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IJGGC-2042; No. of Pages 13
ARTICLE IN PRESS
International Journal of Greenhouse Gas Control xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
International Journal of Greenhouse Gas Control
journal homepage: www.elsevier.com/locate/ijggc

Economic assessment of natural gas decarbonization technology for carbon emissions reduction of bitumen recovery from oil sands

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ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form 16 October 2016
Accepted 23 October 2016
Available online xxx

Keywords:
Natural gas decarbonization
Oil sands bitumen recovery
Steam generation
Process analysis
Economic assessment

ABSTRACT

We present an economic evaluation of natural gas decarbonization (NGD) applied to reduce CO_2 emissions from oil sands recovery processes. NGD produces hydrogen by removing carbon from natural gas (NG) fuel and generates valuable carbon black product instead of the unwanted CO_2 emissions. The produced hydrogen is used to generate steam by combustion, a process that produces water, which offsets a significant fraction of process water losses from bitumen recovery. Significant energy and cost penalties are associated with processes that reduce CO_2 emissions, and the process described here is no exception. The research documented in this paper is a first attempt at evaluating the economic viability of an integrated NGD and bitumen recovery process. The energetics and economics of a combined oxy-combustion and NGD are assessed and compared with the conventional steam assisted gravity drainage (SAGD) on the basis of energy efficiency and economic viability. Other factors considered are the effect of oil prices, CO_2 tax and credits, and potential revenues from the carbon black product. The findings from this study are also useful in broadening the discussion on the factors that affect the development and commercial deployment of decarbonization technologies under carbon regulations in Alberta, Canada. This study and its findings, though at a preliminary stage, would help prospective investors and the oil sands industry to make investment decisions towards research and development and commercialization of this technology.

1. Introduction

Analysts now advocate for a strong policy shift towards developing carbon mitigation technologies that allow onsite processing of industrial-scale CO_2 emissions into commercially valuable by-products (Maddali et al., 2015). Natural gas decarbonization (NGD) is an interesting alternative to technologies that capture and store post-combustion CO_2 emissions. This is because NGD precludes the production and capture of CO_2 from combustion through thermal decomposition of natural gas (NG) to produce clean energy in the form of hydrogen, and elemental carbon. Therefore, NGD can be considered as a permanent carbon sequestration solution which produces an economically viable by-product, carbon black (Fulcheri and Schwob, 1995; Gaudernack and Lynum, 1998; Muradov, 2001; Muradov and Veziroğlu, 2005, 2008).

Recovery of bitumen from Alberta's huge oil sands resources, a particular focus area for emissions reduction in Canada, seems a perfect candidate for the application of NGD technology. *In situ* bitumen recovery processes, which include steam assisted gravity drainage (SAGD) or cyclic steam stimulation (CSS), as currently employed, are both energy and emissions intensive. However, they are economically strong during periods of low NG prices and high crude oil prices. In the future, *in situ* bitumen extraction processes will dominate oil sands production because 90% of the recoverable oil sands reserves are too deep to mine (Butler, 1998). Both SAGD and CCS use high pressure and temperature saturated steam which must first be generated and then injected into oil sands reservoirs to mobilize bitumen. Steam generation energy is more than 95% of the total energy requirements of the recovery process. Thus, a technology such as NGD, if deployed for steam generation in *in-situ* bitumen recovery processes, presents prospects of dramatic CO_2 emissions reductions.

Approaches to reduce the steam-to-oil ratio (SOR, volume/volume, steam expressed as cold water equivalent) and CO_2

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http://dx.doi.org/10.1016/j.ijggc.2016.10.011
1750-5836/

Please cite this article in press as: Nduagu, E.I., Gates, I.D., Economic assessment of natural gas decarbonization technology for carbon emissions reduction of bitumen recovery from oil sands. Int. J. Greenhouse Gas Control (2016), http://dx.doi.org/10.1016/j.ijggc.2016.10.011

intensity of current commercial bitumen production processes include injection of different non-condensable gases (NCGs) such as methane (Butler, 1999; Yee and Stroich, 2004), pure CO_2 (Bagci et al., 2008) and flue gases from combustion (Yee and Stroich, 2004). Co-injection of steam and NCGs into oil sands reservoirs, performed to improve bitumen recovery during wind-down operations of depleted reservoirs, has been studied for almost two decades (Butler, 1999; Butler et al., 2000, 2001; Jiang et al., 1998). Flue gas and/or CO_2 have some advantageous over methane – these include being inexpensive and having higher solubility. However, co-injection of NCGs with steam leads to a reduction of drainage rate, though this can be compensated by the improvement of the SOR (Yee and Stroich, 2004).

Previous studies (Nduagu and Gates, 2014, 2015a) modeled co-injection of steam and hot CO_2 flue gas for bitumen mobilization and recovery through the application of the NGD-based processes. The results show that CO_2/steam co-injection is possible and beneficial, and leads to lower SORs than that of conventional SAGD. The benefits can be attributed to the energetic prospects that co-injection of hot CO_2 brings: the energy content and viscosity-reducing properties of co-injected hot CO_2 reduce the steam demand of the process.

