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Post-Combustion Carbon Capture- Chemical Absorption Process

K.K.G.L.Chathumini, N.P.Dassanayake, D.D.P.Preethika, R.T.Wadanambi, L.S.Wandana
Faculty of Technology, University of Sri Jayawardenapura

Abstract— Globally Green House Gas emission becomes a large environmental problem since the industrial revolution began. Power plants, boilers, and some machines are emitting a high amount of Green House Gasses to the atmosphere. Throughout the gasses, CO_2 especially plays a significant role, because its contribution is very high compare to the others. So, we need to find solutions to mitigate CO_2 emission. Our study mainly depends on post-combustion technology under the chemical absorption process, because it has a wide variety of technical usability. Furthermore, this study covers the solvent types, selection, and alternative solvents. This paper mainly reveals the industrial process like cement industry, coal fire power plants, aluminium plants, and fired power plants. We finally discussed the challenges of the chemical absorption process.

Index Terms—CO2 emission, chemical absorption, solvents, post-combustions.

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1 INTRODUCTION

Global greenhouse gas level tremendously increases day by day due to the anthropogenic activities. Because of that, it causes to generate more environmental problems like global warming and climate change. They are leading to devastating events like droughts, floods, hurricanes, wildfires, and torrential rains across the world. So, these issues generate more social and economic issues. CO_2 concentration plays a considerable contribution among other gases. Because of that, we need to find more effective solutions to mitigate that emission.

Greenhouse gas concentration balance by the natural process, but anthropogenic activities cross the line and imbalance the concentration throughout the world. As a solution, post-combustion is introduced as a new trend for the industries, and it consists of many technologies like chemical absorption, physical absorption, membrane separation, cryogenic separation, and adsorption. Throughout these, we mainly focus on the chemical absorption method. If we implement this chemical absorption method, we need to concern about the solvent types, because it is varied according to the process and usage. As mentioned above, studies identified high CO_2 emission plant processes like cement manufacturing industries, coal fire plants, aluminium plants, and gas-fired plants.

2 POST-COMBUSTION

CO_2 capture is become a leading process because of the rapid increase in atmospheric CO2 concentration globally. There are main three approaches use for that called pre-combustion capture, post-combustion capture, and oxy-fuel process.

The post-combustion capture is the approach which is used majorly in worldwide because of its advantages rather than other technologies. Post-combustion capture simply means capturing carbon dioxide from the flue gas after fossil fuel has been burned. In the post-combustion CO_2 capture, coal combusts with air supply. After the combustion happens, the flue gas emission needs a cleanup to avoid NOx, SOx, and PM, which causes corrosion and fouling. The O_2 and N_2 release by separating the CO_2 gas with H_2O. That passes through the drying and compression stage to avoid water, and finally, CO_2 has been captured. Fig. 1 shows the post-combustion CO_2 capture process flow.

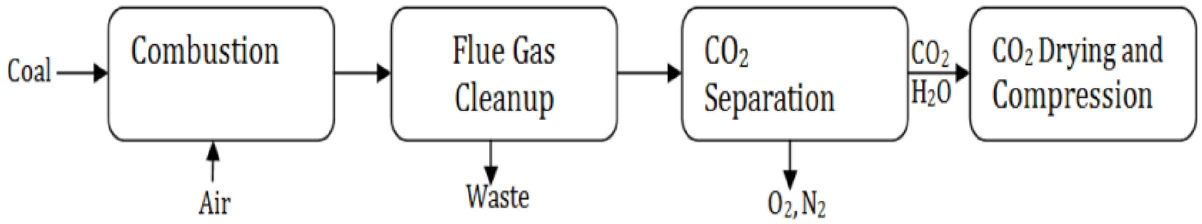

Fig. 1. Post-combustion CO_2 capture process [1]

There are main five options uses in this method according to their separation technology. Those are,

- Chemical absorption
- Physical absorption
- Membrane separation
- Cryogenic separation
- Adsorption

3 CHEMICAL ABSORPTION

Chemical absorption is the one of widely applied technology for CO_2 separation because of its benefits like low equipment cost, high removal efficiency, etc. Chemical absorption is the method that is based on the solubility factor of CO_2 and other gases that are coming along with the flue gas stream. In this method, CO_2 reacts with absorbent during the absorption process, and also CO_2 is separated by the scrubbing system continuously. Fig. 2 shows the process flow of the chemical absorption method.

