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Description and evaluation of flowsheet modifications and their interaction for an efficient monoethanolamine based post-combustion CO_2 capture

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The purpose of this study is to assess and compare most of the flowsheet modifications described in the literature through modelling. The main component of the process, absorber and stripper were specifically modelled around a rate based model with mass transfer and kinetics limitations. The different case studies are compared to a reference case presenting a standard good performance in term of energy consumption. Their impact on thermal power plant is also briefly studied in order to permit performances comparison. The solvent used for the study is MEA.

These process modifications can improve the overall efficiency. The best individual simple modifications are: a stripper operating with moderate void pressure (around 0.75 bar), the staged feed of the stripper, the lean solvent flashing and compression of resulted vapour and the overhead stripper compression. They allow a reduction of efficiency penalty of 4 to 8%. Some other modification contributes to the good performance of the process such as: intercooler, improved economizer, boiler condensate vapour compression, with a reduction of efficiency penalty around 2%. These individual modifications can be combined in order to build very efficient process with efficiency penalties reduction ranging from 10% to 25%. Finally, some drastic process modification can improve very significantly the process performance such as advanced split-flow with a reduction of efficiency penalty around 30% or direct steam stripping with a reduction of efficiency penalty of 27%.

1. Introduction

The main limitation of post-combustion CO_2 capture technology is the high energy consumption leading to a power output loss of approximately 25% including CO_2 compression. Studies to break this limitation follow two main pathways: formulation of new solvents and optimisation of the process flowsheet. This work focuses on flowsheet optimisation which may allow, on a short term basis, significant reduction in energy consumption (20% at least).

Numerous patents, publications and communications from academic and industrial world propose some flowsheet modification in order to upgrade the process and his energetic integration with steam cycle (Harkin et al., 2009). The most discussed process

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features are the cooling of solvent in the middle height of absorber: intercooling (Freguia and Rochelle, 2003, Tobiesen et al., 2007, Plaza et al., 2010), the cooling of flue gas before the absorber: precooling (Tobiesen et al., 2007, Kvamsdal et al., 2009, Oexmann and Kather, 2009) and the bleeding of a fraction of solvent from the stripper coupled with a staged feed of the absorber: split-flow scheme (Leites et al., 2003, Aroonwilas and Veawab, 2007). In addition to these well-known modifications, the use of sensible heat contained in the various stream exiting the stripper focuses a lot of work (Reddy et al., 2004, Rochelle, 2007, Chen et al., 2007, Rochelle and Oyenekan, 2008). It consists, mostly, in flashing a hot liquid stream in order to produce vapour, this steam is then recompressed to the right operating pressure. Some other smaller modifications are also studied such as a lower pinch in the economizer, the use of the stripper condenser heat, the optimization of rich solvent injection in the stripper (Leites et al., 2003). Finally, some processes use multiple stripper in order to achieve a more efficient solvent regeneration (Reddy et al., 2004, Rochelle and Oyenekan, 2008).
The purpose of this study is to assess and compare most of the flowsheet modification described in the literature through modelling. The modelling tool used is ASPEN Plus®. The main component of the process, absorber and stripper were specifically modelled around a rate based model with mass transfer and kinetics limitations. The different case studies are compared to a reference case presenting a standard good performance in term of energy consumption. Their impact on the thermal power plant is also briefly studied in order to permit a performance comparison. The solvent used for the study is MEA.

2. Reference capture process

The reference capture process used is the standard one, presented in Figure 1. The solvent used is aqueous MEA at 30 % mass. The chosen packing have the same performance than Mellapack 250Y. Both absorber and stripper have 10 m of packing bed. The economizer temperature pinch is 10 °C. The minimum cooling temperature is 40 °C.

