DESIGN OF CARBON DIOXIDE ABSORPTION FROM POLLUTED CITY AIR

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ABSTRACT

Global climate change is the most serious environmental problem which the world is facing now. To avoid dangerous climate change, the growth of atmospheric concentrations of greenhouse gases must be halted and may have to be retarded. The concentration of carbon dioxide, CO_2, the most dominant greenhouse gas, has increased from 280ppm in the pre-industrial age to more than 380ppm now and is now increasing by more than 2ppm per year driven by global CO_2 emissions that are now increasing at more than 3.3% per year. Controlling the level of carbon dioxide in the atmosphere without limiting access to fossil energy resources is only possible if carbon dioxide is collected and disposed of from the atmosphere. While it may be cost-advantageous to collect the carbon dioxide at concentrated sources without ever letting it to enter the atmosphere but this approach is not available for the many diffuse sources of carbon dioxide. Similarly, for many older plants a retrofit to collect the carbon dioxide is either impossible or prohibitively expensive. For this reason current research investigate the possibility of collecting carbon dioxide directly from the atmosphere. In this case a small scale packed column was designed to be portable and can be operated in polluted city centers. 2-amino-2-methyl-1-propanol (AMP) solution was used as absorbent in the packed column. In order to investigate efficiency of the proposed design by employing mass and heat transfer equations a model was proposed for the system. The model was solved numerically and was validated successfully with experimental data of the literature. Finally the model was used to predict carbon dioxide removal from Tokyo city. It was found that the contactor able to capture at least 50% at each run which is designed in small scale. Furthermore, a parameter sensitivity test including physicochemical properties and operation condition was carried out.

ABSTRAK

Perubahan iklim global adalah masalah yang paling serius alam sekitar yang dihadapi dunia sekarang. Untuk mengelakkan perubahan iklim yang berbahaya, pertumbuhan kepekatan atmosfera gas rumah hijau mesti dihentikan dan mungkin perlu terbantut. Kepekatan karbon dioksida, CO_2, gas rumah hijau yang paling dominan, telah meningkat daripada 280ppm dalam usia pra-industri kepada lebih daripada 380ppm sekarang dan kini semakin meningkat oleh lebih daripada 2ppm setahun didorong oleh pelepasan CO_2 di seluruh dunia yang kini meningkat pada lebih daripada 3.3% setahun. Mengawal tahap karbon dioksida di atmosfera tanpa menghadkan akses kepada sumber tenaga fosil hanya boleh dilakukan jika karbon dioksida dikumpul dan dilupuskan dari atmosfera. Walaupun ia mungkin kos berfaedah untuk mengumpul karbon dioksida pada sumber pekat tanpa pernah membiarkan ia memasuki atmosfera tetapi pendekatan ini tidak tersedia untuk banyak sumber meresap karbon dioksida. Begitu juga, bagi tumbuh-tumbuhan yang lebih tua banyak retrofit untuk mengumpul karbon dioksida adalah sama ada mustahil atau terlampau mahal. Bagi penyelidikan sebab ini semasa menyiasat kemungkinan mengumpul karbon dioksida secara langsung dari atmosfera. Dalam kes ini penuh skala kecil tiang telah direka untuk menjadi mudah alih dan boleh dikendalikan di pusat-pusat bandar yang tercemar. 2-amino-2-metil-1-propanol (AMP) penyelesaian telah digunakan sebagai penyerap dalam ruang yang penuh sesak. Dalam usaha untuk menyiasat kecekapan reka bentuk yang dicadangkan oleh jisim dan persamaan pemindahan haba yang menggunakan model telah dicadangkan untuk sistem itu. Model ini telah diselesaikan secara berangka dan telah disahkan berjaya dengan data eksperimen kesusasteraan. Akhirnya model telah digunakan untuk meramal penyingkiran karbon dioksida dari bandar Tokyo. Ia telah mendapati bahawa kontaktor mampu untuk menangkap sekurang-kurangnya 50% pada jangka setiap yang direka dalam skala kecil. Tambahan pula, ujian parameter sensitiviti termasuk hartanah fizikokimia dan keadaan operasi telah dijalankan.