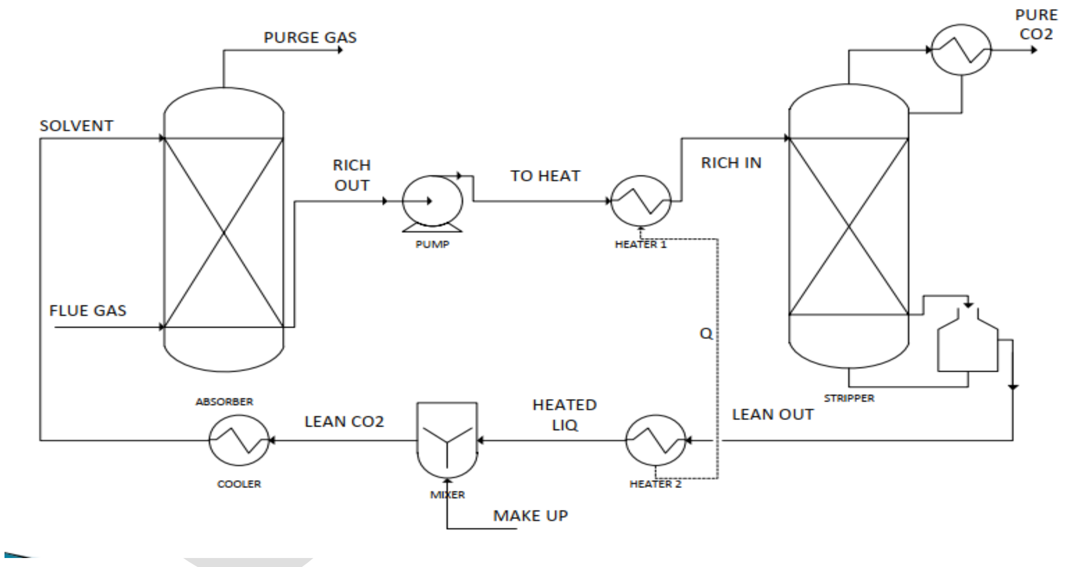

Fig. 2. Process flow of chemical absorption [1]

3.1 Preparation needs

- Acid gases such as SO_2, NO_2 must be removed because they cause salt generation.
- SO_2 concentration less than 10ppm is recommended.
- Oxygen levels less than 1ppm are recommended.
- Flue gas should cool between 45ºC-50ºC before supply to the absorber column[2].

3.2 Process

The flue gas stream is entering the absorption column at the bottom while the solvent is entering at the top. Flue gas going upward and solvent coming downward direction, then the reaction can easily happen. When the reaction happens, non-reacted gases are leaving the top, and the rich solvent is leaving at the bottom. This rich solvent pumped to the striper column through the heat exchanger to heat solvent. In this column, regenerated CO_2 is captured on top of the stripper by using low-pressure steam in the regeneration process while the condensed water out. That liquid passes through the heat exchanger to transfer heat to heat exchanger 1 which we have discussed before the stripper column. When the process happening some amount of solvent is degrading; hence the makeup system has used to recirculate the stream. That stream flow through the cooler to reduce their heat because the absorber column operates at low temperature.

3.3 Chemistry of amine with CO2 reacting systems

Hydrolysisreaction:
$MEACOO\text{-} + H_2O \leftrightarrow MEA + HCO_3^-$
Dissociationofdissolvedcarbondioxide:
$CO_2 + 2H_2O \leftrightarrow HCO_3^- + H_3O^+$
Dissociationofbicarbonate:
$HCO_3^- + H_2O \leftrightarrow H_3O^+ CO_3^{2-}$

DissociationofprotonatedMEA;
$MEAH^+ + H_2O \leftrightarrow MEA + H_3O^+$

Ionizationofwater:
$2H_2O \leftrightarrow O\,H^- + H_3O^+$ [3]

3.4 Issues

- High capital cost.
- Large water consumption
- Environmental effects
- Large energy requirement for the regeneration process
- High operating cost
- Environmental impact from accidental spills of amines
- Point discharge of purge gases on top of the absorber
- Impacts on fugitive emissions by leaks

3.5 Selection of packing material

There are main two types of packing materials are available called random packing and structured packing. Structure packing materials have high efficiency rather than random packing due to the high mass transfer coefficient. Packing materials are providing surface area for the gas and liquid phase to contact with each other. Hence those packing materials should have maximized specific surface area, uniform spread surface area, maximize void space per unit column volume, minimize friction, less cost, etc[4].

