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The Potential of Amine to Feed Flowrate Ratio for Post-Combustion Carbon Capture Systems Using Aspen HYSYS

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ABSTRACT

This investigation into carbon capture systems using ASPEN HYSYS provides significant insights into optimising operational parameters, such as the solvent to feed flow rate ratio, and their impact on energy consumption and economic feasibility. The analysis of separator temperature reveals an inverse relationship with CO_2 capture efficiency, peaking at 25°C due to increased CO_2 solubility at lower temperatures. However, efficiency gains diminish beyond this threshold, indicating the necessity for optimal thermal management in the separation process. Pressure variations similarly exhibit a peak capture efficiency at approximately 220 KPa, attributed to enhanced CO_2 solubility under higher pressures, though efficiency declines at higher pressures due to solvent capacity limitations and operational challenges. Investigation into the solvent to feed flow rate ratio shows that increasing the solvent flow rate improves CO_2 capture up to a point, beyond which efficiency gains taper off, indicating diminishing returns. This finding emphasises the need to optimise solvent usage to balance capture efficiency with energy and operational costs. Achieving a 100% capture rate at a solvent-to-feed flow rate ratio of 7.0 demonstrates the potential of CCS technologies, though the economic and environmental implications of high solvent usage require careful consideration for overall process sustainability.

Keywords: *Carbon, Capture, System, Aspen HYSYS, Post-Combustion.*

INTRODUCTION

The relentless increase in anthropogenic greenhouse gas emissions, driven primarily by industrial processes and the combustion of fossil fuels, poses a profound threat to the global environment. This poses a huge threat to human and global security. At present, the CO_2 concentration in the atmosphere has exceeded 400 ppm, which is about 40% higher than before industrialisation, and the surface temperature has increased by about 0.8 ∘C [1]. The physical, biological, and human systems are changing negatively on a global scale. Sea, ice, and snow cover levels have dropped by roughly 15%, and as global temperatures rise, more diseases are spreading, droughts are occurring, and fertile soil is increasingly exposed to desertification all of which are typically linked to rising emissions of greenhouse gases, including nitrous oxide, halocarbons, carbon dioxide (CO_2), methane (CH_4), and water vapour [2].

Carbon dioxide (CO_2), a principal greenhouse gas, plays a pivotal role in the observed climate change, characterised by rising global temperatures, extreme weather events, and disruptive ecological consequences [3]. As our understanding of the implications of climate change deepens, the need for proactive measures to reduce and mitigate CO_2 emissions becomes increasingly urgent.

Historically, the scientific recognition of the link between industrial activities and climate change dates to the late 19th century, with Svante Arrhenius's ground-breaking work on the greenhouse effect [4]. However, it was in the latter half of the 20th century that the industrial-scale release of CO_2 and its impact on global climate change became evident. International consensus and regulatory efforts, including the Kyoto Protocol and subsequent climate agreements, have underscored the necessity of adopting strategies to reduce carbon emissions. According to a number of studies, CO_2 emissions will linger in the atmosphere for hundreds of years [2]. The main challenge for the entire world is how to reduce emissions even more while benefiting the economy and the environment. One of the most promising and practical strategies to address this challenge is Carbon Capture and Storage (CCS), a technology designed to capture CO_2 emissions from industrial processes and power generation, transport the captured CO_2 to suitable storage sites, and securely store it underground in geological formations. CCS has evolved from theoretical concepts to practical applications, with pioneering projects demonstrating its viability and safety. These projects, including Sleipner in Norway, In Salah in Algeria, and Petra Nova in the United States, have paved the way for the global adoption of CCS.

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Aspen HYSYS, widely recognised and versatile process simulation software developed by Aspen Technology, Inc., has emerged as a fundamental tool in the field of chemical engineering and process optimisation. Its capacity to simulate complex systems, analyse thermodynamic properties, and optimise process designs makes it an invaluable asset for engineers and researchers. Its use in simulating CCS processes and assessing their feasibility has garnered significant attention in recent years, solidifying Aspen HYSYS as the major driver for the simulation and optimisation of Carbon Capture and Storage systems and positioning it as a pivotal resource in the ongoing efforts to address climate change through practical and efficient solutions [5].

The Carbon Capture Storage Framework

The CO_2 sequestration – Carbon Capture and Storage (CCS), may be subdivided into three systems:

1. CO_2 capture and compression system.
2. Transport system for taking the captured CO_2 to appropriate locations.
3. Injection and storage system for its permanent storage away from the atmosphere. The various components of CCS are depicted in Fig. 2.1.

