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Process integration approaches to optimal planning of unconventional gas field development

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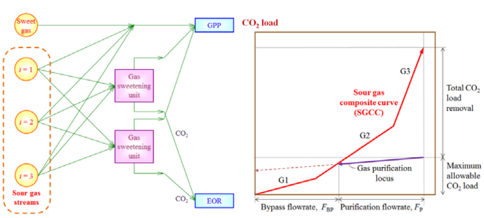
HIGHLIGHTS

- Process integration methods for development of gas fields with high CO_2 content.
- Graphical technique to determine minimum requirement for sour gas sweetening.
- Pinch-based optimization model to determine appropriate gas sweetening unit.

GRAPHICAL ABSTRACT



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ABSTRACT

In recent years, the oil and gas industry has been moving to develop unconventional gas fields, which include those contaminated with high carbon dioxide (CO_2) content. Typically, the CO_2 has to be separated from the natural gas (NG) in offshore processing facilities (in situ) before the NG can be sent for processing at the gas plant onshore. To date, commercial-scale CO_2 capture and storage (CCS) has proven to be viable mainly for CO_2 that is separated from NG and subsequently injected at or near the gas field itself for permanent storage (CO_2 sequestration) or utilized for the purpose of Enhanced Oil Recovery (EOR). In the case of multiple adjacent reservoirs exhibiting variations in NG quality and CO_2 content, it may be necessary to have in situ CO_2 removal using NG sweetening processes (e.g. membrane or amine absorption) to achieve a quality level such that the pooled NG streams meets the sales gas specification required for further processing at an onshore facility for sales. In this work, new process integration approaches are proposed to aid in the integrated planning of such joint field development projects, to rationalize the development of contaminated gas fields together with conventional sweet gas fields in meeting the required sales gas specifications of CO_2 content. These approaches are based on analogous techniques previously developed for distributed effluent treatment systems and carbon capture planning for the power generation sector. A case study is used to illustrate how general insight-based policies for gas field development can be drawn from process integration perspectives.

1. Introduction

Climate change is widely perceived to be the modern world's most pressing environmental issue (Rockström et al., 2009; Steffen et al., 2015). Despite the ambitious long-term commitments of various countries at the recent United Nations Climate Change Conference (COP 21) in Paris (Goldberg et al., 2015), in the short

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term, fossil fuels will remain an important part of the world's energy mix. Among the various types of fossil fuels, natural gas (NG) may be considered the "cleanest" energy source with its lower carbon dioxide (CO_2) intensity (in comparison with oil and coal), and thus presents a valuable interim option towards gradual decarbonization of energy markets. Note however that, to unlock the global NG reserves, contaminated gas has to be treated accordingly as CO_2 content in these NG fields varies with the reservoir and geological formation. For instance, Darman and Harun (2006) reported that CO_2 content for individual NG fields in Malaysia ranges from 28% to 87%. Traditionally, only high quality NG fields of low CO_2 content were developed due to the extensive investment required to treat and remove CO_2 and the subsequent disposal of the CO_2 adhering to environmental requirements. In recent years, possibility of developing those "sour" NG fields has been reported (Offshore Energy Today, 2012). It has also been reported that the utilization of contaminated NG may become more prevalent in the future as conventional reserves become depleted. In such scenarios, it will become necessary to develop systematic methods to enable integrated field development planning to be performed effectively so as to achieve both economic and environmental goals (Ettehadtavakkol et al., 2014).

The sweetening of sour NG streams is mandatory for several reasons. It is a well-known fact that the presence of CO_2 reduces the heating value of NG; hence, its content is to be kept low to meet the specification of the gas network grid. Besides, CO_2 is corrosive and forms hydrates easily that may clog and damage pumps and other equipment. Also, the corrosive nature of CO_2 may require downstream facilities such as export pipelines to be constructed of exotic material such as corrosion resistant alloy (CRA) eventually leading to higher development cost. For cases where the NG fields are located in the offshore area, CO_2 is commonly captured in-situ in offshore processing facilities (along with the removal of other impurities such as H_2S and H_2O, using amine absorption and triethlyene glycol absorption respectively), before the NG may be sent to the gas processing plant (GPP) onshore, primarily due to the reasons mentioned above. The GPP has been designed to cater for NG of low CO_2 content (depending on the Gas Sales Agreement (GSA), but typically less than 5 mol%). To justify the high investment cost spent to develop a high CO_2 gas field, the captured CO_2 is often used for *enhanced oil recovery* (EOR) projects (Mazzetti et al., 2014). Conventionally, amine absorption is the most commonly used sweetening technique for CO_2 capture (Tan et al., 2012; Muhammad and GadelHak, 2015). In recent years, membrane separation has emerged as a competitive sweetening technique, due to its high permeability and selectivity (George et al., 2016). Hence, for the purpose of field development planning of contaminated gas field(s), it is important to conduct preliminary screening and to identify the appropriate gas sweetening technique, and its CO_2 capture capacity. Note also that one of the common techniques adopted by the industry in meeting the required sales gas specifications on CO_2 content is to blend the sour gases with "sweet" gas of lower CO_2 content from other fields in order to meet the CO_2 specification of the GPP. However, the sweet gas is normally scarce and has limited availability (Mazzetti et al., 2014). Therefore, the main subject of this work is to identify the optimum field development concept considering a combination of the selection of appropriate gas sweetening techniques required, the extent of CO_2 removal and the potential blending of NG from nearby "sweet" gas fields.

