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Technical and economic analysis of retrofitting a post-combustion carbon capture system in a Thai coal-fired power plant

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Abstract

Mitigating CO_2 emissions is an important clean energy research topic. Post-combustion carbon capture is a well established and vital carbon capture technology for existing fossil-fueled power plants. In this work, monoethanolamine (MEA) based carbon capturing unit was designed using AspenPlus V.10 software for a 300 MWe power unit of Mae Moh power plant in Thailand. Technical and economic analysis of retrofitting a lean aqueous MEA system was investigated. From the simulation study, it was revealed that the optimal lean CO_2 feeding for the amine-based carbon separation plant was about 0.2 mol/mol using packed columns with Sulzer Mellapak 250Y product. The optimal liquid-to-gas ratio with a flue gas containing 15% CO_2 was approximately 3.0. Furthermore, the optimal total costs of the plants were less than 55 \$/ton of CO_2 captured.

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Keywords: Decarbonization; CCS; Lignite; Power generation; Process simulation

1. Introduction

For separating CO_2 from flue gas stream, an aqueous MEA solvent is usually used as the Ref. [1]. Among the pilot-scale studies for the amine solvent, Notz et al. [2] provided a through report regarding comprehensive studies of carbon capture with amine based solutions in a pilot setup. The design approach and conception adopted is of huge interest such that a commercial process simulation program, AspenPlus, has been deployed in technical and economic analysis of the amine-based decarbonization plants that research scientists and engineers can straightforwardly follow and adopt for their needs.

In this work, MEA based carbon separation plant was proposed for a 300 MWe electricity generation unit of Mae Moh power plant, the biggest pulverized coal plant in Thailand. Technical and economic analysis of retrofitting the designed system using AspenPlus V.10 was investigated.

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2. Methodology

2.1. Process modeling framework

Post-combustion capture is about CO_2 separation from flue gas via chemical absorption, followed by desorption or stripping to release the CO_2 [3]. For modeling framework, AspenPlus RadFrac model, an improved rate-based model for multiple stage process which was employed for simulating the absorption and desorption in the amine-based carbon removal plants. Thermodynamic and reaction kinetics model proposed by Zhang et al. [4,5] that utilizes the electrolyte non-random two-liquid (ENRTL) property method for liquid and perturbed chain — statistical association fluid theory (PC-SAFT) equation of state for gas phase properties was also employed. The kinetic expressions (Eqs (1) to (4)) for the carbamate and bicarbonate with the kinetic constants were summarized in Table 1. The rates are given as Eq. (5).

$$r_j = k_j^0 \exp\left(-\frac{\varepsilon_j}{R}\left[\frac{1}{T} - \frac{1}{298.15}\right]\right)\prod_{i=1}^{N}(a_i)^{\alpha_{ij}} \tag{5}$$

where r_j, k_j^0, ε_j, R, T, a_i and α_{ij} are the rate for reaction j, the preexponential factor, the activation energy, the gas constant, the temperature (K), the activity of species i, and the reaction order of species i in reaction j, respectively. Summary of the models in AspenPlus which were used for calculations of the transport properties are shown in Table 2.

Table 1. Kinetic parameters of rate equations for the MEA-CO_2 absorption.

Eq no.	Reaction	Reaction direction	k_j^0(kmol/m^3 s)	ε_j (kJ/kmol)
(1)	$MEA + CO_2 + H_2O \rightarrow MEACOO^- + H_3O^+$	Forward	3.02×10^{14}	41.20
(2)	$MEACOO^- + H_3O^+ \rightarrow MEA + CO_2 + H_2O$	Reverse (absorber)	5.52×10^{23}	69.05
		Reverse (desorber)	6.56×10^{27}	95.24
(3)	$CO_2 + OH^- \rightarrow HCO_3^-$	Forward	1.33×10^{17}	55.38
(4)	$HCO_3^- \rightarrow CO_2 + OH^-$	Reverse	6.63×10^{16}	107.24

Table 2. The models in AspenPlus used for calculating the transport property.

