A comparative study of standard carbon capture process and Advanced Flash Stripper configuration using MEA

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Abstract:

The advanced flash stripper (AFS) is proven to have benefits in capital investment and energy saving for carbon capture plants using piperazine, whilst monoethanolamine is still the most used amine in the existing commercial carbon capture plants. The production and use of energy and material consumed during CO_2 absorption and regeneration generate CO_2. In this research, the 130-tonne daily CO_2 capture plants with conventional configuration and AFS configuration are simulated in Aspen Plus. Their total annualized costs are estimated to be 3.33 million USD and 2.87 million USD, respectively. The life cycle assessment is conducted to evaluate the environmental impacts from the cradle and grave of energy and materials consumed during carbon capture, showing 58% equivalent CO_2 in flue gas is generated.

Keywords:

Carbon capture; Monoethanolamine; Advanced flash stripper; Techno-economic analysis; Life cycle assessment.

1. Introduction

Monoethanolamine (MEA) is the widely used amine solvent in commercial post-combustion carbon capture due to its high reaction rate with CO_2, high carbon capture capacity and low cost [1]. Current study related to the amine-based carbon capture process concentrates on the improvement of energy efficiency. The Separation Research Programme (SRP) proposed a novel stripper configuration called Advanced Flash Stripper (AFS) [2] allowing further heat recovery and lower capital investment of the stripper, as the heat duty used to release by a condenser is now partially recovered by a cold bypass stream, and an in-situ reboiler is replaced with a cheaper steam heater. This configuration has been employed in the carbon capture process using 5 m or 8 m piperazine (PZ) [2]. However, the significantly high price of PZ may not be a threat to the position of MEA in the existing commercialized carbon capture plants. Also, the simple but ingenious configuration modification is promising to retrofit the existing plants with low capital investments. Moreover, the CO_2 from flue gas is captured and regenerated in environmental concern, whilst energy and amine solvent is consumed in amine-based carbon capture processes, which may be accompanied by CO_2 emissions again. The impacts of cradle and grave of materials and energy are often ignored in previous work. Therefore, this work aims to investigate the techno-economic and environmental feasibility of AFS configuration in an MEA-based carbon capture process. A rate-based model will be built to validate the plant data from [3] as a base case. The AFS configuration will then be employed. The techno-economic analysis and life cycle assessment will be used to evaluate the equivalent energy for CO2 recovery, total annualized cost as well as environmental impacts.