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LIST OF SYMBOLS

a_w – specific wetted area for mass transfer, m^2/m^3

A_C – specific wetted area for mass transfer, m^2

c^0_{AMP} – specific wetted area for mass transfer, mol/m^3

$c_{p,i}$ – molar heat capacity of component i in the gas phase, J $mol^{-1}K^{-1}$

$c_{p,L}$ – molar heat capacity of the liquid, J $mol^{-1}K^{-1}$

$C_{A,1}$ – concentration of the componenet A at the begining of the transfer path

$C_{A,2}$ – concentration of the componenet A at the end of the transfer path

$D_{i,L}$ – diffusivity of component i in the liquid, m^2/s

G – molar gas flow, mol/s

h – heat transfer coefficient in gas, J $s^{-1}K^{-1}m^{-2}$

H_{CO_2} – Henry's Law constant for CO2, Pa m^3mol^{-1}

ΔH_{H_2o} – heat of condensation of H_2o, J/mol

ΔH_{CO_2} – heat of absorption ofCO_2, J/mol

$k_{G,i}$ – gas – side mass – transfer coefficient of component i, mol $m^{-2}s^{-1}Pa^{-1}$

$k_{L,i}$ – liquid – side mass – transfer coefficient of component i, m/s

k_L^o – liquid mass – transfer coefficient

k_2 – rate constant, $m^3mol^{-1}s^{-1}$

$K_{G,i}$ – overall mass – transfer coefficient of component i, mol $m^{-2}s^{-1}Pa^{-1}$

K_{CO_2} – Combined Henry's Law and chemical equilibrium constant for CO_2 partial pressure, Pa

L – molar liquid flow, mol/s

N_i – molar flux of component i, mol $m^{-2}s^{-1}$

N_A – $mass$ – transfer flux or the component A

p_i – partial pressure of component i in the bulk gas phase, Pa

p_i^* – partial pressure of component i gas phase if it were in equilibrium with the liquid, Pa

q – heat flux, J $m^{-2}s^{-1}$

T_G – gas – phase temperature, K

T_L – liquid – phase temperature, K

x_i – liquid – phase mole fraction of component i, mol/mol

X_{CO_2} – liquid – phase mole fraction of CO_2 in both reacted and unre – acted forms

y_i – gas – phase mole fraction of component i, mol/mol

z – height of packing, m

E – Enhancement factor

M – *dimensionless number used in the enhancement factor*

$\mathrm{Fr}_L = \frac{\mathrm{u}_L^2}{g d_h}$ *Froude number of liquid*

$Re_L = \frac{u_L d_h}{v_L}$ *Reynolds number of liquid*

$Re_V = \frac{u_V}{v_V a}$ *Reynolds number of gas or vapour*

$Sc_L = \frac{v_L}{D_L}$ *Schmidt number of liquid*

$Sc_V = \frac{v_V}{D_V}$ *Schmidt number of gas or vapour*

$\mathrm{We} = \frac{u_L^2 \rho_L d_h}{\sigma_L}$ *Weber number of liquid*

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

To avoid dangerous climate change, the growth of atmospheric concentrations of carbon dioxide must be halted, and may have to be reduced. The concentration of carbon dioxide, the most important greenhouse gas, has increased from about 280 ppm in the preindustrial age to more than 385 ppm and it is now increasing by more than 2 ppm per year driven by global CO_2 emissions that are now increasing at more than 3.3% per year (Keith and Ha-Duong, 2003)

Carbon capture and storage (CCS) technologies target CO_2 removal from large fixed-point sources such as power plants. Dispersed sources, however, emit more than half of global CO_2 emissions. Direct capture of CO_2 from ambient air, "air capture", is one of the few methods capable of systematically managing dispersed emissions. Therefore, while air capture is more expensive than capture from large point sources it still remains necessary to capture CO_2 from dispersed sources such as transportation which can be very expensive to mitigate (Keith and Ha-Duong, 2003).

