Techno-economic evaluation of an ammonia-based post-combustion process integrated with a state-of-the-art coal-fired power plant

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A R T I C L E   I N F O

A B S T R A C T

A techno-economic evaluation of the application of an ammonia-based post-combustion CO_2 capture system to an existing, state-of-the-art, coal-fired power plant. The study comprised an assessment of the ammonia-based capture process together with a detailed cost analysis, based on which the overall design of the capture process is presented, including a power plant integration strategy and estimates of the specific CO_2 capture cost (€/tCO_2). The evaluations of the power plant and the CO_2 capture plant were based on process modeling. The cost analysis was based on the installed cost of each unit in the equipment list derived from the process simulation, which was determined using detailed-factor estimation. We show that the steam required for a CO_2 capture efficiency of 90% lowers the electric output from 408.0 MW$_{el}$ to 341.8 MW$_{el}$. The capital expenditure related to the retrofit of the reference power plant with CO_2 capture is 230M€ and the operating expenditure is determined to be 66.5M€/year, corresponding to a relative capture cost of 35€/tCO_2. Furthermore, the present work proposes design improvements that may reduce the cost of capture to 31€/tCO_2.

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1. Introduction

Ammonia has been proposed as an absorbent of carbon dioxide (CO_2) in post-combustion capture processes as it offers several potential advantages compared to the most commonly investigated absorbent in post-combustion, monoethanolamine (MEA). These advantages include: lower heat requirement for regeneration (Jilvero et al., 2012); lower cost of absorbent; higher resistance to degradation; and thermodynamic features that allow for pressurized desorption. However, ammonia is highly volatile and its absorption kinetics is slower than that of MEA. The potential problems associated with ammonia slip and the effects of a slow absorption process have been researched previously (Jilvero et al., 2014a; Versteeg and Rubin, 2011; Darde et al., 2011).

If carbon capture and storage (CCS) is realized on a large scale, it is likely to be first implemented for processes that rely on coal as their primary fuel, as in coal-fired power plants. The integration of an ammonia-based post-combustion capture system into existing power plants has previously been investigated (Versteeg and Rubin, 2011; Valenti et al., 2012; Linnenberg et al., 2012; Jilvero et al.,

2011; Zhang and Guo, 2013) using process simulations conducted with the Aspen Plus software to simulate the capture process or with the Ebsilon Professional software to simulate the process in the power plant (Linnenberg et al., 2012; Jilvero et al., 2011). The objectives of these works have been to evaluate the cost of capture at the power plant (Versteeg and Rubin, 2011; Valenti et al., 2012), to determine the net decrease in efficiency of the power plant once equipped with the capture system (Valenti et al., 2012; Linnenberg et al., 2012; Jilvero et al., 2011), and to evaluate the heat requirement for regeneration of the absorbent (Zhang and Guo, 2013). The primary results (both technical and economic) and the assumptions made are summarized in Table 1. All of the studies, with the exception of that of Zhang and Guo (2013), have assumed equilibrium-controlled chemistry to describe the absorption process.

Although the studies listed in Table 1 provide valuable information regarding the performance and cost of applying ammonia-based capture of CO_2, there is no investigation that combines a detailed process assessment with a correspondingly detailed cost analysis. The present work presents an updated design of an ammonia-based post-combustion process that includes a two-stage absorber set-up with significant reductions in ammonia slip. Furthermore, this work describes the absorption chemistry in greater detail than has been done in previous works. Thus, there

Table 1
Studies in which ammonia-based post-combustion capture of CO_2 has been integrated with a power plant.

	Absorber modeling approach	Heat requirement[a] [kJ/kg CO_2]	Power plant efficiency decrease [%]	Annual Load factor [h]	Interest rate [%]	Economic life-time [years]	Capture cost [/tCO_2]
Jilvero et al. (2011)	Eq.-based	2200	9.2	–	–	–	–
Linnenberg et al. (2012)	Eq.-based	–	8.5	–	–	–	–
Versteeg and Rubin (2011)	Eq.-based	–	11.2[b]	6570	8.25	30	73.2\$[c]
Valenti et al. (2012)	Eq.-based	2460	8.4	7500	8	40	38.6€[d]
Zhang and Guo (2013)	Rate-based	3630	–	–	–	–	–

[a] No ammonia reduction included.
[b] Higher heating value.
[c] Value in Year 2007 US dollars.
[d] Value in Year 2012 Euro.

is a need for an updated economic estimation which includes the advances in both process design and simulation. The aim of the present study is to apply an ammonia-based capture process to an existing state-of-the-art power plant, so as to evaluate the technical and economic performances. Process simulations are used to evaluate the performances of the capture process and the power plant. The dimensions and performance indicators of the units included in the capture process are thereafter used as the basis for evaluations of the capital expenditure (CAPEX) and operating expenditure (OPEX) of the retrofitted power plant with CO_2 capture.

