the FPSOs, giving a clear image of the large-scale nature of the operation. Large vessels were decided for two reasons: (i) greater robustness, large oil capacity and economic benefits; and, (ii) design assumes maximum CO_2 content in the produced gas along project lifetime of 50%. FPSOs have also sulfate removal units for seawater injection, membrane permeation (MP) modules for CO_2 capture and reinjection (CO_2-EOR), and molecular sieves (MS) for dehydration and H_2S removal. It is shown that ultra-deepwater FPSOs have installed power of 100 MW or superior and topside weight of 20 kt or beyond. It is worth noting that SBM statistics of FPSO complexity is based on shaft power, counting all rotating machinery greater than 1 MW. Where compressors have electrical drivers, the turbo-shaft power and the compressor power are both counted. Another indicator of complexity is the growth of installed topside weight of FPSOs over the years: 1st generation at 1 kt, 2nd generation at 10 kt and 3rd generation at 20 kt (SBM Offshore, 2013). Pinto et al. (2014) consider a regular FPSO to analyze the impact of different processing capacities on energy demand, weight and footprint. For oil flowrate of 150 kbpd, with 40% CO_2 gas, an

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