Carbon dioxide adsorption by plants indicates the physical possibility of CO_2 capturing from the air. On the other hand, it is more than half a century that technologies have been developed for cleaning the atmosphere of carbon dioxide. Chemical sorbents, in all methods, play the essential role. They deliver carbon dioxide from the concentrated stream which can be pressurized and stored, respectively. Chemical reactions employed in these capture devices have the advantages of being fast with low energy demand. Therefor a system, which can effectively collect carbon dioxide, is reachable. But, being physically feasible is not enough. Commercial viability of the system must be also demonstrated. In a systems analysis approach showed that air capture can be fulfilled at a slightly higher cost and energy penalty than that of direct CO_2 scrubbing from a conventional power plant flue stack. It can be concluded that a commercially viable system is not beyond the reach (Lackner, 2001).

Air capture can be implemented without modifying or abandoning existing infrastructures. This removes a major obstacle to its introduction. It also suggests that air capture as a solution may become more widespread than would be justified based on first principles. It also suggests that the time for its introduction could be quite short. On a country scale, it could be as fast as the transition to nuclear energy in France, which was essentially completed within twenty years (Lackner, 2001).

Air capture can serve many needs, as a commercial use, for better oil recovery by providing carbon dioxide. In these regards, the reduction of greenhouse either coincidentally or as a byproduct would be desirable. However, these collected carbon dioxides can be used for the development and enhancement of the technology. The next step after establishing the technology in such a niche is to capture and utilize the carbon dioxide from the air for the primary purposes. These purposes can be offsetting emission of carbon dioxide at other places. Unlike uncertain offset scheme comparing actual emissions with theoretical ones, which is always considered as a business scenario, a true carbon offset option is provided when deal with capture of carbon dioxide from the air and its combination with

carbon storage technologies. Undoubtedly, additional baselines need to be defined in terms of carbon dioxide capture and storage. As long as gasoline and diesel are persistently sold, an air capture carbon management system will have developed. At €30/ ton CO_2, which is a reasonable price goal, the carbon dioxide capture cost surrounded in the price of gasoline would amount to 7¢/liter (Lackner, 2001).

Air capture could go further and function in other carbon dioxide emission reductions. For example, it could be used to treat the residual emission from power plants after 85% of the carbon dioxide has been removed. Zero emission is reachable with the help of carbon dioxide capture from air. Air capture would be usefully used for poor developing countries which have not yet succeed to manage their own carbon footprint. In compare with the cost of removing at the source, the air capture cost does not increase significantly as net reductions approach 100%. Therefore, the reduction of the atmospheric level of carbon dioxide by scrubbing more carbon dioxide than which is emitted would be feasible. The technology of air capture is one of the rare technological choice that truly allow the return to smaller levels of carbon dioxide in the air with no need to natural processes for absorbing the carbon dioxide (Dubey et al., 2002).

In the case of carbon dioxide for playing this role in carbon management, a safe and reliable storage of carbon dioxide is necessary as well. Several technologies such as geological storage, mineral sequestration and sub-ocean storage have shown promise but still need to be improved before a sink for the carbon dioxide has been established. A report on carbon dioxide capture and storage have been described in the IPCC (Dubey et al., 2002).

Air capture technology in combination with carbon dioxide storage and synthetic fuel production provide a pathway toward the development of energy infrastructure that preserves the wanted characteristics of the existing infrastructure as well as solving the main challenge of atmosphere changes (Dubey et al., 2002).

1.2 Statement of Problem

CO_2 is long-lived in the atmosphere, and it seems increasingly likely that CO_2 emissions will overshoot the limit on the cumulative total that is likely to be needed to limit a global temperature rise to below 2^0C above pre-industrial levels. It may, therefore, become necessary to remove CO_2 from the atmosphere. It will be difficult or impossible to achieve such a significant reduction in direct emissions in some sectors like agriculture and food production, air or marine transport. However, reduction carbon dioxide strategies in industrial activities could be promising way. But there are various limitations and restrictions in post capture processes in industries which obstacle for implementing such approaches especially in developing countries. Therefore designing and developing process for CO_2 extraction from the polluted air have been identified as having potential to remove CO_2 from the atmosphere. Most of the components in capturing carbon dioxide from ambient air operate in existing industrial, but the component making contact with air for initial extraction of CO_2 (contactor) is not well understood.