Transport properties	Gas phase	Liquid phase
Fluid density	PC-SAFT EoS	Clarke density model
Thermal conductivity	Stiel–Thodos model/Wassiljewa–Mason–Saxena mixing rule	Reidel model
Binary diffusivity	Chapman–Enskog–Wilke–Lee model	Nernst–Hartly model
Viscosity	Chapman–Enskog model with Wilke approximation	Jones–Dole model
Surface tension	–	Onsager–Samaras model

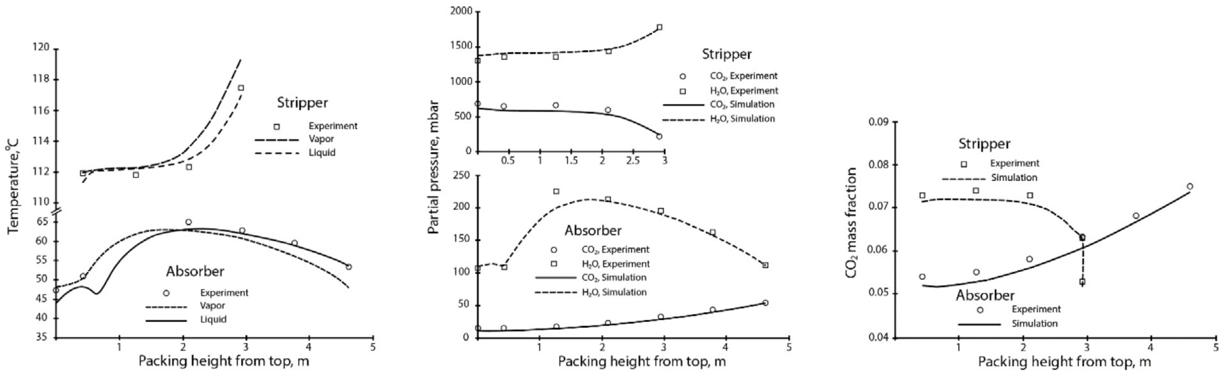
2.2. Column design and validation of models

The diameter of a column at given gas and liquid flow rates was typically resolved based on; (i) allowable maximum pressure drop and, (ii) acceptable maximum capacity (usually about 80 per cent for the flood velocity). The height of the column was determined using the concept of the height equivalent to a theoretical plate (HETP). Diameter sizing and packed height according to Agbonghae et al. [3] were subsequently proposed.

The column model of absorber and desorber with the structured packing (Sulzer Mellapak 250Y) was revalidated against the pilot plant (experiment 1) of Notz et al. [2] before adopted in the scaling-up designs. According to Fig. 1, the model predictions were found to agree very well with the experimental findings. Therefore, it could be assuredly applied for scaling-up design within a cautious uncertainty within 10%.

2.3. Scaling-up applications

The absorber and desorber sizings were designed with the stripper reboiler capacity at 90% carbon removal rate for 30% w/w aqueous MEA. Table 3 shows the flue gas conditions and compositions, and relevant technical



(a) (b) (c)

Fig. 1. Pattern of (a) Temperature profiles; (b) Pressure profiles; (c) CO_2 concentration profiles in the proposed absorber and desorber.

Table 3. Conditions used for the designed cases.

List	Value/Data	Unit
Flue gas conditions (after FGD to stack)		
Flue gas temperature	80	°C
Flow rate (actual O_2)	458	kg/s
Pressure	0.2	kPa
Gas velocity	19.66	m/s
Flue gas composition		
Carbon dioxide (CO_2)	15.3	%
Moisture (H_2O)	21.96	%
Oxygen (O_2)	5.3	%
Nitrogen (N_2)	57.44	%
General information for design		
Calculation type	Rate-based model	–
The flood point velocity	∼80	%
Max. press. drops per unit height	∼20.83	mmH_2O/m
	∼0.002042	bar/m
MEA conc. without CO_2	0.3	mol CO_2/mol MEA
CO_2 capture rate	∼90	%
Equipment		
Cross HX temp.	110	°C
Cross HX temp. approach, hot end	10	°C
Cross HX ΔP	0.1	bar
Lean amine cooler ΔP	0.1	bar
discharge press. of Lean amine pump	3.0	bar
eff. of Lean amine pump	75	%
discharge press. of Rich amine pump	3.0	bar
eff. of Rich amine pump	75	%
Blower discharge press.	1.2	bar
Blower efficiency	75	%
Cooling water temp.	20 (for Thailand)	°C
Absorber		
Aspen Plus block	RadFrac model	–
Number of stages	20	stages
Reaction no.	(1), (2 for absorber), (3), (4)	–
Method for mass transfer coefficient	Bravo (1985)	–
Interfacial area method	Bravo (1985)	–

(*continued on next page*)

Table 3 (*continued*).