2. Process description

2.1. Conventional configuration

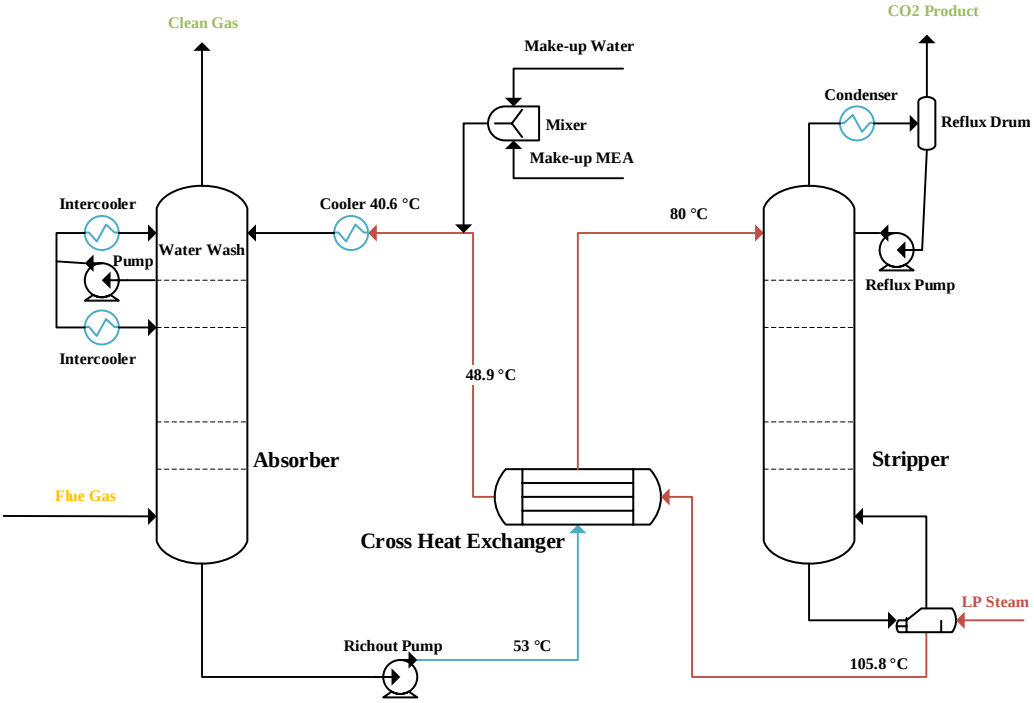

Figure 1. Simplified flowsheet of the carbon capture plant using MEA.

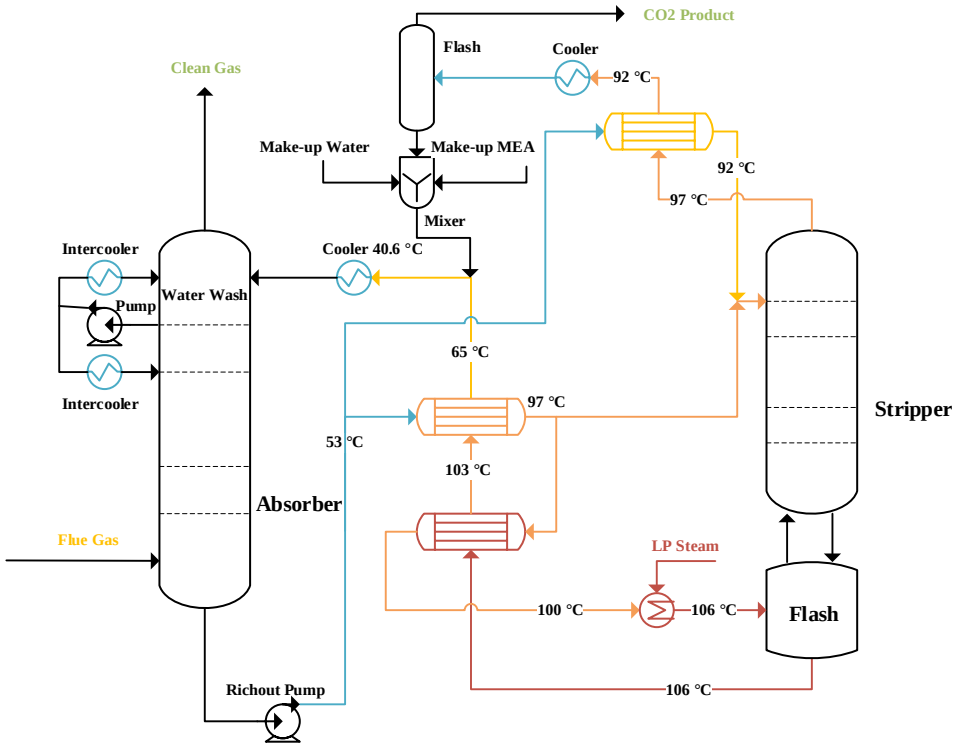

Figure 2. AFS configuration of carbon capture plant using MEA.

This simplified conventional configuration shown in Figure 1 is based on an existing carbon capture plant removing 130 tonnes of CO_2 per day [3]. After exhausted, desulphurized and cooled to 40 ºC, the flue gas (12 vol% CO_2) enters the bottom of the absorber packed with Polypropylene Ring, captured by the amine countercurrent (16%-17 wt% MEA). Around 80% of the liquid in the connection of the wash

section and absorption section is pumped back to the top of the absorber so that the amine loss of MEA can be alleviated. And the liquid is cooled to 40 ºC for the improvement of absorption performance and mitigation of MEA volatility. The clean gas is vented with nearly all nitrogen, oxygen and water. The rich solvent with high CO_2 loading is then heated to 80 ºC and pumped to the top of the stripper for CO_2 and amine regeneration. The 26-tray stripper is equipped with a condenser and reboiler. Approximately 14% of the bottom liquid is boiled up in the kettle reboiler and comes back to the stripper for further regeneration. The thermal energy of lean amine regenerated is recovered by a cross heat exchanger. After releasing the heat to the rich amine exiting from the absorber, the regenerated lean amine is then cooled and returned to the top of the absorber, before being mixed with amine and water makeup.