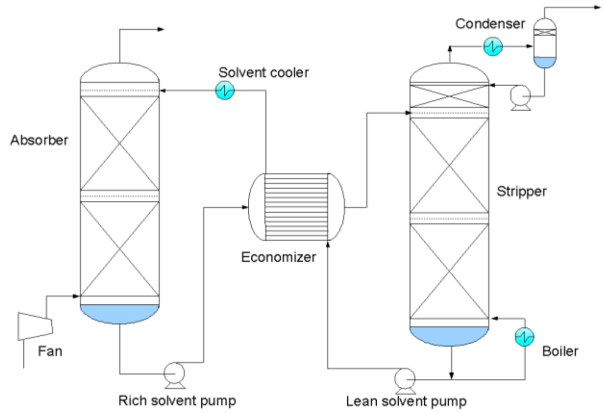

Figure 1: Standard CO_2 capture process

3. Modelling results and discussion

For each studied case, the stripper regeneration energy is optimized with respect to solvent flow rate and lean CO_2 loading in the same way as Abu-Zahra et al. (2007).

3.1 Individual process modification results summary and literature review

The simulations performed show that the process modification which has the most impact seems to be:

- a stripper operating with moderate void pressure (around 0.75 bar) which allows a gain of 0.7 %pt of efficiency compared to the standard stripper pressure of 2.5 bar;
- the staged feed of the stripper which allows a gain of 0.85 %pt of efficiency;
- the lean solvent vapour compression which allows a gain of 0.4 and 0.9 %pt of efficiency for a stripper operating pressure of respectively 1 and 2.5 bars
- the overhead stripper compression for a high pressure stripper which allows a gain of 0.5 %pt of efficiency;
- the internal stripper compression for a high pressure stripper which allows a gain of 0.5 %pt of efficiency.

Some other modifications improved the performance of the coupled capture plant and power plant but less significantly: intercooler, improved economizer, boiler condensate and vapour compression.

A few publications have already studied some individual processes modifications. The Table 1 summarizes some of these studies. In most of the case, some of the key parameters to couple the capture process with the power plant are not disclosed (stripper pressure, lean and rich loading, boiler duty, ...).

Table 1: Electrical works break down and efficiency loss for different process modification reported in the literature.

	Stripper pressure bar	Boiler duty GJ/t_{CO2}	Parasitic load kWh/t_{CO2}	Fan works KWh/t_{CO2}	Pumping works kWh/t_{CO2}	Comp. Works kWh/t_{CO2}	Addition al works kWh/t_{CO2}	Total eq. works kWh/t_{CO2}	Efficien. loss %pt
Intercooler[1]	***bar***	3.11	269.9	23.4	4.8	85.4	0.0	383.6	11.65
Intercooler[2]	2.5	3.18	275.5	23.4	4.8	85.4	0.0	389.2	11.82
Economizer+[3]	2	3.23	262.1	23.4	4.9	92.1	0.0	382.5	11.62
Overhead comp.[3]	2	1.94	160.8	23.4	4.8	31.7	152.5	373.2	11.34
Stripper Int. comp.[3]	2	2.65	218	23.4	4.9	58.2	71.3	375.9	11.42
Internal exchange[4]	n.a.	n.a.	n.a.	23.4	n.a.	n.a.	n.a.	325.0	9.87

[1]: Freguia and Rochelle, 2003, [2]: Tobiesen et al., 2007, [3]: Jassim and Rochelle, 2006, [4]: Oyenekan and Rochelle, 2007.

In order to make results comparable, some assumptions have been made: the published reference boiler duty has been considered equals to our works boiler duty at the same stripper pressure. From this main assumption, other boiler duty of the same publication have been extrapolated. Fan, pumping and compression works have been recalculated with the specified pressure and capture rate. The performance calculated in the works of Oyenekan and Rochelle (2007) has to be considered with caution because the paper do not show sufficient data to allow the electrical works breakdown. The same method than for other publications has been used but the reference is the total equivalent works and not the boiler duty because it is not available. The studies found in literature for the individual process modification are summarized in Table 5.

The intercooler studies show an efficiency loss ranging from 11.65 to 11.82 %pt (11.77 for this paper), the improved economizer study show an efficiency loss of 11.62 %pt (11.78 for this study), the overhead compression and stripper internal compression show an efficiency loss of, respectively, 11.34 and 11.42 %pt (11.44 and 11.46 for this study). The reproducibility of the performance evaluation seems adequate with an uncertainty of approximately 0.1 %pt of efficiency. Rochelle and Oyenekan (2007) studied an internal exchanger equipped stripper and calculate an efficient loss of 9.87 %pt.

