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A parametric investigation of the Chilled Ammonia Process from energy and economic perspectives

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ABSTRACT

As carbon dioxide anthropogenic generation and climate change appear to be correlated, carbon capture becomes advisable, in particular if applied to coal-fired power plants. The Chilled Ammonia Process (CAP) is a promising technology to be proved for the purpose. Continuing an ongoing study, this work examines the integration of Ultra Super Critical (USC) power plants with CAP, conducting a parametric investigation on the design parameters of the capture block in order to find the optimum from an energy perspective, analyzing then in details the power block and estimating ultimately the overall investment and annual costs. The commercial code Aspen Plus and the in-house research code GS are employed. The index SPECCA is adopted as preferred figure of merit of the global performance. With respect to a reference plant of 758 MW_e net electric production at 45.2% net electric efficiency, the carbon capture of 88.4% of the generated CO_2 reduces the net electrical power by 19% and the net electrical efficiency by 8.6% points. The optimum SPECCA is 3.22 MJ/kg_{CO_2} and the corresponding specific heat duty to the reboiler is 2.46 MJ/kg_{CO_2}. Finally, despite the investment cost of the capture block is about 15% of the power block, the cost of electricity increases from 59.9 to 82.4 €/MWh_e because of the net electric efficiency penalty, the additional operation and maintenance costs as well as the consumable costs. The resulting cost of avoided CO_2 is 38.6 €/t_{CO_2}. For comparison, the European Benchmark Task Force (EBTF) computes for conventional MEA a SPECCA of more than 4 MJ/kg_{CO_2}, a cost of electricity of approximately 92 €/MWh_e and a cost of avoided CO_2 of about 51 €/t_{CO_2}.

1. Introduction

The ongoing scientific discussion does not focus on whether fossil fuels will have to meet a major portion of the short- and the mid-future energy demand, but rather on how they will be most effectively exploited in doing so, in terms of the overall efficiency and the environmental impact. At the same time, renewable sources will have to be more diffusely implemented in the energy infrastructure to allow independence from fossils in the far future. In this outlook, coal will play most likely a primary role among the conventional sources, being the most abundant and diffuse of all. However, as carbon dioxide anthropogenic generation and climate change appear to be correlated, the capture of that generated carbon dioxide and its storage in geological formations turns to be advisable. There are three classes of capture technologies that are being investigated worldwide: (i) those that capture the carbon before the combustion process, named pre-combustion capture, (ii) those after the combustion, called post-combustion capture, and (iii) those that have the combustion occur in high-purity oxygen, said oxy-combustion, in order to generate flue gases at a high concentration of carbon dioxide that can be sequestered after a less energy-intensive clean-up with respect to the previous two classes.

Post-combustion capture has the large benefit of being readily applicable to already existing power plants, both coal- or natural gas-fired. The carbon capture can be accomplished by adsorption or chemical absorption. The use of amine aqueous solutions for the chemical absorption is widely used in other industrial sectors, such as the oil&gas or the urea industries. Currently, the so-called advanced amines are under intensive analysis by industrial and academic centers with the common scope of reducing the energy demand when applied to the power generation industry. In the recent years, the alternative chemical absorption in ammonia aqueous solutions has been proposed. In particular, the absorption in chilled working conditions, a process commercially named Chilled Ammonia Process (CAP), is considered a promising technology that still needs further numerical modeling and pilot testing to prove its viability.

As a continuation of an older investigation [1] and an extension of a more recent one by the authors [2], this work simulates in details the integration between modern Ultra Super Critical (USC) power plants and the conventional layout for CAP, which was implemented by the company Alstom in the pilot plant that has

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Nomenclature

η_{CO_2}	carbon capture efficiency (nondimensional), see Section 4.8	HC	hydrocyclone
η_e	net electrical efficiency (nondimensional), see Section 4.8	HR	heat rate (MJ_{th}/MWh_e), see Section 4.8
AB	absorber	HX	heat exchanger
AC	air-cooler	GS	gas steam
CAP	Chilled Ammonia Process	LP	low pressure
CCS	Carbon Capture and Storage	MEA	MonoEthanolAmine
CH	chiller	O&M	Operation & Maintenance
CM	compressor	PM	pump
COE	Cost Of Electricity	PR	purge
COP	Coefficient Of Performance	RB	reboiler
CC	contact cooler	REF	reference, see Section 4.8
E	specific CO_2 emission (kg_{CO_2}/MWh_e), see Section 4.8	RG	regenerator
EBTF	European Benchmark Task Force	SPECCA	Specific Primary Energy Consumption For Carbon Avoided (MJ_{th}/kg_{CO_2}), see Section 4.8 and Eq. (1)
EOS	Equation Of State	USC	Ultra Super Critical
FGD	Flue Gas Desulfurization	WK	water knockout
FN	fan	WT	washing tower
FP7	European Commission Seventh Framework Programme	q_{co_2}	specific heat duty (MJ_{th}/kg_{CO_2}), see Section 4.8