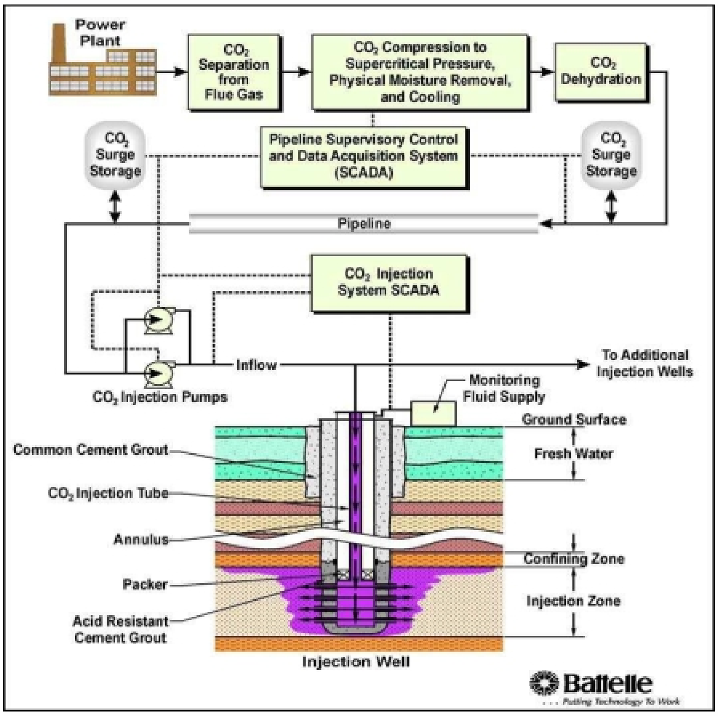


Fig. 1: Carbon Capture and Storage Technology Systems [6]

Efforts to enhance the operational dependability of carbon capture and storage (CCS) are generally organized across three interconnected phases: capture, transport, and permanent sequestration [7]. With respect to the initial capture stage, fossil-fuel-fired power stations typically rely on one of three primary technological pathways. Pre-combustion capture involves gasifying the fuel to produce a synthesis gas from which hydrogen and CO_2 are separated prior to combustion; the hydrogen is subsequently used for power generation while the CO_2 is directed toward storage. Oxy-fuel combustion, by contrast, enriches the combustion atmosphere with oxygen to generate flue gases with a substantially higher CO_2 concentration, thereby simplifying the subsequent separation process.

Post-combustion capture, the third approach, employs chemical or physical absorption to extract CO_2 directly from the flue gas stream following combustion [8]. Each of these capture routes presents distinct technical and economic trade-offs, and their relative maturity varies considerably [8], [9].

Once captured, the transportation of CO_2 to suitable geological repositories necessitates substantial infrastructure investment. Pipelines remain the most widely adopted mode of transport for both onshore and offshore routes, owing to their established technology base and cost-effectiveness over medium distances. However, shipping becomes economically viable for offshore storage sites where pipelines are absent or transport distances are prohibitively large, albeit with additional requirements for CO_2 liquefaction and specialized carrier vessels [8].

The final sequestration stage involves the selection of an appropriate storage medium, while considering storage capacity, containment security, and long-term risks. Deep saline aquifers such as porous rock formations, contains saline water, which offers the largest potential storage volume globally. Depleted oil and gas fields represent the second largest storage category and benefit from decades of geological characterization and monitoring data accumulated during hydrocarbon production, which enhances confidence in their containment integrity. Enhanced oil recovery (EOR) sites provide a comparatively smaller storage capacity but offer short-term economic incentives by improving oil extraction yields; however, this revenue stream is finite and ceases once the oil field is depleted, with some CO_2 inevitably being co-produced with the extracted oil. Emerging approaches include enhanced coal-bed methane recovery, in which CO_2 is injected to enhance methane desorption from coal seams, and CO_2 mineralization, a process that mimics natural weathering by chemically binding CO_2 into stable carbonate minerals such as calcite and limestone, although this remains at an early stage of [8], [9], [10].

Capture Technologies

The terms post-combustion, pre-combustion, and oxyfuel combustion refer to a variety of methods for capturing CO_2 [11]. Pre-combustion, which promotes the high volume at a ratio of 10:1, is a generally used and very simple method.

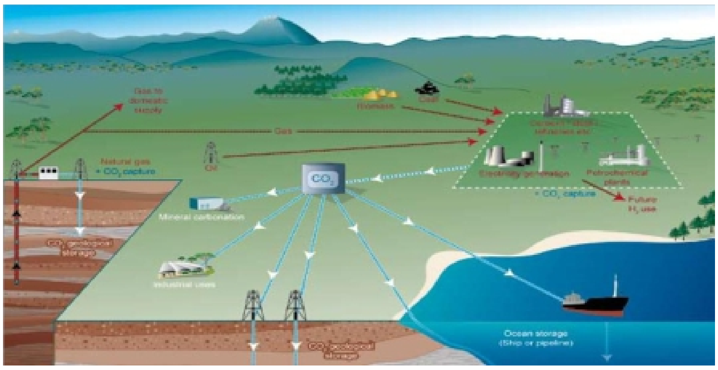


Fig. 2: Schematic diagram of possible CCS systems [12]

On the other hand, the post-combustion approach works well at lower CO_2 streams [13]. Pre-combustion CCS uses an integrated gasification combined cycle in conjunction with a shift reactor to convert carbon to CO_2 [14], [15]. Table 1 lists the various CO_2 capture classes and storage.

