

ENERGY SAVINGS POTENTIAL THROUGH WASTE HEAT RECOVERY FROM FLUE GAS FOR POST COMBUSTION CO₂ CAPTURE

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ABSTRACT

Flue gas from a plant using fossil fuels contains CO₂. Thus power/process plants using fossil fuels contribute to climate change if CO₂ in flue gas is not captured. The process of CO₂ capture from flue gas is called 'post-combustion' CO₂ capture. Existing plants may be retrofitted with this process to minimize CO₂ emission. Amine solutions are mostly used for this process to scrub the flue gas. Amine based CO₂ capture involves two-stage process. In absorber column flue gas containing CO₂ is scrubbed by amine solution to produce CO₂-rich solution which is subsequently stripped off absorbed CO₂ by heating in a stripper column. The inlet flue gas to the absorber column must be ~40°C and hence needs cooling. On the other hand, subsequent stripping process needs significant heating. Thus process of post-combustion CO₂ capture has an energy penalty which reduces the overall efficiency of the plant. In this paper, waste heat recovered from the flue gas during its cooling before being introduced to the absorber is proposed to be utilized for partial supplement in subsequent heating in stripper. System layouts have been conceptualized and ASPEN Plus[®] simulation results for three improved layouts are discussed for energy savings with respect to a base case process. It shows that significant energy savings potential exist by improved process conceptualization.

Key words: Post combustion carbon capture, MEA, ASPEN Plus[®] simulation, flue gas, waste heat recover

1. INTRODUCTION

Economic growth and standard of living of a country is often grossly measured by per capita energy consumption. The major source of energy for industrial use including power generation has been fossil fuels over a long period and still expected to continue for significant period in future [1]. As fossil fuels are mixture of hydrocarbons, CO₂ is inevitably one of the products of combustion. Greater the use of fossil fuels more is the emission of CO₂ unless some active measures are adopted to capture it. Unfortunately, anthropogenic CO₂ emission with industrial growth all over the world has increased CO₂ level in atmosphere to an alarming amount led to possibility of climate change, presently greatest challenge for survival of life on earth [2]. However due to matured technology with existing infrastructure, fossil fuels will continue as the major source of energy even for a significant future period [3]. Due to this compulsion of use of fossil fuels and associated climate change problem, CO₂ capture and storage is urgently required for future energy use [4].

Use of fossil fuels without net CO₂ emission to the atmosphere can be done by either of three possible major options - pre combustion CO₂ capture [5], post combustion CO₂ capture [6] or oxy-fuel combustion with CO₂ capture [7]. However, post combustion CO₂ capture option is most suitable for retrofitting to existing utilities emitting CO₂ [8]. In this process flue gas containing CO₂ is usually scrubbed by a suitable solvent to capture CO₂ from the flue gas mixture. This CO₂-rich liquid solvent is subsequently heated to release captured CO₂ for subsequent sequestration. However significant amount of energy is required for this process of heating. This energy requirement affects the overall efficiency of the plant [9, 10, 11].

In this paper a possible option for saving energy has been explored theoretically for post combustion CO₂ capture. For CO₂ being absorbed by a solvent (say, methylethanolamine) the gas mixture must be scrubbed by the solvent at a temperature (say, ~40°C) much lower than the usual temperature of flue gas as in industrial process. Hence flue gas from the plant must be cooled before being introduced for CO₂ capture.

In this paper the potential for using the recovered waste heat during this cooling process to utilize for subsequent heating recover CO₂ again from the solvent is explored. Several process layouts are conceptualized and energy savings potential is estimated and compared using ASPEN Plus[®].