1.3 Objective of the Study

The main purpose of this research is to design and model an absorber packed column process to capture atmospheric CO_2 in order to reduce CO_2 accumulation in big cities.

1.4 Scope of the Study

i. A computer model was solved in MATLAB for the simulation of the absorption of carbon dioxide (CO_2) from polluted air in aqueous 2-amino-2-methyl-1-propanol (AMP) solution in a packed column.

ii. Predict the concentration profile along the packed column for the Air-CO_2-Amp system.

iii. A parameter sensitivity test including physicochemical properties and operation condition has been carried out.

iv. As a case study the model applied for a high CO_2 concentration location in Tokyo.

REFERENCES

Amdur, I., J. W. Irvine, E. A. Mason and J. Ross . (1952). Diffusion Coefficients of the Systems CO_2-CO_2 and CO_2-N_2O. *J. Chem. Phys.* . 20: 436-443. .

Astaria, G., Savage, D.W.andBisio, A. (1983). Gas treating with chemical solvents.

Baciocchi, R., Storti, G.andMazzotti, M. (2006). Process design and energy requirements for the capture of carbon dioxide from air. *Chemical Engineering and Processing.* 45(12), 1047-1058.

Bertram, C. (2010). Ocean iron fertilization in the context of the Kyoto protocol and the post-Kyoto process. *Energy Policy.* 38(2), 1130-1139.

Bhatkhande, D.S., Pangarkar, V.G. and Beenackers, A.ACM., (2001). "Photocatalytic

Degradation for Environmental Application-A Review," J. Chem. Technol.

Biotechnol., 77, 102,. .

Billet, R.andSchultes, M. (1999). Prediction of mass transfer columns with dumped and arranged packings. *Trans IChemE.* 77(Part A), 498-504.

Bolland, O. (2004). "CO_2 Capture Technologies-an Overview," The Second Trondheim

Conference on CO_2 Capture, Transport and Storage, .

Bosch, H., Versteeg, G.andVan Swaaij, W. (1990). Kinetics of the reaction of CO< sub> 2</sub> with the sterically hindered amine 2-Amino-2-methylpropanol at 298 K. *Chemical Engineering Science.* 45(5), 1167-1173.

Buesseler, K.O.andBoyd, P.W. (2003). Will ocean fertilization work? *Science.* 300(5616), 67.

Caruso, H.G., 2006. Reduction of CO_2 emissions from cement plants. University of Waterloo.

Castle, W.F. (2007). “Fifty-Years’ Development of Cryogenic Liquefaction Processes”, Chap.

8, Springer New York.

Chiu, L.F.andLi, M.H. (1999). Heat capacity of alkanolamine aqueous solutions. *Journal of Chemical & Engineering Data.* 44(6), 1396-1401.

Chiu, L.F., Liu, H.F.andLi, M.H. (1999). Heat capacity of alkanolamines by differential scanning calorimetry. *Journal of Chemical & Engineering Data.* 44(3), 631-636.

Clarke, J. (1964). Kinetics of Absorption of Cardon Dioxide in Monoethanolamine Solutions at Short Contact Times. *Industrial & Engineering Chemistry Fundamentals.* 3(3), 239-245.

Danckwerts, P. (1951). Significance of liquid-film coefficients in gas absorption. *Industrial & Engineering Chemistry.* 43(6), 1460-1467.

Dubey, M.K., Ziock, H., Rueff, G., Elliott, S., Smith, W.S., Lackner, K.S.andJohnston, N.A., 2002. Extraction of carbon dioxide from the atmosphere through engineered chemical sinkage, 1 ed, pp. 81-84.

Elliott, S., Lackner, K., Ziock, H., Dubey, M., Hanson, H., Barr, S., Ciszkowski, N.andBlake, D. (2001). Compensation of atmospheric CO2 buildup through engineered chemical sinkage. *Geophysical Research Letters.* 28(7), 1235-1238.

Falk-Pedersen, O.andDannström, H. (1997). Separation of carbon dioxide from offshore gas turbine exhaust. *Energy Conversion and Management.* 38, S81-S86.

Feron, P.H.M., and Jansen, A.E., (1997). "The Production of Carbon Dioxide from Flue

Gas by Membrane Gas Adsorption," Energy Convers. Mgmt., 38 (Suppl.), S93,

. .