Table 1: Different classes of CO2 capture and storage

Classes	Explanation
Carbon Positive	The release of a significant amount of carbon when the process of combustion takes place such as coal to liquid, refineries and natural gas processing. EOR operations are sometimes carbon positive depending on the project specifics
Carbon Neutral	Conversion of carbon into CO_2 that can be used to produce commercial products
Carbon Negative	Removal of CO_2 from the atmosphere directly or by this process applied to biomass combustion for generation of electricity

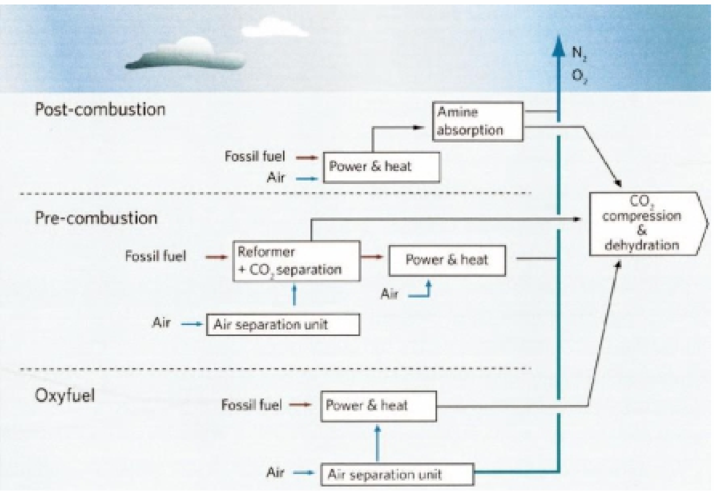


Fig. 3: Simplified diagram illustrating the three main approaches to carbon capture [16]

Review of Related Literature

The body of research on CO_2 capture using Aspen HYSYS has extensively covered various aspects of the process, including solvent efficiency, process optimisation, and economic considerations. Studies like those conducted by Ahmed *et al.* [17] delved into identifying the most efficient amine solvents for CO_2 capture, focusing on absorption capabilities and capture efficiencies, where MEA was superior to other amine-based solvents. The results obtained also demonstrated that the absorber height, solvent circulation rate and reboiler duty have the most remarkable effects on the CO_2 capture ability.

Birkelund [18] explored the technical nuances of CO_2 absorption and desorption, providing a solid technical foundation for understanding the process. In his work, three different configurations were evaluated for post-combustion CO_2 capture from a combined heat and power plant using chemical absorption. The configurations evaluated are a standard absorption process, a vapour recompression modification, and a lean split with vapour recompression modification, with the lean split with vapour recompression being too complex and having too low flexibility to achieve converged calculations in sensitivity cases.

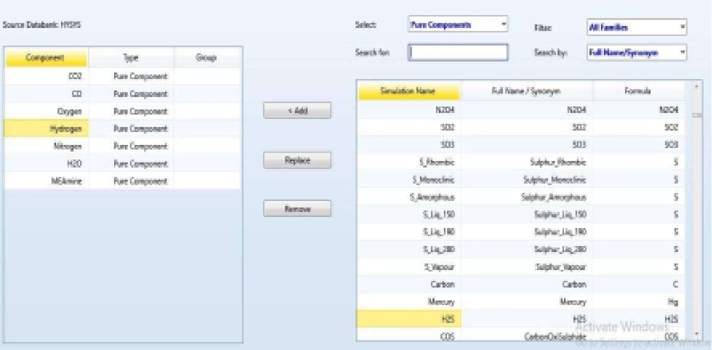
Oluwafemi [19] demonstrated a CO_2 capture process with a CO_2-rich flue gas feed and a CO_2-free effluent using Monoethanolamine (MEA) as absorbent, which captures up to 93% from the stream.

Lars Erik *et al.* [20] focused on the cost of CO_2 capture using equipment cost data from Aspen In-plant and optimum conditions for the heat exchanger and number of plates in the absorber to maximise carbon capture.

However, despite the valuable insights into cost estimation done also by Dehghanizadeh [21] and the specific focus on coal-based power plants in studies like Eviani *et al.* [22], there remains a gap in comprehensive analysis that combines process efficiency, economic viability, and environmental sustainability with an emphasis on optimising operational parameters such as the solvent to feed flow rate ratio and energy comparison to economic value of captured Co_2.

MATERIALS AND METHOD

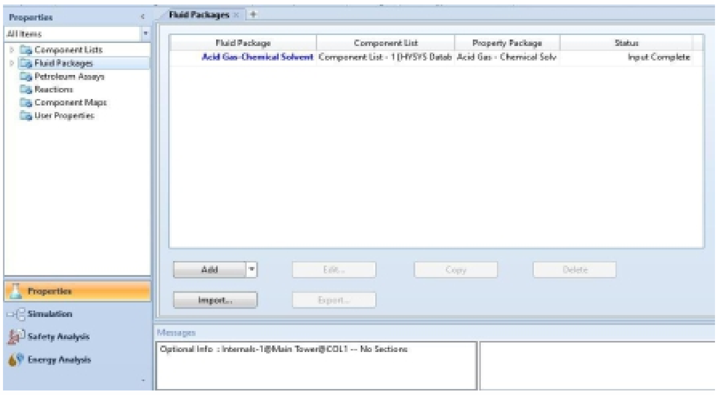
The model utilised was simulated using the flue gas data obtained from the Refinery Fluid Catalytic Cracking (FCC) Unit [19]. The plant was assumed to operate at steady state. The process was simulated using ASPEN HYSYS v.11 with the Acid Gas-chemical solvent fluid package. Figure 4 to 11 shows screenshots of major steps in carried out in the simulation environment. The process flow sheet is shown in figure 4.9.