3.6 Parameter optimization

Some parameters should control well to optimize the process of chemical absorption like inlet gas flow rate, composition, pressure, temperature, packing material data, solvent properties, etc. there are parameter optimization methods such as single parameter effect and multi-parameter effect. In those methods simply doing is by changing one or more parameters, the energy consumption and efficiency are investigated to get maximum efficiency from the process.

4 SOLVENTS FOR CHEMICAL ABSORPTION

Post-combustion chemical absorption processes use a solvent for the chemical process of CO2 and the flue gases in the column. After that CO2 is absorbed by that chemical solvent. There are several solvents available, and from those amine-based solvents are most widely used in many industries Those can be categorized as primary amines (MEA, DGA), secondary amines (DEA), tertiary amines (MDEA, TEA), hindered amines (AMP) and cyclic amines (Piperazine) [5]. Table 1 represents the basic properties of different amines.

Table 1. Properties of different Amines [5]

Amine	MEA	DEA	DGA	MDEA
Name	Monoethanolamine	Diethanolamine	Diglycolamine	Methyldiethanolamine
Chemical formula	C_2H_7NO	$C_4H_{11}NO_2$	$C_4H_{11}NO_2$	$C_5H_{13}NO_2$
Amines category	Primary	Secondary	Primary	Tertiary
Molecular weight [g/mol]	61.08	105.14	105.14	119.163
Density [g/cm3]	1.012	1.090	1.06	1.043
Boiling point[°C]	170	217	223	247
Efficiency [mol%]	85	58	90	16
Concentration [%]	22	45	50	7

The CO2 removal efficiency rapidly increases as the amine solvent concentration increases.

4.1 Solvent selection

The selection of the best solvent is much more important for the efficient CO2 capture process because the efficiency of the removal process strongly depends on the solvent properties [6]. Several factors should be considered when selecting the solvent such as solvent concentration, CO2 lean loading for the CO2 capture process, absorption capacity, absorption rate, solvent heat of absorption, solvent temperature, solvent price, toxicity, etc. These can be varied with the industry. For example, the optimum MEA solvent specifications for the coal and gas processes are summarized in Table 2.

Table 2. Optimum solvent conditions for both coal and gas-fired power plant flue gas capture process [7].

Specification	85% Removal Efficiency	90% Removal Efficiency	95% Removal Efficiency
Coal-fired power plant CO_2 capture			
MEA concentration [w/w%]	40	40	40
CO_2 lean loading per mole MEA [mole CO_2/mole]	0.27	0.27	0.25
Solvent flow rate [tonne/hr]	7965	8719	8940
Gas-fired power plant CO_2 capture			
MEA concentration [w/w%]	40	35	30
CO_2 lean loading per mole ME	0.30	0.25	0.25
Solvent flow rate [tonne/hr]	3775	3224	4240

4.2 Alternative Solvents

Even though MEA is a widely used solvent for CO2 capture, regeneration energy requirement is much high for that process. Therefore, alternative solvents should be analyzed to perform the post-combustion capture process with minimum energy requirements.

- DEA – It has a less corrosive effect, required less amount of energy in the regeneration, process, lower re-boiler duties than MEA. The 85% removal model of the DEA process has 3371 kJ/kg CO2 for the coal-fired system and 3381 kJ/kg CO2 for the gas-fired system. However, the circulation rate is high in the DEA model compared to MEA process because of low reactivity. That will affect to increase operational cost. DEA solvent can be recommended for coal and gas-fired flue gas capture systems [2].
- Ammonia- It has a high CO2 absorption capacity, low molecular weight, absorbs CO2 with a low heat of reaction, and therefore the regeneration energy requirements are also low. Corrosivity is less when compared to the MEA solvent [2].
- Piperazine promoted K2CO3- K2CO3 in solution with catalytic amounts of piperazine (PZ) has a fast absorption rate, 29–33% regeneration energy savings when compared to the MEA [2].
- Concentrated aqueous piperazine- It has a faster aqueous PZ. Thermal degradation can be negligible in concentrated aqueous piperazine up to a temperature of 150 ◦C [2].
- Blended amines- The use of another amine, together with a primary or secondary amine, will reduce the amount of solvent requirement and energy consumption. And also, it requires less solvent. For example, MEA and MDEA blend reduce the energy consumption for regenerating CO2 [2].