3.2 Combination of process modifications

Interaction between process modifications can lead to significant improvement. Some modifications interact positively, some others negatively. The purpose of this part is to explain some of these interactions. The Table 2 summarizes qualitatively process modification interaction. This table propose a clear representation of the good process modification combination. For example, the mix of a high pressure stripper, an improved economizer, a stripper staged feed and a stripper intermediate compression would lead to an efficient design.

Table 2: Summary of the interaction between process modifications studied in this paper.*

	Stripper split-flow	Partial flash regen.	Direct steam stripping	Stripper Int. Comp.	Condensate Comp.	Overhead Comp.	Lean Vapour Comp.	Vacuum stripper	Atm. stripper	Normal stripper	Imp. economizer	Staged stripper feed	Intercooler/precooler
Intercooler/Precooler	0	0	0	0	0	0	0	0	0	0	0	0	0
Staged stripper feed	++	0	+	+	0	0	0	0	+	+	++	0	
Imp. economizer	+	+	++	+	0	+	-	0	+	+	0		
Normal stripper	0	0	-	+	0	++	++	X	X	0			
Atm. stripper	0	-	+	0	0	0	+	X	0				
Vacuum stripper	0	-	++	-	0	-	-	0					
Lean Vapour Comp.	?	?	0	0	0	0	0						
Overhead Comp.	0	0	?	-	0	0							
Condensate Comp.	0	0	X	0	0								
Stripper Int. Comp.	?	0	?	0									
Direct steam stripping	?	?	0										
Partial flash regen.	-	0											
Stripper split-flow	0												

* 0: no specific interaction (neutral), -: negative interaction, +: positive interaction, ++: very positive interaction, X: modification not compatible, ?: no conclusion yet

4. Conclusion

Process modification in order to optimize the overall efficiency of a system coupling a power plant and a CO_2 capture process is an efficient way to proceed. This modification can be quite rapidly evaluated by simulation with state of the art rate based column model. This paper shows that these process modifications can improve the overall efficiency. The best individual simple modifications are:

- a stripper operating with moderate void pressure (around 0.75 bar);
- the staged feed of the stripper;
- the lean solvent vapour compression;
- the overhead stripper compression.

They allow a reduction of efficiency penalty of 4 to 8 %. Some other modifications contribute to the good performance of the process such as intercooler, improved economizer and boiler condensate vapour compression, with a reduction of efficiency penalty around 2%. These individual modifications can be combined in order to build very efficient process with efficiency penalties reduction ranging from 10% to 25%. Some modification such as stripper internal heat exchanger can be considered as a mix of an improved economizer with a staged feed of the stripper. Finally, some drastic process modification can improve very significantly the process performance such as: advanced split-flow with a reduction of efficiency penalty of around 30% or direct steam stripping with a reduction of efficiency penalty of 27 %.

This paper proposes a qualitative summary of binary interaction between process modifications. An analysis of heat transfer and mass transfer pinches for the different heat exchanger and columns could help in this optimization of parameters (Dunn et al., 2003, Leites et al., 2003).

All these modifications are based on a few simple principles which are: the minimization of the driving force along column and heat exchanger and the reduction of wasted heat. Limitation of excessive driving force and maximisation of thermodynamic potential are key concepts in order to optimise the energy consumption of such process (Leites et al., 2003). All modifications that reduce the wasted heat or the cooling water demand induces a reduction in boiler duty.

Monoethanolamine (primary amine) is the most studied solvent with or without innovative flowsheets. The same kind of study should be carried out with different solvents. Methyldiethanoamine (tertiary amine) and aminomethylpropanol (sterically hindered primary amine) could be good candidate because they have a different behaviour than monoethanolamine.

All the process modifications mentioned in this study have not been demonstrated at the pilot scale. This step is necessary in order to validate the simulated performance and to verify operational problem such as corrosion, maintenance and operability.

These modifications allow an overall power plant efficiency loss of 9 %pt at the strict minimum. This 9 %pt is not enough to cope with most utilities companies target of 5 %pt as maximum efficiency loss due to the CO_2 capture process and, therefore, are not sufficient to enable large scale CO_2 capture deployment. These process modifications must be coupled with using new solvents and innovative power plant heat integration strategies in order to show the true potential of the amine-based post-combustion capture processes.

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