List	Value/Data	Unit
Flooding method	Wallis	–
Method for heat transfer coefficient	Chilton and Colburn	–
Film resistance options	Discrxn	–
Flow model	Countercurrent	–
Top pressure	1	atm
Lean MEA inlet temperature	∼40	°C
Packing type	Sulzer Mellapak 250Y	–
Stripper		
Aspen Plus block	RadFrac model	–
Number of stages	20	stages
Reaction no.	(1), (2 for stripper), (3), (4)	–
Method for mass transfer coefficient	Bravo (1985)	–
Interfacial area method	Bravo (1985)	–
Flooding method	Wallis	–
Method for heat transfer coefficient	Chilton and Colburn	–
Film resistance options	Discrxn	–
Flow model	VPlug	–
Condenser temp. and press.	35, 1.62	°C, bar
Packing type	Sulzer Mellapak 250Y	–
Economic analysis assumption		
Electricity cost	0.12	\$/kWh
Cooling water cost	0.0317 (in UK)	£/m^3
Plant equipment metallurgy	316L stainless steel	–
Exchange rate	∼30	THB/\$

and economic considerations used for design cases. The operating expenditure (OPEX) and the capital expenditure (CAPEX) of the retrofit were determined using the AspenPlus Economic Analyzer. The costing assumptions for Thailand and the U.K. in the Economic Analyzer with given values were used. It was worth noting that the CAPEX and OPEX are expected to be more for a real installation when other equipment will have to be fitted according to a hazard and operability (HAZOP) study [3].

Table 4. Cases for simulation in this paper at lean carbon loading 0.2 mol CO_2/mol MEA.

Case	LN-IN (kg/s)	L/G	Absorber		Stripper		CO_2 captured (%)	Q reboiler(MJ/kgCO_2)
			Diameter (m)	Height (m)	Diameter (m)	Height (m)		
1	982.262	2.625	14.34	40	8.277	15	90.43	3.482
2	1005.836	2.688	14.51	25	8.43	15	90.06	3.580
3	1029.036	2.750	14.60	20	8.475	15	90.75	3.634
4	1075.811	2.875	14.71	12.5	8.725	15	90.65	3.804
5	1122.585	3.000	14.77	10	8.865	15	90.10	3.994
6	1216.134	3.250	14.95	8.38	9.1	15	89.96	4.327
7	1309.683	3.500	15.1	7.5	9.65	15	90.12	4.634
8	1403.231	3.750	15.25	7.12	9.95	15	90.10	4.908

FG-IN = 374.195 kg/s, Lean carbon loading = 0.2 mol CO_2/mol MEA, Flooding ∼80%.

The cases considered here are listed in Table 4. The optimal design was that with the minimum operating expenditure (OPEX). To check the soundness of deploying the minimum OPEX and CAPEX as a base for the optimal design criteria, additional economic appraisal was undertaken for the annualized total cost (TOTEX). It was computed by taking plant service life of 20 years ($n = 20$) and 10 per cent ($i = 0.1$) for interest rate, and is given by Eq. (6):

$$\text{TOTEX} = \text{OPEX} + \text{CAPEX}\left(\frac{i\,(1+i)^n}{(1+i)^n - 1}\right) \tag{6}$$

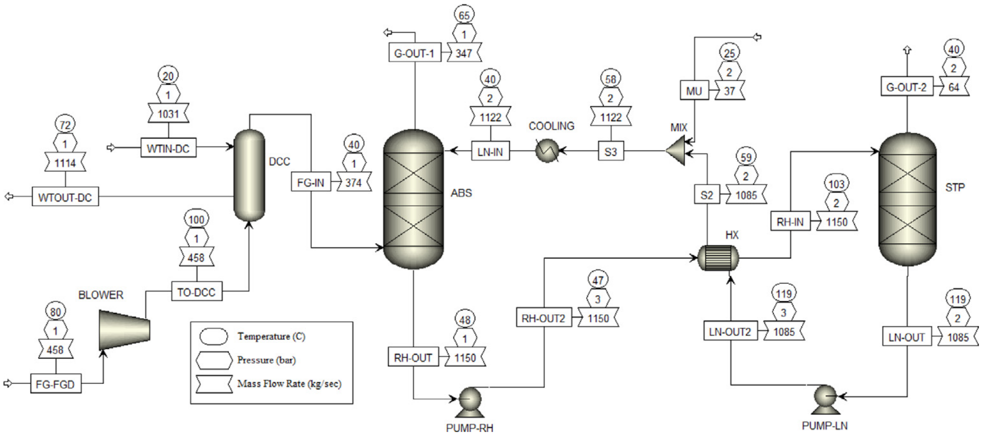


Fig. 2. The MEA-based carbon capture retrofit for Mae Moh power plant.