2. Post combustion CO₂ capture process using amines

In industrial flue gas the mole fraction of CO₂ is relatively low. For example, it is 4-8% by volume in natural gas fired and 12-15% by volume in coal fired power plant flue gases respectively [12]. Different methods have been developed at laboratory scale for post combustion capture of CO₂ [13]. However amine based capture of CO₂ from flue gas is most developed and reliable technology presently [12, 13, and 14]. In this process organic liquids in the form of aqueous solution of various alkanolamines are used to absorb CO₂ from the flue gas. Flue gas has to be cooled to about 40°C before being used for CO₂ capture. Presence of other impurities, specifically acid gases like SO_x and NO_x will cause some loss of amine, as permanent salt. Thus NO_x and SO_x in the flue gas should be limited before this process for CO₂ capture using amine solutions. Recommended NO_x level of less than 20 ppmv [15] is fortunately achieved by most modern low NO_x burners. However regarding SO_x, specifically for high sulfur fuel, a trade-off between the cost of flue gas desulfurization and cost of makeup solvent to compensate the degraded solvent is to be evaluated.

In this paper a few systems have been conceptualized to capture CO₂ from the flue gas using waste heat of flue gas itself. ASPEN Plus[®] simulation is done to evaluate the energy performance of these conceptualized schemes. Electrolyte Non Random Two Liquid vapor phase modeled (ELECNRTL) property method has good accuracy to estimate thermo-physical properties of carbon capture and hence used for this simulation. Relative performance for these improved schemes is compared with a base case scheme as reference. The ASPEN Plus[®] models for the base case as well as the same for improved schemes using methylethanolamine is described below.

2.1 ASPEN Plus[®] model for base case

The simplest possible base case is shown in Fig.1. Cooled flue gas (at 40°C) is introduced at the bottom and amine solution is introduced at the top of the absorber column. Flue gas gets scrubbed in counter flow direct contact between the flue gas and the amine. CO₂-free flue gas leaves from the top of the absorber while CO₂-rich amine solution leaves at the bottom of it. CO₂ rich solution is then pumped to the stripper column through a preheater. Preheater is necessary for introduction of CO₂-rich solution to the stripper column at a specified temperature (~81°C). Subsequent heating in stripper column releases CO₂ gas from the solution and it leaves from the top of the column while CO₂-stripped amine solution is recycled back from the bottom of the column.

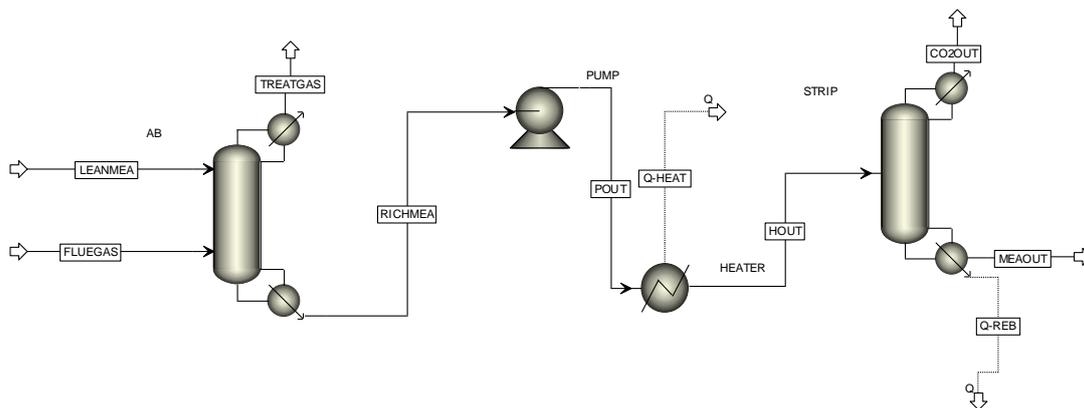


Fig.1: ASPEN Plus[®] model for base case

Heating requirement for this process is divided in preheater (relatively smaller amount) and in stripper column (majority of heating).

In this base case simulation, no waste heat recovery during flue gas cooling is considered.