5 MODEL DEVELOPMENT FOR CHEMICAL ABSORPTION

5.1 Cement industry

The cement industry is one of the largest industries in the world. The amount of CO_2 release in the cement manufacturing process is about 50% of the total CO_2 emission [9]. There are lots of model development has been done to reduce the CO2 emission through the chemical absorption process.

5.1.1 The specific thermal energy demand and the false air factor on carbon capture applied to cement kiln exhaust gases

This model has been developed by the aspen plus simulation software considering a flue gas composition of a generic cement manufacturing plant with 1Mt clinker per year and coal as the primary thermal energy source. The energy demand and the false air factor affect the flue gas composition and flow rate. The base energy demand was 3400 MJ/kg $_{\text{clinker,}}$ and the false air factor was 25%. This energy demand varied from 3000 MJ/kg $_{\text{clinker}}$ to 3800 MJ/kg $_{\text{clinker,}}$ and false air factor varied from 25% up to 50% and 70%. The monoethanolamine (MEA) used as the solvent and concentration of the solvent and lean $CO_{2\ \text{loading}}$ at the inlet stream selected as 30 wt% and 0.3 mol CO2/mol MEA, respectively. The packing material chosen for the model was the Mellapak-Sulzer 350 Y for the absorber and Flexipak-1Y for the stripper. Table 3 shows the modeled data for the 90% CO_2 removal efficiency [10]. Regeneration energy demand with equal superficial gas velocities are represented by table 3.

Table 3. Regeneration energy demand with equal superficial gas velocity [10]

			Specific thermal energy demand			**False air factor**		
Description	**Unit**	**Base Case**	**3000 MJ/t_cli**	**3400 MJ/t_cli**	**3800 MJ/t_cli**	**25 %**	**50 %**	**70%**
Reboiler duty	MW	108.7	103.7	108.7	113.8	108.7	110.2	113.2
Amount of	kg/s	29.2	28.0	29.2	30.6	29.2	29.3	29.3

CO2 captured								
Specific Reboiler duty	kJ/kg CO_2	3710.3	3697	3710	3719	3710	3753	3855
	kJ/kg clinker	3428	3270	3428	3589	3428	3476	3568
Solvent flowrate	tonne/hr	2795	2665	2795	2928	2795	2840	2925

According to this model variations on the specific energy, demand doesn't show a considerable impact on the CO_2 capture plant, but the false air factor that increases from 25% to 70% indicates a 4% increase in reboiler duty. This model shows that the false air factor should be maintained low to reduce energy consumption in the CO_2 capture plant [10].

5.1.2 Utilization of waste heat in a cement kiln flue gas in an amine-based CO_2 absorption process

This study aims to recover heat from flue gas in cement kilns to generate steam through a waste heat boiler and supply to the stripping section of the CO_2 capture plant. The model was developed using aspen plus simulation software. The waste heat boiler replaces the conditioning tower that has a downstream temperature of about 150°C. The required temperature for the absorption process is about 40°C. By replacing the conditioning tower with a waste heat boiler helps to recover excess heat from the kiln gas that is about 18MW for the base case 350°C and 150°C inlet and outlet temperatures. This waste heat can provide the part of the energy that use for the regenerating process that is about 18% of the total energy requirement. According to this model, the amount of steam that can be generated by the waste heat boiler is about 28862 kg/hr. The cost of the boiler system is USD 39 million, and the payback time is approximately about one year [11]. Fig 3. illustrates the heat recovery system in the cement industry,