Component	Type	Group
CO2	Pure Component	
CO	Pure Component	
Oxygen	Pure Component	
Hydrogen	Pure Component	
Nitrogen	Pure Component	
H2O	Pure Component	
MEAmine	Pure Component	

Simulation Name	Full Name / Synonym	Formula
N2O4	N2O4	N2O4
SO2	SO2	SO2
SO3	SO3	SO3
S_Rhombic	Sulphur_Rhombic	S
S_Monoclinic	Sulphur_Monoclinic	S
S_Amorphous	Sulphur_Amorphous	S
S_Liq_150	Sulphur_Liq_150	S
S_Liq_180	Sulphur_Liq_180	S
S_Liq_280	Sulphur_Liq_280	S
S_Vapour	Sulphur_Vapour	S
Carbon	Carbon	C
Mercury	Mercury	Hg
H2S	H2S	H2S
COS	CarbonOxSulphide	COS

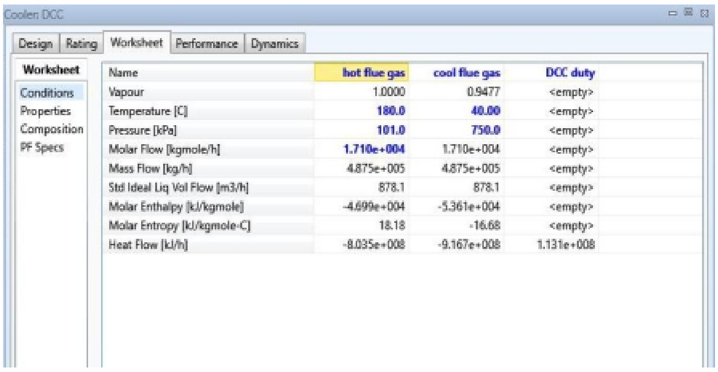
Figure 4: component Selection



Fluid Package	Component List	Property Package	Status
Acid Gas-Chemical Solvent	Component List - 1 [HYSYS Datab	Acid Gas - Chemical Solv	Input Complete

Optional Info : Internals-1@Main Tower@COL1 -- No Sections

Fig. 5: Selection of fluid package



Name	hot flue gas	cool flue gas	DCC duty
Vapour	1.0000	0.9477	<empty>
Temperature [C]	180.0	40.00	<empty>
Pressure [kPa]	101.0	750.0	<empty>
Molar Flow [kgmole/h]	1.710e+004	1.710e+004	<empty>
Mass Flow [kg/h]	4.875e+005	4.875e+005	<empty>
Std Ideal Liq Vol Flow [m3/h]	878.1	878.1	<empty>
Molar Enthalpy [kJ/kgmole]	-4.699e+004	-5.361e+004	<empty>
Molar Entropy [kJ/kgmole-C]	18.18	-16.68	<empty>
Heat Flow [kJ/h]	-8.035e+008	-9.167e+008	1.131e+008

Fig. 6: DCC worksheet

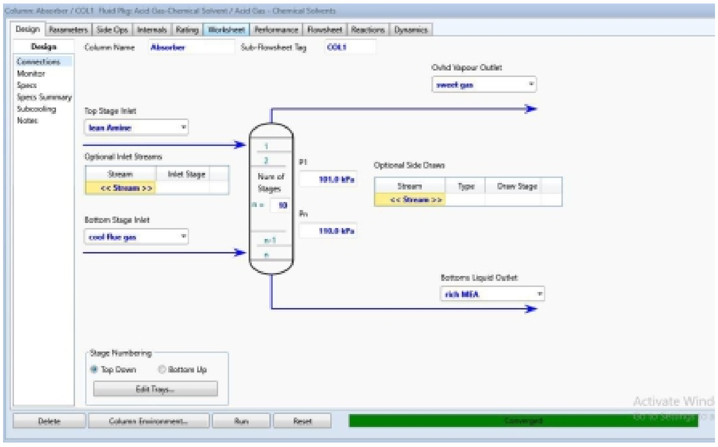
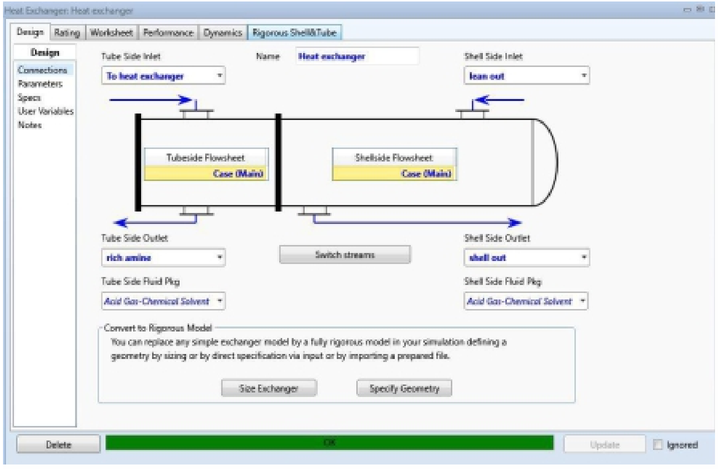
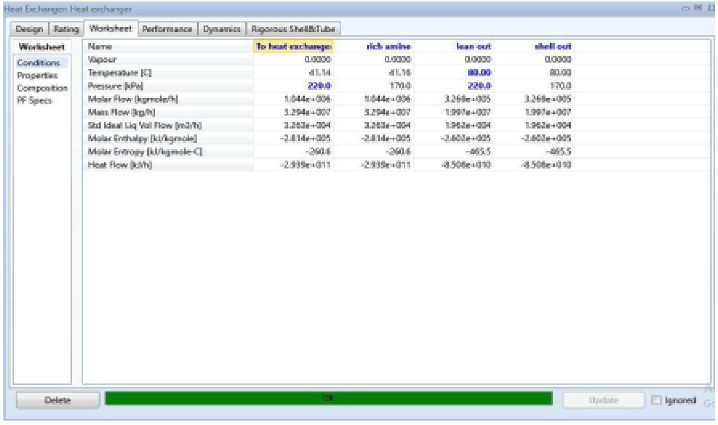