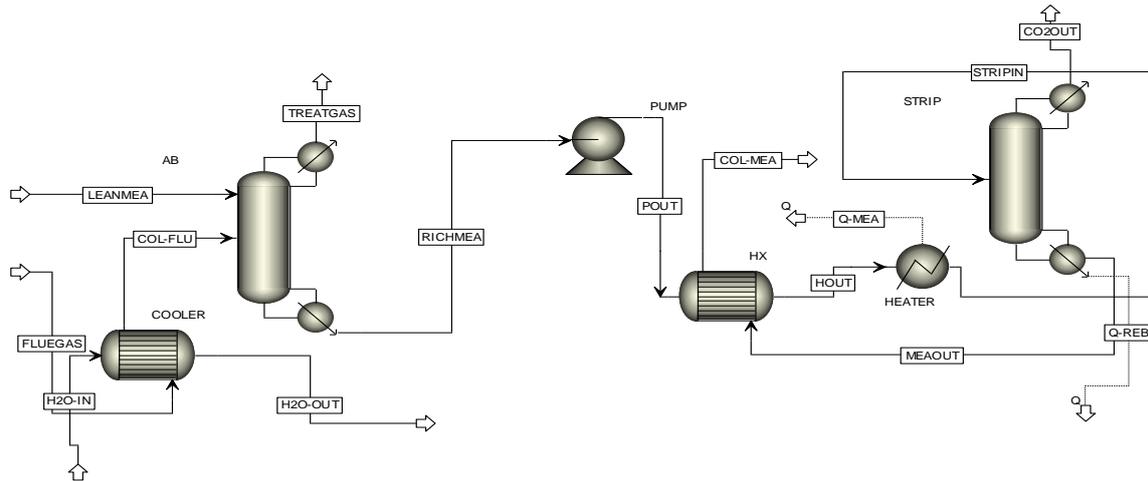


Fig.2: ASPEN Plus® model for improved system #1

2.2 Improved system # 1

The heat required in preheater can be reduced through a heat exchange process between return amine solution from the stripper column at a higher temperature and CO₂-rich solution from the absorber column at a lower temperature. Depending on heat gained by the CO₂-rich solution, preheater heat load decreases accordingly.

This improves energy performance due to reduction of preheating energy. This scheme is shown in Fig.2.

2.3 Improved system # 2

The next layout for improved energy performance is shown in Fig.3. In this scheme waste heat from the flue gas during its cooling is proposed to utilize.

