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An algebraic targeting approach for optimal planning of gas sweetening problem in non-conventional gas field development

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ABSTRACT

An algebraic technique based on pinch analysis has been developed for the planning of non-conventional natural gas (NG) field development projects. The development of NG fields with high carbon dioxide (CO_2) content has become increasingly common in the oil and gas industry. In such cases, the raw NG needs to be treated in situ for CO_2 removal to meet the sales gas specifications before being sent to the onshore gas processing plants (GPPs). The captured CO_2 can either be reinjected into the reservoir for permanent storage, or utilised for *enhanced oil recovery* (EOR), for which partial sequestration may also be achieved. These options create the need to develop systematic techniques to provide high-level decision support for field development planning. The algebraic technique developed in this work overcomes the limitations of a recently developed graphical technique (Foo et al., 2016), as it relaxes the previous simplistic assumptions on stream purity requirements. Two case studies are used to illustrate the methodology.

1. Introduction

Human activities place significant stress on ecological systems. In particular, climate change is widely regarded as a critical environmental issue affecting the entire world (Steffen et al., 2015). Despite the increasing use of renewable energy sources (e.g. solar, wind, etc.), fossil fuels remain the dominant global energy source, and are likely to remain so in the near future. Thus, the greenhouse gas (GHG) emissions from the use of fossil fuels have to be managed accordingly, adopting strategies such as fuel switching and CO_2 sequestration. Among various fossil fuels, natural gas (NG) is considered a relatively clean energy source, with its lower carbon dioxide (CO_2) intensity being attributable to its high content of light hydrocarbons (i.e., methane and ethane). Thus, increasing the usage of NG in the fossil fuel share of the world's energy mix can be an important decarbonisation strategy.

Because of the depletion of many high-quality NG reserves, there has been increased development of non-conventional NG fields in recent years, including those contaminated fields with high CO_2 content of up to 70% (Offshore Energy Today, 2012). Such "sour" NG needs to undergo the sweetening process (i.e., CO_2 removal) for two reasons. Firstly, the presence of CO_2 reduces the heating value of NG. Secondly, it can lead to acid corrosion in presence of moisture, especially for pipelines made from carbon steel material; the latter is commonly adopted in offshore facilities due to lower cost as compared to corrosion resistant alloy. Thus, for offshore facilities, CO_2 from sour NG is typically captured in situ before NG is sent to the onshore gas processing plant (GPP). Sweetening also involves the removal of other impurities such as H_2S and H_2O, using amine absorption and triethylene glycol absorption, respectively. The onshore GPP is normally designed to process NG of low CO_2 content that conforms to the Gas Sales Agreement (GSA). The level of CO_2 is typically limited to a maximum of 5%. In-situ removal of CO_2 offers many additional advantages that result in cost reductions downstream. For example, it reduces the duty for export gas compression and allows the use of conventional (as opposed to corrosion resistant) pipeline materials. The captured CO_2 can also be utilised as a valuable by-product for *enhanced oil recovery* (EOR) operations (Mazzetti et al., 2014), or sent for permanent storage in

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depleted reservoirs or other suitable geological formations. Amine absorption is the most commonly used technique for CO_2 removal from NG streams (Muhammad and GadelHak, 2015). On the other hand, membrane separation has also emerged as a competitive technique in recent years (George et al., 2016). Both purification techniques can separate CO_2 from the NG to the extent required by downstream requirements. Given these options, it is important to identify the appropriate gas sweetening technique that can be used for a given case of field development. This problem also requires that the final fate of the separated CO_2 be taken into account, and hence entails the identification of CO_2 capture capacity in the gas field. The blending of sour gas with sweet gas (SG) of lower CO_2 content (typically lower than 5%) to meet the required GPP specification of sales gas is a common practice in the industry. This strategy helps to reduce the dependency on gas sweetening units, or to optimise the units with lower design capacities to meet affordability. However, SG supply is normally limited, so its utilisation (for CO_2 blending) also needs to be minimised to ensure that optimum development is achieved in unlocking the development potential of the non-conventional gas fields.

