CHEMICAL ENGINEERING TRANSACTIONS
VOL. 45, 2015
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216 DOI: 10.3303/CET1545046

Numerical Evaluation of CO_2 Capture on Post-combustion Processes

Rosa-Hilda Chavez*[,a], Javier J. Guadarrama[b]

[a]Instituto Nacional de Investigaciones Nucleares. Carretera México-Toluca s/n, La Marquesa, Ocoyoacac, Edo. México C.P. 52750, México
[b]Instituto Tecnológico de Toluca. Av. Instituto Tecnológico s/n, Ex-Rancho la Virgen, Metepec, Edo. México, C.P 52140, México
rosahilda.chavez@inin.gob.mx

This paper is focused on the evaluation of a CO_2 capture post-combustion process of three Mexican power plants. They were compared with each other to determine what obtains the biggest CO_2 capture flow using the same size of experimental absorption column, by means of the hydrodynamic behavior and maximum CO_2 absorption with 30 % Monoethanolamine in aqueous solution. The chemical absorption with amines is the best technology for post-combustion CO_2 capture, due to handle large volumes of flue gas, low pressures of operation, rapid response and low cost, although it is highly energy intensive because of the thermal energy requirement needed to regenerate the amine solution while another disadvantage is the loss of amine. Numerical evaluations were developed by computer simulation models applied to the structured packing. The results shows the greater CO_2 capture flow obtained was from a coal-fired Piedras Negras power plant with 3.03 t/d, followed by caldera gas type of Valley of Mexico power plant with 1.88 t/d, and the lowest one was the gas turbine type of Poza Rica power plant with 0.8011 t/d.

1. Introduction

One of the main challenges of implementing CO_2 capture at a power plant is the penalty on electrical output (De Miguel Mercader et al., 2012). The performance of the combined installation, measured by the net electrical output is therefore, a key indicator for process optimization (Biliyok et al., 2013), and CO_2 capture development (Klemeš et al., 2007).
The post-combustion process using amine, is the most promising technology among post-combustion processes due to its ability to handle large volumes of flue gas (Canepa et al., 2015), rapid reaction of CO_2, operation at ambient conditions, high efficiency separation of CO_2 and low cost, (Sipöcz and Tobiesen, 2012). However, it is still highly energy intensive (Mores et al., 2012) due to the thermal energy requirement needed to regenerate the amine solution which increases the operating cost drastically (Neveux et al., 2013) and another drawback of this method is the loss of amine in the regenerator unit, because of oxidative and thermal degradation of amine (Porcheron et al., 2011).
The amine absorption processes have the advantage of improving the understanding of the solution behavior associated with absorption and regeneration reactions (Grncarovska et al., 2013) and thus provide scientific tools for the objectives of climate change actions and the stabilization of atmospheric concentrations of greenhouse gases (MacDowell et al., 2011).

2. Methodology

During the last years research activities in CO_2 capture have been done in different lines from experimental studies at laboratory scale and pilot plants (Mores et al., 2012) to the development and implementation of mathematical models in computers (Kakaras et al., 2013).
Figure 1 shows the flowchart of a system for capturing CO_2, used to obtain several parameters needed to evaluate CO_2 capture with this system using diverse study cases with Aspen Plus simulator (Timmerman 2013); the system consist of five several columns, two heat exchangers and a mixer, (Tous et al., 2013) to

Please cite this article as: Chavez R.-H., Guadarrama J.J., 2015, Numerical evaluation of co2 capture on post-combustion processes, Chemical Engineering Transactions, 45, 271-276 DOI:10.3303/CET1545046

carry out the CO_2 capture process (Moioli and Pellegrini, 2013). The CO_2 loaded solvent (rich solvent) is regenerated in stripper and sent back to the absorber to close the cycle (De Miguel Mercader et al., 2012). Between the absorber and the stripper (Damartzis et al., 2013), a heat exchanger transfers part of the heat from the lean to the reach solvent (Meldom, 2011). At the top of the stripper, high purity CO_2 is produced as CO_2 capture flow (Lucquiaud and Gibbins, 2011) and is sent to a compression unit for further transport (Mikulcic et al., 2013) and storage (Saavedra et al., 2013).

