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Techno-economic analysis of a CO_2 capture plant integrated with a commercial scale combined cycle gas turbine (CCGT) power plant

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HIGHLIGHTS

- A post-combustion CO_2 capture plant model has been developed and has been extensively validated at pilot scale.
- Capture plant model has been scaled up to meet the requirement of a commercial 427 MW CCGT power plant.
- Sensitivity analysis has been conducted to reduce thermal energy requirement to 4.1 GJ/tonne CO_2.
- Levelized cost of the electricity from CCGT power plant is increased by 47% when CO_2 capure process is added.

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ABSTRACT

In this study, a combined cycle gas turbine (CCGT) power plant and a CO_2 capture plant have been modelled in GateCycle® and in Aspen Plus® environments respectively. The capture plant model is validated with experimental data from the pilot plant at the University of Texas at Austin and then has been scaled up to meet the requirement of the 427 MWe CCGT power plant. A techno-economical evaluation study has been performed with the capture plant model integrated with flue gas pre-processing and CO_2 compression sections. Sensitivity analysis was carried out to assess capture plant response to changes in key operating parameters and equipment design. The study indicates which parameters are the most relevant (namely absorber packing height and regenerator operating pressure) and how, with a proper choice of the operating conditions, both the energy requirement for solvent regeneration and the cost of electricity may be reduced.

1. Introduction

1.1. Background and motivations

Carbon Capture and Storage (CCS) is regarded as an essential technology to meet greenhouse gases reduction goals [1]. CO_2 capture with chemical absorption using amine solvent is a proven and well established technology. Despite this, CO_2 capture from exhaust gas coming from a power plant poses many technical and economical challenges. Current CO_2 capture projects involve pilot plants on a scale much smaller than required to capture CO_2 from a commercially available power plant. In September 2012, Global CCS Institute has identified 75 large-scale integrated CCS projects (LSIP) running globally [2]. An LSIP is defined by Global CCS institute as a project involving the capture, transport and storage of CO_2 at a scale of at least 800,000 tonnes of CO_2 annually for coal-based power plants or at least 400,000 tonnes of CO_2 annually for other emission-intensive industrial facilities (including natural gas-based power generation). More than half of all projects started during 2012 are located in China, and all of these are investigating enhanced oil recovery (EOR) options as an additional source of revenue. Among these LSIPs only 16 are, however, currently operating or in construction, for a global capture capacity of around 36 million tonnes per annum. These projects require investments of the order of dozens millions of Euros. It is expected that a full scale demonstration project for CO_2 capture would require over a billion dollars [3]. Accurate modelling of CO_2 capture plant, for the insight it can provide, is therefore a necessary intermediate step towards demonstrating full scale CO_2 capture. Both technical performance and costs are determinant factors to select optimal operating conditions.

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1.2. Novel contributions of this paper

CO_2 capture process is, with current available technology, a very expensive and energy-intensive process. Despite this, it is gaining attention among researchers and policymakers as a short-mid term solution to contain carbon emissions from existing or yet to be built fossil fuelled power plant. However, as usual for a substantially new technology (at least at the scale required for capturing CO_2 from power plants), much resistance remains, mainly due to the uncertainty connected to actual performance and costs. Therefore, accurate modelling constitutes a stepping-stone to increase confidence about CO_2 capture process. In this perspective, rate-based modelling procedure adopted by the Authors constitute, when compared to equilibrium based calculations, a superior solution in terms of accuracy and sensitivity to changes in the operating parameters. In addition to this pilot plants currently existing or, even more, large scale demonstration projects currently being built, are limited in the range of parameters that can be changed. Capture plant modelling, if based on a rigorous and trusted modelling procedure, can overcome this intrinsic limitation and following this idea a wide sensitivity analysis has been conducted on the main operating and design parameters in order to identify optimal working conditions, thus reducing uncertainty in thermal and economics characteristics of the process. Furthermore, combining capture plant commercial scale modelling with an extensive validation campaign (over a wide range of L/G ratio and process conditions) constitute an emblematic element of novelty. Summarizing, the main novelties of this article are:

a. Extensive validation campaign of capture plant at pilot plant scale combined with commercial scale modelling and simulation
b. Capture plant operating conditions and design parameters sensitivity analysis

2. Modelling of CCGT power plant

A commercial Combined Cycle Gas Turbine (CCGT) power plant, targeted to 427 MWe production (before capture) is modelled in GE's GateCycle® software. GateCycle® software allows an accurate modelling of design but also off-design power plant components operation. The performance of the steam cycle sections, sized for the reference non-capture case, is automatically scaled to take into account the modified pressure and temperature they will face after retrofitting to capture CO_2.