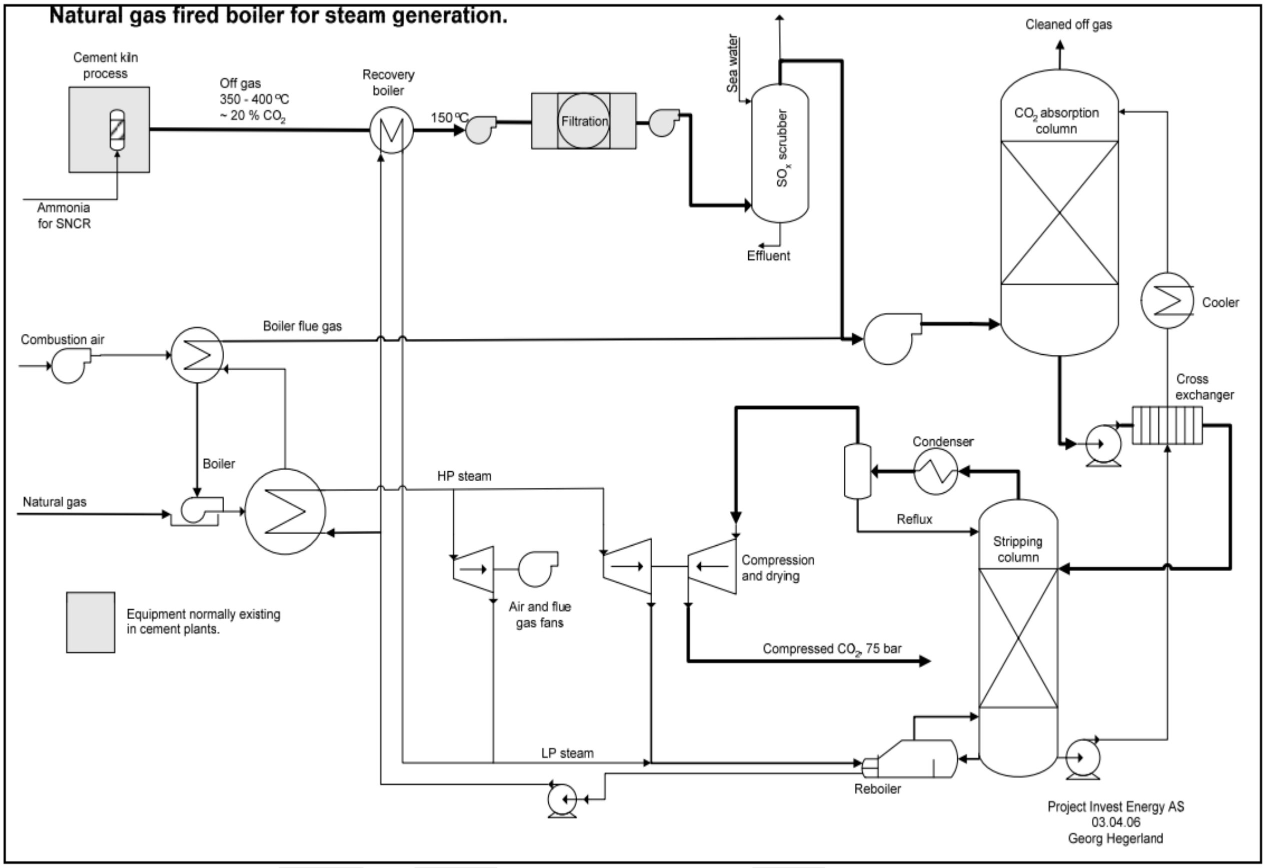

Fig. 3. The heat recovery system (Waste Heat Utilization for CO2 Capture in the Cement)[11]

5.1.3 Post-combustion amine absorption of CO_2 in a cement manufacturing process is modeled with Aspen Plus.

This model focus on the effectiveness of installing a CO_2 capture plant in the cement manufacturing process using the method of post-combustion amine absorption of CO2 in Aspen Plus. Before capturing the CO_2, the reduction of $SO_{x\text{ and}}$ NO_x is important because these pollutants can cause solvent degradation. An electrostatic precipitator is used flowed by a De-NOx unit and De-Sox unit to reduce NO_x and SO_x. Two processes contribute to the CO_2 concentration in the flue gas those are the de-carbonation and the combustion. The CO_2 concentration in the flue gas is in the range of 14% to 33%. In this model, amine concentration and CO_2 lean loadings are varied for 85%, 90%, 95% removal efficiencies. The results of the model show that the optimum MEA concentration and CO_2 lean loading was 40 w/w % and 0.30 (mol CO2/mol MEA). The increment of the CO_2 lean loading causes the decrease of the reboiler duty, and the energy demand for the reboiler carbon capture process increases with the efficiency increment [12].

5.1.4 Model development for CO2 capture in the cement industry

The following fig 4 shows the process diagram of the CO_2 capture process.

