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Design guidance for an energy-thrift absorption process for carbon capture: Analysis of thermal energy consumption for a conventional process configuration

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ABSTRACT

The development of an energy-thrift carbon capture process to reduce atmosphere CO_2 emissions is an urgent need; however, comprehensive and systematic design guidelines for energy-minimized gas separation processes are not easily available. This study aims to understand the fundamentals of thermal energy usage in an absorption system and provide quantitative and integrated guidelines to design a minimum-energy-demanding, absorption-based carbon capture process using aqueous solvents. Solvent capacity and absorption performance are the most important factors, whereas the heat of reaction, considered important in many studies, is actually not a critical factor to determine the thermal energy usage. The shape of the vapor–liquid equilibrium curve also has a significant effect on the regeneration energy. When designing a minimum thermal energy process, the cyclic capacity, absorption performance, and heat of reaction should be considered simultaneously rather than separately because they affect the total thermal energy demand interactively. The minimum achievable regeneration energy in an absorption-based process with a typical process configuration for coal-fired plant flue gas was estimated as 2.3–2.5 GJ/t-CO_2 with an optimized heat of reaction of approximately 60–70 kJ/mol-CO_2. Brief analysis of the equivalent work up to the compression stage was also made, and the relationship with the thermal energy is discussed. The fundamentals learned through this study can be extended to other absorption-based gas separation processes.

1. Introduction

Carbon capture and storage (CCS) is believed to be an essential component in the future sustainable society with a hope that CCS contributions will prevent disasters caused by climate change (ETP, 2012; Mikkelsen et al., 2010). There is an increasing understanding in society that the atmosphere cannot accommodate an infinite amount of harmful gases, which has led to the initiation of collaborative efforts to mitigate greenhouse gas emissions (BP Energy Outlook 2030, 2011; Markewitz et al., 2012; D'Alessandro et al., 2010; Stauffer et al., 2011; Rubin et al., 2012).

The most promising and technically proven option for carbon capture is the absorption-based process using an aqueous solvent, whereas other processes still bear technological uncertainties (Rochelle, 2009; Technology Roadmap, 2013). The most significant challenge for the immediate deployment of the absorption-based process for carbon capture is the large amount of energy required for the process operation. Using currently available processes, approximately 20–30% of the electricity generated by a coal-fired power plant is consumed solely to capture 90% of the CO_2 in the flue gas (BP Energy Outlook 2030, 2011; Rubin et al., 2012).

With various efforts to reduce the high energy demand, there have been noticeable improvements in the technology (Markewitz et al., 2012; D'Alessandro et al., 2010; Stauffer et al., 2011), and some critical points have also been identified. The total thermal energy demand in the absorption process, termed the regeneration energy (Q_{reg}), is composed of three thermal energy terms (Oexmann and Kather, 2010): sensible heat (Q_{sen}) used for solvent heating, latent heat (Q_{lat}) used for water evaporation, and heat of reaction (Q_{rxn}) used for CO_2 desorption.

$$Q_{reg} = Q_{sen} + Q_{lat} + Q_{rxn} \ (\mathrm{GJ/t} - \mathrm{CO_2}) \tag{1}$$

The value of Q_{reg} is in the range of 3.5–4.5 GJ per ton of CO_2 removal when using 30 wt% mono-ethanolamine (MEA) solvent, the most well-known solvent, with a typical process configuration (Boot-Handford et al., 2014; Rochelle et al., 2011). Continued studies

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using advanced solvents, mostly blended amines, have reduced the energy demand, and processes that claim a Q_{reg} value in the range of 2.5–3.0 GJ/t-CO_2 in the conventional process configuration have been presented (Boot-Handford et al., 2014; Rochelle et al., 2011). One approach that has made the energy reduction possible is to increase the CO_2 cyclic capacity (Chowdhury et al., 2013; Puxty et al., 2009). This increased capacity lowers the solvent flow rate and thus decreases Q_{sen} (Oexmann and Kather, 2010). Another approach is to lower Q_{rxn} by designing new amines (Chowdhury et al., 2013). This approach appears rational and competent but was found to be rather unsuccessful; a low Q_{rxn} correspondingly leads to a high Q_{lat}, negating the energy reduction gained from lowering Q_{rxn} (Oexmann and Kather, 2010). Moreover, solvents with a low Q_{rxn} tend to have low absorption rates. These interdependencies stated above indicate that complex trade-offs exist among the energy terms, as already discussed in published findings (Erga et al., 1995; Svendsen et al., 2011; Chakma, 1997; Hopkinson et al., 2014), and attempts to reduce the energy terms individually are prone to fail to curtail Q_{reg}.

