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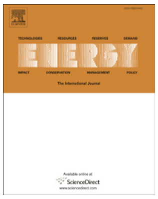

Carbon capture simulation using ejectors for waste heat upgrading

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ABSTRACT

Reducing the valuable energy consumption of solvent regeneration remains the biggest technical challenge to full-scale deployment of post-combustion carbon capture. Aspen Plus modeling is applied to validate the new application of ejectors to upgrade external waste heat in the conventional absorption and desorption process for carbon capture. In this application, ejectors upgrade external waste heat with the goal of reducing the quantity of valuable turbine steam required to regenerate the solvent. The energy consumption of the base case capture process in this study is within the range of published data. The reference solvent is 20% wt. MEA (monoethanolamine). Three strategies for producing the ejector secondary steam are evaluated. Producing the ejector secondary steam from either the stripping column condensate or from the lean solvent are viable options, showing respectively valuable energy savings of 10 and 14%. In both cases the potential valuable energy reductions are limited by the finite amount of condensate available to create the ejector primary steam. Using the rich solvent stream to produce the ejector secondary stream does not reduce the valuable energy consumption. The choice of preheating the ejector primary fluid by means of waste heat or by heat integration is also discussed.

1. Introduction

The burning of fossil fuels is the main source of greenhouse gases associated with human activity, principally due to the release of CO_2 (carbon dioxide) into the atmosphere [1]. CCS (CO_2 capture and storage) is a promising option to diminish climate change resulting from greenhouse gas emissions. CCS, the process of removing CO_2 from industrial sources and sending it to long-term storage, can most effectively be applied by targeting large scale stationary emission sites. Thermal electric power plants make up more than 75% of the worldwide sites that emit more than 0.1 $MtCO_2$/yr [2]. There are currently more than 8000 such power plants, which are potential targets for CCS. Although pre-combustion, post-combustion and oxy-combustion are technology paths for carbon capture, post-combustion will be the first applied to retrofitting existing electricity production facilities [3].

The most industrially mature technology for the separation of CO_2 from other gases is the process of absorption and desorption with amine solvents. The absorption of CO_2 and other acid gases, such as hydrogen sulfide, has been used on a large scale since the 1930s in the production of commercial grade natural gas and hydrogen [4,5]. The usual reference amine is MEA (monoethanolamine), which is often used in the 20%–30% weight range. Chemical absorption with amine solvents is appropriate for gas streams that contain CO_2 concentrations of 12–15% by volume, which are typical of coal-fired flue gases. Absorption/desorption technology adapted for flue gas carbon capture was evaluated on a pilot plant basis in the 1980s [5]. The first full scale CCS process was put on stream in 2014, at the Boundary Dam power plant in Saskatchewan, Canada, using a proprietary amine based solvent. The biggest technical challenge to the absorption/desorption process remains the large amount of energy required to regenerate the solvent, which can consume close to the equivalent of up to 30% of the power plant output [5].

Several recent studies have evaluated alternative solvents, such as Idem et al. [6] or Ohashi et al. [7]. Alternative process configurations have also been studied, including for example multistage flash [8], multi-pressure or interheated stripping columns [8,9], or a matrix configuration [10] having the rich stream split between two stripping towers at different pressures. In the Benfield process, where hot potassium carbonate is the absorbent, ejectors have been proposed for the purpose of reallocating energy within the capture process [4]. In the process of separating CO_2 from synthetic ammonia using the Benfield process, Lu et al. proposed ejectors for

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Nomenclature

Cr	ejector compression ratio
m	mass flow rate (kg/h)
P	pressure (kPa)
Q	heat duty (MW)
Greek	
ω	ejector entrainment ratio
Subscripts	
exit	ejector exit
FT	flash tank
PP	primary preheater
prim	ejector primary
RB	reboiler
sec	ejector secondary
SGEN	primary steam generator
VAL	valuable

flashing the lean stream [11]. More recently, ejectors were proposed by Zhang et al. [12] for thermal vapour compression in two improved capture systems.