recently concluded the experimental operation, as indicated by Sherrick et al. [3], but outdated by a modified version for the plants that will be built, as depicted by Black et al. [4]. The numerical results referred to the former layout have the advantage of being comparable against the experimental results, which however have been limitedly diffused so far. The extension includes (i) a review of the literature of experimental studies that may be adopted in calibrating or validating the thermodynamic codes, (ii) the modeling of the removal of the ammonia slipping out of the absorber and (iii) an estimation of the investment as well as the operation costs of both capture and power islands and their influence on the Cost Of Electricity (COE).

The following sections describe in sequence: (i) the scope of the work and the methodology adopted in seeking it, (ii) the review of a number of articles from the open literature providing experimental vapor–liquid equilibrium data in the region of interest for CAP, (iii) the modeling approach, comprising both the energy and the economic analyses, and the simulations launched with the developed models and (iv) the results along with the discussion of the trends.

2. Scope and methodology

The scope of this work is (i) to identify the design parameters of the capture block and (ii) to quantify their influence on the energy performance indexes of the overall plant through a parametric investigation in order to determine the optimal set of values. This optimal set is used to define the best case. Moreover, (iii) to model precisely the integration between the carbon capture and the power generation through a specific investigation of the best case. Finally, (iv) to evaluate the investment cost and the operational cost of the capture block, which result in an increase in the overall cost of the generated electricity. For the sole parametric analysis, the power block is simulated in an approximate manner in order to handily calculate the electrical power loss due to the steam extraction. Subsequently, the accurate model of the power block is coupled to the optimal capture block. The energy analysis is executed with the commercial software Aspen Plus version 2006.5, outlined on the company webpage [5], and the GS (which stands for Gas Steam) in-house software, developed for over two decades of research in the field of power plant design and outlined on the authors' webpage [6]. Finally, the economical assessment is conducted in similarity to the existing amine plants.

3. Experimental data bibliography review

This paragraph reviews the experimental vapor–liquid and vapor–liquid-solid equilibrium data that can be found in the open literature and exploited for either the calibration or the validation of the thermodynamic models used to simulate CAP. The NH_3–H_2O is widely studied for application as a refrigerating fluid or as a working fluid in the Kalina cycle. The CO_2–H_2O is considered for various physical chemistry phenomena. The CO_2–NH_3–H_2O system is researched for process water treatment and for urea production; unfortunately, the available information regards primarily the sole vapor–liquid equilibrium, whereas it comprises rarely the salt precipitation because the investigated temperatures are higher than those employed in CAP.

For the binary water–carbon dioxide system at low pressure a review of experimental study is described in the paper of Carroll et al. [7]. For high pressures instead many investigations can be found in literature dated in the mid of the last century. The work of Wiebe in 1941 [8] resumes the three previous ones started by Wiebe and Gaddy in 1939 [9–11] and it reports data between 12 °C and 100 °C at pressures up to 700 atm. In the study of Markham and Kobe (1941) some measurements are reported for temperature of 0–40 °C and atmospheric pressure [12]. For atmospheric pressure more data in a similar range of temperature are given by: Harned and Davis (1943) for 0–50 °C [13], Morrison and Billet (1952) for 13–75 °C [14], Murray and Riley (1971) for 1–35 °C [15]. Higher pressures and temperature are included in the study of Zawisza and Malesinska (1981) that spans 0.2–5 MPa and 50–200 °C [16]. Contemporary experiments are carried out by Valtz et al. (2004) for 5–45 °C up to 8 MPa [17] and by Han et al. (2009) for 40–70 °C and 4.33–18.34 MPa [18].

For the water–ammonia system an exhaustive review for the experimental works over a very wide range of operating conditions is given by Tillner-Roth and Friend [19]. Therefore, their manuscript can be adopted as a starting point to choose the most appropriate references for the application of interest. Old experiences on this mixture are witnessed by Mittasch's article back in 1927 [20],