Experimental validation of split flow modification of amine-based post-combustion CO_2 capture process

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Abstract

Process development unit for amine-based post-combustion carbon capture located at Clean Coal Technologies Centre in Zabrze, Poland was used to validate split steam configuration. PDU plant having capacity up to 100 m^3_n/h was designed to test the amine scrubbing carbon capture process from flue gases or mixtures of technical gases. Plant's flexible process flowsheet allowed validation of the split flow process.

The split flow flowsheet modification was compared to a standard system for chemical absorption based CO_2 capture. The tests were conducted using baseline solvent: 30%wt MEA aqueous solution. The tests were conducted using well-accepted baseline solvent: 30%wt aqueous MEA solution. The flow sheet modification resulted in a decrease of reboiler heat duty by 4-6% and an increase in CO_2 recovery. Split flow process modification was validated during numerous tests in different process conditions and its value was proven. The split flow modification coupled with new solvents showed considerable potential of the amine-based post-combustion CO_2 capture process, despite the increasing process complexity.

Introduction

Carbon capture from flue gases is gaining interest in European Union due to current council obligations [1] concerning reduction of greenhouse gas emissions. To fulfil council liabilities, it is necessary to develop technically feasible CO_2 separation processes allowing the reduction of greenhouse gases from fossil fuel power plants. Amine based flue gas scrubbing is the most promising technology which may be used in CO_2 separation processes. The main advantage of this process is simplicity of incorporation into existing power plants [2]. However, amine based CO_2 separation processes adds serious energy penalty, reducing the efficiency of the power plant [3]. Therefore, current research concentrate on examination of energy-saving design approaches [4] and on solvent developments [5].

This paper deals with the results of tests of the split-flow modification of amine scrubbing flowsheet. Splitting the flow of the solvent is advantageous and can reduce energy consumption of the process [6] and increases CO_2 recovery [7].

The concept of the flow splitting was first suggested by [8] in patent aiming to remove H_2S from fuel gases using sodium phenolate. Shoeld suggested splitting the streams of both lean and rich amine and claims that such modification reduces steam usage by 50% comparing to conventional single flow process.

Shoelds idea have been improved by several authors [9–11]. Despite the differences in various split-flow modifications, there is one common feature present in every split flow configuration. Because of semi-lean amine drawn off the middle of the stripper, the amount of the solvent remaining in the stripper for further regeneration is lower, therefore it can be regenerated to a higher extent than for conventional process. Resulting lean amine is very clean and can be fed to the top of the absorber to ‘polish’ the gas [7]. Semi-lean amine recycled to an intermediate stage of the absorber is used to absorb the bulk of CO_2. Additionally semi-lean amine, which is cooled before being fed to the column, suits as inter-stage absorber cooling. More optimal temperature profile obtained makes better absorption of CO_2 possible [12].

In split-flow designs lean amine is fed to the stripper at various heights (Fig. 2). Forcing the lean solvent at different column heights, changes temperature and concentration in the stripper, bringing together the operating and the equilibrium line [6]. According to the Second Law of Thermodynamics, in order to reduce heat consumption of the process, it is necessary to reduce driving force [12]. Therefore split-flow designs are advantageous in terms of the reduction of the heat consumption.

Comprehensive analysis of the heat reduction potential of the split-flow designs, based on exergy losses was presented by [13].

Flow sheet of the PDU shown in Fig. 2. contains also rich split modification suggested by [14]. One of the streams of the lean amine is routed directly to the amine stripper bypassing heat exchangers. This stream is heated by condensing steam in the column which would normally be lost from the stripper. Reducing the losses of the steam and heating of a portion of amine reduces the overall energy requirements of the process.

Simulations of CO_2 removal in split-flow processes confirms beneficial character of split-flow modifications. The reduction of the reboiler heat duty by 5-18% than for conventional process was claimed by [15]. In [16] authors presented simulations of rich split and split-flow modifications where the reduction of the reboiler heat duty over standard process reached 10.3% and 11.6% respectively.

Process development unit description

The overview of the process development unit for amine-based post-combustion carbon capture is shown in Fig. 1.

Fig. 1: Overview of the PDU for amine-based post-combustion carbon capture at Clean Coal Technologies Centre in Zabrze, Poland.