Fig. 7: Column Absorber Worksheet



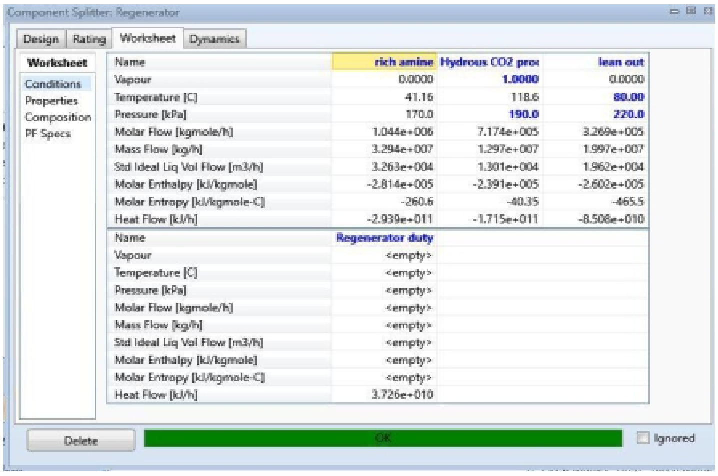
You can replace any simple exchanger model by a fully rigorous model in your simulation defining a geometry by sizing or by direct specification via input or by importing a prepared file.

Fig. 8: Heat Exchanger fluid Specification



Name	To heat exchange	rich amine	lean out	shell out
Vapour	0.0000	0.0000	0.0000	0.0000
Temperature [C]	41.14	41.16	80.00	80.00
Pressure [kPa]	220.0	170.0	220.0	170.0
Molar Flow [kgmole/h]	1.044e+006	1.044e+006	3.269e+005	3.269e+005
Mass Flow [kg/h]	3.294e+007	3.294e+007	1.997e+007	1.997e+007
Std Ideal Liq Vol Flow [m3/h]	3.263e+004	3.263e+004	1.962e+004	1.962e+004
Molar Enthalpy [kJ/kgmole]	-2.814e+005	-2.814e+005	-2.602e+005	-2.602e+005
Molar Entropy [kJ/kgmole-C]	-260.6	-260.6	-465.5	-465.5
Heat Flow [kJ/h]	-2.939e+011	-2.939e+011	-8.508e+010	-8.508e+010

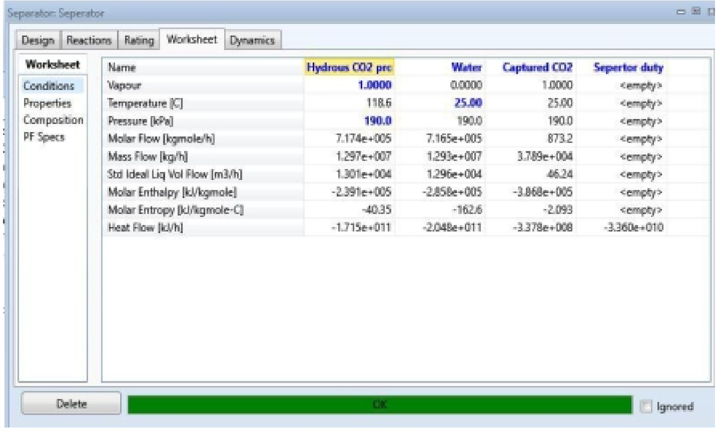
Fig. 9: Heat Exchanger Worksheet



Name	rich amine	Hydrous CO2 pro	lean out
Vapour	0.0000	1.0000	0.0000
Temperature [C]	41.16	118.6	80.00
Pressure [kPa]	170.0	190.0	220.0
Molar Flow [kgmole/h]	1.044e+006	7.174e+005	3.269e+005
Mass Flow [kg/h]	3.294e+007	1.297e+007	1.997e+007
Std Ideal Liq Vol Flow [m3/h]	3.263e+004	1.301e+004	1.962e+004
Molar Enthalpy [kJ/kgmole]	-2.814e+005	-2.391e+005	-2.602e+005
Molar Entropy [kJ/kgmole-C]	-260.6	-40.35	-465.5
Heat Flow [kJ/h]	-2.939e+011	-1.715e+011	-8.508e+010