The lack of integrated knowledge regarding the relationship of solvent properties with the regeneration energy is complicating further reductions in the energy demand, and clearer guidance must be developed based on an in-depth understanding. Design guidelines for the gas separation process have been largely given to meet target impurity levels, as in natural gas plants (Kohl and Neilsen, 1997), and systematic guidelines to minimize energy demand are rarely found. A typically known rule of thumb is to prefer a solvent with high cyclic capacity, a faster absorption rate, greater thermal and oxidation stability, and optimized Q_{rxn} (Technology Roadmap, 2013; Oexmann and Kather, 2010; Boot-Handford et al., 2014; Chowdhury et al., 2013; Puxty et al., 2009; Global Status of CCS, 2014; Oyenekan, 2007; Van Wagener, 2011; Frailie, 2014). This guideline is true but rather ambiguous to apply in practice because it is suggested for certain, specific solvent systems or is given in qualitative terms. A further complication in designing a low-energy demand CO_2 capture process arises when the CO_2 source is diversified. The CO_2 content in the flue gas varies in the range of 11–15%, depending on the type of coal used in a coal-fired power plant, and even more widely depending on the fuel source (e.g., gas-fired: ~3–4%, steel industry: ~20%, direct air capture: ~0.04%). Searching for an appropriate low-energy demanding solvent for a given CO_2 source is not a trivial task and should be guided by integrated knowledge and a quantitative analysis method.

This study provides integrated and quantitative guidelines in terms of the thermal energy (in GJ/t-CO_2), for designing a minimum energy-demand absorption-based carbon capture process using an aqueous solvent. A quantitative in-depth understanding of the factors affecting the thermal energy demand, analyzed using the so-called short-cut estimation method (Kim et al., 2015), presents a clear pathway to the criteria for designing a minimum energy-demand process adaptable to numerous applications. Achievable minimum values of Q_{reg} (depending on the CO_2 source concentration) were also suggested. This proposed guideline can be applied to any single or blended aqueous solvent because the analysis was conducted with respect to the vapor–liquid equilibrium (VLE) and mass transfer properties.

Note that only the thermal energy demand, expressed in GJ/t-CO_2, in the absorption process was investigated in this study. This investigation will serve as a stepping stone for analyzing the overall energy demand up to the CO_2 liquefaction stage in terms of the equivalent work demand in kWh/t-CO_2, which is the subject of the follow-up paper. As a comprehensive analysis must address additional degrees of freedom and requires further, extensive discussion, only brief description of equivalent work is included in this paper.

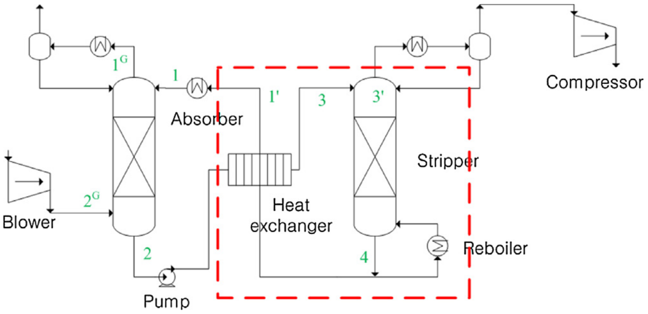

Fig. 1. Typical process flow diagram of the absorption-based carbon capture process. The numbered streams correspond to numbered points in Fig. 2(a). The red box indicates the system boundary for discussion in Section 3 (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.).

2. Understanding the process and solvent

An in-depth understanding of the system can lead us to an advanced design. This section is devoted to the exploration of key features of the absorption carbon capture process and the solvent. Although the fundamental principles drawn from this study can be applied to other absorption-based gas separation processes, subsequent descriptions will be confined mainly to CO_2 capture from the flue gas of a coal-fired power plant, assuming 15% CO_2 in the gas and 90% CO_2 capture rate, for lucid description and understanding. The main principle of the absorption-based gas separation process is to utilize the difference in the cyclic capacity of a solvent depending on temperature. The process should be designed to readily absorb a large amount of the target gas at a low temperature and to easily desorb the absorbed gas at a high temperature, using a minimum amount of energy.

2.1. Typical absorption process

Fig. 1 shows a typical configuration of the absorption-based CO_2 capture process considered in this study. Modifications from Fig. 1 have been studied to further reduce the energy demand and have achieved considerable energy-saving effects through advanced stripper configurations, vapor recompression, intercooling/heating, semi-lean/rich, and other advances (Oyenekan, 2007; Van Wagener, 2011; Cousins et al., 2011; Moullec and Kanniche, 2011; Mimura et al., 1995, 1997; Iijima et al., 1998a,b; Roberts et al., 2003; Radgen et al., 2014; Kadono et al., 2013; Lin et al., 2014). This study will assume only the conventional process in Fig. 1 for a fair comparison of the energy performance by the solvent characteristics. The flue gas enters the absorber at the bottom and flows upward, with CO_2 being transferred to the downward CO_2-lean solvent through absorption. The CO_2-rich solvent from the bottom of the absorber is pumped to the stripper after gaining thermal energy through heat exchange with the hot, lean solvent. The hot, rich stream from the heat exchanger is fed typically to the top stage, where a portion of CO_2 is flashed off to the vapor phase. Through mass transfer, the upward vapor flow from the reboiler is enriched with stripped CO_2, whereas the water content in the liquid phase is increased as the liquid from the reflux and the rich solvent feed flows downward. Stripped CO_2 gas mixed with some water vapor exits through the stripper top. The energy to produce the vapor stream is provided at the reboiler. The lean solvent from the stripper bottom is recycled to the absorber top after transferring its thermal energy to the rich solvent.

The operating variables, or the degrees of freedom, that can be manipulated in Fig. 1 are the solvent flow rate, stripper pressure, and reboiler temperature. These three variables are used to satisfy