2.2. Advanced flash stripper configuration

The configuration of the carbon capture plant with an advanced flash stripper is presented in Figure 2. Unlike a conventional configuration where the thermal energy of distillate in the stripper is wasted, the in-situ condenser is replaced with an external cross heat exchanger to recover part of the heat. Moreover, two stream splitters are used to adjust the flowrate of rich solvent, which allows managing the feasibility of heat exchange (assume the minimum temperature approach is 5 ºC). Consequently, cold rich bypass and warm rich bypass are mixed and fed to the top of the stripper, contacting the gaseous countercurrent from a flash tank where part of hot rich solvent is vaporized and CO_2 is released to the bottom of the stripper. The regenerated lean solvent exits as the liquid product from the bottom of the flash tank. Its heat is recovered by a hot cross heat exchanger and a warm cross heat exchanger.

3. Methodology

The rate-based carbon capture process using MEA as an absorption solvent is developed in Aspen Plus V12.1. The property method employs an electrolyte NRTL model with the Redlich-Kwong equation of state [4]. For the rate-based setup, the Onda model is applied to calculate the mass transfer coefficient and interfacial area [5]. The heat transfer coefficient is then obtained from the mass transfer coefficient using the Chilton and Colburn analogy [6]. And the liquid holdup at each packing stage is estimated by the correlation of Stichlmair [7]. The chemistry of MEA absorbing CO_2 is described by a set of equilibrium reactions listed below in eqs. 1-5. The built-in power law expression is used to represent the kinetic reactions for controlling the performance of CO_2 absorption and regeneration. The corresponding kinetic parameters are provided in Table 1.

$$2H_2O \leftrightarrow H_3O^+ + OH^- \quad (1)$$
$$CO_2 + 2H_2O \leftrightarrow HCO_3^- + H_3O^+ \quad (2)$$
$$HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H_3O^+ \quad (3)$$
$$MEA^+ + H_2O \leftrightarrow MEA + H_3O^+ \quad (4)$$
$$MEA + HCO_3^- \leftrightarrow MEACOO^- + H_2O \quad (5)$$
$$CO_2 + OH^- \rightarrow HCO_3^- \quad (6)$$
$$HCO_3^- \rightarrow CO_2 + OH^- \quad (7)$$
$$MEA + CO_2 + H_2O \rightarrow MEACOO^- + H_3O^+ \quad (8)$$
$$MEACOO^- + H_3O^+ \rightarrow MEA + CO_2 + H_2O \quad (9)$$

Table 1. Kinetic parameter for build-in power law expression (eqs. 6-9)

Reaction No.	k_{abs}	$E_{abs}\ (cal/mol)$	k_{reg}	$E_{reg}\ (cal/mol)$
6	1.33e+17	1.32e+4	1.33e+17	1.32e+4
7	6.63e+16	2.57e+4	6.63e+16	2.57e+4
8	3.02e+14	9.86e+3	3.02e+14	9.86e+3
9	5.52e+23	1.65e+4	6.50e+17	2.28e+4

The cost estimation of the carbon capture process with two configurations is completed by Aspen Process Economic Analyzer (APEA). Instead of using installation factors to evaluate costs, APEA is able to manage that by required materials and labour. Furthermore, the combination of mathematical models and expert systems contributes to a more detailed economic measurement [8]. The parameters for calculating the costs are presented in Table 2. The annual cost is calculated by the summation of operating cost and annualized capital cost [9], which is represented by eqs. 10-11 below.

$$ACCR = \frac{DR \times (DR+1)^n}{(DR+1)^n - 1} \quad (10)$$

$$TAC = ACCR \times CAPEX + OPEX \quad (11)$$

Where ACCR is the annualized capital cost ratio; DR is the discount rate, assumed to be 10%; n is the estimated period; TAC, CAPEX and OPEX represent the total annualized cost, capital cost and operating cost, respectively.