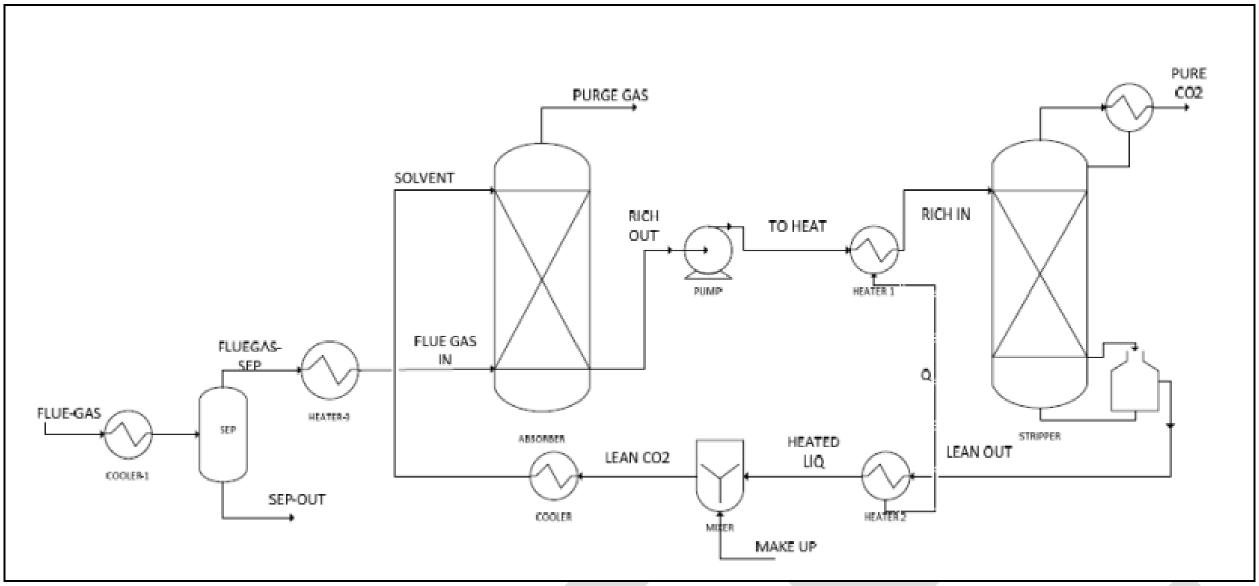

Fig. 4. Process Flow diagram [12] (Model Development for CO2 Capture in the Cement Industry)

5.2 Coal-Fired Power Plant.

5.2.1 Model development.

- Monoethanolamine (MEA) is used as the solvent with a 30% concentration.
- 0.30 lean CO2 loading.
- Three different models were developed with 85%, 90% and 95% of CO2 removal efficiencies.
- Closed-loop model
- Simulations are performed with 13.5% (0.135) CO2 content [13].

5.2.2 Results of the calculations.

Required reboiler duties for the coal-fired power plant are represented by table 4.

Table 4: Required reboiler duties (KJ/Kg CO2) [13]

	85%	90%	95%
0.30 CO_2 loading	3481	3620	3840
0.135 CO_2 loading	3634.2	3736.4	4185.5

5.3 Aluminium Plant.

5.3.1 Model development.

- The MEA is taken as the solvent.
- Three different solvent conditions are used to develop the process model to check the most suitable operating conditions.
- 85%, 90%, and 95% removal efficiencies.
- The CO2 loading varies from 0.15 - 0.35 (mol CO2/mol MEA), with the MEA concentration of 30% and 40%.
- The MEA concentration 40% and lean CO2 loading 0.3 give the optimum solvent condition for the CO2 capture process [14].

5.3.2 Results of the calculations.

Required reboiler duties for the aluminium plant are represented by table 5.

Table 5: Required reboiler duties (KJ/Kg CO2) [14].

	85%	90%	95%
Re boiler duty values (MJ/Kg CO_2)	3.0 - 3.5	3.2 - 3.5	3.4 - 3.6

According to the CO2 content in flue gas, the required boiler energy duty is changing. If the CO2 percentage is high in flue gas, it will directly contribute to reducing the reboiler energy requirement.

5.4 Gas-Fired Power Plant.

5.4.1 Model development.

- Open Loop

Solvent stream conditions and absorber and stripper column parameters are represented by table 6 and table 7, respectively.

Table 6: Solvent Stream Conditions [15].

Specification	85% removal eff.	90% removal eff.	95% removal eff.
MEA concentration (w/w%)	40	35	30
Lean CO_2 loading (mol CO_2/mol MEA)	30	25	25
Solvent flow rate (Kg/s)	1048.6	895.6	1177.8

Table 7: Absorber and Stripper Column Parameters [15].

Specification	Value	
	Absorber	Stripper
Operating pressure	1 bar	1.6 bar
Pressure drop	0.1 bar	0.1 bar
Re boiler	None	Kettle
Packing height	24 m	18m
Packing diameter	18 m	12 m

- Closed-loop

Compositions of makeup stream and the required reboiler duties are represented by table 8 and table 9, respectively.