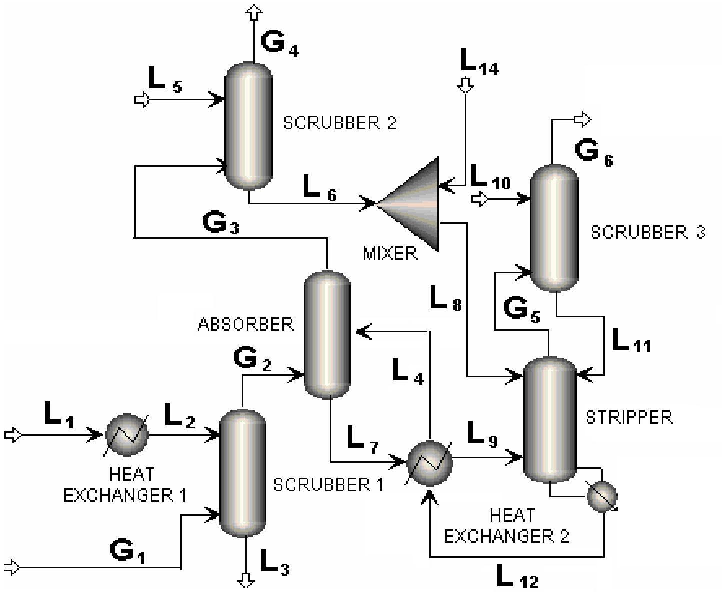

Figure 1: Flow diagram of the CO_2 capture system, using the Aspen Plus simulator

In order to determine the optimum operational condition of a packed column irrigated, it was determined hydrodynamic behavior of the column filled with ININ 18 structured packing. Loading or load point is the maximum gas rate condition above which the efficiency of a packed bed rapidly deteriorates with an increase in gas rate. Hold up is the amount of liquid held on the surface of the packing and in the voids of the packed bed. Hold up increases with an increase in liquid rate but the effect of gas rate on hold up appears minimal up to the load point. The load point usually occurs between 75 to 90 % of the flooding gas rate for structured packing. Packed columns flood occurs when excessive liquid hold up results from the interaction of gas and liquid in a packed bed. Characteristic of this condition is very poor separation efficiency and usually excessive pressure drop in the packed bed. Due to the efficiency decreases very rapidly at rates beyond the load point, the flood point of packed column usually is not a useful design criterion parameter as the load point (Yazgi and Kenig, 2013).
Packed columns are mainly used for mass transfer processes and for direct heat transfer between two phases (Petrova et al., 2013). Their design and operation require knowledge of the operating zone. Particular interest is attached to the load at which the liquid commences to hold up in the column and when flooding occurs.
The methodology developed was:

1) Obtain experimental data using an absorption column. The experimental column has 0.30 m diameter, 3.5 m packed height, and 0.0706 m^2 cross sectional area, and it was used Monoethanolamine (MEA) at 30 % weight aqueous solution for the chemical absorption of CO_2. The experimental column filled with ININ 18 structured packing has the capacity to process 10.9 t/d of flue gas released from the chimneys of power plant, at 30 ºC and 0.69 bar. The column with ININ 18 structured packing, was operated at different L/G rates in order to obtain loading operation.
2) A hydrodynamic model for structured packing (Stichlmair et al., 1989) was used to obtain parameters such as pressure drops at different liquid and gas flows in the absorption and desorption columns, energy requirements, were determined with 10.9 t/d fed as flue gas to absorption column size. Experimental values were fed as known parameters in the numerical evaluation of pressure drop per liquid and vapor rate at 75 to 90 % with respect to the flooding vapor rate.

The results obtained in this research not only improve the understanding of solution behavior associated with absorption and regeneration reactions (Linnenberg et al., 2011) but also provide the information needed to develop a model capable of describing the L/G ratio (Matsuda, 2013) which is fundamental for simulation and optimization (Sun et al., 2013) of CO_2 capture process using amines (Moullec, 2012).
The efficiency of packing is a strong function of packing size, physical properties and proper liquid distribution. In general, the packing efficiency increases when the height of overall vapor phase transfer unit decreases, but also becomes progressively more sensitive to the uniformity of the liquid distribution.
In reality, for each industrial plant to meet plant specific demands and conditions (Anantharaman et al., 2013), each one has specific solution (Semkov et al., 2013).
Table 1 shows the actual characteristics of flue gas of the three power plants in Mexico named and located: Valle de México, Queretaro State; Poza Rica, Veracruz State and Rio Escondido, Coahuila State, power plants.