The beneficial application of CO_2-steam co-injection is not only applicable to NGD-based processes alone but is also relevant to processes where oxy-combustion is used. Since NGD requires high-temperature heat, oxy-combustion of NG (thereafter referred to as OxyNG) has been evaluated in previous studies (Nduagu and Gates, 2014, 2015a,b) to satisfy the process energy requirements. OxyNG combustion generates a CO_2-rich flue gas stream which can be co-injected with steam into an oil reservoir for the dual purpose of sequestering CO_2 and reducing bitumen recovery steam demand. Results showed that the flue gas stream from oxy-combustion (which typically contains 90%-wt. CO_2), if co-injected with steam into an oil sands reservoir, will improve recovery performance. Yee and Stroich (2004) suggest that such a system could also potentially reduce corrosion. The use of O_2-rich flue gas cause corrosion to surface piping and subsurface tubular (Yee and Stroich, 2004). Hot CO_2-rich and low-O_2 content oxy-combustion flue gas streams fulfill these requirements and thus, we expect corrosion to be reduced. It can be pointed out that CO_2 may cause corrosion to carbon steel though the conditions and mechanisms are not well understood (Kermani and Morshed, 2003). However, the basic chemistry of CO_2 corrosion involves the dissolution of CO_2 in water to form carbonic acid, which is corrosive. An effective way to prevent CO_2 corrosion is to operate at conditions that inhibit the dissolution of CO_2 in water (Kermani and Morshed, 2003).

The energetic performance and environmental impact of applying NGD technology to bitumen recovery and upgrading have been assessed (Nduagu and Gates, 2014, 2015a,b). Results from process modeling, energy and greenhouse gas analysis show that this process could bring significant benefits in terms of GHG emissions, energy efficiency, and water consumption. However, the economics of this process have not been studied. This paper bridges that gap with a preliminary economic assessment to determine the economic viability of an integrated OxyNG combustion-fired NGD and bitumen recovery process and compares the results with that of a conventional SAGD plant.

2. Process description

2.1. Conventional steam generation process or business as usual (BAU) case

Once-through steam generators (OTSGs) have been widely used for steam generation in the oil sands industry. OTSGs produce steam with quality range of 70–80%. Downstream of the OTSG, flash drums are used to separate the liquid part (Gwak and Bae, 2010). A UniSIM Design® process model for the BAU case for oil sands steam generation was described previously (Nduagu and Gates, 2015a) and was used in this assessment. The process consists of an air compressor, boiler, heat exchangers, pumps and flash drums; the process parameters are listed in Table 1.

Table 1
Steam and NG parameters for the BAU case.

Steam generation	
Boiler steam outlet pressure, bar	50
Boiler steam outlet temperature, °C	250
Boiler steam outlet quality, x	0.8
Steam injection quality, x	1
Steam injection pressure, bar	40
Low heating value (LHV) of NG, kJ/mol	802.34

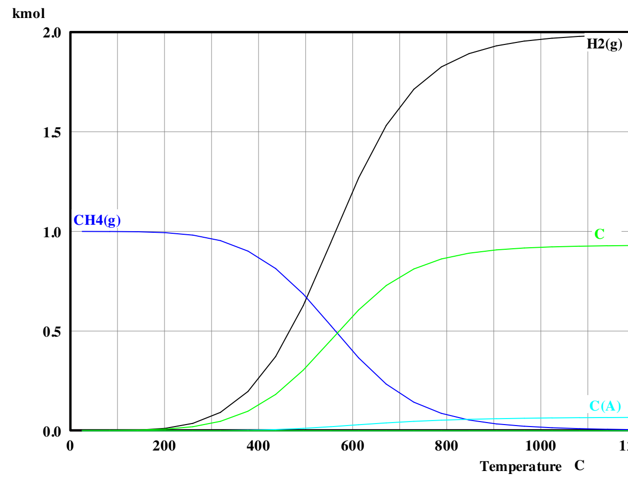

Fig. 1. NGD reaction equilibrium compositions of reactants and products at different temperatures. The input is 1 kmol CH_4(g) whereas the outputs are H_2(g) and two forms of carbon: amorphous carbon, C(A) and carbon black, C. Thermodynamic calculations were performed using Gibbs Energy Minimization Routine in HSC Chemistry® Software.

NG is combusted in the boiler with air providing oxygen for the combustion process. By using heat exchangers, the heat generated from NG combustion is transferred to a pressurized boiler feed water (BFW). The BFW is heated to boiler steam outlet conditions (Table 1) and thereafter flashed in a drum to produce high-quality steam for bitumen recovery and saturated steam for utility applications.

2.2. Natural gas decarbonization

NGD chemistry is represented by Eq. (1) if natural gas is assumed to comprise mostly of methane (typically >95 mol.%).

$$CH_{4(g)} \rightarrow C_{(s)} + 2H_{2(g)} \qquad \Delta H_r = 75.6\,\text{kJ/mol} \qquad (1)$$

This reaction is endothermic and maximum conversion is possible at temperatures ~1000 °C (Fig. 1). However, when catalyzed, the reaction proceeds at significantly lower temperature (Amin et al., 2011; Monnerat et al., 2001). On a per mole hydrogen basis, 37.8 kJ/kmol energy is required for NGD whereas the energy requirement for a competing steam methane reforming (SMR) process is about 1.7× higher (63.3 kJ/kmol). Carbon black production from the process can be considered as an asset – carbon emissions that would have been generated from NG combustion are sequestered as solid carbon, a valuable product. It can also be liability because the H_2 energy produced is limited to 54% of NG