Table 8: Compositions of makeup stream [15].

Removal efficiency (mol%)	Amount of make up stream	
	Water (Kg/s)	MEA (Kg/s)
85	17.90	0.22
90	25.15	0.21
95	29.52	0.36

Compared to the inlet solvent stream in an open-loop mode, a small amount of makeup flow is required to continue re-circulation. When the removal efficiency is increased, the required amount of makeup flow also increased.

Table 9: Required reboiler duties (KJ/Kg CO_2) [15].

	85%	90%	95%
Re boiler duty values (Kj /Kg CO_2)	3481	3620	3840

5.4.2 Parameters Effect on Removal Process.

- The base case models are developed for removal efficiencies which are 85%, 90% and 95%.
- The selected solvent properties are used to develop the model, and the implemented model is used for further simulations.
- The implemented open loop 85% removal efficiency base case model is used to check the parameters' effect on removal efficiency and re-boiler duty [15].

The main input parameters considered for sensitivity analysis in gas-fired power plant is represented by table 10.

Table 10. Main input parameters considered for sensitivity analysis [15].

Input parameter	Base case value	Range of the parameter varied
Absorber packing height (m)	24	18-30
Absorber packing diameter(m)	18	12-20
Absorber operating pressure (bar)	1	0.8-1.2
Flue gas temperature (K)	313	303-313
Solvent temperature (K)	313	307-319
Stripper packing height (m)	18	14-24
Stripper packing diameter (m)	12	10-18

5.4.3 Parameters' Effect on Removal Efficiency.

Absorber packing height is varied from 18-30 m. The diameter is varied from 12-20 m. Removal efficiency is proportional to the packing height and diameter. Because the solution contact area is increasing with the increase in packing height and diameter. Therefore, the residence time for the reacting system is increased and then the removal efficiency is increased.

The removal efficiency is quite increasing with the flue gas temperature. The simulations are carried out in solvent temperature range from 307-319 K. The removal efficiency increases with the increase of solvent temperature. As the solvent temperature increases, the rate of reaction and diffusivity increase, and the efficiency of the CO2 removal is increased [15].

5.4.4 Parameters' Effect on Re-boiler Duty.

Regeneration energy requirements can mainly be categorized into three parts. They are,

- The energy requirement to release the CO2.
- The energy requirement to evaporate the water.
- The energy requirement to heat the solvent in the stripper.

When the absorber packing height and diameters increase, contacting surface area for the reaction medium is increased. This means that amount of solvent required to react with CO2 is reduced. As a result, the required energy to heat the solvent in stripper is reduced. Therefore, regeneration energy is decreased in the re-boiler with packing height and diameter. Re-boiler duty is increased with the flue gas temperature [15].

6 CHALLENGES FOR CHEMICAL ABSORPTION METHOD

The post-combustion carbon-capturing using chemical absorption is widely using technology that reduces the CO_2 emission from many industries due to easy fitting to existing and new plants. Even though this has widespread attention in industries, some challenges hold the development and implementation of this technology [16].

One of the main reasons is the high cost and high energy penalties. The cost of the electricity produced by a coal power plant with this technology can be increased up to 80%. Implementing this technology in an existing system can be half the cost of building a new coal power plant without a post-combustion carbon-capturing system [17]. Another primary reason is the high energy demand in the regeneration process that accounts for two-thirds of the operational cost. This energy demand consists of three parts [18].

1. Absorption heat for CO2-stripping reaction.
2. Sensible heat for elevating the temperature of the solution.
3. Vaporization heat for evaporating liquid water to vapor for CO2 stripping

Estimating the energy demand for the regeneration process is very complex due to the many operating parameters. Nowadays, there are computer simulations software to simulate the processes such as Aspen Plus and ProMax. Other than this, there are some challenges due to degradation and corrosion. Degradation of the solvents happens due to the unwanted pollutants in the flue gas such as SO_X, NO_X, Heat stable salts (HSS), and particulates. These pollutants reduce the ability of CO_2 absorption. Corrosion damage the equipment, reduce the operating efficiency, and increase the maintenance cost of the capture plant. Corrosion occurs due to the oxidization and reduction reactions on the surface between the metal and electrolyte solution [18] (Review on current advances, future challenges and consideration issues for post-combustion CO2 capture using amine-based absorbents).