Table 2. Parameters for cost estimation

Parameters	Price
Carbon fee/carbon tax ($/kg)	0.051
Make-up water ($/cum)	3
Make-up MEA ($/ton)	1200
Electricity ($/kJ)	1.60e-5
LP steam ($/kJ)	1.90e-6
Cooling water ($/kJ)	2.12e-7

The life cycle assessment is employed to identify improvement potential for environmental performance. The principles, frameworks, requirements and guidelines can be found in ISO 14040 and ISO 14044. An “operational guide to the ISO standards” was published by the Centre of Environmental Science of Leiden University (CML) in 2001, summarizing a list of impact categories and characterization methods and factors for corresponding substances. Guinee et al. explained these categories [10]. In this work, the ReCiPe method [11] is chosen to evaluate the environmental impact of material and energy consumption for equivalent CO_2 regeneration in two carbon capture processes. All impact indicators are obtained by commercial LCA software SimaPro, and the most 7 influential impact indicators are presented in Table 3. The “global warming potential” refers to the global temperature increment resulting from greenhouse gas emissions, which is measured by the kilogram of carbon dioxide equivalent. The exposure to “ionizing radiation” is detrimental to human health, which is estimated by the equivalent kilobecquerels of Cobalt-60 to air. The “land use” is a composite indicator measuring the use and occupation of land for agriculture, housing, mining, or other purposes, so the unit is square meter in the total period. The essential idea behind “fossil resource scarcity” is that the depletion of fossil fuels forces the extraction of other resources in the future, which is estimated in kilogram of equivalent oil. The following indicators are measured in kilogram of 1,4-dichlorobenzene emitted. Particularly, “terrestrial ecotoxicity” indicates the impact of toxic substances on terrestrial ecosystems (i.e., individual species and the functioning of the ecosystem). The “human carcinogenic toxicity” and “human non-carcinogenic toxicity” reveals the potential health damage leading to cancers and other diseases, respectively.

Table 3. Impact indicators for life cycle assessment

Abbreviation	Indicator	Unit
GWP	Global warming potential	kg CO_2 eq
IR	Ionizing radiation	kBq Co^{-60} eq
TEC	Terrestrial ecotoxicity	kg 1,4-DCB
HCT	Human carcinogenic toxicity	kg 1,4-DCB
HNCT	Human non-carcinogenic toxicity	kg 1,4-DCB
LU	Land use	m^2a crop eq
FRS	Fossil resource scarcity	kg oil eq

4. Results and discussion

The feasibility of the rate-based carbon capture model is validated by the plant data from [3]. The comparison between plant data and modelling results in terms of CO_2 loading, temperature, recovered CO_2 amount, steam usage and clean gas composition, is listed in Table 4. The modelling results show a great agreement with plant data. It is worth noting that the O_2 content takes account for a larger proportion with about 40% deviation. This may result from the oxidative degradation of MEA in reality, which is not considered in the model. Nevertheless, this model is still feasible to predict the absorber and stripper performance.

Table 4. Comparison between plant data and modelling results

	Plant	Model	RD (%)
Lean Loading (mole of CO2/mole of amine)	0.11	0.114	3.77
Rich Loading (mole of CO2/mole of amine)	0.411	0.425	3.33
Rich Amine Discharge temperature from absorber bottom (ºC)	57.22	53.479	6.54
Clean Gas Temperature (ºC)	40	40.57	1.43
CO2 Production (tonne/day)	125.2	127.225	1.62
Steam flowrate to reboiler (kg/hr)	17460	17466	0.03
Clean Gas Composition (mol%)			
CO2	0.223	0.228	2.24
O2	5.762	8.046	39.63
N2	87.315	85.005	2.65
H2O	6.672	6.591	1.22

*RD is the relative deviation.