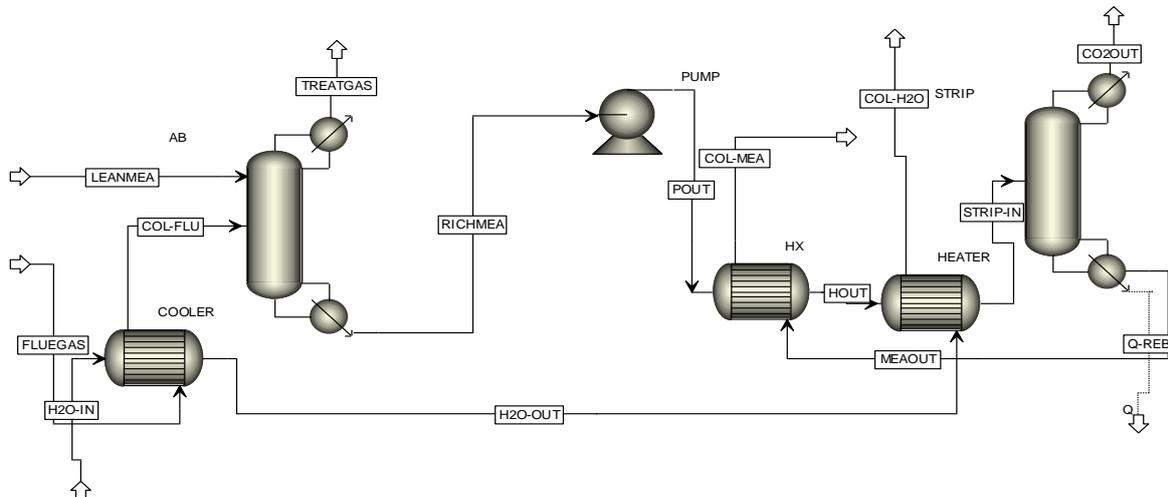


Fig.3: ASPEN Plus® model for improved system #2

Table 1
Description of components of ASPEN Plus model

Block ID	ASPEN Plus ID	Description
COOLER	HeatX	Cools the flue gas to 40 ⁰ C by cooling water
ABSORB PUMP	RadFrac Pump	Absorbs carbon dioxide from flue gas by amine solution Increases pressure of CO ₂ -rich solution to compensate pressure drop across stripper column
HX	HeatX	Exchanges heat between CO ₂ -rich and CO ₂ -lean solution
HEATER	HeatX	CO ₂ -rich solution gets heated by hot water generated at flue gas cooling process
STRIP	RadFrac	CO ₂ be separated from amine solution by reboiler heat
MHX	MHeatX	Exchanges heat between three stream i.e. CO ₂ -rich, CO ₂ -lean solution and hot flue gas from plant

Hot flue gas is assumed to pass through a heat exchanger for cooling before being introduced to the absorber at 40⁰C. Presence of any acid gas may cause acid condensation with moisture content of flue gas. Usually flue gas cooling below acid dew point is not recommended within process equipment to avoid corrosion. However development of anti-corrosion (with proper material and coating) heat exchangers can resist corrosion and recover waste heat from flue gas oven containing some acid gases [16]. Cooling water is used in the heat exchanger at atmospheric pressure. Generated steam in the heat exchange process is proposed for partial preheating of the CO₂-rich amine solution to the stripper.

Rest heat load of the preheating process is provided in a similar heat exchange between CO₂-rich and CO₂-lean solutions as described for system #2.

2.4 Improve system #3

In this scheme waste heat recovered from the flue gas is proposed to heat the CO₂-rich amine solution rather than using cooling water. Heat exchange from CO₂-lean solution from the stripper is also assumed in this multi-stream heat exchanger as shown in Fig.4. Thus preheating of CO₂-rich solution to stripper column is obtained by waste heat recovery from the flue gas and CO₂-lean solution from the stripper column. The heat exchanger should be corrosion resistance if flue gas contains acid gas beyond certain volume fraction.

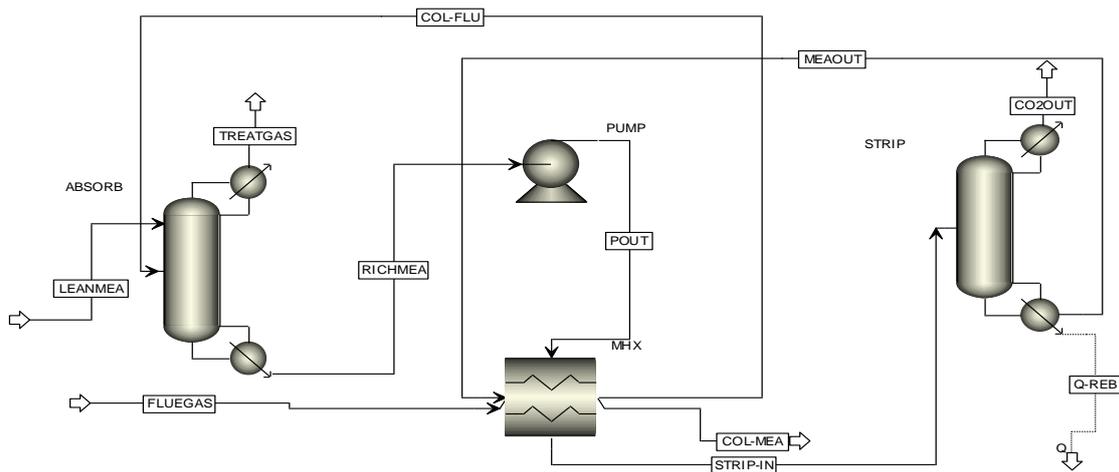


Fig.4: ASPEN Plus® model for improved system #3

3. RESULTS AND DISCUSSION

Table 2

Flue gas condition

Pressure =1.033 bar
 Hot gas temperature=160°C
 Cold gas temperature=40°C
 Total flow=0.158kg/s
Mass fraction
 H₂O=0.0193
 CO₂=0.2415
 N₂=0.7392