7 REFERENCES

[01] S., Arachchige U. "Carbon Dioxide Capture by Chemical Absorption: Energy Optimization and Analysis of Dynamic Viscosity of solvents." *Natural Sciences and Maritime Studies, Faculty of Technology.* (2019).

[02] M. Wang, A. Lawal, p. Stephenson, J. Sidders, C. Ramshaw. "Post-combustion CO2 capture with chemical absorption: A state-of-the-art review." *ELSEVIER Chemical Engineering Research and Design.* (2011): 1609-1624. .

[03] M. Fang, D. Zhu. "Chemical Absorption. ." *handbook of Climate Change Mitigation and Adaptation.* (2015.).

[04] S. P. R. Arachchige Udara, Rasenthiran Kohilan, M.A.L. Lakshan, M.K. Lakshitha Madalagama, P.R. Prabhath Pathirana, P.W. Sakuna Sandupama. "Simulation of carbon dioxide capture for industrial applications. ." *ELSEVIER* (2020): 659-663.

[05] Arachchige., Udara S. P. R. "Amine's effect on CO2 removal efficiency. ." *International Journal of Research.* (2019).

[06] Udara Sampath P. R. Arachchige, Morten Christian Melaaen. "Aspen plus simulation of CO2 removal from coal and gas fired power plants. ." *ELSEVIER.* (2012): 391-399.

[07] Udara S. P. R. Arachchige, Muhammad Mohsin, MortenC. Melaaaen. "Optimization of post combustion carbon capture process-solvent selection. ." *International Journal of Energy and Environment.* (2012): 861-870.

[08] Udara S. P. R. Arachchige, Morten C. Melaaen. "Alternative solvents for post combustion carbon capture. ." *International Journal of Energy and Environment.* (2013): 441-448.

[09] Perera K.D.A.S, Ranathunga R.G.S.A, Keshani Y.H.N, Asanka K.A.L, Prabhamini T.M.D.N, Piyathilaka K.M.S.N,. "Cement Industry in Sri Lanka." *JOURNAL OF RESEARCH TECHNOLOGY AND ENGINEERING* 1.1 (2020).

[10] Udara S. P. R. Arachchige, Dinesh Kawan, Lars-André Tokheim, Morten C. Melaaen. "Impact of kiln thermal energy demand and false air on cement kiln flue gas CO2 capture." *INTERNATIONAL JOURNAL OF ENERGY AND ENVIRONMENT* 5.1 (2014): 45-52.

[11] —. "Waste Heat Utilization for CO2 Capture in the Cement." *International Journal of Modeling and Optimization* 4.6 (2014): 438-442.

[12] Udara S.P.R. Arachchige, Dinesh Kawan, Lars-André Tokheim, and Morten C. Melaaen. "Model Development for CO2 Capture in the Cement Industry." *International Journal of Modeling and Optimization* 3.6 (2013): 535-540.

[13] Udara. S. P. R. Arachchige, Kohilan Rasenthiran, M. P. P. Liyanage. "Modelling of CO2 Capture Using Aspen Plus For Coal Fired Power Plant. ." *INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY RESEARCH.* (2019).

[14] Udara S. P. R. Arachchige, Dinesh Kawan, Morten C. Malaaen. "Simulation of Carbon Dioxide Capture for Aluminium Production Process. ." *International Journal of Modeling and Optimization.* (2014).

[15] Udara S. P. R. Arachchige, Muhammad Mohsin, Morten c. Melaaen. "Optimized Carbon Dioxide Removal Model for Gas Fired Power Plant. ." *European Journal of Scientific Research.* (2012): 348-359.

[16] Muhammad Asif , Muhammad Suleman, Ihtishamul Haq, Syed Asad Jamal. "Post-combustion CO2 capture with chemical absorption and hybrid system: current status and challenges." *Greenhouse Gas Science and Technology* (2018).

[17] Tabbi Wilberforce, A. Baroutaji, Bassel Soudan, Abdul Hai Al-Alami, Abdul Ghani Olabi. "Outlook of Carbon Capture Technology and Challenges." *Science of the total environment* 657 (2019): 56-72.

[18] Liang Zhiwu, Kaiyun Fu, Raphael Idem, Paitoon Tontiwachwuthikul. "Review on current advances, future challenges and consideration issues for post-combustion CO2 capture using amine-based absorbents." *Chinese journal of chemical engineering* (2015).