2. Methodology

The process simulations were performed within two different modeling frameworks. For the power plant simulations, the heat and mass balance software Ebsilon Professional 10.0 was employed. Since the CO_2 capture analysis requires a framework to account for the non-ideal behavior of the absorption process, the process simulation software Aspen Plus 8.0 was used. Fig. 1 shows a schematic of the CO_2 capture process described in this work. A detailed equipment list is presented in Table 2.

2.1. Modeling aspects

The thermodynamic model for the NH_3–CO_2–H_2O system presented by Que and Chen (2011) was used. As for the auxiliary models (e.g., viscosity, heat capacity, surface tension), the built-in property model package ENRTL-RK was used. The carbamate and bicarbonate reaction rates proposed in (Jilvero et al., 2014a) were used in the rate-based modeling set-up in this work. All units were assumed to be equilibrium-controlled, except for columns A1, A2 and WW2, which were rate-based. The simulation of the capture process shown in Fig. 1 is divided into four separate flow-sheets: flue gas pre-treatment; CO_2 capture cycle; CO_2 compression; and ammonia abatement cycle. The two cyclic processes, the CO_2 capture cycle, and the ammonia abatement cycle, are simulated as closed loops, each with an additional internal loop. The inner loop is formed by the stripper (ST1) and the rich/lean heat exchanger (HX3). All the closed loops were solved sequentially by the default Broyden solver with a tolerance of 10^{-6} for the inner loop and 10^{-5} for the outer loop. All the simulations converged within these tolerance limits.

2.2. Power plant modeling

The Danish power plant Nordjyllandverket (NJV) served as the reference plant in the present work. The NJV plant is a state-of-the-art pulverized coal-fired power plant with the water, steam, and flue gas flows outlined in Fig. 2 (solid lines). The dashed lines indicate the streams and units that are added when the reference power plant is equipped with a CO_2 capture process. The square

designated as CO_2 removal in Fig. 2 encompasses the absorption process illustrated in Fig. 1. The electrical power output is 408 MW, and the electric efficiency is 47% (LHV). The relatively high electrical efficiency is ascribed to an advanced feed water preheating system, double reheating cycles, and access to low-temperature cooling water (plant is located by the sea). Heat from the steam cycle is taken from existing intermediate-and low-pressure extractions to the stripper and the ammonia stripper. Only steam extractions at existing pressure levels in the reference power plant are considered. Thus, the integration is simply a matter of matching the operating temperatures of the heat requirements of the capture process to the pressure levels in the steam cycle. Since the reboiler of the stripper operates at around 150 °C, the steam must have a pressure of 6–7 bar, considering the heat exchanger temperature difference. An extraction stream from the IP0 outlet (dashed line in Fig. 2), which is at a pressure >7 bar, is used to operate the reboiler (HX4) in the CO_2 capture cycle. The reboiler of the ammonia stripper (HX7) has an operating temperature of 100 °C and requires a steam pressure of 1.5–2.0 bar. The outlet steam from IP1 has a pressure of 1.5 bar, which makes the stream useful for the ammonia stripper (see Fig. 2). Since the reference power plant uses a double reheating cycle, the temperature of the steam is relatively high even at low pressures. The IP0 and IP1 outlets have temperatures of 429 °C and 233 °C, respectively. In amine-based post-combustion processes it is common to use a desuperheater to decrease the temperature of the steam down to saturation, to avoid thermal degradation (Ahn et al., 2013). However, ammonia is not as prone to thermal degradation (Telikapalli et al., 2011), and it is assumed that the desuperheater can be omitted. The condensate from the reboiler is returned to the feed-water preheating system at a location that matches the temperature of the condensate. The CO_2 capture process is placed downstream of the wet flue gas desulfurization.

2.3. CO_2 capture process and CO_2 compression

The flue gases (S1) enter the post-combustion process after the wet desulfurization plant. A booster fan (F1) is used to transport the gases through the capture process and to the stack. The flue gases are cooled to 8 °C by direct contact cooling (WW1). The mass flow of the cooling water is varied until the desired absorber inlet temperature is attained. A set-up with two absorbers connected in series, based on our previous work (Jilvero et al., 2014a), is used. The flue gases enter at the bottom of the first absorber (A1 in Fig. 1). The CO_2-lean solution is also introduced into A1. Most of the CO_2 is absorbed in A1, and the main purpose of the second absorber (A2) is to reduce ammonia slip. The packing material of all columns is a structured metallic packing (Sultzer Mellapak 250Y). The diameter of the absorbers is set so as to operate within the pressure drop range of 2.0–3.2 mbar/m (0.25–0.40 in H_2O/ft) of column height. The built-in correlation in Aspen Plus for the pressure drop of the assumed packing material is used to determine the diameters of all the columns