Gabrielsen, J., Michelsen, M.L., Stenby, E.H.andKontogeorgis, G.M. (2005). A model for estimating CO2 solubility in aqueous alkanolamines. *Industrial & engineering chemistry research.* 44(9), 3348-3354.

Gabrielsen, J., Michelsen, M.L., Stenby, E.H.andKontogeorgis, G.M. (2006). Modeling of CO2 absorber using an AMP solution. *AIChE Journal.* 52(10), 3443-3451.

Geankoplis, C.J. (1993). Transport Processes and Unit Operations, Third Edition

Hassan, S.M.N. (2005). Techno-Economic Study of CO2 Capture Process for Cement Plants. *Waterloo, Ontario, Cananda.*

Heinrich, J.J. (2003). "CO_2 capture from Air – Current Practices" Publication No. LFEE 2003-

001-WP, Massachusetts Institute of Technology, Cambridge, MA, USA.

Henni, A., Hromek, J.J., Tontiwachwuthikul, P.andChakma, A. (2003). Volumetric properties and viscosities for aqueous AMP solutions from 25 C to 70 C. *Journal of Chemical & Engineering Data.* 48(3), 551-556.

Herzog, H. (2003). Assessing the Feasibility of Capturing CO_2 from the Air. *Massachusetts Institute of Technology, Laboratory for Energy and the Environment, Publication No. LFEE.* 2.

Higbie, R., 1935. The rate of absorption of a pure gas into still liquid during short periods of exposure. THE UNIVERSITY OF MICHIGAN.

Hocking, D.and (2005). "Air quality in airplane cabins and similar enclosed spaces". *Pg 357-364 Springer.*

House, K.Z., Baclig, A.C., Ranjan, M., van Nierop, E.A., Wilcox, J.andHerzog, H.J. (2011). Economic and energetic analysis of capturing CO_2 from ambient air. *Proceedings of the National Academy of Sciences.* 108(51), 20428-20433.

Hsu, C.H.andLi, M.H. (1997). Densities of aqueous blended amines. *Journal of Chemical & Engineering Data.* 42(3), 502-507.

IPCC (2001). Intergovernmental Panel on Climate Change (IPCC): Summary for policymakers; in

Climate Change 200J: The Scientific Basis, Cambridge University Press

IPCC, 2007. Climate change 2007: the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ Pr.

Kaya, Y. (1990). Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios. *IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris.* 76.

Keith, D.W.andHa-Duong, M., 2003. - CO2 Capture from the Air: Technology Assessment and Implications for Climate Policy, in: J. GaleandY. Kaya (Eds.), Greenhouse Gas Control Technologies - 6th International Conference. Pergamon, Oxford, pp. 187-192.

Keith, D.W., Ha-Duong, M.andStolaroff, J.K. (2006). Climate strategy with CO 2 capture from the air. *Climatic Change.* 74(1), 17-45.

Kheshgi, H.S. (1995). Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy.* 20(9), 915-922.

Klaus S. Lackner, P.G.andZiock., H.-J., 1999. CARBON DIOXIDE EXTRACTION FROM AIR: IS IT AN OPTION?, p. 2.

Ko, J.J., Tsai, T.C., Lin, C.Y., Wang, H.M.andLi, M.H. (2001). Diffusivity of nitrous oxide in aqueous alkanolamine solutions. *Journal of Chemical & Engineering Data.* 46(1), 160-165.

Kucka, L., Müller, I., Kenig, E.Y.andGórak, A. (2003). On the modelling and simulation of sour gas absorption by aqueous amine solutions. *Chemical Engineering Science.* 58(16), 3571-3578.

Lackner, K., Grimes, P.andZiock, H., 1999. Carbon dioxide extraction from air? Los Alamos National Laboratory. LAUR-99-5113, Los Alamos, NM.

Lackner, K.S. (2009). Capture of carbon dioxide from ambient air. *The European physical journal-special topics.* 176(1), 93-106.

Lackner, K.S., Grimes, P.andZiock, H.J., 2001. Capturing carbon dioxide from air.