Name	Regenerator duty
Vapour	<empty>
Temperature [C]	<empty>
Pressure [kPa]	<empty>
Molar Flow [kgmole/h]	<empty>
Mass Flow [kg/h]	<empty>
Std Ideal Liq Vol Flow [m3/h]	<empty>
Molar Enthalpy [kJ/kgmole]	<empty>
Molar Entropy [kJ/kgmole-C]	<empty>
Heat Flow [kJ/h]	3.726e+010

Fig. 10: Regenerator Worksheet



Name	Hydrous CO2 pro	Water	Captured CO2	Sepertor duty
Vapour	1.0000	0.0000	1.0000	<empty>
Temperature [C]	118.6	25.00	25.00	<empty>
Pressure [kPa]	190.0	190.0	190.0	<empty>
Molar Flow [kgmole/h]	7.174e+005	7.165e+005	873.2	<empty>
Mass Flow [kg/h]	1.297e+007	1.293e+007	3.789e+004	<empty>
Std Ideal Liq Vol Flow [m3/h]	1.301e+004	1.296e+004	46.24	<empty>
Molar Enthalpy [kJ/kgmole]	-2.391e+005	-2.858e+005	-3.868e+005	<empty>
Molar Entropy [kJ/kgmole-C]	-40.35	-162.6	-2.093	<empty>
Heat Flow [kJ/h]	-1.715e+011	-2.048e+011	-3.378e+008	-3.360e+010

Fig. 11: Separator worksheet

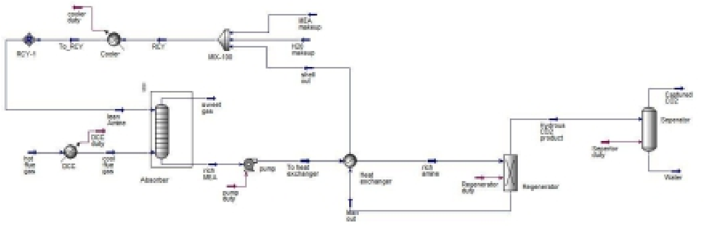


Fig. 12: Simulation Process Flow sheet

In the comprehensive analysis of the simulation outcomes facilitated by Aspen HYSYS, detailed insights into the process's operational efficiency are presented. Table 2 delineates the characteristics and compositions of the feed stream. Following this, Table 3 elucidates the properties and compositions of the product stream, illustrating the transformation achieved through the process. Table 4 presents an exhaustive account of the material streams, cataloguing the flows within the system. The intricacies of material transitions and conservation are further expounded in Table 5, where a detailed material balances is provided, offering a quantitative evaluation of input-output relationships. Lastly, Table 6 consolidates the energy balance, providing a critical assessment of energy conservation and efficiency within the system.

Table 2: Feed Stream Analysis

	H$_2$0 makeup	MEA makeup	hot flue gas
Pressure [kPa]	101	101	101
Temperature [C]	30	30	180
Mass Flow [kg/h]	12888235.8	148.4334396	487535.4027
Std Ideal Liq Vol Flow [m3/h]	12913.07469	0.145839123	878.1318459
Vapor / Phase Fraction	0	0	1
Molar Enthalpy [kJ/kgmole]	-285334.0627	-268597.1479	-46990.06062

Table 3: Product Stream Analysis

	Captured CO$_2$	Water	sweet gas
Pressure [kPa]	190	190	101
Temperature [C]	25	25	39.99775123
Mass Flow [kg/h]	37891.63963	12928061.41	410111.1309
Std Ideal Liq Vol Flow [m3/h]	46.24059387	12960.04557	785.2082335
Vapor / Phase Fraction	1	0	0.999999945
Molar Enthalpy [kJ/kgmole]	-386793.8379	-285809.9711	-10206.81485