ASPEN Plus® flowsheet simulation has been carried out for a base case as well as three improved systems. A standard flue gas composition is assumed for simulation for all these four schemes. This assumed flue gas composition is given in Table 2. For comparison of energy savings potential of all three improve systems relative to each other as well as with respect to the base case, operating parameters for all schemes are maintained identical as represented in Table 3. Assumed solvent for these analyses is methylethanolamine.

Table3

Operating parameters for the simulation with name of block/stream in parenthesis

Configurations (BLOCK/STREAM)	Parameters	Value
Hot/Cold flue gas (FLUEGAS)	Temperature	160/40°C
	Pressure	1.033 bar
	Mass flow rate	0.158 kg/s
Lean amine solution (LEANMEA)	Temperature	40°C
	Pressure	1.7 bar
	Amine concentration	30% by mass
Cooling water (H2O-IN)	Temperature	25°C
	Pressure	1 atm
	Mass flow rate	0.035 kg/s
Flue gas cooling (COOLER)	Hot stream outlet temperature	40°C
	Absorber column (ABS)	Calculation type
Pump (PUMP)	No. of stages	7
	Condenser pressure	1 atm
	Pressure increases	20 psia
Rich-lean heat exchanger (HX)	Hot inlet- cold outlet temperature difference	10°C
	Rich solution heater (HEATER)	Outlet temperature approach
Stripper column (STRIP)	Calculation type	Equilibrium
	No. of stages	7
	Condenser type	Partial vapor
	Condenser pressure	10 psia
	Reboiler type	Kettle
	Distillate rate	96 kg/hr

The major penalty for post combustion CO₂ capture is the energy consumption in this process. The total heat required consists of preheating heat load and reboiler heat duty.

These two energy consumptions as well as sum of them for base case are shown in Fig.5. It is noted that preheater heat load is almost half of the reboiler heat duty.

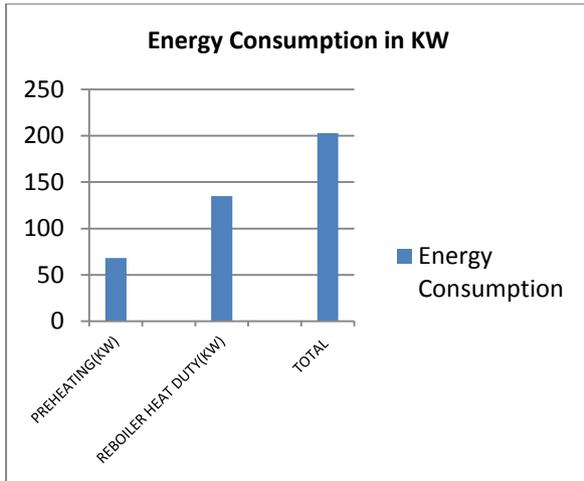


Fig. 5: Energy consumption for base case

In improved scheme #1 energy savings is obtained in preheating process while reboiler heat duty remained unaltered. Significant saving 97.2% in preheating through heat exchange between CO₂-rich and CO₂-lean solution is observed. Reboiler heat duty remaining constant, energy savings through this heat exchanges was 32.5% in total as shown in Fig. 6.

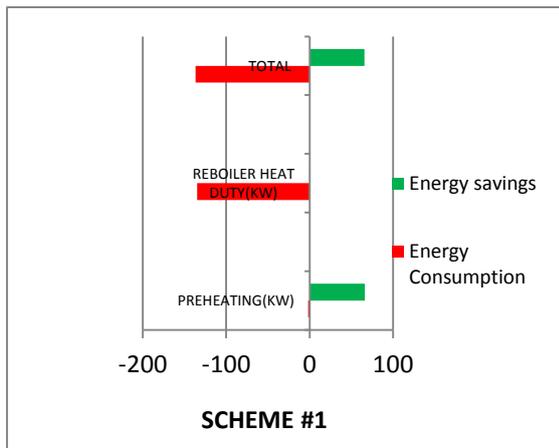


Fig. 6: Energy consumption and savings for scheme # 1

Improved scheme #2 shows better energy performances than the previous one as shown in Fig.7. Energy savings occurred in both preheating and stripping processes. Utilization of waste heat from the flue gas cooling process has significant effect in total energy saving of 36.98%. This total energy savings is contributed by 100% reduction of preheating energy consumption and 5.29% reduction of reboiler heat duty.