Lackner, K.S., Grimes, P. & Ziock, H. J. Year. (2001). Capturing carbon dioxide from air.

.

Levenspiel, O. (1972). Chemical reactions engineering. *John Wiley&Sons,New York.* 67, 02.

Lewis, W.andWhitman, W. (1924). Principles of Gas Absorption. *Industrial & Engineering Chemistry.* 16(12), 1215-1220.

Lipinsky, E.S. (1991). Final report on R&D status of carbon dioxide separation, disposal,

and utilization technologies to TransAlta Utilities Corporation, Battelle, Columbus,

Ohio, .

Lowry, J.K.S.G.V.andKeith, D.W. (2005). CO2 capture from ambient air: An example system.

Maddox, R.N. (1982). Gas conditioning and processing. Vol. 4: gas and liquid sweetening.

Mahmoudkhani, M.andKeith, D.W. (2009). Low-energy sodium hydroxide recovery for CO2 capture from atmospheric air—Thermodynamic analysis. *International Journal of Greenhouse Gas Control.* 3(4), 376-384.

McCarthy, J.J., 2001. Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge Univ Pr.

Meisen, A.andShuai, X. (1997). Research and development issues in CO2 capture. *Energy Conversion and Management.* 38, S37-S42.

Meisen, A.andShuai, X. (1997). Research and development issues in CO< sub> 2</sub> capture. *Energy Conversion and Management.* 38, S37-S42.

Nikulshina, V., Galvez, M.andSteinfeld, A. (2007). Kinetic analysis of the carbonation reactions for the capture of CO_2 from air via the Ca (OH) 2-$CaCO_3$-CaO solar thermochemical cycle. *Chemical Engineering Journal.* 129(1-3), 75-83.

Nikulshina, V., Hirsch, D., Mazzotti, M.andSteinfeld, A. (2006). CO_2 capture from air and co-production of H2 via the Ca (OH) $_2$-$CaCO_3$ cycle using concentrated solar power-Thermodynamic analysis. *Energy.* 31(12), 1379-1389.

Nikulshina, V.andSteinfeld, A. (2009). CO_2 capture from air via CaO-carbonation using a solar-driven fluidized bed reactor-Effect of temperature and water vapor concentration. *Chemical Engineering Journal.* 155(3), 867-873.

Pacheco, M.A.andGary, T. (1998). Rate-based modeling of reactive absorption of CO_2 and H2S into aqueous methyldiethanolamine. *Industrial & engineering chemistry research.* 37(10), 4107-4117.

Pandya, J. (1983). Adiabatic gas absorption and stripping with chemical reaction in packed towers. *Chemical Engineering Communications.* 19(4-6), 343-361.

Perry, R.H., Green, D.W.andMaloney, J.O., 1984. Perry's chemical engineers' handbook. McGraw-Hill New York.

Plasynski, S.andChen, Z. (2000). Review of CO_2 capture technologies and some improvement opportunities. *Papers of the American Chemical Society.* 220, U391.

Ranjan, M.andHerzog, H.J. (2011). Feasibility of air capture. *Energy Procedia.* 4(0), 2869-2876.

Reid, R.C., Prausnitz, J.M.andPoling, B.E. (1987). The properties of gases and liquids.

Ruthven, D.M., 1997. Encyclopedia of separation technology. Wiley New York.

Saha, A.K., Bandyopadhyay, S.S.andBiswas, A.K. (1993). Solubility and diffusivity of nitrous oxide and carbon dioxide in aqueous solutions of 2-amino-2-methyl-1-propanol. *Journal of chemical and engineering data.* 38(1), 78-82.

Saha, A.K., Bandyopadhyay, S.S.andBiswas, A.K. (1995). Kinetics of absorption of CO< sub> 2</sub> into aqueous solutions of 2-amino-2-methyl-1-propanol. *Chemical Engineering Science.* 50(22), 3587-3598.

Simon, L.L., Elias, Y., Puxty, G., Artanto, Y.andHungerbuhler, K. (2011). Rate based modeling and validation of a carbon-dioxide pilot plant absorbtion column operating on monoethanolamine. *Chemical Engineering Research and Design.* 89(9), 1684-1692.