Table 1: Characteristics of flue gas

Characteristics of flue gas	Valle de Mexico (caldera gas type)	Poza Rica (gas turbine type)	Rio Escondido (coal type)
Power plant total flue gas (t/h)	627.6	1,645.6	1,338.3
Electrical output (MW)	158.17	170.55	300.00
% mol CO_2 (% mass)	7.85 (12.45)	3.70 (5.78)	12.47 (19.46)
% mol SO_2	0.0	0.0	0.06
% mol N_2	70.53	72.79	72.02
% mol O_2	3.28	12.19	4.81
% mol H_2O	17.49	10.44	9.78
% mol Ar	0.85	0.8767	0.87
CO_2 flow (t/h)	78.13	95.11	260.43
Flue gas temperature (ºC)	126.7	601.1	151.2
Pressure (atm)	1	1	1
Molecular weight of flue gas (g/gmol)	27.74	28.14	29.31
Flue gas density (kg/m^3)	1.13	1.15	1.19
Flue gas dynamic viscosity (kg/ms)	1.43×10^{-5}	1.56×10^{-5}	1.54×10^{-5}
Flue gas kinematic viscosity (m^2/s)	1.26×10^{-5}	1.35×10^{-5}	1.29×10^{-5}
MW equivalent related 10.9 t/d	0.115	0.047	0.100

3. Results and Discussion

The methodology described was developed based on L/G = 1.5 ratio and 0.3 m columns diameter, 90 % of absorption efficiency and 90 % of CO_2 captured. To evaluate the maximum capacity of CO_2 absorption and regeneration of the solvent, numerical simulations were performed to three power plants. Table 2 shows the results for the hydrodynamic behaviour of each one. Values from Table 1 and 2, as % CO_2 concentration flue gas and irrigated pressure drop, were used in the evaluation per each power plant.

Table 2: Hydrodynamic parameters (Stilchmair et al., 1989) with L/G = 1.5 relationship and 0.3m columns diameter

Hydrodynamic parameters	Valle de Mexico (caldera gas type)	Poza Rica (gas turbine type)	Rio Escondido (coal type)
Gas velocity U_G (m/s)	2.74	2.75	2.69
Equivalent diameter (m)	1.2×10^{-3}	1.2×10^{-3}	1.2×10^{-3}
Reynolds number	244.66	262.98	251.43
Friction factor	0.5392	0.5304	0.5358
Dry pressure drop (N/m^2)	473.27	460.59	469.49
Dimensionless factor	0.0477	0.0464	0.0473
Froude number	0.00118	0.001191	0.00113
Liquid holdup	0.0588	0.0588	0.0579
c exponent	-0.2323	-0.2238	-0.2291
Irrigated pressure drop (Pa/m)	935.55	907.84	916.88

Figure 2 shows that CO_2 production rises when increasing the column diameter, while Figure 3 shows CO_2 production is reduced when L/G ratio increase, as these were expected.

Figure 2 shows that Rio Escondido power plant is the highest CO_2 flow production, and then Valley of Mexico plant has greater advantage than Poza Rica plant as result of its CO_2 concentration in the flue gas. Figure 3 shows for handling 0.3 m as columns diameter, the best L/G ratio is 1.5 due to optimum operational condition of a packed column irrigated. From these results presented, it is shown that the maximum discharge of CO_2 from coal-fired with 3.03 t/d was obtained, followed by caldera gas type of Valley of Mexico, with 1.88 t/d, and the lowest one was gas turbine type of Poza Rica, with 0.8011 t/d. In contrast, coal-fired power is the one with SO_2 and other gases which imply pre-treatment combustion gases to reduce these before passing them to the capture of CO_2 through the amine (see Table 2).