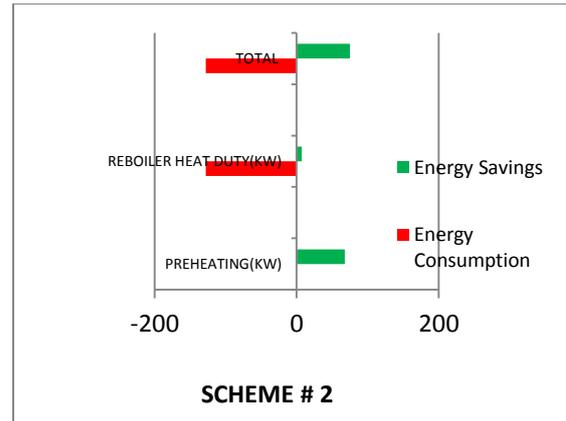


Fig. 7: Energy consumption and savings for scheme # 2

In heat exchange process using amine directly instead of cooling water led to even better energy performance for improved scheme #3 as shown in Fig. 8. Simulation results shows that in addition to complete saving of preheating energy requirement, the reboiler heat duty was also reduced by 9.27% as shown in Fig.8. Energy saving for the whole process with respect to the base case for the improve scheme #3 is 39.67%.

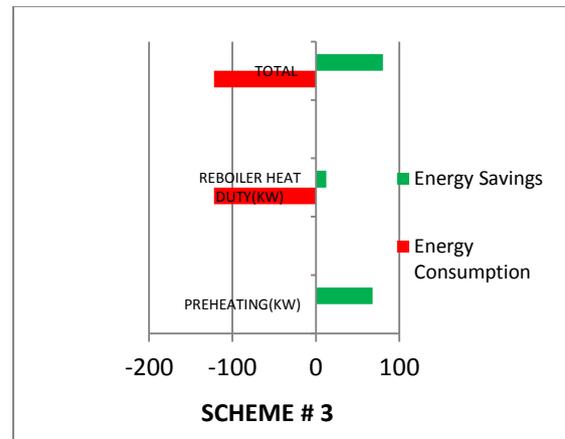


Fig. 8: Energy consumption and savings for scheme # 3

Schemes #1, #2, #3 were progressively more complex than the base case. Also heat exchangers for better heat utilization involved higher capital investment and greater operational difficulty. Moreover heat exchanger that cooled flue gas containing acid gases below acid dew point needed special coating and/or corrosion-resistant material and hence was costly equipment.

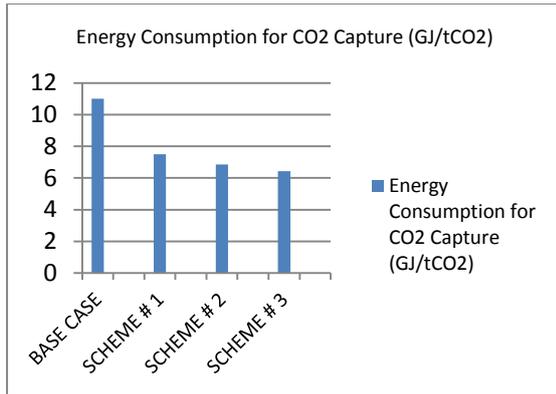


Fig. 9: Comparison of total energy consumption for different scheme

Additional capital investment would be justified if running cost decreased during operation. An estimation for heat required per ton of CO₂ capture for all three improved schemes with respect to the base case is shown in Fig.9. It is noted that with increasing complexity, improved schemes show better energy saving potential too. Thus scheme #3 had the best operating performance with respect to energy required per ton of CO₂ capture. However subsequent techno-economic optimization study considering capital investment against energy savings potential must be done to decide the best scheme out of these possible options.