Within the research community of *process integration*, many systematic techniques have been developed in the past decades aiming for the removal of specific impurities in the process streams. In particular, in the seminal work of *mass exchange network* (MEN) synthesis (El-Halwagi and Manousiouthakis, 1989), the graphical *pinch analysis* technique was developed to determine the minimum mass separating agent (MSA, e.g. solvent, ion exchange etc.) needed for the removal of specific loads in the impurity-rich streams. The authors later extended their work using mathematical optimization techniques (El-Halwagi and Manousiouthakis, 1990a, 1990b). Other variants of MEN synthesis such as *reactive MEN* (El-Halwagi and Srinivas, 1992), *waste interception network* (El-Halwagi et al., 1996) and other *mass integration* problems have also been reported and may be found in review papers (El-Halwagi, 1998) and textbooks (El-Halwagi, 1997, 2011).

Several important special cases of mass integration problems were reported in the mid-90s, including water minimization, refinery hydrogen network and property integration, which are commonly referred to as *resource conservation networks* (RCNs) (El-Halwagi and Foo, 2014). For the case of water minimization, most of the earlier works were dedicated to water being used as an MSA in purifying rich streams that contain sour gases (Wang and Smith, 1994a). To date, various *water pinch* techniques have been developed and can be found in the literature (Smith, 2005; Foo, 2009, 2012). One important variant is the systematic design of *distributed effluent treatment networks* (Wang and Smith, 1994b; Kuo and Smith, 1997), where the minimum treatment flowrate is to be determined for a set of wastewater streams to reach the acceptable impurity content. Later works on more generic waste treatment targeting were also reported (e.g. Ng et al., 2007; Bandyopadhyay, 2009). Note however that in all these earlier works on treatment targeting, the impurity content is relatively low, typically at ppm levels. Hence, flowrate losses (due to the removal of impurity) is not significant. However, this is not the case for the sour NG sweetening problem discussed here. When the sour NG streams contain about 10–20% of CO_2 or higher, the sweetening process will entail significant flowrate losses from the total gas produced from the field, which translate into lower output from the GPP. This calls for the development of new targeting tool in this work.

It is also worth mentioning that another important development in recent years is the targeting for retrofit planning of CO_2 capture and storage (CCS) for sustainable power generation (Tan et al., 2009). In the latter work, the *CCS planning pinch diagram* was presented by plotting CO_2 load versus energy output. This follows the targeting concept of Ng et al. (2007) which was developed for distributed effluent treatment networks. The main advantage of this targeting tool is that, the flowrate losses of the system can be incorporated easily. This feature becomes the basis of the new pinch diagram presented in this work.

On the other hand, a pinch-based optimization technique known as the *automated targeting model* (ATM) has also been developed in the past decade, aiming to determine the minimum resource (Ng et al., 2009a), interception (Ng et al., 2009b) and treatment flowrates (Ng et al., 2010) needed for RCN synthesis problems. Apart from being able to incorporate process constraints and cost considerations, the ATM is capable of handling *partitioning interception* units with significant flowrate losses (e.g. membrane and amine adsorption) – this is not possible with the conventional pinch analysis techniques (Ng et al., 2007). In recent years, the ATM was extended for CCS retrofit planning for single – (Ooi et al., 2013) and multi-period problems (Ooi et al., 2014). In those works, the ATM was used to determine the minimum compensatory power when CCS is retrofitted into the power plants. In this work, the ATM is utilized to supplement the pinch diagram in overcoming the pitfalls of the latter.

In this paper, new process integration techniques are developed for determining the optimum CO_2 captured required from sour gas streams by rationalizing on removal techniques, extent of removal and blending with sweet gas. In addition, it is intended to minimize the sweet gas that is used as a make-up stream to supplement the flowrate losses experienced during the sour NG