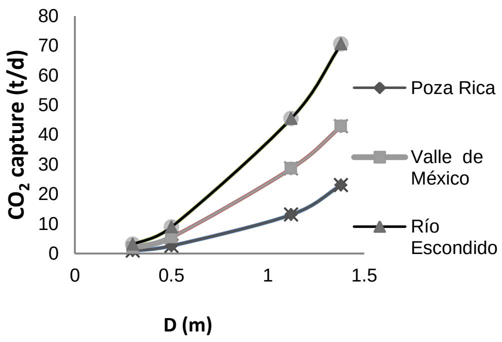

Figure 2: CO2 capture vs column diameter, at L/G = 1.5

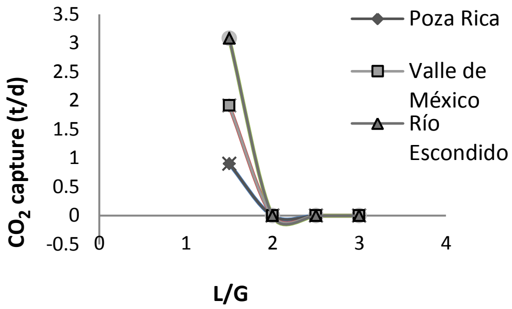

Figure 3: CO2 capture vs L/G ratio

Figure 4 shows the equivalent energy requirements with respect of different values of flue gas processed. It shows that MW_{eq} raises when flue gas increasing, it was expected as bigger scale of plants. Valle de Mexico plant, of caldera gas type, has bigger MW equivalent than Rio Escondido plant, of coal type; and this last one bigger than Poza Rica Plant, of gas turbine type, as the same flue gas processed.

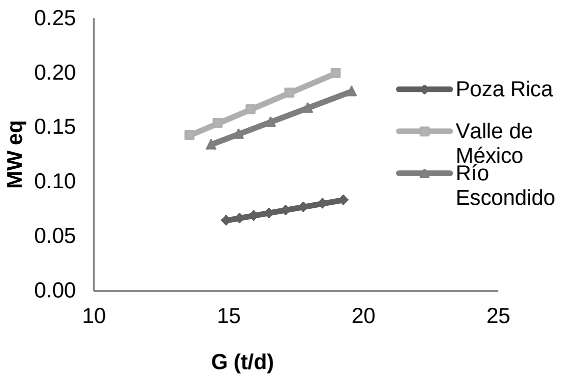

Figure 4: MW equivalent vs flue gas

4. Conclusions

The projection on the amount of CO_2 captured requires L/G ratio close to unity, since higher or lower values lead to failures in the mathematical procedures. In addition, having this magnitude of L/G will achieve efficiency in capturing within the process interval indicated.

By adding the capture system to power plants, large volumes of CO_2 according to the concentration of this gas produced is captured, taking advantage of modifying the installation of post-combustion system.

The simulation results show that MW_{eq} values to dimensions of capture plants are always lower than those of generating plant and it is necessary to use many capture units to process volumes observed art real gas streams obtained and therefore the size of such post-combustion power plants with CO_2 capture increases and thus the amount of energy required for its operation also increases.

From these results presented, it is shown that the maximum CO_2 capture is from Rio Escondido plant coal-fired but it is the one with SO_2 and other gases which implies pre-treatment combustion gases to reduce these before passing them to the capture of CO_2 through the amine.

Acknowledgements

For the partial financing EDOMEX-2009-C02-135728, SEP-CONACyT-CBII-2007-01-82987, Staff of the Department of Models and Prototypes of National Institute for Nuclear Research, and pay airfare by Mexican Ministry of Foreign Affairs (SRE).

References

Anantharaman R., Jordal K., Berstad D., Gundersen T., 2013, The role of process synthesis in the systematic design of energy efficient fossil fuel power plants with CO_2 capture, Chemical Engineering Transactions, 35, 55-60.

Biliyok C., Canepa R., Wang M., Yeung H., 2013, Techno-economic analysis of a natural gas combined cycle power plant with CO_2 capture, Computer Aided Chemical Engineering, 32, 187-192.

Canepa R., Wang M., 2015, Techno-economic analysis of a CO_2 capture plant integrated with a commercial scale combined cycle gas turbine (CCGT) power plant, 74, 10-19.

Damartzis T., Papadopoulos A.I., Seferlis P., 2013, Generalized framework for the optimal design of solvent based post-combustion CO_2 capture flowsheets, Chemical Engineering Transactions, 35, 1177-1182.

De Miguel Mercader F., Magneschi G., Sanchez Fernandez E., Stienstra G.J., Goetheer E.L.V., 2012, Integration between a demo size post-combustion CO_2 capture and full size power plant. An integral approach on energy penalty for different process options, International Journal of Greenhouse Gas Control, 115, S102-S113.

Grncarovska T.O., Poposka E., Zdraveva P., 2013, Best practices for preparation of GHG inventory for industrial processes, Chemical Engineering Transactions, 35, 1207-1212.

Kakaras E.K., Koumanakos A.K., Doukelis A.F., 2013, Greek lignite-fired power plants with CO_2 capture for the electricity generation sector, Chemical Engineering Transactions, 35, 331-336.