Process integration techniques may be used to address the gas field planning problem described here. Process integration may be defined as "*a holistic approach to design and operation that emphasises the unity of the process*" (El-Halwagi and Foo, 2014). Process integration techniques based on *pinch analysis* or mathematical programming have proven successful for optimizing industrial use of resources, such as energy (Linnhoff et al., 1982), water (Foo, 2012), and other material resources (El-Halwagi, 2011). The methodologies developed and used in this area of research make use of key process data from engineering problems, which are then solved in simplified forms to facilitate practical, insight-based decision-making (Geoffrion, 1976). An important extension of process integration for carbon emissions reduction, introduced in the last decade, is the *carbon-constrained energy planning* (CCEP), where energy resources are to be allocated to various demands subject to CO_2 emissions limits. In the seminal work of Tan and Foo (2007) on *Carbon Emissions Pinch Analysis* (CEPA), a graphical targeting technique was used to determine the minimum amount of carbon-neutral energy needed for the system to meet its internal emissions constraints. Lee et al. (2009) improved the CEPA graphical technique of Tan and Foo (2007) to handle clean energy resources with non-zero carbon intensity. CCEP was later extended to sustainable power generation with *CO_2 capture and storage* (CCS) (Tan et al., 2009). Since then, CEPA has been adopted for energy planning for different countries, such as Ireland (Crilly and Zhelev, 2008), New Zealand (Atkins et al., 2010), China (Jia et al., 2009), United States (Walmsley et al., 2015), and United Arab Emirates (Lim et al., 2018). A comprehensive review of process integration techniques on various CCEP works has been reported by Foo and Tan (2016). Tan et al. (2017) then introduced the term *Carbon Management Network* (CMN) to describe a broad class of networks optimised via process integration in order to minimise CO_2 emissions. Gas sweetening in the current work can be viewed as a special case of CMN synthesis because optimum CO_2 planning is to be conducted. Similar research works were reported for the design and scheduling of EOR (Tapia et al., 2016), as well as *CO_2 capture, utilization and storage* (CCUS) operations (Tapia et al., 2018).

Various techniques have been developed for the removal of a specific impurity in process streams in the process integration literature. In their seminal work of *mass exchange network* (MEN) synthesis (El-Halwagi and Manousiouthakis, 1989), a graphical *pinch analysis* technique was developed to identify the minimum mass separating agent (MSA) required to remove impurity from some impurity-rich streams in an MEN. Wang and Smith (1994a) later developed another graphical pinch analysis method for *water network synthesis* as a special case of MENs. Their work was later extended into *distributed effluent treatment networks* (Wang and Smith, 1994b), where impurity loads are to be removed from effluent streams before they are sent for final discharge. Newer techniques have also been reported for distributed effluent treatment networks, e.g. the *waste treatment pinch diagram* for single (Ng et al., 2007) and two impurities (Soo et al., 2013), as well as the *source composite curve* (Bandyopadhyay, 2009). These methods are used to identify the minimum treatment flowrate for the distributed effluent treatment network, in order to reduce its capital and operating costs. An inherent limitation in these works is that they are meant to handle very diluted waste streams with low impurity content (typically at ppm levels). Thus, flowrate losses due to impurity removal are insignificant in such cases. This assumption does not hold for the sour NG sweetening problem, since the NG streams can contain more than 30–70 % CO_2. Since the removal of CO_2 will significantly affect the overall gas flowrate, the existing methods for waste treatment are not suitable for this problem.

To overcome this limitation, Foo et al. (2016) proposed a graphical technique known as the *gas sweetening pinch diagram* (GSPD) to identify the minimum extent of CO_2 removal for the NG sweetening problem. The GSPD is based on the waste treatment pinch diagram (Ng et al., 2007), with the assumption that SG is made available to supplement the flowrate losses (due to CO_2 removal from sour gas). The main limitation of this approach is the assumption that the SG has the same CO_2 concentration as the product stream of the gas sweetening unit (Foo et al., 2016). In other words, GSPD cannot be applied to more generic cases where the SG concentration differs from that of the product stream of the gas sweetening unit. To overcome this limitation, Foo et al. (2016) also proposed an optimisation-based technique called the *automated targeting model* (ATM) to determine the minimum CO_2 removal target for such cases. Adaptation of the mathematical programming-based ATM in industry may be limited by the need for optimization software to implement it. The development of a generic method that can be readily implemented algebraically (i.e., using commercial spreadsheets) is the main goal of this work.

In this work, the *composite table algorithm* (CTA) is extended to solve the sour NG sweetening problem. The CTA is an algebraic technique that serves as an alternative to the graphical GSPD technique proposed by Foo et al. (2016), and yet overcomes its limitations. The CTA was originally developed for fixed flowrate problems in water network synthesis (Agrawal and Shenoy, 2006). It was later improved by Parand et al. (2016) for water regeneration networks, where interactions of various important parameters are analysed. Note however that the purification units used for gas sweetening involve significant flowrate losses, an issue which was not encountered in previous works on water network synthesis (e.g. Agrawal and Shenoy (2006); Parand et al. (2016)). Hence, the original procedure is extended here for its application to the sour NG sweetening problem. The rest of the article is organised as follows. A formal problem statement is given in the next section, followed by the description of the developed methodology. Next, two case studies are solved to illustrate the methodology. Finally, concluding remarks and future research opportunities are discussed.

2. Problem statement

The formal problem to be addressed is stated as follows. Given:

- A set of sour NG sources where CO_2 is to be removed before the NG streams are sent to the downstream GPP. The latter can tolerate a given maximum CO_2 content.
- A set of gas sweetening units (typically amine absorption and membrane separation) of known performance (i.e. CO_2 con-