Smith, J., Van Ness, H.andAbbott, M., 2003. Introduction to chemical engineering thermodynamics 6th edition. McGraw-Hill Korea, Seoul.

Stolaroff, J.K., 2006. Capturing CO_2 from ambient air: a feasibility assessment. Carnegie mellon university.

Stolaroff, J.K., Keith, D.W.andLowry, G.V. (2008). Carbon dioxide capture from atmospheric air using sodium hydroxide spray. *Environmental science & technology.* 42(8), 2728-2735.

Stolaroff, J.K., Lowry, G.V.andKeith, D.W. (2005). Using CaO-and MgO-rich industrial waste streams for carbon sequestration. *Energy Conversion and Management.* 46(5), 687-699.

Tamimi, A., Rinker, E.andSandall, O. (1994). Diffusivity of nitrous oxide in aqueous solutions of N-methyldiethanolamine and diethanolamine from 293 to 368 K. *Journal of chemical and engineering data.* 39(2), 396-398.

Tamimi, A., Rinker, E.B.andSandall, O.C. (1994). Diffusion coefficients for hydrogen sulfide, carbon dioxide, and nitrous oxide in water over the temperature range 293-368 K. *Journal of chemical and engineering data.* 39(2), 330-332.

Thambimuthu, K.a.D., J., (2004). "Overview of CO_2 Capture," 7th International

Conference on Greenhouse Gas Control Technologies, Vancouver, Canada, .

Tontiwachwuthikul, P., Meisen, A.andLim, C.J. (1992). CO_2 absorption by NaOH, monoethanolamine and 2-amino-2-methyl-1-propanol solutions in a packed column. *Chemical Engineering Science.* 47(2), 381-390.

Treybal, R.E., 1980. Mass-transfer operations. McGraw-Hill Singapore.

Usubharatana, P., McMartin, D., Veawab, A.andTontiwachwuthikul, P. (2006). Photocatalytic process for CO2 emission reduction from industrial flue gas streams. *Industrial & engineering chemistry research.* 45(8), 2558-2568.

Van Krevelen, D.andHoftijzer, P. (1948). Kinetics of gas- liquid reactions part I. General theory. *Recueil des travaux chimiques des Pays-Bas.* 67(7), 563-586.

Vázquez, G., Alvarez, E., Navaza, J.M., Rendo, R.andRomero, E. (1997). Surface tension of binary mixtures of water+ monoethanolamine and water+ 2-amino-

2-methyl-1-propanol and tertiary mixtures of these amines with water from 25 C to 50 C. *Journal of Chemical & Engineering Data.* 42(1), 57-59.

Versteeg, G.F.andVan Swaalj, W. (1988). Solubility and diffusivity of acid gases (carbon dioxide, nitrous oxide) in aqueous alkanolamine solutions. *Journal of chemical and engineering data.* 33(1), 29-34.

Wellek, R., Brunson, R.andLaw, F. (1978). Enhancement factors for gas-absorption with second-order irreversible chemical reaction. *The Canadian Journal of Chemical Engineering.* 56(2), 181-186.

White, C.M., Strazisar, B.R., Granite, E.J., Hoffman, J.S.andPennline, H.W. (2003). Separation and capture of CO2 from large stationary sources and sequestration in geological formations—coalbeds and deep saline aquifers. *Journal of the Air & Waste Management Association.* 53(6).

Wilson, M., Wrubleski, R.andYarborough, L. (1992). Recovery of CO_2 from power plant flue gases using amines. *Energy Conversion and Management.* 33(5-8), 325-331.

Wolsky, A., Daniels, E.andJody, B. (1994). CO_2 Capture from the flue gas of conventional fossil- fuel- fired power plants. *Environmental Progress.* 13(3), 214-219.

Zeman, F. (2007). Energy and material balance of CO_2 capture from ambient air. *Environmental science & technology.* 41(21), 7558-7563.

Zeman, F. (2008). Experimental results for capturing CO_2 from the atmosphere. *AIChE Journal.* 54(5), 1396-1399.

Zeman, F.S.andLackner, K.S. (2004). Capturing carbon dioxide directly from the atmosphere. *World Resource Review.* 16(2), 157-172.