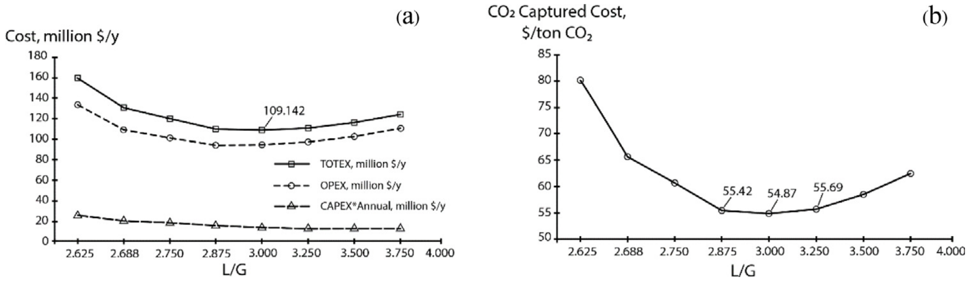


Fig. 3. (a) TOTEX, OPEX, CAPEX; (b) CO_2 captured cost for Mae Moh power plant.

3. Results and discussion

The proposed project for an amine-based carbon separating plant which may be retrofitted to Mae Moh power plant is depicted in Fig. 2. The best available design in this work (case no. 5) is summarized in Table 5. The optimal lean loading that can serve a commercial power station was around 0.2 mol/mol for absorber and desorber/stripper columns. The optimal liquid-to-gas ratio for Mae Moh power plant was 3.0 for a flue gas with a CO_2 content of approximately ∼15%. The cost considerations of the plant are shown in Fig. 3. The optimal case with the least OPEX by 0.2 lean CO_2 feed and 3.0 liquid-to-gas ratio affecting the entire expenditure of the plants per gross MWh is 41.53 $/MWh. The total costs of the retrofit per ton of CO_2 removed is 54.87 $ which was quite costly.

4. Conclusion

The technical and economic consideration for retrofitting a MEA-based carbon separation plant to a 300 MWe unit of Mae Moh coal power generation plant was conducted using the process simulation program, AspenPlus. Technically, the technology is feasible, but economically, it appeared to be rather expensive for the present situation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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Table 5. Main results for absorber and stripper column design.

Lists	Value	Unit
Gross plant size	300	MWe
Flow rate of flue gas	458	kg/s
OPT liquid/gas ratio, L/G	3.0	kg/kg
OPT lean CO_2 loading	2.0	mol/mol
OPT rich CO_2 loading	0.471	mol/mol
CO_2 captured at 90% rate	63.075	kg/s
	1,790,217.0	tCO_2/year
Degraded efficiency of power plant	∼23.47	%
Electricity consumed from power plant	70.428	MWe
Plant equipment metallurgy	316L stainless steel	-
Absorber		
Number of absorbers	1	-
Absorber packing	Mellapak 250Y	-
OPT absorber diameter	14.77	m
OPT absorber height	10	m
Stripper		
Number of strippers	1	-
Stripper packing	Mellapak 250Y	-
OPT stripper size	8.87	m
OPT stripper height	15	m
Reboiler temperature	119.13	^{O}C
Reboiler duty	251,933 (69.981)	kWth (MWe)
Specific reboiler duty	3.994	$MJ/kgCO_2$
Specific condenser duty	1.268	$MJ/kgCO_2$
Cross HX		
Duty	236,604	kW
Rich amine inlet/outlet temperature	47.4/103	^{O}C
Lean amine inlet/outlet temperature	119.2/59.3	^{O}C
Required exchanger area	22,942.5	sqm
Average U (Dirty)	0.85	kW/sqm-K
UA	19501.1	kJ/sec-K
LMTD (corrected)	12.133	^{O}C
Lean amine cooler		
Duty	72,713.19	kW
Lean amine pump		
Duty	171.91	kW
Rich amine pump		
Duty	275.87	kW
Economic results		
CAPEX	14.458	Million $/year
OPEX	94.684	Million $/year
TOTEX	109.142	Million $/year
Total cost per gross MWh	41.53	$/MWh
Total cost per CO_2 captured	54.87	$\$/tonCO_2$

References

[1] Bui M, Adjiman CS, Bardow A, Anthony EJ, Boston A, Brown S, et al. Carbon capture and storage (CCS): the way forward. Energy Environ Sci 2018;11(5):1062–176.

[2] Notz R, Mangalapally HP, Hasse H. Post combustion CO_2 capture by reactive absorption: Pilot plant description and results of systematic studies with MEA. Int J Greenhouse Gas Control 2012;6:84–112.

[3] Agbonghae EO, Hughes KJ, Ingham DB, Ma L, Pourkashanian M. Optimal process design of commercial-scale amine-based CO_2 capture plants. Ind Eng Chem Res 2014;53(38):14815–29.

[4] Zhang Y, Que H, Chen C-C. Thermodynamic modeling for CO_2 absorption in aqueous MEA solution with electrolyte NRTL model. Fluid Phase Equilib 2011;311:67–75.

[5] Zhang Y, Chen C-C. Modeling CO_2 absorption and desorption by aqueous monoethanolamine solution with Aspen rate-based model. Energy Procedia 2013;37:1584–96.