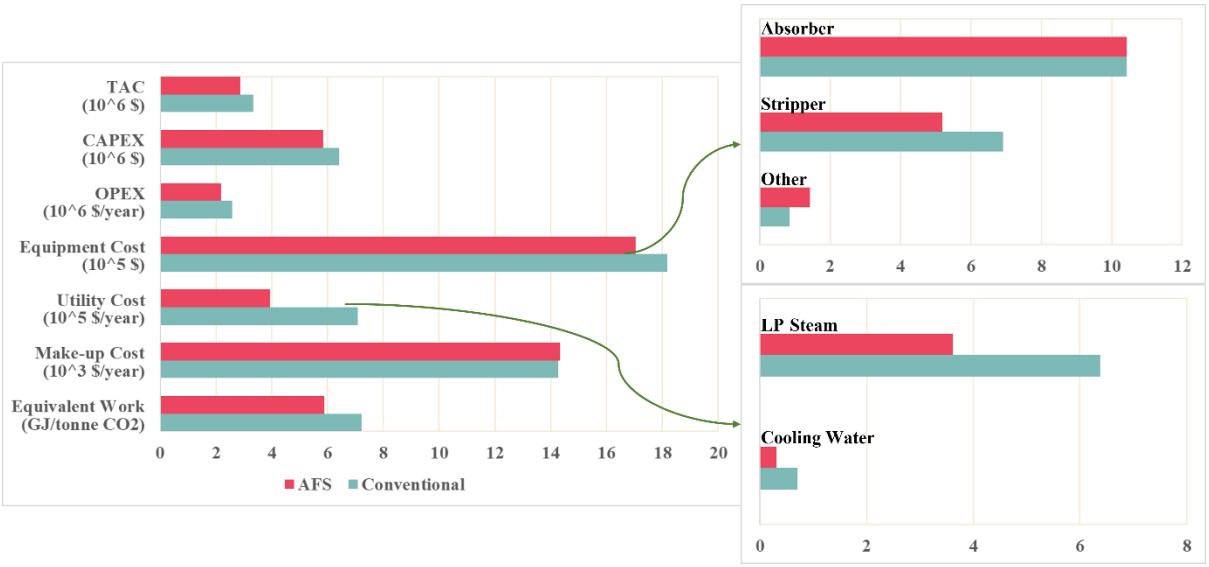

Figure 2. The comparison of conventional process and AFS process related to costs and equivalent work.

The comparison between conventional and AFS configurations is presented in Figure 2 in terms of costs and equivalent energy requirements for CO_2 recovery. The total annualized costs of conventional configuration and AFS configuration are 3.33 million USD and 2.87 million USD, respectively. It is shown that the capital investment costs around 6 million USD, and the annual operating expenditure is 2 million USD. Compared to the conventional configuration, using the AFS configuration will save about 8.94% and 15.1%, receptively for capital cost and operating cost. Although over 24% saving from eliminating the condenser and reboiler of the stripper in AFS configuration is reduced by the additional costs from two cross heat exchangers and one advanced flash drum, making the equipment cost reduction only 6.23%, the energy saving is tremendous due to the significant heat recovery realized by AFS configuration. The LP steam cost, contributing to 90% of the total utility cost, is reduced by 43.24%, and the demand for cooling water is reduced to over half, leading to a 44.55% reduction in utility cost. The same absorber condition and regenerative temperature result in nearly equal thermal degradation, showing great agreement with the negligible difference in make-up cost. As a kettle reboiler is replaced with a steam heater in AFS configuration, the heat duty is significantly reduced, and then the amount of regenerated CO_2 becomes less. Evaluating the energy usage by equivalent work per tonne of CO_2 regenerated is a relatively fair way. The existing carbon capture plant using standard MEA-absorption configuration consumes 7.22 GJ/tonne CO_2, whilst the AFS configuration is able to consume 5.89 GJ/tonne CO_2, saving 18.49% energy usage.

Table 5. Detailed characterization results of two carbon capture configurations

		Electricity	MEA makeup	Water makeup
Fossil resource scarcity	Conventional	30621.65	36.85	0.12
	AFS	24960.77	56.72	0.07
Land use	Conventional	39021.16	4.36	0.03
	AFS	31807.50	6.70	0.02
Human non-carcinogenic toxicity	Conventional	46117.39	43.68	0.52
	AFS	37591.88	67.22	0.32
Human carcinogenic toxicity	Conventional	3396.49	3.78	0.06
	AFS	2768.60	5.82	0.04
Terrestrial ecotoxicity	Conventional	60160.37	50.70	1.38
	AFS	49038.80	78.02	0.85
Ionizing radiation	Conventional	54628.20	7.32	0.04
	AFS	44529.34	11.26	0.02
Global warming potential	Conventional	86344.88	71.27	0.41
	AFS	70382.70	109.70	0.25

