High-temperature pressure swing adsorption cycle design for sorption-enhanced water–gas shift

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HIGHLIGHTS

- Sorption-enhanced water–gas shift (SEWGS): H2 from syngas in single unit operation.
- SEWGS cycle design based on recently published CO_2 and H_2O interaction with K-HTC.
- Adsorption of steam during rinse enhances CO_2 product purity.
- Cycle consumes significantly less steam than previously reported cycle designs.

GRAPHICAL ABSTRACT
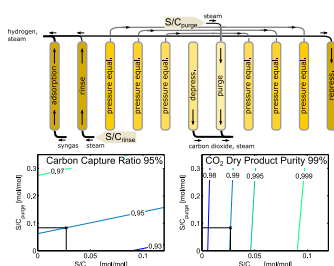
ARTICLE INFO

ABSTRACT

Sorption-enhanced water–gas shift (SEWGS) combines the water–gas shift reaction with in situ adsorption of CO_2 on potassium-promoted hydrotalcite (K-HTC) and thereby allows production of hot, high pressure H_2 from syngas in a single unit operation. SEWGS is a cyclic process, that comprises high pressure adsorption and rinse, pressure equalisation, and low pressure purge. Here, results are presented of a SEWGS cycle design study, based on recently developed expressions for the interaction of CO_2 and H_2O with K-HTC. It is shown that during the cycle, steam adsorbs in the rinse step and desorbs during the subsequent reduction in pressure, thereby improving the CO_2 purity in the column and thus enhancing the efficiency of the rinse. A parameter study based on numerical simulations shows that the carbon capture ratio depends mainly on the purge steam to carbon feed ratio, whereas the CO_2 product purity depends mainly on the rinse steam to carbon feed ratio. An optimisation yields a SEWGS cycle that consumes significantly less steam than cycle designs previously reported in the literature.

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1. Introduction

Against a backdrop of rising atmospheric CO_2 concentration, an intensified greenhouse gas effect, and accelerating climate change, political bodies on many levels have expressed commitment to curb CO_2 emissions. I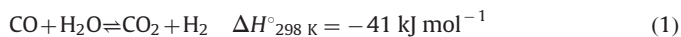n line with these ambitions, deployment of renewable energy is increasing rapidly, energy efficiency is being improved, and in parts of the world gas is replacing coal in power generation. Nevertheless, in a striking contrast energy related CO_2 emissions continue to increase, reaching a record high of 31.6 Gt in 2012 due to the steady increase in fossil fuel consumption (Birol, 2013). Clearly, additional measures are required for a timely, technically and economically feasible transition to a low carbon energy system. One such measure would be capture and geological storage of CO_2 (CCS). CCS could be effectively applied to coal and gas fuelled power plants, as well as to fossil fuel consuming industries. Whereas it has been proposed since the late 1980s,

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the implementation of CCS has been hampered mainly by political and economical challenges (Metz et al., 2005; Birol, 2013). Clearly, the economical prospects of CCS would benefit greatly from a reduction in the cost of capture, being the most expensive part of the CCS chain, and/or an increase in the price of CO_2 emission allowances.

One process scheme with a high potential of bringing down the cost of CO_2 capture is integrated precombustion CO_2 capture and hydrogen production by sorption-enhanced water–gas shift (SEWGS). SEWGS combines the water–gas shift (WGS) reaction (1) with in situ adsorption of CO_2 (2), at about 300–500 °C and 10–40 bar.

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \quad \Delta H^\circ_{298\ K} = -41\ kJ\ mol^{-1} \tag{1}$$

$$CO_2 + \bullet \rightleftharpoons CO_2 - \bullet \tag{2}$$

$$H_2O + \bullet \rightleftharpoons H_2O - \bullet \tag{3}$$

A potassium promoted hydrotalcite (K-HTC) catalyses the WGS reaction (1) and is capable of reversibly adsorbing CO_2 (Hufton et al., 1999; Yong et al., 2002; Lee et al., 2008; Boon et al., 2014). Relatively pure CO_2 is released during regeneration of the K-HTC. Because of the periodic loading and regeneration of the sorbent, a state of the art SEWGS process comprises multiple columns which are operated in pressure cycles, resembling the cycles of a pressure swing adsorption (PSA) process and allowing the production of continuous product streams (see Fig. 1). After the adsorption step, a CO_2 or H_2O rinse is performed to improve the CO_2 product purity, by preventing the loss of efficiency due to the slip of H_2 into the CO_2 product. Depressurisation is followed by a steam purge to allow a high recovery of CO_2 and to enhance sorbent regeneration. The detailed discussion of all steps in the SEWGS cycle continues below. Thus, the overall process directly converts syngas into separate streams of H_2 at 10–40 bar and CO_2 at lower pressure, both at 400 °C. The SEWGS process is therefore exceptionally suited for precombustion CO_2 capture, and hence mitigation of greenhouse gas emissions. In fact, Manzolini et al. (2013a) have recently shown that for a coal fuelled IGCC power plant, the cost of CO_2 avoided can be brought down with SEWGS by 15% or more, compared to state of the art precombustion CO_2 capture by Selexol, to 31–33€$t^{-1}_{CO_2}$ (K-HTC *sorbent alpha*: −15%) or even 23–25€$t^{-1}_{CO_2}$ (K-HTC next generation *sorbent beta*, −35%). Excluding CO_2 compression, the costs of CO_2 capture with SEWGS were shown to come mainly from investment costs (55% of the increased cost of electricity) and additional fuel costs for production of high-pressure rinse steam and low-pressure purge steam (23% of the increased cost of electricity)—the economy of the SEWGS process is dominated by investment cost and steam consumption.