In Fig. 2 process flow sheet of the PDU is introduced. The PDU allows CO_2 separation from gas streams. Either flue gas fed by blower or mixture of technical gases can be treated. The CO_2 rich gas (volumetric flow up to 100 m^3_n/h) is fed into the pre-treatment scrubber where the temperature of the gas is set and gas is saturated with water. Pre-treatment scrubber suits therefore as direct contact cooler using water as cooling medium. To avoid excessive amine degradation while testing the process on flue gases, the activated coal SO_x adsorber is located downstream of the scrubber. The CO_2 rich gas enters the absorber at the bottom. The absorber is built of three sections. Middle section, where gas contacts counter currently with semi-lean amine, top section where lean amine is fed and water wash section above the lean solvent inlet. The water wash section, where make-up water is added, acts as cooler and prohibits the increase of amine concentration in the solvent. Packing parameters and dimensions of the absorber are given in Table 1.

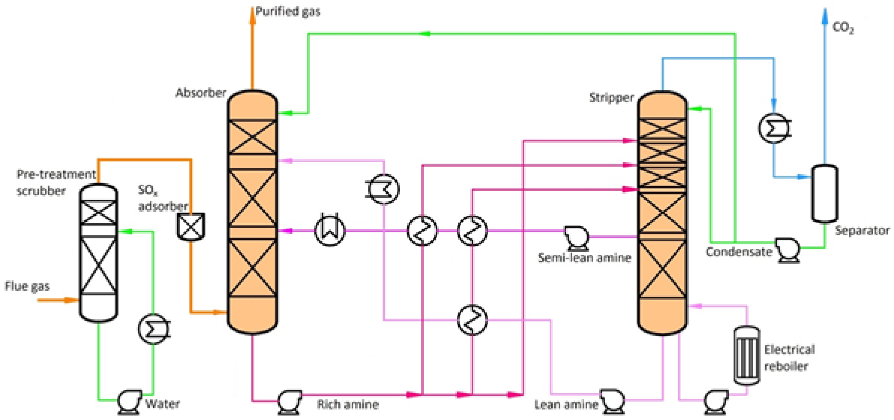

Fig. 2: Flow sheet of the process development unit.

Carbon dioxide from CO_2 rich gas is absorbed into the liquid phase. The rich solvent is pumped into the stripper through rich lean and rich semi-lean heat exchangers. The rich solvent is heated to higher temperatures through hot solvents leaving the stripper. Such split flow configuration is based on the invention proposed by [8]. In Fig. 2 additional line of rich solvent, bypassing heat exchangers, can be noticed. Using this line, small portion of rich solvent remains unheated and enters the top of the stripper. This modification known as ‘rich split’ was suggested by [14]. Concluding, the rich amine can be fed to the stripper by means of three feed points: as unheated or heated either with semi-lean or lean solvent.

The solvent in the bottom of the stripper is heated using electrical heating element. Energy delivered to the rich solvent is spent on its regeneration. A portion of the solvent is drawn from the intermediate section (semi-lean solvent) of the stripper and fed to the absorber at some mid-column feed point. Because of the side draw, remaining amine flow to the reboiler is lower, resulting lower lean amine loading. Lean amine is pumped back to the absorber and enters the top of the column, as for conventional process flow sheet. Further details regarding construction, packing and dimensions of the stripper are given in Table 1.

Product CO_2 saturated with water vapours is collected from the top of the stripper. Remaining part of water is removed in condenser installed downstream of the column and almost pure CO_2 is obtained.

Effects of foregoing modifications will be described in detail in consecutive sections.

The PDU uses 30 wt% MEA (monoethanolamine) aqueous solution as solvent.

Tab. 1: Column size, packing heights and packing materials at the process development unit for amine-based post-combustion carbon capture.

Column	Diameter	Packing Height	Packing material
Absorber	273 mm	1400 mm	Cylindrical ring 5mm VFF GmbH
		1200 mm	Berl saddles 10mm VFF GmbH
		2000 mm	Novalox saddles 13 VFF GmbH
Stripper	273 mm	320 mm	Sulzer CY
		320 mm	SulzerCY
		480 mm	Sulzer CY
		1600 mm	Interpack #2 VFF GmbH
		1000 mm	Interpack #1 VFF GmbH

For additional details concerning the PDU as well as other facilities located at Clean Coal Technologies Centre in Zabrze, Poland see [17].