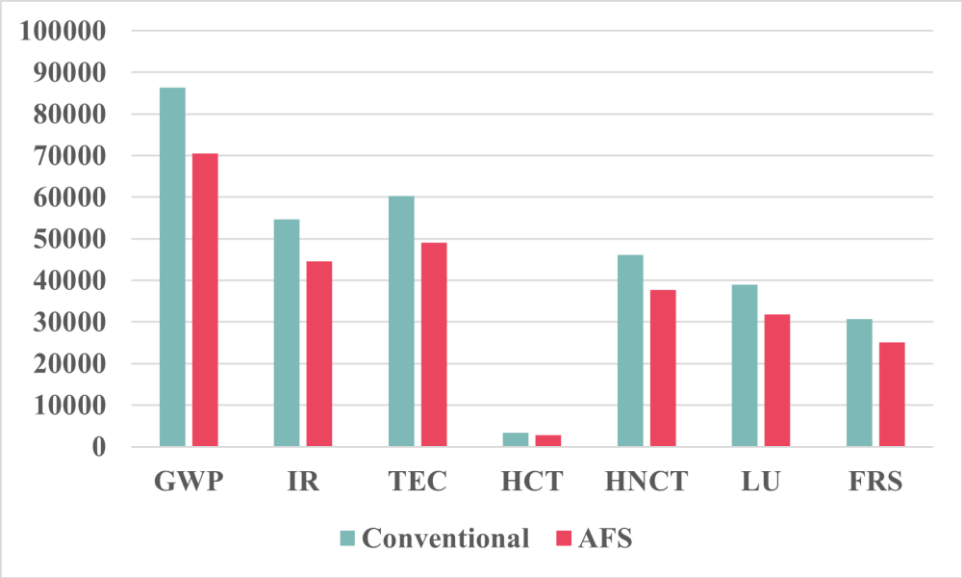

Figure 3. Characterization results of two carbon capture configurations using ReCiPe 2016.

The life cycle assessment measures the environment impacts of material and energy consumption in the carbon capture process quantitively: approximately 78000 kg CO_2, 50000 kBq Co-60, 55000 kg 1,4-DCb, 3000 kg 1,4-DCB, 42000 kg 1,4-DCB, 35000 m^2a cropland and 28000 kg oil. Furthermore, electricity contributes to around 99% of all impact indicators. The general pattern of impact indicators presented in Figure 3 shows that the AFS configuration contributes less to environmental and healthy damage, compared to the conventional configuration. This can be attributable to the significant reduction of energy usage in the carbon capture process using AFS configuration, according to Table 5 electricity (energy consumption is converted to equivalent electricity use) makes the main contribution to environmental influence. The most significant indicator is the global warming potential and the least influential indicator is human carcinogenic toxicity. This is because the cradle to grave of electricity generated by fossil fuels leads to a tremendous amount of greenhouse gas emissions whilst a relatively tiny amount of substance resulting in cancer potential to human health. As the aim of the carbon capture process is to capture CO_2 for sequestration or utilization, and the energy consumption itself leads to 78 tonnes of equivalent CO_2 (responsible for 58% of the flue gas in this work), the emphasis on the improvement of energy saving in carbon capture processes is not only reasonably in economic, but in climate change concern. Measured by the same units, the amount of toxic substances detrimental to

terrestrial individuals and the functioning of the ecosystem is relatively higher than that of toxic substances leading to non-carcinogenic diseases for humans. This is due to a larger scope of the terrestrial system including the living place of the human. Table 5 gives more details related to the impact contribution of electricity, MEA makeup and water makeup. In addition to the aforementioned role of electricity, it is interesting to see some clues from chemical processes and properties: MEA is produced by ammonia which is mainly produced via the energy-intensive Haber-Bosch process, leading to the scarcity of fossil resources and greenhouse gas emissions. Also, the toxic property of MEA corresponds to the detrimental impacts on human health and the terrestrial ecosystem associated with its individuals. Therefore, life cycle assessment gives a new perspective to see the improvement potential in the carbon capture process environmentally.