Although the concept of SEWGS is not new (Chemische Fabrik Griesheim-Elektron, 1915; Gülker, 1927; Gluud et al., 1931), a major breakthrough in efficiency since the early twentieth century came with the development of K-HTC sorbent, a sorbent (Hufton et al., 1999) that can be efficiently regenerated by pressure swing. Since then, considerable progress has been made in the materials science behind the sorbent, in understanding the sorbent–sorbate interaction, and in the development of SEWGS cycles—all in all SEWGS is now classified on NASA's technology readiness level 5–6 (Jansen et al., 2013). Firstly, in sorbent preparation, it has been shown that the Mg:Al ratio of the sorbent plays a crucial part (Oliveira et al., 2008). Depending on this ratio and operating conditions, bulk $MgCO_3$ can be formed during adsorption, which leads to very high capacities (Walspurger et al., 2010; Marono et al., 2013), yet at the same time gives rise to CO_2 slip and loss of mechanical integrity in a SEWGS cycle (van Selow et al., 2009b). Secondly, sorbent–sorbate interaction has been the subject of many studies, indicating that different sites and mechanisms on the sorbent may play a role in the adsorption of CO_2 (2) and H_2O (3) at the relevant temperature and partial pressure levels (Lee et al., 2007; Ebner et al., 2007; Oliveira et al., 2008; Walspurger et al., 2010, 2011; Wang et al., 2012; vanSelow et al., 2013; Wu et al., 2013; Marono et al., 2013; Marono et al., 2014; Boon et al., 2014). Thirdly, SEWGS cycles have received less attention so far. Allam et al. (2005) have developed a SEWGS cycle in which the adsorption step is followed by a high pressure rinse with repressurised CO_2 product, in order to remove syngas species present in the column voids and enhance the CO_2 product purity. In modelling studies by Wright et al. (2009) and van Selow et al. (2009a), the use of rinse steam instead of CO_2 was shown to significantly improve the efficiency of the cycle. Reijers et al. (2011) have simulated a steam rinse cycle and shown the importance of rinse for the CO_2 product purity and the CO_2 recovery to increase with increasing purge. For 90% carbon capture ratio and 98% CO_2 purity, they found an optimum S/C_{rinse} of 0.55 and S/C_{purge} of 1.3. For *sorbent alpha*, Gazzani et al. (2013) used a S/C_{rinse} of 0.44 and a S/C_{purge} of 1.06 in order to obtain 95% carbon capture ratio and 99% CO_2 purity. Wright et al. (2011) have shown that a significant improvement can be made to decrease steam consumption by increasing the number of pressure equalisation steps from one to three, although this must be balanced with higher investment costs because of the larger number of columns. They arrived at a total S/C of 1.9 for precombustion CO_2 capture in an IGCC. Jansen et al. (2013) have shown the impact of purge steam on the carbon capture ratio, and of both S/C_{rinse} and S/C_{purge} on the CO_2 purity.

The state of the art SEWGS cycle follows a number of steps that govern the performance of the process. The steps are schematically shown in Fig. 1 for the SEWGS cycle proposed in the current work, aiming at a high carbon capture ratio and CO_2 purity for a power plant configuration. First, during the adsorption step,
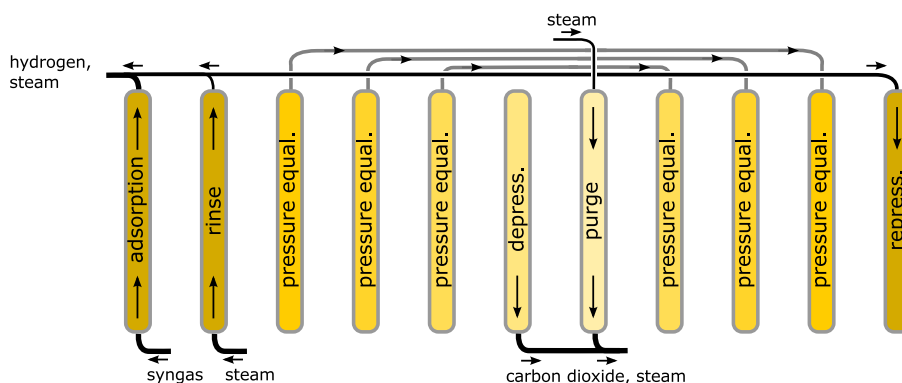

Fig. 1. 11-step SEWGS cycle with co-current steam rinse.