Table 4: Material Stream Analysis

Stream Identifier	Pressure [kPa]	Temperature [C]	Mass Flow [kg/h]	Std Ideal Liq Vol Flow [m3/h]	Vapor / Phase Fraction	Molar Enthalpy [kJ/kgmole]
To heat exchanger	220	41.14056494	32935711.9	32627.01397	0	-281392.0589
rich amine	170	41.15730507	32935711.9	32627.01397	0	-281391.5778
lean out	220	80	19969758.85	19620.72781	0	-260236.41
shell out	170	80.00384785	19969758.85	19620.72781	0	-260237.9465
Hydrous CO2 product	190	118.5856766	12965953.05	13006.28616	1	-239099.8829
Captured CO2	190	25	37891.63963	46.24059387	1	-386793.8379
Water	190	25	12928061.41	12960.04557	0	-285809.9711
H20 makeup	101	30	12888235.8	12913.07469	0	-285334.0627
MEA makeup	101	30	148.4334396	0.145839123	0	-268597.1479
RCY	101	75.01900015	32858143.08	32533.94834	0	-277462.7077
To_RCY	101	40	32858143.08	32533.94834	0	-281206.3936
hot flue gas	101	180	487535.4027	878.1318459	1	-46990.06062
cool flue gas	750	40	487535.4027	878.1318459	0.947744154	-53606.32275
sweet gas	101	39.99775123	410111.1309	785.2082335	0.999999945	-10206.81485
rich MEA	110	41.1233353	32935711.9	32627.01397	0	-281396.6158
lean Amine	101	40	32858287.63	32534.09036	0	-281206.3699

Table 5: Material Balance Analysis

Component Identifier	Stream Identifier	Flow Rate In (kgmole/h)	Flow Rate Out (kgmole/h)
Direct Contact Cooler (DCC)	Hot Flue gas	17100	
	Cool flue gas		17100
	Total	**17100**	**17100**
Absorber	Lean Amine	1042335.002	
	Cool flue gas	17100	
	Sweet gas		15098.02335
	Rich MEA		1044336.979
	Total	**1059435.002**	**1059435.002**
MEA Pump	Rich MEA	1044336.979	
	To heat exchanger		1044336.979
	Total	**1044336.979**	**1044336.979**
Heat Exchanger	To heat exchanger	1044336.979	
	Lean out	326924.4055	
	Rich Amine		1044336.979
	Shell out		326924.4055
	Total	**1371261.384**	**1371261.384**
Regenerator	Rich Amine	1044336.979	
	Hydrous CO_2 product		717412.573
	Lean Amine		326924.4055
	Total	**1044336.979**	**1044336.979**
Separator	Hydrous CO_2 product	717412.573	
	Captured CO_2		873.2385762
	Water		716539.3344
	Total	**717412.573**	**717412.573**
Mixer	MEA makeup	2.43	
	H_20 makeup	715405.8	
	Shell out	326924.4055	
	RCY		1042332.635
	Total	**1042332.635**	**1042332.635**
Cooler	RCY	1042332.635	
	To RCY		1042332.635
	Total	**1042332.635**	**1042332.635**

Table 6: Energy Balance Analysis

Component Identifier	Stream Identifier	Energy In (kJ/h)	Energy Out (kJ/h)
Direct Contact Cooler (DCC)	DCC Duty	–	113,138,082.376
Pump	Pump Duty	4,758,807.688	–
Regenerator	Regenerator Duty	37,256,734,278.758	–
Cooler	Cooler Duty	–	3,902,165,995.912
Separator	Separator Duty	33,598,587,522.996	–
Total		70,860,080,609.442	4,015,304,078.287
Net Energy Requirement		**66,844,776,531.154 kJ/h**	

RESULTS AND DISCUSSION

Analysis of the effect of temperature and pressure of the separator vessel on the percentage of captured CO_2 was also carried out. This was made possible using case studies where the percentage captured CO_2 was assigned as an independent variable while varying the temperature and pressure of the separator vessel. Figure 13 and 14 shows the graph obtained when the data obtained was plotted.