Klemeš J., Bulatov I., Cockerill T., 2007, Techno-economic modelling and cost functions of CO_2 capture processes, Computers and Chemical Engineering, 31, 445-455.

Linnenberg S., Liebenthal U., Oexmann J., Kather A., 2011, Derivation of power loss factors to evaluate the impact of post-combustion CO_2 capture processes on steam power plant performance, GHGT-10, Energy Procedia, 4, 1385-1394.

Lucquiaud M., Gibbins J., 2011, Steam cycle options for the retrofit of coal and gas power plants with post-combustion capture, GHGT-10, Energy Procedia, 4, 1812-1819.

MacDowell N., Florin N., Buchard A., Hallett J., Galindo A., Jackson G., Adjiman C.S., Williams C.K., Shah N., Fennell P., 2010, An overview of CO_2 capture technologies. Energy & Environmental Science, 3(11), 1645-1669.

Matsuda K., 2013, Low heat power generation system. Chemical Engineering Transactions, 35, 223-228.

Meldom J.H., 2011, Amine screening for flue gas CO_2 capture at coal-fired power plants: Should the heat of desorption be high, low or in between? Current Option in Chemical Engineering, 1, 55-63.

Mikulcic H., Vujanovic M., Markovska N., Filkoski R., Ban M., Duic N., 2013, CO_2 emission reduction in the cement industry, Chemical Engineering Transactions, 35, 703-708.

Moioli S., Pellegrini L.A., 2013, Regeneration section of CO_2 capture plant by MEA scrubbing with a rate-based model, Chemical Engineering Transactions, 35, 1849-1854.

Mores P., Rodríguez N., Scenna N., Mussati S., 2012, CO_2 capture in power plants: Minimization of the investment and operating cost of the post-combustion process using MEA aqueous solution, International Journal of Greenhouse Gas Control, 10, 148-163.

Moullec Y.L, 2012, Assessment of carbon captures thermodynamic limitation on coal-fired power plant efficiency. International Journal of Greenhouse Gas Control, 7, 192-201.

Neveux T., Le Moullec Y., Corriou J.P., Favre E., 2013, Energy performance of CO_2 capture processes: Interaction between process design and solvent, Chemical Engineering Transactions, 35, 337-342.

Petrova T., Darakchiev S., Vaklieva-Bancheva N., Popov R., 2013, Analysis, quantitative estimates and methods for reducing of the maldistribution created from gas distribution devices for column apparatuses, Chemical Engineering Transactions, 35, 1165-1170.

Porcheron F., Gibert A., Jacquin M., Mougin P., Faraj A., Goulon A., Bouillon P.A., Delfort B., Le Pennec D., Raynal L., 2011, High throughput screening of amine thermodynamic properties applied to post-combustion CO_2 capture process evaluation, GHGT-10, Energy Procedia, 4, 15-22.
Saavedra J., Merino L., Kafarov V., 2013, Determination of the gas composition effect in carbon dioxide emission at refinery furnaces, Chemical Engineering Transactions, 35, 1357-1362.
Semkov K., Mooney E., Connolly M., Adley C., 2013, Energy efficiency improvement through technology optimization and low grade heat recovery – industrial application, Chemical Engineering Transactions, 35, 1219-1224.
Sipöcz N., Tobiesen F.A., 2012, Natural gas combined cycle power plants with CO_2 capture – opportunities to reduce cost, International Journal of Greenhouse Gas Control, 7, 98-106.
Stichlmair J., Bravo J.L., Fair J.R., 1989, General model for prediction of pressure drop and capacity of countercurrent gas/liquid packed columns. Gas Separation and Purification, 3(1), 19-28.
Sun L., Doyle S., Smith R., 2013, Cogeneration improvement based on steam cascade analysis, Chemical Engineering Transactions, 35, 13-18.
Timmerman J., Deckmyn C., Vandevelde L., 2013, Techno-economic energy models for low carbon business parks, Chemical Engineering Transactions, 35, 571-576.
Tous M., Fryba L., Pavlas M., 2013, Improving calculation of lower heating value of waste by data reconciliation – analysis and evaluation, Chemical Engineering Transactions, 35, 877-882.
Yazgi M., Kenig E.Y., 2013, Hydrodynamic-analogy-based modelling of CO_2 capture by aqueous monoethanolamine, Chemical Engineering Transactions, 35, 349-354.