The reference commercial CCGT power plant employs a heavy duty single shaft Ansaldo Energia AE94.3A gas turbine from which exhaust gas is led to an unfired heat recovery steam generator (HRSG). The steam cycle consists of three pressure levels (124, 28 and 4.5 bar respectively) with a reheat loop. The steam is condensed in a condenser with outer water at 15 °C. Deaeration is attained in the deaerator, which operates at 4.5 bar, by using low pressure steam. The condensate from the condenser is heated by means of a closed cycle loop in order to increase heat utilization from flue gas as much as possible. All the parameters required for the calculation comes from various sources: Ansaldo company private communications, GateCycle® software library and common practice for large combined cycle power plants.

3. Integration between CCGT power plant and capture plant

An exhaust gas with mass flow rate of 702 kg/s is delivered to flue gas pre-processing and consequently capture sections. Applying post-combustion CO_2 capture to a CCGT power plant requires minimal structural changes to the original cycle and is therefore regarded as the best capture option for existing power plants. Enough space should be provided for flue gas pipeline and capture related sections (notably flue gas pre-processing, CO_2 capture and compression) which should be located in the vicinity of the power plant. The main connections between power plant and the capture plant are as follows:

a. Flue gas pre-processing;
b. Steam draw-off from the steam turbine in CCGT power plant to feed the reboiler of the regenerator in the CO_2 capture plant;
c. Condensate return from capture plant to the power plant.

The first two processes result in a reduction of electricity output from the CCGT power plant.

3.1. Flue gas pre-processing

Exhaust gases coming from the HRSG, before being sent to the capture plant, need to be cooled down to 40–50 °C in order to improve absorption and reduce solvent losses due to evaporation [4]. The cooling system consists of a direct contact cooler (DCC) in which a spray of water cools down flue gases to the desired temperature level.

This process has been modelled in Aspen Plus® environment by using RadFrac block for the DCC, regarded as a two theoretical stages tower with Rashig rings packing. Flue gases are cooled down to 40 °C by direct contact with a spray of water at 25 °C. During the cooling process water is recovered from the flue gas because of condensation. Finally, a blower increases the pressure of the cooled flue gases to a pressure above the atmospheric level, to balance the pressure losses in the capture plant. In Fig. 1, the entire Aspen Plus® flowsheet for flue gas pre-processing is presented. Assuming a blower isentropic efficiency equal to 88.5%, compression power requirement has been found to be equal to 8896 kW.

3.2. Steam draw-off

The steam required by solvent regeneration in the reboiler is provided by means of a steam bled from the IP/LP crossover. As a result, the LP steam turbine will see a major reduction of steam flow rate, which will result in the reduction of both its efficiency and power output. A throttled pressure configuration is used in this study. Given the reduced mass flow rate going through the LP steam turbine, its inlet pressure would drop. To guarantee a sufficient temperature (and thus pressure) for extraction, a valve has been added at IP/LP crossover. This adds pressure throttling losses to the efficiency penalty connected to reduced LP steam turbine mass flow rate and efficiency.

To avoid solvent degradation due to high temperature, the steam has to be cooled down to a temperature just above saturation with a water spray. The waste heat resulting from this process has been partially recovered by combining the steam with some of the condensate coming from the reboiler. In this way steam draw-off is also reduced. The remaining condensate is then returned to the condenser.

4. Modelling of CO_2 transportation and compression

At ambient condition, CO_2 is a gas. At a temperature between −56.5 and 31.1 °C, it may be turned into a liquid by compressing it up to the corresponding liquefaction pressure. The critical point occurs at 73.825 bar and 31.4 °C. Above this critical pressure (and at temperatures higher than 60 °C), only supercritical or dense-phase liquid conditions exist. If the temperature and pressure are both above the critical point, supercritical conditions