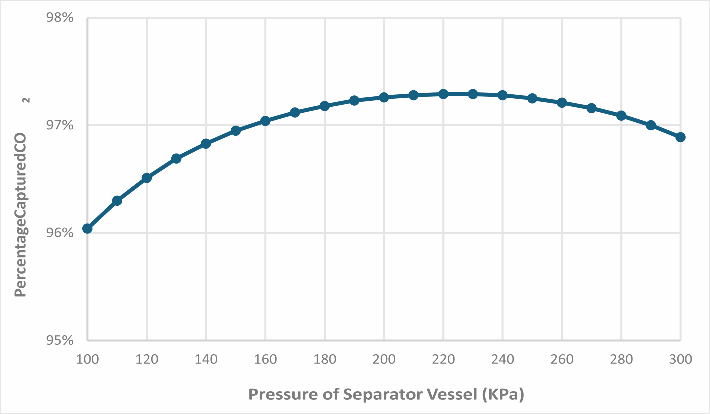


Fig. 13: Effect of Temperature of Separator on Captured Co2

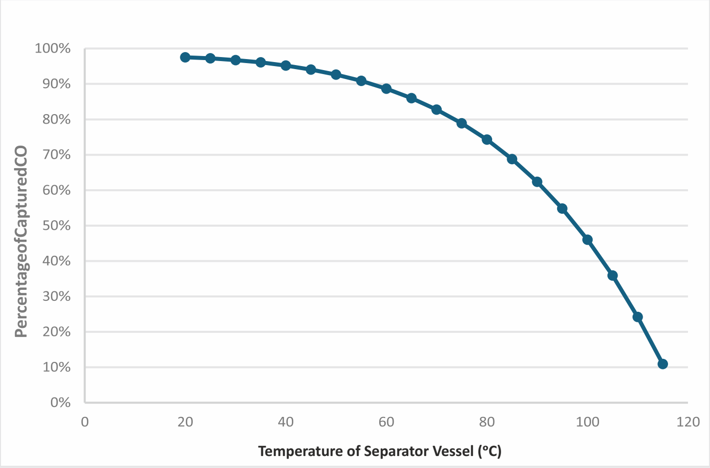


Fig.14: Effect of Pressured of Separator on Captured CO2

Furthermore, a major research gap which is the optimum feed to amine flowrate was examined using a case study. The Feed flowrate was held constant and the ratio of Amine to feed flowrate was varied from 2.8 to 7.0. The resulting mole fraction of CO_2 in sweet gas was tabulated for each ratio and is summarized in figure 15 Formula for ratio is:

$$Ratio = \frac{flowrate\ of\ amine}{flowrate\ of\ feed}$$

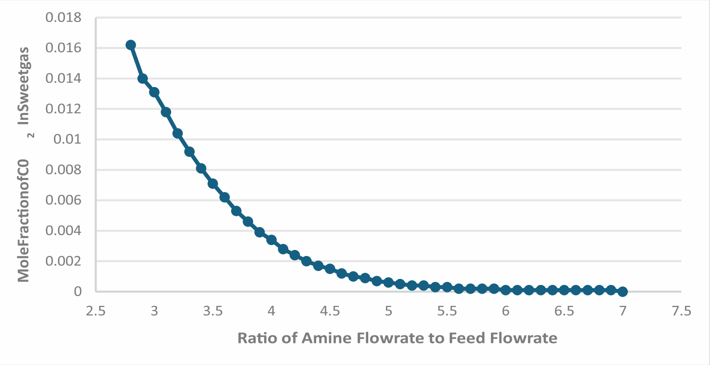


Fig. 15: Amine to feed flowrate Analysis

The outcomes of this investigation highlight significant findings that contribute to narrowing the identified research gap in optimising the solvent to feed flow rate ratio, its impact on energy consumption, and the economic implications of CO_2 capture. Notably, the variation in temperature and pressure of the separator, which is central to the separation of hydrous CO2 from steam and CO_2, indicates a complex relationship between these operating conditions and the efficiency of CO_2 capture.

The observed inverse relationship between the separator temperature and the percentage of captured CO_2, as shown in Fig 13 with an efficiency peak at 25 $^{\circ}$C, underscores the critical role of lower operating temperatures in enhancing CO_2 capture. This phenomenon can be attributed to the increased solubility of CO_2 in the solvent at lower temperatures, which facilitates a more effective separation process. However, the concave downward curve as temperature increases suggests a diminishing return on CO_2 capture efficiency beyond a certain temperature threshold. This finding is essential for optimising the thermal management of the separation process, balancing the need for efficient CO_2 capture with the practical limitations imposed by thermal energy requirements.

Similarly, the pressure variation results, fig 14, exhibiting a peak capture efficiency at approximately 220 KPa, illuminate the pressure-dependency of CO_2 capture processes. The initial increase in capture efficiency with pressure can be explained by the enhanced physical solubility of CO_2 in the solvent under higher pressures. Nonetheless, the subsequent decline in efficiency, even if at a slower rate, points to the diminishing benefits of increased pressure, likely due to the limitations of solvent capacity and potential operational challenges at higher pressures.

The analysis of the solvent-to-feed flow rate ratio reveals a critical insight into the diminishing efficiency gains with higher ratios. The exponential decay curve in fig 15 associated with this variable indicates that while increasing the solvent flow rate relative to the feed can enhance CO_2 capture, the efficiency gains taper off, highlighting a point of diminishing returns.

This observation is pivotal for optimising solvent usage, where an excessive increase in solvent flow rate may not justify the marginal improvements in capture efficiency, especially when considering the associated energy and operational costs.

The findings related to the mole fraction of CO_2 in the sweet gas further illustrate the effectiveness of optimising the solvent to feed flow rate ratio. The achievement of a 100% capture rate at a ratio of 7.0, albeit at the cost of increased solvent usage, presents a significant milestone for CO_2 capture technologies. However, the economic and environmental implications of such high solvent usage warrant careful consideration, particularly in the context of the overall sustainability of the capture process.

CONCLUSION

This investigation provides key insights into optimising the solvent to feed flow rate ratio, impacting energy consumption and the economic feasibility of CO_2 capture systems. The study highlights the importance of operating conditions, revealing that CO_2 capture efficiency peaks at a separator temperature of 25°C and a pressure of 220 kPa. Lower temperatures enhance CO_2 solubility in the solvent, while optimal pressure levels maximise capture efficiency without significant diminishing returns.

The analysis also indicates diminishing efficiency gains with increasing solvent to feed flow rate ratios, emphasising the need to balance enhanced CO_2 capture with associated energy and operational costs. Achieving a 100% capture rate at a ratio of 7.0 underscores the potential for high efficiency, though it necessitates careful consideration of economic and environmental impacts.

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