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A simplified method for the evaluation of the performance of coal fired power plant with carbon capture

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HIGHLIGHTS

- A simplified method to evaluate the performance of power plants with carbon capture is presented.
- The method applies to coal fired steam power plants.
- The influence of coal ultimate analysis is considered.
- The method is verified on a case study of a 75 MW power plant.
- An economic analysis is also presented to calculate the COE with CCS.

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ABSTRACT

This paper presents a study of carbon capture systems based on chemical absorption and stripping with amines in pulverized coal fired power plants. The technical feasibility is shown for a 90% CO_2 removal on 100% of the exhaust gas flow rate.

A simplified method to calculate the performance penalty in comparison with the original power plant is presented including the effect of coal ultimate analysis. The method is verified with data from an existing 75 MW coal fired power plant.

The economic analysis is presented in terms of cost of electricity and cost of carbon capture and the results are that the cost of electricity nearly doubles in comparison with the reference plant, whereas the cost of captured CO_2 is considerably higher than the actual cost of CO_2 in the carbon trading markets.

1. Introduction

Different strategies and technologies have been proposed for reducing CO_2 emissions in power generation. However, it is quite clear that the objective to reverse the increasing trend of carbon dioxide concentration in the atmosphere and keep it under 550 ppm can be achieved only if carbon capture and storage will be extensively applied to fossil fired power generation [1].

Even with different political positions toward the Kyoto Protocol, the EU, the USA, Japan and more recently China, have developed strategies to promote CCS in their power generation industry.

A large number of demonstration projects were proposed in the EU in the last decade [2] based on a funding program, which included several countries and different technologies. The EU strategy was to promote all of the three technologies for carbon capture, namely: post combustion, pre-combustion and oxy-fired combustion, since there is no definitive assessment about the costs and the best technology. In fact, pre-combustion is not included in the feasible technologies for retrofitting existing power plants, but it is promising as a clean coal technology for new power plants.

Although the list of projects has been long for some years, most of them have been withdrawn or stopped, due to the economic crisis, the increase in renewable energy share, which caused a significant reduction of fossil fired power generation, and the nimby attitude of the population toward the development of carbon dioxide storage sites.

USA, even from the standpoint of a critical position against the Kyoto Protocol, has not stopped from developing carbon capture technologies for the internal and the international markets, considering as the primary storage option for carbon dioxide, the depleted oil and gas fields as a way to enhance oil recovery [3], which was not included among the measures of the Kyoto protocol and the following conference of parties for the final disposal of

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Nomenclature

CEP	condensate extraction pump
COE	cost of electricity
CW	Curtis turbine
DEA	deaerator
FGD	flue gas desulfurization
FWP	feedwater pump
HHV	higher heating value [kJ/kg]
HHV_{WET}	higher heating value on a wet basis [kJ/kg]
HP	high pressure
HPHR	high pressure heat recovery feedwater heater
LHV	lower heating value [kJ/kg]
LHV_{WET}	lower heating value on a wet basis [kJ/kg]
LP	low pressure
LPHR	low pressure heat recovery feedwater heater
MEA	monoethanolamine
MP	medium pressure
O&M	operating & maintenance cost [$/kWh]
Q-COND	condensate heat demand
Q_{REB}	reboiler heat demand
Q_{sg}	heat supply from coal combustion
Q_1	heat supply to the steam power plant
Q_{SPEC}	solvent regeneration specific heat demand [kW/kg]
RH	reheater
SH	steam generator with superheater
ST	steam extraction
TCI	total cost of investment [$]
η_{REG}	efficiency of steam cycle after steam extraction
η_{sg}	steam generator efficiency
$\eta_{with\ capture}$	power plant efficiency with carbon capture system
$\eta_{without\ capture}$	power plant efficiency without carbon capture system
$\dot{m}_{coal}$	coal flow rate [kg/s]
$\dot{m}_{CO_2rem}$	removed CO_2 flow rate [kg/s]

carbon dioxide. The US strategy was also to develop all of the three technologies mentioned above for carbon capture, with a clear option for post-combustion capture in the case of retrofitting existing power plants.