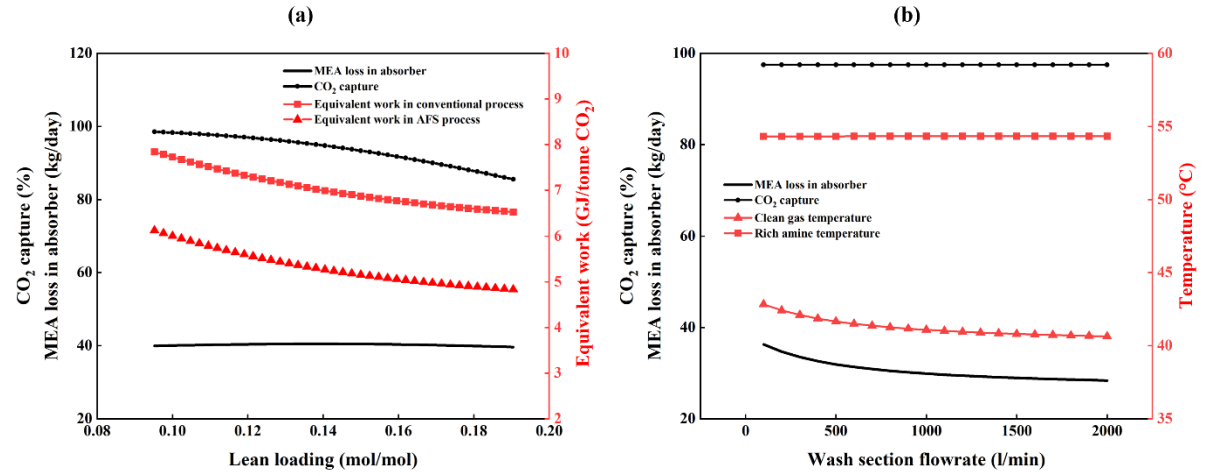

Figure 4. The effects of (a) CO2 loading and (b) water wash amount on CO2 removal, solvent loss and equivalent work.

The sensitivity analysis is conducted to investigate the effects of lean loading and wash section flowrate on absorption performance and energy usage. In Figure 3(a), no effect on amine loss is observed as the CO_2 loading in a lean solvent increases. The significantly decreased curves of equivalent work for CO_2 regeneration in both configurations show great benefits in energy saving. Specifically, with the increment of lean loading from 0.09 to 0.19, the equivalent work in conventional and AFS carbon capture processes reduces by 16.8% and 20.1%, respectively. Albeit the energy benefits, the capability of removing CO_2 is weakened to only 85%. The trade-off of energy saving and carbon penalty is therefore formed when the carbon tax is considered. The MEA loss in clean gas discharged to the atmosphere contributes to potential health and environmental consequences. In addition, the main degraded product of MEA is ammonia, which is soluble in water and detrimental to human health and the environment [12]. Therefore, the wash section is essential in carbon capture processes using MEA. In Figure 3(b), as the flowrate of the wash stream increases from 100 to 2000 litres per minute, the MEA loss decreases by 22%. Moreover, the outlet temperature of the overhead vapour is decreased from 42.8 ºC to 40.6 ºC. However, the wash section flowrate contributes little influence on the removal of CO_2 and the bottom temperature. The off-gas temperature can be a general reference to know the extent of amine loss.

Conclusion

Started with the rate-based simulation to study the operating performance of carbon capture processes with two configurations, the capital costs and operating costs were estimated, followed by the life cycle assessment. Finally, sensitivity analysis was conducted to locate key parameters. The conclusions are as follows:

1. The total annualized costs of the 130-tonne daily carbon capture plant were 3.33 million USD and 2.87 million USD, respectively for the conventional configuration and AFS configuration.
2. Energy consumption contributed to the main environmental impacts, and the cradle and grave of energy and materials consumed in the carbon capture process made approximately half of

the CO_2 capture in vain. Therefore, improving energy efficiency or using renewable energy could be environmentally beneficial.

3. The increment of lean loading reduced energy consumption for CO_2 regeneration but weakened the capability of CO_2 removal. The wash section was able to reduce amine loss significantly.

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