Another path to reducing the reboiler energy consumption includes redirecting flue gas heat to the carbon capture process [13,14]. The flue gas temperature upstream of the absorber can vary from 100 to 150 °C, depending on at what point in the desulphurization process it is taken [14]. Recently, Reddick et al. [15,16] have shown that the incorporation of a steam ejector, combined with the upgrading of external waste heat, is a promising method of reducing the amount of valuable heat required to regenerate the solvent. Their first study presented a shortcut method using a MATLAB (matrix laboratory) computer program and was based on CO_2-MEA-H_2O physical–chemical properties to model only the desorption process and evaluate the proposed ejector method [15]. In a second study the chemical process simulator Aspen Plus was applied, using equilibrium models, to compare three strategies of ejector incorporation into the absorption/desorption process assuming a stripping column pressure of 140 kPa [16]. The second study used heat integration for the preheating step to prepare the ejector primary steam. It was found that creating the ejector secondary flow from either the stripping column condensate or from the lean stream were promising options, while using the rich stream offered no reduction in valuable steam consumption. Both studies showed the advantages of the ejector application, but did not reproduce well the typical specific energy consumption for the base case, expected to be in the range of 4–5 GJ/tCO_2 [17].

In the current study the authors propose applying Aspen Plus rate-based modeling to evaluate three ejector integration strategies into the carbon capture process, varying the stripping column pressure over the range of 140 kPa ± 10%. Nagy et al. explain why rate-based models, in contrast with equilibrium based models, give results that are much closer to published experimental results, particularly in the context of the highly non-ideal CO_2-MEA-H_2O reactive absorption/desorption process [18]. Further, in contrast with a previous study [16], a new method of producing the ejector secondary steam from the rich stream will be evaluated in an attempt to prevent the desorbed rich stream CO_2 from entering the stripping tower. Finally, a discussion comparing preheating the ejector primary fluid using heat integration versus waste heat upgrading will be presented within the context of the proposed simulations. The aim of the three simulation target strategies remains the replacement of a portion of the valuable solvent regeneration heat duty with upgraded low cost waste heat.

2. Methods

The methods section is divided into five subsections. Section 2.1 will begin by reviewing the conventional base case carbon capture process. Section 2.2 explains the basics of an ejector, and how it will be modeled. In Section 2.3 the notion of valuable energy will be discussed. Section 2.4 presents the three ways that the ejector will be incorporated into the capture process in this study. Finally, Section 2.5 describes how the rate-based Aspen Plus base model was completed, hopefully providing sufficient detail to be of help to other newcomers to carbon capture using Aspen Plus.

2.1. Base case CO_2 capture process

A simplified version of the conventional base case absorption/desorption CO_2 capture process is shown in Fig. 1. The flue gas to be purified, having already passed through a desulphurization unit, rises in the absorber and contacts the descending solvent solution. The purified flue gas leaves the top of the absorber while the solvent solution, now rich in absorbed CO_2, leaves the bottom. The relatively cool rich solvent stream is preheated in the cross heat exchanger before entering the top of the stripping column. In the stripping column, the rising steam produced in the reboiler provides the required energy to desorb the CO_2. The hot mixture of steam and CO_2 leaving the top of the column is condensed to 40 °C, where the CO_2 is separated, compressed, and sent to long term storage. The condensate, at least partially, is returned to the column. The hot stream leaving the bottom of the stripping column, now with a much lower concentration of CO_2 and called the “lean solvent”, passes through the cross heat exchanger and is further cooled to 40 °C at the top of the absorber. The lean solvent enters the absorber and the process begins again.

2.2. Ejector concept

The basic ejector components, shown in the upper portion of Fig. 2, were described in previous publications [15,16]. In brief, the primary fluid refers to the higher pressure steam that enters the ejector nozzle, that induces the lower pressure secondary fluid to enter the ejector. The secondary fluid is steam with possibly some CO_2. The thoroughly mixed fluids exit the ejector at an intermediate pressure, that of the stripping column. The inset image in Fig. 2 introduces the ejector and flash tank symbols that will be discussed in Section 2.4.

Fig. 3 shows the assumed ejector empirical model that will be input into the Aspen Plus simulations. It is the same as that used and described in Reddick et al. [15]. The entrainment ratio, ω, is the ratio of the mass flow rate of the secondary flow, m_{sec}, to that of the primary mass flow rate, m_{prim}. The compression ratio, Cr, is the ratio of the ejector exit pressure, P_{exit}, to that of the secondary entrance pressure, P_{sec}. The primary fluid is assumed to be saturated steam at 300 kPa. For the secondary fluid conditions, we begin with the assumption of having available waste heat at 100 °C. Supposing a temperature difference of 10 °C in the heat transfer equipment, and supposing that the secondary fluid is principally saturated steam, the corresponding secondary pressure, P_{exit}, is assumed to be at 70 kPa.

2.3. Problem statement

The goal of the simulations is to minimize the valuable heat duty, Q_{VAL}, that must be extracted from the power plant steam cycle