Japan has also focused on the technologies to optimize carbon capture and Japanese industry has taken a lead in developing new solvents and energy efficiency for post-combustion technologies [4].

In any scenario of future power production, coal will continue to be used and, even though novel clean coal technologies and more efficient power plants will reduce the specific carbon dioxide emissions, global CO_2 emissions from coal fired plants will continue to be a reason of concern for climate change.

Chemical absorption of CO_2 from flue gases followed by stripping and geological storage is one of the solutions to this problem, that can be applied either to new or to existing power plants.

Several studies in the last two decades have compared the above mentioned three low carbon technologies (pre-combustion, post-combustion and oxy-combustion) that can be used in fossil fired power plants.

Pre-combustion capture is normally considered as the most efficient path since it separates carbon from the fuel, but it cannot be applied as retrofit in existing power plants [5]. Absorption processes with chemical solvents are expected to be the most widely used technology for post-combustion CO_2 capture, since they are suited for new power plants and can be more easily applied to retrofit existing power plants [5–7]. Yang et al. [8] have shown that chemical absorption systems are performing better than systems based on pressure swing adsorption and membranes.

Several studies have focused on costs [9] with results which are not easy to compare because the cost estimates are quite difficult in a field with no commercial systems in operation. The cost optimization, done in different times, produced different results, from cases where oxy-firing seemed more attractive [10] to cases where chemical absorption came out as the most cost effective [11,12].

Chemical absorption processes are applicable to gas streams with a low CO_2 partial pressure at high or low pressure, and they use the reversible nature of the chemical reactions, which are affected by temperature and pressure changes.

The stripping process requires significant amounts of heat, which are normally extracted from the steam power plant reducing the turbine flow rate at some point during the expansion.

A number of studies in the field of chemical absorption have focused on the selection or development of new solvents, which are expected to perform better than monoethanolamine (MEA), which is the reference solvent for carbon capture systems and still considered a very good one [13,14]. Alternatives to MEA were tested at lab scale or in small pilot plants by different authors [15–17]. In all cases MEA had a poorer performance than new solvents.

Ahn et al. [18] have compared ten different amines based systems and found some interesting configurations with superior performance by treating the same flue gases.

In any application of carbon capture to fossil fired power plants, there is a power and efficiency penalty that has to be evaluated.

Desideri and Paolucci [12] presented a sensitivity analysis of the main parameters affecting the performance of chemical absorption systems and calculated the power and efficiency penalty in a fossil fired steam power plant. A more extensive and detailed study, including costs was presented in 2007 by a Dutch research group [19,20], with similar results to those in Ref. [21]. A detailed review of the efficiency penalty of power plants with carbon capture systems was presented by Goto et al. [22]. They actually showed that the penalty does not depend on the type of steam cycle (sub-critical, super critical and ultrasupercritical) and the type of coal.

The results of the above studies were obtained with dedicated software tools simulating the performance of the chemical capture system and the power plant.

Linneberg et al. [23] proposed a complete but quite complicated method to calculate the performance of steam power plant with carbon capture. The main drawback is the detailed information that is necessary to perform the calculation, which is not always available before a detailed design of the power plant.

Two more papers, published in 2009, have proposed curves of efficiency penalty from the analysis of steam power plants, but the results are quite specific for the case studies and cannot be easily generalized to all applications [24,25].

This paper proposes a simplified method to evaluate the power and efficiency penalty in coal fired steam power plants when an absorption/stripping system is introduced to remove CO_2 emissions from the flue gases. The aim of this paper is to provide a simple correlation for the evaluation of the efficiency penalty which can be used in preliminary studies of fossil fired steam cycles with chemical carbon capture. The approach is simple and can be easily applied to different cycle configurations and different solvents and includes the effect of the use of different coal ranks.