Results and discussion

Figure 3 show a comparison between absorber operating lines for standard and split-flow process flow sheets and equilibrium curves. . The equilibrium curves are plotted based on experimental data taken from [18]. Temperature in the absorber varies along the columns height from 40°C to 60°C for a typical test, and the equilibrium data for this temperature range are presented in Figures 3.

The experimental data for the CO_2 partial pressure is available at three points of the absorber: at the inlet, in the middle section and at the outlet; however, straight lines were used to connect experimental data, but these lines serve only to join the data points.

Despite the semi-lean amine loading is higher than the lean amine loading for standard case, the slope of the operating lines for both process flow sheets remain similar for lower section of the absorber. This fact is clearly visible in Figure 3, where the operating lines almost overlap for higher partial pressures of CO_2 (lower section of the absorber), which in terms of driving force means the same CO_2 absorption capabilities.

Contrary, the driving force for top section of the absorber in split-flow process is much higher than for standard process flow sheet. This is expected because the lean solvent loading for split-flow process is lower than for standard process flow sheet.

Summarizing, the CO_2 recovery in lower part of the absorber remains similar for both process flow sheets, as the driving force is also at a similar level. However, split-flow process becomes beneficial in top part of the absorber where the gas is contacting the solvent having very low loading. Thanks to increased driving force in upper part of the column, overall CO_2 recovery is higher for split-flow process by 1.4% when comparing case 1 (standard) and case 2 (split-flow) . It should be noted here that comparisons between standard and split-flow process were carried out for constant power delivered to the process. The increase in CO_2 recovery while leaving constant power delivered to the process causes the decrease of the reboiler heat duty by approx. 4%: from 5.25 MJ/kg_{CO2} for standard process to 5.05 MJ/kg_{CO2} for split-flow modification.

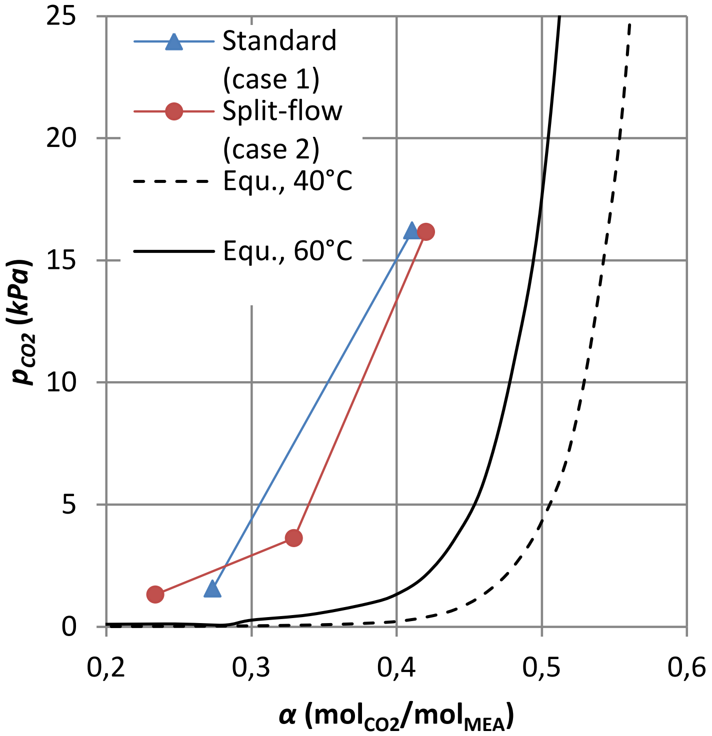

Fig. 3: Comparison of absorber operating lines for cases 1 and 2 to equilibrium curve.

As shown above the split-flow process increases CO_2 recovery comparing to standard process. The advantage of split-flow designs would reveal more significantly for systems where the lean solvent loading is very low. The split flow designs are particularly preferred when high quality CO_2 lean gas is required [7].

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