4. CONCLUSION

Carbon dioxide emission from fossil fuel based process or power plants are one of the major sources of climate change. Complete replacement of fossil fuels by renewable resources is also impossible in near future. Thus CO₂ capture retrofitting with existing power/process plants emerges as urgent necessity. Amine based CO₂ capture process is most reliable process presently. Large energy requirement is the most serious penalty for this CO₂ capture process. However improved process layouts with additional heat exchangers have strong potential for better energy performance. Result of ASPEN Plus[®] simulations for three such improved schemes are presented. It is concluded that significant energy saving potential exists through such improved process modification for better performance. However additional capital investment for installation of more equipment has to be justified against the saving of energy.

REFERENCES

1. IEA 2011, International Energy Agency, World Energy Outlook, 2011, Paris.
2. IPCC, IPCC 4th Assessment Report, Climate change 2007 (AR4), (available at: <http://www.ipcc.ch/>)

3. Splithoff, H., 2010, *Power generation from solid fuels*, First Edition, Springer, Germany.
4. IEA, IEA Statistics 2011 edition : CO₂ emissions from fuel combustion highlights, International Energy Agency, Paris, 2011.
5. Cormos, C.-C., 2012, "Integrated assessment of IGCC power generation technology with carbon capture and storage (CCS)", *Energy*, 42: 434-445.
6. Peng, Y., Zhao, B., Li, L., 2012, "Advance in Post-Combustion CO₂ Capture with Alkaline Solution: A Brief Review", *Energy Procedia*, 14: 1515-1522.
7. Scheffknecht, G., Al-Makhadmeh, L., Schnell, U., Maier, J., 2011, "Oxy-fuel coal combustion-A review of the current state-of-the-art" *Intrnational Journal of Greenhouse Gas Control*, 5S: S16-S35.
8. Lucquiaud, M., Gibbins, J., 2011, "On the integration of CO₂ capture with coal-fired power plants: A methodology to assess and optimize solvent-based post-combustion capture systems", *Chemical Engineering Research and Design*, 89: 1553-1571.
9. Strube, R., Manfrida, G., 2011, "CO₂ capture in coal-fired power plants-Impact on plant performance", *International Journal of Greenhouse Gas Control*, doi: 10.1016/j.ijggc.2011.01.008.
10. Feron, P.H.M., 2010, "Exploring the potential for improvement of energy performance of coal fired power plants with post-combustion capture of carbon dioxide", *International Journal of Greenhouse Gas Control*, 4: 152-160.
11. Harkin, T., Hoadley, A., Hooper, B., Reducing the energy penalty of CO₂ capture and compression using pinch analysis", *Journal of Cleaner Producton*, 18: 857-866.
12. Padurean, A., Cormos, C.-C., Cormos, A.-M., Agachi, P.-S., 2011, "Multicriterial analysis of post combustion carbon dioxide capture using alkanolamines", *International Journal of Greenhouse Gas Control*, 5: 676-685.
13. Rubin, E.S., Mantripragada, H., Marks, A., Versteeg, P., Kitchin, J., 2012, "The outlook for improved carbon capture technology", *Progress in Energy and Combustion Science*, 38(5): 630-671.
14. Wang, M., Lawal, A., Stephenson, P., Sidders, J., Ramshue, C., 2011, "Post combustion CO₂ capture with chemical absorption: A state-of-the-art review", *Chemical Engineering Research and Design*, 89: 1609-1624.
15. King, I., Svendsen, H.F., 2007, "Heat absorption of carbon dioxide in monoethanolamine and 2-(aminoethyl) ethanolamine solutions", *Industrial and Engineering Chemistry Research*, 46: 5806-5809.

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